CH-99-14-3

Comparison of Residential Air Infiltration Rates Predicted by Single-Zone and Multizone Models

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ABSTRACT

Residential air infiltration rates predicted by a detailed multizone computational model are compared with those predicted by a single-zone model. The multizone model is created using the public domain program CONTAM96, which allows the user to break the house into a number of zones connected to one another and the outdoors by leakage paths with user-defined characteristics. Actual floor plans for a ranch-style house and typical published leakage characteristics of residential building components are used to construct a very detailed model with roughly 2,000 zones and 7,000 leakage paths. The leakage path configuration of this multizone model is then validated by performing fan pressurization tests on two houses constructed according to the floor plan used to develop the computational model. At pressure differences typical of infiltration conditions, the leakage of the multizone model is in between that of the two identical houses. Infiltration rates computed by the multizone model for representative outdoor temperatures and wind speeds are then compared to those predicted by the single-zone LBL model. Four ventilation systems are modeled: no mechanical ventilation or exhaust, supply fan only, exhaust fan only, and balanced supply and exhaust fans. Comparisons are initially made based on the single-zone model predictions using typical assumptions. The multizone computational model is then used to calculate more precise wind parameters and building leakage characteristics for use in the single-zone model, and the resulting infiltration is again compared with that predicted by the multizone model. These comparisons show that the predictions of both models are sensitive to the choice of wind-related parameters and that the assumption that leakage is evenly distributed throughout the building envelope has little effect on the predictions of the single-zone model. The predictions of the single-zone model most closely match those of the multizone model when flows are added using a quadrature method that takes into account the flow exponent obtained using the multizone model.

INTRODUCTION

Because infiltration impacts both energy consumption and ventilation rates in residences, there is a need for methods to estimate it reliably. Traditionally, this has been done with both simplified single-zone models and with more complex multizone models. Simplified single-zone models have the advantage of being fast and simple to use, and their results provide enough information for most analyses. Multizone models allow a number of distinct pressure regions and typically require significantly more detailed input from the user, with the benefit of more detailed results. Unlike the single-zone model used in this study, the multizone model calculates the flow through each individual leakage path. This makes multizone models well suited to parametric studies and other detailed investigations.

This study was motivated by an investigation of the effects of changes in individual envelope components and insulation type on overall house leakage and annual infiltration-related energy consumption. The comparisons that were desired required modeling of flows through individual stud spaces. This level of detail required the use of a multizone model with an unusually large number of zones and leakage paths. With the computer time to obtain a steady-state solution for a computational model of this size averaging 15 to 20 minutes (using a 586/90MHz personal computer), an 8,760-

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hour analysis was not feasible. To resolve this dilemma, the multizone computational model was used to obtain input values for a single-zone model, which was used for the annual analysis. To justify this approach, infiltration rates predicted by the single-zone LBL model and the CONTAM96 multizone model were compared for representative values of wind speed, indoor-outdoor temperature difference, and fan size.

In addition to providing a comparison of infiltration rates predicted by the single-zone and multizone models, this study offered an opportunity to examine the impact of assumptions that are typically made by users of these models. These include the effects of local terrain on wind speed and the distribution of leakage between walls, floor, and ceiling. Because the multizone model provides an idealized situation with which to compare, difficulties in measuring wind speed and leakage distribution were avoided, and the effect of transients was also eliminated.

SINGLE-ZONE MODELS

Numerous simplified models that predict infiltration have been developed (ASHRAE 1997). Typically, these models assume that a single zone can represent the entire building and are therefore appropriate only for small buildings such as residences. One such model that has been widely used is the LBL model (Sherman and Grimsrud 1980). This model predicts infiltration based on the results of fan pressurization tests. The user must also provide values for wind speed and outdoor temperature, a description of local terrain and shielding, and information regarding the distribution of leakage between floor, ceiling, and walls.

The LBL model characterizes building airtightness using the results of fan pressurization testing. Typically, the house is pressurized using a fan, and flow is recorded at a variety of indoor-outdoor pressure differences. These readings are then fitted to the power law relationship,

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

where

Q = airflow rate,

ΔP = indoor-outdoor pressure difference,

C, n = constants empirically determined for the best possible curve fit.

Results of pressurization tests are often reported either as a flow rate at a given pressure difference or as an equivalent leakage area defined at a pressure difference. Airflow rate is converted to equivalent leakage area according to the relation

$$A_o = Q_r \frac{\sqrt{\rho / 2\Delta P_r}}{C_D} , \tag{2}$$

where

A_o = equivalent leakage area,

ΔP_r = reference pressure difference,

Q_r = airflow rate at ΔP_r, taken from curve fit to pressurization test data,

ρ = air density,

C_D = discharge coefficient.

The LBL model uses pressurization test results to characterize building airtightness as an equivalent leakage area at a reference pressure of 0.016 in. of water (4 Pa) and with discharge coefficient $C_D = 1.0$.

In the LBL model, the contributions of stack and wind effects to infiltrat on are calculated separately and combined using simple quadrature:

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{3}$$

where

Q = total infiltration airflow,

Q_s = infiltration caused by stack effects,

Q_w = infiltration caused by wind effects.

The effects of ventilation fans can also be considered. Sherman (1992) provides relationships for adding balanced and unbalanced ventilation fans. For general cases in which little is known about the details of a building, s mplifying assumptions can be made and the following relationship results:

$$Q = Q_{bal} + \sqrt{Q_s^2 + Q_w^2 + Q_{unbal}^2} \tag{4}$$

where

Q_{bal} = airflow from balanced supply and exhaust fans,

Q_{unbal} = airflow from unbalanced fans.

Some details about the weather and the distribution of leakage in the building envelope must be known to obtain the infiltration rates due to stack and w nd effects. These rates are calculated as

$$Q_s = f_s A_o (\Delta T)^{1/2} \tag{5}$$

$$Q_w = f_w A_o v' , \tag{6}$$

where

A_o = equivalent leakage area of house, calculated at ΔP = 0.016 in. of water (4 Pa);

ΔT = indoor-outdoor temperature difference;

v' = wind velocity measured at a nearby weather station;

f_s = stack factor;

f_w = wind factor.

In Equations 5 and 6, the stack and wind factors, f_s and f_w, take into account the effects of the distribution of leakage between the walls, floor, and ceiling and adjust the measured wind velocity to site-specific conditions. Sherman and Modera (1986) derive these factors as

$$f_s = \frac{2}{3}\left(1+\frac{R}{2}\right)\frac{\sqrt{2\beta_o(1-\beta_o)}}{\sqrt{\beta_o}+\sqrt{1-\beta_o}}, \qquad (7)$$

$$f_w = C'(1-R)^{1/3}\left(\frac{\alpha}{\alpha'}\right)\left[\frac{\left(\frac{H}{10\text{ m}}\right)^{\gamma}}{\left(\frac{H'}{10\text{ m}}\right)^{\gamma'}}\right], \qquad (8)$$

where

H	=	elevation at top of building wall,
H'	=	height of weather measurement,
C'	=	shielding coefficient,
α, γ	=	terrain parameters,
R	=	fraction of total building leakage area in floor and ceiling,
β_o	=	dimensionless height of the neutral pressure plane,
Primed quantities	=	wind measurement location,
Unprimed quantities	=	site location.

Typically, a number of assumptions must be made in computing stack and wind factors. The distribution of leakage within the building envelope is often unknown, and it may be difficult to determine values for R and β_o. In this case, leakage is often assumed to be evenly distributed among the floor, ceiling, and walls, in which case both R and β_o equal 0.5. The terrain parameters α and γ are estimated by choosing one of five standard terrain classes, which are described according to topography and nearby development. These values adjust the measured wind speed for site-specific conditions. The shielding coefficient (C') is also estimated by choosing one of five standard shielding classes, which describe the shielding situation at the building. The shielding coefficient replaces wind pressure coefficients, which are functions of the wind angle and the building orientation, shape, and shielding. Because the LBL model is a simplified method that does not take into account wind direction, wind pressure coefficients for various shielding conditions are averaged over the surface area of the building and the shielding coefficient is obtained (Sherman and Modera 1986).

The LBL model has been extensively validated using experimental data (Sherman and Modera 1986). Predicted infiltration has been compared with results of short-term tests at 15 sites in which the infiltration was measured with a tracer gas decay test and the weather with a portable weather tower. On average, the predicted infiltration was within about 2% of the measured infiltration, and most of the individual predictions were within 20%. Sherman and Modera also performed more detailed tests in which infiltration was measured over time and compared to that predicted by the model. These tests show that the predictions of the model are able to track the experimental results quite well in both a simple test structure and an occupied test house.

Persily and Linteris (1983) compared infiltration rates measured in eleven identical homes with those predicted by four single-zone models. In that study, weather data used in the single-zone analyses were averaged for three local weather stations. They found that for the terrain class most closely matching the site conditions, the LBL model overpredicted infiltration by 30% to 71%, depending on the assumed distribution of leakage. Changing the terrain class to a more obstructed situation improved the correlation of the results considerably, suggesting that the wind can be overpredicted by the LBL model under some circumstances.

A study of 472 all-electric homes located in the Pacific Northwest produced similar results (Palmiter et al. 1991). Time-averaged perfluorocarbon tracer tests provided measured infiltration rates, which were compared to those predicted by the LBL model. Wind was measured at the weather station closest to each home, and terrain factors were estimated by field contractors. Infiltration rates predicted by the model averaged 40% greater than those measured in the field tests, and the amount of overprediction correlated strongly to the amount of wind-induced infiltration predicted by the model. New shielding and terrain factors were then calculated, and the correlation of results improved considerably. This result also suggests that overestimation of wind effects can lead to unrealistic predictions when using the LBL model without on-site wind measurements.

MULTIZONE MODELING

A 1992 survey revealed the existence of over 50 multizone airflow models (Feustel and Dieris 1992). These models were developed primarily to understand building infiltration, the transport of airborne particles, and the movement of smoke in fire situations. Of these, less than one-third are available to the public.

The public domain multizone modeling program CONTAM96 (Walton 1997) was selected for this study. In CONTAM96, a building can be represented by any number of zones connected to one another and to the outdoors via leakage paths with user-defined characteristics. Airflow between zones is calculated as a function of the pressure difference between them. Flows within the building are obtained by assuming quasi-steady conditions, such that the sum of the flows into and out of each zone must equal zero. A detailed explanation of the mathematical basis for this model can be found in the model documentation (Walton 1997).

Because the multizone model allows each leakage path to be defined individually, each can be placed at the proper elevation on an exterior wall that faces in the proper direction with respect to wind. The locations and characteristics of these individual leakage paths define the overall building leakage in the multizone model. Therefore, if realistic values are assumed for these leakage paths, fan pressurization testing is not required. Although much more extensive input is needed than for the single-zone LBL model, the problem of estimating the neutral level height and the leakage distribution is eliminated. Of course, the characteristics of each individual leak must still be estimated, but the process of accounting for leaks individually allows the user to realistically estimate the leakage of a house based on its design.

An additional benefit of multizone modeling is the ability to predict infiltration for a variety of wind directions. For each leakage path, the user can specify a wind pressure coefficient profile, describing the distribution of wind pressure on the building walls for various wind directions. For this analysis, wind pressure coefficients for low-rise buildings published by ASHRAE (1997) were used. The wind velocity at the site is estimated using coefficients similar to α and γ in the LBL model. Again, these coefficients are chosen according to a subjective description of terrain at the site.

The primary advantage of using a multizone model to predict infiltration is in the level of detail that can be accommodated. Any number of zones and paths can be defined, allowing the user to obtain detailed results that show the contributions of each path to the overall infiltration. Because wind direction can be considered, a multizone model could also be used to predict the effects of house orientation relative to wind direction.

Several sources of uncertainty still exist in multizone simulations. One of these is weather. Like the LBL model, CONTAM96 requires the user to input the wind velocity at a nearby weather station and then adjusts this value based on the local terrain and the height of the building. Because local wind patterns can be very complex, these relationships are not exact and can complicate efforts to correlate simulation results to experimental data, especially when wind measurements are not taken at the site. In addition, the user must choose wind-related factors based on individual judgement and interpretation. Characteristics of individual leakage paths provide another significant source of uncertainty. While typical leakage values can be found in the literature and engineering judgements can be made as to whether the leakage of any building component is greater than or less than the typical, it is impractical to measure the exact leakage characteristics of each path for a particular building.

The solutions obtained by the CONTAM96 model have also been extensively validated against experimental data and analytical solutions. Upham (1997) provides a detailed summary of validation efforts undertaken for this code. Its mathematical basis has been documented by Walton (1984, 1989).

PROTOTYPE HOUSE

The house used for this study is a single-story ranch-style house with an attached garage and a partial basement. The house also has two ventilated crawl spaces located adjacent to the basement. Floor plans of the prototype house are shown in Figure 1. Two houses constructed according to this floor plan (called House B and House C) are located adjacent to one another on a site in central Ohio. The houses were constructed for research purposes and have never been occupied. However, care was taken in their design and construction to make them as realistic as possible. Openings for electrical outlets, light switches, and plumbing penetrations have been located exactly as they would be in an occupied residence. Typical local construction techniques were used so that the airtightness of the houses would be representative of other local construction.

A very detailed multizone model of the prototype house was developed prior to any pressurization testing of the two houses. All leakage paths used in the model were located according to the detailed floor plans, elevation drawings, and specifications that were used to construct the houses. "Best estimate" effective leakage areas published by ASHRAE (1997) provided the values input into the model for each leakage path. Because airflow within the house walls was investigated, each stud space was modeled as eight separate zones, stacked four zones high and two zones deep. Leakage paths connecting these eight zones are defined by the permeability of the fiberglass batt insulation used in the test houses (Wilkes and Graves 1993). Separate zones, connected by open doors, represent each room of the house. Simulations were performed with closet doors and doors to the outside, basement, and garage closed.

The detailed multizone model required nearly 2,000 zones and 7,000 leakage paths to describe a one-story ranch-style house. This level of detail was necessary to model flow

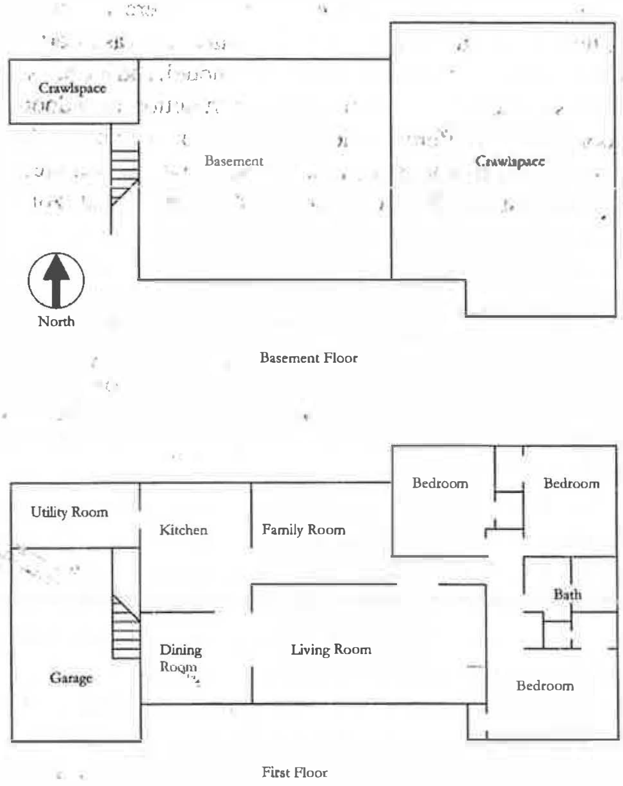

Figure 1 *Prototype house floor plan.*

through the walls with the level of detail required by the study. However, this is not a typical usage of multizone models. In most cases, the house shown in Figure 1 would be modeled by 10 to 20 zones (see, for example, Emmerich and Persily 1995). For comparison, a more typical 20-zone model of the house was also constructed, with rooms, closets, basement, and attic spaces representing separate zones. Where possible, leakage paths such as doors, windows, plumbing, and lighting penetrations were modeled using exactly the same leakage characteristics as were used in the 2,000-zone model. The primary difference between the two models is that leakage through the walls was simplified substantially.

Validation of the Computational Model

The airtightness of the two identical houses was measured with extensive fan pressurization testing. The repeatability of each test was checked by making frequent duplicate measurements, and the standard deviation was found to be about 1% (Yuill 1997). For these tests, interior doors were open, and all closet doors, exterior doors, garage doors, and basement doors were closed. Readings taken at pressures between 0.06 in. w.g. (15 Pa) and 0.20 in. w.g. (50 Pa) were recorded and fit to the power law relationship given by Equation 1. Results of these tests and the equations obtained from curve fitting are plotted in Figure 2. The leakage of the two houses was not identical, due to slight differences in construction. At 0.12 in. w.g. (30 Pa), House C is roughly 8% leakier than House B.

For comparison, fan pressurization tests were simulated using the computational models. A simulated fan was inserted into the front door of each computational model, and the house was pressurized. A plot of airflow as a function of indoor-outdoor pressure difference yields an equation similar to that obtained for the two houses. Figure 2 also shows plots of pressurization test results from the 2,000-zone and 20-zone computational models. At 0.12 in. w.g. (30 Pa), roughly 7% less leakage is predicted by the 20-zone model compared with the 2,000-zone model. Therefore, the difference between the predictions of the two models is roughly the same as the difference between the two identical houses.

The results taken from the multizone models agree quite well with the results obtained in the two houses. The most notable difference between the results is in the value of the exponent, n. The computational models somewhat underpredict n as approximately 0.65 compared to that obtained from pressurization testing, which averages 0.71. This is because most of the leakage paths for the computational models were input as leakage areas measured at 4 Pa with a flow exponent of 0.65, a value typical of residential construction. As a result, the computational models underpredict the leakage at high pressure differences. In general, however, the predictions of the model agree quite well with the leakage measured in the houses. At indoor-outdoor pressure differences less than 0.1 in. w.g. (25 Pa), the leakage predicted by the 2,000-zone computational model is in between those measured for the two "identical" houses. Lower leakage values are predicted by the 20-zone computational model; however, these are between that experienced in the two actual houses for pressures less than 0.05 in. w.g. (12.5 Pa). Therefore, the predictions of both models fall between that experienced in the two "identical" houses for indoor-outdoor pressure differences typical of infiltration situations. Table 1 shows the leakage predicted by the curve fits for the models, the two houses, and the average of the two houses at three commonly reported pressures. At 0.016 in. w.g. (4 Pa) and 0.0410 n. w.g. (10 Pa), the leakage predicted by both models is between that measured in the two houses.

It should be emphasized that the close agreement of the mult zone model predictions and the house measurements was

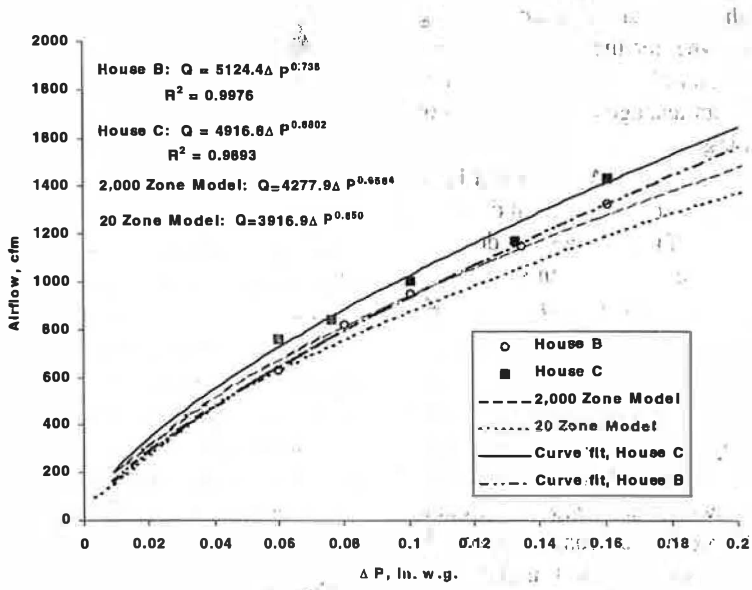

Figure 2 Fan pressurization test results.

TABLE 1
House Airtightness at Three Commonly Reported Pressure Differences

Pressure in. w.g. (Pa)	2,000-Zone Model cfm (m^3/s)	20-Zone Model cfm (m^3/s)	House B cfm (m^3/s)	House C cfm (m^3/s)	Average, Houses B and C cfm (m^3/s)
0.016 (4)	284.3 (0.134)	266.5 (0.126)	243.1 (0.115)	296.2 (0.140)	269.7 (0.127)
0.040 (10)	518.8 (0.245)	483.4 (0.228)	478.1 (0.226)	552.4 (0.261)	515.3 (0.243)
0.121 (30)	1067.0 (0.504)	992.6 (0.468)	1075.5 (0.508)	1166.2 (0.550)	1120.9 (0.529)

achieved without any use of house airtightness data in the model. Only the geometry of the houses was used. All airtightness data were estimated using tabulated values and from first principles before examining the measured airtightness of the houses.

Tests were also performed in the two real houses to calculate the airflow through the floor. This was done by performing a number of tests on the houses with the basement open and closed to the outside. Yuill (1997) derives an expression for floor leakage and reports results in the form of equivalent leakage area at 30 Pa. Table 2 compares this leakage to that predicted by the 2,000-zone computational model, using independently estimated leakage properties. The floor leakage predicted by the model is roughly 12% higher than the average leakage measured by the fan pressurization tests. This discrepancy may be explained by the discovery of a vapor barrier (not included in the original specifications and therefore not taken into account in the model) under the floor of the two test houses. Given this discovery, the multizone model could be adjusted to more closely resemble the test houses. However, since this vapor barrier is not typically a part of local construction, the multizone model was not altered for the remainder of the study.

TABLE 2
Floor Leakage at 0.121 in. w.g. (30 Pa)

Pressure in. w.g. (Pa)	2,000-Zone Model cfm (m^3/s)	House B cfm (m^3/s)	House C cfm (m^3/s)	Average, Houses B and C cfm (m^3/s)
0.121 (30)	400 (0.189)	387 (0.183)	324 (0.153)	356 (0.168)

ANALYSIS

Representative simulations were performed using the 2,000-zone computational model of the prototype house and compared with the predictions of the single-zone LBL model. In the single-zone analysis, leakage was initially assumed to be evenly distributed within the building envelope ($R = \beta_o = 0.5$). Wind effects were evaluated for no wind and for an 18 mph (8 m/s) wind speed, striking each of the four faces of the building. Stack effects were evaluated at indoor-outdoor temperature differences of 0°F and 73.4°F (23°C). Infiltration rates due to wind (in one direction) and stack effects were also predicted for cases with unbalanced supply and exhaust fans and for balanced fans. Unbalanced fan flows of 45 cfm (0.02124 m^3/s) and balanced fan flows of 20 cfm (0.00944 m^3/s) were modeled. To simulate the effects of choosing among subjective descriptions for wind conditions, these were initially used for both the single-zone and multizone models. In the CONTAM96 simulations, wind was simulated for "suburban" conditions. Infiltration was predicted by the single-zone model for the two terrain classes closest to this description. Table 3 and Figure 3 compare the results of the CONTAM96 simulation with the results of the single-zone model. The wind directions reported in Table 3 indicate the direction from which the wind blows, with a zero-degree wind blowing from the north, a 90-degree wind blowing from the east, etc.

Inspection of the regression plot in Figure 3 reveals many trends in the predictive capabilities of the LBL model. In Figure 3, the x-axis represents the infiltration rate calculated by CONTAM96. The predictions of the LBL model are plotted on the y-axis for the two terrain classes with descriptions most closely matching the CONTAM96 terrain description. The solid line represents perfect agreement between the two models, and the large and small dashed lines indicate deviations of ±10% and ±20%, respectively.

Infiltration rates predicted by the LBL model for the four cases in which wind was not considered were all within 10% of the CONTAM96 prediction. The best of these estimates was for the cases with no fan and with balanced fans. When unbalanced exhaust and supply fans are added, infiltration is somewhat underpredicted but still within 10%. This underprediction is slightly more pronounced for exhaust fans than for supply fans.

Perhaps the most striking result shown in Figure 3 is the effect of the choice of terrain class on the wind-related infiltration predicted by the LBL model. The two terrain classes plotted in Figure 3 were chosen because their subjective descriptions best matched that used in the CONTAM96 model. When terrain class III is chosen, the infiltration due to wind alone is overpredicted by 50% or more. When wind effects are combined with unbalanced fans, the predictions look somewhat better, but this is because the overpredicted wind mitigates the effects of underpredictions caused by adding unbalanced fans. Predictions using terrain class IV agree much more closely with the computational model, but the infiltration due to wind alone is still overpredicted by an average of 20%. Because the difference in predicted infiltra-

TABLE 3
Infiltration Predicted by CONTAM96 and LBL Model
(with Standard Wind Descriptions and Evenly Distributed Leakage)

Wind Speed mph (m/s)	Wind Direction Degrees	Temperature Difference °F (°C)	Fans	CONTAM96 Infiltration cfm (m^3/s)	LBL Infiltration cfm (m^3/s)	LBL Infiltration cfm (m^3/s)
				"Suburban" Terrain	Rural (Terrain Class III)	Urban (Terrain Class IV)
17.9 (8)	0	0	None	58.1 (0.0274)	107.3 (0.0506)	78.7 (0.0371)
17.9 (8)	90	0	None	65.1 (0.0307)	107.3 (0.0506)	78.7 (0.0371)
17.9 (8)	180	0	None	72.1(0.0340)	107.3 (0.0506)	78.7 (0.0371)
17.9 (8)	270	0	None	65.1(0.0307)	107.3 (0.0506)	78.7 (0.0371)
0		73.4 (23)	None	89.7 (0.0423)	93.0 (0.439)	93.0 (0.0439)
17.9 (8)	0	73.4 (23)	None	126.7 (0.0598)	142.0 (0.0670)	121.9 (0.0575)
0		73.4 (23)	Supply	109.1 (0.515)	103.3 (0.0488)	103.3 (0.0488)
17.9 (8)	0	0	Supply	93.3 (0.0440)	116.4 (0.0549)	90.7 (0.0428)
17.9 (8)	0	73.4 (23)	Supply	144.3 (0.0681)	149.0 (0.0703)	129.9 (0.0613)
0		73.4 (23)	Exhaust	114.4 (0.0540)	103.3 (0.0488)	103.3 (0.0488)
17.9 (8)	0	0	Exhaust	100.3 (0.0473)	116.4 (0.0549)	90.7 (0.0428)
17.9 (8)	0	73.4 (23)	Exhaust	153.1 (0.0723)	149.0 (0.0703)	129.9 (0.0613)
0		73.4 (23)	Balanced	109.1 (0.0515)	113.0 (0.0533)	113.0 (0.0533)
17.9 (8)	0	0	Balanced	77.4 (0.0365)	127.3 (0.0601)	98.7 (0.0466)
17.9 (8)	0	73.4 (23)	Balanced	147.8 (0.0698)	162.0 (0.0765)	141.9 (0.0670)

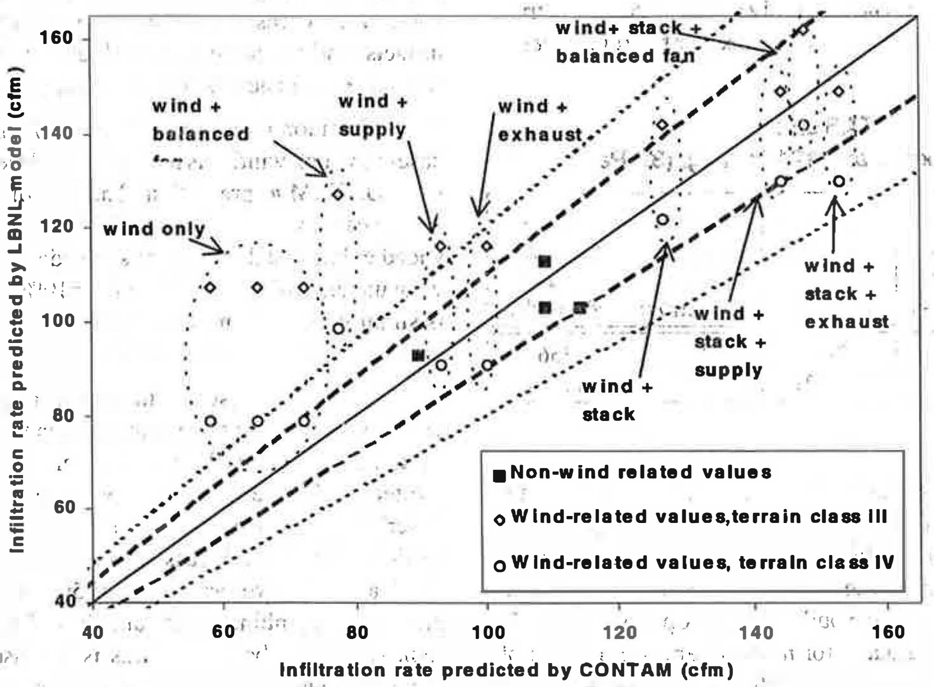

Figure 3 *Regression plot of infiltration predicted by CONTAM96 and LBL model (with standard wind descriptions and evenly distributed leakage).*

tion for these two terrain classes was so pronounced, a more detailed investigation of the specification of wind in each of the models was undertaken.

Specification of Wind Conditions

Both the CONTAM96 model and the LBL model allow the user to make choices about the relationship between wind measured at a nearby weather station and the wind condition actually found at the building site. There are essentially two adjustments that can be made. First, measurements taken at the weather station must be adjusted for the differences between terrain at the site and at the weather station. Second, measurements also must be adjusted to take into account the height of the building being modeled.

In the LBL model, the relationship between wind speed at the top of the building wall (v) and the wind speed measured at a nearby weather station (v') is given as (Sherman and Modera 1986)

$$v = v'\left[\frac{\alpha\left(\frac{H}{10m}\right)^{\gamma}}{\alpha'\left(\frac{H'}{10m}\right)^{\gamma'}}\right]. \quad (9)$$

In Equation 9, unprimed quantities relate to the site and primed quantities describe the weather tower location. H represents the height of the top of the wall in meters and H' represents the height of the weather tower reading, usually 10 m. The quantities α and γ are terrain parameters, which are selected from one of five standard terrain classes by the user. Recommended values of these constants are shown in Table 4.

The CONTAM96 wind model adjusts the wind velocity as follows:

$$v = v'A\left(\frac{H}{H'}\right)^{a}. \quad (10)$$

Here, the constants A and a are selected to describe the terrain at the building site (Walton 1997). Values recommended by the CONTAM96 user's manual are shown in Table 5.

TABLE 4
Standard Terrain Constants for Use with LBL Model (Sherman and Modera 1986)

Class	α	γ	Description
I	1.30	0.10	Ocean or other body of water with at least 5 km or unrestricted expanse
II	1.00	0.15	Flat terrain with some isolated obstacles
III	0.85	0.20	Rural areas with low buildings, trees, or other scattered obstacles
IV	0.67	0.25	Urban, industrial, or forest areas or other built-up area
V	0.47	0.35	Center of large city or other heavily built-up area

TABLE 5
Standard Terrain Constants for Use with CONTAM96 Model (Walton 1997)

A	a	Description
1.00	0.15	Airport
0.6	0.28	Suburban
0.35	0.40	Urban

Since weather measurements are typically taken at airports (Terrain Class 2 for the LBL model) at a height of 10 m, the term in Equation 9 that describes the measurement site is often equal to one. In this case, Equations 9 and 10 are equivalent, with constants $A = \alpha$, and exponents $a = \gamma$. To accurately compare infiltration predicted by CONTAM96 and the LBL model under windy conditions, both models must assume the same wind velocity at the site.

For the building described, with a top of wall elevation of 8 ft (2.43 m), Equations 9 and 10 can be reduced to the form

$$v = Bv', \quad (11)$$

with the factor B as a constant describing the adjustment of wind for building height and terrain. Table 6 shows values of B obtained for this building using the standard terrain descriptions presented by the LBL and CONTAM96 models. Wind adjustments for airport-like terrain (CONTAM96 model) and LBL Terrain Class II are nearly identical. For other conditions, the LBL adjustment results in consistently higher wind velocities at the site. For example, Terrain Class III conditions produce wind velocities that are 1.6 times higher than the "suburban" condition in CONTAM96. The perhaps more realistic comparison of Terrain Class IV with the same "suburban" condition overpredicts wind by a factor of 1.16. Likewise, wind velocities predicted by Terrain Class V are higher than those calculated for "urban" areas by a factor of 1.44. This observation explains the higher infiltration predicted by the LBL model for both terrain classes compared, as shown in Table 3.

Differences in the factors reported in Table 6 indicate that the LBL model predictions cannot be expected to match those

TABLE 6
Wind Adjustment Factors for Local Terrain

Terrain Class	Model	B
II: Flat with isolated obstacles	LBL	0.809
III: Rural with low, scattered obstacles	LBL	0.641
IV: Urban, industrial, or forest	LBL	0.470
V: Center of large city	LBL	0.286
Airport	CONTAM96	0.808
Suburban	CONTAM96	0.404
Urban	CONTAM96	0.199

of CONTAM96 when either Terrain Class III or IV is used and that a true comparison of the two models would require selection of wind-related parameters to produce identical site wind velocities. However, the results of such a comparison are quite relevant to real situations in which the effects of terrain must be estimated and assessed by users of either model. The significant difference that results from choosing Terrain Class III in this case indicates that the choice of terrain class must be made with care because if the terrain class closest to the actual situation is not chosen, errors of significant magnitude can result. However, comparison with predictions for Terrain Class IV (the closest of the five classes to the condition modeled using CONTAM96) results in overprediction of wind by 10%. Since real terrain conditions will not always perfectly match the categories listed in Table 4, uncertainties of this magnitude can be expected when using either the LBL or CONTAM96 models without wind measurements taken at the site.

Refinements to LBL Model Assumptions

In order to compare identical wind situations, the LBL analysis was performed using terrain constants that allow the wind velocity at the building to exactly match that used by the CONTAM96 model. In comparing the two models, the terrain constants for either could have been changed to match the other. The LBL model was changed because it is simpler and the analysis is less time consuming. In the adjusted analysis, Terrain Class II conditions at the measurement site and terrain constants of $\alpha = 0.60$ and $\gamma = 0.28$ at the building site were used. This reduces the wind parameter, f_w, from 0.0895 (Terrain Class IV) to 0.0769. Table 7 compares infiltration predicted using these values to that predicted by the CONTAM96 model.

A further refinement to the LBL model can be made using results from the CONTAM96 simulations. The LBL model predictions shown in Figure 3 assume an even leakage distribution ($R = 0.5$ and $\beta_o = 0.5$). However, these quantities can be calculated using the multizone model. The height of the neutral pressure plane was obtained by running a simulation in which only stack effect was present. The pressure differences across one leakage path located just below and one path located just above the neutral pressure plane were linearly interpolated to obtain the elevation at which there was zero pressure drop across the house wall. The neutral pressure plane was thus located at an elevation of 3.021 ft (0.921 m) above the floor, a dimensionless height of 0.378. The fraction of house leakage area in the floor and ceiling was obtained by performing additional fan pressurization tests on the multizone model with all leakage paths not located in the floor or ceiling deleted. The airflow at 0.016 in. w.g. (4 Pa) was then used to obtain an equivalent leakage area for the floor and ceiling. This was then divided by the leakage area of the entire house to obtain the fraction of leakage in the floor and ceiling, $R = 0.5214$. An analysis using these adjusted values as well as the adjusted wind profile was then performed. Results are shown in the far right column of Table 7.

The results shown in Table 7 are also presented as a regression plot in Figure 4. These results match the CONTAM96 predictions much more closely, with all predictions within 20%. In all cases, the changes in the floor-ceiling leakage fraction (R) and the height of the neutral level (β_o) had

TABLE 7
Infiltration Predicted by CONTAM96 and LBL Model (with Adjustments to Wind and Leakage Distribution)

Wind Speed mph (m/s)	Wind Direction Degrees	Temperature Difference °F (°C)	Fans	CONTAM Infiltration cfm (m^3/s)	LBL Infiltration cfm (m^3/s)	LBL Infiltration cfm (m^3/s)
					Adjusted Wind Condition	Adjusted Wind R and β
17.9 (8)	0	0	None	58.1 (0.0274)	67.6 (0.0319)	66.9 (0.0316)
17.9 (8)	90	0	None	65.1 (0.0307)	67.6 (0.0319)	66.9 (0.0316)
17.9 (8)	180	0	None	72.1 (0.0340)	67.6 (0.0319)	66.9 (0.0316)
17.9 (8)	270	0	None	65.1 (0.0307)	67.6 (0.0319)	66.9 (0.0316)
0		73.4 (23)	None	89.7 (0.0423)	93.0 (0.0439)	91.6 (0.0432)
17.9 (8)	0	73.4 (23)	None	126.7 (0.0598)	115.0 (0.0543)	113.4 (0.0535)
0		73.4 (23)	Supply	109.1 (0.0515)	103.3 (0.0488)	102.1 (0.0576)
17.9 (8)	0	0	Supply	93.3 (0.0440)	81.2 (0.0383)	80.6 (0.0380)
17.9 (8)	0	73.4 (23)	Supply	144.3 (0.0681)	123.5 (0.0583)	122.0 (0.0576)
0		73.4 (23)	Exhaust	114.4 (0.0540)	103.3 (0.0488)	102.1 (0.0482)
17.9 (8)	0	0	Exhaust	100.3 (0.0473)	81.2 (0.0383)	80.6 (0.0380)
17.9 (8)	0	73.4 (23)	Exhaust	153.1 (0.0723)	123.5 (0.0583)	122.0 (0.0576)
0		73.4 (23)	Balanced	109.1 (0.0515)	113.0 (0.0533)	111.6 (0.0527)
17.9 (8)	0	0	Balanced	77.4 (0.0365)	87.6 (0.0413)	86.9 (0.0410)
17.9 (8)	0	73.4 (23)	Balanced	147.8 (0.0698)	135.0 (0.0637)	133.4 (0.0630)

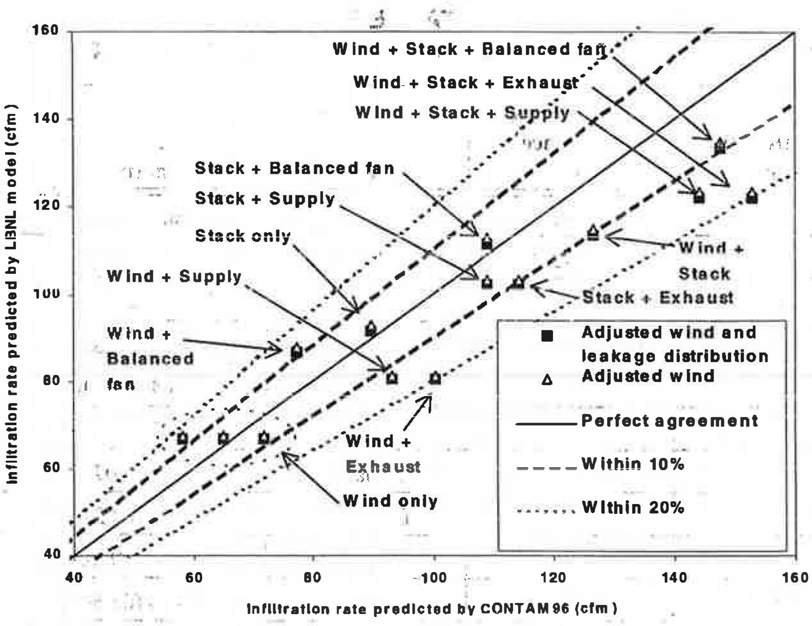

***Figure 4** Regression plot of infiltration predicted by CONTAM96 and LBL model (with adjustments to wind and leakage distribution).*

little effect on the infiltration rate computed by the LBL model. For the case in which only stack effects were considered, adjusting these parameters reduced the difference between LBL and CONTAM96 predicted infiltration from 4% to 2%.

The correlation of results for the cases in which wind was considered improved drastically. For the four cases in which wind from four directions was modeled, the average infiltration predicted by the CONTAM96 model was 65.1 cfm. With only the wind adjusted, the LBL model prediction differed from this average by only 4%, and with the additional adjustments to R and β_o, the difference is roughly 3%. Infiltration is overestimated by about 10% for the combination of balanced fan and wind, about the same percentage as the wind-only case with the same wind direction. This result indicates that although wind-related infiltration rates predicted by both models model can be very sensitive to the assumed terrain constants, they can provide very reliable results when wind speed at the site is known. Therefore, it is realistic to expect much better correlation between measured infiltration and that predicted by the LBL or CONTAM96 models when wind measurements are taken at the site.

In all cases, when stack and wind effects are combined using the LBL model, the resulting infiltration is underpredicted. For the no-fan and balanced-fan situations, the underprediction is roughly 10%. This is especially significant since wind effects have been shown to be overpredicted for the given wind direction. Since the infiltration predicted for stack and wind effects alone is very close to that predicted by CONTAM96, the underprediction must be related to the method used to combine the flows due to stack and wind. The simple quadrature method used to combine flows in Equation 3 assumes orifice flow with a leakage exponent of ½ (Sherman 1992). Other models combine stack and wind effects using a quadrature method that uses the leakage exponent (n) of the structure (Reardon 1989):

$$Q^{1/n} = Q_s^{1/n} + Q_w^{1/n} \tag{12}$$

Fan pressurization tests performed using the multizone model produced $n = 0.66$. If the airflows due to stack effects and wind (at 0 degrees) are combined using this method, the total infiltration becomes 126.1 cfm, a near perfect match with the 126.7 cfm predicted by the multizone model. This result suggests that in this case, combined airflow predictions could be improved by using a quadrature relationship that takes into account the actual flow exponent associated with the structure.

For the cases shown in Figure 4, in which one or more of the natural driving forces are combined with unbalanced fans, the resulting combination is also underpredicted. Furthermore, the underprediction is more pronounced for cases in which the unbalanced fan is an exhaust fan as opposed to a supply fan. One possible explanation for this phenomenon is that the assumptions made in developing Equation 4 could benefit from further refinement. Sherman (1992) presents a more sophisticated analysis for the addition of small fans. For small fans ($Q_{fan} < Q_{nat}$), he develops the relation

$$Q^2 = Q_{nat}^2 + Q_{fan}^2 + \left(2\varepsilon_+ + (\varepsilon_+^2 - 1)\frac{Q_{fan}}{Q_{nat}}\right) Q_{fan} Q_{nat} \tag{13}$$

where

Q_{nat} = predicted infiltration airflow due to a natural driving force (wind or stack),

TABLE 8
Infiltration Predicted by CONTAM96 and LBL Model (with n = 0.656 Used in Quadrature Relationship)

Wind Speed mph (m/s)	Wind Direction Degrees	Temperature Difference °F (°C)	Fans	CONTAM Infiltration cfm (m³/s)	Single-Zone Infiltration (n = 0.656) cfm (m³/s)
17.9 (8)	0	73.4 (23)	None	126.7 (0.0598)	126.1 (0.0595)
0		73.4 (23)	Supply	109.1 (0.0515)	111.0 (0.0524)
17.9 (8)	0	0	Supply	93.3 (0.0440)	89.1 (0.0421)
17.9 (8)	0	73.4 (23)	Supply	144.3 (0.0681)	142.6 (0.0673)
0		73.4 (23)	Exhaust	114.4 (0.0540)	111.0 (0.0524)
17.9 (8)	0	0	Exhaust	100.3 (0.0473)	89.1 (0.0421)
17.9 (8)	0	73.4 (23)	Exhaust	153.1 (0.0723)	142.6 (0.0673)
0		73.4 (23)	Balanced	109.1 (0.0515)	111.6 (0.0527)
17.9 (8)	0	0	Balanced	77.4 (0.0365)	86.9 (0.0410)
17.9 (8)	0	73.4 (23)	Balanced	147.8 (0.0698)	145.8 (0.0688)

Q_{fan} = fan airflow,
ε_+ = fan addition efficiency.

The value of fan addition efficiency (ε_+) in Equation 13 can be estimated depending on whether summer or winter stack effects or wind effects are being added to a supply or return fan. However, as the size of the fan approaches the size of the natural driving force, this relationship breaks down due to the significance of higher order terms. This seems to be the case for the combinations of flows used in this analysis, since application of Equation 13 yields results that are far less accurate than those obtained using Equation 4. Therefore, for fan flows of this magnitude, more reliable results seem to be possible when flows are added using simple quadrature.

Since the quadrature relationship given by Equation 12 improved agreement between the multizone and single-zone models for wind and stack effects, its use was also investigated for fan addition. This relationship has the form:

$$Q = (Q_s^{1/n} + Q_w^{1/n} + Q_{unbal}^{1/n})^n + Q_{bal} \quad (14)$$

Combined flows calculated using Equation 14 are given in Table 8 and plotted as a function of the corresponding CONTAM96 prediction in Figure 5. In general, this method of combining flows improved agreement with the CONTAM96 model, with all flows calculated using the single-zone model within 10%. For most cases, the predictions of the two models are nearly identical. The largest overprediction (roughly 10%) of the LBL model occurs for the case in which wind is combined with a balanced fan. This result would be expected, since the wind direction modeled using CONTAM96 has been shown to produce roughly 10% less infiltration than the average of the four wind directions. The largest underpredictions occur when natural forces are combined with exhaust fans, and those that include wind may, in fact, be closer to the CONTAM96 prediction than for wind directions with higher infiltration. However, these predictions are closer to the CONTAM96 prediction than those obtained using simple quadrature.

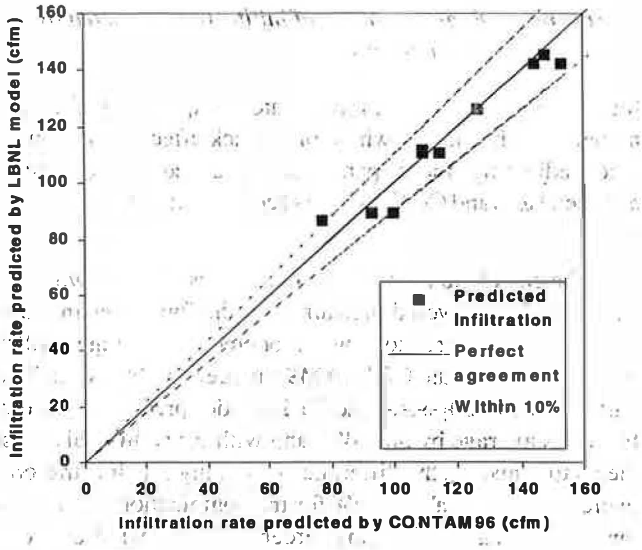

Figure 5 Regression plot of infiltration predicted by CONTAM96 and LBL model (with n = 0.656 used in quadrature relationship).

CONCLUSIONS

A detailed multizone computational model has been developed using typical leakage characteristics for residential building components found in the literature, and its leakage predictions have been compared with field measurements in two identical houses with reasonable success. Infiltration rates predicted by this detailed multizone model were then compared to infiltration rates predicted by a single-zone analysis performed using the LBL model. Several conclusions are apparent from these results.

Published leakage characteristics of typical residential building components can be used to assemble multizone models that reasonably resemble real world construction. In this analysis, the detailed multizone model predicted leakage in between the leakages measured in two identical houses for pressures below 0.12 in. w.g. (30 Pa).

The detailed (2,000-zone) multizone model has been compared with a more conventional 20-zone model of the same house. The 20-zone model predicted slightly less airflow under simulated fan pressurization tests, roughly 7% at 0.12 in. w.g. (30 Pa). However, this difference was of the same order of magnitude as the difference measured in the two identical houses. Furthermore, the 20-zone model predicted leakage between that measured in the two houses for pressures below 0.05 in. w.g. (12.5 Pa). Based on these comparisons, development of a highly detailed multizone model, such as the one developed for this study, is not likely to be worthwhile unless very detailed comparisons are required.

Infiltration predicted by both single-zone and multizone models is very sensitive to parameters used to convert wind velocity at the measurement site to a velocity at the building site. Guidelines for making these assumptions are based on subjective descriptions of local topography and surrounding construction. Even when the terrain class closest to the average local condition is chosen, departures from actual site wind speeds can be significant. It is, therefore, clear that these models will provide more reliable and accurate predictions when wind measurements are taken at the site. When this is not possible, care should be taken not to overestimate site wind velocity.

For the test house, which had a flow exponent of approximately 2/3, the addition of natural flows using simple quadrature in the single-zone model underestimated the total airflow on the order of 10%. These estimates were improved by using the house flow exponent in the quadrature relationship.

When infiltration due to natural driving forces was added to unbalanced fans of nearly the same magnitude, an underprediction by the single-zone model on the order of 10% resulted when the simple quadrature method was used to combine the airflows. A more sophisticated addition method that considers fan addition efficiencies did not provide a more reliable estimate in this case. However, including the flow exponent in the quadrature model again improved agreement between the two models.

For this house, the assumption that leakage was distributed evenly throughout the floor, walls, and ceiling had little effect on the results obtained using the single-zone model. Although the floor-ceiling leakage fraction of the house modeled computationally was very close to 0.5, the dimensionless height of the neutral level was 0.378, significantly lower than the 0.5 originally assumed. However, an updated analysis incorporating these assumptions changed the results by less than 2%.

NOMENCLATURE

A	= terrain constant, CONTAM96 model
a	= terrain exponent, CONTAM96 model
B	= wind adjustment factor
C	= empirically determined constant, power law relationship
C_D	= discharge coefficient
f_s	= stack factor
f_w	= wind factor
n	= empirically determined exponent, power law relationship
ΔP	= indoor-outdoor pressure difference
Q	= airflow rate, cfm (m³/s)
Q_s	= infiltration airflow due to stack effects, cfm (m³/s)
Q_w	= infiltration airflow due to wind effects, cfm (m³/s)
Q_{bal}	= airflow rate of balanced fans, cfm (m³/s)
Q_{unbal}	= airflow rate of unbalanced fans, cfm (m³/s)
Q_{nat}	= infiltration airflow due to a natural driving force (stack or wind), cfm (m³/s)
A_o	= equivalent leakage area, in.² (m²)
Q_r	= airflow rate at ΔPr, taken from curve fit to pressurization test data, cfm (m³/s)
R	= fraction of total building leakage area in floor and ceiling
ΔT	= indoor-outdoor temperature difference, °F (°C)
v'	= wind velocity measured at nearby weather station, mph (m/s)
v	= wind velocity at site, mph (m/s)
C'	= shielding coefficient
H	= elevation at top of building wall, ft (m)
H'	= height of weather measurement, ft (m)
α	= terrain constant, LBL model
β_o	= dimensionless height of neutral level
ε_+	= fan addition efficiency
γ	= terrain exponent, LBL model
ρ	= air density

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