Airtightness of U.S. dwellings

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2 authors:

Max Howard Sherman
University of California, Berkeley

Darryl Dickerhoff
University of California, Berkeley

AIR-TIGHTNESS OF U.S. DWELLINGS*

Max Sherman
Darryl Dickerhoff

Energy Performance of Buildings Group
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California

Blower Doors are used to measure the air tightness and air leakage of building envelopes. As existing dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by whole-house mechanical ventilation systems, quantification of air-tightness data is critical in order to answer the following kinds questions: What is the Construction Quality of the Building Envelope? Where are the Air Leakage Pathways? How Tight is the Building? Tens of thousands of unique fan pressurization measurements have been made of U.S. dwellings over the past decade; LBL has collected the available data into its air leakage database. This report documents what is in that database and then uses that data to determine relevant leakage characteristics in the U.S. housing stock in terms of region, age, construction type and quality.

Keywords: Infiltration, Ventilation, Air Leakage, Indoor Air Quality, Energy, Blower Door, Fan Pressurization, Measurements

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INTRODUCTION

Virtually all knowledge about the air tightness of buildings comes from field measurements of *fan pressurization* using *Blower Door* technology. Infiltration is the interaction of this envelope tightness with driving forces such as those caused by weather. Blower Doors measure air tightness of the building envelope, or equivalently, *air leakage*. This report summarizes our measured air leakage data for U.S. dwellings.

This report does not intend to cover issues related to the (fan pressurization) measurements themselves. There exist many measurement standards[11] throughout the world, but the two used by the ASHRAE Standards relevant to much of the work in North America are the ASTM Standard[3] and the Canadian Standard[10]. Issues of measurement uncertainty[27] and reproducibility,[20] while important, will not be discussed in detail. Both technical[7] and popular[14,13] articles are available to familiarize the reader with some of the relevant issues. While this data can be used to produce representative information about the U.S. housing stock[29] the conclusions in this report are not so extrapolated.

This report focuses on single-zone buildings. While fan pressurization techniques are sometimes used for component or multizone leakage measurements, the vast majority of measurements have been made for whole-building, single-zone situations, such as single-family homes. The data summarized herein will deal with single-family homes throughout the United States for a wide variety of vintages, construction types, and conditions.

BACKGROUND

Air leakage data is now used for a wide variety of purposes from the qualitative (e.g. construction quality control) to the quantitative (e.g. envelope tightness standards). As the key envelope property related to air flow, it is used in one form or another for infiltration-related modeling. Given such diverse uses it, it is not surprising that it often treated as a stand-alone quantity, even though air leakage is only an intermediate value.

Before proceeding on to summarize the current measurements, it may be instructive to briefly review the history of fan pressurization measurements and their relationship to air flow modeling. Blower-Door technology was first used in Sweden as a window-mounted fan to test the tightness of building envelopes.[8] The technology was brought to the U.S. by Blomsterberg and used in Princeton to help find and fix the leaks[16], where it became a Blower *Door*.

During this period the diagnostic potentials of Blower Doors began to become apparent. Blower Doors helped to uncover hidden *bypasses*[17] that accounted for a much greater percentage of building leakage than did the presumed culprits of window, door, and electrical outlet leakage. The use of Blower Doors as part of retrofitting and weatherization became known as *House*

Doctoring[18,12] and led to the creation of instrumented audits[15] and computerized optimizations.[32]

While it was well understood that Blower Doors could be used to measure air tightness, the use of Blower-Door data could not be generally used to estimate real-time air flows under natural conditions. When compared with tracer-gas measurements, early modeling work[9] was found wanting. Attributed to (and often denied by) Kronvall and Persily,[22] there was a rule of thumb that seemed to relate Blower-Door data to seasonal air change data in spite of its simplicity[*]:

$$ACH \approx \frac{ACH_{50}}{20} \qquad \text{(EQ 1)}$$

That is, the seasonal amount of natural air exchange could be related to air flow necessary to pressurize the building to 50 Pascals, where “ACH” is the natural air changes per hour and “ACH_{50}” are the air changes induced by a 50 Pa pressure using a fan.

To overcome the physical limitations of such rules of thumb, it is necessary to physically model the situation which, in this case, means separating the leakage characteristics of the building from the (weather) driving forces. As the early versions of the ASTM Standard show, leakage is conventionally described as a power law, Equation 3[*], which was found to be empirically valid but without theoretical substantiation (until recently[21]).

Using orifice flow (Equation 4[*]) as a physical model, the Blower-Door data can be used to estimate the Effective Leakage Area (*ELA* from Equation 5). Using this orifice-flow paradigm, the LBL Infiltration model[25] was developed and validated[26] and became incorporated into the ASHRAE Handbook of Fundamentals[2]. Much of the subsequent work on quantifying infiltration is based on that model, including ASHRAE Standards 119[3,23] and 136[4]. A more detailed description of how to use fan pressurization data is currently available.[31]

While ACH_{50} is a popular single-parameter quantification of leakage, the one used most by ASHRAE is called “Normalized Leakage”, *NL*, which, like ACH_{50} can be calculated from fan pressurization measurements[5] (i.e. the exponent, n, and the Effective Leakage Area, *ELA*) and the building geometry (i.e. the floor area, A_f, and the building height, H):

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3} \qquad \text{(EQ 2)}$$

Blower Doors are still used to find and fix the leaks, but more and more the values generated by the measurements are used to estimate infiltration for both indoor air quality and energy consumption estimates. These estimates in turn are used to compare to standards or to base program or policy decisions. Each spe-

*. The important equations are derived in “APPENDIX: LEAKAGE MODELING” on page 12.

cific purpose has a different set of issues associated with it as it regards the use of the Blower-Door data. An earlier work[28] describes related data sources and their use in determining energy liabilities in more detail.

DESCRIPTION OF LEAKAGE MEASUREMENTS

The primary kind of data used in this report is, of course, leakage data. We required that all data in our dataset be from single-family detached dwellings with a known, U.S. location. We also required the size of the dwelling and the number of stories to be known. We requested but did not always receive more detailed information including the leakage exponent, the year of construction, the type of construction, floor/basement type and HVAC system, the building height, and any information regarding retrofits or general building condition. We used all acceptable data available to us. Most of the data we used was not collected by us but was either published or volunteered by other researchers or practitioners. The largest published dataset used was the AIVC Leakage Database[19]. Those who volunteered published or unpublished data are listed in the “ACKNOWLEDGMENTS” .

We can summarize the dataset we have in a number of ways. Figure 1

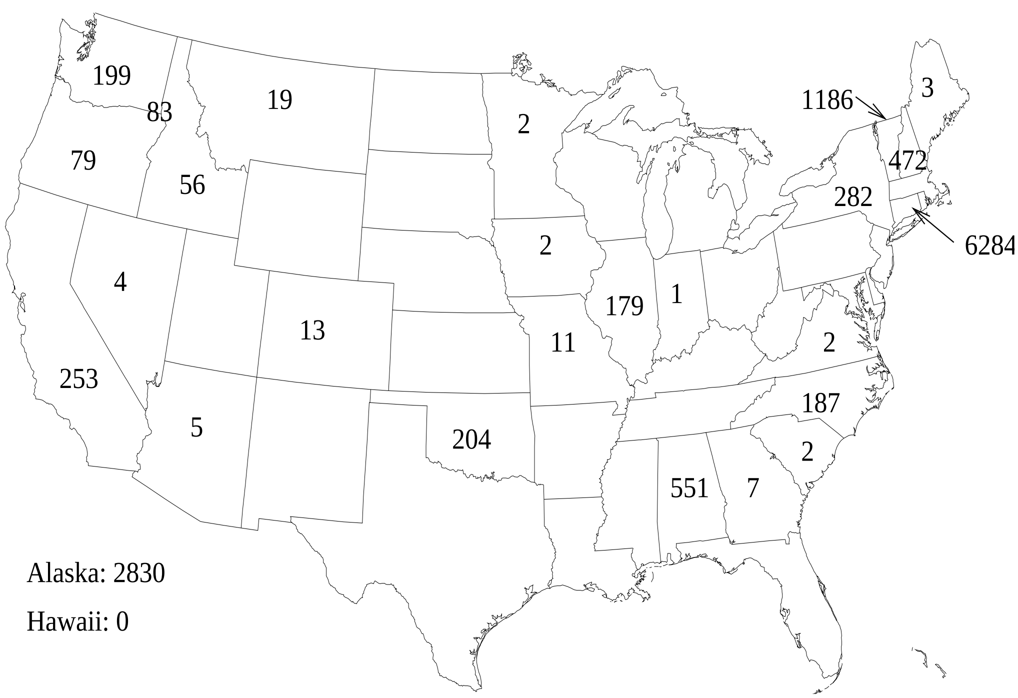

FIGURE 1: Geographic Distribution of Leakage Measurements in Database (September 1994)

graphically displays the location and number of leakage measurements that have been incorporated into our database. Included in our database are 12946 individual measurements on over 12500 houses from the sources listed in the ACKNOWLEDGMENTS, including about 450 homes from the AIVC's numerical data base. The largest sources of data consisted of 10800 houses from Alaska, Alabama, Vermont and Rhode Island, from Energy Rated Homes of America.

RESULTS

In the collection process data was sought from all over the U.S. So one important breakdown of the data we looked at was the examination of leakage by State. Our data breaks down as indicated in Table 1, "NORMALIZED LEAKAGE BY STATE," which does not include any data from twenty-two states, although some of these states may be included in the "Other" group

TABLE 1. NORMALIZED LEAKAGE BY STATE

State	Average Normalized Leakage	Standard Deviation	N	State	Average Normalized Leakage	Standard Deviation	N
Alabama	0.85	.33	30	Minnesota	0.38	.21	2
Alaska	1.99	1.16	2830	Missouri	1.64	.45	11
Arizona	0.66	.49	5	Montana	0.14	.11	19
Arkansas	1.95	.98	551	Nevada	0.78	.49	4
California	0.73	.30	253	New Hampshire	1.13	N/A	1
Colorado	0.87	.35	13	New York	0.73	.58	282
Connecticut	0.50	N/A	1	North Carolina	1.48	.86	187
Georgia	1.57	.29	7	Oklahoma	1.12	.70	204
Idaho	0.50	.49	56	Oregon	0.40	.21	79
Illinois	0.66	.60	179	Rhode Island	1.88	.50	6284
Iowa	0.14	.07	2	South Carolina	0.78	.36	2
Indiana	0.39	N/A	1	Vermont	1.56	.55	1186
Maine	0.40	.10	3	Virginia	0.23	.05	2
Massachusetts	0.53	.22	3	Washington	0.44	.24	199
Northeast[a.]	1.26	.78	467	*Other*[a]	0.72	.39	83

a. These homes come from three studies in which the state was not identified: one in the Northeastern States, the other two from the Pacific Northwest and Iowa.

In examining regional trends we attempted to use regression techniques to determine if there were any leakage trends with climate, latitude, etc. Our analysis showed no significant trends with these climate-related parameters indicating the trends in leakage are more dominated by construction quality, local practices, age distribution, etc. than they are by weather. As an example, one can examine more extreme climates such as Alaska and Vermont which appear leakier than the mild climates such as California and Oregon, but other mild climates such as North Carolina appear quite leaky.

Any such analysis, however, may be confounded by the fact that the large (Energy Rated Homes) datasets are in general leakier than the rest of the data. This suggests that the other datasets included in our study may be more biased by new, tight, or novel construction. While the authors know of other large datasets, most of these were not accessible or usable for this study. Data, however, continues to be generated in both the public and private sector which could be used in the future to address these issues.

By its very nature the sample we have collect is not statistically representative of the almost 75 million single-family households in the U.S. Furthermore, different component datasets and measurements are of different qualities and should not be treated equally. Figure 1 demonstrates this fact by showing how

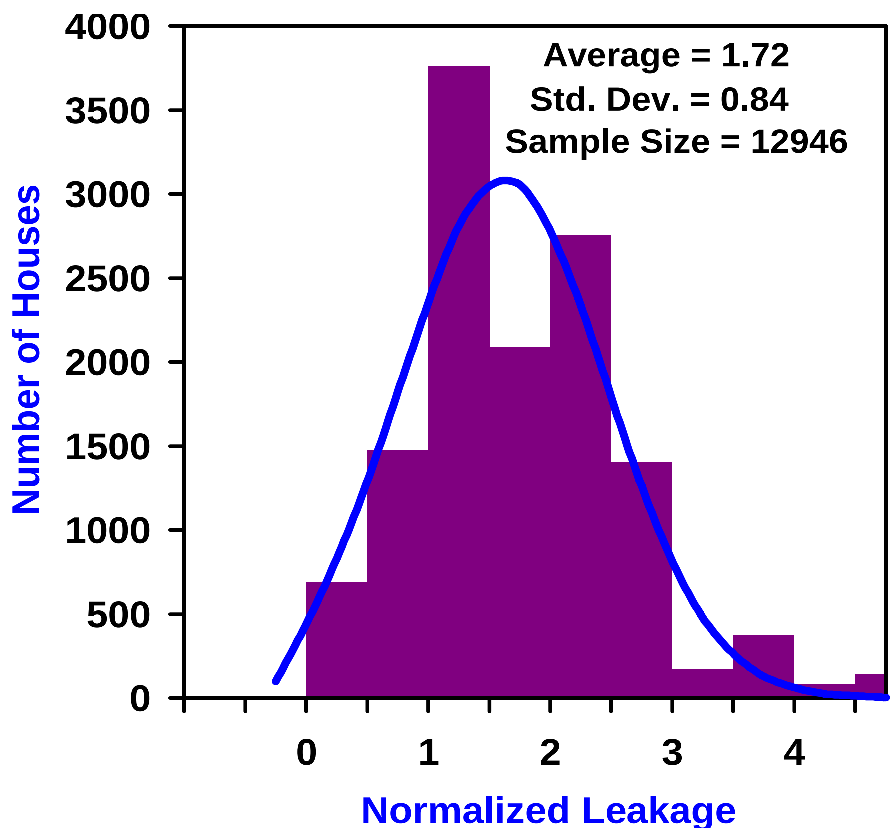

FIGURE 2: Distribution of Leakage Measurements by Value

unevenly distributed over the range of leakage values our sample is. Having said that, we must realize that this data represents the best set we could then generate and we shall use it to summarize the important physical characteristics contained in this database. Work continues on extrapolating this dataset to be representative of the U.S. stock.

Table 2, "SUMMARY OF LEAKAGE MEASUREMENTS," presents the overall content of the dataset and contains the year of construction, the size of the dwellings and several variables relating the leakage information. We have chosen two ways of expressing air leakage (ACH_{50} and NL) because they are the two most commonly in use in practice or in standards; the exponent and year built are

TABLE 2. SUMMARY OF LEAKAGE MEASUREMENTS

	Mean	Std Dev.	Number of Houses	Min.	Max
Year Built	1965	24.2	1492	1850	1993
Floor Area [m^2]	156.4	66.7	12946	37	720
Normalized Leakage	1.72	0.84	12946	0.023	4.758
ACH_{50}	29.7	14.5	12902	0.47	83.6
Exponent	0.649	0.084	2224	0.336	1.276

important diagnostic and comparative tools as we see below; the floor area was chosen as the size normalizing parameter because it is used in the ASHRAE standards.

We can use the dataset to see if there is a useful correlation between the two ways of quantifying leakage. The average ratio between ACH_{50} and NL is 17.5, with a standard deviation of 2.3, indicating that a 13% extra uncertainty (in the form of a bias) can be introduced when converting directly between these two quantities. Equation 7 suggests that these two quantities are directly related and there should be no need for comparing them. While there is a general relationship, it varies with the quantities such as the exponent and building height; thus creating the extra 13% uncertainty. In general we will use Normalized Leakage rather than air changes at 50 Pascals to make our leakage comparisons.

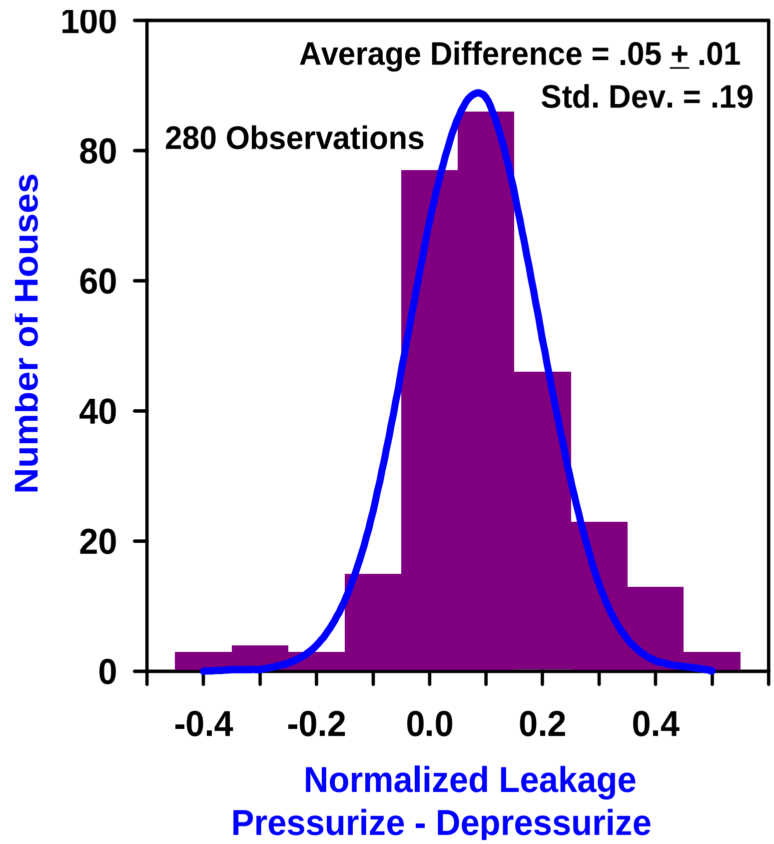

FIGURE 3: Probability distribution of the difference between pressurization and depressurization.

The leakage values in Table 2 are averages of pressurization and depressurization values whenever both existed. One question that has often been posed is whether or not there is a significant difference between the two. Figure 3 is a plot of their fractional difference. The outliers are principally from very tight houses in which the absolute difference was small but the percentage difference was quite large. We analyzed all of the cases in which both were measured and found that of the 280 usable measurements pressurization tests reported 9% higher leakage on average than did depressurization.As the error of the mean was 2% this difference is significant.The 9% value was calculated from the Normalized Leakage values. We repeated the analysis using the air changes at 50 Pascals and found the same trend but a larger (i.e. 12%) value, but a narrower distribution.

This result suggested that there might be a difference in exponent between pressurization and depressurization, but our analysis shows that there was no statistically significant difference. Figure 6 shows the general distribution of expo-

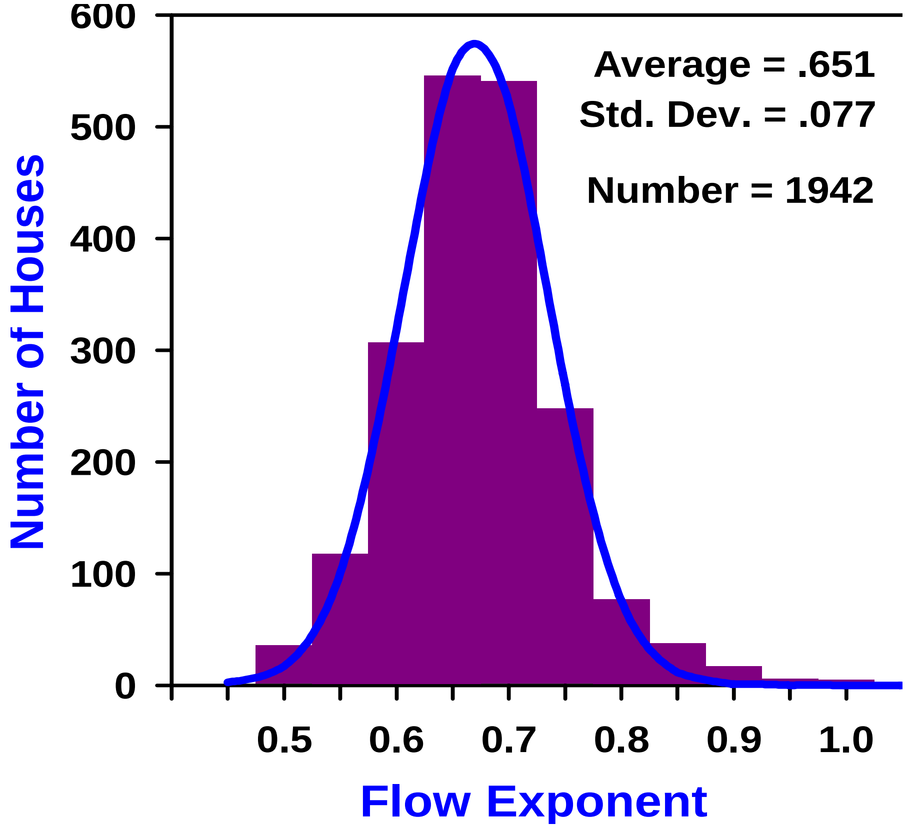

FIGURE 4: Distribution of Leakage Exponents

nents and they appear quite clustered, even though there were many non-physical outliers. The average exponent for the over 1900 measurements that reported exponents is 0.65 with a standard deviation of 0.08; multiple measurements on the same house were treated as independent.

We examined the dataset in some detail to look at five building criteria that may impact leakage: number of stories; year of construction; floor/basement type;

thermal distribution system and retrofitting. We discuss below the impact of each of these factors.

Number of Stories: Most of the U.S. Housing stock is in one and two story, single-family dwellings. We looked at the entire dataset to determine if that difference in construction type affects the leakage. Approximately 56% of our measurements are of multistory dwellings. We find that multistory houses are 11% leakier (i.e. NL=1.8) than single-story houses (i.e. NL=1.6) with an error of the mean near 1%. This value is, therefore, statistically significant, and we can conclude that there is a difference between single and multiple storied dwellings.

Floor/Basement Type: We restricted our consideration of this issue to two classes: those dwellings that had floor leakage to outdoors (i.e. crawlspace homes and unconditioned basements) and those that had no floor leakage to outdoors (i.e. slab-on-grade and fully conditioned basement homes). The vast majority (80%) of our dataset had floor leakage (at NL=1.75). The subset that did not was slightly (5%) tighter (at NL=1.64) and this value was statistically significant.

Dwelling Age: We examined the data for which year of construction was available to see if there were leakage trends correlating to the age of the dwelling. Examining the data in detail we found a break point at the year 1980. Figure 6 is a plot of aver-

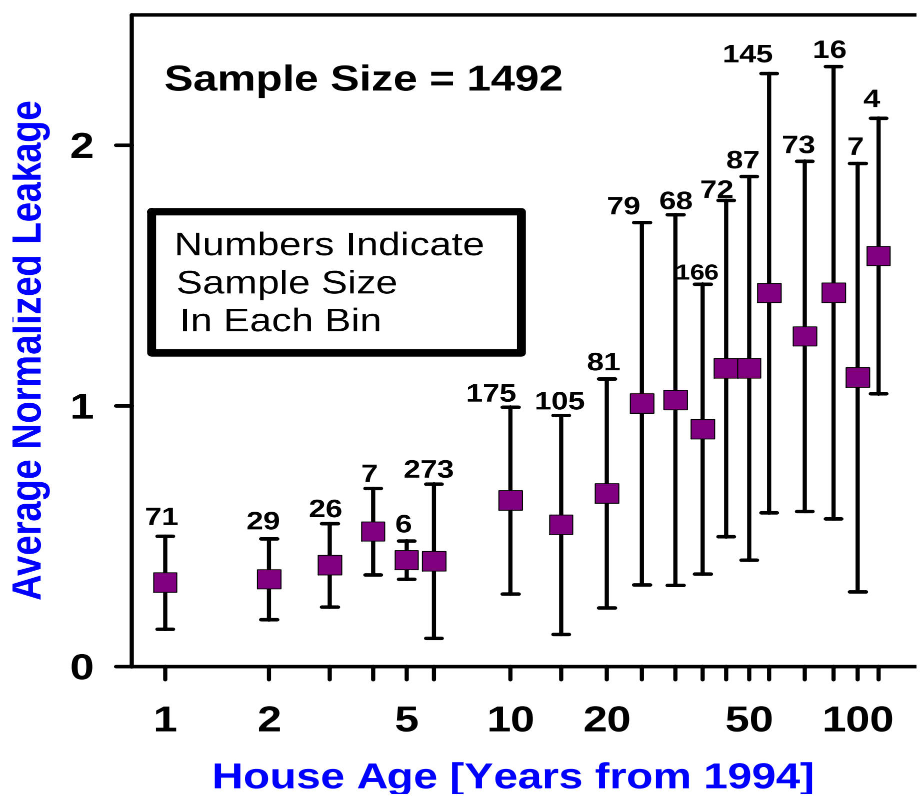

FIGURE 5: Plot of Normalized Leakage vs. Age (base year 1994). Fit lines are best fits to data with an exclusive knot at 1980 (i.e. 14 years old).

age NL (and standard deviation) for various house age bins for those houses where the year of construction was known. The bin spacing is irregular in an attempt to improve bin-size distribution and to respond to the grouping of the data. The 628 houses built after 1980 did not show any trend with age and were tighter (NL=0.47) than average. The 869 houses built prior to 1980 showed a clear increase in leakage with increasing age and were on average leakier (NL=1.05) than new houses but still tighter than the average of the entire dataset (NL=1.72).

Thermal Distribution System: Because of the current interest in the efficiency of residential thermal distributions systems, we analyzed those homes (about 11% of the total sample) where there was knowledge about the existence (or absence) of a duct system. The surprising result was that the homes with duct systems (43% of this subset) were tighter (NL=0.7) than those homes that did not have duct systems (NL=0.9). Where duct systems were measured separately (about 1% of the total sample), they accounted for just under 30% of the total leakage–a finding consistent with other studies.

Retrofitting: A (465 house) subset of the houses were measured as part of retrofit or weatherization projects and had measurements both before and after the retrofits were done. Figure 6 shows the distribution of retrofit impacts on the normal-

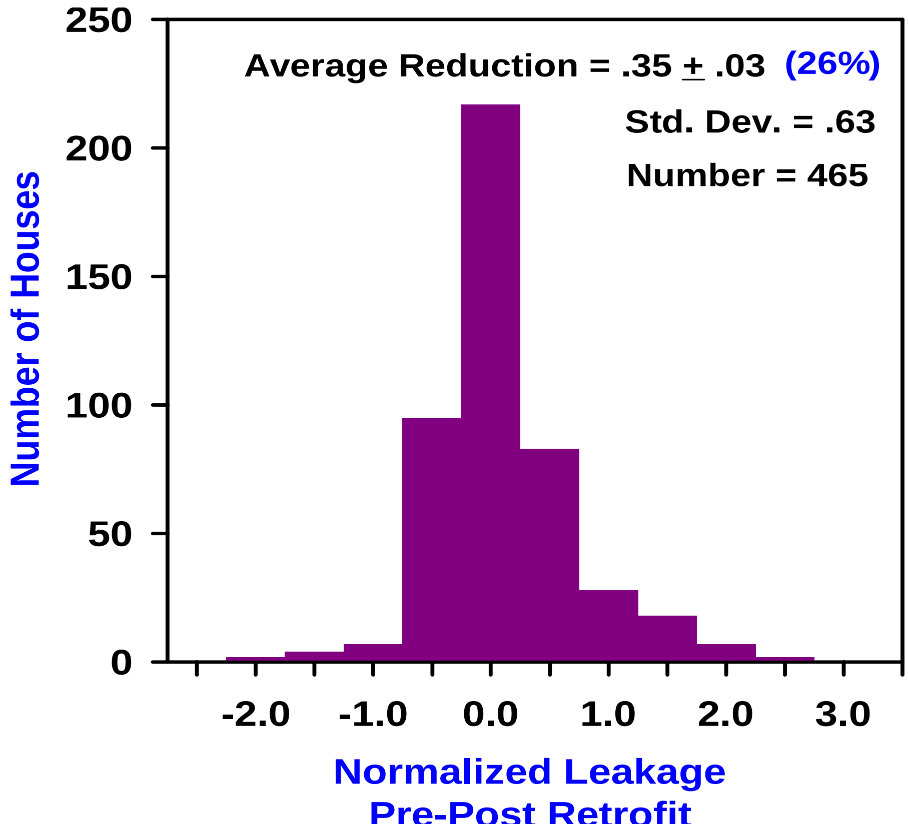

FIGURE 6: Distribution of Leakage Changes due to Retrofits

ized leakage. From these measurements we found that the average retrofit reduced the leakage by about 25% (from NL=1.34 to NL=0.99 with the error of the mean difference being NL=0.03).

CONCLUSIONS

The first significant finding is that dwellings appear to be even leakier than previously estimated. This current analysis includes large datasets that represent much more comprehensive cross-sections of ordinary homes in particular locations (e.g. Rhode Island, Alaska, Vermont etc.) than had been previously studied. Although not spread evenly around the country these more intensive studies suggest that our previous leakage estimates were biased towards tighter housing, probably because more energy efficient houses have been studied in detail.

Unlike the fields for leakage, floor/basement type and the number of stories, the impact of ducts, the effect of retrofits, and year of construction information is available on only subsets of the data. Furthermore these subsets themselves appear to be tighter than the dataset as a whole, probably reflecting the fact in the larger, broader studies, less information was recorded and that the detailed studies probably tended to be on better (or newer) construction. Future studies should endeavor to do internal controls to try to ascertain whether such factors could bias the results.

We examined the data subsets in many ways and looked at distributions of various quantities. In almost every distribution we looked there were more outliers than would be expected from a normal distribution; some of them were non-physical and induced most likely by measurement problems such as weather effects or mismatches between equipment capacities and dwelling conditions. Outliers may also be caused by data entry errors. Outlier studies can provide useful insight into physical effects present in special subsets. Care must be taken when trying to make certain extrapolations to the population because some statistical quantities, such as percentile estimates or kurtosis, may be significantly biased by the non-guassian nature of the population. The simple averages taken in this report, however, a reasonably robust and not very sensitive to such effects.

Our earliest study[28] had indicated that approximately half the U.S. would meet ASHRAE's airtightness standard[3]. This dataset has less than 10% of the country meeting that standard. We have recently completed a new study[29] that uses this leakage data and other datasets to extrapolate residential ventilation performance to the existing stock in a statistically meaningful way. The reader should consult that report to see the regional impacts of air leakage and ventilation system choices on the ventilation, energy, and economics related to house tightness.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of leakage and related data made by individuals and organizations. Table 3, "LIST OF DATA CONTRIBUTORS USED IN THIS REPORT," includes those sources for which data was included in our analysis.

TABLE 3. LIST OF DATA CONTRIBUTORS USED IN THIS REPORT

CONTRIBUTOR	INSTITUTION	REGION
Ron Hughes, Evan Brown	Energy Rated Homes of America	Alaska, Arkansas, Rhode Island, and Vermont
Kenneth Wiggers	American Radon Services,	Iowa
Mark Ternes	Oak Ridge National Lab	Northeastern States, and Oklahoma
Terry Sharp	Oak Ridge National Lab	North Carolina
Rose Girer-Wilson	University of Illinois	Illinois
Bill Levins	Oak Ridge National Lab	Northeastern States
Larry Palmiter &Tami Bond	Ecotope	Pacific Northwest
Bruce Wilcox	Berkeley Solar Group	California
Victor Espanosa	Las Angeles Dept. of Water & Power	California
Peter Strunk	Synertech	New York
Bob Carver, Bob Kelly	New York State ERDA	New York
Matson, Jump, Modera	Lawrence Berkeley Labs	California
Liddament et al.	Air Infiltration and Ventilation Centre	U.S. Wide

The data presented here represents a small fraction of the total air leakage measurements taken and it is hoped that further sources will be developed. While we have been contacted by individuals and organizations offering data sources, we are not now actively updating this database.

APPENDIX: LEAKAGE MODELING

Blower doors can generate sets of fan flow, house pressure pairs. Empirically, these data can be expressed as a power law[21]:

$$Q_f = \kappa P_f^n \tag{EQ 3}$$

For ease of use and understanding this two-parameter characterization of flow is reduced to the one-parameter characterization of the effective leakage area of an orifice:

$$Q_f = ELA \cdot \sqrt{\frac{2P_f}{\rho}} \tag{EQ 4}$$

If we assume that these two expression characterize the flow at some reference pressure, P_r, then we calculate ELA from the blower door data:

$$ELA = \kappa \cdot P_r^{n-1/2} \cdot \sqrt{\frac{\rho}{2}} \tag{EQ 5}$$

which leads to

$$Q_f = ELA \cdot \sqrt{\frac{2P_r}{\rho}} \cdot \left(\frac{P_f}{P_r}\right)^n . \tag{EQ 6}$$

While 10 Pa is sometimes used as the reference pressure in Canada, ASHRAE Standards and Handbooks normally use 4 Pa for the reference pressure. Accordingly, 4 Pa has been used as the reference pressure throughout this report.

The effective leakage area, *ELA*, quantifies the absolute size of the openings in the building and for the LBL infiltration model is determined by summing the respective component leakage areas of a specific building. A better measure of the relative tightness, however, is the normalized leakage as defined in ASHRAE Standard 119[3] as displayed in Equation 2. If we combine this expression with Equation 6 we find that for typical conditions found in a single-story situation ($\rho = 1.2\frac{\mathrm{kg}}{m^3}$; *n=2/3, H=2.5m)*:

$$NL = \frac{ACH_{50}}{20} \tag{EQ 7}$$

where ACH_{50} is the air leakage induced by a 50 Pascal pressure from blower door operation divided by the house volume.

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LIST OF SYMBOLS

A	stack coefficient [-]
A_f	building floor area [m^2]
ACH	air change rate (ach) [h^{-1}]
ACH_{50}	air change rate at 50 Pascals pressure difference (ach) [h^{-1}]
B	wind coefficient [-]
C'	generalized shielding coefficient [-]
C_p	heat capacity of air [1.022 kJ/kg-°K]
E	annual energy load [kJ]
ELA	effective leakage area [m^2]
f_s	stack factor [$(m/s)(°K)^{1/2}$]
f_w	wind factor [-]
g	gravity [9.8 m/s^2]
H	building height [m]
HI	inside enthalpy [kJ/kg]
HO	outside enthalpy [kJ/kg]
IDD	infiltration degree days [°C-day]
n	power-law exponent [-]
N	number of hours [h]
NL	normalized leakage area [-]
P	pressure [Pa]
Q	air flow rate [m^3/s]
R	fraction of total leakage area in the floor and ceiling [-]
s	specific infiltration [m/s]
s_o	average specific infiltration [0.71 m/s]
ΔT	inside-outside temperature difference [°C]
T_o	absolute temperature [298 °K]
κ	leakage coefficient [$m^3/s/Pa^n$]
v	measured wind speed [m/s]
X	difference in ceiling/floor fractional leakage area [-]
w	air change rate factor accounting for effect of local weather (m/s)*
ρ	density of air [1.2 kg/m^3]
[h]	indicates hourly value

*. Note that in ASHRAE Standard 136 the units are expressed in air changes per hour. For a single-story structure the conversion factor between ach and m/s is 1.44.