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# VARIABILITY IN RESIDENTIAL AIR LEAKAGE

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ABSTRACT

Air leakage is the single most important quantity in the determination of air infiltration in residential structures. Air leakage is most commonly measured using the fan pressurization technique (see ASTM standard E779); the data gathered with this method is often used to determine a leakage constant and a flow exponent. In this report, data gathered from the literature will be compiled into a list of leakage constants and flow exponents, and the variability of these values over climate and housing types will be examined.

Keywords: air leakage measurements

## INTRODUCTION

Conventional wisdom holds that infiltration, which is characterized by the process of air leakage, accounts for about one-third of the space conditioning load of residential buildings. Over the past several years researchers have measured the air tightness of many houses using the technique known as fan pressurization (ASTM E779). The fan pressurization measurements, often known as blower door measurements, give a quantitative estimate of the building tightness, which is independent of climate and weather.

For this report we have gathered together all the fan pressurization measurements at our disposal. This large dataset is used to draw conclusions based on statistical inference. We have used this dataset to compare measurements made on individual houses throughout North America.

### Data Reduction

In most fan pressurization measurements the flow through the building is recorded as a function of pressure for several (e.g. five) different pressures, typically in the range of ten to fifty pascals (0.04 to 0.2 inches of water). The measurements are usually made for both pressurization (i.e. blowing air through the fan into the house) and depressurization (i.e. sucking air through the fan out of the house), although some data are for unidirectional flow only. Empirically it has been found that the data follows a power-law expression, and, accordingly, the most common data reduction technique is a least-squares regression to a power law:

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

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 $A_l$ in our equations. It is defined by assuming a Bernoulli equation approximation to (1)

$$Q = A_l \sqrt{\frac{2\Delta P}{\rho}} \qquad (2)$$

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 $A_l$ in terms of the leakage coefficient and the exponent:

$$A_l = C \frac{\rho}{2} \left[\Delta P_{ref}\right]^{n-.5} \qquad (3)$$

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, $A_l$, and the floor area, $A_f$.

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*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 import is the flow in the natural pressure range around 4 Pa. We must, therefore, sacrifice some precision for physical modeling.

## Data Base of Tested Houses

An initial database of over 700 houses and over 1000 measurements was extracted from the literature and from unpublished data of research efforts known to the authors over a several year period. Not all the data, however, was used in the final analysis; there were three criteria that had to be met for the data to be accepted in our sample: sufficiency, reliability, and background. The data had to contain both the leakage value (e.g. $A_1$, C, etc.) and the exponent, or it would be rejected. The data had to be reliable in the sense that either all necessary information was in the archival literature, or the researchers that took the data were available and able to answer questions. Finally, there had to be sufficient background about the houses, including age, type of construction, etc.

From the large number of reported pressurization tests, a data base was selected for which the physical characteristics of the house were adequately described, and for which data was available for both the coefficient C (or the leakage area $A_1$) and the flow exponent n. Because many investigators fail to report the flow exponent for each house tested when quoting effective leakage area, this requirement limited the size of the data base. Surprisingly, it was also difficult to find data sets which adequately described the construction details of each house tested. 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 blower door tests give only a vague real estate type description of house construction. In any case where the data appeared insufficient, an attempt was made to contact the appropriate researcher to clarify any insufficiencies.

Although some data was rejected because of the criteria, the authors know of no large dataset that was not considered. The final data base selected consisted of 515 houses, (about 2/3 of the initial set) 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 trend to a single depressurization test for Canadian houses is clearly evident. The Canadian data base was assembled using measurements from Dumont et al.,[1] Beach,[2] and unpublished data of Wilson and Kiel. Houses in the United States were tabulated from Lipschutz et al.,[3] Offerman et al.,[4] Diamond,[5] and Turner et al.[6]

Because our goal was to assemble the largest possible data set, no attempt was made insure that the data set so gathered would be representative of any particular housing stock. The United States' data is biased towards houses from the warmer west coast climate, while the reverse was true for the Canadian houses, all of which came from the cold continental climate of central Canada. As might be expected, this led to dramatic differences between the leakage areas for Canadian and U.S. data sets.

## PRESSURIZATION vs. DEPRESSURIZATION

Before we compare the leakages of different houses, there is one issue we can address for an individual house - pressurization vs. depressurization. Because of valve action and the presense of wind and stack pressures during the measurement, we expect that the two techniques may yield different results. We can use our data set to estimate both the systematic error (bias) and random error (scatter) associated with using one process instead of both. To examine these differences, the 196 houses with both pressurization and depressurization measurements were analyzed to determine the specific leakage and flow exponent. The results are summarized in Table 2. We see that for this large sample there is no significant difference in either the flow exponent or the leakage area determined from depressurization and pressurization measurements.

One of the best methods for quantifying the bias and scatter of the data is to construct a histogram of the ratio of the pressurization leakage area, $A_1^+$, to depressurization leakage area, $A_1^-$; Figure 1a is such a histogram. The mean of this dataset indicates the bias between pressurization and depressurization. The fact that the mean is 1.05 indicates that for this dataset the pressurization results that are 5% higher on average than those from depressurization. Since this bias is small, we can conclude that there is little systematic difference between pressurization or depressurization. Thus, if we are interested in finding the mean leakage area of a large set of data, there are only small differences between using pressurization or depressurization or both; the mean value should be accurate.

Although a mean near unity in Figure 1a indicates that there is little systematic error, the large standard deviation indicates a significant amount of random error. The dataset indicates that for an individual pair of pressurization/depressurization measurements, we can expect a 29% difference between them (direction unknown). Equivalently, a single measurement (either pressurization or depressurization) can be expected to differ by 14% from the average of the two. Thus a single-direction measurement of leakage area has an extra 14% error associated with it. one contributing factor for this scatter is likely to be wind-induced.

Figure 1b shows the distribution of the ratio of the pressurization exponent to the depressurization exponent, made in a manner analogous to the above distribution. The mean of the exponent distribution of 1.02 indicates that the pressurization exponent is only 2% greater on average than the depressurization exponent - well within measurement error. While smaller than the previous scatter of 29%, the standard deviation in the exponent of 15% is still significant. Thus, the exponent distribution corroborates the conclusion of the previous two paragraphs: that there is no systematic difference between pressurization and depressurization, but that there is significant uncertainty associated with an individual measurement.

## DATA VARIABILITY

Because the previous section has shown us that there is no systematic bias between pressurization and depressurization, each of these tests could be considered as a separate sample point to expand the data base without changing mean values or trends. Furthermore, because there is a large amount of bias associated with single-direction measurements, inclusion of both pressurization and depressurization as independent measurements decreases the random error in the sample. By expanding the data base in this way we obtain 395 sample measurements for U.S. houses, and 316 measurements for Canadian houses. The frequency distribution histograms for these 711 samples are shown in Figure 2. While the normal Gaussian probability distribution is a reasonably good fit to the variability of flow exponent n, it is clearly inappropriate for the highly skewed distribution of specific leakage $A_l/A_f$ in Figure 2.

The mean flow exponent of 0.67 confirms the widely held assumption that a flow exponent near 0.65 is typical of air infiltration leakage sites. On the other hand, the mean and variability of the specific leakage in Figure 2 is difficult to interpret. With a wide range of construction types ranging from tight northern Canadian. houses to rather loose California housing, and construction dates that range from 1850 for one house in the Vermont sample to 1982 for the Oroville houses, the high variability in specific leakage is not unexpected.

It is clear from an inspection of the specific leakage that in order to understand the cause of the variability, we must disaggregate the sample. Two of the most reasonable (and, fortunately, available) criterion are building age and construction type. In the two sections that follow we will investigate the effects these two factors have on specific leakage.

## Age

Of 711 tests, a total of 613 listed the year of construction. Of these, 297 were measurements in the U.S.A., and 316 in Canada. The data was sorted into age groups using the system recommended by Dumont, Orr and Figley (1981). This system identified the years 1945 and 1960 as approximate boundaries where significant changes in construction materials and methods were made. For pre-1945 housing the interior walls were generally lathe and plaster with no air-vapor barrier. In the period 1946 to 1960 a mixture of gypsum wall board and wax paper vapor retarders were employed, while after 1960 most construction used gypsum wall board and (when installed) polyethylene air-vapor barriers.

Figure 3 shows the variability of flow exponent and specific leakage ($A_l/A_f$) for these age groups. In addition, 91 houses (51 from the Winnipeg sample and 40 from Saskatoon) identified as "energy efficient" are shown separately as well as included in the 554 samples from the 1961 - 1983 period. The data shows that there is no trend in flow exponent with age of construction. What is most surprising is that houses built between 1961 and 1983 are no tighter than the group from 1946 to 1960. However, with only 26 houses in the 1946 - 1960 sample it is difficult to be sure of any trend. What is clear, is that the Canadian houses classified as energy efficient are much tighter than the general housing stock, with a mean leakage ten times less than the overall average.

The effect of climate on house construction is apparent in Figure 4, which shows the variability of specific leakage for housing in the U.S. and Canada. For recent housing, built between 1961 and 1983, Canadian houses are twice as tight as their U.S. counterparts. One interesting point is that blower-door tests in both countries tend to focus on new housing (built after 1961), rather than on older houses that might benefit more from retrofit programs. There is a need to expand the data base by testing a larger proportion of older housing so that the overall sample properly reflects the mix of ages in North American housing.

## Construction Type

The second criterion selected for disaggregating the data was construction type. Of the 711 in the entire sample, 519 cases had wall construction specified. These samples were divided into five construction types, listed below in order of increasing tightness:

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.

Figure 5a presents the specific leakage for each of these five categories. It is encouraging that, as expected, the leakage area decreases with improved construction. The most significant reduction in leakage area occurs with the addition of a single interior vapor barrier which reduces leakage area by more than a factor of three. One surprising result is the addition of exterior insulating-foam sheathing results in another 40% decrease in leakage area. Finally, the super tight houses demonstrate conclusively that the use of blower door pressurization methods during construction can increase the tightness of a standard air vapor barrier by more than a factor of ten. Given the incentive, and a means of measuring their own performance with an on-site blower door, construction crews were able to achieve a remarkable level of quality workmanship.

As shown in the lowest three bars of Figure 5b, the flow exponent also showed some of the expected trend. As one examines the data from no vapor barrier to a vapor barrier plus sheathing, the exponent increases, as would be expected if the size of the leaks were decreasing. Although the double wall houses are tighter than the vapor barrier plus sheathing house, the flow exponent is about the same or slightly less. A possible explanation for this is that leaks in double wall houses may have to go through a separate leak in each wall. Thus the exponent may not increase even though the flow resistance does. Furthermore, the 51 houses in the Winnipeg sample that were constructed using super-tight techniques had a mean exponent <u>lower</u> than the very leaky houses with no vapor barrier. One possible reason for this behavior is that the blower door was being operated below its normal flow range. Because the calibration of most blower doors cannot be trusted at these low flow rates, the results must be viewed with some caution. Future studies must be examined to see if either of these effects can be substantiated.

## CORRELATING SPECIFIC LEAKAGE AND FLOW EXPONENT

If we compare the exponent and specific leakage variability-by-construction plots, we see that there is a slight trend of lower exponents for higher specific leakages. This suggests that loose houses might be dominated by large holes in the building envelope and behave like orifice flow, while very tight houses would be dominated by small cracks and behave like laminar flow. With this in mind, we ought to see a general decrease in flow exponent from 1.0 to 0.5 as specific leakage increases. To investigate this possibility we have plotted the exponent as a function of the specific leakage in Figures 6a and 6b for all houses. Although the large variability of the flow exponent obscures most of it, this expected trend is visible - with a little imagination.

The only major exception to this trend is the set of super tight homes from Winnipeg. As mentioned above, these 51 Winnipeg houses represent a very special case, where blower door depressurization was used to carry out vapor barrier tightening during the construction of the house, while the vapor barrier was still exposed on the inside walls. While it is clear that this is a remarkably successful technique these houses are so tight that it is difficult to apply any generalizations for the other 464 houses to this specific group.

## SUMMARY AND CONCLUSIONS

In this report, we have used over five hundred homes on which pressurization measurements were made. Although the dataset has contributed much to the understanding of air leakage, it is not, because of the type of houses that are measured and recorded, reflective of the building stock, and thus cannot be used to define the leakage distribution of the average house. We have shown that while specific leakage (effective leakage area divided by floor area) may vary over an order of magnitude (See Figure 2a.), the flow exponent appears to have a normal distribution with a mean of 0.67 and a standard deviation of 0.09 (See Figure 2b.). The data confirms the common perception that the average flow exponent is between 0.65 and 0.68; this fact can be especially useful when trying to analyze fan pressurization data when insufficient information on the exponent was available.

We used the data to compare pressurization and depressurization with each other; we found that on average there was only a 5% difference between pressurization and depressurization, but for any single measurement there was a 28% difference. (See Figure 1a.) The result suggests that while it may be necessary to test an individual house using both pressurization and depressurization to determine the leakage, it is probably not necessary to carry out both types of tests when the average leakage performance of a large group of houses is desired. This finding has significant implications for the planning of both community air leakage test programs, and at the other extreme, for performance tests of individual houses aimed at retrofit improvements; the time/money/accuracy trade-off must be considered for each program. Future research into the cause of random variability of pressurization and depressurization results could allow a single measurement of either to be used.

In an attempt to categorize the variability of the leakage, we disaggregated the sample by both age and construction type. We found that there was little significant correlation of leakage with age when the age categories used are pre-1945, 1945-1960, and post-1960. (See Figure 3.) It is interesting to speculate on whether any correlation would develop if the post-1960 data were broken down by decade. Further measurement of new homes (i.e. post-1980) would be needed in order to investigate such a possibility. When we broke down the data by both age and country (i.e. United States and Canada), we discovered the unsurprising result that in the colder climate the houses are tighter. (See Figure 4.)

Some of the observed differences between U.S. and Canadian results might be traceable to the different way in which the tests were made and the different way in which the houses were used. Most of the Canadian measurements were done with all intentional ventilation sites taped; most of the U.S. tests were done with dampers closed but rarely taped. These differences are a result of the different standard test methods used in the two countries. A contributing effect is that most Canadians have fully conditioned and utilized basements (which tend to have few leaks) while most U.S. housing does not. This difference is especially important when the building volume is being calculated.

The examination of the effect of construction type on the variability produced the expected result; the specific leakage decreased through the five categories: no vapor barrier, vapor barrier, vapor barrier with sheathing, double wall, and super tight. The mean value of these categories can serve as guidelines for designers who are attempting to design for a certain tightness level. (See Figure 5.) With the exception of the two tightest categories the exponent also behaved as expected. The reason for this unexpected behavior is not clear; the two hypothesis are that 1) these tight houses have many cracks in series which do not necessary cause increased flow exponents for tighter configurations, and 2) the blower doors were operating below their valid range and calibration errors may cause the variability. More accurate measurements of fan pressurization of very tight houses must be done in order to explain this result.

The fact that the exponent generally goes down as the leakage goes up led us to attempt a simple, qualitative correlation between specific leakage and flow exponent (Figs. 6a, 6b). With the exception of the super tight houses there does appear to be a correlation, albeit not a strong one (See Figs. 6a, 6b). If a strong correlation existed, auditors or other blower door users would be able to make single point measurements of flow vs. pressure and accurately calculate effective leakage area. Because this simplification would greatly speed the process of fan pressurization, the authors plan to investigate the possibility in greater depth.

The amount of data currently available on envelope leakage is still quite small so that the authors view this collection and analysis of leakage data as an on-going and necessary effort. We intend to continue the effort of cataloging and analysing leakage data and would encourage those with significant data sets to make them available for this effort.

ACKNOWLEDGEMENTS

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This study was also 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 Corp. Scholarship to D.E.K. is gratefully acknowledged.

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TABLE 1

DATA BASE COMPOSITION

| U.S.A. | | | CANADA | | |
|---|---|---|---|---|---|
| LOCATION | SAMPLE SIZE | | LOCATION | SAMPLE SIZE | |
| | -ΔP* | +ΔP | | -ΔP | +ΔP |
| Oroville, California | 56 | 56 | Saskatoon, Saskatchewan | 176 | --- |
| Rochester, New York | 50 | 50 | Ottawa, Ontario | 67 | --- |
| Davis, California | 32 | 32 | Winnipeg, Manitoba | 51 | --- |
| Eugene, Oregon | 24 | 24 | Edmonton, Alberta | 11 | 11 |
| San Fransisco, Calif. | 16 | 16 | | | |
| Atlanta, Georgia | 7 | 7 | | | |
| Waterbury, Vermont | --- | 25 | | | |
| TOTAL | 184 | 210 | TOTAL | 305 | 11 |

* - ΔP = depressurization

+ ΔP = pressurization

TABLE 2

COMPARISON OF PRESSURIZATION AND DEPRESSURIZATION

SAMPLE SIZE 196 HOUSES

| | FLOW EXPONENT n | LEAKAGE AREA $cm^2 / m^2$ |
|---|---|---|
| PRESSURIZATION | 0.66 ± 0.09* | 5.9 ± 3.8 |
| DEPRESSURIZATION | 0.66 ± 0.08 | 5.6 ± 3.4 |

* sample standard deviation

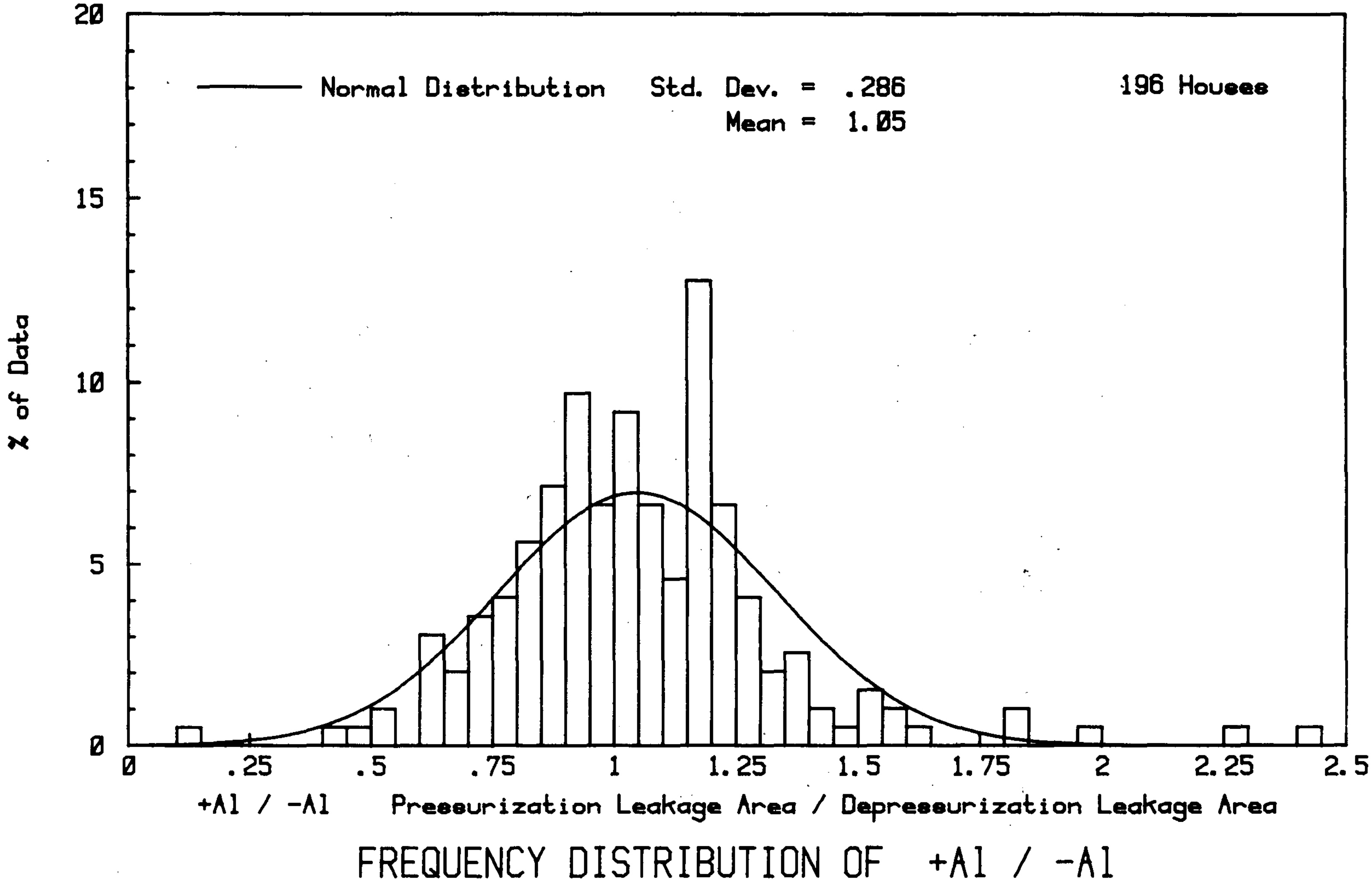


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Fig. 1a. Frequency distribution of the ratio of pressurization to depressurization for effective leakage area.

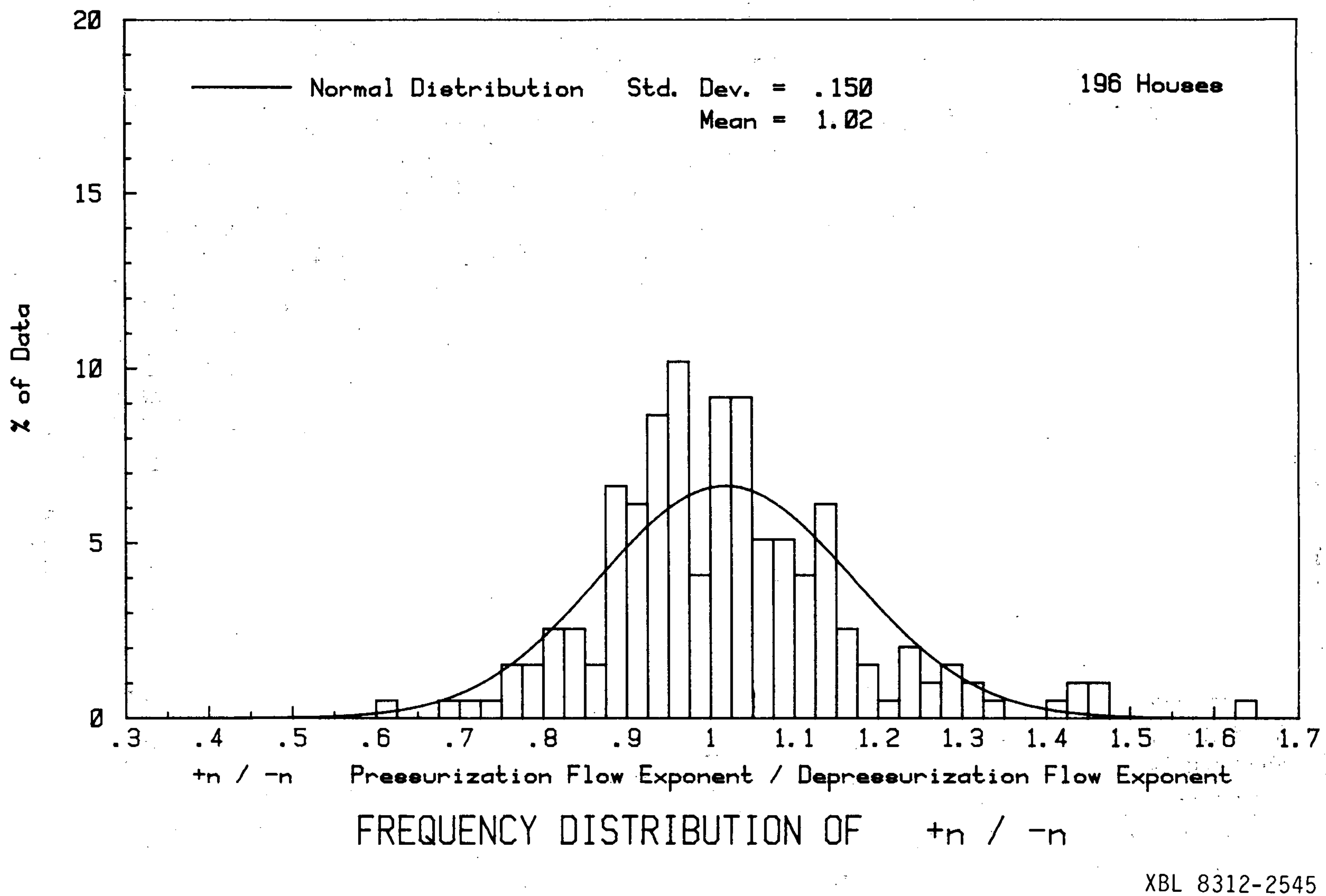
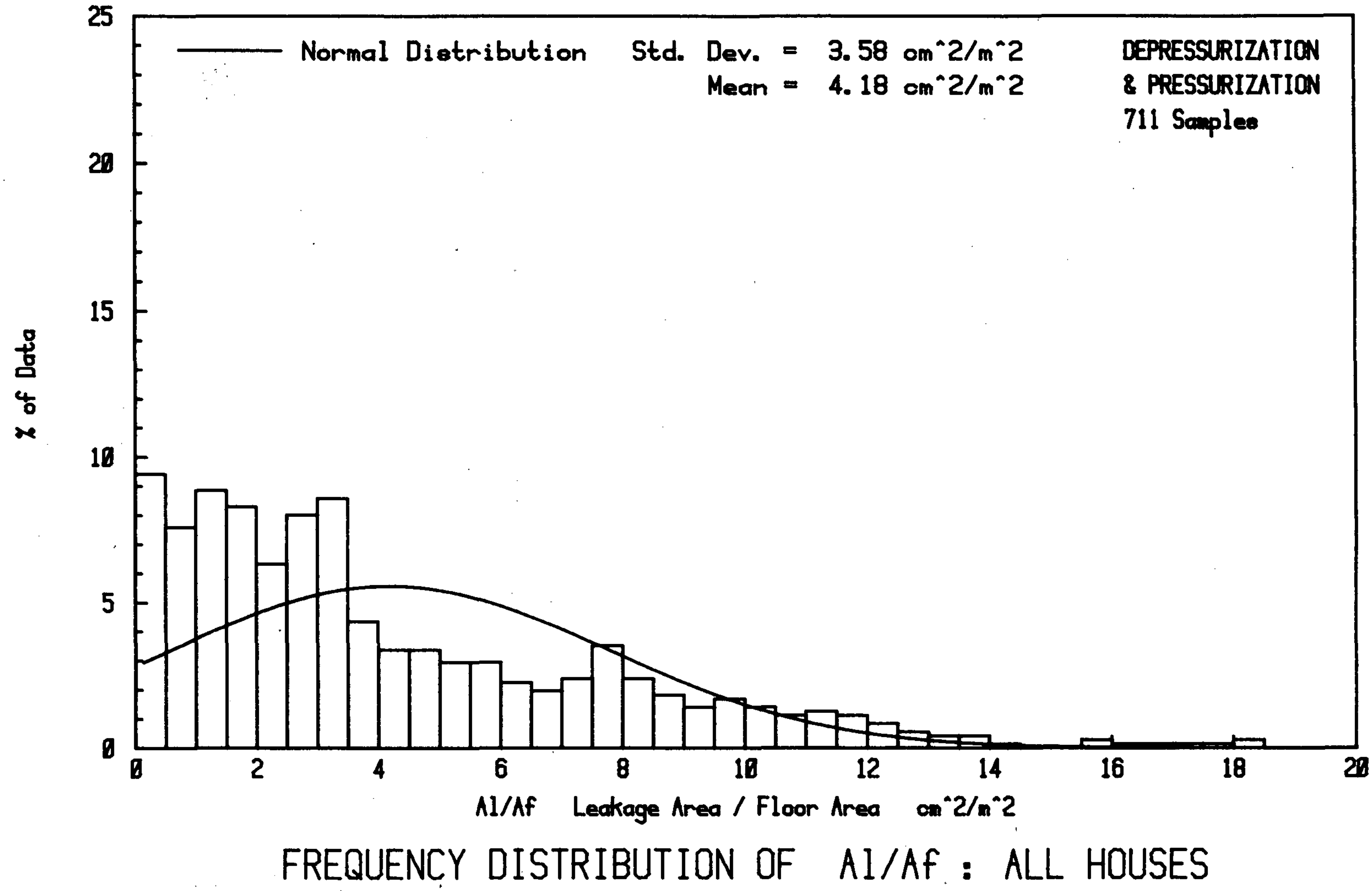
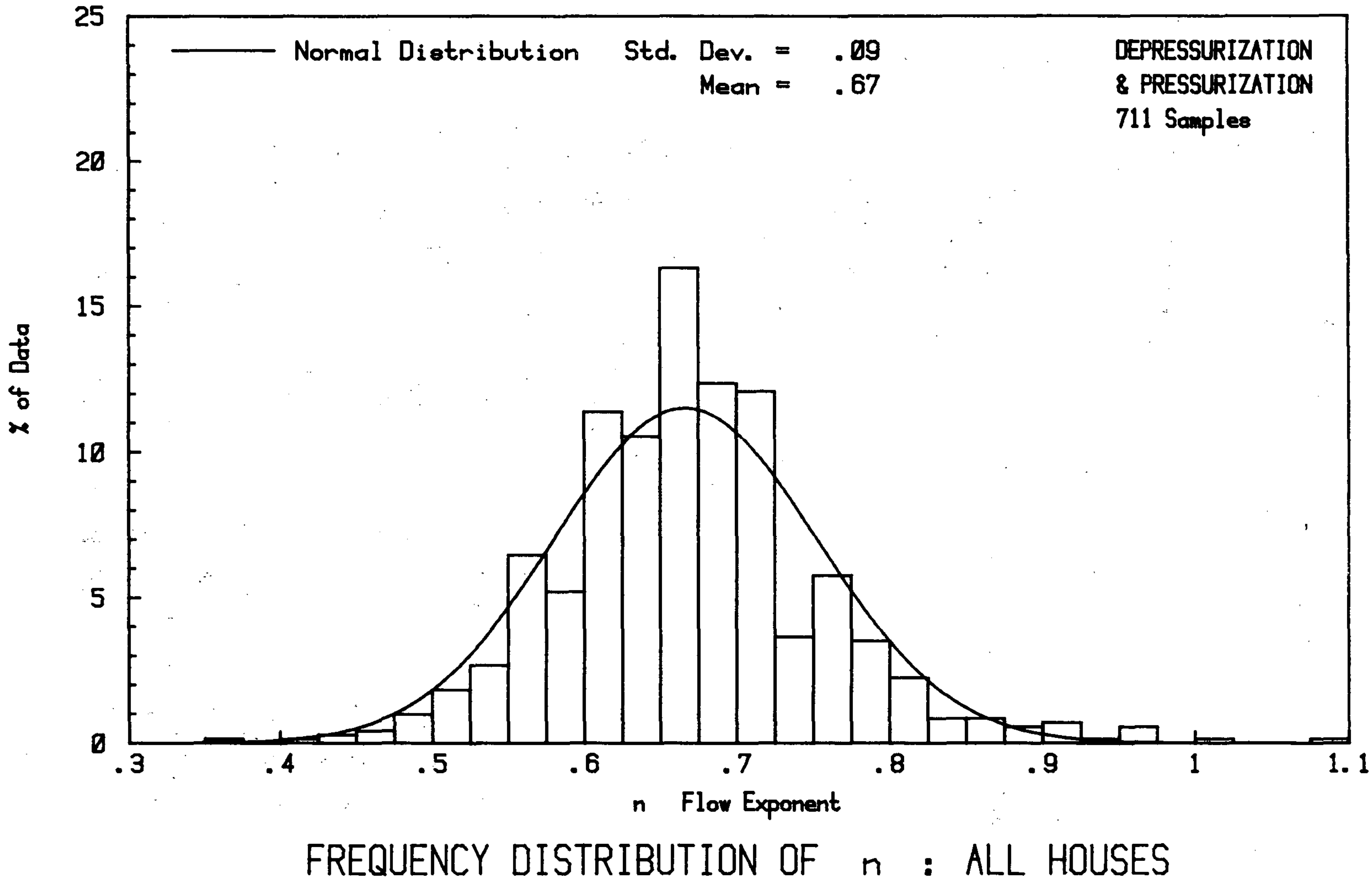



Fig. 1b. Frequency distribution of the ratio of pressurization to depressurization for flow exponent.




XBL 8312-2540

Fig. 2a. Frequency distribution of entire sample of houses for specific leakage.




XBL 8312-2544

Fig. 2b. Frequency distribution of entire sample of houses for flow exponent.

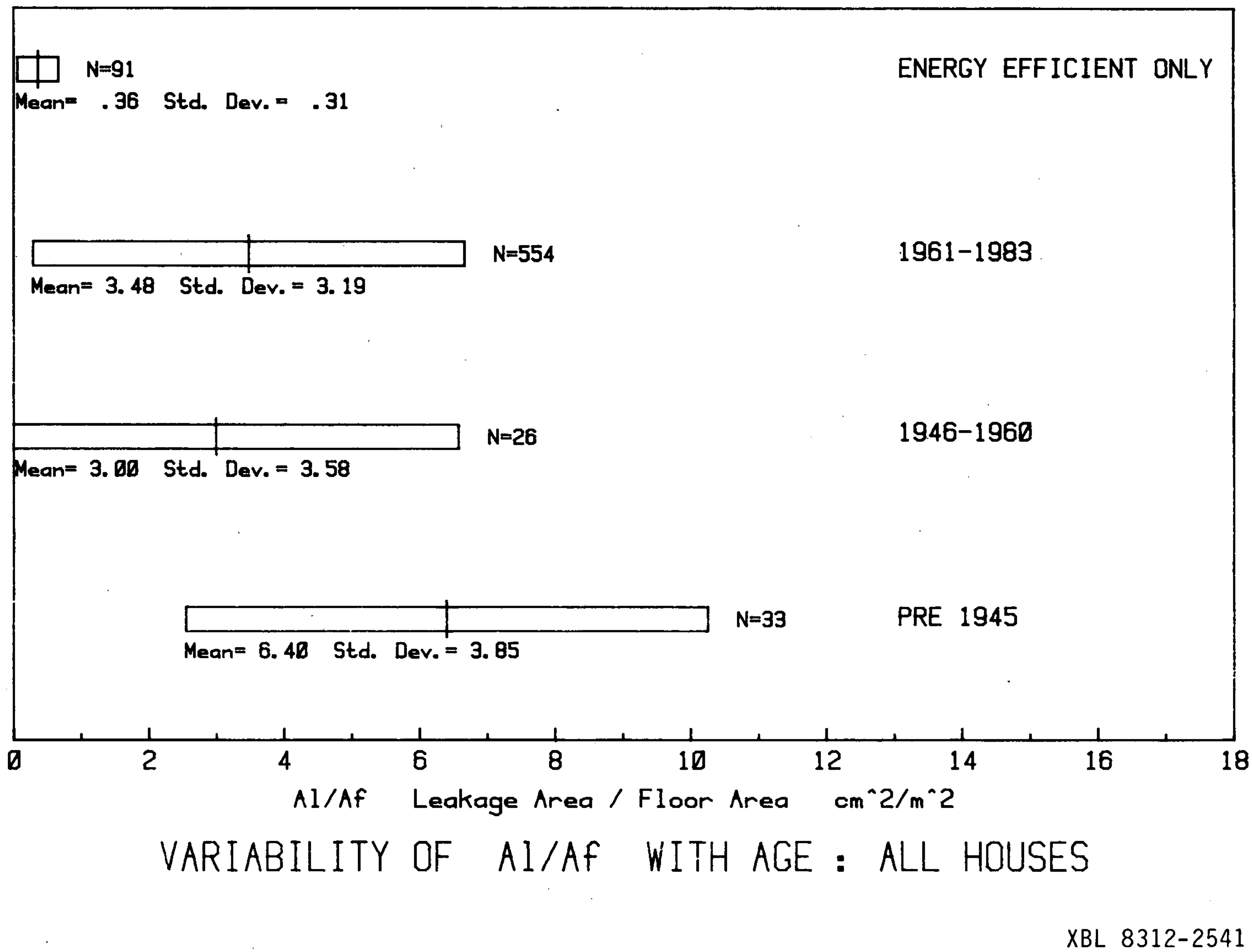



Fig. 3a. Disaggregation for entire sample by age for specific leakage.

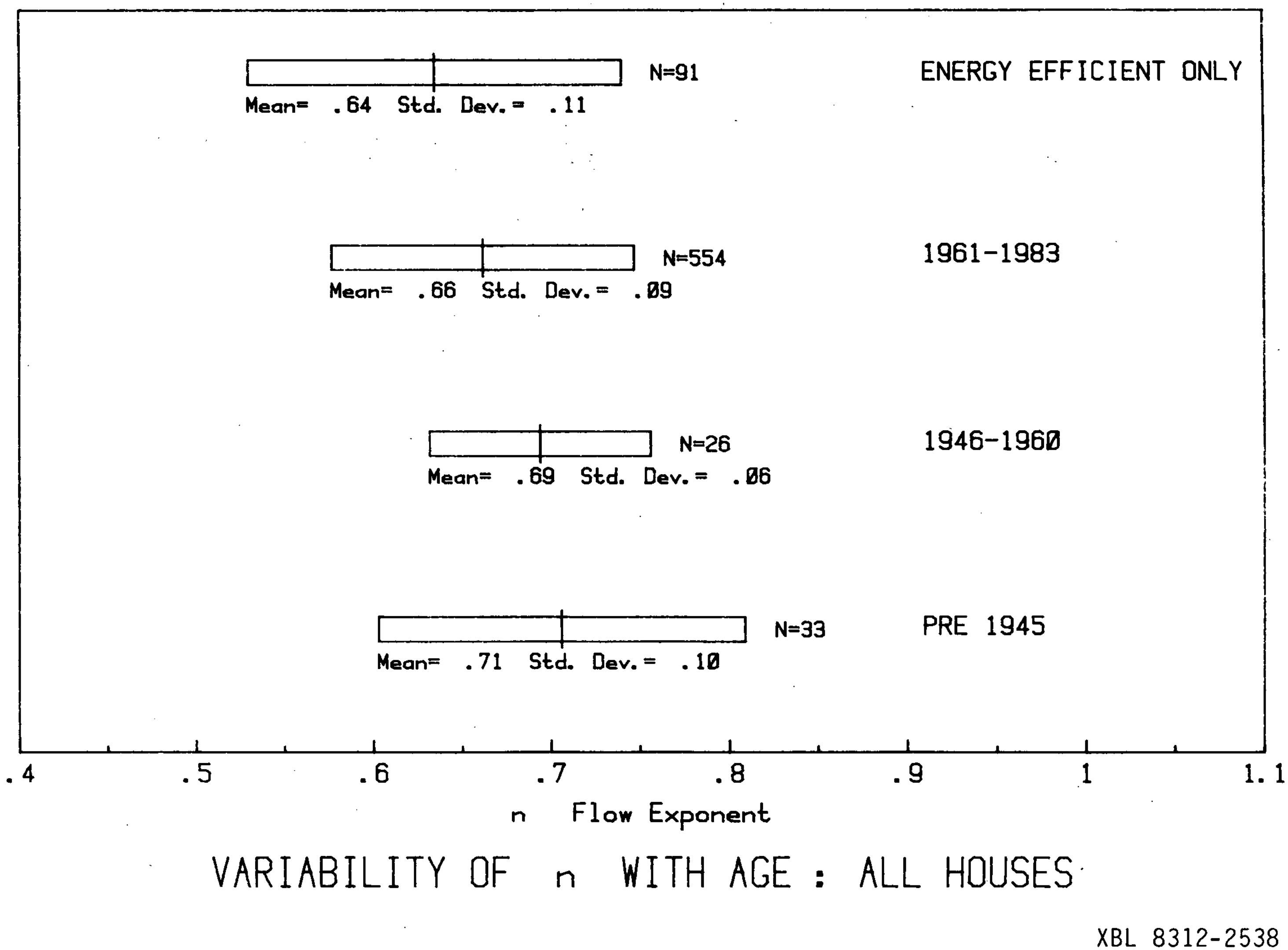
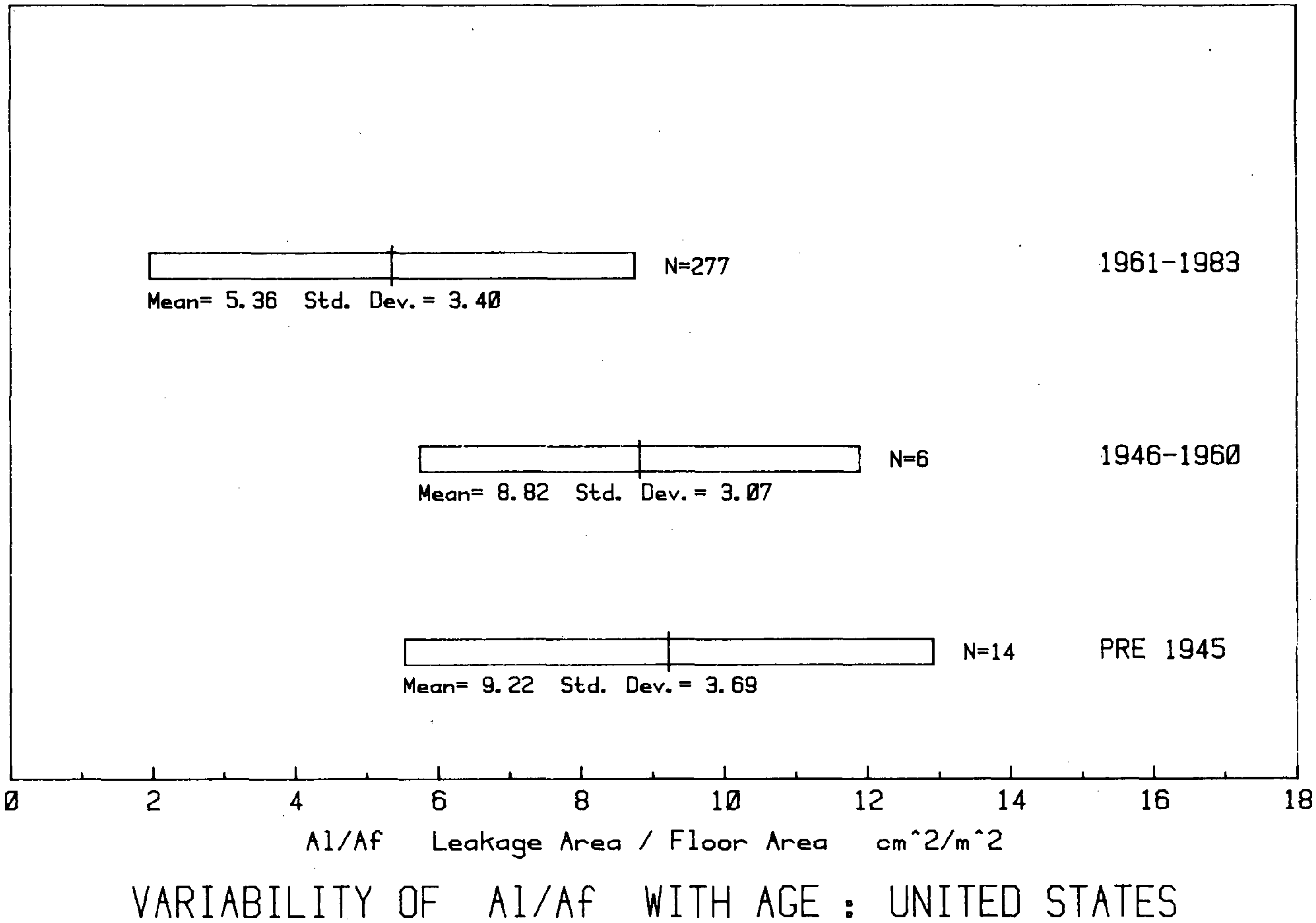
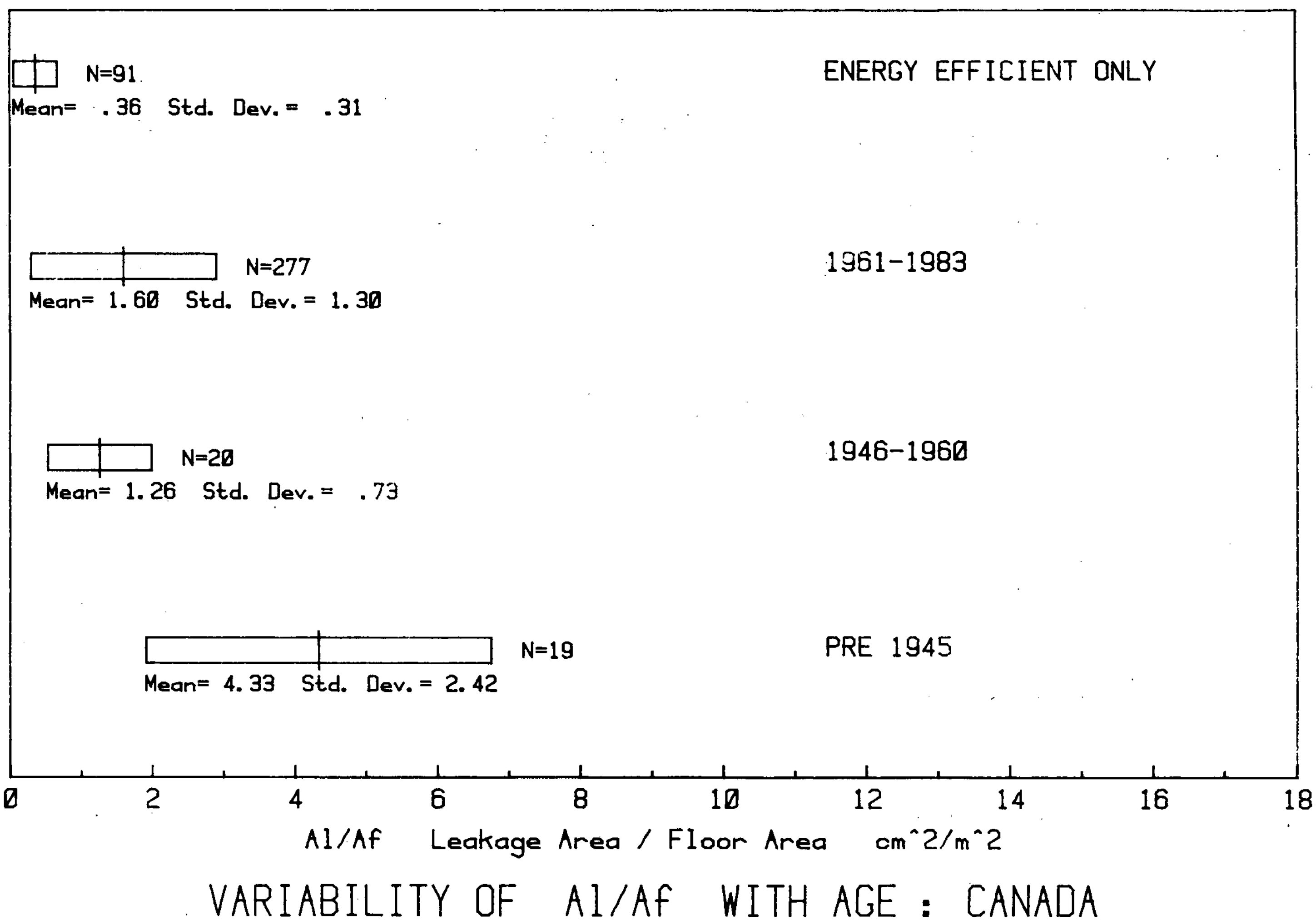



Fig. 3b. Disaggregation for entire sample by age for flow exponent.



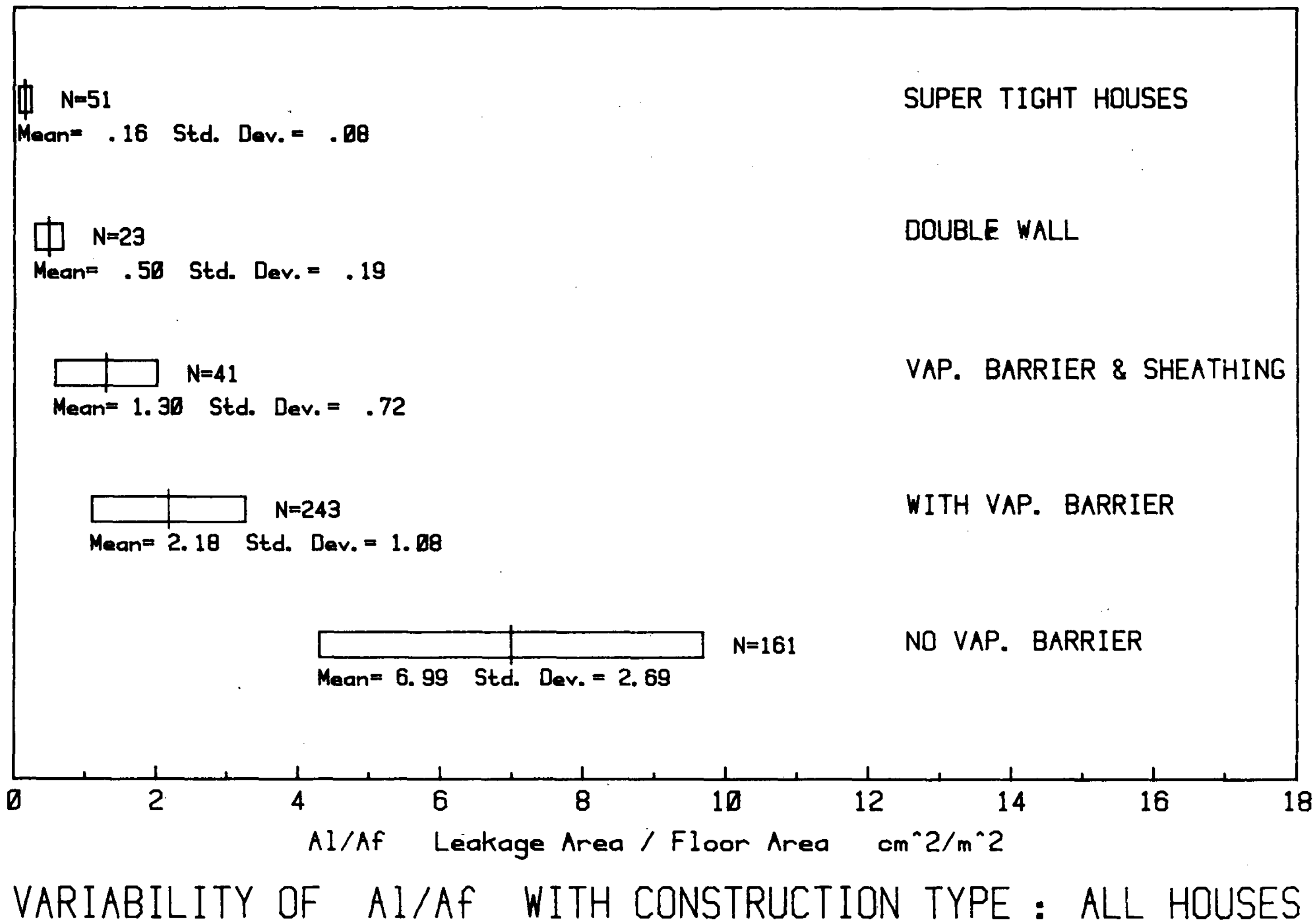

XBL 8312-2539

Fig. 4a. Disaggregation of specific leakage by age for United States.




XBL 8312-2537

Fig. 4b. Disaggregation of specific leakage by age for Canada.




XBL 8312-2536

Fig. 5a. Disaggregation of entire sample by construction type for specific leakage.

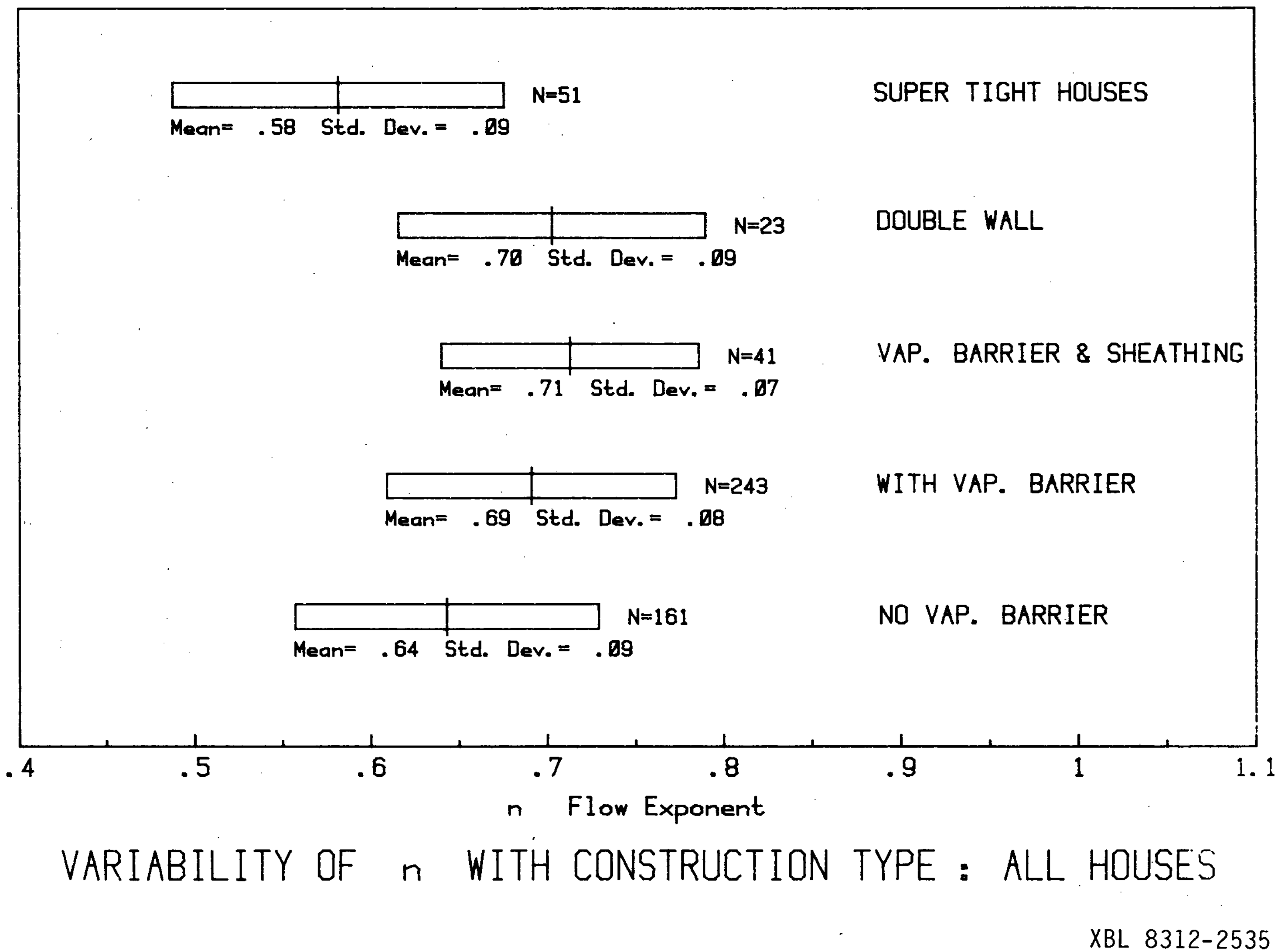



Fig. 5b. Disaggregation of entire sample by construction type for flow exponent.

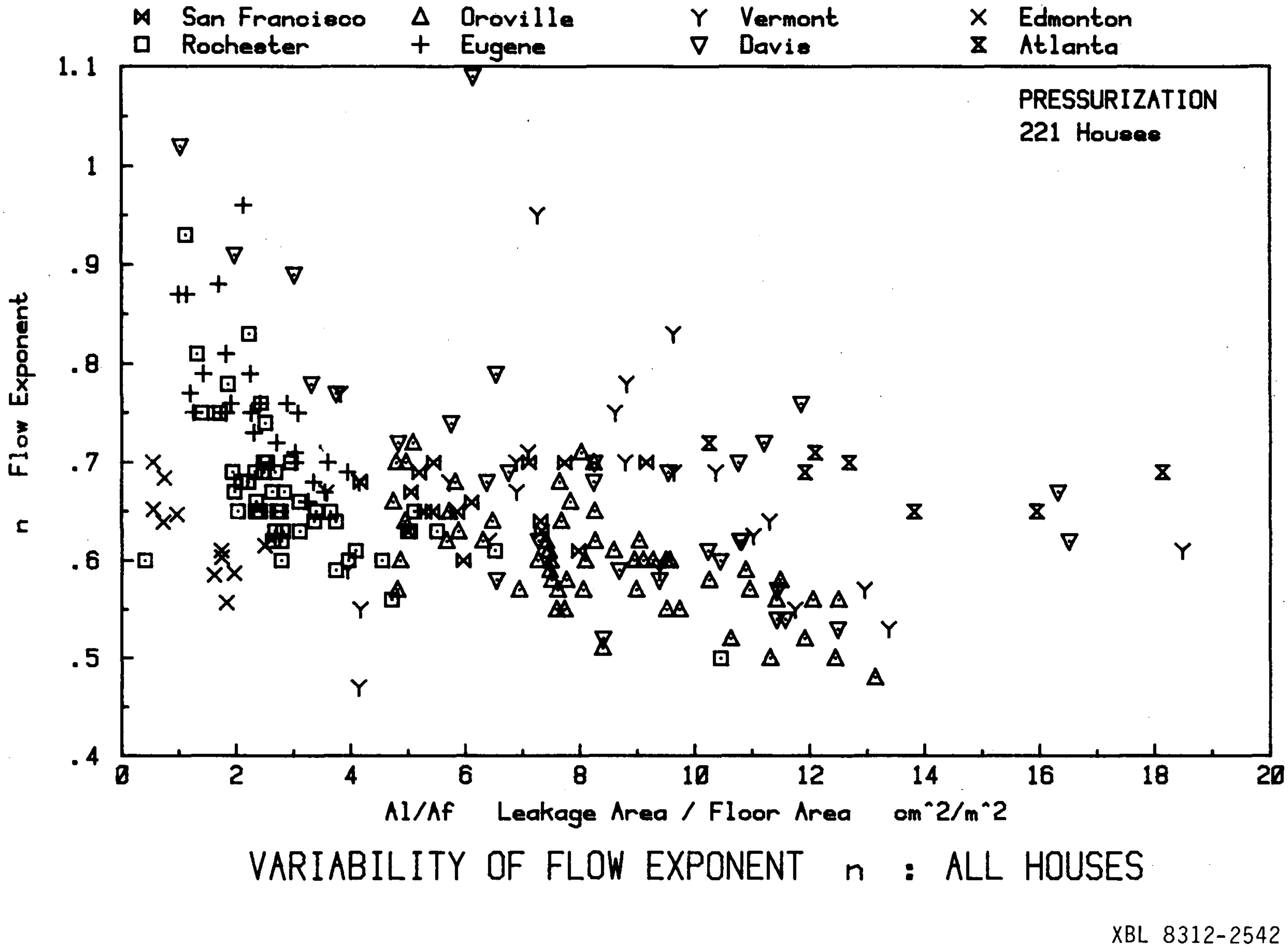
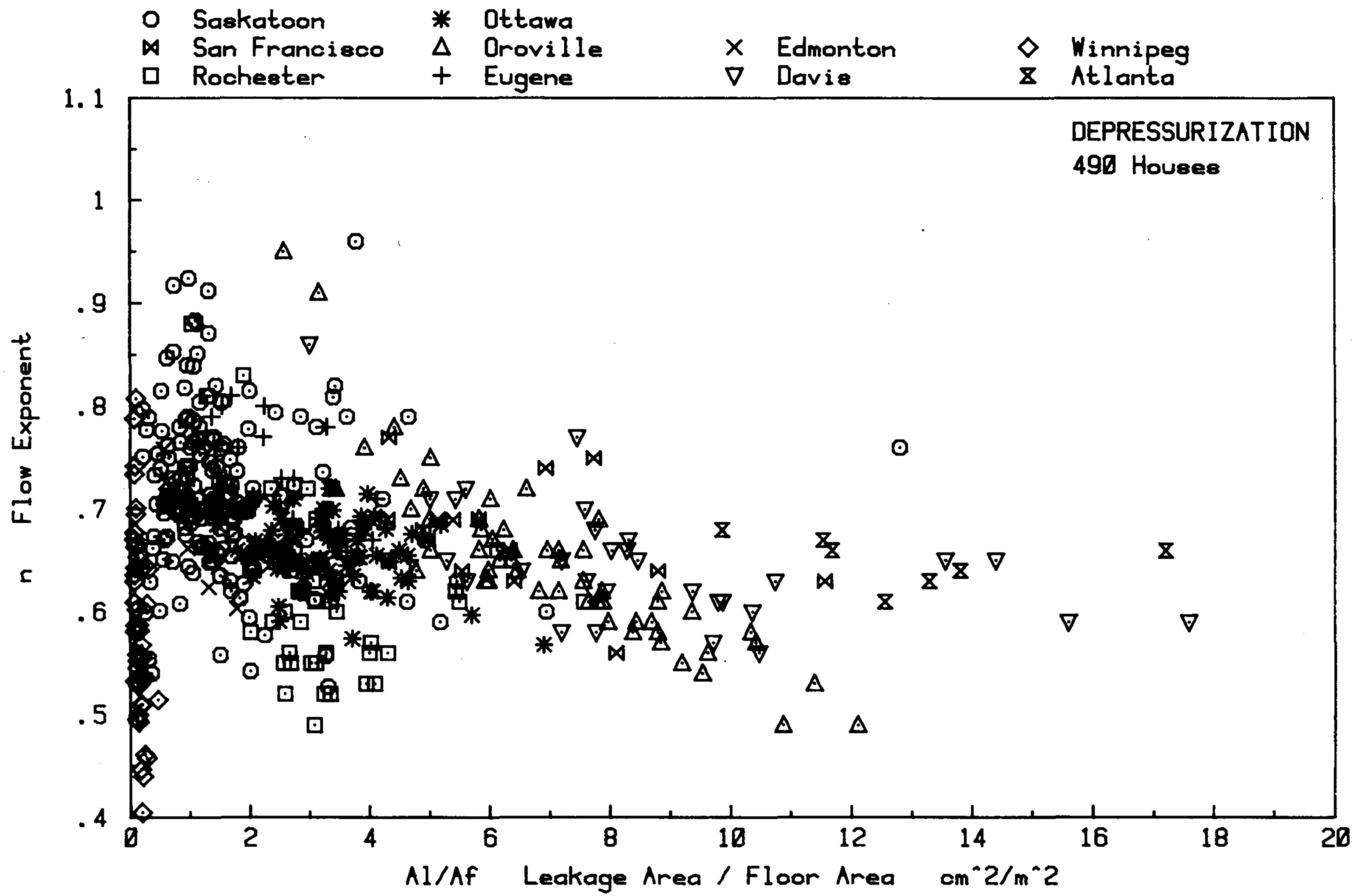



Fig. 6a. Correlation of flow exponent with specific leakage for pressurization.




VARIABILITY OF FLOW EXPONENT n : ALL HOUSES

XBL 8312-2543

Fig. 6b. Correlation of flow exponent with specific leakage for depressurization.

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