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ANALYSIS OF ERRORS FOR A FAN-PRESSURIZATION TECHNIQUE FOR MEASURING INTER-ZONAL AIR LEAKAGE

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ABSTRACT

The problem of predicting air flows in a multi-zone building has received considerable attention in the past ten years. An important issue identified by this work was the lack of reliable measurements of the flow resistances between the zones of such buildings. This report analyzes the uncertainties associated with a fan-pressurization technique for measuring the inter-zonal leakage (inverse flow resistance) in a multi-zone building. The technique involves two blower doors, one in each of the two zones between which the leakage is being measured. The evaluation of the technique is based upon simulations using MOVECOMP, a multizone infiltration and ventilation simulation program, which is used to determine what data would be recorded when using the procedure in a multi-family building under typical wind conditions using typical fan pressurization equipment. These simulations indicate that wind-induced uncertainties in the determined leakage parameters do not exceed 10% for windspeeds lower than 5 m/s, but that pressure and flow measurement uncertainties raise leakage parameter uncertainties above 40% at any wind speed. By performing additional simulations, the sensitivity of our results to the subtleties of the measurement protocol and the assumed test conditions are examined. These examinations highlight the importance of using an appropriate reference for the pressure difference across the primary-zone envelope, as well as the importance of improving the precision this measurement.

INTRODUCTION

The problem of predicting air flows in a multi-zone building has received considerable attention in the past ten years. An important issue identified by this work was the lack of reliable measurements of the flow resistances between the zones of such buildings (Feustel 1987).

Several multi-zone leakage measurement techniques have been tried over the past several years, some of which determine only the Effective Leakage Area (ELA) of the inter-zonal path, while others determine both the flow coefficient and flow exponent needed in power-law models of crack flow. One technique used six blower doors simultaneously to measure the total envelope leakage area of a six-unit building, and used single-zone blower-door measurements to measure the total leakage area of each apartment, which in combination were used to determine the split between exterior-envelope and inter-zonal leakage (Modera 1985). Modera used data taken with this technique in a multi-zone infiltration model by apportioning the inter-zonal leakage area by surface area, and assuming a constant flow exponent. Another technique used two blower doors simultaneously to measure each inter-zonal flow path, measuring the flow required to maintain several nominal differential pressures across the primary zone with and without pressurizing the secondary zone to the same pressure. With this technique, the leakage area of the primary zone could be determined with and without the inter-zonal path, or the flows at each nominal pressure differential could be subtracted and used to obtain the flow exponent and coefficient of the inter-zonal path (Diamond 1986).

In general, multi-zone leakage measurements are acknowledged to have large uncertainties compared to single-zone leakage measurements. This increased uncertainty has been attributed to a number of effects, most notably the fact that any uncertainties in the measured blower-door flow rates are compounded by the flow subtractions used in multi-zone techniques, and also the fact that multi-zone buildings are usually taller than single-family residences and are therefore subjected to higher windspeeds. We therefore decided to compare the effects of wind with the effects of flow and pressure measurement uncertainties on multi-zone leakage measurements made with a two blower-door technique. However, due to the considerable expense, logistical difficulties, and the uncontrolled nature of field experiments, we decided to evaluate the these uncertainties using a detailed multizone air-flow network model.

MULTI-ZONE MEASUREMENT TECHNIQUE

The multizone leakage measurement technique that we examined utilizes two blower doors, one in each of the zones adjacent to the leakage path being measured. The technique is to maintain a constant indoor-outdoor pressure differential in one zone (e.g. 50 Pa), while simultaneously varying the pressure in the second zone. Thus, for a series of differential pressures (e.g. between 0 and 50 Pa) between the primary and secondary zones, the flow rates required to maintain the constant pressure differential across the primary zone are recorded. This technique was chosen because of two potential advantages it has over the techniques that have been examined in the past. First, because the primary zone is kept at a constant large pressure differential, the effects of wind on the measured flow should be reduced. Also, because the pressure differential across the leakage path is measured directly, the sensitivity to uncertainties in the measured pressure differentials should be reduced.

Assuming that the flow from the primary zone to adjacent zones and outside is maintained constant, the flow through the fan pressurizing the primary zone can be expressed as:

$$Q_p = Q_{pout} + k_{ps}\,\Delta P_{ps}^{n_{ps}} \qquad (1)$$

where:

Q_p	is the total flow into the primary zone (i.e. measured by the fan) [m^3/s],
Q_{pout}	is the flow from primary zone to outside and to all zones except the secondary zone (assumed to be constant) [m^3/s],
k_{ps}	is the flow coefficient of the leakage path between the primary and secondary zones [m^3/s Pa^n],
ΔP_{ij}	is the pressure difference between the primary and secondary zones [Pa], and
n_{ij}	is the flow exponent of the leakage path between the primary and secondary zones [dimensionless].

Equation 1 relates the fan flow to the leakage-path pressure differential via three parameters, Q_{pout}, k_{ps} and n_{ps}. Thus, by performing a non-linear search for the three parameters based upon a series of pressure-difference/fan-flow pairs, both the flow exponent and coefficient are obtained.

In addition to Equation 1, there are a number of methodology options associated with using this technique, many of which have significant implications for the uncertainty associated with the leakage characteristics determined. The options which have to be addressed by any examination of the technique include: what pressure differential to maintain across the primary zone, how to choose the outside pressure upon which to base the pressure differential across the primary zone, how to specify the leakage conditions of the adjacent zones (i.e. open or closed windows), how many pressure-differential/fan-flow pairs to use for a measurement, and what operator technique and instrumentation to assume for obtaining the pressure-differential/fan-flow pairs. The reference technique examined was chosen based upon a combination of uncertainty-reduction and practical-application considerations. The chosen configuration uses 50 Pa as the pressure differential (due to practical limitations of fan size), uses a pressure-averaging probe covering the three exterior surfaces of the primary zone for the outside pressure (to reduce uncertainty), assumes that the windows and doors of adjacent zones are closed during the test (based upon the practical difficulties associated with having all windows in an apartment building open at the same time), and uses six pressure-differential/fan-flow pairs (to conform with customary measurement practices). To gauge the sensitivity of our results to these assumptions, the effects of each of these choices on measurement uncertainty are examined individually at a typical wind condition. In addition, to obtain each pressure-flow pair it is assumed that the operator adjusts the fan flow so as to maintain the 50 Pa primary-zone pressure differential and then records the fan-flow and inter-zone pressure differential simultaneously. It is further assumed that the observed pressures are not affected by windspeed fluctuations at frequencies higher than 0.25 Hz (period < 4 sec), or at frequencies lower than 1.67 x 10^{-3} Hz (period > 10 min).

TEST CONDITIONS

As for any simulation-based study, a number of decisions had to be made early-on in choosing the conditions under which to examine the technique. These conditions included: the type of building, the choice of primary zone, the choice of leakage path, the total and inter-zonal leakage levels, the degree of shielding, and the type of wind. The effects of these uncertainties on the determination of the leakage characteristics can be be included in the simulations in a manner similar to that used for the wind. The reference set of test conditions chosen and the reference technique described above are summarized in Table 1.

Table 1: Reference Simulation Description	
Building Type	3-story multifamily with 2 units/floor
Primary Zone	Second-story apartment
Leakage Path	Between two second-story apartments
Total Leakage	Relatively High (Specific leakage area = 10 cm^2/m^2)
Inter-Zone Leakage	17% of Total (i.e., equal leakage for all leakage paths)
Shielding	Average of unshielded and surrounded by similar-height buildings
Mean Wind Speed	1-6 m/s
Wind Distribution	Lognormal
Wind Variance	Average Variance of Unstable and Neutral conditions
Wind Directions	Towards primary zone, towards secondary zone, parallel to common wall
Primary-zone Pressure	50 Pa
Outdoor Pressure Reference	Linear average of three outdoor surface pressures
Adjacent Apartments	Closed windows and doors
Measurements	6 pressure-difference/fan-flow pairs (0,10,20,30,40,50 Pa)

The building chosen for the reference simulation is typical of those built around the turn of the century in many U.S. cities, similar to the building measured by Diamond. The range of wind speeds was chosen to bracket the typical average windspeed of 4 m/s, and to show what kind of improvement can be expected at lower windspeeds. This examination of lower windspeeds necessitated the use of a positive definite distribution, in this case lognormal. The wind variance was chosen to conform with a small city environment, and as a compromise between unstable (clear sky) and neutral (overcast) wind conditions (Panofsky and Dutton 1984). The choice of wind variance was assumed to be an important issue, as the variation in windspeed over the course of a test is the principal cause of wind-induced measurement uncertainties. Table 2 contains a summary of the wind variances used for the simulations.

Table 2: Wind Variance

Mean Windspeed [m/s]	Unstable Wind Std. Dev. [m/s]	Neutral Wind Std. Dev. [m/s]	Reference Std. Dev. [m/s]
1	0.83	0.30	0.57
2	1.19	0.60	0.90
3	1.36	0.90	1.13
4	1.50	1.20	1.35
5	1.65	1.50	1.58
6	1.90	1.80	1.85

Assuming perfect instrumentation accuracy as we have, measurements made during a constant windspeed have no uncertainty. To compare these wind-induced uncertainties with the uncertainties due to imperfect pressure and flow measurements, an additional series of simulations were performed assuming 1 Pa uncertainties in pressure measurements, and 20 kg/h uncertainty in the measured fan flow.

NETWORK-MODEL SIMULATION

The principal method used to examine the wind-induced uncertainties associated with the multi-zone leakage measurement technique was to simulate the measurements that would be made under field conditions. These simulations were based upon MOVECOMP, a multizone infiltration and ventilation simulation program (Herrlin 1987). The major features of this program are described in the Air Infiltration Review (Herrlin 1988). Due to the flexibility and speed of this program, the leakage-measurement technique could be examined under a large range of conditions.

Given the reference technique and reference measurement conditions, the simulation proceeds as follows. For each mean windspeed and wind direction, two hundred measurements of the leakage coefficient (k) and the leakage exponent (n) are simulated. Each of these measurements is obtained from six pressure-flow pairs, one for each of six inter-zonal pressure differentials (i.e., ΔP_{ps} = 0,10,20,30,40,50 Pa). To obtain each pressure-flow pair, a windspeed is chosen at random from a lognormal distribution with the specified mean and variance. As using two hundred measurements was found to provide repeatable values for the bias and uncertainties in the leakage parameters, a new random set of 1200 windspeeds was generated for each wind and test condition. At each windspeed, surface pressures are computed for the entire building, using one pressure coefficient for each surface. Then, based upon the pressure differential to be maintained between the primary zone and outside, the specified pressure differential across the leakage path, and the known wind-induced surface pressures, the network model iterates to find the primary-zone and secondary-zone flows required to maintain the specified pressure differentials, and the resulting pressures in all zones of the building.

Based upon the reference simulation conditions described in Table 1, the uncertainty and the bias in the measured characteristics of the inter-zonal leakage were estimated. Simulations were also performed to examine the sensitivity of the results to the chosen methodology and test conditions, and to compare wind-induced uncertainties with uncertainties stemming from imperfect pressure and flow measurements.

The effects of pressure and flow uncertainties were included by adding offsets chosen at random from normal distributions with the specified variances. Pressure measurement errors were assumed to have no bias and a standard deviation of 1 Pa, and were included in the input to the network model. The primary-zone fan-flow error was assumed to be unbiased and to have a standard deviation of 20 kg/h, and was added to the fan-flow determined by the network model simulation.

SIMULATION RESULTS

Based upon the reference simulation, the bias and uncertainty in the flow coefficient and flow exponent of the inter-zonal leakage path are summarized for six wind speeds in Table 3.

Table 3: Results of Reference Measurement Technique Simulation[a]

Mean Windspeed [m/s]	Flow Coefficient (k)		Flow Exponent (n)	
	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]
1	1	1	1	0
2	1	3	1	1
3	0	6	1	2
4	-1	7	2	3
5	-2	10	2	4
6	1	34	2	9

[a] Average of four wind directions.

The results in Table 3 indicate a small bias in the measured inter-zonal flow coefficients and exponents at all windspeeds. The bias in the flow coefficient changes sign, whereas the bias in the flow exponent is consistently positive. This consistent bias in the flow exponent can be explained by the fact that the windows were assumed to be closed during the measurements. When the windows are closed, increasing the pressure in the secondary zone increases the pressure in adjacent zones, thereby reducing the flow from the primary zone to the adjacent zones. Thus, as increasing the pressure in the secondary zone decreases the pressure difference across the leakage path, the apparent flow through the leakage path will appear to increase disproportionately with the pressure difference across it, thereby causing an overprediction of the flow exponent.

Table 3 also indicates that the uncertainty induced by the wind, as indicated by the standard deviation of the results, remains smaller than 10% up to a wind speed of 5 m/s. Although this result is encouraging, we must remember that this assumes perfect measurements of pressure and flow, and therefore represents a lower limit on the total uncertainty. Also, Table 3 represents the uncertainty to be expected with no knowledge of wind direction. Figure 1 presents the data from the three wind directions used to generate Table 3, and shows the significant variations in uncertainty with respect to wind direction. Examining Figure 1, it seems that the uncertainties for all three wind directions increase linearly with windspeed up to 5 m/s. When the primary zone is completely on the leeward side of the building (direction 3), the uncertainties continue to increase linearly with windspeed above 5 m/s, whereas the uncertainties seem to increase dramatically above 5 m/s for the the other two directions.

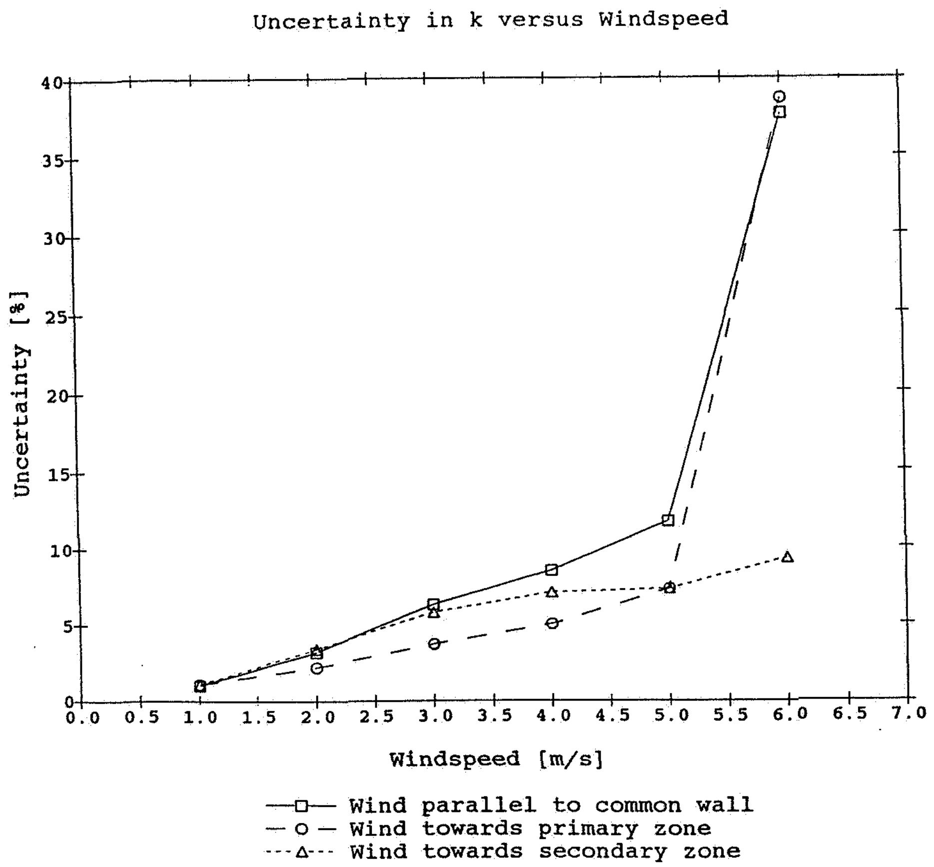

Figure 1. Uncertainty (scatter) in the measured leakage coefficient of the common wall between two apartments as a function of windspeed for three different wind directions (based upon reference simulation).

This indicates that the wind-induced uncertainty cannot be assumed to simply scale with windspeed or with the dynamic pressure of the wind, but rather must also depend upon other factors. One potential factor is the interaction of the pressurization of the primary and secondary zones, the non-linearity of the building leaks, and the wind-induced surface pressures.

A more careful examination of the raw simulation results indicated that the flow exponent and flow coefficient were negatively correlated. This correlation is illustrated in Figure 2, which is a scatter plot of the flow coefficient, k, versus the flow exponent, n, for the reference simulation conditions at a windspeed of 4 m/s. The negative sign of the correlation stems from the fact that the bulk of the measurements are made at pressures around 25 Pa, whereas the flow coefficient k is equivalent to the leakage (flow) at 1 Pa. Thus, excluding any correlated bias in the pressure and flow measurements, an increase in the determined exponent translates into a decrease in the determined flow coefficient.

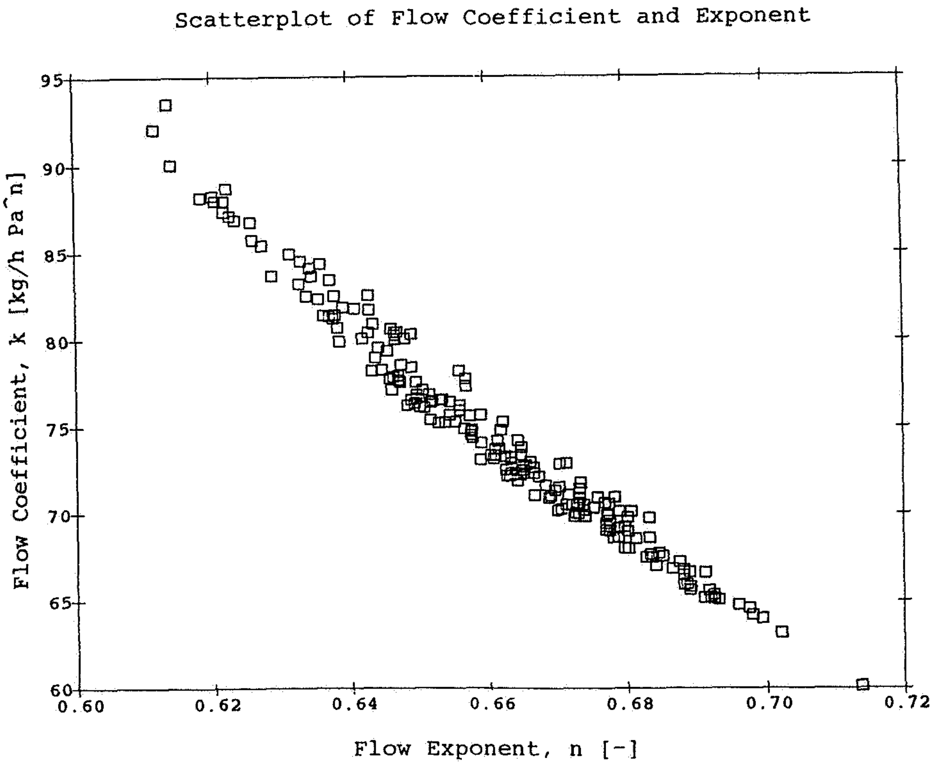

Figure 2. Scatter plot of flow coefficient and exponent determined for wind parallel to the common wall at 4 m/s (based upon reference simulation). The true values of the flow coefficient and exponent are 75 kg/h Pa^{n} and 0.65.

This finding is consistent with Persily's observation (Persily 1985) that to reduce uncertainty, the most logical choice for a single leakage parameter is the leakage at 25 Pa. However, from the point of view of applicability to the pressures driving flows in buildings, the most reasonable choice for a single parameter is probably the Effective Leakage Area (ELA), which used extensively to characterize single-zone leakage (Sherman 1986). As ELA, defined in Equation 2, is directly proportional to the flow at 4 Pa, and thus will have uncertainties smaller than that for k, but larger than that for the flow at 25 Pa.

$$ELA = k\sqrt{\frac{\rho}{2}}\,\Delta P_{ref}^{\,n-\frac{1}{2}} \qquad (2)$$

where:

ρ is the density of air [kg/m^3], and
ΔP_{ref} is the reference pressure differential [4 Pa].

The bias and standard deviation of the ELA and the leakage at 25 Pa, computed with the same data used to generate Table 3, are compared with the bias and standard deviation of the flow coefficient in Table 4.

Table 4: k, ELA and Flow at 25 Pa from Measurement Technique Simulation[a]

Mean Windspeed	k		Effective Leakage Area (ELA)		Leakage at 25 Pa	
[m/s]	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]
1	1	1	2	1	3	0
2	1	3	2	2	3	1
3	0	6	1	4	3	1
4	-1	7	1	5	3	2
5	-2	10	0	7	3	3
6	1	34	2	20	3	7

[a] Average of four wind directions.

The results presented in Table 4 are consistent with those presented by Persily for single-zone fan pressurization measurements. Namely, the determination of a flow in the middle of the measurement range has the least uncertainty, while predicted flows become more uncertain as they move towards the lower extreme of the measurement range. Although this result is not surprising, it is worth noting that the uncertainties in k, ELA, and Q_{25Pa} roughly correspond to the uncertainties in the flows predicted with a multi-zone airflow model at characteristic pressures of 1, 4 and 25 Pa, the flow at 4 Pa having approximately two thirds the uncertainty at 1 Pa, and the flow at 25 Pa having approximately half the uncertainty at 4 Pa. Also worth noting in Table 4 is the increased positive bias in the predicted flows at higher pressures, in particular the consistent bias in the flow at 25 Pa. Similar to the systematic overprediction of the flow exponent discussed above, this bias stems from the assumption of closed windows used for the simulation.

The effects of different methodology options on the uncertainty and bias of the measurement technique are summarized in Table 5.

Table 5: Effects of Methodology Changes on Measurement Technique Results[a]

Condition	Flow Coefficient (k)		Flow Exponent (n)		ELA	
	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]
Reference	**-1**	**7**	**2**	**3**	**1**	**5**
12 Data Pairs	-1	6	2	2	1	4
100 Pa Primary Pressure	1	7	1	3	2	5
Open Windows	1	9	0	4	0	6
4-Surface Average Pressure	7	56	3	17	4	33

[a] Average of four wind directions at mean windspeed of 4 m/s.

The methodology options in Table 5 are listed in order of decreasing beneficial effect on the uncertainty of the flow coefficient. In general, most of the options examined have negative impacts on the quality of the determined parameters. The only option which has a beneficial effect on measurement uncertainty is the use of 12 pressure-flow pairs to determine the flow coefficient and exponent. This option corresponds to taking twice as much data in the field, and results in a one percentage point improvement in the uncertainty in the flow coefficient, flow exponent and effective leakage area.

Somewhat surprisingly, the use of 100 Pa as the reference pressure in the primary zone has virtually no effect on the parameter uncertainties. Although a higher primary-zone pressure is expected to decrease the effect of wind on flow measurements, this beneficial effect does not appear in the simulated uncertainties. The uncertainties obtained with a 50 Pa primary-zone pressure were also compared with the 100-Pa uncertainties at an average windspeed of 6 m/s, at which point the 100 Pa uncertainties were half the 50 Pa uncertainties, consistent with expectations. Apparently, the benefits of increasing the primary-zone pressure do not become significant until the windspeed exceeds 4 m/s. As mentioned above, this behavior most likely stems from interactions between the internal building pressures, the non-linearity of building leaks, and the fact that wind-induced pressures scale with the square of the windspeed.

Opening the windows in the adjacent zones, although it apparently eliminates the bias in the flow exponent and effective leakage area, increases the uncertainty associated with all parameters. This result is not surprising, as opening the windows implies larger pressure fluctuations in the adjacent zones and therefore larger fluctuations in the measured fan flow.

The most significant methodology change is the use of a four-wall rather than a three-wall pressure average, which increases the parameter uncertainties by approximately a factor of five. An even more dramatic increase was found when using a single surface-pressure probe for the outside pressure. For one wind direction, the use of a single surface pressure results in biases as high as 80% and uncertainties over 100%. Although the results for other wind directions were not as severe, as one cannot specify wind direction when making a measurement, this technique has to be considered unworkable. Both these results highlight the importance of using a pressure average that is representative of the pressures affecting the flow out of the primary zone. Overall, the results in Table 5 indicate that the choice of reference methodology seems to have been fortuitous.

The uncertainty and bias implications of several of the reference simulation assumptions are summarized in Table 6.

Table 6: Effects of Simulation Assumptions on Measurement Technique Results[a]

Assumption	Flow Coefficient (k)		Flow Exponent (n)		ELA	
	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]
Reference	**-1**	**7**	**2**	**3**	**1**	**5**
Well Shielded	0	5	1	2	1	3
Neutral Wind	0	7	2	3	1	5
Smaller Total Leakage ($3.3 cm^2/m^2$)	0	7	2	3	1	5
Smaller Interzone Leakage (9%)	-2	15	4	6	1	10
No Shielding	0	16	2	6	1	10
Unstable Wind	0	18	2	6	1	9

[a] Average of four wind directions at mean windspeed of 4 m/s.

Similar to Table 5, the simulation assumptions in Table 6 are listed in order of decreasing beneficial effect on the uncertainty of the flow coefficient. Also similar to Table 5, the results in Table 6 indicate that the choice of reference simulation was fortuitous, apparently corresponding to a lower limit on the uncertainties to be expected. The only improvement in measurement uncertainty occurs by assuming that the building was well shielded from the wind. Somewhat surprisingly, going from average wind variance to neutral wind variance does not have a significant effect on the measurement uncertainty. This result, combined with the significant increase in uncertainty associated with assuming unstable wind, seems to indicate that the effects of wind turbulence on measurement uncertainty do not scale linearly with turbulence intensity, but rather result from complex interactions between the internal building pressures, the non-linearity of building leaks, and the fact that wind-induced pressures scale with the square of the windspeed. The non-linear dependence of measurement uncertainty on the pressure variations is further illustrated by the significant increases in uncertainty associated with assuming that the building is unshielded.

Not surprisingly, the determined biases and uncertainties in the measured parameters do not depend on the absolute level of leakage in the building (remember we are not including instrumentation uncertainties), but do show approximately linear dependence on the relative size of the leakage path being measured. This latter result indicates a constant absolute uncertainty in the parameters being determined.

To put the wind-induced leakage measurement uncertainties into perspective, several simulations of measurements made with flow and pressure uncertainties were performed. The results of these simulations, based upon the uncertainties specified above, are presented in Table 7.

Table 7: Effects of Flow and Pressure Measurement Uncertainties on Measurement Technique Results[a]

Assumption	Flow Coefficient (k)		Flow Exponent (n)		ELA	
	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]	Bias [%]	Std. Dev. [%]
Reference at 4 m/s	**-1**	**7**	**2**	**3**	**1**	**5**
Reference plus Flow and Pressure Uncertainty at 4 m/s	23	64	2	25	12	42
Reference plus Flow and Pressure Uncertainty at 1 m/s	16	63	3	23	8	42

[a] Average of four wind directions.

The results in Table 7 point out the importance of uncertainties in measurements of pressure differentials and fan flows. Compared to the reference simulation, the addition of these measurement uncertainties increases the leakage parameter uncertainties by approximately a factor of eight. Table 7 also indicates a large positive bias in k and ELA resulting from the addition of measurement uncertainties.

DISCUSSION

The demonstrated importance of pressure and flow measurement uncertainties for producing accurate measurements of interzonal leakage is probably the key finding of this report. Due to the significance of this finding, additional simulations were performed to separate the effects of pressure and flow uncertainties. These simulations indicated that pressure measurements were a more important source of uncertainty and bias in the measured leakage parameters. These results imply that techniques for reducing measurement uncertainty, particularly pressure measurement uncertainty, will have significant impacts on leakage-parameter uncertainty. As the chosen uncertainties in pressure and flow measurements represent typical values for existing leakage-measurement equipment, there are a number of uncertainty-reduction techniques which could be applied. For example, the use of well-calibrated electronic pressure measurement equipment could reduce pressure measurement uncertainties by almost a factor of ten. Further improvement could be potentially be obtained by using time averaged (or filtered) pressure and flow measurements, or by using multiple pressure transducers rather than a single averaging probe to determine an average primary-zone pressure differential.

Pressure and flow measurement uncertainties, in addition to increasing uncertainty, also induced a significant positive bias in the measured flow coefficients and leakage areas. As the observed bias can have important implications, and because the use of different random samples indicated the need for a larger sample size, the causes and potential means of mitigating this bias will be a topic for future investigation.

The final discussion point concerns the distributions of errors in the measured leakage parameters, which in general were found to be normal. The exceptions occurred at high uncertainties, in particular those associated with windspeeds above 5 m/s, and those obtained for the flow coefficient when including measurement errors. In both cases the error distributions were found to be positively skewed. This result indicates that the well-developed error analysis techniques for normal distributions cannot be generally used for analyzing field leakage measurements.

CONCLUSIONS

Several conclusions can be drawn based upon the results presented in this report. First, we feel that the simulations used to examine the proposed fan pressurization technique for measuring inter-zonal leakage proved to be an invaluable tool. Besides providing meaningful estimates of the expected field performance of the technique, the simulations provided quantitative analyses of the relative importance of various methodology options. The results of these simulations can thus be used to design a selective (i.e., economically-viable) experimental effort to test the proposed technique, and can serve as a yardstick for comparing alternative measurement techniques.

The simulations also provided a clear separation between the contributions of measurement uncertainties and wind-induced uncertainties to the overall uncertainty in the measured leakage parameters. Perhaps the most significant findings based upon this study are the demonstrated importance of the choice of outdoor pressure reference for the primary zone, and the demonstrated importance of improving the accuracy of pressure and flow measurements. On the one hand, using a 3-face pressure average improves measurement uncertainty by a factor of five compared to using a four-face pressure average or a single-face pressure. On the other hand, including pressure and flow measurement uncertainties produces an eight-fold increase in leakage parameter uncertainty. The simulations demonstrate that at windspeeds below 6 m/s, the uncertainties associated with the described inter-zonal leakage measurement technique are predominantly caused by imperfect pressure and flow measurements. Up to 5 m/s the uncertainties due to the wind remain smaller than 10%, whereas the uncertainties stemming from imperfect measurements push the uncertainty above 40%. Based upon this demonstrated importance of pressure and flow uncertainties, the use of signal enhancement and scatter-reduction techniques are recommended. Specific techniques, such as temporal averaging or filtering of pressure signals, which were specifically not considered, may play an important role in reigning in the presently unacceptable leakage-parameter uncertainties.

REFERENCES

R.C. Diamond, M.P. Modera, H.E. Feustel, "Ventilation and Occupant Behavior in Two Apartment Buildings", Lawrence Berkeley Laboratory, LBL-21862, Presented at the 7th AIC Conference, Stratford-upon-Avon, UK, September 1986.

H.E. Feustel, "A Simplified Model for Predicting Air Flow in Multizone Structures", February 1987, submitted to Building and Environment, Lawrence Berkeley Laboratory Report LBL-22325.

M.K. Herrlin, "Luftstromning i byggnader - en berakningsmodell", Division of Building Services Engineering, Royal Institute of Technology, Stockholm, Sweden, May 1987.

M.K. Herrlin, "MOVECOMP - A Multizone Infiltration and Ventilation Simulation Program", Air Infiltration Review, Volume 9, No. 3, Air Infiltration and Ventilation Center, Bracknell, England, May 1988.

M.P. Modera, J.T. Brunsell, R.C. Diamond, "Improving Diagnostics and Energy Analysis for Multi-Family Buildings: A Case Study," Proceedings of ASHRAE/DOE Conference, *Thermal Performance of the Exterior Envelopes of Buildings III*, Clearwater, FL, December 1985.

H.A. Panofsky, J.A. Dutton, *Atmospheric Turbulence*, John Wiley & Sons, New York, 1984.

A.K. Persily, R.A. Grot, "Accuracy in Pressurization Data Analysis", ASHRAE *Trans.* 91(II), 1985.

M.H. Sherman, "Exegesis of Proposed ASHRAE Standard 119: Air Leakage Performance for Detached Single-Family Residential Buildings", Proceedings of BTECC/DOE Symposium, *Guidelines for Air Infiltration, Ventilation and Moisture Transfer*, Fort Worth, TX, December 1986, Lawrence Berkeley Laboratory Report LBL-21040.