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Accuracy in Pressurization Data Analysis

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ABSTRACT

Several different ratings of building airtightness are used to report the results of fan pressurization tests. These are generally based on airflow rates at specific reference pressures, predicted by curve fits to the test data. The statistical analysis used to obtain these curves allows estimates of the uncertainties associated with these calculated airtightness ratings. The accuracy of the various ratings of building airtightness are important issues in airtightness standards enforcement and the evaluation of retrofit effectiveness. In this paper we present the various airtightness ratings being used and discuss the uncertainties associated with these ratings due to measurement errors, fan calibration, and test conditions. We also apply standard statistical techniques to calculate confidence limits for the predicted airflow rates used in the airtightness ratings. Using data from many pressurization tests, we calculate several common airtightness ratings and determine the predictive uncertainties associated with each. This discussion is based on a data set of pressurization test results in about seventy houses of different sizes, construction, and airtightness, along with detailed measurements made on a single house. The results of this analysis have implications for the reporting of pressurization test results, for their use in models to predict natural infiltration rates, and in the enforcement of airtightness standards.

INTRODUCTION

Whole building pressurization testing has been used for many years as a diagnostic tool to assist in the location of air leakage sites and to quantify the airtightness of residential buildings. To conduct a pressurization test, a large fan is mounted in a door or window of a house and is used to force air into or out of the building in order to induce specific inside-outside pressure differences. The airflow rate required to induce each pressure difference is measured, and the test results consist of several combinations of pressure difference and airflow rate. These data points are generally converted to a single value, which serves as a rating of the building's airtightness. There are several different airtightness ratings in use today, and their appropriateness and accuracy is the subject of this paper.

The airtightness ratings that are reported from fan pressurization tests can be used for studying the effectiveness of building tightness retrofits, for use in models to predict natural air infiltration rates, and for the enforcement of building airtightness standards (Jackman 1984). Several Scandanavian countries have airtightness standards for residential buildings (Norwegian Royal Ministry 1980; Swedish Building Code 1980), and ASHRAE is considering the developement of such a standard (Sherman 1984). These standards generally take the form of a maximum value of a particular airtightness rating. In formulating and enforcing such standards, measuring error and the uncertainty associated with the various airtightness ratings are important issues.

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Some research has been done on the relative accuracy of pressurization test results (Persily 1982), but very little is known about the absolute accuracy of these measurements. In addition, questions have been raised about the relative merit of the different airtightness ratings, particularly which value of the reference pressure is most appropriate in terms of accuracy and physical significance. Also, differences of opinion exist as to whether pressure tests should involve measurements only when the interior pressure is greater than outside (pressurization), when the interior pressure is lower (depressurization), or under both sets of conditions. There are also differences in the values of the pressure differences that are actually induced during a pressure test. In this paper we discuss these three questions in detail.

The paper begins with a discussion of the various ratings of building airtightness calculated from pressurization test results. The following section discusses errors in measurement, including some discussion of the effects of these errors on the different airtightness ratings. Statistical techniques are then presented for the calculation of uncertainties or confidence limits on the predicted airflow rates that serve as the basis for airtightness ratings. Finally, these uncertainties are calculated for a sample of pressurization test data and the results are discussed.

AIRTIGHTNESS RATINGS

After a pressurization test has been conducted on a house, there are several ways to convert the test data into a rating of airtightness. Most of them involve fitting the data to a curve of the form

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

where

Q = airflow rate, cfm (m^3/h)
Δp = inside-outside pressure difference, in H_2O (Pa)

C = flow coefficient, cfm/(in $H_2O)^n$ ($m^3/h\ Pa^n$)
n = flow exponent.

The various ratings of airtightness are based on the airflow rates predicted by equation 1 at particular reference pressures. The basic difference between the different ratings is in the value of the reference pressure. There are also differences in how the predicted airflow rates are normalized.

In most cases, the test data are fitted to equation 1 using standard linear regression techniques applied to the following transformation of equation 1,

$$\ln Q = \ln C + n \ln \Delta p. \qquad (2)$$

In this case, $\ln\Delta p$ is the independent variable and $\ln Q$ is the dependent variable. Standard least squares regression techniques (Draper and Smith 1966) can then be applied to $\ln\Delta p$ and $\ln Q$ to determine the slope of the best fit line, n, and the intercept, $\ln C$. The fact that one is regressing transformed variables leads to questions whether the errors in the transformed variables fulfill the assumptions of linear regression techniques. This is a complicated statistical analysis question that is beyond the scope of this paper. Because of such concerns regarding the appropriateness of the assumptions about the errors in the transformed variables, the CSGB draft standard (Canadian General Standards Board 1984) proposes an alternative technique for fitting the test data to equation 1 which is intended to avoid the problems of simply using standard regression techniques on $\ln\Delta p$ and $\ln Q$. This alternative calculation strategy may prove to be more useful and appropriate. Some calculations by the authors show that the uncertainties in the airtightness measures described below do not change significantly when using the CSGB technique, except for cases in which equation 1 provides a poor fit to the data. All of the results presented in this paper use standard regression techniques applied to $\ln\Delta p$ and $\ln Q$.

There is significant variation in the actual pressure differences that are induced during pressurization tests. Table 1 shows several examples of these pressure differences. The first example contains the test pressures from the CSGB draft standard, which range from 0.06 to 0.20 in H_2O (15 to 50 Pa) in increments of 0.02 in H_2O (5 Pa), for a total of eight points. This standard requires measurements only in the depressurization mode, i.e., inducing lower pressures within the house than outside. The ASTM standard test pressures are given next and consist of six points ranging from 0.05 to 0.30 in H_2O (12.5 to 75 Pa). The ASTM standard requires measurements under both pressurization and depressurization. The third example is a common group of test pressure differences, which includes multiples of 0.04 in H_2O (10 Pa) from 0.04 to 0.28 in H_2O (10 to 70 Pa). Finally, the last group is an example of a proposed approach using pressure differences that are more or less equally spaced in terms of $\ln\Delta p$, as opposed to being equally spaced in Δp. This is just one example that uses nine points from 0.044 to 0.28 in H_2O (11 to 70 Pa); there are other groups of pressure differences based on the same idea.

At times, due to the house's volume and leakiness, and the pressurization device airflow capacity, one cannot make measurements at some of the higher pressure differences. In these cases, the testing personnel may attempt to take some readings at intermediate pressure differences in order to obtain an adequate number of data points. Some blower doors, which employ fan speed calibrations, are provided with calibration curves only at specific pressure differences. However, this does not necessarily limit the user to testing only at these pressure differences. A more general calibration curve can be generated from the provided curves, enabling calculation of the airflow rate at any pressure difference (Persily 1984).

Once the test data are fitted to equation 1, various airtightness ratings can then be determined based on the predicted airflow rate at specific reference pressure differences. In some cases these predicted flows are converted to so-called "equivalent" or "effective" leakage areas by using the equation for the flow rate through an orifice

$$q = A\hat{C}\sqrt{2\Delta p/\rho} \qquad (3)$$

where

q = flow rate
A = opening area
C = dimensionless discharge coefficient
Δp = pressure difference
ρ = air density

The value of the discharge coefficient depends on the opening geometry and the value of the Reynolds number, and, therefore, it depends on the airflow rate. In this case, one is basically combining all the openings in the building envelope and all their discharge coefficients into an overall opening area and discharge coefficient for the building. In some cases, users of the leakage area approach set the discharge coefficient equal to 1.0 and report the value of AC. Others assume that C = 0.6, i.e. the value of the discharge coefficient for a sharp-edged orifice.

Whether one bases an airtightness rating on leakage area or simply uses the predicted airflow rate alone, either quantity is generally normalized by some factor to account for the building size. These normalization factors include floor area, outside envelope area, and volume. Normalization by envelope area provides a measure of the envelope construction quality, while normalization by volume is more closely related to the building air exchange rate.

With the wide variety of possible approaches to normalization and reference pressure, and the use of the leakage area concept, it is not suprising that many different airtightness ratings are being used. This is an unfortunate situation because it can inhibit comparison of pressurization test results from different airtightness studies. Starting with the lowest reference pressure, researchers at the Lawrence Berkeley Laboratory advocate the reporting of the effective leakage area (C = 1.0) at 0.016 in H_2O (4 Pa), normalized by the building floor area. The 0.016 in H_2O (4 Pa) leakage area also serves as an input to their predictive model of air infiltration rates (Sherman and Grimsrud 1980). They state that since weather-induced pressure differences generally lie in the range of 0.016 in H_2O (4 Pa), it is the flow rate at this pressure difference that is relevant to the situation (Sherman et al. 1979). Others argue that 0.016 in H_2O (4 Pa) is out of the range of the measured pressure differences and, therefore, the predicted flow rate at 0.016 in H_2O (4 Pa) is subject to significant uncertainty. The magnitude of such predictive uncertainty at this and other reference pressures is discussed below.

The next highest reference pressure is 0.04 in H_2O (10 Pa). The predicted flow rate at 0.04 in H_2O (10 Pa) has been normalized by building envelope area (Beach 1979) and also converted into an equivalent leakage area. The CSGB draft standard (Canadian General Standards Board 1984) assumes a discharge coefficient of 0.6 in equation 3 and normalizes the calculated leakage area by the building envelope area. Others have reported the 0.04 in H_2O (10 Pa) effective leakage area assuming a discharge coefficient of 1.0 and normalizing by the building floor area (Murakami and Yoshino 1983). Since 0.04 in H_2O (10 Pa) is at the lower end, or even outside, of the range of measured data, it will generally be associated with significant uncertainties, though not as large as those at 0.016 in H_2O (4 Pa).

Another common airtightness measure is the predicted flow rate at 0.20 in H_2O (50 Pa) normalized by the building volume, generally expressed in air changes or exchanges per hour (Dumont 1981). The 0.20 in H_2O (50 Pa) exchange rate is used in the Norwegian and Swedish airtightness standards (Norwegian Royal Ministry 1980; Swedish Building Code 1980). The 0.20 in H_2O (50 Pa) flow rate has also been normalized by the building envelope area (Kronvall 1978). Finally, Tamura (1975) has used the predicted flow at 0.30 in H_2O (75 Pa) normalized by envelope area. A pressure difference of 0.30 in H_2O (75 Pa) is commonly used for airtightness rating of windows but has not been used much for reporting whole house pressurization test results.

Little research has been done on the relative merits of the various reference pressures. A study of the repeatability of pressurization test results for a single house revealed that after many pressurization tests, the 0.20 in H_2O (50 Pa) flow rates had a standard deviation equal to less than 2% of the mean value. The standard deviation of the flow rate at 0.016 in H_2O (4 Pa) was about 5% of the mean value.

Regardless of which airtightness rating one uses, the linear regression technique used to determine the coefficients in equations 1 and 2 enable estimation of the uncertainty of the predicted flow rate at any pressure difference. The techniques used to estimate these predictive uncertainties and examples of their values from actual pressurization test data are presented below.

MEASUREMENT ERRORS

There are two types of errors associated with whole house pressurization tests. First, there are errors in measurement associated with the determination of airflow rate and inside-outside pressure difference. Also, there are errors caused by test conditions, such as the outdoor weather and peculiarities of the building's leaks. These latter problems include leaks that change physically as the pressure difference becomes large or changes direction. The first type of errors, those associated with measurement accuracy, are addressed by standards for the test procedure, such as ASTM E779-81 (ASTM 1981). The fulfillment of the accuracy requirements of such a standard is a matter of equipment selection and calibration. The second type of errors, those associated with test conditions, involve more difficult issues, but there are some guidelines and experience concerning the importance of weather conditions during the test. The sensitivity of the various airtightness ratings to "test condition" errors are difficult to quantify but are discussed below in a qualitative sense.

The ASTM standard for pressurization testing spells out specific requirements for the accuracy of the pressure difference and airflow rate measurements. The inside-outside pressure difference must be measured with a device that is accurate within ± 0.01 in H_2O (2.5 Pa). This can be done with an inclined manometer (draft gauge) or with a magnetic linkage type differential pressure gauge, provided that a model with an appropriate scale is chosen. The authors have found that magnetic linkage gauges are often significantly out of calibration and must be individually calibrated at least once a year.

The ASTM pressurization standard requires that the airflow rate measurement be accurate within ± 6% of the average measured airflow rate. The question of the calibration of fan pressurization devices, or blower doors, and the accuracy of the airflow rate measurements has not been well investigated. The calibration of blower doors is not a simple problem and there is an ASTM task group (E6.41.05) considering a standard for blower door calibration. Various manufacturers of blower doors report accuracies within the ASTM specification, while others make no accuracy claims. One study of a particular calibration technique applied to a so-called "rpm" or "fan speed" blower door yielded an accuracy of ± 4% of the average airflow rate in the calibration range (Persily 1984). Additional research into airflow rate measurement accuracy and calibration is necessary before definitive accuracy statements can be made.

There can also be errors in pressurization measurements due to the test conditions, such as the physical characteristics of the building leaks and the weather conditions during the test. When conducting a pressurization test on a house, there are generally differences between the results obtained under positive and negative pressure differences. These can be caused by leaks that behave differently when the inside is at a higher pressure than the outside, as opposed to the inside pressure being lower. However, such a difference between the positive and negative pressure difference results can also be caused by inaccurate blower door calibrations. Since such directional "openings" probably do exist, it may be advisable to test buildings at both positive and negative pressure differences to avoid serious errors due to extreme directional effects. Additional research into directional leaks is required to understand the importance of such leaks in pressurization testing and naturally induced air infiltration.

Additional inaccuracies may also be caused by leaks that are physically altered by the test pressure differences. Such data points will influence the curve that is fitted to the test data and affect the results that are reported. The physical alteration of leaks by large pressures has implications for the choice of pressures that are induced during a test, but insufficient research has been done to determine recommended maximum test pressures. Also, the ASTM standard requires that the interior pressure be uniform within less than 20% of the measured inside-outside pressure difference. This may be difficult to achieve in very large buildings with many internal partitions, but this problem has not been investigated.

The weather conditions during the test, wind speed and direction and inside-outside temperature difference, can lead to measurement errors due to weather induced pressure differences interfering with the test pressure differences. A significant inside-outside temperature will cause a pressure difference across the building envelope that varies with height, leading to results that may not correctly characterize the building's leakage. Excessive wind speeds induce unsteady exterior pressures, which inhibit the establishment of a constant inside-outside pressure difference during a test. The ASTM standard recommends that the test be carried out with an inside-outside temperature difference less than 20 F (11°C) and an on-site wind speed less than 10 mph (4.5 m/s). A study involving a large number of pressurization tests on a single house has revealed that significant wind-induced errors occurred at local wind speeds greater than or equal to 5.5 mph (2.5 m/s) (Persily 1982). In considering the effects of wind speed on pressurization test results, the location of the house relative to the wind speed measurement and the shielding of the house are important.

In summary, while little research has been done on the measurement errors associated with pressurization testing, some general recommendations can be made. The existence of directional openings suggests that one induce both positive and negative pressure differences during a test. Also, the fact that leaks may be physically altered by large pressure differences suggests that one avoid extreme pressure differences during the test, but exactly what constitutes an extreme pressure difference is not known.

ACCURACY OF AIRTIGHTNESS RATINGS

The various ratings of airtightness discussed above are all based on airflow rates predicted from equation 1. Even the leakage areas equal to are predicted airflow rates multiplied by a constant. It is the accuracy of these airflow predictions that concerns us here. Techniques exist for estimating these predictive uncertainties when using linear regression procedures to predict the airflow rates. We briefly outline and discuss these techniques, and then apply them in the next section.

Considering the transformed variables lnQ and lnΔp in equation 2, we will use conventional notation and express lnQ as Y and lnΔp as X. We have N pairs of (X,Y) values, the ith pair denoted as (X_i, Y_i). The value of Y predicted from the regression equation is expressed as $\hat{Y}$. The estimate of the standard error of a particular (the kth) predicted value of Y, i.e., $\hat{Y}_k$, is given by Draper and Smith (1966),

$$EY_k = s \{ (1/N) + [(X_k - \bar{X})^2 / \sum_{i=1}^{N} (X_i - \bar{X})^2] \}^{0.5} \quad (4)$$

where

$$s = \{ [\sum_{i=1}^{N} (\hat{Y}_i - Y_i)^2] / (N-2) \}^{0.5}. \qquad (5)$$

Thus, one must have at least three (X,Y) pairs to make these calculations. Some interesting observations can be made based on the form of these equations. First, as the number of points increases, the value of s in equation 5 and the value of EY_k generally decrease. Also, the sum in equation 4 becomes larger if the X values cover a wider range and if they are well-distributed along the X axis. Finally, EY_k is a minimum at the average value of X, i.e., $\bar{X}$ (in our case $\overline{\ln\Delta p}$), and its value increases as we move in either direction away from $\bar{X}$.

Based on the value of EY_k in equation 4, one can calculate confidence limits on the predicted values of Y. This involves the "t-distribution" (Draper and Smith 1966), which in practice means that one multiplies EY_k by a value of t, which depends on N, and the percent confidence limits that one decides are appropriate to one's problem. As the value of N increases, t decreases asymptotically towards a value which depends on the particular percentage chosen for the confidence limits. In the calculations below, we determine the 95% confidence limits for several predicted airflow rates. The predicted airflow rates with their 95% confidence limits, i.e., $Y_k \pm tEY_k$, means that there is a 95% probability that this interval contains the true value of Y at X_k. However, this interval is defined in terms of Y = lnQ. One can convert the errors in lnQ, ΔlnQ, to the errors of interest to us, ΔQ, by the following

$$\Delta Q \simeq (\Delta \ln Q)\, Q \qquad (6)$$

or,

$$\Delta Q_k \simeq t\, EY_k\, Q_k. \qquad (7)$$

This is the procedure used to calculate the 95% confidence limits of the predicted values of the airflow rates below. These confidence limits are also referred to as predictive uncertainties in this paper. They correspond to the uncertainty in the predicted airflow rates based on the test data, not to the absolute difference between the predicted and the actual airflow.

EXAMPLES OF PREDICTIVE UNCERTAINTIES

In this section, the above techniques for estimating the confidence limits of the predicted airflow rates are applied to examples of pressurization test data. For these tests, the predicted airflow rates at 0.016, 0.04, 0.10, and 0.20 in H_2O (4, 10, 25, and 50 Pa) are considered. The analytical techniques are applied first to pressurization test results from a group of 68 recently constructed, passive solar homes located throughout the U.S., the so-called Class B homes (Persily and Grot 1984). While these homes were designed with passive solar features, their construction is not significantly different from typical construction in their respective localities, nor are their airtightness levels. In addition, the predictive uncertainies are studied for a single home in Washington, DC, which was pressure tested in order to enable comparison of the different test pressure groupings in Table 1.

Class B Homes

These 68 homes were part of a project to evaluate passive solar residential buildings. As part of the evaluation, each of these homes was pressure tested. The tests were conducted by a different person in each of six regional and one "housing style" groups into which the homes were divided. The homes varied greatly in size and leakiness. Some of the leakier homes were only tested at pressure differences less than or equal to about 0.12 to 0.14 in H_2O (30 or 35 Pa). Other homes were tested up to 0.28 to 0.30 in H_2O (70 or 75 Pa). All of the homes were subjected to both pressurization and depressurization conditions. The design of the blower doors used in these tests provided larger airflow capacities in the depressurization mode than in pressurization. Therefore, in large and leaky homes the depressurization data generally include higher pressure differences than the pressurization results. Only homes with more than two measurements in each mode are considered.

Table 2 is an example of the test data and the subsequent predictive uncertainty analysis. The test data are listed at the top of the table. There are seven points each of pressurization and depressurization data. Equations such as equation 1 are fitted to the pressurization data alone, to the depressurization data alone, and to all the points together. These three equations are used to predict the 0.016, 0.04, 0.10, and 0.20 in H_2O (4, 10, 25, and 50 Pa) airflow rates shown in the lower half of the table. The uncertainty analysis techniques outlined above are used to calculate the 95% confidence limits for each predicted flow. These are expressed as percentages of the predicted flows in Table 2. We note that the highest percentage uncertainties occur at 0.016 in H_2O (4 Pa). This is expected, since 0.016 in H_2O (4 Pa) is out of the range of the measured data. In this particular example, the uncertainties in the predictions for the pressurization-only data and all-point data are similar in magnitude, while the uncertainties for the depressurization data are smaller. This result is simply a characteristic of these particular data and is not a general property of pressurization test data. In other cases, the depressurization uncertainties are larger. When there is a significant difference between the pressurization and depressurization airflow rates, the all-point uncertainties are much larger than those of the other two groups. In all cases, the smallest uncertainties occur around the middle range of the measured pressure differences. In this example, the 0.10 in H_2O (25 Pa) uncertainties are the smallest, though they are only slightly less than those at the 0.20 in H_2O (50 Pa). Note that the all-point analysis involves more points than either the pressurization or depressurization cases, and therefore the value of t in equation 7 will always be smaller. For cases in which the test data covers a limited range of pressure differences, for example from 0.04 to 0.12 in H_2O (10 to 30 Pa), the uncertainties are generally larger, in part due to the smaller number of points and the influence of this number on the value of t in equation 7. Also in these cases, the uncertainty at 0.20 in H_2O (50 Pa) can be quite large, since this pressure difference is now outside of the range of the measured data.

Table 3 summarizes the predictive uncertainties, as percentages of the predicted airflows, for all the Class B data. Figures 1, 2, and 3 are histograms of the same percentage uncertainties for pressurization, depressurization, and all-points respectively. Considering the pressurization results first, we see the largest percentage uncertainties for the 0.016 in H_2O (4 Pa) flow rate. The 0.04 in H_2O (10 Pa) flow uncertainties are smaller and the 0.10 in H_2O (25 Pa) uncertainties are the smallest. The average 0.20 in H_2O (50 Pa) uncertainties are comparable to the 0.04 in H_2O (10 Pa) uncertainties, due mostly to the fact that some of the houses could not be pressurized up to 0.20 in H_2O (50 Pa). This leads to some very large predictive uncertainties at 50 Pa, since it is now out of the range of the measured data. For all the pressure differences, there are cases of predictive uncertainties greater than 100%.

Going on to the depressurization data, we see that the predictive uncertainties are lower at all the pressure differences than the pressurization uncertainties. In addition, the difference between the 0.10 and 0.20 in H_2O (25 and 50 Pa) uncertainties is significantly less than in the case of pressurization. This change is due to the fact that the blower doors used in these tests have a higher airflow capacity in the depressurization mode. Thus, the depressurization measurements of large or leaky houses cover a wider range of pressure differences than the pressurization measurements in the same houses, and, therefore, the depressurization uncertainties are smaller. Finally, the all-point predictive uncertainties are somewhat larger than the pressurization uncertainties, except at 0.20 in H_2O (50 Pa). However, the standard deviation of these uncertainties, i.e., their spread, and the number of uncertainties greater than 100% are significantly reduced. In fact, uncertainties greater than 100% occur only for the 0.016 in H_2O (4 Pa) flows. This is due to the fact that the all-point results for large and leaky houses exhibit less severe predictive uncertainties than the pressurization and depressurization uncertainties for these same houses. This is true in part because the value of N is larger for the all-point analysis and, therefore, the value of t in equation 7 is smaller. This points out the value of taking both pressurization and depressurization data, especially in large and leaky houses.

Table 4 summarizes the predictive uncertainties, as percentages of predicted airflow rates, for only the Class B homes which were tested up to 0.20 in H_2O (50 Pa) under both positive and negative pressure differences. There is no longer any significant difference between the uncertainties for pressurization and depressurization, as was seen in Table 3 for all the Class B data. The smallest uncertainties again occur at 0.1 in H_2O (25 Pa), with only slightly larger uncertainties at 0.20 in H_2O (50 Pa). The predictive uncertainties for the all-point predictions are larger than in the case of either pressurization or depressurization, due to directional effects, i.e., differences between the measured airflow rates under positive and negative pressure differences. While the all-point uncertainties are larger, the predicted flows based on all the points may provide a better measure of airtightness than either the pressurization or depressurization alone. As stated above, additional research into "directional leaks" is required to understand this question.

The analysis of the predictive uncertainties of the Class B airflow rates has shown that the magnitude of these uncertainties follows the expected trends. They are largest for pressure differences outside of the range of the measured data, i.e., 0.016 in H_2O (4 Pa). They are smaller at the extremes of the measured test data, at 0.04 in H_2O (10 Pa), and even less at 0.20 in H_2O (50 Pa). The predictive uncertainties are smallest in the middle of the range of the test data, i.e., 0.10 in H_2O (25 Pa). Also, the predicted flows based on all the data points, pressurization and depressurization, exhibit less extreme uncertainties than either group of points alone, when considering all the Class B data.

Single House Test

In this case, we pressure tested a house at all the pressure differences listed in Table 1, only in the depressurization mode. This exercise was intended to enable a comparison of the relative merits of the different groups of test pressures in terms of the predictive uncertainties associated with the airflow rates at 0.016, 0.04, 0.10, and 0.20 in H_2O (4, 10, 25, and 50 Pa). The results of this analysis are given in Table 5. One problem with this experiment is that different data points are used in the different curve fits, complicating comparison between the results. For instance, the reading at 0.15 in H_2O (37.5 Pa) is only in the ASTM pressures. If this reading happens to be more inaccurate than the others, its inaccuracy will only influence this particular curve fit. This is a general problem in comparing the results in Table 5. In addition to the four pressure difference groups shown in Table 1, we include modifications of the "tens" and "log-weighted" groups, which only go up to 0.20 in H_2O (50 Pa), thereby enabling comparison to the CGSB pressures.

As in the Class B data presented above, the largest uncertainties are at 0.016 in H_2O (4 Pa) and the smallest are at 0.10 in H_2O (25 Pa), except for the ASTM group for which the uncertainty is minimized at 0.20 in H_2O (50 Pa). The "log-weighted" pressure group using all nine points exhibits the smallest uncertainties. This is probably due to the large number of data points, the wide pressure range, and the fact that the values of $\ln\Delta p$ are evenly spaced. In our earlier discussion of equations 4 and 5 we pointed out that all these factors should reduce the predictive uncertainties. Comparing the complete "log-weighted" group to the partial "log-weighted" group, we see that the partial group has larger uncertainties due to the smaller number of points and the narrower range of pressure differences. This is also true when comparing the complete "tens" group to the partial "tens" group. On the average, the three groups that only go up to 0.20 in H_2O (50 Pa) have larger uncertainties than the three groups that go up to 0.28 to 0.30 in H_2O (70 or 75 Pa). The larger uncertainties occur because there are less points in these "0.20 in H_2O " (50 Pa) groups, and the pressure differences cover a narrower range of values. It is difficult to compare the specific magnitude of the predictive uncertainties among these different groups, because there are different data points in each group, as mentioned above. Thus, the results of this single house experiment are not quantitatively significant, but they do exhibit the expected patterns. The predictive uncertainties are generally lower when there are more points and when the data cover a wider range of pressure differences. Also, the use of log-weighted pressure differences appears to reduce the predictive uncertainty, as opposed to the use of evenly spaced pressure differences. The determination of the numerical significance of all these effects requires the study of a larger number of houses.

CONCLUSIONS

In this report we have discussed some of the sources of errors in pressurization testing and reviewed the various airtightness ratings used to report pressurization test results. We presented statistical techniques for estimating the uncertainties associated with the predicted airflow rates used in determining these airtightness ratings. These statistical techniques were applied to a large group of pressurization test results from many houses and the results of a detailed pressurization test of a single house.

As expected, the predictive uncertainties were largest outside of the range of the measured data and smallest around the middle of the measured pressure differences. The prediction of airflow rates from the combination of both pressurization and depressurization data reduced the occurrence of very large predictive uncertainties relative to using either set alone. This was due to tests in large and leaky houses that could not be pressurized to the full range of pressure differences.

In choosing the pressure differences at which to conduct a pressurization test, there are several general guidelines. The more data points that one obtains, the lower are the predictive uncertainties. For a wider range of measured pressure differences, the uncertainties will also be less. However, a maximum pressure difference of 0.30 in H_2O (75 Pa) is probably advisable to avoid potential problems of altering the leakage of the building. Log-weighted pressure differences appear to reduce predictive uncertainties as compared to evenly spaced pressure differences, but the extent of the reduction is not known.

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TABLE 1
EXAMPLES OF TEST PRESSURE DIFFERENCES

CSGB Standard 8th Draft 1984		ASTM Standard E779-81		TENS		LOG-WEIGHTED	
in H_2O	(Pa)	in H_2O	(Pa)	in H_2O	(Pa)	in H_2O	(Pa)
0.06	(15)	0.05	(12.5)	0.04	(10)	0.044	(11)
0.08	(20)	0.10	(25)	0.08	(20)	0.056	(14)
0.10	(25)	0.15	(37.5)	0.12	(30)	0.072	(18)
0.12	(30)	0.20	(50)	0.16	(40)	0.092	(23)
0.14	(35)	0.25	(62.5)	0.20	(50)	0.12	(30)
0.16	(40)	0.30	(75)	0.24	(60)	0.16	(40)
0.18	(45)			0.28	(70)	0.20	(50)
0.20	(50)					0.24	(60)
						0.28	(70)

TABLE 2

EXAMPLE OF PRESSURIZATION TEST DATA AND UNCERTAINTY ANALYSIS FOR A SAMPLE HOUSE

TEST DATA

Pressure Difference		Airflow Rate			
		Pressurization		Depressurization	
in H_2O	(Pa)	cfm	(m^3/hr)	cfm	(m^3/hr)
0.04	(10)	543	(922)	691	(1175)
0.08	(20)	1075	(1826)	1069	(1816)
0.12	(30)	1413	(2401)	1382	(2349)
0.16	(40)	1864	(3168)	1697	(2884)
0.20	(50)	2220	(3772)	1894	(3218)
0.24	(60)	2512	(4269)	2139	(3634)
0.28	(70)	2748	(4669)	2359	(4008)

PREDICTED AIR FLOW RATES AND UNCERTAINTIES

Pressure Difference		Airflow Rate		Estmated Uncertainty/Predicted Flow (95% Confidence Limits)
in H_2O	(Pa)	cfm	(m^3/hr)	
Pressurization				
0.016	(4)	265	(450)	14.8%
0.04	(10)	568	(966)	9.1%
0.10	(25)	1221	(2075)	4.7%
0.20	(50)	2177	(3699)	4.9%
Depressurization				
0.016	(4)	388	(660)	3.7%
0.04	(10)	692	(1176)	2.3%
0.10	(25)	1234	(2097)	1.2%
0.20	(50)	1912	(3249)	1.3%
All Points				
0.016	(4)	321	(545)	16.4%
0.04	(10)	627	(1066)	10.1%
0.10	(25)	1228	(2086)	5.2%
0.20	(50)	2040	(3467)	5.5%

TABLE 3
PREDICTIVE UNCERTAINTIES FOR ALL THE CLASS B DATA

	Predictive Uncertainty as a Percentage of Predicted Airflow Rate			
	0.016 in H2O (4 Pa)	0.04 in H2O (10 Pa)	0.10 in H2O (25 Pa)	0.20 in H2O (50 Pa)
Pressurization				
Mean	38.0%	20.6%	11.9%	19.5%
Standard Deviation	80.8%	41.0%	23.1%	46.7%
Depressurization				
Mean	28.3%	16.6%	8.2%	10.6%
Standard Deviation	47.6%	27.3%	13.0%	19.2%
All Points				
Mean	44.6%	25.8%	13.2%	15.7%
Standard Deviation	25.9%	14.4%	7.2%	10.4%

TABLE 4
PREDICTIVE UNCERTAINTIES FOR A SUBSET OF THE CLASS B DATA

	Predictive Uncertainty as a Percentage of Predicted Airflow Rate			
	0.016 in H_2O (4 Pa)	0.04 in H_2O (10 Pa)	0.10 in H_2O (25 Pa)	0.20 in H_2O (50 Pa)
Pressurization				
Mean	19.1%	11.5%	5.7%	6.7%
Standard Deviation	19.3%	11.4%	5.7%	7.4%
Depressurization				
Mean	19.1%	11.3%	6.1%	6.3%
Standard Deviation	18.1%	10.6%	5.6%	6.1%
All Points				
Mean	39.4%	25.7%	12.7%	14.1%
Standard Deviation	21.8%	15.3%	7.5%	9.3%

TABLE 5
RESULTS OF SINGLE HOUSE TEST

	N	Maximum Pressure Difference	Predictive Uncertainty as a Percentage of Predicted Airflow Rate			
			0.016 in H_2O (4 Pa)	0.10 in H_2O (10 Pa)	0.10 in H_2O (25 Pa)	0.20 in H_2O (50 Pa)
CGSB	8	0.20 in H_2O (50 Pa)	8.9	5.1	1.9	2.7
ASTM	6	0.30 in H_2O (75 Pa)	4.9	3.1	1.5	0.6
TENS	7	0.28 in H_2O (70 Pa)	9.3	5.7	2.9	3.1
	5	0.20 in H_2O (50 Pa)	15.0	8.5	4.4	6.6
LOG-WEIGHTED	9	0.28 in H_2O (70 Pa)	3.7	2.2	1.1	1.4
	7	0.20 in H_2O (50 Pa)	5.7	3.1	1.6	2.8

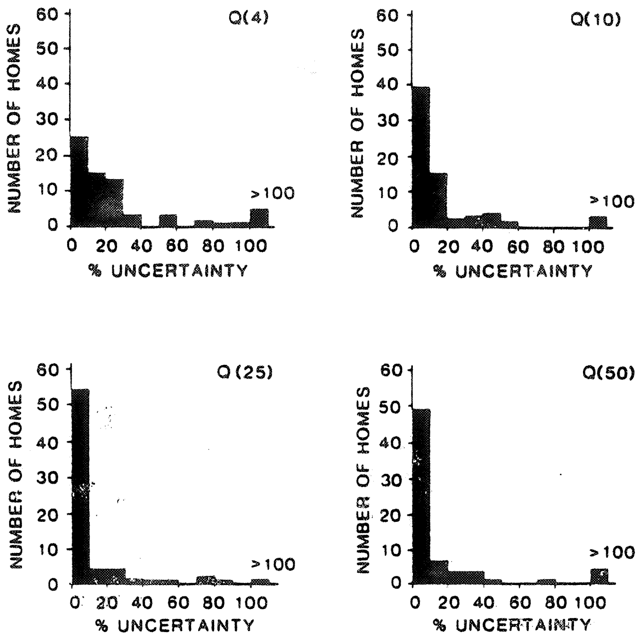

Figure 1. Percent uncertainties in predicted flows - pressurization

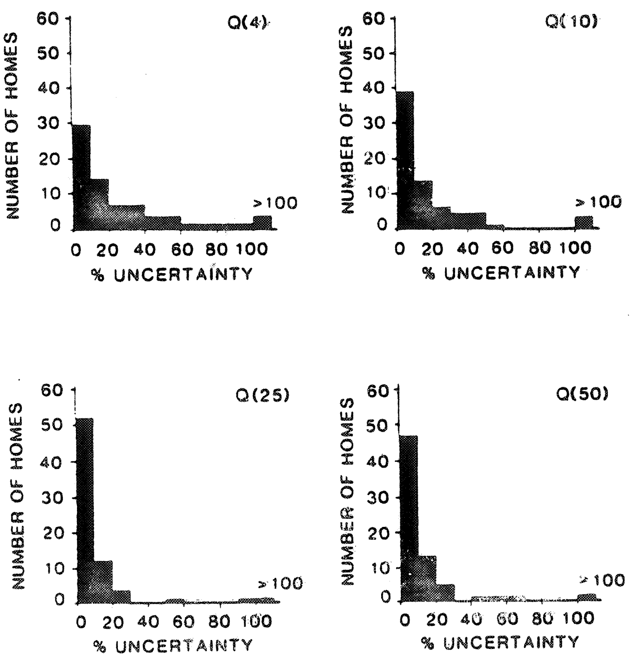

Figure 2. Percent uncertainties in predicted flows - depressurization

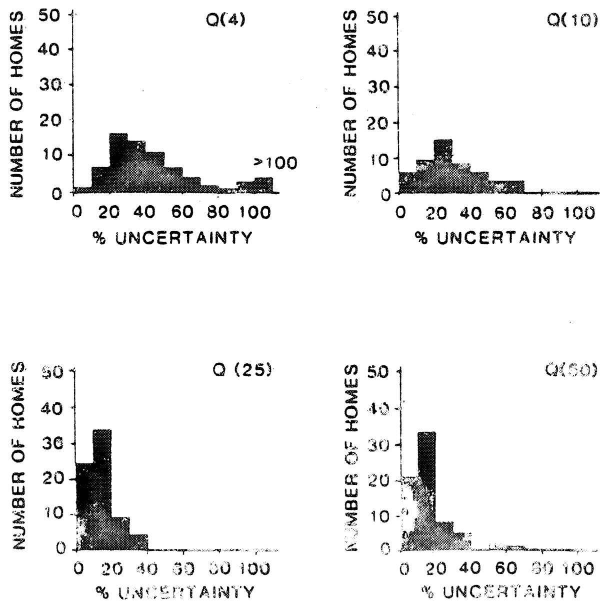

Figure 3. Percent uncertainties in predicted flows - all points