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AIR TIGHTNESS OF US HOMES: MODEL DEVELOPMENT

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Air Tightness of US Homes: Model Development[1]

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ABSTRACT

Air tightness is an important property of building envelopes. It is a key factor in determining infiltration and related wall-performance properties such as indoor air quality, maintainability and moisture balance. Air leakage in U.S. houses consumes roughly 1/3 of the HVAC energy but provides most of the ventilation used to control IAQ. The Lawrence Berkeley National Laboratory has been gathering residential air leakage data from many sources and now has a database of more than 100,000 raw measurements. This paper uses that database to develop a model for estimating air leakage as a function of climate, building age, floor area, building height, floor type, energy-efficiency and low-income designations. The model developed can be used to estimate the leakage distribution of populations of houses.

KEYWORDS: Air leakage; airtightness; fan pressurization; leakage area

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INTRODUCTION

Air leakage through the building envelope contributes to ventilation, heating and cooling costs and moisture migration. Understanding the magnitude of the leakage in an individual envelope is important in optimizing the HVAC system and in retrofitting. Understanding the magnitude of leakage in the building stock is important for prioritizing both research efforts and conservation measures for policy makers in both the public and private sector.

The Lawrence Berkeley National Laboratory (LBNL) has gathered air leakage data from homes all over the United States. The database contains more than 100,000 individual measurements of residential envelope leakage. The purpose of this article is to use this data to develop a descriptive model of residential air leakage as a function of house characteristics.

AIR TIGHTNESS BACKGROUND

"Air Tightness" is the property of building envelopes most important to understanding ventilation. It is quantified in a variety of ways all of which typically go under the label of "air leakage". Air tightness is important from a variety of perspectives, but most of them relate to the fact that air tightness is the fundamental building property that impacts infiltration. There are a variety of definitions of infiltration, but fundamentally infiltration is the movement of air through leaks, cracks, or other adventitious openings in the building envelope.

The modeling of infiltration (and thus ventilation) is a separate topic, but almost all infiltration models require a measure of air tightness as a starting point. While the magnitude of infiltration depends on the pressures across the building envelope, the air tightness does not, making air tightness a quantity worth knowing in its own right for such reasons as stock characterization, modeling assumptions or construction quality.

In buildings with designed ventilation systems, especially those with heat recovery, air tightness may be a determining factor in the performance of that system. For example unbalanced ventilation systems such as exhaust fans require that make-up air come through building leaks. Overly leaky or overly tight buildings could reduce the effectiveness of such systems.

When poor air tightness allows air to be drawn in from contaminated areas, indoor air quality can be reduced even though total ventilation may be increased. These contaminated areas could be attics, crawlspaces or even the outdoors. Sometimes the building envelope itself may be a source of contamination because of mold or toxic materials.

Moisture is a special class of contaminant because it commonly exists in both liquid and vapor form and is a limiting factor in the growth of molds and fungus. Poor air tightness that allows damp air to come in contact with cool surfaces is quite likely to lead to the growth of microbiologicals. In cold climates poor air tightness can lead to the formation of ice in and on exterior envelope components.

Often the most noticeable impact of poor air tightness is draft and noise. Tight buildings provide increased comfort levels to the occupants, which in turn can have impacts on energy use and acceptability of the indoor environment.

More extensive information on air tightness can be found in Sherman and Chan (2003), who review the state of the art. This information is also part of a broader state of the art review on ventilation compiled by Santamouris and Wouters (2005).

AIR LEAKAGE MEASUREMENT

While there are other methods, the principal technique used for measuring the airtightness of a building envelope is called “fan pressurization.” The fan pressurization technique has been around a long time and there are many standard test methods that describe its use, such as ASTM (2002, 2004), CAN/CGSB (1986) and ISO (1996). The basic technique involves measuring the steady-state flow through the fan necessary to maintain a steady pressure across the building envelope.

The first level reporting of this data is generally the same for all of the testing methods. One reports the pressure and volumetric flow at whatever measurement stations were chosen. If necessary, the raw readings from the equipment may need to be corrected for zero offsets, temperature, altitude etc. Such corrections are standard experimental practice, but will depend on the details of the apparatus and experimental layout.

What distinguishes the different test methods and protocols derived from them is the analyses of the pressure-flow data. The simplest protocol and the one that is used most often is to measure air leakageat a single pressure. The pressure chosen is conventionally high enough to overpower pressure noise and zero drifts caused by wind or stack effects. Thus it is reasonably precise and therefore reproducible. The simplicity of a single-point measurement and its reproducibility are why it is the most popular measurement.

Unfortunately, the flow at high pressure is not the quantity of interest if one is trying to understand what envelope air flows are under natural driving pressures, which are much lower. To have an accurate estimate of air tightness is it necessary to determine it at normal pressures. Furthermore, higher pressures can induce non-linear effects such as valving that would not be relevant for normal pressures.

Depending on the metric chosen such reference pressures would be in the 1-4 Pa range, but because these pressures are the size of the natural pressure variations, it is very difficult to get a precise measurement of air flow. One must sacrifice precision to get accuracy or must sacrifice accuracy to get precision.

In order to mitigate these errors, many test methods require that the flow be measured over a range of pressures and then extrapolated to the reference pressure of interest using a power law relationship. Because of the non-linearities of the power-law and the biases that can be associated with pressure measurements, care must be taken not to introduce unnecessary errors into the data analysis. Modera and Wilson (1990) looked at the impact that wind pressure variations have on the analysis of pressurization data and methods to mitigate them using pressure averaging.

Sherman and Palmiter (1995) have examined the errors associated with analyzing fan pressurization data including precision, bias and modeling errors. They examined the overall uncertainty for a variety of analysis strategies and recommended optimal strategies for selecting instrumentation and pressure stations.

NORMALIZED LEAKAGE

Sherman and Chan (2003) discuss the topic of metrics, reference pressures and one vs. two parameter descriptions in some detail. Among the metrics they consider, we have chosen to use the metric of Normalized Leakage (NL) as defined by ASHRAE (1988, 2005) as our primary metric:

Eq. 1. $$NL = 1000 \cdot \frac{ELA}{Area} \cdot \left(N_{story}\right)^{0.3}$$

(See NOMENCLATURE for definitions.)

AIR LEAKAGE DATA

The LBNL air leakage database has more than 100,000 entries, but it is quite far from being a statistically representative sample of any kind. While LBNL made some of the measurements in the database, the vast majority of the data is data voluntarily shared with LBNL from various public or private programs. Furthermore each data source used different measurement protocols, had different acceptance criteria and focused on their own particular objectives. Previous analyses using this data have been done by Sherman and Matson (2001) for new construction and by Chan (2003) for the dataset as a whole. All of the U.S. data described by Sherman and Chan (2003) are included in this database. This database as used in this analysis has some additional measurements, but those additions are not likely sufficient to make qualitative changes in the earlier conclusions.

Not all of the entries in the database are going to be useful in this analysis. For example, some of the entries do not have sufficient information to determine the Normalized Leakage (e.g. they do not have floor area). Some programs measure or identify certain building properties (e.g. age) and other do not; some fields have impossible values that cannot be accepted or fixed. All told there were approximately 93000 usable data points.

If we attempt to understand the dependence of Normalized Leakage on a parameter that only exists in a subset of the data, we will be limiting ourselves to that subset of the data. Because that subset comes from distinct programs, it may well be biased compared to the sample as a whole. We must use analyses techniques that minimize the impact that such biases could have.

he largest single subset of the data comes from the Ohio Weatherization Program (OWP) and represents over half our total dataset. These 50,000 data points also represent all of the data we have on low-income homes. Because of these facts, we separate these data out and use them only for generating parameters related to low-income housing.

Of the remaining measurements we define a core dataset. This dataset is the subset that has information on all of the following parameters: leakage, floor area, building height, location and whether or not it is an energy-efficient home. The latter parameter is both self reported and imputed. That is, if the home is identified in any way as being an energy-efficient home (e.g. EnergyStar) then it is treated as such. If it is not identified, it is presumed not to be. The distribution of the core data over the U.S. can be found in figure 1

There are approximately 43,000 entries in the core dataset. There are subsets of the core data where additional parameters are known. There are a variety of such additional parameters. In particular there are about 10,000 data points were the age of the building was known when tested and about 5,000 data points where the presence or absence of floor leakage is known.

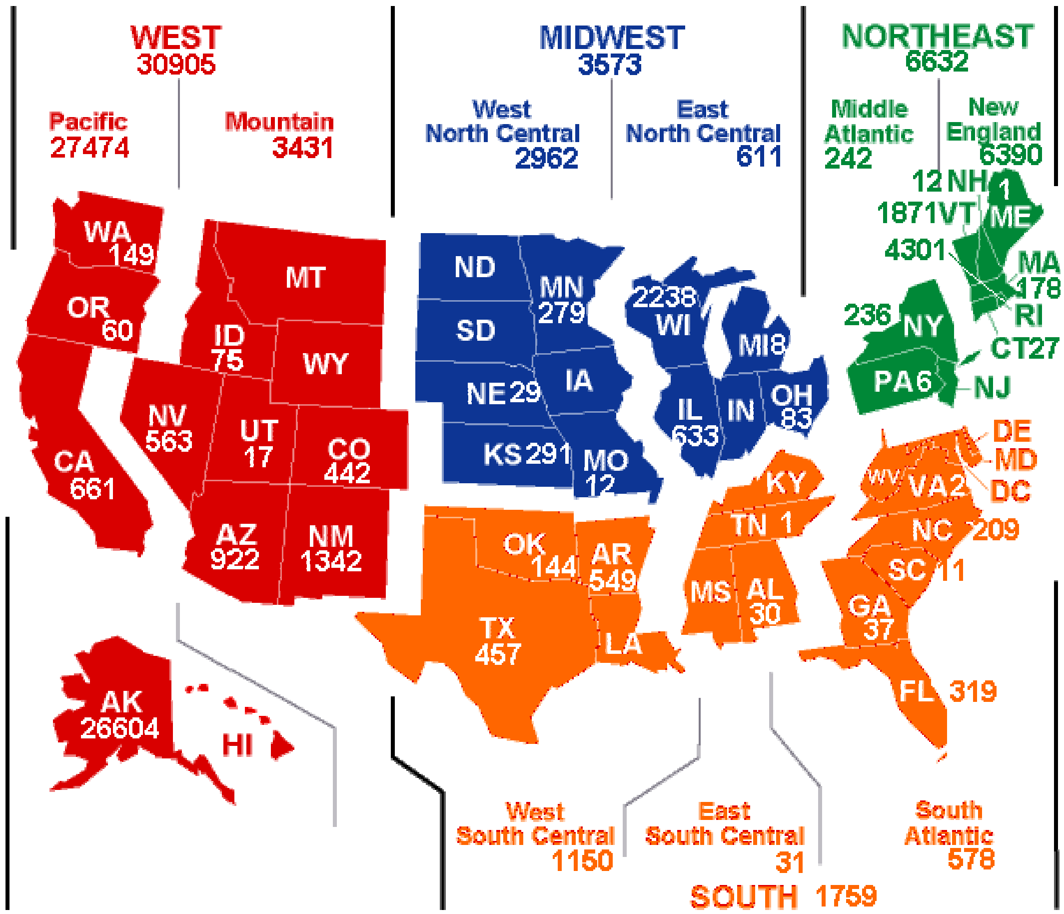

Fig. 1: Geographic Distribution of Leakage Measurements in the LBNL database excluding the data from the Ohio Weatherization Program

MODEL DEVELOPMENT

Our objective is to use the data in the database to create a predictive model that can be used to estimate the air tightness of a house based on certain physical characteristics. While we use regression techniques to achieve this objective, it is a different use of regression compared to finding the best fit to the data in the database. This distinction is not terribly important if the data we have is an unbiased sample of the population of all houses, but that may not be the case.

McWilliams and Jung (2006) have examined various regression approaches to analyzing this data and some associated problems. The development below follows their results, but will be presented without extensive justification. Their original work should be consulted for more detailed explanations. The model coming out of that work for non-low-income houses is as follows:

Eq. 2. $$NL = NL_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\varepsilon}^{p_{Eff}} \cdot \phi_{Age}^{Age} \cdot \phi_{Floor}^{p_{Floor}}$$

The functional form of equation 2 was chosen by assuming that leakage is distributed in a log-normal manner. This assumption is the simplest one for a positive definite quantity such as leakage and is empirically observed to be roughly true as can be seen, for example, in Sherman and Dickerhoff (1998) and McWilliams and Jung (2006). This form neglects interactions between the different factors, which as shown later can cause biases.

CORE ANALYSIS

The determination of the coefficients in Eq. 2 must be done in stages. In the first stage the entire core dataset is used to fit only those parameters that are in all of the core data (i.e. the equation above without the last two factors.)

Eq. 3. $$NL = NL'_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\varepsilon}^{p_{Eff}}$$

Where P_{Eff} is unity if it is an energy-efficient house and zero otherwise. Note also that the climate zone coefficient in the core fit is a different numerical value than in our target equation because of the offsets due to the additional terms. This effect will be included below, but for a more detailed discussion see McWilliams and Jung (2006).

The coefficients for area, height and efficiency programs are determined to be 0.841, 1.156 and 0.598 respectively. From the regression we estimate the error of an individual prediction would be roughly 1/2 (55%) of the mean prediction.

AGE AND FLOOR TYPE COEFFICIENTS

To infer an additional parameter we use only that subset of the data that has that parameter and do a secondary regression for just that parameter. For the age coefficient this would be of the form

Eq. 4. $$\frac{NL}{NL'_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\varepsilon}^{p_{Eff}}} = \phi_{Age}^{Age} \big/ \phi'_{Age}$$

Where only the two parameters on the right are being fitted.

This procedure is then repeated for the floor leakage variable. The primed coefficients can then be combined to find the normalized leakage coefficient for each climate zone. The values of the age and floor coefficients are 1.0118 and 1.08 respectively

CLIMATE ZONES

It seems self-evident that houses built in different parts of the country and hence different climates will have different air tightness. Indeed, if one looks at simple averages one can see such differences. It is not, however, clear whether such differences are caused by differences in construction quality, differences in house style or materials, or differences in size or age.

If one uses size, height, age and energy efficiency status, it is possible to fit the data in our database reasonably well without an explicit climate variation, but that does not mean there is no climate variation. Chan (2003) did not find climate to be a significant variable. The apparent lack of a climate variation could be due to the fact size, height, age and efficiency status tend to vary regionally—as does climate. In such a case the parameters are correlated rather than independent and it becomes a practical choice as to which parameters to use. Because including climate both makes physical sense and does somewhat improve the fit, we have elected to keep the climate variables.

Figure 1 breaks up the U.S. by region, but these regions are not directly related to climate and therefore may not be the best choice for climate zones. The ICC (2004) defines 17 climate zones for the purposes of code compliance. Since these zones are based on climate, they make a reasonable starting point, unfortunately, that would be more independent zones than could be supported by the data in database.

Examining trends in the data and the differences within regions, we believe that the most functional approach is to use four climate zones: dry, humid, cold and Alaska. Alaska was separated out from the rest of the cold climate data due to the fact that there were clear qualitative differences, most likely due to substantially different construction and operation techniques in Alaska compared to the rest of the U.S.

The four climate zones can otherwise be described as groupings of the 17 ICC climate zones. Those definitions as well as their values are included in Table 1:

TABLE 1: NORMALIZED LEAKAGE COEFFICIENTS BY CLIMATE

CLIMATE ZONE	NL_{cz}	DEFINITION
Alaska	0.36	All climates in Alaska
Cold	0.53	ICC Climate zones 5 and higher w/o Alaska
Humid	0.35	ICC Climate zones 1A, 2A, 3A, 4A
Dry	0.61	All other climate zones

LOW-INCOME

Because we did not include any data known to be from a low-income household, the model so far does not represent low-income housing and needs to be extended using data known to come from low-income housing. The largest subset of the data in the database comes from low-income households and we can use that data to find out how air tightness differs in low-income houses from middle and upper-income households.

We use a similar procedure to estimate the coefficients associated with low-income housing using only the low-income data:

Eq. 5.
$$\frac{NL}{NL'_{cz}\cdot\phi_{Area}^{size-1}\cdot\phi_{Height}^{N_{story}-1}\cdot\phi_{\varepsilon}^{p_{Eff}}}=\phi_{LI}\cdot\phi_{LI,Age}^{Age}\cdot\phi_{LI,Area}^{size-1}$$

The three new coefficients, ϕ_{LI}, $\phi_{LI,Age}$, and $\phi_{LI,Area}$ represent differentials specific to low-income housing. The values of these coefficients are 2.45, 0.9942 and 0.775 respectively.

DISCUSSION

Putting the model together leads to the following complete expression:

Eq. 6. $$NL = NL_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\varepsilon}^{p_{Eff}} \cdot \phi_{Age}^{Age} \cdot \phi_{Floor}^{p_{Floor}} \cdot \left(\phi_{LI,Age}^{Age} \cdot \phi_{LI,Area}^{size-1} \cdot \phi_{LI}\right)^{P_{LI}}$$

Where P_{LI} is unity for a low-income house and zero otherwise. This, similar to all of the "P" parameters, can be treated in the model as either the probability of being true or as a fraction of the sample for which it is true.

Although this model can be applied to an individual house, it is important to understand the limitations of doing so. The regression tells us that this model is able to explain about one half of the variation in the data using these dozen parameters. The original reference describes the statistics in more detail.

From a statistical viewpoint explaining half the variation in over 93,000 data points with only a dozen parameters is quite good. It suggests that most of the important parameters have been captured. There is, however, still quite a bit of variation in making an individual prediction. The mean-squared error in the regression was roughly 50% of the mean, indicating that an individual prediction has at least this much scatter in it.

Nevertheless we expect the trends and differences indicated the model to be generally followed. The model predictions become more robust when estimating the mean impact on groups of houses compared with an individual house.

CLIMATES

The Normalized Leakage coefficients for the four climate zones, $NL_{cz,}$ represent the average normalized leakage for a house in the reference condition. The reference condition is when all of the exponents are zero, which means a 100 m^2 (1000 ft^2), single-story, non-energy efficient, unaged, slab-on-grade, non-low-income house.

There is not a huge range in direct climate differences with the tightest climate being 57% of the leakiest. It is not a surprise that the dry climate is the leakiest or that Alaska is the tightest, but it is somewhat surprising that the humid zone is as tight as Alaska. Alaska has twelve times as many measurements in the database as does the humid zone—which has the smallest number of measurements associated with it of any of the four zones. While there could be regional differences in construction accounting for this difference, unusual distributions of age, area, etc. could also be responsible for making the humid zone appear to have tighter homes than the other three zones.

These coefficients for the climate zones should not be treated as average or representative values—only reference values. To find the average leakage of homes one needs to use the model with an understanding of the distribution of houses. Such an analysis is beyond the scope of this paper.

INTERPRETATION OF MODEL COEFFICIENTS

The Normalized Leakage coefficients describe the leakage of a reference house, the rest of the parameters are used to adjust the reference house to match the condition of interest. We can examine these additional coefficients further:

HEIGHT

The height coefficient is 1.15. That means that—all other things being equal—adding one story of height (but not changing the total floor area) of a house increases the normalized leakage by 15%. This effect embodies not just a simple height scaling (such as that included in the definition of NL), but the fact that multistory houses may be constructed differently than single-story ones and that the inter-floor leakage paths could be significant.

AREA

As the area of the house goes up the normalized leakage goes down. At first this may seem counter-intuitive, but it is not. The total leakage area (i.e. ELA as opposed to NL) still goes up with increased area. The normalized leakage going down with increased area is exactly the effect one would expect from the fact that the surface-to-volume ratio is going down with increased area.

AGE

As one would expect houses generally get leakier as they age. Our results show that it happens at an average rate of somewhat over one percent per year. We have made the simplest assumption (i.e. that the rate is constant), but there are no physical reasons to support that. For example, first few years of a house's existence may be different than the rest. Given that we do not have measurements on a single house from very different times, it is difficult to separate changes in technology from aging. This coefficient was developed to describe the stock as a whole; the issue of new houses is discussed in more detail in a later section.

FLOOR LEAKAGE

Houses with floor leaks (e.g. vented crawlspaces) do appear to be leakier than those without (e.g. slab-on-grade) floor leaks. The size of the difference, however, is only eight percent suggesting that there are some compensating leakage paths in those houses which do not have floor leaks. The small value is not significant in making a prediction of a single house, but could be when trying to find the average of a specific populations.

EFFICIENCY PROGRAM

This coefficient was intended to describe the impact that energy efficiency programs have on building air tightness. The value of it, however, is so far from unity that it suggests something more is going on.

The value of the efficiency program parameter suggests that energy efficient houses are 40% tighter than those that are not. Sherman and Dickerhoff (1998) showed that it was more typical in existing buildings for retrofits to achieve 25% tightening. Sherman and Matson (2001) showed an equally small differential in new construction between conventional and energy efficient houses. This issue will be developed further in a following section.

LOW INCOME PARAMETERS

There are three parameters that are used to describe the difference between low-income and other houses. The main low-income coefficient is a simple multiplier and it indicates that low income houses are over a factor of two leakier than the reference house. This effect is partially offset by the other two low-income parameters that only tend to make the house relatively tighter than the reference.

AREA

There is a separate area-related coefficient for low-income. It has the same effect as that in the core set so that low-income houses get relatively tighter with increased floor area.

AGE

The age-related parameter for low-income is also paired with one in the core, but those two have opposing effects. The two of them come close to canceling each other.

The data suggests that while low-income houses are leakier than others, the total leakage area is not very dependent on either age or floor area. One could speculate that this could be due to low-income houses becoming leakier very quickly with age and then stabilizing. Such a result is constant with our result that low-income homes are leakier than conventional, but age less.

NEW HOUSES

New houses represent a rather special subset of the building stock. Because changes in new construction are usually much cheaper and easier to make, new houses get a disproportionate emphasis compared to their roughly 2% share of the stock. New houses have new technologies in them that could make them qualitatively different from existing houses.

For those same reasons, the properties of new houses may not be easily extrapolated from the properties of the stock as a whole. For example, it could be that the leakage of relatively new houses is substantially smaller but degrades faster than older houses. McWilliams and Jung (2006) did not investigate this issue, perhaps because of the difficulty in doing so with the existing data and because of the need to have multiple measurements over time on the same house.

There is some indirect evidence to support a qualitative difference for new construction compared to the rest of the stock in the database and it comes from looking at the energy efficiency coefficient. Less than 10% of the existing houses in the database were considered to be "energy efficient." This could be due to an increase in new home programs and also to a relatively smaller amount of efficient retrofit programs; in any case this coefficient is correlated with age and thus to a large degree a surrogate for new construction. Any future work on the database should consider this issue.

Since all new houses eventually become existing houses, the model developed here is probably quite robust for looking at the stock of buildings, but the arguments in this section suggest it may not be an appropriate model for looking at new construction. Analyses, such as Sherman and Matson (2001) that evaluate only "new" house data and do not conflate it with existing house data are superior for looking at new construction. We do not recommend that the model developed herein be used to look at new construction by setting the Age parameter to zero.

CONCLUSIONS

We have developed a model to estimate the envelope air leakage of houses in the United States. The model is as follows:

Eq. 7. $$NL = NL_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\varepsilon}^{p_{Eff}} \cdot \phi_{Age}^{Age} \cdot \phi_{Floor}^{p_{Floor}} \cdot \left(\phi_{LI,Age}^{Age} \cdot \phi_{LI,Area}^{size-1} \cdot \phi_{LI}\right)^{P_{LI}}$$

Where the model parameters have been found from regression:

TABLE 2: Values of Model Parameters

NL_{Alaska}	0.36	ϕ_{Height}	1.156	ϕ_{Floor}	1.08
NL_{Cold}	0.53	ϕ_{ε}	0.598	ϕ_{LI}	2.45
NL_{Humid}	0.35	ϕ_{Age}	1.0118	$\phi_{LI,Age}$	0.9942
NL_{Dry}	0.61	ϕ_{Area}	0.841	$\phi_{LI,Area}$	0.775

This model is based on a biased dataset, but should provide accurate leakage estimates when applied to broad enough spectrum of houses. Although the uncertainty of an individual prediction is estimated to be on the order of 50%, larger biases may be present when the narrow samples are used. For example, this model is expected to be biased high for conventional new construction.

As seen from Figure 1, many areas of the country are under-represented. It is not known whether this under-representation causes bias errors, but efforts should be made to fill in the gaps in the database to determine the sizes of such biases and to improve the model. Other data gaps can be identified from McWilliams and Jung (2006).

This model is ideally suited for estimating regional air leakage averages from the statistical properties of the housing stock. It is anticipated that future efforts will use data such as that available from the U.S. Census or from Residential Energy Conservation Surveys as input to the model in much the same way as Sherman and Matson (1997) did.

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NOMENCLATURE

Age	Age of house (yr)
Area	floor area inside the pressure boundary (m^2) [ft^2]
ELA	Effective Leakage Area as measured by ASTM E779 or equivalent (m^2) [ft^2]
N_{story}	height of the building above grade divided by the height of a single story (-)
NL	Normalized Leakage (-)
NL_{cz}	Normalized Leakage coefficient for each climate zone (-)
size	Floor area divided by the reference area of ($100m^2$) [$1000\ ft^2$]
ϕ	Model coefficient (-) for property indicated by subscript
P	Probability (-) Is zero if it does not have property indicated by subscript; is unity if it does.
Subscripts:	
Eff	Designates Energy-Efficient construction
Floor	Floor leakage possibility (e.g. vented crawlspace)
Height	Height of house above grade
LI	Designates Low-income