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Measurements of Air Infiltration and Airtightness in Passive Solar Homes

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ABSTRACT: The airtightness of 82 passive solar homes located throughout the United States was studied using tracer gas measurements of air infiltration and pressurization testing. The air infiltration measurements employed the tracer gas decay technique in a low-cost mode employing air sample bags and off-site infiltration determination. The infiltration rates measured under natural conditions ranged from about 0.05 to almost 2 air changes per hour (ACH). The pressurization test results ranged from 1 to more than 30 ACH at 50 Pa, with an average of about 10 ACH. By comparing the pressurization measurements on these homes to measurements on other homes, the passive solar homes were found to be in general no tighter than other U.S. homes. The air infiltration and pressurization measurements of the Class B homes were compared using existing infiltration models and other empirical relations.

KEY WORDS: air infiltration, air leakage in buildings, airtightness of buildings, building airtightness, blower door tests, passive solar buildings, pressurization testing, tracer gas measurement

The Solar Energy Research Institute (SERI), funded by the Department of Energy, has established programs to evaluate the thermal performance of passive solar residential buildings. The programs, Class A, B, and C, vary in the detail and expense of the monitoring. The homes described in this paper belong to the middle level of monitoring, Class B. The purpose of the Class B program is to determine the thermal performance of different types of passive houses located in different climates by calculating the monthly building energy balance, the solar fraction, and solar savings [*1–2*].

As part of the Class B monitoring, each home was subjected to pressurization testing [*3*] to measure the airtightness of the building shell and to a small number of tracer gas decay tests [*4*] to measure air infiltration rates. This

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paper discusses the techniques used for both measurements and reports on the results obtained. Such a large group of passive solar homes was never subjected to airtightness measurements before. The air leakage rates of this type of home are often assumed to be below average, and these tests reveal the actual performance of these homes.

The two methods of measurements also were compared to one another to assess their accuracy and consistency for evaluating the airtightness of these buildings. Preliminary measurement results for some of these homes have been published previously [5].

Homes

The Class B homes, located throughout the United States, employ several different passive features, including sunspaces, Trombe walls, and greenhouses. Most of the homes are occupied, while some serve as models for homebuilders. The homes discussed in this report are divided into five regional groups (Denver, Northeast, South, California, and Mid-America) and one group of "manufactured," or factory-built, homes located throughout the country. All the homes were designed to have thermal envelopes of above average integrity in terms of both insulation levels and airtightness. Eighty-two homes have received at least one pressurization test or infiltration measurement.

Measurements

The Class B homes were subjected to pressurization tests to measure the airtightness of the building shell and to tracer gas measurements of air infiltration rates under natural conditions. Both techniques have been used for several years to evaluate the airtightness of homes.

Pressurization Measurements

In whole house pressurization, a large fan mounted in a door or window induces a large and roughly uniform pressure difference across the building envelope [3]. The leakier the house, the more airflow is necessary to induce a specific pressure difference between inside and outside. The pressurization tests of the Class B homes employed devices called "blower doors," consisting of a variable speed d-c motor and a large fan mounted in a wooden frame of adjustable height and width. The blower doors used in these tests are calibrated to yield the flow rate through the fan as a function of the rate of fan rotation and the inside-outside pressure difference. In conducting the blower door tests, the homes were pressurized and depressurized to pressure differences from 12 to 60 Pa in increments of about 12 Pa. Some of the leakier or larger houses could not be pressurized to all of these levels. During the pressurization tests, all interior doors were open and any flues or vents were in their normal positions. The tests were conducted with sunspace or greenhouse doors open and with these same doors closed, but generally the result with the doors open was used to characterize a house's leakiness.

The pressurization tests were performed by several different subcontractors and SERI, and the data were sent to the National Bureau of Standards (NBS) for analysis and interpretation. Of the many possible ways to convert the pressure difference and airflow data to a measurement of building tightness, we present the flow rate required to maintain an inside-outside pressure difference of 50 Pa. To obtain the 50-Pa flow rate, the flows and pressure differences from the test are fit to an equation of the form

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

where

Q = flow rate, m^3/h,
Δp = inside-outside pressure difference, Pa, and
C,n = empirical constants from regression analysis.

The equation is fit to data obtained by both pressurizing and depressurizing the house. Equation 1 is used to determine the 50-Pa flow rate in m^3/h, which is then normalized by the house volume (including the basement) to yield the flow rate in house volumes per hour or ACH. The 50-Pa flow rate measurement is accurate within about $\pm 10\%$. Typically, U.S. homes lie in the range of 10 to 20 ACH but can be tighter or looser [*6–7*].

Air Infiltration Measurement

Air infiltration rates in buildings have been measured for many years using tracer gas techniques [*4,8–9*]. The infiltration rates of the Class B homes were measured using the tracer gas decay or dilution method in which the gas is released all at once and the decay in concentration is monitored. Automated equipment can be used to measure infiltration continuously, but using such equipment in the large number of Class B homes would have been prohibitively expensive. Instead, a low-cost system was used involving on-site sampling of the interior air and off-site measurement of the tracer gas concentration. This "air bag" technique has been used successfully to measure the infiltration rates of a large number of homes with only a single tracer gas concentration measuring device at a central laboratory [*7*].

The air infiltration rate of a building is strongly influenced by the weather conditions during the measurement, and this rate can vary over a range of 5 to 1 for a single home depending on the weather conditions. Therefore, a single infiltration measurement is only of limited use for characterizing building tightness. The original experimental design was to test each home from five to ten times; however, most of the homes were tested only once or twice.

In each tracer gas test, the experimenter released a small amount of sulfur hexafluoride (SF_6) into the interior of the house. The amount of SF_6 injected was determined according to the house volume, the target concentration being 100 ppb. To increase the uniformity of the gas distribution, the tracer was released slowly as the experimenter walked through the house. Forced air distribution systems and fans were used to mix the interior air more completely. A waiting period of about one-half hour after the tracer gas release further ensured a uniform distribution of tracer gas. At this point a sample bag was filled with interior air while walking through the house. A total of four sample bags were filled at roughly half-hour intervals.

The air sample bags then were shipped to NBS, where the SF_6 concentration in each bag was measured with a gas chromatograph equipped with an electron capture detector. The rate of decay of the SF_6 concentration over time then was used to calculate the infiltration rate. The infiltration rates determined in this manner are accurate within about 0.1 ACH. During each infiltration measurement, the inside and outside temperatures and the wind speed were measured at the site.

Results

Figure 1 is a frequency distribution of the 50-Pa flow rates in ACH for the 74 homes which were pressure tested. The average 50-Pa flow rate for these homes is 10.1 ACH with a standard deviation of 6.1 ACH. Figure 2 is a frequency distribution of the 87 measured infiltration rates in ACH for 54 of the Class B homes. The average measured infiltration rate of the Class B homes is 0.42 ACH with a standard deviation of 0.30. The average weather conditions for these infiltration measurements are a wind speed of 2.1 m/s and an inside-outside temperature difference of 10.6°C.

The average infiltration rate measured in the houses is not representative of the heating season due to the mild weather conditions under which many of

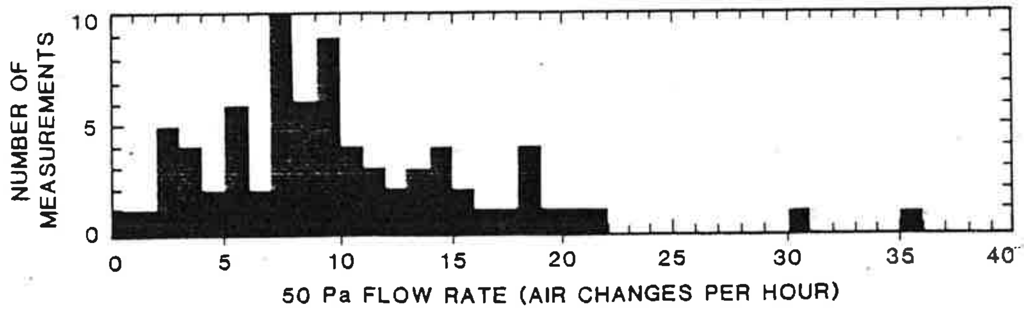

FIG. 1—*Frequency distribution of pressurization test results.*

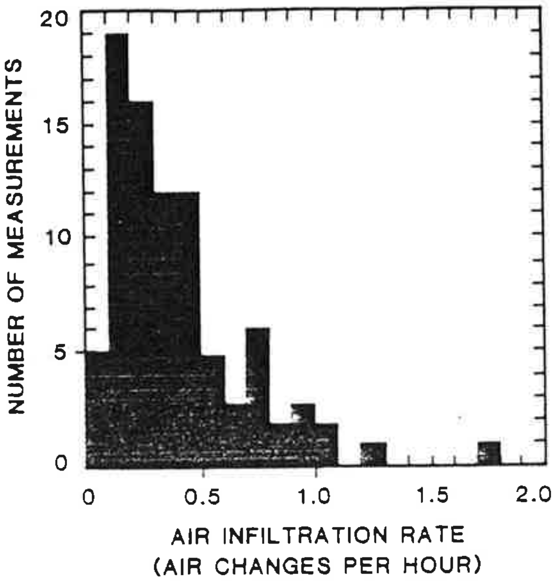

FIG. 2—*Frequency distribution of air infiltration measurements.*

the measurements were made. Table 1 shows the distribution of infiltration measurements with weather conditions. The number in each square is the number of infiltration measurements made under the corresponding conditions of wind and temperature difference. As can be seen in the table, many of the measurements have been made under relatively mild weather conditions: 24 of the 87 infiltration rates were measured with temperature differences of 5°C or less, and 61 of the rates were measured with a temperature difference less than 15°C. Roughly one third of the homes never had their infiltration rates measured for temperature differences greater than 5°C. This preponderance of mild weather infiltration measurements is the result of contractor actions and must be kept in mind when considering the magnitude of the measured infiltration rates. Also, for many of the homes, we have not reliably characterized their heating season infiltration rates.

TABLE 1—*Distribution of infiltration measurements with weather conditions.*

	ΔT(°C)				
u(m/s)	<0	0 to 5	5 to 15	15 to 25	25 to 35
0 to 1	3	6	9	9	1
1 to 3	3	7	20	7	2
3 to 5	0	3	2	2	0
5 to 7	1	0	5	4	1
>7	1	0	1	0	0

NOTE—ΔT = the inside-outside temperature difference; u = the wind speed. Both values are averages over the infiltration measurement period.

Comparison to Other Homes

This data set of airtightness and infiltration measurements on passive solar homes provides an opportunity to compare the tightness of these buildings to other homes. These passive solar buildings, designed to consume relatively low levels of energy for space conditioning, are expected to be more airtight than other homes by builders, designers, and others involved with this proj-

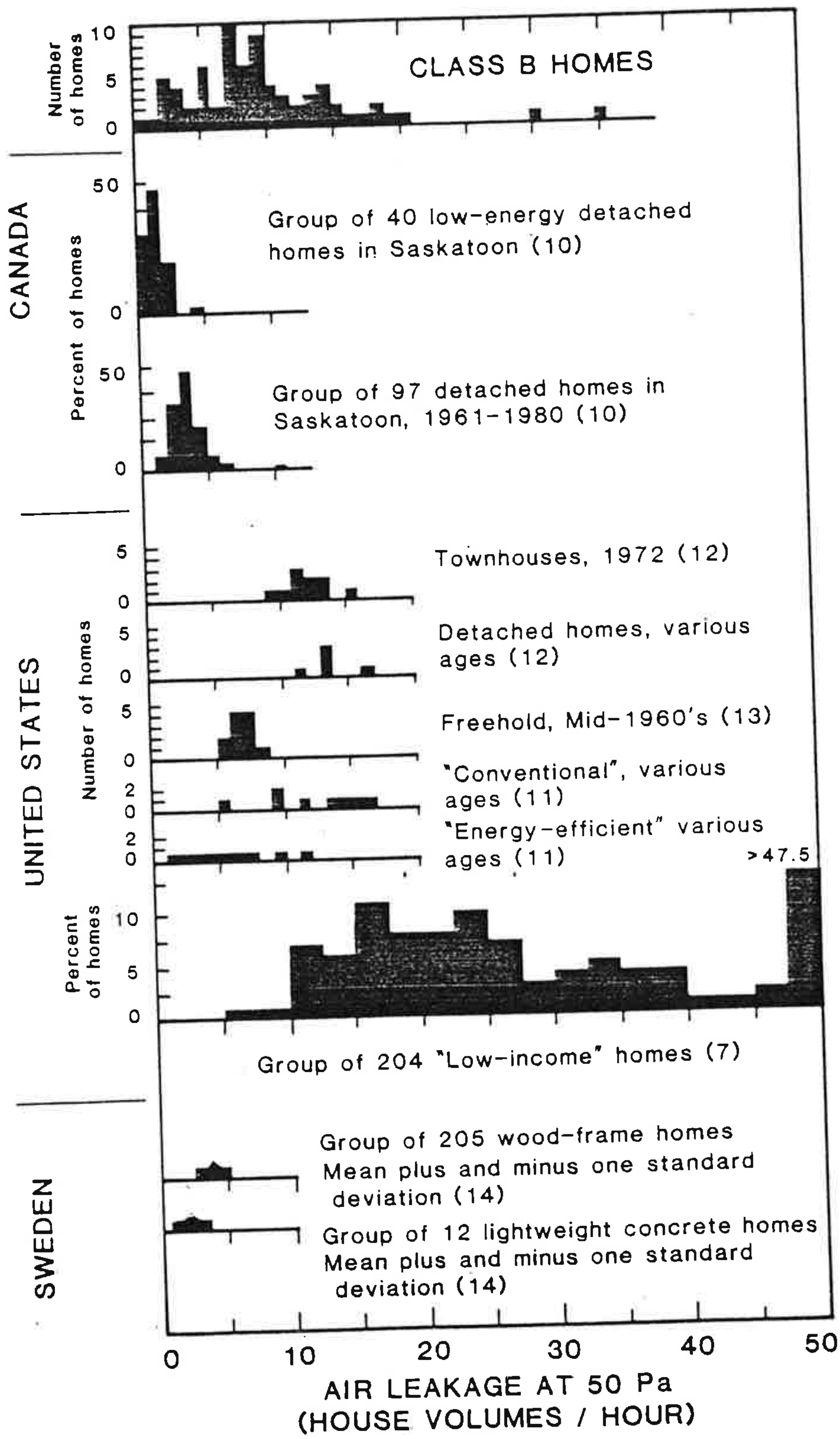

FIG. 3—*Comparison of pressurization test results.*

ect. The data presented in this report do not support this expectation. Figure 3 is a series of frequency distributions comparing the pressurization test results for the Class B homes to other homes. The Class B data are at the top of the figure, followed by two groups of Canadian homes [*10*], six groups of U.S. homes [*7,11–13*], and two groups of Swedish homes [*14*]. The Canadian and Swedish homes are examples of successful construction of tight homes. The recently built, low-energy homes in Saskatoon are tighter than their older counterparts, but the older homes are still quite tight.

The Class B homes are not as tight as the Canadian and Swedish homes, nor are they significantly different from the other U.S. homes, except for the "low-income" group. The fourth and fifth U.S. groups are divided by the researchers who studied the homes into "conventional" and "energy efficient." This distinction is based on design and intended level of energy use, not on the actual performance of the buildings. Similar to the Class B homes, the "energy efficient" homes are not necessarily tighter than the so-called "conventional" homes or other U.S. homes. Thus, the pressurization tests on these passive solar homes show that they are in general no tighter than typical U.S. homes and not as tight as levels being achieved in Canada and Sweden.

Comparing the air infiltration rates of the Class B homes to those in other residences is more difficult than comparing pressurization test results because of the strong dependence of infiltration on weather. The average infiltration rate for the "low-income" homes in Fig. 3 is about 1.0 ACH, averaged over 1000 measurements on 266 homes [7]. The average infiltration rate for the Class B homes is only 0.42 ACH, which is lower than the "low-income" homes and slightly lower than rates generally found in U.S. homes. The very tight homes in Sweden have infiltration rates on the order of 0.1 ACH [*15*].

As discussed earlier, the average infiltration rate for the Class B homes is somewhat misleading because of the mild weather conditions during most of the infiltration measurements. It is difficult to determine the infiltration rates under less mild temperature conditions, but they certainly would have been larger and probably not significantly different from U.S. homes in general. Empirical relations between pressurization test results, weather, and infiltration, which could be used to generalize infiltration data to weather conditions more representative of the heating season, are discussed in following paragraphs.

Infiltration Measurement and Pressurization Testing

The primary purpose of the pressurization and infiltration measurements on the Class B homes was to gather air leakage data on passive solar homes, but it also presents an opportunity to compare the two evaluation techniques. The relation between pressurization and infiltration has been discussed before, and the data presented here may contribute to our understanding of this relation [*6,16–19*]. In addition, the consistency of the two measurement techniques can be assessed by comparing the results of both measurements. One must note that the tests were conducted by field personnel of limited experience with the measurement techniques and that the wind data was of variable accuracy. Therefore, this is not a comparison of pressurization and infiltration under ideal experimental conditions, but rather a realistic demonstration of the accuracy and reliability achievable in the field.

At the most basic level, the relation between the 50-Pa flow rate Q_{50} and measured air infiltration rates can be examined. Figure 4 is a plot of measured infiltration I for a house against Q_{50} for the same house, both in ACH. There is indeed significant scatter in the data. A least squares, linear regression of I against Q_{50} yields the following equation

$$I = 0.06 + 0.041\ Q_{50} \tag{2}$$

The standard error of the estimate of this regression is 0.222, which is 52.4% of the mean measured infiltration rate for these homes, and the coefficient of determination r^2 has a value of 0.50. If these same data are regressed without the point in the upper right hand corner, the value of r^2 drops to 0.36. This simple comparison neglects the dependence of infiltration on wind speed and temperature difference. Empirical relations between pressurization and infil-

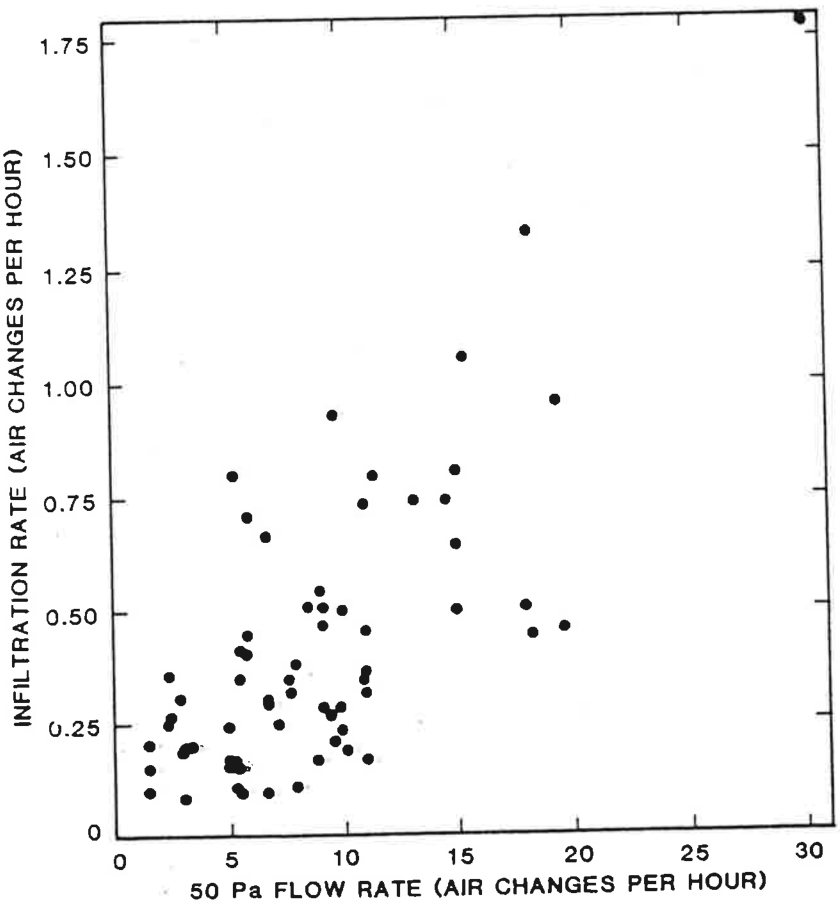

FIG. 4—*Measured infiltration versus 50-Pa flow rates.*

tration that include weather effects, and existing pressurization-infiltration models, are discussed in following paragraphs.

Empirical Relations

It is difficult to relate infiltration to pressurization measurements and weather conditions. The dependence of the infiltration rate of any particular house to wind speed and temperature difference depends on the building dimensions, leakage distribution, and exposure to the wind. In this section, empirical relations between infiltration, pressurization test results, and weather conditions are presented and applied to the data. In these relations, a house's leakiness is characterized by its 50 Pa flow rate Q_{50}. The weather variables include temperature difference ΔT and wind speed u. The first expression has separate terms in wind and temperature along with a product term

$$I = AQ_{50}u + BQ_{50}|\Delta T| + CQ_{50}u|\Delta T| \tag{3}$$

In Eq 3, Q_{50} serves as a leakage coefficient for the house while A, B, and C characterize two aspects of the pressurization-infiltration relation, the connection between Q_{50} and infiltration and the weather dependence of the house's infiltration rate. The value of A also depends on where the wind speed u is measured. Physically, infiltration should depend on the square of the wind speed, but it is not clear whether this change will result in a better fit to the data. The second empirical relation includes u^2 in place of u in Eq 3

$$I = A'Q_{50}u^2 + B'Q_{50}|\Delta T| + C'Q_{50}u^2|\Delta T| \tag{4}$$

Instead of having separate terms in wind and temperature difference along with a product of the two, the two weather terms can be added together and their sum raised to a power m

$$I = Q_{50}(\bar{A}u^x + \bar{B}|\Delta T|)^m \tag{5}$$

As mentioned earlier, x can take on values of 1 or 2. Physical considerations lead one to expect that m will have a value between $\frac{1}{2}$ and 1. Pressurization testing has shown that the exponent n in Eq 1 generally has a value around 0.65. Several infiltration models have been developed which assume m is equal to $\frac{1}{2}$ [*18,20*]. Thus, Eq 5 is applied in four different forms, x equal to 1.0 and 2.0 and m equal to 0.5 and 0.65.

The results of applying Eqs 3 through 5 to the Class B data are shown in Table 2. The six different empirical equations fit to the data are shown along with results of regressing the infiltration rates calculated using each expression against the measured infiltration rates. In all six cases the value of r^2 is about 0.70, and the standard error of the estimate is about 40% of the mean

TABLE 2a—*Empirical relations between pressurization, weather conditions, and air infiltration.*

P0: $I = Q_{50}[(1.35\ 10^{-2})u + (3.09 \times 10^{-3})\lvert\Delta T\rvert + (-6.77 \times 10^{-4})u\lvert\Delta T\rvert]$
P1: $I = Q_{50}[(3.12\ 10^{-3})u^2 + (3.24 \times 10^{-3})\lvert\Delta T\rvert + (-1.72 \times 10^{-4})u^2\lvert\Delta T\rvert]$
P2: $I = Q_{50}[(3.17\ 10^{-4})u + (1.60 \times 10^{-4})\lvert\Delta T\rvert]^{0.5}$
P3: $I = Q_{50}[(4.38\ 10^{-5})u^2 + (1.71 \times 10^{-4})\lvert\Delta T\rvert]^{0.5}$
P4: $I = Q_{50}[(1.35\ 10^{-3})u + (5.88 \times 10^{-4})\lvert\Delta T\rvert]^{0.65}$
P5: $I = Q_{50}[(1.80\ 10^{-4})u^2 + (6.45 \times 10^{-4})\lvert\Delta T\rvert]^{0.65}$

TABLE 2b—*Regression Results:* I_P *numbers against* $I_{measurements}$.

Equations	r^2	s_e	$\bar{I}_P$	$s_e/\bar{I}_M$
P0	0.71	0.168	0.386	39.6%
P1	0.68	0.185	0.365	43.6%
P2	0.69	0.160	0.407	37.7%
P3	0.66	0.167	0.389	39.4%
P4	0.70	0.162	0.392	38.2%
P5	0.65	0.174	0.371	41.0%

[a] s_e is the standard error of the regression estimate.

infiltration rate. Most infiltration models have a form similar to one of these six equations, and therefore these results may serve as a reference for comparing the predictive accuracy of the models. Six corresponding empirical relations can be formed by substituting the 4-Pa flow rate from Eq 1 for the 50-Pa flow rate in Eqs 3 through 5. The predictive accuracy of the 4-Pa equations is almost identical to that of the 50-Pa equations.

Model Predictions

This data set of infiltration and pressurization measurements is useful for checking some existing models of the relation between the two measurement techniques. Five models have been applied to the Class B data. The first is the model developed by Sherman and Grimsrud of the Lawrence Berkeley Laboratory [*18*]. This model is based on a detailed formulation of the phenomena of air infiltration in homes and characterizes the leakiness of a house through the 4-Pa flow rate. Its predictive equation is identical in form to Equation P3 in Table 2 if the 4-Pa flow rate is substituted for the 50-Pa flow rate. In applying the Lawrence Berkeley Laboratory (LBL) model to this data set, the required inputs were determined for each house by the people responsible for testing the house.

The second model, developed by Shaw and Tamura of Canada [*17*], is based on empirical relations between pressurization and infiltration derived from detailed studies of two houses and uses the values of C and n from Eq 1 to characterize a house's leakiness. This model has separate predictive equations for when wind and temperature difference effects dominate and another equation when both effects are important.

Values of the temperature difference and wind speed, which determine the particular predictive equation which should be used, are given by Shaw and Tamura for the two houses used to develop their model. The specific values of temperature difference and wind speed, which determine the predictive equation that should be used, are house dependent, and we used the same values for the Class B houses that Shaw and Tamura used for their homes. For this reason, we expect that the predictions for this model will be in poor agreement with the measured infiltration rates.

The third model, developed by Kronvall [*16*], also uses the constants C and n from Eq 1. In Kronvall's model, one predicts the infiltration rate from the equation

$$I = C/V\,(0.026|\Delta T| + 0.010u^2)^n \tag{6}$$

where V is the house volume. The coefficients in front of ΔT and u^2 were derived empirically from pressurization and infiltration measurements on 19 tight Swedish homes. The fourth model uses Eq 3 to predict infiltration rates. The values of the constants A, B, and C are based on averages for several other homes. These values are, of course, different from those obtained from the regression of the Class B data, but in checking the models they are used as if one does not know the actual measured infiltration rates. This is the way the models would be used in practice, and we do not want to take advantage of the fact that we know the measured infiltration rates. The values of A, B, and C used to predict the Class B infiltration rates are 0.0075, 0.0025, and -0.0005, respectively.

Finally, the infiltration rates are predicted with an approximate rule of thumb which states that the infiltration rate under natural conditions is the 50-Pa flow rate in ACH divided by 20. This rule is crude and based on empirical results, not physical effects. It predicts only a single infiltration rate for each house, independent of weather conditions.

The results of the predictions from the five models are summarized in Table 3. The mean measured infiltration rate and the standard deviation of the measurements are given at the top of the table. For each of the models, the mean predicted infiltration rate and the average of the absolute value of the percentage difference between the predictions and measurements are shown. The table gives the results of linear regressions of the predictions against the measurements, including the coefficient of determination r^2 and the standard error of the regression estimate s_e. The ratio of s_e to the mean measured infiltration rate also is given. The values of r^2 are similar for the five models, but the mean predicted infiltration rates and the average percentage errors are variable. Kronvall's mean predicted rate is close to the average of the measured rates, and the average error is low.

TABLE 3—*Results of predictive models of infiltration. Mean Measured Infiltration Rate*[a] = *0.424. Standard Deviation = 0.312 (73.6% of the mean).*

Model	$\bar{I}_P$	Average Percentage Error	Regression Results		
			r^2	s_e	$s_e/\bar{I}_M$
LBL	0.547	58%	0.60	0.248	58.5%
Shaw-Tamura	1.212	210%	0.59	0.615	145.0%
Kronvall	0.400	39%	0.61	0.188	44.3%
ABC	0.270	41%	0.69	0.128	30.2%
Divide by 20	0.449	60%	0.50	0.192	45.3%

[a]This mean is calculated only from measurements in those houses which were pressure tested.

The *ABC* predictions are low on average but have a small percentage error. The model of Shaw and Tamura makes some very bad predictions when wind and temperature effects both are significant, and therefore there are large errors for this model. This is because we divided weather conditions into wind and temperature difference dominance according to the same conditions that Shaw and Tamura found appropriate for their two test houses. These distinguishing conditions are house dependent, and the use of the same conditions for all the Class B homes would be expected to cause the significant predictive errors which occurred.

Comparing the model predictions to the empirical fits in Table 2, we see that the value of r^2 for the empirical fits are somewhat higher, about 0.7 compared to 0.6, and that the associated errors are much less. The mean predicted empirical infiltration rates are closer to the mean measured rate, and the standard errors of the estimates are also smaller than for the model predictions.

Conclusions

As part of the SERI Class B study of the thermal performance of passive solar buildings, pressurization and infiltration measurements have been made on about 80 homes. This is the largest set of such air leakage measurements on passive solar homes. Seventy-four homes have been pressure tested to obtain a weather independent measure of envelope tightness. The resulting 50-Pa flow rates range from about 1 to 36 ACH, with an average of 10.1. The infiltration rates of 54 homes have been measured with the tracer gas decay method employing on-site sampling with air bags and off-site analysis of these bags. The average infiltration rate is 0.42 ACH, but the measurements were made under relatively mild weather conditions.

The measurements indicate that the passive solar homes are not significantly tighter than other U.S. homes. Although the Class B homes are designed and constructed for below average energy consumption, they are not exceptionally tight. One must note the important difference between design intentions and actual construction. Although a building may be designed to be airtight or well insulated, the tightness of the resultant building depends on the attention to detail and the quality of the actual construction. The relation between pressurization and infiltration also was studied, and it was found that the correlations developed for other houses were appropriate for these passive solar homes.

Acknowledgments

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DISCUSSION

David Saum[1] *(written discussion)*—(1) Did these houses have air-vapor barriers? (2) Do your results suggest that the models that relate infiltration to pressurization measurements are no more accurate than dividing the 50 Pa ACH by 20?

Andrew K. Persily (author's closure)—(1) Some of the houses have air-vapor barriers, and others do not. The construction details of each house are available in SERI publications on the Class B programs. (2) Our results do seem to indicate this, but this is only a small number of houses, and this result will not necessarily apply to other houses.

Terry Brennan[2] *(written discussion)*—Using grab samples of tracer gas taken by homeowners and mailed in to a central lab for processing makes it possible to collect a large number of samples with a small number of field personnel and only one set of processing instrumentation. It also introduces the possibility of a number of errors (timekeeping, container damage, container leaks, container mislabeling) that have happened frequently enough to trained personnel (me, for example) to prompt the following question. Can you give us some idea of the reliability of the data collected by homeowners in the study? As people with experience at making such a data acquisition

[1] Infiltec, Waynesboro, VA.

method work perhaps you could give one or two insights that would be helpful to others contemplating using the same method.

Andrew K. Persily (author's closure)—The potential for error due to the causes you mention does exist, but such errors can be minimized if careful instructions are provided and followed. It is very important that field personnel be properly trained and that they closely follow the correct procedures. This is the most important advice we can provide. When the appropriate procedures are applied, the infiltration rates should be accurate within 0.1 ACH and only about 10% of the tests will have to be thrown out due to some unavoidable mishaps (leaks, inappropriate injection volumes).