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AIR LEAKAGE FLOW CORRELATIONS
FOR VARYING HOUSE CONSTRUCTION TYPES

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ABSTRACT

Fan pressurization techniques are being employed by an increasingly large number of contractors and auditors to determine the leakage characteristics of structures. In this study, a large data base of flow exponents and flow coefficients are compiled to determine the degree of correlation that exists between flow parameters. The resulting empirical relationships are then used to determine the feasibility of predicting these flow parameters directly from a single pressure difference test. On the basis of these correlations, a new pressure independent tightness parameter is proposed.

INTRODUCTION

Fan pressurization (ASTM E779) is commonly used to provide a weather independent, quantitative estimate of house tightness. Based on an empirical analysis of the test data, a flow coefficient and a flow exponent are determined. Variation in these parameters may provide clues to the physical nature of the leakage flow and assist in assuring that correct interpretations of the parameters are made.

Pressurization and depressurization tests compiled from many sources will be examined in this report to determine whether there are any significant empirical relationships between the flow parameters. The possibility of using these relationships to solve for the flow parameters directly from a single pressure test will also be considered.

DATA REDUCTION

Current pressure test practice consists of the measurement of airflow through a structure at several (5 to 10) pressure differentials in the range of 10 to 60 [Pa]. As has been shown by many authors, the functional relationship in this pressure range is very well described by a power law of the form

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

On physical grounds, we expect that the exponent should lie between 0.5 (for orifice flow) and 1.0 (for fully developed, long pipe laminar flow). Beyond this general expectation, it is very difficult to develop any simple physical interpretation for the flow coefficient, C, and the flow exponent, n.

For simplification, most users have resorted to a single parameter function to describe the leakage of a structure. The most commonly used form is effective leakage area, A_l, and is defined by assuming a Bernoulli flow approximation

$$Q = A_l \left[\frac{2 \, \Delta P}{\rho}\right]^{0.5} \tag{2}$$

combining Equations 1 and 2 at some reference pressure difference, ΔP_{ref}, gives

$$A_{l,ref} = C \left[\frac{\rho}{2}\right]^{0.5} \Delta P_{ref}^{\,n-0.5} \tag{3}$$

We must be careful not to attach too much physical significance to the leakage area, A_l, and remember that it is a variable which adjusts with reference pressure difference to correct for the Bernoulli flow approximation.

Both effective leakage area and flow rate must be normalized if comparisons are to be made between structures. Several physical quantities are available for normalization, including floor area, A_f, envelope area, A_e, or volume, V. From physical considerations we expect that envelope area would be the most appropriate normalizing parameter. Often, the more readily available floor area is used for convenience.

For some correlations examined in this paper, evidence is available to substantiate the choice of envelope area as a normalizing parameter for leakage area, A_l, and flow coefficient, C. However, in the most general correlations, there are many sources of variability and using envelope area rather than floor area has only a small effect in reducing scatter. This, combined with the fact that envelope area is not included in a portion of our data base, leads us to use floor area for the more general correlations in order that the maximum amount of data may be included. Envelope area will be used for some correlations where significant reductions in scatter result. Normalized leakage area and normalized flow rate will be referred to as specific leakage area, A_L, and specific flow rate, q.

DATA BASE

From the large number of reported pressurization tests, a data base was selected for which the physical characteristics of the houses were adequately described and for which data were available for both the flow coefficient, C (or the leakage area), and the flow exponent, n. Some investigators failed to report the flow exponent for each house tested, limiting the size of the data base.

Surprisingly, it was also difficult to find data sets that adequately described the construction details of each house. While it would seem obvious that air-leakage measurements can only be interpreted if details of the house envelope construction are known, much of the existing data on pressure tests give only a vague "real-estate" type description of house construction. House size parameters were often poorly evaluated, the most notorious being floor area which ranged from "main floor only" to "developed living space" to "heated floor area" (sometimes including garages or basements and sometimes not). In some cases, floor area was stated without providing any definition. Envelope area on the other hand, when given, was always defined similarly: as the total above-grade leakage area (for parallel surfaces such as ceilings and roofs, the surface with the maximum flow resistance was always selected). If sufficient descriptive information was provided by the author, a simple algorithm was applied to generate an approximate envelope area, which resulted in improved data correlations.

The final data base selected consisted of 515 houses, about two-thirds in Canada and one-third in the United States. The specific locations of the houses and sample sizes are listed in Table 1, where the use of only depressurization tests for Canadian houses is clearly evident. The Canadian data base was assembled using measurements from Dumont et al.(1981), Beach (1979), and unpublished data of Wilson and Kiel. Houses in the United States were tabulated from Lipschutz et al.(1981), Offerman et al.(1982), Diamond (1983) and Turner et al. (1982). This data set was analyzed for variability of leakage area by Sherman, Wilson, and Kiel (1984).

SPECIFIC LEAKAGE AREA CORRELATIONS

Figure 1 shows that there is a strong dependence of the specific leakage area on wall construction type. The "super-tight" category of houses used blower door pressurization during construction as a quality control test to allow the builder to seal joints in the vapor barrier. Quality of construction also shows some degree of correlation with climate in Figure 2, reflecting the response of homeowners and contractors to economic and comfort factors. Some caution must be used in drawing any conclusions from Figure 2, because the data sets used are biased toward tight houses in cold climates. It would be better if the data sets were composed of a random sample of typical housing stock, but few investigators, with the exception of Dumont et al. (1981), have taken this approach.

The expectation that loose houses (large A_l) might be dominated by large orifice-type holes (n=0.5) and tight houses (small A_l) dominated by small cracks exhibiting primarily laminar flow (n=1.0) is examined in Figure 3. We see that such a correlation may exist but is obscured by variability caused by other factors, such as construction type.

Although only a weak correlation exists for the combined data sets, closer examination suggests that for sufficiently similar data sets, an empirical relationship does exist. The best set of houses to examine for such a relationship would be an identical group of houses constructed by the same contractor, with the same materials and construction methods, and all tested with the same blower equipment. Fortunately, there is just such a set in the data base consisting of 28 units meeting all of the above requirements with only slight differences in their common wall overlap areas. These units are a senior citizens complex located in Oroville, California (Diamond 1983).

The correlation of specific leakage area with flow exponent for this very similar group is shown in Figure 4. Every unit has the same floor area and the same envelope area, and as a result, the selection of a normalizing parameter is arbitrary. It effects only the scaling of the x-axis and not the correlation itself. The existence of a correlation is clear from Figure 4, but what is most interesting is the influence of the reference pressure used in evaluating leakage area.

Referring back to Equation 3, the source of this pressure dependence is apparent. As n approaches 0.5, our physical leakage area is very similar to our defined leakage area (i.e., Bernoulli-like) and is therefore independent of pressure differential and reflects the correct flow rate. Conversely, as n approaches 1.0, our 1/2 power definition is inappropriate and large adjustments are required to reflect the correct flow rates.

This pressure dependence of specific leakage area makes it unattractive for direct correlation with flow exponent, and a pressure-independent correlation is sought. The obvious choice is to correlate flow exponent, n, directly with flow coefficient, C. This correlation is less attractive from the point of view of physical interpretation but will be pressure independent. Substitution of the correlation into Equation 3, would yield specific leakage area as a function of flow exponent and pressure differential.

FLOW COEFFICIENT NORMALIZATION

Unlike leakage area or flow rate, the normalization of the flow coefficient is not as simple, and dimensional analysis must be used to determine an appropriate form. From Equation 1, the dimensions of the flow coefficient C are,

$$C \sim [m^{3+2n}\ N^{-n}\ s^{-1}] \qquad (4)$$

where the units of Q and ΔP are $[m^3/s]$ and $[N/m^2]$ respectively.

To develop a physical basis for the flow coefficient, C, in terms of fluid variables and flow geometry, the following assumptions are made.

- -- All the functional dependence of Q on ΔP is contained in Equation 1, so that C is independent of Q and ΔP.
- -- The physical variables that describe flow through the ensemble of cracks that make up the leakage paths can be expressed as a single equivalent crack length, L_c, and flow area, A_c. These two variables contain the crack roughness, entry and exit geometry, shape, and number of bends.
- -- The functional relation between C and the flow variables can be approximated as a power law with each variable raised to an exponent, except for the crack parameter, which may be a function of the ratio $L_c/A_c^{0.5}$.

The only fluid properties that enter into Reynolds number effects and dynamic pressure are density, ρ, and dynamic viscosity, μ, so that

$$C = C(A_c, L_c, \mu, \rho)$$

$$C = C(A_c, \mu, \rho, L_c/A_c^{0.5})$$

so the power law is

$$C = A_c^{\alpha} \cdot \mu^{\beta} \cdot \rho^{\gamma} \cdot f_c(L_c/A_c^{0.5}) \tag{5}$$

where f_c is the crack geometry function. Using the units of $\rho \sim [\mathrm{kg/m^3}]$ and $\mu \sim [\mathrm{Ns/m^2}]$, the dimensions of Equation 4 require exponents of

$$\alpha = n + 0.5$$

$$\beta = 1 - 2n$$

$$\gamma = n - 1$$

so that

$$C = \frac{\rho^{n-1} \cdot A_c^{n+0.5}}{\mu^{2n-1}} f_c \left[\frac{L_c}{A_c^{0.5}}\right] \tag{6}$$

Making the final assumption that the crack flow area, A_c, is proportional to building envelope area leads to the normalized flow coefficient C_*, in the form

$$C_* = \frac{C}{A_e^{n+0.5}} \tag{7}$$

The crack geometry function, f_c, and the crack to envelope area ratio, A_c/A_e, will cause C_* to vary with the type of envelope construction.

CORRELATION OF NORMALIZED FLOW COEFFICIENT WITH FLOW EXPONENT

Following the normalizing form developed above and plotting flow exponent against normalized flow coefficient for the Oroville data, the correlation shown in Figure 5 is obtained. The physics of the problem suggests that as n approaches 0.5, C should approach infinity and as n approaches 1.0, C should approach zero. Several functional forms conform to these limits; however, one which provides a particularly good correlation is

$$C_* = K \left[\frac{n - 1.0}{0.5 - n}\right] \tag{8}$$

The most satisfying thing about this particular form is the need for only one adjustable constant with a quality of fit as good as any of the more complex forms examined (but not discussed here). The functional form given by Equation 8 is shown in Figure 5 for the Oroville pressurization and depressurization data and is found to provide excellent correlation.

PRESSURIZATION AND DEPRESSURIZATION RESULTS

Sherman, Wilson and Kiel (1984), found that for the combined sets of data, there was no significant difference in either the average flow exponent or the average leakage area determined from depressurization and pressurization measurements. However, for an individual pair of pressurization and depressurization measurements on a single house, factors of two difference in 4 [Pa] leakage areas and 50% changes in exponent n, were observed. On the basis of that analysis, it was concluded that there is no systematic difference between pressurization and depressurization measurements for large populations but that significant uncertainty is associated with an individual measurements. A condensation of these results are shown in Table 2.

For a similar group of houses, it is possible that systematic difference between pressurization and depressurization measurements may exist. The most likely explanation of such differences lies in the existence of structural elements that exhibit some form of valving action; that is, elements which tend to seal tighter when pressure is applied from one side than when pressure is applied from the opposite side. Based on the results in Table 2, it appears that either configuration is possible and both occur with approximately the same frequency in large data sets. In a single house either inward or outward sealing elements may dominate. This would result in the significant differences between pressurization and depressurization leakage areas observed in some houses. If the same elements are incorporated into a group of similar houses, it would be reasonable to expect the entire group to respond in a similar manner. These ideas can be considered in context with the Oroville data set.

Of the 28 Oroville houses, 26 had larger 4 [Pa] pressurization leakage areas compared to depressurization leakage areas for the sealed configuration. The average pressurization and depressurization specific leakage areas were found to be 2.41 [cm^2/m^2] and 1.98 [cm^2/m^2] respectively, with average flow exponents of 0.61 and 0.69. The larger flow exponents are associated with smaller 4 [Pa] leakage areas. Particularly interesting is the fact that both depressurization and pressurization n:C distributions fall on virtually the same K-correlation line. The 4 [Pa] pressurization leakage areas are larger because they have moved to the right on the correlation curve rather than taking on a larger correlation constant, K.

REPEATABILITY OF PRESSURE TEST RESULTS

Observing the Oroville depressurization data in Figure 5, it is interesting to note that the flow exponents range from 0.95 to 0.58. From Figure 4, this range can be seen to represent a remarkable 200% difference in 4[Pa] leakage area. Considering the similarity of the houses, it seems unlikely that this entire variation is a result of envelope differences alone. Some of the observed variation may be related to test repeatability.

Repeated pressure test data obtained by two independent researchers were examined. The first house is located in the Princeton area and was tested repeatedly by A. Persily (1982), the second house is located in the Edmonton area and is part of the Alberta Home Heating Research Facility (unpublished data of Wilson and Kiel). Both sets of data were taken under calm conditions over a period of months and therefore contain a good representation of the sort of variability that might be expected in the values of n and C obtained for a house tested only once.

The average flow exponents and standard deviations are 0.72 ± 0.049 and 0.69 ± 0.023 for the Edmonton house and Princeton house respectively. This represents a variation in 4 [Pa] leakage area of 100-200 [cm^2] and 650-810 [cm^2] respectively. The most interesting finding is that the flow coefficient varies with the flow exponent such that every value of n in the Edmonton data set falls within 0.01 of the correlation curve defined by K=31.1 and every value of n in the Princeton data falls within 0.01 of the curve defined by K=38.9.

These results suggest that some of the variation in the Oroville data is due to a combination of test conditions, test data regression analysis, experimental errors or subtle envelope changes over time. The most important observation is that these effects cause a systematic variation of n and C identical in form to Equation 8, consistent with the assumption that K is a function of crack area and crack geometry such that it remains nearly constant for a given structure. In this context, the relatively invariant correlation constant K, may provide an alternative measure of envelope tightness having the virtues of being independent of pressure difference and relatively independent of the systematic errors associated with test repeatability. To evaluate these ideas, the variation in correlation constant, K, with construction type will be examined.

CORRELATIONS FOR GROUPS OF "SIMILAR" HOUSES

Other groups of "similar" houses will now be examined to confirm the generality of the proposed exponent-coefficient correlation and to further investigate the relationship between the correlation function given in Equation 8 and structural tightness. Unfortunately, at this time, another group of data which exhibits the same degree of similarity shown by the Oroville group is not available and it is therefore necessary to resort to more general groups. Construction details appear to be most influential and therefore the following categories are examined:

1. Walls without integral vapor barriers.
2. Walls with a vapor barrier.
3. Walls with vapor barrier and exterior foam insulation sheathing.
4. Double-wall construction.
5. Super tight houses using blower door pressurization during construction.

These categories reflect the most significant physical details influencing leakage characteristics. Sorting by house style provides no additional resolution within groups, particularly if envelope area is used as the normalization parameter; however, subgroups established on the basis of geographic location are worthwhile.

Figure 6 and Figure 7 are plots of the "Single Stud With Air Barrier" group normalized with floor area and envelope area respectively. The significant scatter in both curves is not surprising because the data set includes houses from many different locations in North America, constructed by different builders with many differences in construction details. The functional form of Equation 8, holds for this group of data in a manner similar to the Oroville case. A reduction of 15% in the standard deviation in flow exponent can be achieved through the use of envelope area rather than floor area. Considering the many sources of scatter, this reduction may not justify the extra effort involved in estimating a structures envelope area for setting standards. However, for research purposes, envelope area does provide a better correlation than floor area and will be used here.

Limited pressurization-depressurization data are available, but, based on those groups that can be formed, it appears that strong similarities exist between the correlation constants for pressurization and depressurization. Table 3 provides a compilation of the resulting groups, showing the similarities between the depressurization and pressurization correlation constants within each group. Judging from the exponent and leakage area ratios shown in Table 3, it appears that similar groups of houses may tend to have different 4 [Pa] leakage areas under pressurization and depressurization. This suggests that both tests may be required to properly quantify the leakage characteristics of a given house.

Based on the similarities in the correlation constants observed above, pressurization and depressurization results are combined in Figure 8 which presents the best fit correlations for each of the five general construction types. Table 4 provides a breakdown of the correlations for each of the subgroups. The correlation constant, K, can be seen to vary approximately linearly with the average specific leakage area and therefore reflects the relative tightness of each group. Recalling the definition of K in terms of C_* from Equation 8 and noting that the distribution of n is similar for each tightness group we must conclude that the variation in K reflects changes in both the crack geometry function, f_c, and the ratio, A_c/A_e.

Progressively tighter groups of houses do not exhibit the significant increase in average flow exponent expected as the large leakage sites are sealed. For example, the average flow exponent for the "no vapor barrier" group is 0.64 compared to 0.70 for the "double wall group". Within a particular group however, tighter houses lie toward the extreme of n=1.00 and leakier houses closer to n=0.5. So, although n may not reflect the absolute tightness, it may reflect the quality with which a particular construction method has been executed. The correlation constant, K, can be evaluated to determine the absolute tightness range that the house lies in and the flow exponent, n, would indicate the relative quality of construction, keeping in mind the limited accuracy in the flow exponent associated with repeatability errors.

PREDICTION OF THE FLOW COEFFICIENT AND FLOW EXPONENT FROM A SINGLE PRESSURE TEST

One of the most compelling reasons for pursuing an empirical correlation between flow coefficients and flow exponents is the possibility of combining such relationships with Equation 1, allowing the simultaneous solution of both n and C from a single pressure test. To illustrate this idea, suppose that a single 50 [Pa] pressure test was conducted on a hypothetical Oroville unit that was constructed identically to the existing 28. The information from this test could be inserted into Equation 1 giving,

$$Q_{50} = C(50[Pa])^{n} \qquad (9)$$

where Q_{50} is the absolute flow rate. Knowing that for similar construction type the correlation constant in Equation 8 should be roughly K=41.8, Equation 8 may be solved with Equation 9, yielding a solution for n and C.

Figure 9 illustrates the functions graphically by showing the correlation functions as well as lines of constant flow rate. Note that envelope area, A_e, is constant for this set and may be absorbed into the functions allowing the direct plotting of n against C. Selecting a known n and C for one of the Oroville houses and following its constant flow line until it intersects the correlation function provides us with the predicted n and C of this house, assuming that only the Q_{50} was known. Instantly, a major problem is recognized, the functions intersect at very small angles and are therefore so ill-conditioned that large prediction errors are likely. For example, if the house having n=0.64 and C=0.029 [m^3/sPa^n] is chosen (testers #53), a single 50 [Pa] test would have indicated Q_{50}=0.36 [m^3/s] and the intersection of this flow rate and the correlation function predicts a flow exponent of 0.94.

The degree of ill-conditioning is sufficiently severe that solutions are unacceptable using a 50 [Pa] pressure test. The correlation function is fixed for the particular group, but we do know that the lines of constant Q become more vertical as the test pressure is reduced. Note from Equation 1 that in the extreme case of ΔP=1 [Pa], Q=C and lines of constant Q are vertical. If a lower test pressure is used we can expect improved conditioning of the equations and correspondingly improved predictions. Reasonable measurement accuracy is difficult to achieve below 10 [Pa] and for practical use this may be an unrealistically low pressure. If a 10 [Pa] test is used, conditioning is improved and the standard deviations in the difference between calculated and actual flow exponents range from 0.05 to 0.2 for groups of similarly constructed houses. Clearly these deviations are too large to consider this technique a success. In general, the equations are simply too poorly conditioned to provide accurate results.

Only groups of nearly identical houses contain the minimal amount of scatter necessary to allow this single test method to provide acceptable predictions of the flow parameters. The best predictions were found using the Oroville data set, resulting in a standard deviation in n predicted of approximately 0.05 using a single 10 [Pa] flow rate. Another problem is the fact that the value of the correlation constant can only be determined after a number of full range pressure tests have been conducted. Despite these problems, possible applications may still exist. For example, if a contractor is constructing a large number of similar units and for quality control is conducting tightness tests, he may find that the first dozen tested correlate very well in the manner suggested here. If that were the case, it may be possible for the remaining tests to be conducted with a single pressure test and the flow constants determined with the general correlation.

CONCLUSIONS

The examination of a large number of pressure test results has shown that significant empirical relationships do exist between houses that are grouped according to wall construction type and location. Despite the large size of the current data base, more tests are needed to allow further sorting and still retain statistically relevant subset sizes. It is also apparent that testing must be conducted on all types and ages of housing stock and not only new stock, which is the current trend. Further testing of similarly constructed groups of houses will also play an important part in advancing our understanding of these relationships and the sources of variability. The following observations are based on the data sets presented in this report.

1. Envelope area produces only 15% less scatter than floor area in correlations when used as the normalizing parameter. So, floor area is probably acceptable for setting general standards.

2. Because $C \sim A_e^{n+0.5}$, it is not possible to think of C and n as completely independent variables. However, at least C and n are independent of ΔP and Q, unlike leakage area.

3. Tight houses show a similar distribution of n from 0.5 to 1.0 as do loose houses, with an average n of approximately 0.67. This suggests that the variation from laminar cracks to orifice leaks depends on the quality of construction, not on its general type. This, in turn, means that a house with n in the range from 0.5 to 0.65 is likely to benefit from retrofit sealing, while houses with n from 0.75 to 1.0 are about as tight as they can be made, a very useful guideline for retrofit strategy.

4. The correlation coefficient, K, is the one parameter that seems to be independent of both pressure difference and test result variability, and provides a good measure of house tightness. The factor K can be calculated from any C, n data pair, and may be a more useful measure of the class of house tightness than either C, n or A_L.

5. A single house or a group of similar houses having different tightnesses under pressurization or depressurization retain approximately the same correlation constant.

6. The correlation between $C/A_e^{n+0.5}$ and n, does not allow a single 50 [Pa] pressure test to be used to determine C and n because:

    a. Equations are ill-conditioned and small errors in Q_{50} or in K, will lead to unacceptably large errors in C and n.

    b. The correlation constant, K, is a strong function of construction type, which is not as yet well enough defined by descriptive phrases to allow a user to confidently estimate K.

NOMENCLATURE

A_c = Crack area [m^2]

A_e = Envelope area [m^2]

A_f = Floor area [m^2]

A_l = Leakage area, defined at ΔP_{ref} [cm^2]

A_L = Specific leakage area, defined at ΔP_{ref} [cm^2/m^2]

C = Empirical flow coefficient [m^3/sPa^n]

C_* = Normalized flow coefficient [cm^3/(m^{2n+1} sPa^n)]

n = Empirical flow exponent

K = Correlation constant [cm^3/(m^{2n+1} sPa^n)]

L_c = Crack length [cm]

ΔP = Pressure differential [Pa]

q = Specific flow rate [s^{-1}]

Q = Flow rate [m^3/s]

V = House volume [m^3]

ρ = Air density [kg/m^3]

μ = Dynamic viscosity [kg/sm]

LIST OF REFERENCES

Beach, R.K. 1979. "Relative tightness of new housing in the Ottawa area." National Research Council of Canada, Div. of Building Research. Note No. 149.

Diamond, R.C. 1983. "Energy and housing for the elderly: preliminary observations." Lawerence Berkeley Laboratory EPB Report.

Dumont, R.S.; Orr, H.W.; and Figley, D.A. 1981. "Air tightness measurements of detached houses in the Saskatoon area." National Research Council of Canada, Div of Building Research, Note No. 178.

Lipschutz, R.D.; Girman, J.R.; Dickinson, J.B.; Allen, J.R.; and Traynor, G.W. 1981. "Infiltration and indoor air quality in energy efficient houses in Eugene, Oregon." Lawerence Berkeley Laboratory, LBL-12924

Offermann, F.J., et al. 1982. "Residential air leakage and indoor air quality in Rochester, New York." Lawerence Berkeley Laboratory, LBL-13100.

Persily, A. 1982. "Understanding air infiltration in homes." Ph.D. dissertation, Princeton University, February.

Sherman, M.H.; Wilson, D.J.; and Kiel, D.E. 1984. "Variability in residential air leakage." Proc. ASTM Symposium on Measured air Leakage Performance of Buildings ,Philadelphia, PA, April.

Turner, W.A.; Treitman, R.D.; Bearg, D.; Sexton, K.; and Spengler, J.D. 1982. "Home energy efficiency and indoor/outdoor air pollution in a predominantly wood burning community." Harvard University Department of Environmental Science and Physiology Report.

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TABLE 1

Data Base Composition

U.S.A.			CANADA		
Location	Sample Size		Location	Sample Size	
	$-\Delta P^*$	$+\Delta P$		$-\Delta P$	$+\Delta P$
Oroville, CA	56	56	Saskatoon, SK	176	----
Rochester, NY	50	50	Ottawa, ON	67	----
**Davis, CA	32	32	Winnipeg, MB	51	----
Eugene, OR	24	24	Edmonton, AB	11	11
**San Fransico, CA	16	16			
**Atlanta, GA	7	7			
**Waterbury, VT	---	25			
TOTAL	184	210	TOTAL	305	11

* $-\Delta P$ = Depressurization
$+\Delta P$ = Pressurization

** Insufficient information to determine accurate envelope area.

Note: Oroville 28 units, tested sealed and unsealed =56 tests
Eugene 12 units, tested sealed and unsealed =24 tests
Edmonton 6 units, 5 tested sealed and unsealed
1 tested sealed =11 tests

TABLE 2

Comparison of Pressurization and Depressurization Data

Sample Size = 196 Houses

	Flow Exponent n	4 [Pa] Specific Leakage Area A_l/A_f [cm^2/m^2]
Pressurization	0.66 ± 0.09*	5.9 ± 3.8
Depressurization	0.66 ± 0.08	5.6 ± 3.4

	Flow Exponent Ratio $+n$ / $-n$	Leakage Area Ratio $+Al$ / $-Al$
$\frac{\text{Pressurization}}{\text{Depressurization}}$	1.02 ± 0.150	1.05 ± 0.286

* Sample Standard Deviation

TABLE 3

Flow Exponent Correlations for Pressurization and Depressurization

$$\frac{C}{A_e^{n+0.5}} = K\left[\frac{n - 1.0}{0.5 - n}\right]$$

Single Stud, No Vapor Barrier

Location	#	Pressurization		Depressurization		$\left(\frac{+n}{-n}\right)$	$\left(\frac{+4A_1}{-4A_1}\right)$
		K*	Std. Dev.** n_{fit}	K	Std. Dev. n_{fit}		
Oroville (sealed)	28	40.93	0.019	42.45	0.017	0.89	1.11
Oroville (unsealed)	28	52.99	0.021	49.85	0.018	0.97	1.21
Rochester	8	56.37	0.021	57.82	0.024	0.97	1.17

Single Stud With Vapor Barrier

Location	#	Pressurization		Depressurization		$\left(\frac{+n}{-n}\right)$	$\left(\frac{+4A_1}{-4A_1}\right)$
		K	Std. Dev. n_{fit}	K	Std. Dev. n_{fit}		
Rochester	42	41.26	0.046	38.95	0.028	1.09	0.91
Eugene (sealed)	12	16.95	0.045	18.52	0.037	1.06	0.94
Eugene (unsealed)	12	19.50	0.033	21.94	0.030	1.07	0.93

* Units of K $\left[\frac{cm^3/sPa^n}{m^{2n+1}}\right]$

** Std. Dev. n_{fit} = standard deviation of $(n - n_{fit})$

TABLE 4

Correlation Constants for Construction Groups
(Pressurization and Depressurization Data Combined)

Type*:Location	#	K	Std.Dev.** n_{fit}	A_l/A_e:Average 4 [Pa]	50 [Pa]
1:Oroville	56	41.79	0.018	2.20	3.16
1:Rochester	16	57.14	0.023	3.83	5.16
1:Saskatoon	19	63.06	0.049	3.06	5.49
1:Combined	91	47.96	0.033	2.67	4.00
1:Oroville (unsealed)	56	51.18	0.020	3.27	4.12
2:Rochester	84	40.27	0.037	2.40	3.43
2:Eugene	24	17.77	0.042	0.86	1.56
2:Saskatoon	91	25.06	0.036	1.30	2.18
2:Edmonton	10	15.12	0.036	0.74	1.15
2:Combined	209	25.63	0.046	1.16	2.56
2:Eugene (unsealed)	24	20.69	0.032	1.00	1.74
3:Saskatoon	41	17.92	0.061	1.02	1.74
4:Saskatoon	22	6.79	0.050	0.37	0.64
5:Winnipeg	51	1.64	0.045	0.14	0.17

* 1: Walls without integral vapor barriers
2: Walls with a vapor barrier
3: Walls with a vapor barrier and exterior foam insulation sheathing
4: Double stud construction
5: Super tight construction (pressure tests and sealing during const.)

** Std. Dev. n_{fit} = standard deviation of $(n - n_{fit})$

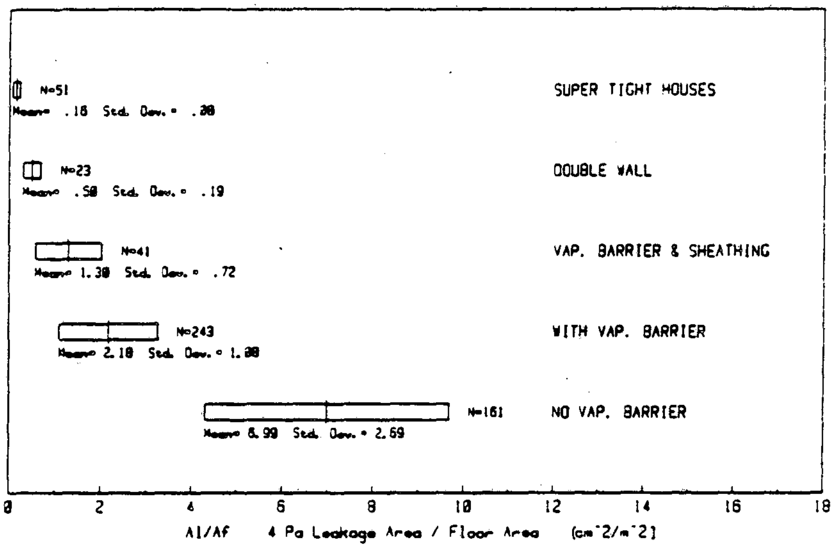

Figure 1. *Variability of 4 (Pa) specific leakage area with wall construction type, normalized with floor area; all houses available; pressurization and depressurization data; sealed configuration*

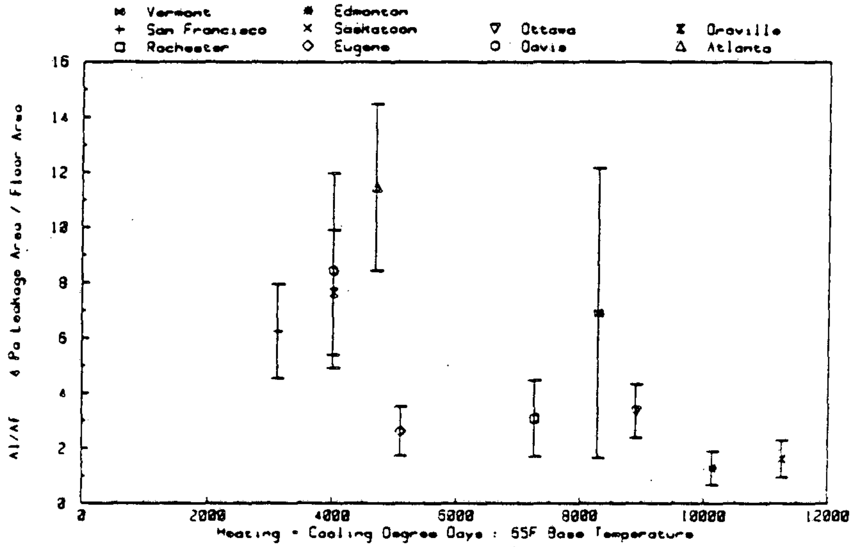

Figure 2. *Correlation of heating and cooling degree days with 4 (Pa) leakage area using a 65 F base temperature; normalized with floor area; all houses available; pressurization and depressurization data; sealed configuration*

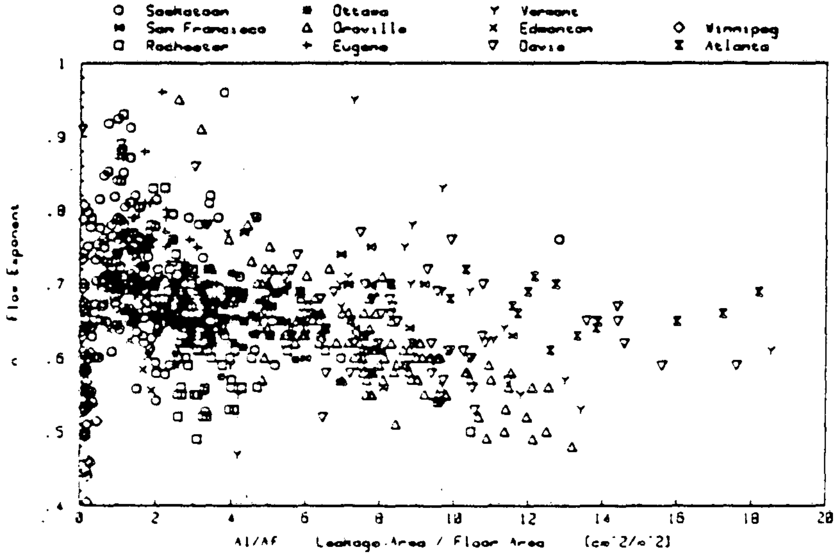

Figure 3. *Variability of flow exponent with 4 (Pa) specific leakage area; normalized with floor area; all houses available; pressurization and depressurization*

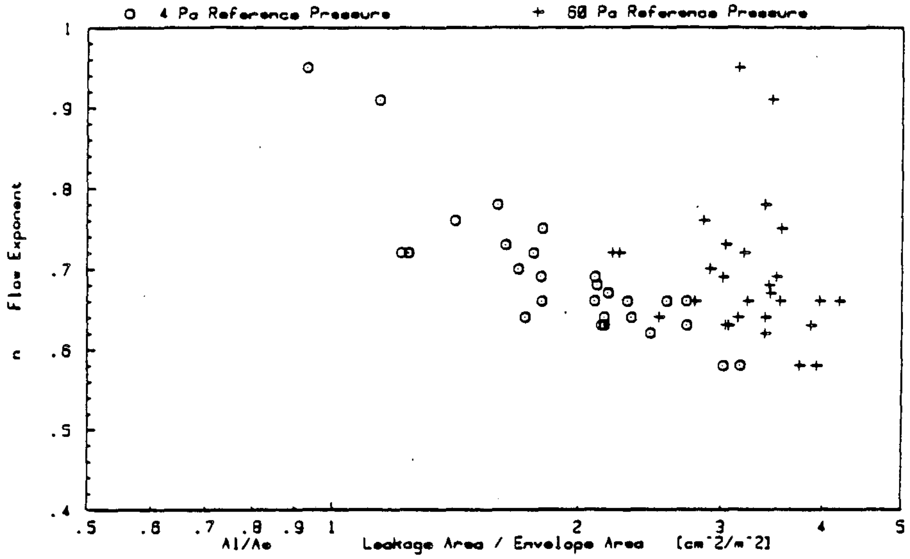

Figure 4. Effect of leakage area reference pressure on flow exponent correlation with specific leakage area; Oroville data set; normalized with envelope area; depressurization data; sealed configuration

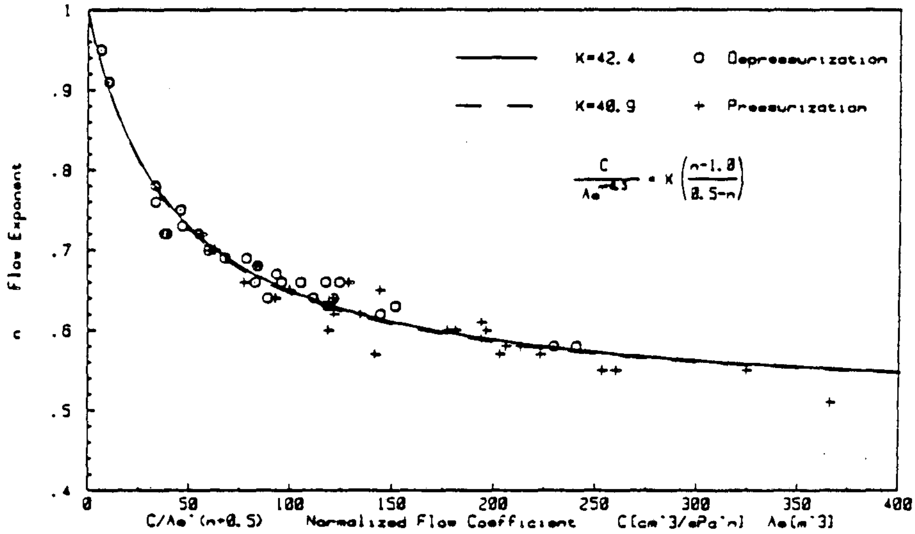

Figure 5. Correlation of flow exponent with normalized flow coefficient for Oroville data; normalized with envelope area; pressurization and depressurization data; sealed configuration

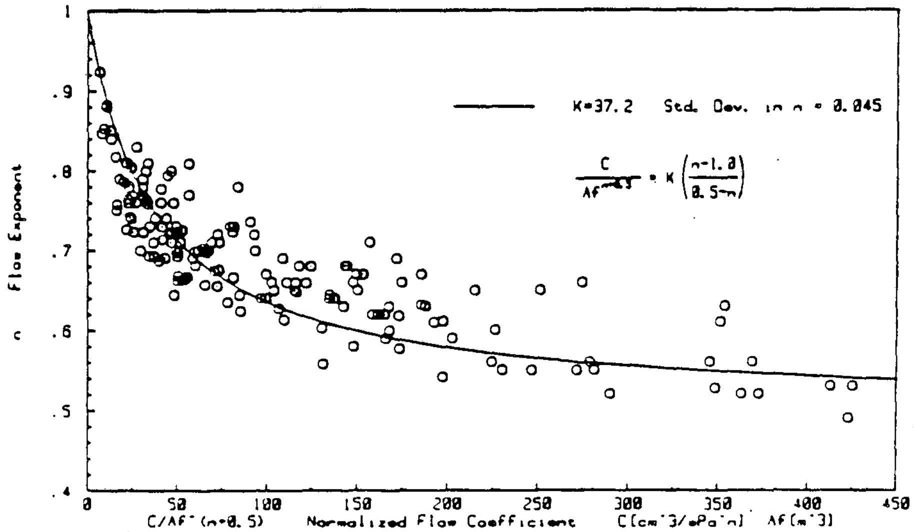

Figure 6. Correlation of flow exponent with normalized flow coefficient for houses with single stud and vapor barrier walls; normalized with floor area; depressurization data; sealed configuration

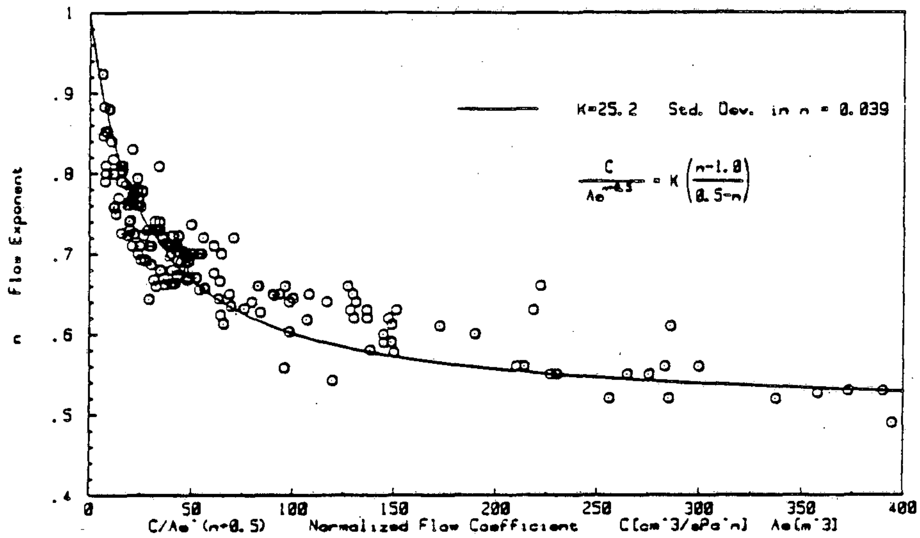

Figure 7. Correlation of flow exponent with normalized flow coefficient for houses with single stud and vapor barrier walls; normalized with envelope area; depressurization data; sealed configuration

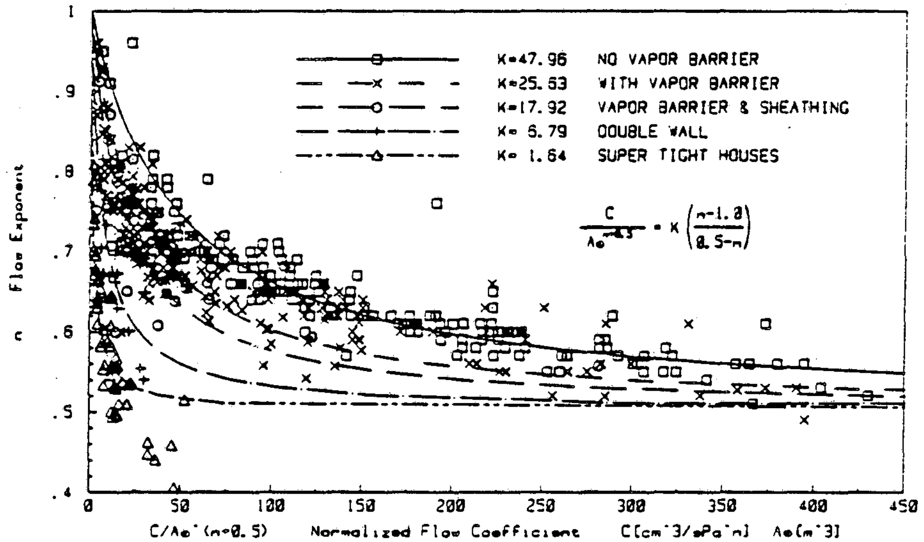

Figure 8. Correlation of flow exponent with normalized flow coefficient for various wall construction types; normalized with envelope area; pressurization and depressurization data; sealed configuration

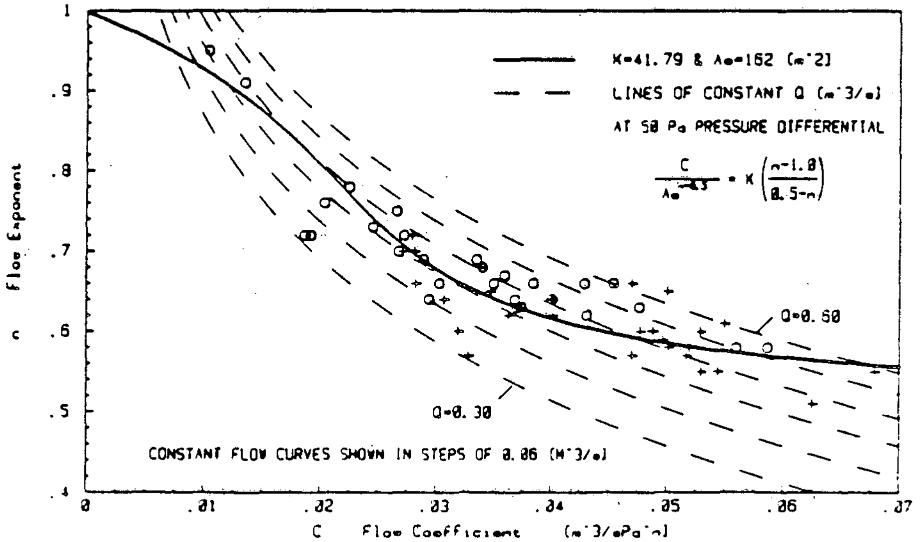

Figure 9. Constant 50 (Pa) flow curves and Oroville empirical correlation curve; Oroville pressurization and depressurization data; sealed configuration