

# Air Leakage Flow Correlations for Varying House Construction Types



D.E. Kiel    D.J. Wilson, Ph.D.    M.H. Sherman, Ph.D.  
ASHRAE Member



## 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

$$Q = C \Delta P^n \quad (1)$$

---

D.E. Kiel, Research Associate and D.J. Wilson, Professor, Dept. of Mechanical Engineering, University of Alberta, Edmonton.

M.H. Sherman, Research Scientist, Energy Efficient Buildings Group, Applied Science Division Lawrence Berkeley Laboratory, Berkeley California.

THIS PREPRINT FOR DISCUSSION PURPOSES ONLY. FOR INCLUSION IN ASHRAE TRANSACTIONS: 1985, V. 91, Pt. 2. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329. Opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE.

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,  $A_1$ , and is defined by assuming a Bernoulli flow approximation

$$Q = A_1 \left[ \frac{2 \Delta P}{\rho} \right]^{0.5} \quad (2)$$

combining Equations 1 and 2 at some reference pressure difference,  $\Delta P_{ref}$ , gives

$$A_{1,ref} = C \left[ \frac{\rho}{2} \right]^{0.5} \Delta P_{ref}^{n-0.5} \quad (3)$$

We must be careful not to attach too much physical significance to the leakage area,  $A_1$ , 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,  $A_1$ , 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),

April 16, 1984

regression to a power law:

$$Q = C \Delta P^n \quad (1)$$

On physical grounds we expect the exponent to lie between 0.5 (for orifice flow) and 1.0 (for fully developed/long pipe laminar flow). It is interesting to note that simple power law correlations of blower door tests occasionally yield exponents less than the Bernoulli limit of 0.5. In fact, it is physically possible for such low exponents to occur. For example, flow through orifice meters in pipes at Reynolds number greater than 1000 have orifice coefficients which decrease with Reynolds number, leading to a flow-pressure difference exponent less than 0.5.

Although the parameters  $C$  and  $n$  describe the fan pressurization data, they do not have a simple physical interpretation. For this reason many users prefer to use one simple physical parameter to describe the leakage, even though complete generality is sacrificed. One of the most common single leakage parameters currently in use is the effective leakage area, which is often abbreviated as ELA; we use the symbol  $A_1$  in our equations. It is defined by assuming a Bernoulli equation approximation to (1)

$$Q = A_1 \sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

at a specific reference pressure  $\Delta P_{ref}$ . The effective leakage area of a leak or group of leaks can be thought of as the amount of open area that would allow the same flow at the reference pressure difference. Equating (1) and (2) at the reference pressure difference gives  $A_1$  in terms

April 16, 1984

of the leakage coefficient and the exponent:

$$A_1 = c \frac{Q}{2} \left[ \Delta P_{\text{ref}} \right]^{n-.5} \quad (3)$$

Because effective leakage area is in more common usage than the leakage coefficient and exponent, all of the data presented below is in terms of effective leakage area, with four pascals as the reference pressure difference.\*

Because effective leakage area is an extensive property of a building envelope, we will not be able to compare the values for different houses unless we properly normalize the leakage area. Several schemes for normalizing leakage area have been suggested: 1) by volume, 2) by envelope area, and 3) by floor area. Although normalization by envelope area is probably the most physically significant approach, for practicality we have elected to use floor area as our normalization criterion. (Floor area is the most commonly quoted building characteristic.) Furthermore, floor area and envelope area should correlate rather well for single-family buildings. We therefore define the specific leakage as the ratio between the effective leakage area,  $A_1$ , and the floor area,  $A_f$ .

---

\*Since extrapolations tend to increase the error of the quantity, a measurement at a higher pressure such as 50 Pa would be more precise. Unfortunately, the physical quantity of interest is the flow in the natural pressure range around 4 Pa. We must, therefore, sacrifice some precision for physical modeling.

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,

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

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  $C=0.029$  [ $\text{m}^3/\text{sPa}^n$ ] is chosen (testers #53), a single 50 [Pa] test would have indicated  $Q_{50}=0.36$  [ $\text{m}^3/\text{s}$ ] 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  $\Delta P=1$  [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  $\Delta P$  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 <sup>2</sup> ]
$A_e$	= Envelope area [m <sup>2</sup> ]
$A_f$	= Floor area [m <sup>2</sup> ]
$A_l$	= Leakage area, defined at $\Delta P_{ref}$ [cm <sup>2</sup> ]
$A_L$	= Specific leakage area, defined at $\Delta P_{ref}$ [cm <sup>2</sup> /m <sup>2</sup> ]
$C$	= Empirical flow coefficient [m <sup>3</sup> /sPa <sup>n</sup> ]
$C^*$	= Normalized flow coefficient [cm <sup>3</sup> /(m <sup>2n+1</sup> sPa <sup>n</sup> )]
$n$	= Empirical flow exponent
$K$	= Correlation constant [cm <sup>3</sup> /(m <sup>2n+1</sup> sPa <sup>n</sup> )]
$L_c$	= Crack length [cm]

- $\Delta P$  = Pressure differential [Pa]  
 $q$  = Specific flow rate [ $s^{-1}$ ]  
 $Q$  = Flow rate [ $m^3/s$ ]  
 $V$  = House volume [ $m^3$ ]  
 $\rho$  = Air density [ $kg/m^3$ ]  
 $\mu$  = 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." Lawrence 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." Lawrence Berkeley Laboratory, LBL-12924
- Offermann, F.J., et al. 1982. "Residential air leakage and indoor air quality in Rochester, New York." Lawrence 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.

#### ACKNOWLEDGMENTS

This study was supported by research grants from Energy Mines and Resources Canada, grant EMR-305, and the Natural Sciences and Engineering Research Council of Canada, grant A8438. Assistance from a Canada Mortgage and Housing Corporation Scholarship and an ASHRAE grant-in-aid to D. Kiel are gratefully acknowledged.

Funds from the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division, of the U.S. Department of Energy under Contract No. DEAC03-76SF00098 provided joint support.

The cooperation of William Turner of Harvard University, Rick Diamond of Lawrence Berkeley Laboratory, and Gren Yuill of G.K. Yuill Associates Winnipeg, who provided their original data sets, contributed to the success of the study.



TABLE 1  
Data Base Composition

U.S.A.			CANADA		
Location	Sample Size		Location	Sample Size	
	- ΔP*	+ ΔP		- ΔP	+ ΔP
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

\* - ΔP = Depressurization  
+ ΔP = 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 $A_1/A_f$ [ $\text{cm}^2/\text{m}^2$ ]
Pressurization	$0.66 \pm 0.09^*$	$5.9 \pm 3.8$
Depressurization	$0.66 \pm 0.08$	$5.6 \pm 3.4$

	Flow Exponent Ratio +n / -n	Leakage Area Ratio +A1 / -A1
<u>Pressurization</u> Depressurization	$1.02 \pm 0.150$	$1.05 \pm 0.286$

\* 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 <sub>fit</sub> **	K	Std. Dev. n <sub>fit</sub>		
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 <sub>fit</sub>	K	Std. Dev. n <sub>fit</sub>		
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  $\left[ \frac{\text{cm}^3/\text{sPa}^n}{\text{m}^{2n+1}} \right]$

\*\* Std. Dev. n<sub>fit</sub> = standard deviation of (n - n<sub>fit</sub>)

TABLE 4

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

Type*:Location	#	K	Std.Dev.** n <sub>fit</sub>	A <sub>1</sub> /A <sub>e</sub> :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<sub>fit</sub> = standard deviation of (n - n<sub>fit</sub>)

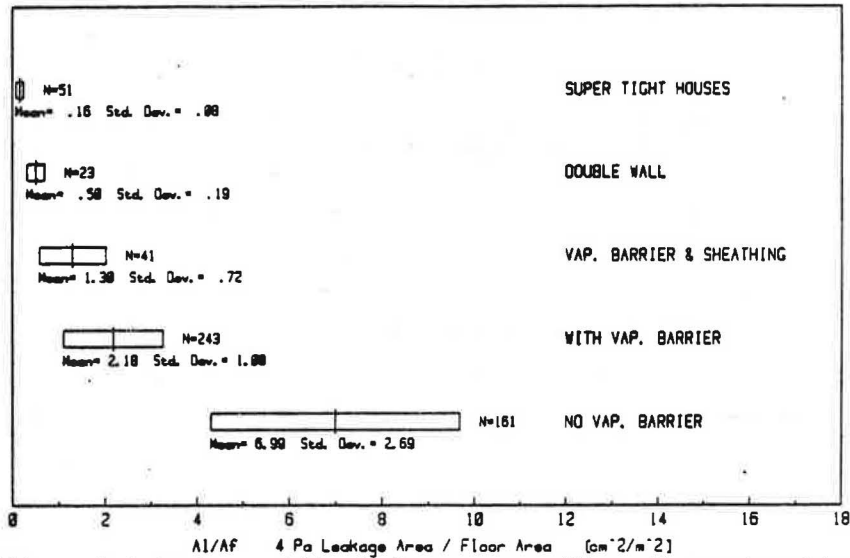


Figure 1. Variability of 4 (Pa) specific leakage area with wall construction type, normalized with floor area; all houses available; pressurization and depressurization data; sealed configuration

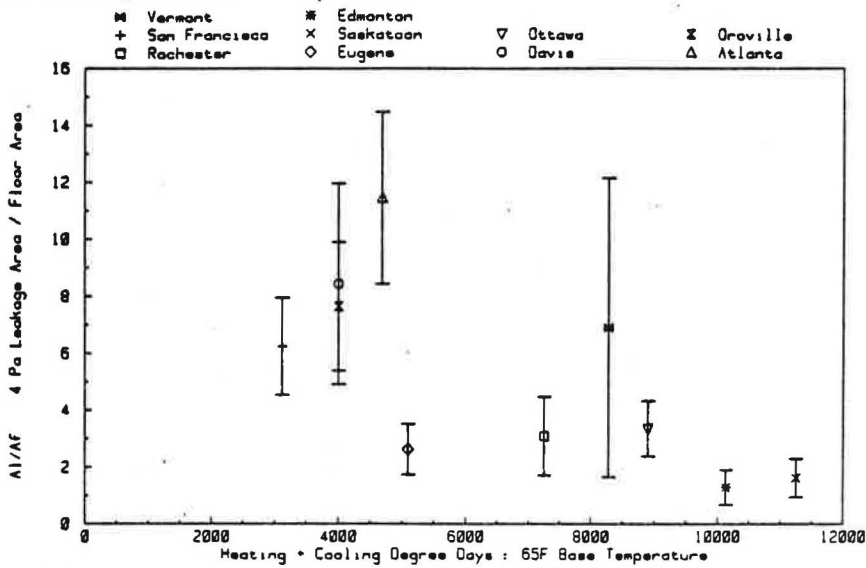


Figure 2. Correlation of heating and cooling degree days with 4 (Pa) leakage area using a 65 F base temperature; normalized with floor area; all houses available; pressurization and depressurization data; sealed configuration

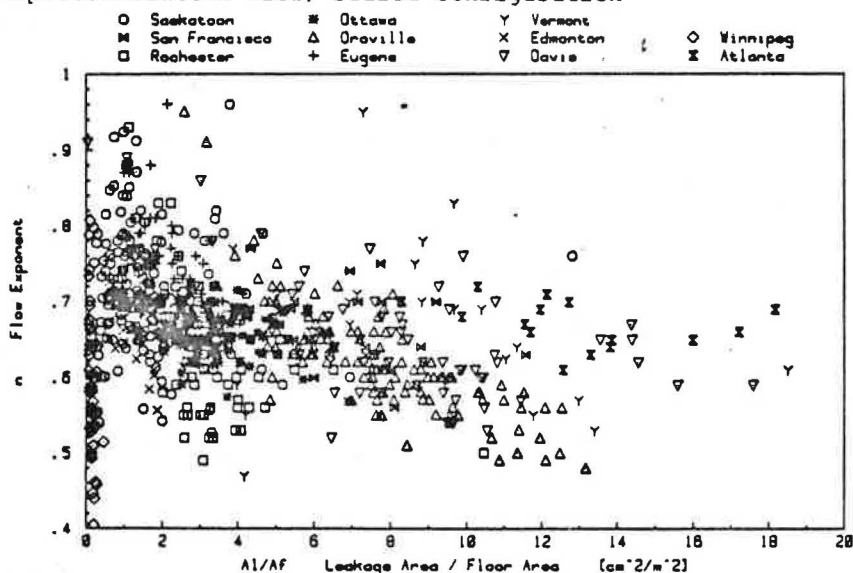


Figure 3. Variability of flow exponent with 4 (Pa) specific leakage area; normalized with floor area; all houses available; pressurization and depressurization

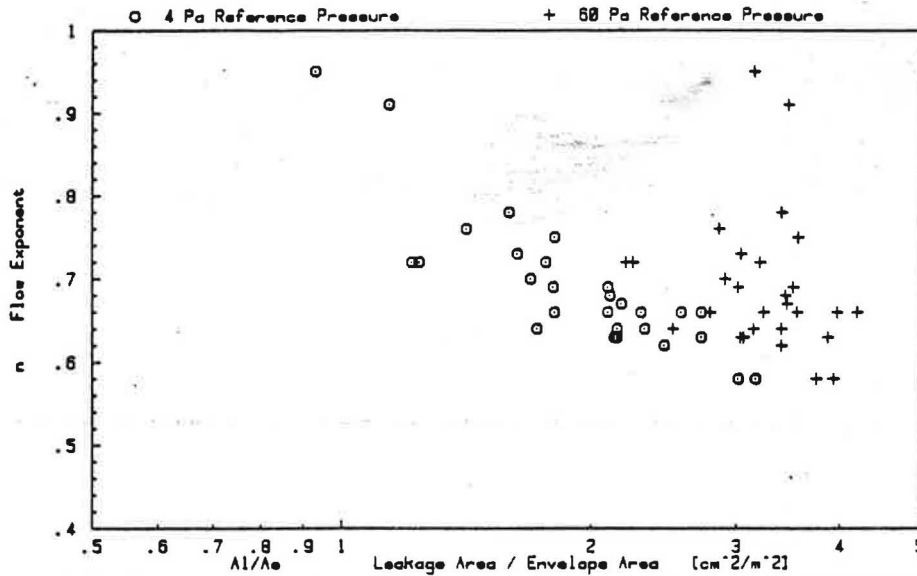


Figure 4. Effect of leakage area reference pressure on flow exponent correlation with specific leakage area; Oroville data set; normalized with envelope area; depressurization data; sealed configuration

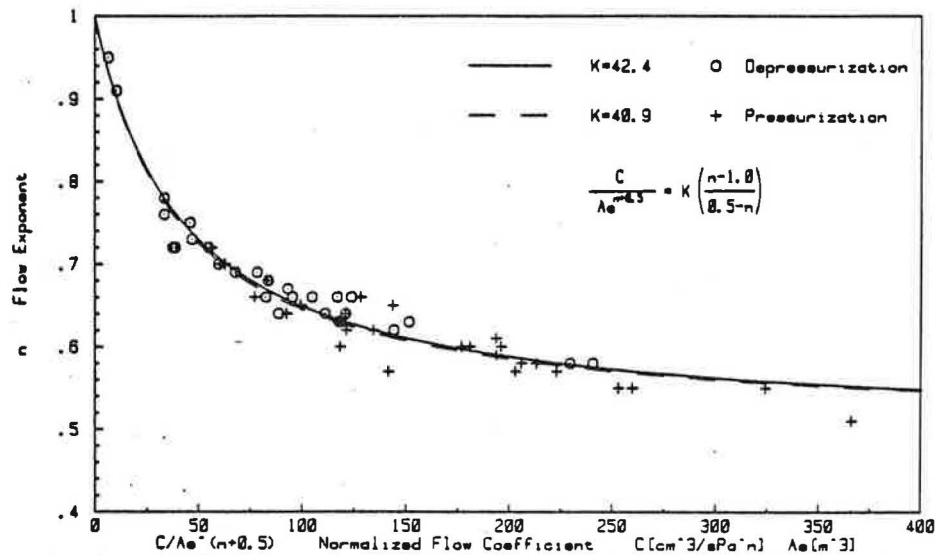


Figure 5. Correlation of flow exponent with normalized flow coefficient for Oroville data; normalized with envelope area; pressurization and depressurization data; sealed configuration

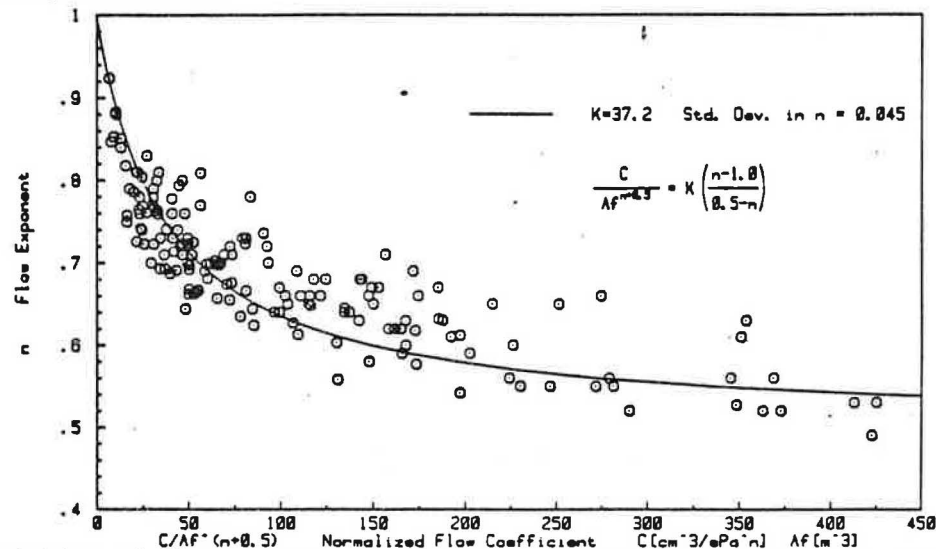


Figure 6. Correlation of flow exponent with normalized flow coefficient for houses with single stud and vapor barrier walls; normalized with floor area; depressurization data; sealed configuration

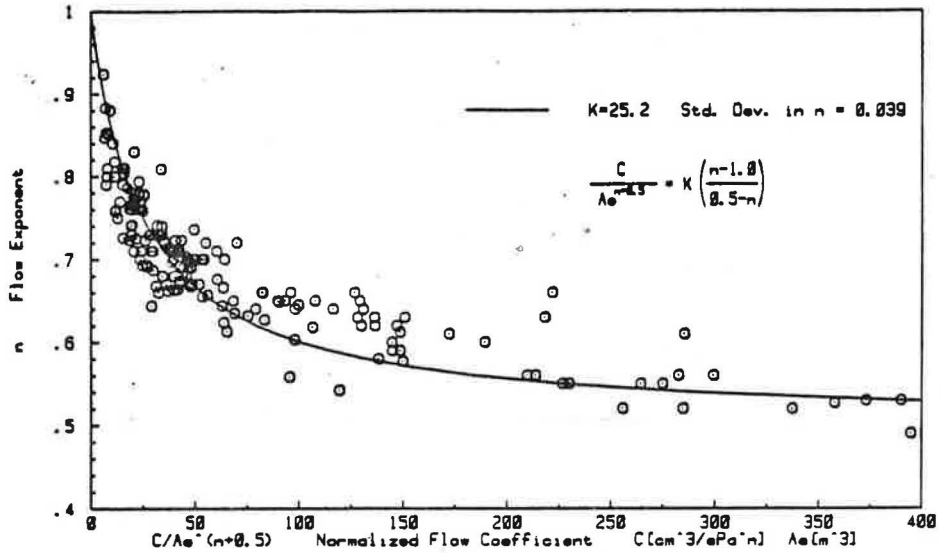


Figure 7. Correlation of flow exponent with normalized flow coefficient for houses with single stud and vapor barrier walls; normalized with envelope area; depressurization data; sealed configuration

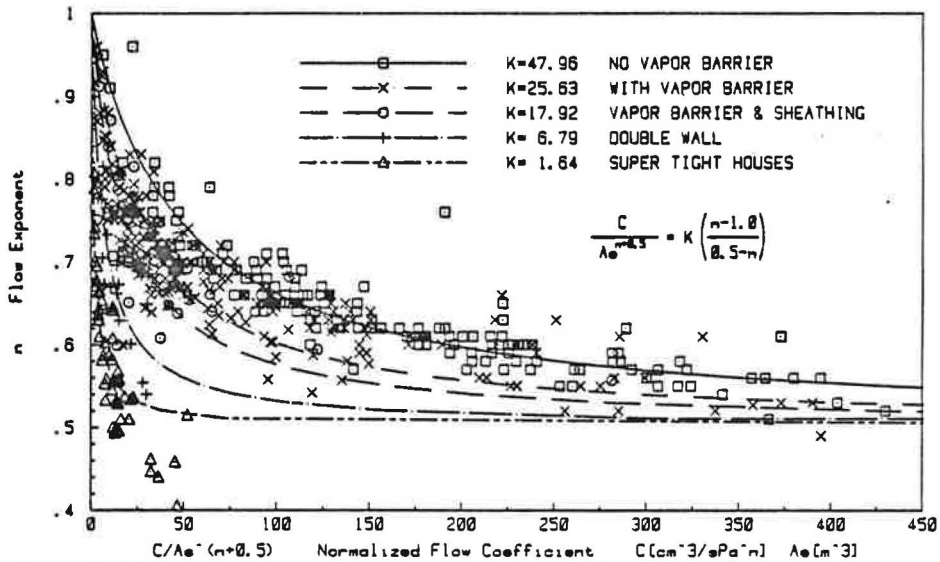


Figure 8. Correlation of flow exponent with normalized flow coefficient for various wall construction types; normalized with envelope area; pressurization and depressurization data; sealed configuration

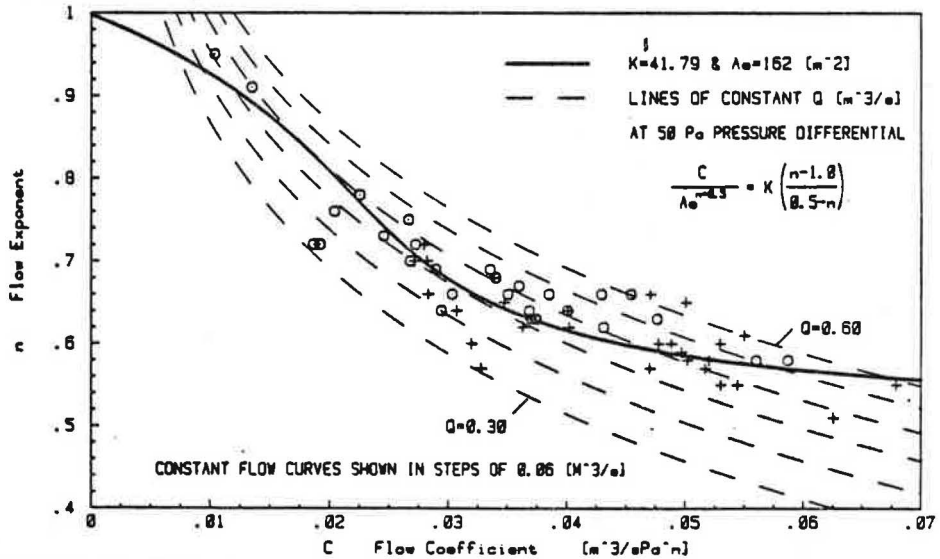


Figure 9. Constant 50 (Pa) flow curves and Orville empirical correlation curve; Orville pressurization and depressurization data; sealed configuration