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Air-Tightness of U.S. Dwellings

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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 airtightness data is critical in order to answer the following kinds of questions: What is the Construction Quality of the Building Envelope? Where are the Air Leakage Pathways? How Tight is the Building? How Much Ventilation Does the Air Leakage Supply? How Much Energy Does the Air Leakage Loose in this Building Too Tight? Is this Building Too Loose? When Should Mechanical Ventilation be Considered? Tens of thousands of unique fan pressurization measurements have been made of U.S. dwellings over the past decade; LBL has recently been collecting available data into its air leakage database containing over 12000 measurements. This report uses that data to determine the leakage characteristics of the U.S. housing stock in terms of region, age, construction type and quality. Results indicate that US dwellings tend to be quite leaky without respect to climate.

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

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1 INTRODUCTION

Virtually all knowledge about the air tightness of buildings comes from field measurements of *fan pressurization* using *Blower Door* technology. Blower Doors measure air tightness which, in turn, is the prime building factor in determining infiltration and *air leakage*. This report summarizes the 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 referenced 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.

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.

2 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, leakage data is used in one form or another for infiltration-related modeling. Given such diverse uses, it is not surprising that this data is often treated as a stand-alone quantity, even though air leakage values are only 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 potential of Blower Doors began to become apparent. Blower Doors helped to uncover hidden *bypasses*[17] that account 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.[31]

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 system 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, which was found to be empirically valid but without theoretical substantiation (until recently[21]). Using orifice flow as a physical model, the Blower-Door data can be used to estimate the Effective Leakage Area (*ELA*).

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.[30]

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 specific 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.

3 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 of single-family detached dwellings from known locations in the U.S. In addition to air tightness data we required that the size of the dwelling and the number of stories 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.

Most of the data we used was not collected by the authors but was either published or volunteered by other researchers or practitioners. The largest sources of data consisted of 10800 houses from Alaska, Alabama, Vermont and Rhode Island, from Energy Rated

Homes of America. The largest *published* dataset used was the AIVC Leakage Database[19]. Those who volunteered published or unpublished data are listed in the "ACKNOWLDEGEMENTS" . We can summarize the dataset we have in a number of ways. Included in our database are 12946 individual measurements on over 12500 houses from the listed sources, including about 450 homes from the AIVC's numerical data base.

By its very nature the sample collected is not statistically representative of the almost 75 million single-family households in the U.S. Furthermore, different constituent datasets and measurements are of different qualities and should not be treated equally. Having said that, we must realize that this data represents the best set currently available 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. housing stock.

4 RESULTS

We analyzed the data first to determine some overall trends in the leakage dataset without regard for the building properties and then we looked to the relationship between the details of the building and its leakage. Table 1, "SUMMARY OF LEAKAGE MEASURMENTS," summarizes the overall content of the dataset and contains the year of construction, the size of the dwellings and several variables relating the leakage information.

TABLE 1. SUMMARY OF LEAKAGE MEASURMENTS

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

We can use the dataset to see if there is a useful correlation between the two ways of quantifying leakage. The average ratio[1] between ACH_{50} and NL is 17.5, with a standard deviation of 2.3, indicating that a 13% extra uncertainty can be introduced when converting directly between these two quantities. In general we will use Normalized Leakage rather than air changes at 50 Pascals to make our leakage comparisons.

The leakage values in Table 1 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. 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 average (i.e. 12%) value, but with a narrower distribution.

1. It should be noted that this ratio is only a relationship between to slightly different ways of summarizing airtightness and does not relate directly to Equation 1 for the calculation of infiltration.

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. We also looked at the general distribution of exponents and they appear quite clustered, even though there were many nonphysical outliers. The average exponent for the 1973 measurements that reported exponents is 0.65 with a standard deviation of 0.08

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 does not include from some states (i.e. Delaware, Florida, Hawaii, Kansas, Kentucky, Louisiana, Maryland, Michigan, Mississippi, Nebraska, New Jersey, New Mexico, North Dakota, Ohio, Pennsylvania, South Dakota, Tennessee, Texas, Utah, West Virginia, Wisconsin, and Wyoming) but breaks down as indicated in Table 2, "NORMALIZED LEAKAGE BY STATE," for the other states. The last line of the table includes data in which the exact state was unknown.

TABLE 2. 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. The se homes come from three studies in which the state was not identified: one in the New England (i.e. "*Northeast*". the other two from the Pacific Northwest and Iowa (i.e. "*Other*").

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.

4.1 Relationship to Building Properties

We examined the dataset in some detail to look at five building criteria that may impact leakage: number of stories; floor/basement type; thermal distribution system; retrofitting; and dwelling age. We discuss below the impact of each of these factors.

Number of Stories: Most of the U.S. Housing stock is one and two story, single-family dwellings. We looked at the entire dataset to determine if differences in construction type affects the leakage. Approximately 56% of our measurements are of multistory dwellings. We find that multistory houses are 11% leakier than single-story houses 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. The subset that did not was slightly (5%) tighter and this value was statistically significant.

Thermal Distribution System: Because of the current interest in the efficiency of residential thermal distributions systems, we analyzed those (1442) homes 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 (only about 130 homes), 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. 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).

Dwelling Age: We examined that data for which the 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. 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.

5 DISCUSSION AND 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 biases towards tighter housing, probably because more energy efficient houses have been studied in detail.

Unlike the impact of 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 construction.- Our previous study[28] had indicated that approximately half the U.S. would meet ASHRAE's airtightness standard[3]. This dataset, although not statistically representative, has less than 10% of the country meeting that standard-indicating that the stock may be leakier than previously estimated.

We examined the data subsets in many ways and looked at distributions of various quantities. In almost every distribution there were more outliers than would be expected from a normal distribution; some of them were nonphysical 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.

Table 2, "NORMALIZED LEAKAGE BY STATE," clearly indicates that more data is needed in certain areas of the country. Our future efforts will be to try to fill these data gaps and then use the kind of statistical techniques we have used before[28] to extrapolate the information to the country as a whole.

6 ACKNOWLDEGEMENTS

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. In addition to those listed below there are many individuals that have sent in data on

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

paper only, and have not been entered in as of this time. It is our intent to continue with the data entry as time permits, starting with areas of the country which are under-represented. The data presented here represents a small fraction of the measurements taken and it is hoped that further sources will be developed.

7 REFERENCES

1 -, Chapter 53. "Thermal Insulation and Airtightness Building Regulations", Royal Ministry of Local Government and Labour, Norway, 27 May, 1987.

2 ASHRAE Handbook of Fundamentals, Chapter 24, American Society of Heating, Refrigerating and Air conditioning Engineers 1989

3 ASHRAE Standard 119, Air Leakage Performance for Detached Single-Family Residential Buildings, American Society of Heating, Refrigerating and Air conditioning Engineers, 1988.

4 ASHRAE Standard 136, A Method of Determining Air Change Rates in Detached Dwellings, American Society of Heating, Refrigerating and Air conditioning Engineers, 1993.

5 ASTM Standard E779-87, "Test Method for Determining Air Leakage by Fan Pressurization", ASTM Book of Standards, American Society of Testing and Materials, Vol 04.07, 1991.

6 ASTM Standard E1186-87, "Practices for Air Leakage Site Detection in Building Envelopes", ASTM Book of Standards, American Society of Testing and Materials, Vol 04.07, 1991.

7 ASTM STP 1067, Air Change Rate and Airtightness in Buildings American Society of Testing and Materials, M.H. Sherman Ed., 1990

8 A. Blomsterberg, "Air Leakage in Dwellings", Dept. Bldg. Constr. Report No. 15, Swedish Royal Institute of Technology, 1977.

9 G.E. Caffey, "Residential Air Infiltration", *ASHRAE Trans*, V85(9) pp41-57, 1979

10 CGSB Standard 149, Determination of the Airtightness of Building Envelopes by Fan Depressurization Method, Canadian General Standards Board 1986

11 K. Colthorpe, "A Review of Building Airtightness and Ventilation Standards", TN 30, Air Infiltration and Ventilation Centre, UK, 1990

12 R.C. Diamond, J.B. Dickinson, R.D. Lipschutz, B. O"Regan, B. Schole, "The House Doctor's Manual:, Lawrence Berkeley Laboratory Report PUB-3017, 1982.

13 *Energy Design Update*, V.4 No. 4, N. Nissan Ed., 1985

14 *Home Energy*, pp. 25-37, V.11 No. 1, A.K. Meier Ed., 1994

15 D.T. Harrje, "Building Envelope Performance Testing," *ASHRAE J.*, p39-41, March 1981

16 D.T. Harrje, A. Blomsterberg, A. Persily, "Reduction of Air Infiltration Due to Window and Door Retrofits", CU/CEES Report 85, Princeton University, 1979

17 D.T. Harrje, G.S. Dutt, J.E. Beya, "Locating and Eliminating Obscure, but Major Energy Losses in Residential Housing," *ASHRAE Trans.* V85(II), pp521-534, 1979

18 D.T. Harrje, G.S. Dutt, "House Doctors Program: Retrofits in Existing Buildings," Proc. 2nd AIVC Conference, p.61-72, 1981.

19 M. Limb, "AIRGUIDE: Guide to the AIVC's Bibliographic Database," Air Infiltration and Ventilation Centre, AIC-TN-38-1992, 1992.

20 W.E. Murphy., D.G. Colliver, Piercy L.R., Repeatability and reproducibility of fan pressurization devices in measuring building air leakage, ASHRAE Trans. V 97(II), 1991.

21 M.H. Sherman, "A Power Law Formulation of Laminar Flow in Short Pipes," J Fluids Eng, Vol 114 No 4 pp 601-605, 1992

22 M.H. Sherman "Estimation of Infiltration from Leakage and Climate Indicators", *Energy and Buildings,* 1987

23 M.H. Sherman, "EXEGESIS OF PROPOSED ASHRAE STANDARD 119: Air Leakage Performance for Detached Single-Family Residential Buildings." Proc. BTECC/DOE Symposium on Guidelines for Air Infiltration, Ventilation, and Moisture Transfer, Fort Worth, TX, December 2-4, 1986. Lawrence Berkeley Laboratory Report No. LBL-21040, July 1986.

24 M.H. Sherman, "Infiltration Degree-Days: A Statistic for Infiltration-Related Climate," ASHRAE Trans. 92(II), 1986. Lawrence Berkeley Laboratory Report, LBL-19237, April 1986.

25 M.H. Sherman, D.T. Grimsrud, "The Measurement of Infiltration using Fan Pressurization and Weather Data" Proceedings, First International Air Infiltration Centre Conference, London, England. Lawrence Berkeley Laboratory Report, LBL-10852, October 1980.

26 M.H. Sherman, M.P. Modera, "Infiltration Using the LBL Infiltration Model." Special Technical Publication No. 904, Measured Air Leakage Performance of Buildings, pp. 325 - 347. ASTM, Philadelphia, PA, 1984; Lawrence Berkeley Laboratory

27 M.H. Sherman, L.E. Palmiter, "Uncertainties in Fan Pressurization Measurements. Special Technical Publication of ASTM, Air Flow Performance of Building Envelopes, Components and Systems, (In Press), LBL-32115 (1994)

28 M.H. Sherman, N.E. Matson, "Ventilation-Energy Liabilities in U.S. Dwellings, Proc. 14th AIVC Conference pp 23-41, 1993, LBL Report No. LBL-33890 (1994).

29 M.H. Sherman and D.J. Wilson, "Relating Actual and Effective Ventilation in Determining Indoor Air Quality." Building and Environment, 21(3/4), pp. 135-144, 1986. Lawrence Berkeley Report No. 20424.

30 M.H. Sherman, "The Use of Blower Door Data" Indoor Air, (In Press), 1994; Lawrence Berkeley Laboratory Report No. 35173.

31 R.C. Sonderegger, J.Y. Garnier, J.D. Dixon, "Computerized, Instrumented, Residential Audit (CIRA)" Lawrence Berkeley Lab Report No. PUB-425, 1981