Repeatability and Accuracy of Pressurization Testing

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ABSTRACT

Pressurization testing is used to evaluate the airtightness of building envelopes. To experimentally determine the repeatability of pressurization test results, a home was pressure tested about eighty times in one year. The effect of weather conditions on the test results was studied, along with changes in the results over time. For local wind speeds less than 5.5 mph (2.5 m/s), the 0.2 in H_2O (50 Pa) leakage rate has a standard deviation of about 2% of the mean over short time periods. For stronger winds, errors as large as 15% compared to the calm weather test results occured. A seasonal variation in the leakiness of the house, on the order of 25%, was also found. This variation is due to changes in the moisture content of the building materials caused by yearly variation in the moisture content of the outside air.

INTRODUCTION

Pressurization testing has been used worldwide to evaluate the airtightness of homes.[1-6] In whole-house pressurization, a large fan mounted in a door or window induces a large and roughly uniform pressure difference across the building shell. The air flow required to sustain this pressure difference is then measured. The leakier the house, the more air flow is necessary to induce a specific inside-outside pressure difference. This test method has proved useful for obtaining a quick measure of the tightness of a home and for the evaluation of the effectiveness of retrofits.[7-8]

Nonetheless, there are some problems with pressurization testing.[9-10] Basically, the test conditions differ from the conditions that normally induce infiltration. The pressure differences induced by the fan are an order of magnitude larger than the pressures caused by the wind and temperature differences. Also, the pressure difference during a test is uniform and constant over the entire envelope, whereas the pressure varies continually in time and space under normal conditions. Finally, a pressurization test determines the net leakage of the house and gives no information on specific leakage locations, which are crucial in determining infiltration.

Questions also exist concerning the repeatability and accuracy of the test results, including the effects of weather conditions on the test results. The outside weather during a test, especially the wind speed, may effect the test results by inducing additional pressure differences across the shell. It has been recommended that pressurization tests be conducted when the wind speed is less than 5 mph (2.2 m/s). Confounding pressures will also be induced by stack effects, and therefore, it is also recommended that one conduct tests with inside-outside temperature differences of 20°C (11°C) or less.[11] The effects of weather on pressurization test results have never been studied experimentally. Also, the short and long term repeatability of test results, independent of weather, have not been measured. In order to answer these questions of

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repeatability and weather effects, a home in the Princeton, NJ area, the so-called "BRAT" house, was pressure tested about once a week for one year.

EXPERIMENTAL PROCEDURE

The BRAT house is a two-story, wood-frame structure built in the mid-1960s with a gas-fired, forced-air heating system. The house has no special construction features or other characteristics that would make it exceptionally airtight. The interior volume (less the basement) is about 15,900 ft^3 (450 m^3), and the floor area is roughly 1990 ft^2(185 m^2). The experiments used the "blower door," designed and built at Princeton University[12], as a pressurization device.

On each trip to the house at least two pressurization tests were carried out. Each test included both pressurizing and depressurizing the house to several inside-outside pressure differences. The weather conditions during the test were monitored at the laboratory weather station, about 2.5 mi (4 km) from the house. The weather data include averages of the outside temperature and wind speed and direction during the test. This local wind speed was measured about 20 ft (6 m) above the roof of a two-story building.

The data from each blower door test are in the form of inside-outside pressure differences and a fan rpm for each pressure difference. The induced pressure differences are 0.05, 0.10, 0.15, 0.20, and 0.25 in H_2O (12.5, 25, 37.5, 50 and 62.5 Pa), although on some days it was not possible to pressurize the house up to 0.25 in H_2O (62.5 Pa). The pressure difference was measured across the front door of the house using a magnehelic pressure gauge. The fan rpm are converted to flow rates using a calibration formula.[13] The data from each test are fit to an equation of the form

$$Q = C\Delta p^n \qquad (1)$$

where

Q = flow rate (ft^3/min [m^3/hr])
C = flow coefficient (ft^3/min-(in H_2O)^n [m^3/hr-Pa^n])
n = flow exponent
Δp = inside-outside pressure difference (in H_2O [Pa])

An equation of this form is found for the pressurization points alone, for the depressurization points, and for both groups of points together. Such a curve is used to find flow rates at various pressure differences to characterize the leakage of the house. The flow rate at 0.20 in H_2O (50 Pa) is commonly used to characterize the airtightness of a home. Flow rates of 0.016 in H_2O (4 Pa) are sometimes used, primarily in connection with the air infiltration model developed at the Lawerence Berkeley Laboratories.[14]

ACCURACY OF THE TEST RESULTS

One source of inaccuracy for the blower door is error in the calibration, which yields the volumetric flow rate through the fan as a function of the inside-outside pressure difference and the fan rpm.[15] This calibration is thought to be accurate within about 10%, with the largest uncertainties at low flow rates. The blower door was calibrated at only one air density and the appendix of this paper presents a calculation of a density correction to the calibration. A more accurate calibration technique will be necessary to verify the density correction. The outside air density can vary from 7.12×10^{-2} lb/ft^3 (1.14 kg/m^3) on a hot, humid day to 8.68×10^{-2} lb/ft^3 (1.39 kg/m^3) on a cold and dry day, and this can affect the calculated flow rates by up to 10%. In the BRAT tests, the current blower door calibration is assumed to be correct, and no density corrections are made except where noted.

We first considered the effects of weather, particularly wind, on pressurization test results. Operating a blower door is difficult under windy conditions because of wind-induced pressures. Also, the turbulent nature of the wind causes the inside-outside pressure difference to fluctuate during the

test. It is very difficult to induce a stable pressure difference with which to associate a fan rpm. Shielding the outside pressure tap is inadequate because the wind also interacts with the fan, affecting the flow rate. One could use inlet and exhaust ducts to shield the fan, but such an addition will reduce the flow capacity and increase the size and weight of the device, thus eliminating the blower door's portability.

To study the effects of wind on blower door tests, the local wind speed was recorded during each test. Fig. 1 is a plot of the measured flow rate required to pressurize the house to 0.20 in H_2O (50 Pa) against the average wind speed during the test. Only tests done in 1980 are included because of changes in the tightness of the house over time. The inset in this graph shows the same data on a scale that contains the origin. As the local wind speed increases above roughly 5.5 mph (2.5 m/s), the scatter in the data increases. Below this wind speed, the flow rate is relatively constant. Tests at wind speeds greater than or equal to 5.5 mph (2.5 m/s) lie in a region bounded below by the flow rate at low wind speeds. The upper bound of this region increases with the wind speed. Tests on windy days yield results both consistent with and significantly higher than tests under calm conditions because of the intermittency of wind effects. Even on days having high average wind speeds, there are calm periods. Tests during these calm periods do not exhibit the errors that occur when the wind speeds were higher. The three tests conducted on the day with u=11.0 mph (4.9 m/s) in Fig. 1 are examples of this effect. Two of the tests have the same 0.20 in H_2O (50 Pa) flow rate as the calm wind tests, whereas, one of the points is about 15% higher. The fact that wind effects on blower door tests are intermittent makes a meaningful wind correction improbable.

In Fig. 2, the average of the predicted pressurization and depressurization flows at 0.016 in H_2O (4 Pa), Q(4), is plotted against wind speed. The 0.016 in H_2O (4 Pa) flows are calculated using Eq 1. These flows exhibit proportionally more scatter than the 0.20 in H_2O (50 Pa) flows, but there is little systematic variation with the wind speed. The effect of wind direction on these test results was also considered, but no relation was evident.

From consideration of the plots of flow rate versus wind speed, tests having local winds of less than 5.5 mph (2.5 m/s) are called calm. Winds equal to 5.5 mph (2.5 m/s) and not blowing into the blower door are also considered calm. These calm test conditions correspond roughly to wind speeds less than about 13.5 mph (6 m/s) as measured by the U.S. Weather Service in nearby Newark, NJ. Quite often, the only wind information available is from such a U.S. Weather Service station. The "cutoff" speed in this study was a local wind speed and is close to the ASTM recommendation of 5 mph (2.2 m/s).[16]

By considering only the calm tests in 1980, the short-term variability in blower door test results can be determined. Tab. 1 summarizes the variation of the measured flows and the flows calculated from curve fits to the test data for the calm tests in 1980. Means, standard deviations, and coefficients of variation are listed for the calculated flows at 0.016 and 0.20 in H_2O (4 and 50 Pa) and the measured flows at 0.20 in H_2O (50 Pa) for both pressurization and depressurization. The same quantities are given for the flows as calculated from all points together. Tab. 1 also includes the average of the pressurization and depressurization flows at 0.016 in H_2O (4 Pa). All of the 0.016 in H_2O (4 Pa) flows have standard deviations of about 20 or 25 ft^3/min (30 or 40 m^3/hr), about 5% of the mean. The 0.20 in H_2O (50 Pa) flow rates have standard deviations from 25 to 50 ft^3/hr (40 to 80 m^3/hr), only 1 or 2% of the mean flows. Thus, the 0.20 in H_2O (50 Pa) flow rate is more well defined than the extrapolation to 0.016 in H_2O (4 Pa). When several tests were made on a single, calm day, the results were essentially identical among the tests.

One may also compare the stability of the 0.016 and 0.20 in H_2O (4 and 50 Pa) flows by relating the flow coefficient C to the flow exponent n from curve fits to the data (see Eq 1). Fig. 3 is a plot of C versus n for the pressurization curves of each 1980 test. The calm wind points lie very close to a straight line. Some of the windy points lie close to the line while others do not. Again we are seeing the intermittency of wind effects on the blower door test results.

Each point in Fig. 3 represents the curve fit to a pressurization test, and the leakage of this home is characterized by this family of curves. One may consider three points along the line in Fig. 3 which cover the range of

calm test data,

$$Q_A = 6370\Delta p^{.66} \quad (2a)$$

$$Q_B = 6690\Delta p^{.69} \quad (2b)$$

$$Q_C = 6890\Delta p^{.72}. \quad (2c)$$

By setting pairs of these equations equal to each other, one finds the range of pressure differences at which they intersect. Q_A equals Q_B at a pressure difference of Δp = 0.20 in H_2O (50 Pa), $Q_B = Q_C$ at Δp = 0.37 in H_2O (93 Pa), and $Q_A = Q_C$ when Δp = 0.27 in H_2O (67 Pa). Thus, these curves are closest to one another at about 0.28 in H_2O (70 Pa), i.e. the differences between the curves are minimized at large pressure differences. For Δp = 0.20 in H_2O (50 Pa), the average of the three flows is 2190 ft^3/min (3723 m^3/hr) with a standard deviation of 22 ft^3/min (38 m^3/hr), i.e. 1.0% of the mean. For a pressure difference of 4 Pa, the mean of the three flows is 384 ft^3/min (653 m^3/hr) with a standard deviation of 32 ft^3/min (54 m^3/hr) or 8.4% of the mean flow. The larger uncertainties in the 0.016 in H_2O (4 Pa) flow rates are to be expected since this flow rate is an extrapolation out of the range of the actual measurements.

LONG TERM VARIATION

A distinction has been made between the 1980 and 1981 blower door tests on the BRAT house because of changes in the tightness of the house over time. One sees this change in Fig. 4, which shows the measured pressurization flow at 0.20 in H_2 (50 Pa) plotted against the Julian date. The flow rate is roughly constant during most of 1980, although the lack of calm wind conditions during the last sixty days of the year obscure any changes. During early 1981, however, the flow rate at 0.20 in H_2O (50 Pa) is about 22% larger than it was in 1980. Around day 100, the flow begins to decrease as the house retightens. The last six points in 1981 are about 10% too high due to problems with the blower door tachometer. The 0.016 in H_2O (4 Pa) flow rate exhibits the same seasonal variation. The maximum 0.016 in H_2O (4 Pa) flow in 1981 is about 25% higher than the 1980 levels.

Contraction and expansion of building materials due to temperature is too small an effect to account for the changes in the tightness of the house. Instead, the change is believed to be caused by effects of moisture on the building materials. During winter weather, the cold outside air contains little water and the wood in the structure dries and shrinks. This shrinkage increases the leakage area and, hence, the flow through the shell at a given pressure difference. During the spring, warmer air and rain provide the structure with a moister environment. The wood absorbs the water and swells to close the openings in the shell.

Fig. 5 is a plot of five day averages of the daily specific humidity against Julian day. The specific humidity is highest in the late summer and decreases to a minimum in early 1981. The moisture content of the air increases again in the spring. Although the maximum flow rate in Fig. 4 is not clearly defined, it occurs at about day 25 of 1981. The minimum level of specific humidity occurs at about day 10. Thus, the minimum in tightness lags behind the minimum in air moisture by about two weeks. Luck and Nelson found a time constant of about 10 days for the moisture absorption of wood.[17]

The seasonal variation of the moisture content of the outside air can explain the variation in the induced flow rate of the house. A seasonal variation in pressurization flow rates on the order of 40% has been measured by Warren and Webb.[18] Their data are shown in Fig. 6 but consist of only eight measurements over 1.5 years compared with roughly three dozen over one year in the BRAT house. Because the Warren and Webb house was unoccupied during the test period, the lack of any internal moisture sources may have led to increased drying of the structure.

In discussing the seasonal variation of building leakiness, effects of outside temperature on the blower door results are very important. As presented in the Appendix, the volumetric flow rate through the fan at a given

pressure difference and fan speed depends on the density, hence the temperature, of the air. Also, because of differences in the inside and outside air densities, the volume flow out of the cracks in a house during pressurization Q_o does not equal the volume flow in through the fan Q_i. These two flows are related by the ratio of the inside and outside temperatures in ^oR,

$$Q_o = (T_i/T_o)\, Q_i \qquad (3)$$

This equation is obtained by equating the mass flow into the house through the fan at a temperature T_o to the mass flow out of the house at T_i. Fig. 7 shows the effects of these two corrections on the seasonal variation of the 0.20 in H_2O (50 Pa) flow rate. Only tests made under calm wind conditions are included in this plot. The lower curve is the unadjusted 0.20 in H_2O (50 Pa) flow rate as shown in Fig. 4. The middle curve is the flow rate through the fan with the density correction applied. The upper curve is the flow out of the house calculated using Eq 3 and assuming that the inside temperature equals 527^oR (293 ^oK). The unadjusted flow rate and the corrected flow rate through the fan both have seasonal variations of about 22%. The calculated flow through the leaks in the house has a seasonal variation of about 36%.

CONCLUSIONS

The pressurization experiments in the BRAT house have revealed useful information concerning the use of this technique for evaluating the tightness of homes. The effects of wind speed on the test results have been measured, and the results were unaffected by winds up to 5.5 mph (2.5 m/s). This is close to the ASTM recommendation of testing at local speeds below 5.0 mph (2.2 m/s), but other homes with different wind exposures must be checked. Errors in the 0.20 in H_2O (50 Pa) flow rate of up to 15% were found at higher wind speeds. But due to the fluctuating nature of wind, tests conducted at high average wind speeds may not be in error.

The BRAT tests have also revealed the repeatability of blower door test results on a home. Repeated measurements of the 0.20 in H_2O (50 Pa) leakage rate yielded a standard deviation of 1 to 2% of the mean, while the 0.016 in H_2O (4 Pa) flows had a standard deviation of about 5% of their means. The 0.016 in H_2O (4 Pa) flow is less well defined because it is an extrapolation outside of the range of measurements. By conducting the pressurization tests on the BRAT house over a year, we found and measured the seasonal variation of the leakage of a home. This variation results from changes in the moisture content of the wood over the year. The magnitude of this tightness variation is about 25% for the BRAT house but becomes larger if one accounts for temperature effects. The BRAT results are useful for developing the pressurization technique into a tightness standard, but similar research needs to be conducted in other homes.

APPENDIX: TEMPERATURE CORRECTION FOR THE BLOWER DOOR

The blower door was calibrated by measuring the flow through the fan q as a function of the fan rpm and the inside-outside pressure difference Δp. These calibrations were made at an air density of $\rho_T = 7.5 \times 10^{-2}$ lb/ft^3 (1.2 kg/m^3). When blower door tests are made in the field, the air density is generally different from ρ_T. It is therefore necessary to know the effect of air density on the blower door calibration. We know the flow rate q as a function of p and rpm at the calibration density, and we need to know how to find the flow rate at a different air density ρ. Fan laws exist to relate several aspects of fan performance under different conditions, but they are not applicable to our situation. One may use the fan laws only when the two conditions lie on the same point of the fan performance curve as described below.

Fan laws are derived through nondimensionalization. We are trying to relate the flow rate q, the fan speed in revolutions per second n, the fan diameter D = 1.5 ft (0.46 m), the air density ρ and the pressure difference Δp. One uses these quantities to formulate expressions for a nondimensional flow rate Q/nD^3 and a pressure difference $\Delta p/\rho(nD)^2$. Using the fan calibration for

the blower door[19] and setting $\rho = \rho_T$, these two nondimensional quantities were calculated for a variety of Δp and n. Fig. A1 and A2 are plots of Q/nD^3 against $\Delta p/\rho(nD)^2$ for the pressurization and depressurization calibrations, respectfully. The fan laws apply only for two sets of conditions which lie on the same point on one of these curves. Our situation of constant Δp and n but varying ρ, moves us along these curves and the fan laws do not apply. These curves must be used to correct for temperature and were used in Fig. 7.

ACKNOWLEDGEMENTS

The author wishes to thank Mike Lavine and Greg Linteris for their help in planning and performing the experiments discussed in this paper. This report is based on research done at Princeton University's Center for Energy and Environmental Studies under Department of Energy Contract No. DE-AC02-77CS20062. The report was written while the author held a National Research Council Postdoctoral Associateship at the National Bureau of Standards.

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TABLE 1

Variation of Pressurization Flow Rate[1]

	Mean (M)	Standard Deviation (s)	Coefficient of Variation[2] (%)
Pressurization			
$Q_{calc}(4)$	378	21	5.6
$Q_{calc}(50)$	2184	25	1.1
$Q_{meas}(50)$	2200	32	1.5
Depressurization			
$Q_{calc}(4)$	348	22	6.3
$Q_{calc}(50)$	2356	41	1.7
$Q_{meas}(50)$	2364	48	2.0
All Points			
$Q_{calc}(4)$	363	18	5.0
$Q_{calc}(50)$	2272	25	1.1
$Q(4)^3$	363	16	4.4

1 All flows in ft^3/min
2 Coefficient of variation equals 100s/M.
3 Q(4) is the average of the 0.016 in H_2O (4 Pa) flows under pressurization and depressurization.

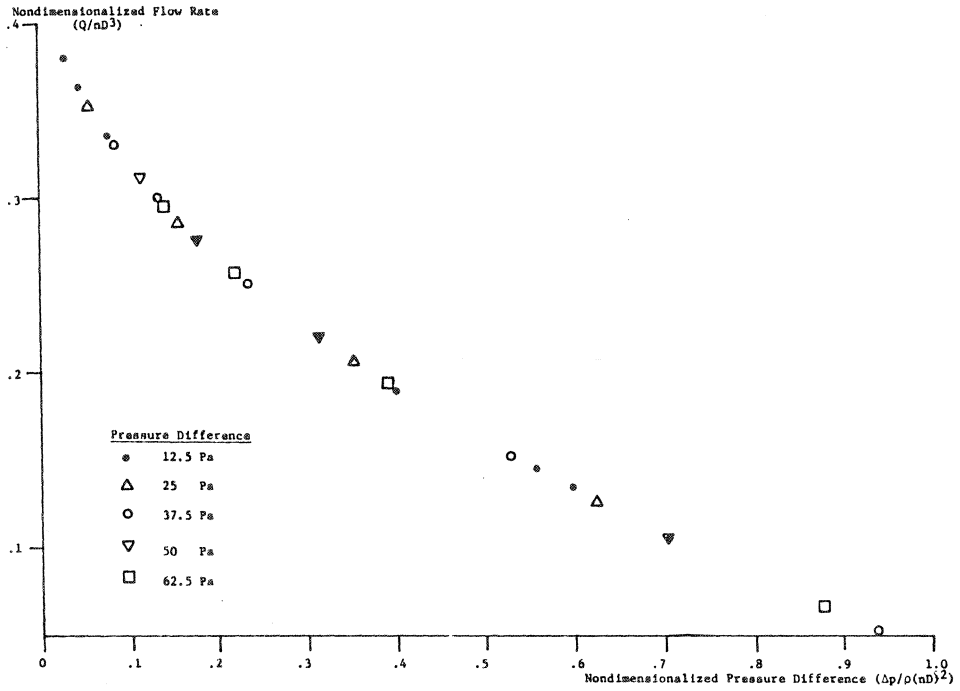

Figure A1. Nondimensionalized flow rate versus nondimensionalized pressure difference for pressurization

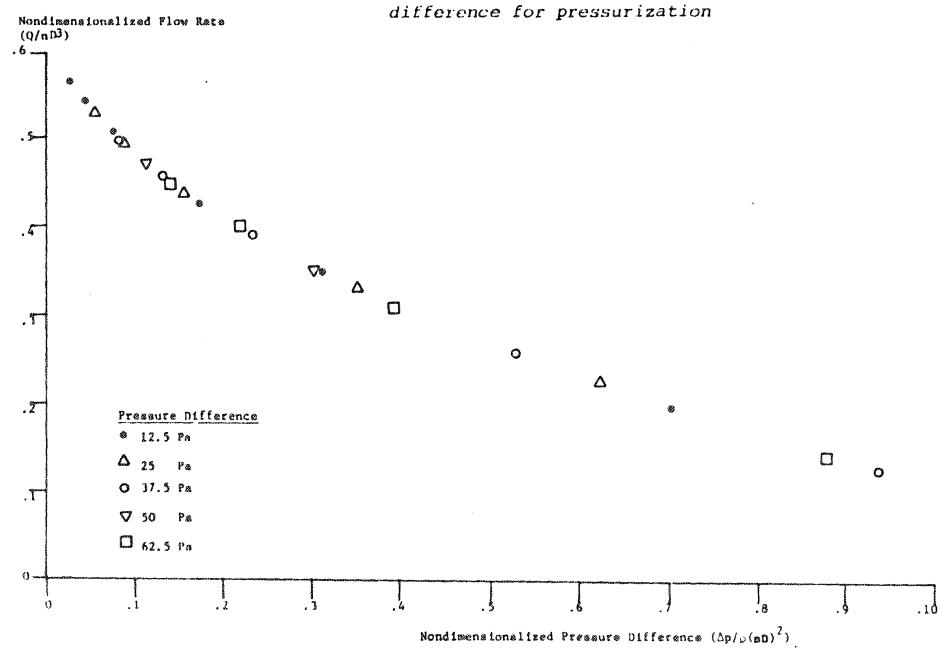

Figure A2. Nondimensionalized flow rate versus nondimensionalized pressure difference for depressurization

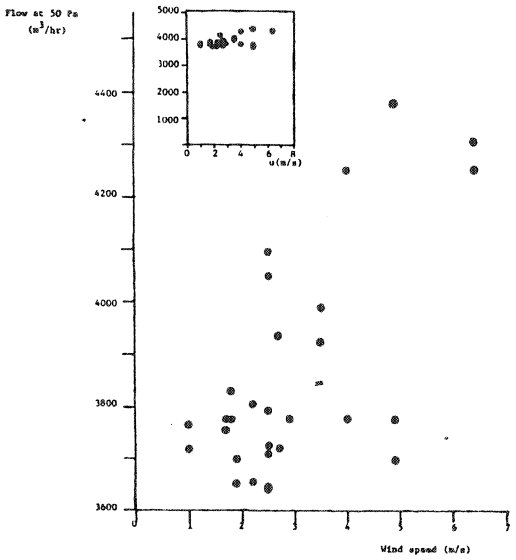

Figure 1. 50 Pa flow rate versus wind speed

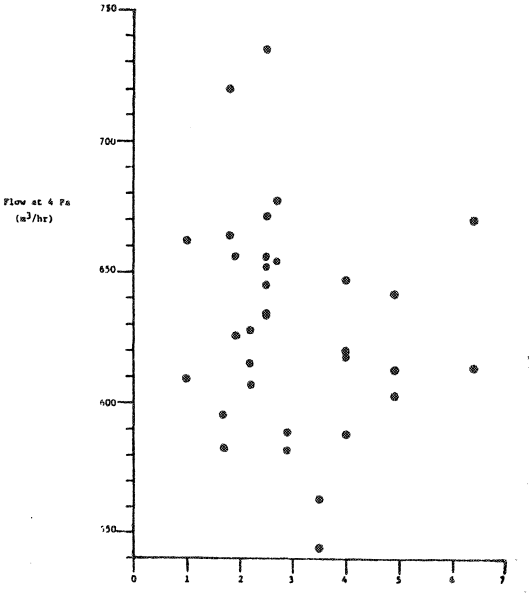

Figure 2. 4 Pa flow rate versus wind speed

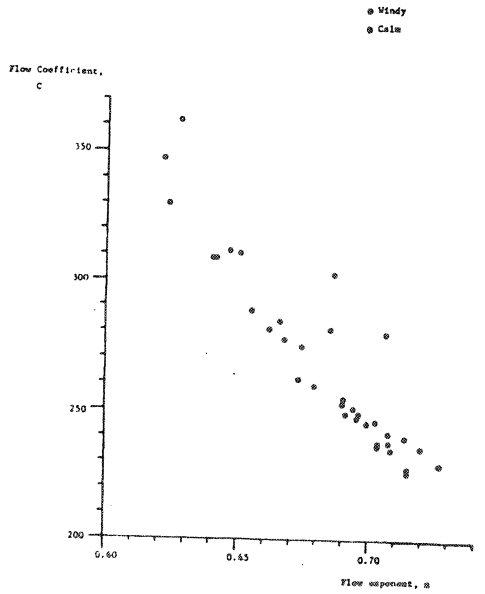

Figure 3. Flow coefficient versus exponent for curve fits to pressurization data (see Eq 1)

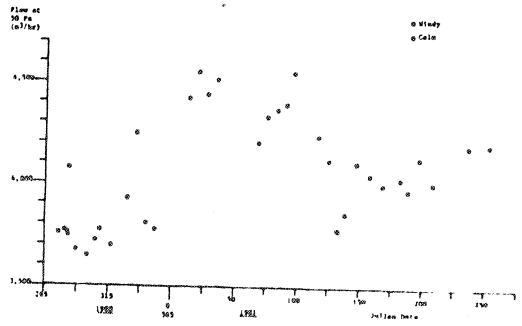

Figure 4. 50 Pa flow rate versus time

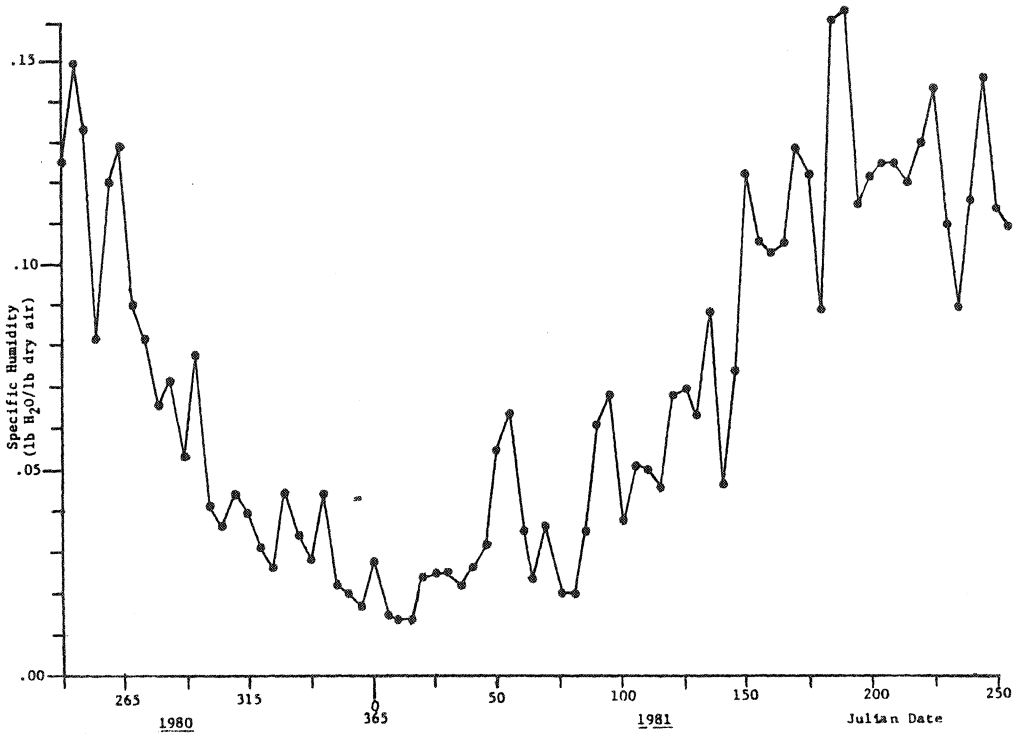

Figure 5. Five day average specific humidity versus time

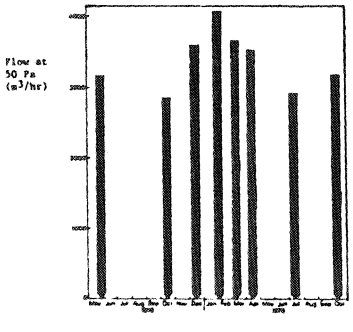

Figure 6. Seasonal variation of 50 Pa flow rate from Ref 4

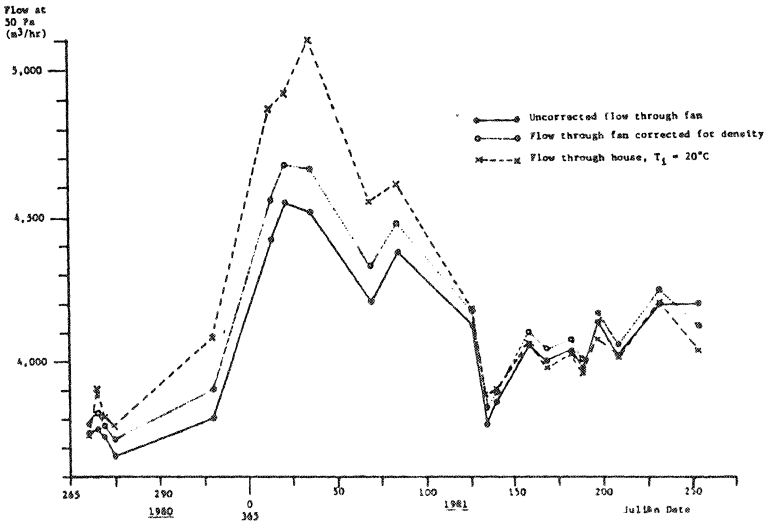

Figure 7. 50 Pa flow rate versus time with temperature corrections

Discussion

J.S. England, Washington St. Univ., Pullman: It weems to me that wind direction would affect these measurements. Please comment on this effect.

A. Persily: A change in wind direction would cause a change in the distribution of pressure differences across the building envelope, and therefore a change in the airflow through the shell. Therefore, one would expect changes in wind direction (at a given wind speed) to yield different pressurization test results. Unfortunately, I did not collect a sufficient amount of data to study such an effect.

T.J. Cardenas, Steven Winter Assoc., New York, NY: The hypothesis that seasonal variations in air leakage are due to fluctuations in moisture content in envelope construction materials cuased by changes in the moisture content of the air is highly relevant and warrants further detailed study.

Principally, the author needs to strengthen his data base. The measurement file presented does not reflect the parametric studies needed to fully correlate test results to the hypothesis. Specifically, the author needs to measure and document the changes in moisture content of the envelope construction materials. This would necessitate a rigorous study plan for test house instrumentation.

The author's presentation of a British study delineating fluctuations in air leakage in the magnitude of 40% annually needs clarification. Of worthy note is the fact that masonry construction is very popular in the United Kindgom, and accounts for close to 75-80% of residential construction. Hence the correlation of this study to the author's work also needs further study.

Persily: I agree that more detailed study of additional houses is necessary to fully understand the interaction between moisture and building teghtness. When we began collecting our data we did not anticipate finding a seasonal variation in tightness due to moisture, and therefore did not record the appropriate independent variables.

M. Modera, Lawrence Berkeley Lab., Univ. of California, Berkeley: Errors in pressuraization results due to windspeed can come from measurements of indoor/outdoor temperature pressure difference.

Persily: Indeed, the wind can make it difficult to measure indoor/outdoor pressure differences and thereby lead to errors in pressurization test results. In addition, wind will lead to an unequal distribution of pressure differences over the building shell. Finally, in pressurization devices with exposed fans, the wind will interact directly with the fan itself. Which of these three wind effects is most important and leads to the largest errors is an open question.

Modera: The difference between pressurization and depressurization flows can be used to quantify valving effect on leakage.

Persily: The difference between pressurization and depressurization flows could be used to study directional valve effects, but due to the crudeness of existing calibrations of pressurization devices, I would be hesitant to do so. At this point, one cannot say whether differences in pressurization and depressurization test results is due to real valves or due to calibration errors.