LBNL-48671

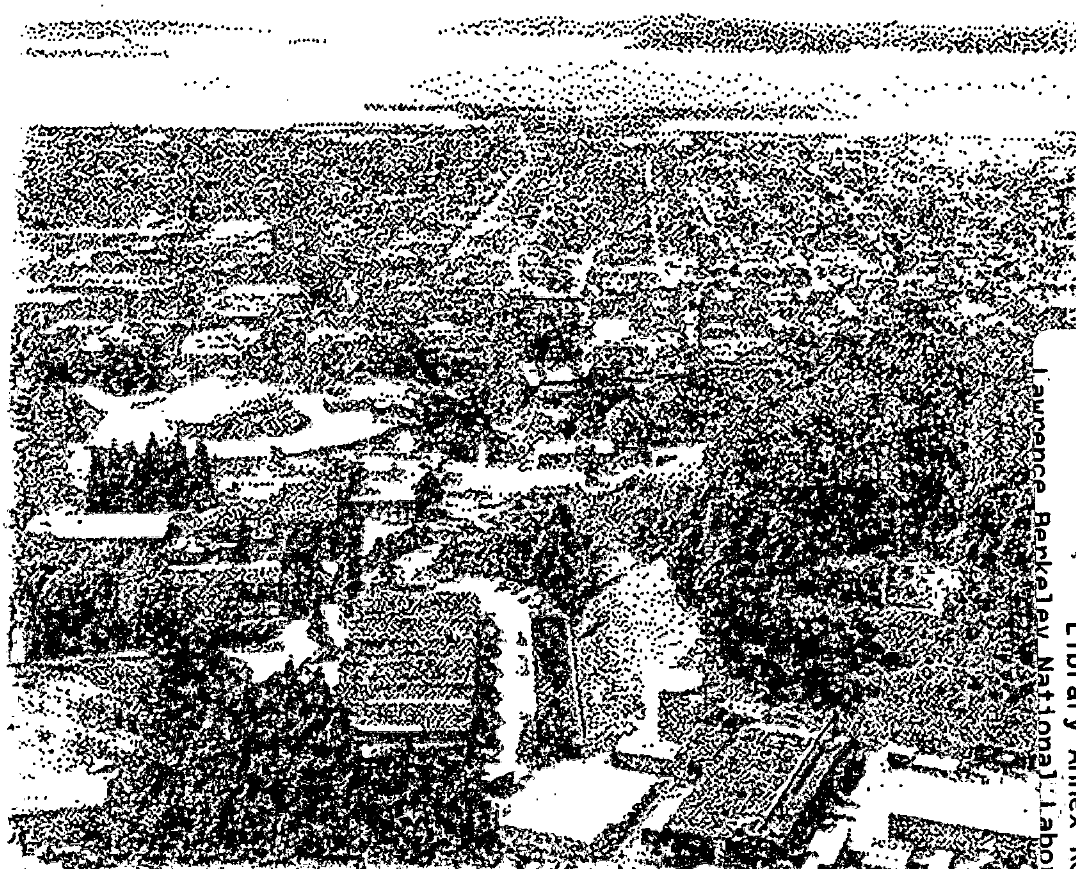
ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Air Tightness of New U.S. Houses: A Preliminary Report

Max H. Sherman and Nance E. Matson

Environmental Energy Technologies Division

March 2002



LBNL-48671

Air Tightness of New U.S. Houses:
A Preliminary Report

Max H. Sherman
Nance E. Matson

Environmental Energy Technologies Division
Energy Performance of Buildings Group
Indoor Environment Department
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

March 2002

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Air Tightness of New U.S. Houses:

A Preliminary Report

Max. H. Sherman
Nance. E. Matson
Environmental Energy Technologies Division
Energy Performance of Buildings Group
Indoor Environment Department
Lawrence Berkeley National Laboratory

ABSTRACT

Most 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. Consequently, quantification of envelope air-tightness is critical to determining how much energy is being lost through infiltration and how much infiltration is contributing toward ventilation requirements.

Envelope air tightness and air leakage can be determined from fan pressurization measurements with a blower door. Tens of thousands of unique fan pressurization measurements have been made of U.S. dwellings over the past decades. LBNL has collected the available data on residential infiltration into its Residential Diagnostics Database, with support from the U.S. Department of Energy. This report documents the envelope air leakage section of the LBNL database, with particular emphasis on new construction.

The work reported here is an update of similar efforts carried out a decade ago, which used available data largely focused on the housing stock, rather than on new construction. The current effort emphasizes shell tightness measurements made on houses soon after they are built. These newer data come from over two dozen datasets, including over 73,000 measurements spread throughout a majority of the U.S. Roughly one-third of the measurements are for houses identified as energy-efficient through participation in a government or utility program. As a result, the characteristics reported here provide a quantitative estimate of the impact that energy-efficiency programs have on envelope tightness in the US, as well as on trends in construction.

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

LBNL-48671

INTRODUCTION

Most of what we know about the air tightness of residences comes from field measurements using *fan pressurization* with blower door technology. Blower doors measure air tightness, or equivalently, the air leakage of the building envelope. Sherman (1995) reviewed the history of the blower door and how its results can be used. ASTM Standards such as E779 define the appropriate test method for using a blower door.

Air leakage data are 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 airflow, it is used in one form or another for infiltration-related modeling. Infiltration is the interaction of this envelope tightness with driving forces such as those caused by weather. Given such diverse uses, it is not surprising that it is often treated as a stand-alone quantity, even though air leakage is only an intermediate value.

Sherman and Dickerhoff (1994) have previously summarized the leakage of U.S. housing. Sherman and Matson (1997) based their analysis of residential ventilation rates and associated energy costs on those data. That dataset gave a good snapshot of the air tightness of U.S. building stock at the time it was taken, but the stock has changed in the intervening years. More importantly, that dataset under represents new construction. While such under representation does not materially impact conclusions for the stock of dwellings as a whole, it does not allow any conclusions to be drawn regarding newly built houses.

Beginning in the 1980s, concern for energy caused the energy efficiency of new houses to improve through a variety of regulatory and voluntary means. As dwellings became more air tight, the concern for new construction became whether new houses were too tight. Sherman and Matson (1997) investigated optimal tightness levels for the stock. Wray et al. (2000) have looked at how tightness levels would interact with proposed residential ventilation standards in the U.S.

The Lawrence Berkeley National Laboratory has an on-going activity to upgrade its database on the air leakage of dwellings. Data collection continues, and at the time of this writing, there are over 80,000 individual entries in the database. Only about a quarter of these data, however, has been vetted sufficiently for use in analyses. Since the purpose of this report is to summarize the current state of knowledge with particular emphasis on the air tightness of new construction, our data screening efforts have given priority to the screening of new construction.

LEAKAGE DATA

Very little of the leakage data used in this report was actually taken by the authors. Instead, others generated the vast majority of the data as part of a program for some other purpose. Not surprisingly, the data were not taken in any single uniform manner or using a single protocol. For the purposes of this study, all data were converted to the same set of variables. Some of the key parameters are listed below:

- *NL*, the Normalized Leakage[1] is the single most important variable as it is the primary leakage variable. It is defined as the total leakage [cm^2] normalized for dwelling size [m^2]. Methods for

[1] Roughly, the normalized leakage is 1/20 of the air changes at 50 Pascals pressure, but the defining relations can be found in ASHRAE Standard 119, in Sherman and Matson (1993), or in the references above.

converting from other leakage variables can be found in Sherman and Dickerhoff (1994) or other air leakage references. All entries must have sufficient data to calculate Normalized Leakage to be included in the database. This is the primary variable used to quantify leakage in this report.

- *n;* the pressure exponent from the power-law fit to the data is not always provided, nor can it always be calculated from the data provided. In such cases, the exponent is assumed to be 0.65. Because very few of the new house observations included measured exponent data, we will not consider the exponent further in this report.
- *A;* Floor Area [m^2] is the most basic size parameter, but volume and building height are also included. Often, at least one of them is calculated. The primary value of the floor area in this analysis is to normalize the blower door data to calculate the Normalized Leakage.
- Date of construction. For some datasets, especially in older dwellings, date of construction is poorly defined; for some others, it is not known at all. For all the data in this report, the date of construction is either known or can be inferred.
- Date of leakage test: Usually, but not always, the date of the leakage test is known. There may be more than one leakage test on the same house. The data for "new" houses include only leakage tests made during the year of construction or in the following year.

The Normalized Leakage for the approximately 22,000 data points considered in this report averaged NL=1.18. The standard deviation [0.81], however, was almost as big as the mean. Figure 1 is a histogram of all of these data points.

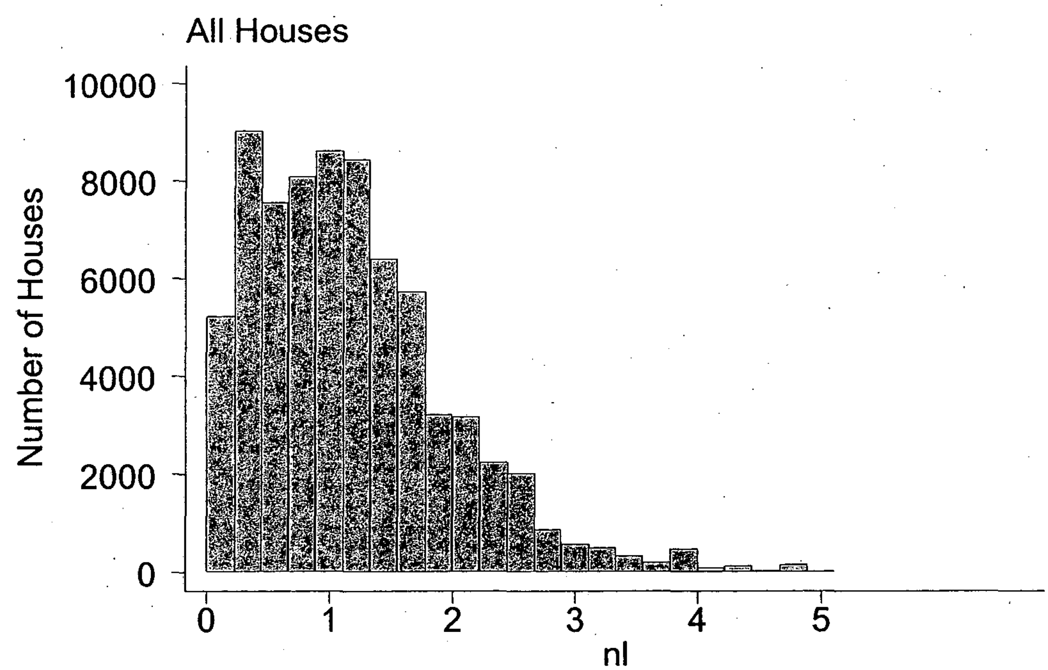


FIGURE 1: Distribution of Normalized Leakage (NL) for approximately 22,000 measured houses currently in LBL Database. Mean is 1.18.

A detailed examination of these data shows that there appear to be two distributions superimposed. There is a narrow distribution of tight houses and a broad distribution of leaky houses. As we shall see below, these two distributions resolve into new vs. existing houses.

For the purposes of this report, we are using the term "new" to mean that the tightness of the house was measured when new. The house could have been built in any year, but if it was tested in that or the following year, we label it as "*new*". Approximately 8,700 of the houses in our dataset of over 73,000 qualify as new by this definition. Table 1 gives a breakdown of the location of our data within the U.S.

Table 1: Location of measured leakage data used in this report

State	Existing Houses	New Conventional	New Energy-Efficient
Alabama	30		
Alaska	3264		4437 (AKWarm)
Arizona	22	98	374
Arkansas	430		
California	380	93	6
Colorado	9	41	79
Connecticut	7	13	7
Florida	267	72	468
Georgia	7	1	8
Idaho	65		5
Illinois	258		165
Indiana			
Iowa			
Kansas			305
Maine	1		
Massachusetts	2	13	164
Michigan		4	
Minnesota	48	1	107
Missouri	10		2
Montana			
Nebraska	5	24	
Nevada	30		198
New Hampshire	1		11
New York	236		
North Carolina	112	60	57
Ohio	5,137	405	70
Oklahoma	108		25
Oregon	60		
Pennsylvania			6
Rhode Island	4299	3	21
South Carolina		6	8
Texas	96	16	101
Utah		17	
Vermont	1061		823
Virginia			
Washington	141		
Wisconsin	1820	301	113
Unknown	280	1	4
Total	**64,366**	**1,169**	**7,564**

If we separate out the new houses, the remaining dataset for existing houses has an average leakage of NL=1.3 and is spread out quite broadly. Although it includes data for different existing houses, the general size and shape of the distribution remains consistent with that reported by Sherman and Dickerhoff (1994).

RESULTS FOR NEW CONSTRUCTION

The distribution of new houses is quite different from that of existing construction. The average leakage of the new houses in this dataset is NL=0.30, with a standard deviation of 0.25. The ACH50 (i.e. Air Changes at 50 Pascals of pressure) of 5 that this represents would be considered leaky for Northern Europe, but is quite an improvement in the U.S. Figure 2 is the histogram of all the new houses in our dataset and displays this effect.

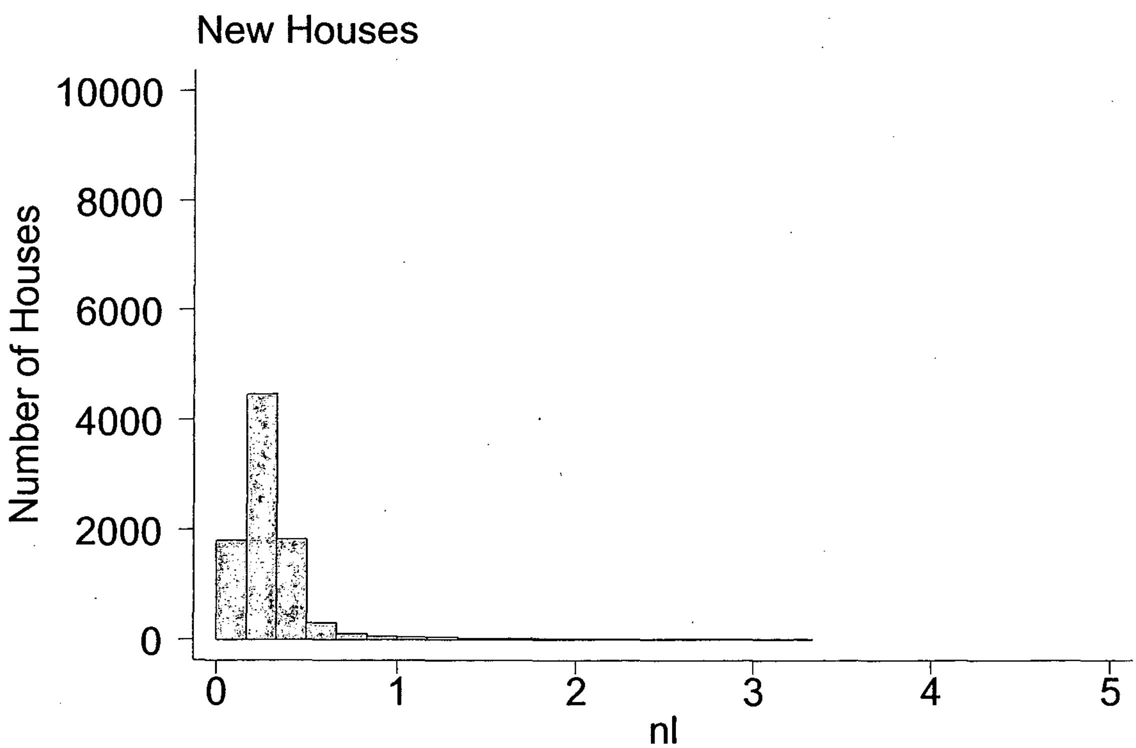


FIGURE 2: Distribution of Normalized Leakage (NL) for approximately 8,300 *new* houses currently in LBL Database. Mean is 0.30.

Energy-Efficiency Programs

Energy-efficiency programs have had a major impact on reducing the overall energy requirements of new construction, but it is not clear how they have impacted air tightness. Few programs in the United States require that specific leakage performance targets be met. It is much more common for programs to have prescriptive requirements for caulking, weather-stripping, etc. One objective of this paper is to determine the impact of these programs.

To evaluate this effect, we have broken up the new home dataset into three broad categories:

- *Conventional:* Conventional houses are ones that were not built as part of any energy-efficiency program. Most of them were measured as part of some voluntary program. Many of the builders knew that their houses would be tested, but no special energy efficiency features were installed. Approximately 1,200 houses fall into this category.

- *Energy Efficient.* There are many federal, state, and local programs that try to attract leading edge builders to demonstrate improved construction techniques for new homes. In this type of program, resources are provided to builders to help them improve the energy efficiency of their new homes with the hope that techniques will find their way from these early adopters to main-stream builders. Approximately 3100, (non-Alaskan houses) fall into this category and mostly come from either the *Energy Star* or *Building America* programs.

- *AKWarm*: Approximately 7,500 new houses were identified as energy efficient, but most of them come from a single program of a single state, the *AKWarm* program in Alaska. We have, therefore, separated out this dataset, not only because of climate,.but because it is quite possible that a large broad-based program could behave quite different from other programs that may try to focus more on early adopters. There are approximately 4,400 houses in the AKWarm category.

The summary of this analysis in included in Table 2 below:

Table 2: Breakdown of Leakage for New Construction Programs

Program	Normalized Leakage (NL)	Standard Deviation
Conventional	0.55	0.55
Energy Efficient	0.31	0.13
AKWarm	0.23	0.10

As one might expect, the energy-efficient programs produced tighter houses. The conventional houses came out significantly leakier and with a lot more spread. The large standard deviation came not from individual house-to-house variation, but from regional differences. The spread between regions is larger than within regions. For example, the houses tested in Wisconsin were a factor of two tighter than the rest of the dataset and in a relatively narrow range. Although identified as conventional houses, they were tighter than most of the houses in our energy-efficient category.

If we apply ASHRAE Standards 136-93 and 62-99 to these tightness levels, we can calculate the contribution that infiltration makes towards meeting ventilation requirements for new construction. Taking any of these categories, we find that very few meet the requirements using infiltration alone. Some houses in the more extreme climates come close; for most of the rest, it appears that infiltration can make up only about half the ventilation requirements. Certainly some of the leakiest new houses (e.g. in Ohio) have a larger fraction of their ventilation made up from infiltration.

Trends over Time

Because our definition of "new" has nothing to do with today's date, but only the test date and the construction date, our dataset contains "new" houses that were built over a broad time period. This allows us to see how the air tightness of new construction has changed over time. Figure 3 is a trend plot for all houses constructed since 1993, showing both the means and standard deviations for each year.

It appears that there may have been a trend toward tighter houses that bottomed out around 1997. The data suggests that the trend toward tighter envelope construction may be over and that it has reached steady state. Further improvements in air tightness, if desired, would require new kinds of programs. The trend may also partially be an artifact of the changing make-up of each year's dataset. If the composition were statistically representative, it would not be an issue, but since it in not, we do not know how robust this trend is until further analysis is done to deal with statistical issues.

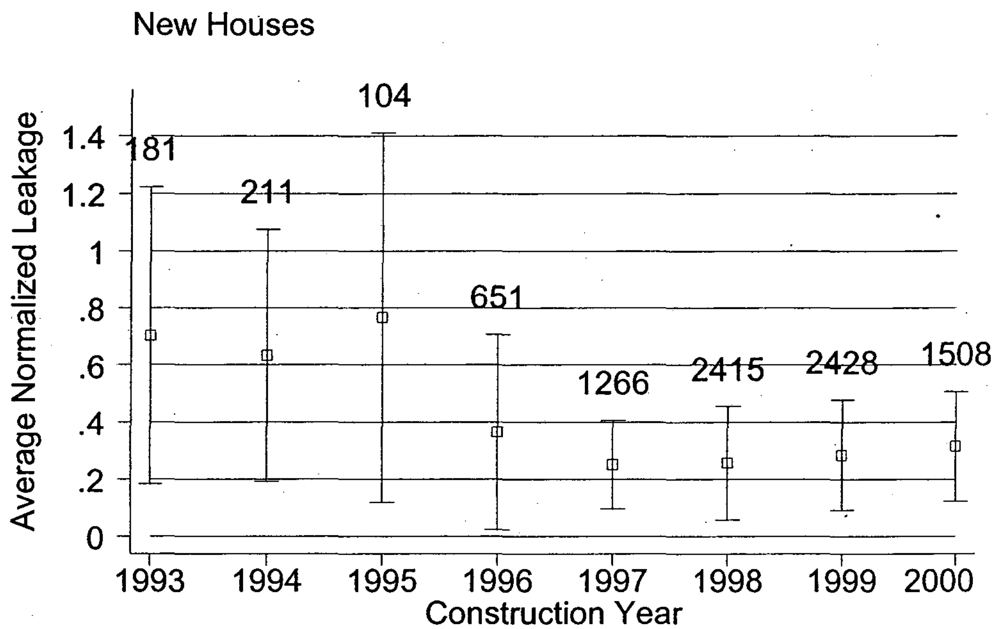


FIGURE 3: Normalized Leakage for new houses by year of construction. Size of bars indicates the standard deviation of the sample for each year. Numbers above bars indicate sample size.

It is instructive to look more deeply at these trends to separate out what is happening to conventional houses and what is happening as part of energy-efficiency programs. Figure 4 is a similar trend plot for only the conventional houses.

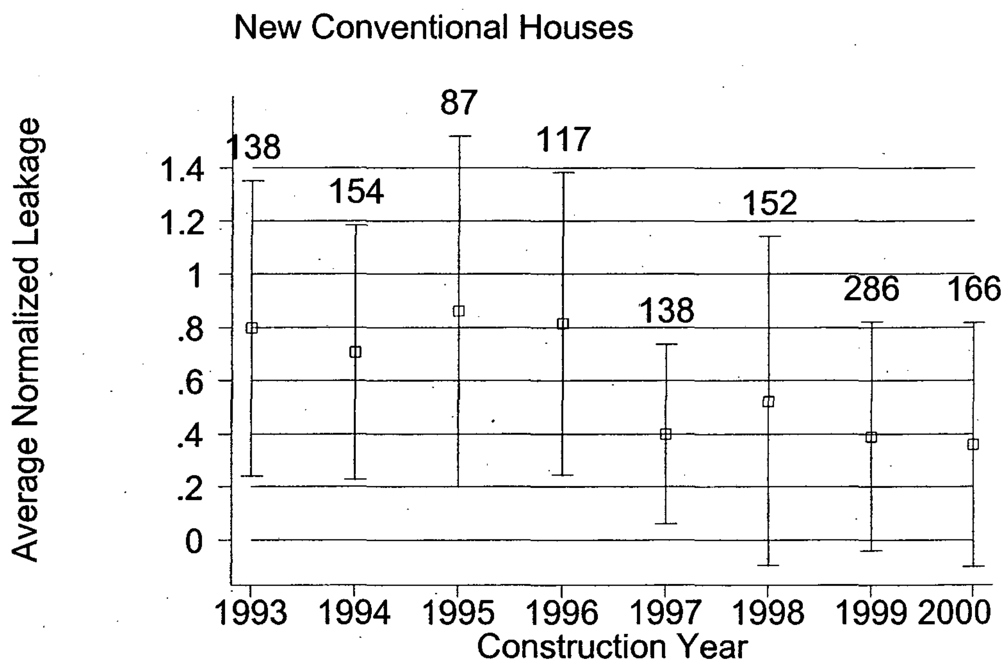
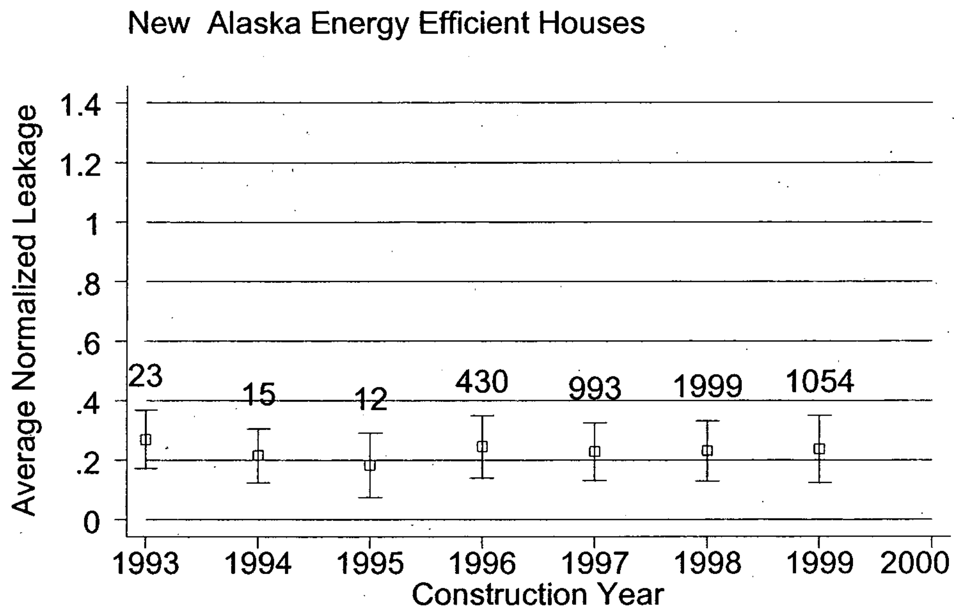


FIGURE 4: Normalized Leakage for conventional new houses by year of construction. Size of bars indicates the standard deviation of the sample for each year. Numbers above bars indicate sample size.

In the eight years studied there seems to be a breakpoint in the middle. Those houses built before 1997 appear significantly leakier than those built after 1996. Within each of those two blocks, however, there are no significant trends. The large variation is due in major part to the year-to-year changes in the regional distribution of houses.

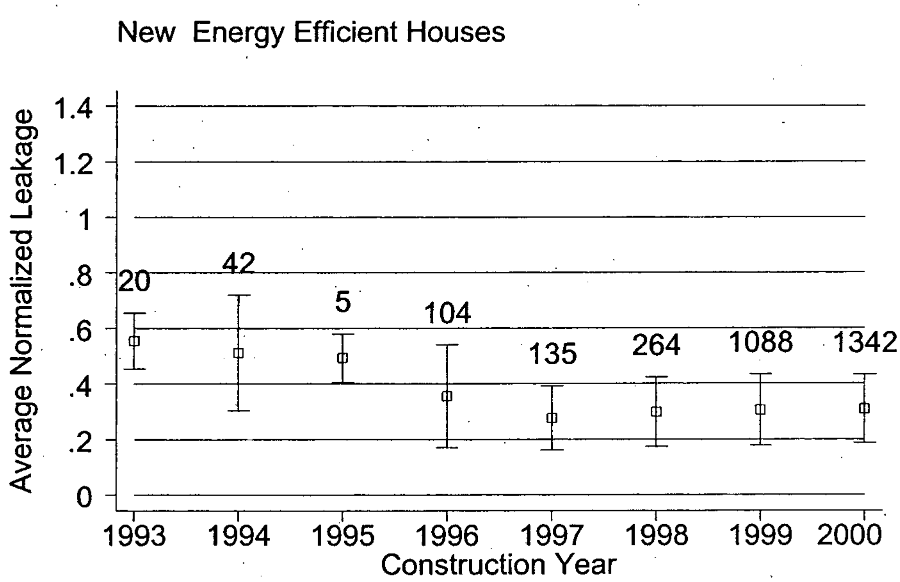
FIGURE 5: Normalized Leakage for new, energy efficient houses by year of construction. Size of bars indicates the standard deviation of the sample for each year. Numbers above bars indicate sample size



By contrast, the AKWarm houses (Figure 5) do not show either a trend with construction year or large variations within or between years, suggesting that once builders learn to build to a new norm, they can continue to reproduce the concept faithfully.

Figure 6 shows the trend line for new energy efficient construction. Because the data comes from different regions, it has a larger standard deviation than the AKWarm data, but a smaller one than the conventional new construction, indicating more consistency than in construction.

FIGURE 6: Normalized Leakage for new, energy efficient houses by year of construction. Size of bars indicates the standard deviation of the sample for each year. Numbers above bars indicate sample size



In Figures 3-6 the error bars are the standard deviation of the data. To see if the error is significant, it is more proper to consider the error of the mean, which is smaller by roughly the square root of the number of observations.

For all of the post 1996 data in figures 3,5 and 6, the error of the mean was less than 0.01 thus indicating that the differences in the mean were significantly different from year to year. For the rest of the data the error of the mean is roughly the size of the year-to-year variation in the mean (0.02-0.07). It is clear for our data that houses got tighter until about 1997 and that the tightness did not significantly change after that year.

DISCUSSION AND CONCLUSIONS

Sherman and Matson (1997) estimated average NL of the U.S. stock to be about 1.2. The data in this study corroborates that finding, but more importantly, demonstrates that new construction is significantly tighter than the stock as a whole. Both this study and the previous one have used data coming from a variety of sources, published and unpublished, with different objectives and standards, making statistical significance of the results difficult to estimate. While some trends appear robust, detailed conclusions based on the data, should be regarded as preliminary.

Sherman (1999) evaluated how air leakage could contribute to meeting the residential ventilation standard currently being proposed by ASHRAE, and found that air leakage alone is rarely sufficient to meet minimum ventilation standards in houses having a normalized leakage less than 0.5. Our recent interpretation of the data suggest that most new houses in the U.S. need some form of additional ventilation. Natural ventilation, passive ventilation, and mechanical ventilation can all be used effectively in some situations to meet minimum requirements.

Our data also suggest that the air tightness of new construction is no longer improving. Builders made a step change of improvement at some time in the past. While this level of air tightness is insufficient to meet ventilation requirements alone, there are still energy-savings opportunities available through further tightening. Making additional improvements requires looking at the house as a system, since air leakage can either be a positive or negative contributor[2] to a designed ventilation system.

Energy efficient programs have probably reduced the air tightness of new construction, but many "conventional" housing samples are tighter than many "energy efficient" ones. One clear benefit of the energy-efficient programs, however, is that they have improved the consistency in new construction, which can be seen from the reduced scatter in the plots. This bolsters the concept that education and training is an important factor in achieving improved construction quality.

The AKWarm houses appear to be substantially tighter than other energy-efficient houses. Given the severe climate in Alaska, it is not unreasonable to expect a greater sensitivity to air leakage issues. Some of this difference, however, may be due to different construction and operating practices used there. For example, it is not uncommon for attached garages to be fully part of the conditioned area of the house and to have tight fitting doors to outside. Because of the way NL is normalized, the addition of the garage area to the total house floor area would reduce the normalized leakage.

The conclusions of this study are subject to revision as the size of our usable database increases. This non-representative sample can allow us to draw conclusions, but still could contain bias errors that are not easily visible. The authors are continuing to collect data and to process those data into a form suitable for the database.

Future efforts will focus on analysis of the data for existing houses and on the use of statistical techniques to extrapolate the data over the U.S. housing stock to explore more closely the energy impacts associated with residential ventilation.

[2] The topic of how air leakage and infiltration impact total ventilation is too extensive an issue to discuss in this report. Many of the references cited discuss it in more detail. Other references can be found in AIRBASE at http://www.aivc.org

ACKNOWLEDGMENTS

The authors acknowledge the contributions of leakage and related data made by individuals and organizations. The authors also thank Jennifer McWilliams her help in the collation and organization of the data. The authors would also like to thank the contributors listed below for allow us to use their data in this report:

Advanced Energy Corporation; Alaska Housing Finance Corporation; Arkansas Energy Office; Building Science Corporation; Building America; Building Industry Institute; Conservation Services Group; Davis Energy Group; Rob DeKieffer; E-Star Colorado; Geoff Feiler (Sitka, Ak); Florida Solar Energy Center; Guaranteed Wattsavers; Kansas Energy-Star; Lawrence Berkeley Laboratory; Ohio Home Energy Rating System; Vermont Energy Investment Corporation / Energy Rated Homes of Vermont; Daran Wastchak, L.L.C.; Wisconsin Energy Conservation Corporation / Wisconsin Energy Star Homes.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Research and Development, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES AND BIBLIOGRAPHY

ASHRAE Handbook of Fundamentals, Chapter 26, American Society of Heating, Refrigerating and Air conditioning Engineers, 2001.

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

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

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

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

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

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

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.

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

M.H. Sherman, "A Power Law Formulation of Laminar Flow in Short Pipes," Journal of Fluids Engineering, Volume 114, No. 4, pp 601-605, 1992.

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

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

M.H. Sherman, "The Use of Blower-Door Data," *Indoor Air*, Volume 5, pp. 215-224,1995 [LBL- 35173]

M.H. Sherman, "Indoor Air Quality For Residential Buildings," *ASHRAE Journal,* Volume 41 *(5),* pp. 26-30; May 1999. [Lawrence Berkeley Laboratory Report No. LBL-42975]

M.H Sherman, D.J. Dickerhoff, "Air Tightness of U.S. Dwellings," Proceedings, 15th Air Infiltration and Ventilation Centre Conference, Buxton, UK, 1994. [LBL-35700]

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.

M.H. Sherman, H. Levin, "Renewables in Ventilation and Indoor Air Quality" in Renewable Energy, Energy Efficiency and the Environment (World Renewable Energy Conf. 1996), *Renewable Energy,* Volume I, pp. 236-240, Pergamon, 1996. [Report No. LBL-38258]

M.H. Sherman, N.E Matson, "Residential Ventilation and Energy Characteristics," *ASHRAE Transactions, Volume 103(1),* pp. 717-730, 1997. [LBNL-39036]

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.

M.H. Sherman, L.E. Palmiter, "Uncertainties in Fan Pressurization Measurements," Air Flow Performance of Building Envelopes, Components and Systems, Philadelphia, American Society for Testing and Materials (STP 1255), Modera & Persily, Editors, pp. 262-283, 1994. LBL-32115

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

M.H. Sherman, N.E. Matson, "Residential Ventilation and Energy Characteristics," ASHRAE Transactions 1997. LBL Report No. LBL-39036.

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.

C.P. Wray, N.E. Matson, M.H. Sherman, "Selecting Whole-House Ventilation Strategies to Meet Proposed ASHRAE Standard 62.2: Energy Cost Considerations," *ASHRAE Transactions,* Volume 106 (II), 2000; Report No. LBNL-44479.

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098