

INTERNATIONAL ENERGY AGENCY  
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community systems programme

**Air Leakage of U.S. Homes:  
Model Prediction**

Max Sherman and Jennifer McWilliams

**Contributed Report 11**



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### **Acknowledgement**

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## **Foreword by the AIVC**

Air tightness and air infiltration has been since the creation of the AIC (Air Infiltration Centre) in 1979 a major topic of concern. Air tightness is a key factor in determining infiltration and related wall-performance properties such as indoor air quality, maintainability and moisture balance.

In US houses, air leakage consumes roughly 1/3 of the HVAC energy but at the same time provides most of the ventilation used to control IAQ.

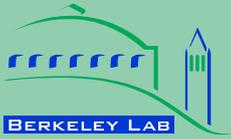
The Lawrence Berkeley National Laboratory has been gathering residential air leakage data from many sources and now has a database of more than 100 000 raw measurements. This paper uses a model developed from that database in conjunction with US Census Bureau data for estimating air leakage as a function of location throughout the US.

The results indicate that the vast majority of the residential US building stock has effective air change rates above 0.35 air changer per hour and therefore gets sufficient ventilation from infiltrations when looked at on an annual basis.

This kind of analysis can help to select which regions may be particularly good candidates for saving energy through air tightening, such as through weatherization programs.



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# Air Leakage of U.S. Homes: Model Prediction

Max Sherman and Jennifer McWilliams

January 2007

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# AIR LEAKAGE OF US HOMES: MODEL PREDICTION

**Max Sherman and Jennifer McWilliams**

January, 2007

## **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 a model developed from that database in conjunction with US Census Bureau data for estimating air leakage as a function of location throughout the US.

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## List of Symbols

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 ( $m^2$ ) [ $ft^2$ ]
$N_{\text{story}}$	height of the building above grade divided by the height of a single story (-)
NL	Normalized Leakage (-)
$NL_{\text{cz}}$	Normalized Leakage coefficient for each climate zone (-)
size	Floor area divided by the reference area of ( $100m^2$ ) [ $1000 ft^2$ ]
$\phi$	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

For equations 3-10:

$A_C$	= leakage area in the ceiling plane [ $m^2$ ]
$A_F$	= leakage area in the floor plane [ $m^2$ ]
$A_o$	= total leakage area of the structure [ $m^2$ ]
C	= wind shielding class parameter
Q	is the airflow [ $m^3/s$ ]
A,B	= terrain parameters
h	= height of structure [m]
$T_o$	= inside temperature [295 K]
g	= acceleration of gravity [ $9.8m/s^2$ ]
$l_i$	= air change rate in the $i^{\text{th}}$ time step
$\Delta t$	= length of each discrete time period [s]

## **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 retrofiting. 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 database has been used to develop a descriptive model of residential air leakage as a function of house characteristics. The purpose of this study is to predict ventilation of houses in each county across the United States using publicly available data.

“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) requires a measure of air tightness as a starting point. 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).

Sherman and Chan (2003) also discuss the topic of metrics, reference pressures and one versus two parameter descriptions in some detail and will not be discussed here. We have chosen to use the metric of Normalized Leakage (NL) as defined by ASHRAE Standard 119 (1988, 2005) as our primary metric to describe air tightness of houses because it removes the influence of house size and height.

$$NL = 1000 \cdot \frac{ELA}{Area} \cdot (N_{story})^{0.3} \quad (1)$$

By such a normalization, this metric allows us to compare the leakiness of different house independent of size.

## **Modeling Methods**

This study consisted of two parts: 1) developing a regression model from the leakage data, and 2) applying that model to existing data of housing stock characteristics to come up with leakage characteristics for the United States housing stock. The regression model is documented in other papers (e.g., McWilliams and Jung (2006)). This paper will focus on the application of that model to predict envelope leakage.

The first step in the prediction is to use the model to calculate the leakage area for each county using publicly available data. Once the leakage area is known, we calculate the airflow through the building envelope for every hour of the year using the LBL model (Sherman, 1980) with hourly temperature and wind speed data. The flow is converted to an air change rate by dividing by the volume of the house, and the air change rate can be related to ventilation effectiveness using the Sherman Wilson model (Sherman and Wilson, 1986)

## **Leakage Model**

McWilliams and Jung (2006) used the data in the LBL air leakage database to create a predictive model that can be used to estimate the air tightness of a house based on certain physical characteristics. Their model is shown in equation (2) and the values of the parameters are shown in Table 1. The parameters, which are all dimensionless, were determined by regression analysis.

$$NL = NL_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_{\epsilon}^{P_{Eff}} \cdot \phi_{Age}^{Age} \cdot \phi_{Floor}^{P_{Floor}} \cdot \left( \phi_{LI, Age}^{Age} \cdot \phi_{LI, Area}^{size-1} \cdot \phi_{LI} \right)^{P_{LI}} \quad (2)$$

**Table 1: Values of Model Parameters**

NL <sub>cz</sub>	Value	Parameter	Value	Parameter	Value
NL <sub>Alaska</sub>	0.36	$\phi_{\text{Height}}$	1.156	$\phi_{\text{Floor}}$	1.08
NL <sub>Cold</sub>	0.53	$\phi_{\epsilon}$	0.598	$\phi_{\text{LI}}$	2.45
NL <sub>Humid</sub>	0.35	$\phi_{\text{Age}}$	1.0118	$\phi_{\text{LI, Age}}$	0.9942
NL <sub>Dry</sub>	0.61	$\phi_{\text{Area}}$	0.841	$\phi_{\text{LI, Area}}$	0.775

All of the “P” parameters ( $P_{\text{LI}}$ ,  $P_{\text{Floor}}$  and  $P_{\text{Eff}}$ ), can be treated in the model as either the probability of being true or as a fraction of the (large) sample for which it is true.  $P_{\text{LI}}$  is unity for a low-income house and zero otherwise.  $P_{\text{Eff}}$  is unity if the house has participated in an energy efficiency program and zero otherwise.  $P_{\text{Floor}}$  is unity if the house has any air leakage through the floor plane and zero if there is no air leakage through that pathway.

The Normalized Leakage coefficients for the four climate zones, NL<sub>cz</sub>, 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<sup>2</sup>, single-story, non-energy efficient, unaged, slab-on-grade, non-low-income house.

The climate zones are based on combinations of those defined by Building Science Corporation as shown in Figure 1. The climates that were used in the model were Humid (made up of Mixed-Humid and Hot-Humid), Dry (made up of Marine, Mixed-Dry and Hot-Dry), Alaska (containing all counties in Alaska), and Cold (all counties in Cold, Very Cold and Subarctic that are not in Alaska). The climate coefficients for Humid and Alaska are similar and substantially lower than the coefficients for the Dry and Cold areas.

This model is based on a limited 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, because of increasing improvements made to envelope air tightness in recent years.

Many areas of the country are under-represented in the database. 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.

**Figure 1: Climate Zones Defined by Building Science Corporation**

## Ventilation Model

The LBL ventilation model, shown in Equations (3) through (8), estimates flow through the building shell,  $Q(t)$ , based on the leakage area of the shell, wind and stack factors, and TMY weather conditions at the house site. The ventilation was calculated for each hour in a typical meteorological year.

$$Q(t) = (ELA) \cdot s(t) \quad (3)$$

where

$$s(t) = \sqrt{f_s^2 \cdot \Delta T + f_w^2 \cdot v^2} \quad (4)$$

$$f_s = \left( \frac{1 + \frac{R}{2}}{3} \right) \left( 1 - \frac{x^2}{2 - R^2} \right)^{3/2} \left( \frac{g \cdot h}{T_o} \right)^{1/2} \quad (5)$$

$$f_w = C(1 - R)^{1/3} A \left( \frac{h}{10} \right)^B \quad (6)$$

$$X = \frac{A_C - A_F}{A_o} \quad (7)$$

$$R = \frac{A_C + A_F}{A_o} \quad (8)$$

## Stochastic Method

A stochastic simulation method was used in the predictive calculation to produce a distribution of calculated building properties using input distributions of floor area, height, age, foundation type, energy efficiency improvements, and resident income for houses in each of the 3141 United States counties. The stochastic simulation allows the estimation of the mean and standard distribution for each of the calculated properties, namely equivalent leakage area (ELA), and the wind and stack parameters,  $f_w$  and  $f_s$  respectively.

For each county, we simulated data for 2000 houses by drawing each of the variables independently from a known distribution for that county. The sample size of 2000 was determined to be sufficient because the distribution did not become better defined when a sample twice as large was used. NL was calculated for each simulated house, and was then transformed into ELA since this is the input variable that is needed to calculate ventilation air flow,  $Q$ , in the ventilation model.

## Ventilation Effectiveness using the Sherman Wilson model

Because ventilation removes pollutants from indoor air, a measure of indoor air quality could be the temporal average of the instantaneous ventilation rate. However, since pollutant concentration is non-linear with respect to ventilation rate a simple average cannot be used. Instead, the term effective ventilation is defined as the steady state ventilation that would yield the same average pollutant concentration over some time period as the actual time varying ventilation in that same time period. It is important to note that the contaminant source strength must be constant over the period of interest. This holds for many building contaminants where the source emission varies slowly with time or operates in a stepwise fashion, and is unaffected by ventilation rate. Some important exceptions are radon, formaldehyde, and carbon monoxide where the emission rate can be affected by the ventilation of the building. In such cases, more detailed techniques may be required.

Effective ventilation is often calculated by first calculating the inverse, the characteristic time ( $\tau_c$ ) for the pollutant concentration to reach steady state, which is given by Equation (9).

$$\tau_{e,i} = \frac{1 - e^{-I_i \Delta t}}{I_i} + \tau_{e,i-1} \cdot e^{-I_i \Delta t} \quad (9)$$

The mean ventilation efficiency is a non-dimensional quantity which is defined as the ratio of the mean effective ventilation to the mean instantaneous ventilation. It is shown in terms of the characteristic time in Equation (10). The closer the actual ventilation rate is to steady state over the period of interest the higher the ventilation efficiency will be.

$$\varepsilon_m = \frac{1}{I \cdot \tau_e} \quad (10)$$

## **Data Sources**

The data used for this project came from several different sources. The house characteristics gathered from publicly available data are: location, floor area, age, height of the structure, whether the house participated in an energy efficiency program, the existence of leakage at the floor level, and the income status of the residents. (See McWillimans and Jung (2006) for more details.) The houses in each county represent a distribution of each of the above variables. We assume in this analysis that each of the variables is independent, although this may not be exactly true. For example, it may be that taller houses tend to have a higher probability of floor leakage, but the data for correlation between most of the variables was unavailable and for simplicity we assumed that they are all independent.

### **RECS data**

The Residential Energy Consumption Survey (U.S.D.O.E., 2001) was conducted by the Energy Information Administration for the U.S. Department of Energy, and is a statistically significant representation of the U.S. housing stock as it pertains to energy. The RECS data consists of approximately 4,800 single-family dwelling observations, each of which has approximately 900 reported survey values on topics of building characteristics, resident information, appliances and energy consumption. RECS data is summarized to the census division level so we use Census data which is summarized to the county level wherever possible.

The data of interest to this study that we obtain from RECS are “Total Floor space” (which can be linked to our *size* variable) and “Number of rooms” used to calculate the average floor space per room, “Number of Stories” used to calculate house height, “Foundation/Basement of Single-Family Homes and Apartments in Buildings” used to determine the existence of floor leaks, and “Income Relative to Poverty Line” used in the determination of the income status of residents. Data for two variables, house height and existence of floor leaks, were collected exclusively from RECS data. Two other variables, floor area and existence of low income residents, used a combination of RECS and Census 2000 data.

### **Census data**

Census data is collected by the U.S. Census Bureau every 10 years. Census 2000 data was used to extract information for: floor area, age, the existence of low income residents for houses in each county across the U.S., and number of rooms given in nine bins of number of rooms per house.

### **Weather data**

The weather data was derived from WYEC (Weather Year for Energy Calculations), TMY (Typical Meteorological Year), TRY (Typical Reference Year), and CTZ (California Climate Zones) weather files. For each county, the most representative weather location was chosen, based primarily on geography. Each weather file contains outside temperature and humidity, wind speed and direction and barometric pressure.

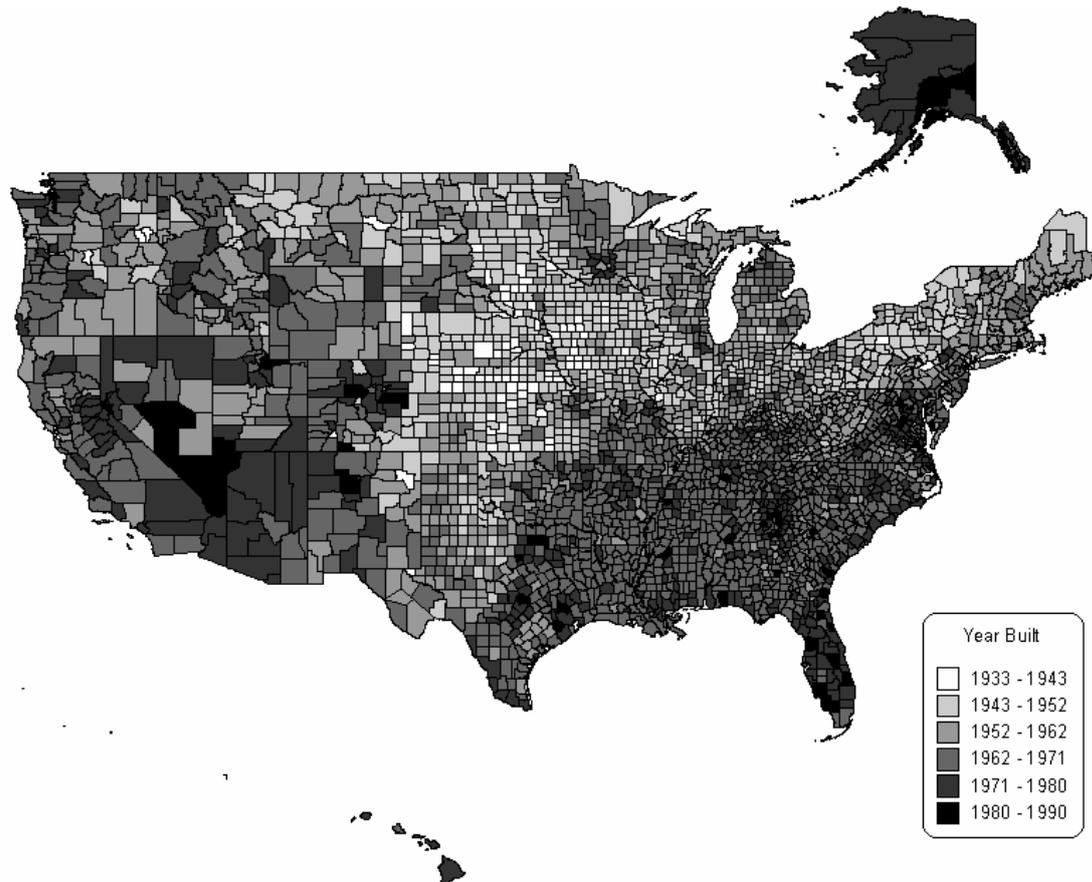
## **Characteristics of the U. S. Housing Stock**

In the figures below we will examine the variation in specific stock characteristics on a regional or county-by-county basis. Each county will be represented by a single value, which is the best estimate of the mean for that county. There is, of course, a distribution around this mean in the stock, but we addressing the distribution of each variable in each country was beyond the scope of this study. Regional variation, however, can sometime be inferred by the county-to-county variation.

First it is useful to look at the spatial distribution of our input data since irregularities in the input data may be recognizable in the calculation output. Most of the data was given not as a single value for each county, but as a distribution with a percentage of houses falling into data bins predefined for each variable. What has been plotted on the following figures is the mean value for the variable in each county.

The Census data was the most detailed, giving data for each county in the US. The year houses were built in each county was given directly in the Census data and needed no additional manipulation for use in the model, but did not go beyond 1990. Figure 2 shows that houses in the Northeast and Midwest were built prior to 1950 for the most part, while houses in the Southeast and Southwest were mostly built after 1960.

**Figure 2: Average Year Houses Were Built in Each County**



Data were also gathered from the Residential Energy Consumption Survey (RECS), which was not available on as fine a scale as the census data. The smallest subdivision for this data was the nine census divisions. The regional divisions are visible in Figure 3 and Figure 4, showing dwelling height and the probability of floor leaks respectively. The Northeast and Midwest have the tallest dwellings whereas the shortest dwellings are located in the south and west.

The probability of floor leakage is based on foundation type, which was given in the RECS data in three categories: basement, crawlspace or slab on grade. Slab on grade foundations are assigned a leakage probability of 0 because there are no leakage pathways through the slab. Crawlspace foundations were assigned a leakage probability of 1 because there are numerous leakage pathways through penetrations in the floor so we can be fairly sure that there will be some air leakage through these pathways. Conditioned basements, like slab on grade foundations, are assigned a leakage value of 0. Unconditioned basements, like crawlspaces, are assigned a leakage value of 1. Conditioned basements were not separated from unconditioned basements in the RECS data so we assumed half the basements were conditioned and half were unconditioned yielding a leakage probability of 0.5 for the basement foundation category.

The mean probability was calculated in each county, and is shown in Figure 4. The highest probability of floor leakage is found in the region consisting of Mississippi, Alabama, Tennessee and Kentucky showing that crawlspace foundations are popular there. The lowest probability of floor leakage is found in the region just next door, containing Texas, Louisiana, Oklahoma and Arkansas where slab on grade foundations are common.

Figure 3: Mean Dwelling Height in Meters by County

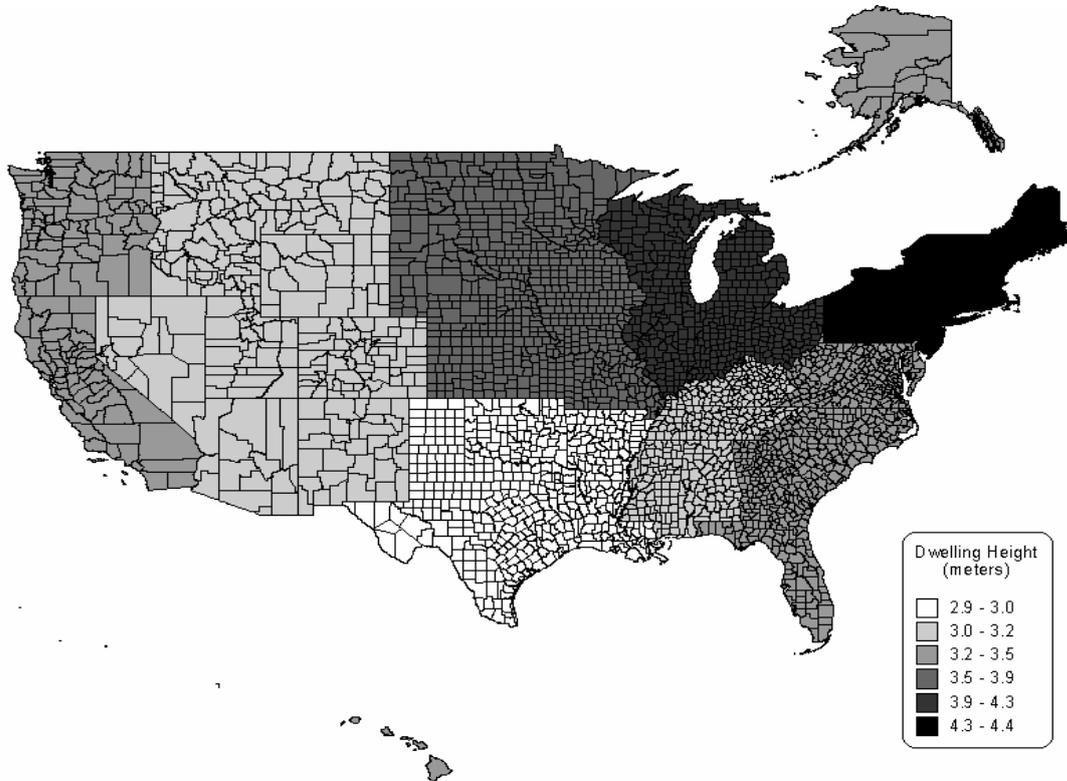
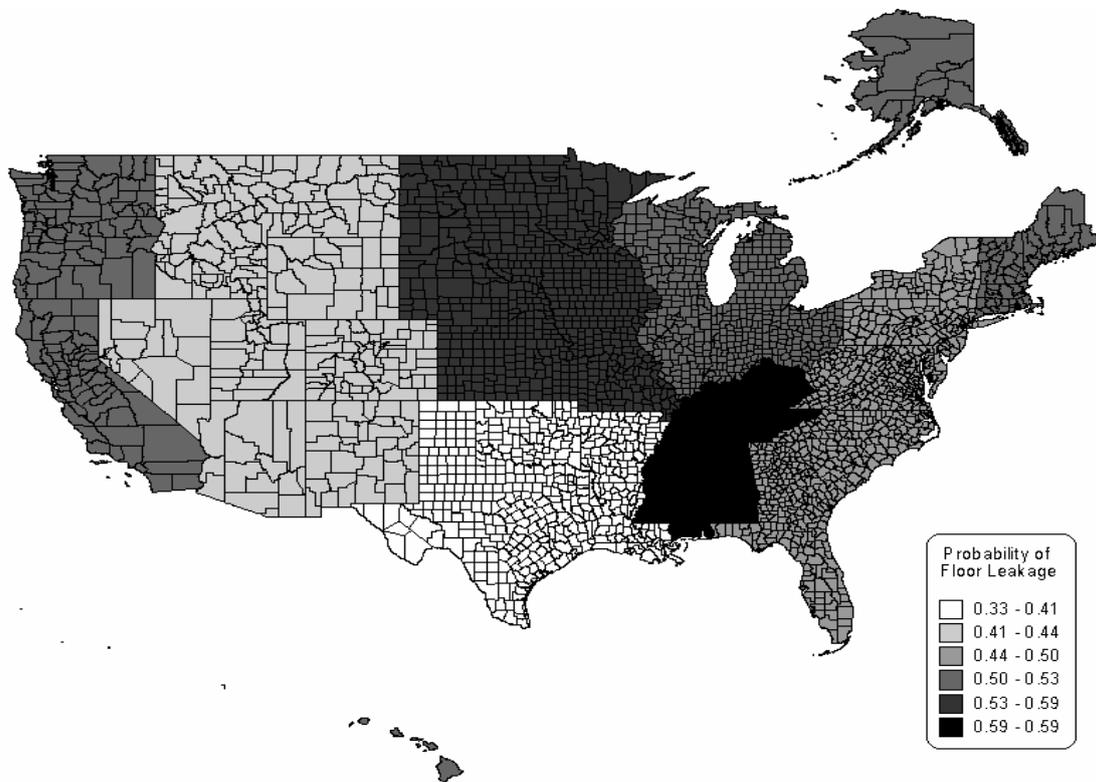


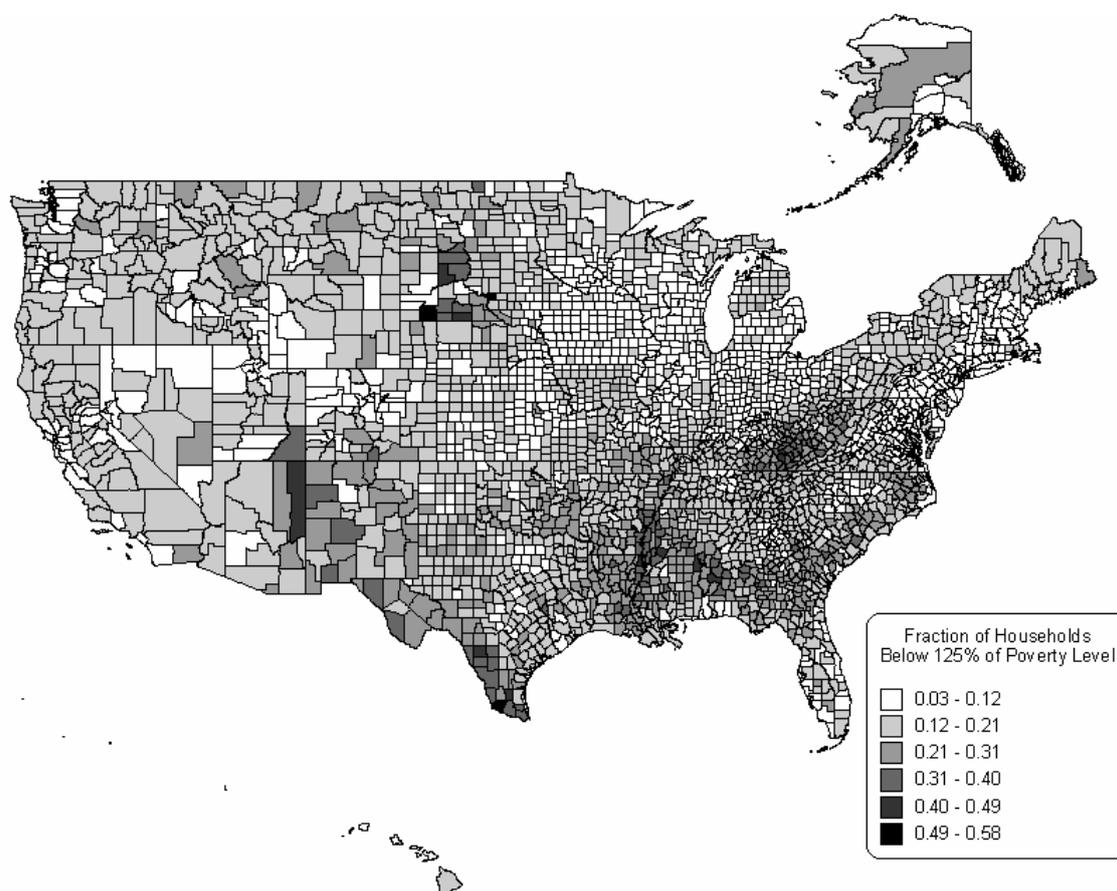
Figure 4: Probability of Floor Leakage by County



For the last two variables, fraction of households below an income threshold and dwelling floor area, it was necessary to combine Census data and RECS data. The income threshold was chosen at 125% of the poverty level because that was the low-income threshold defined in the Normalized Leakage model developed by McWilliams and Jung (2006). This threshold is the qualification criteria used by the the Ohio Weatherization Program, which provided all of the low-income data used to develop the model.

RECS data provided the number of households below the poverty level, between poverty and one and a half times the poverty level, and above one and a half times the poverty level for each census region. These data points were used to define a gaussian distribution for income level. Census 2000 data provided the fraction of households below poverty level for each county, and this value was used to shift the mean of the divisional income distribution for each county. It was assumed that the standard deviation of the income distribution for each county was the same as that for the census division, thus the fraction of households below 125% of the poverty level was inferred. Most of the Northeast and Midwest have a low fraction of households below this poverty threshold, as seen in Figure 5. High poverty is concentrated in Appalachia and the South and Southeast, with a few other isolated areas such as central South Dakota, the southern tip of Texas, and one county in eastern Arizona.

**Figure 5: Fraction of Households Below 125% of the Poverty Level**



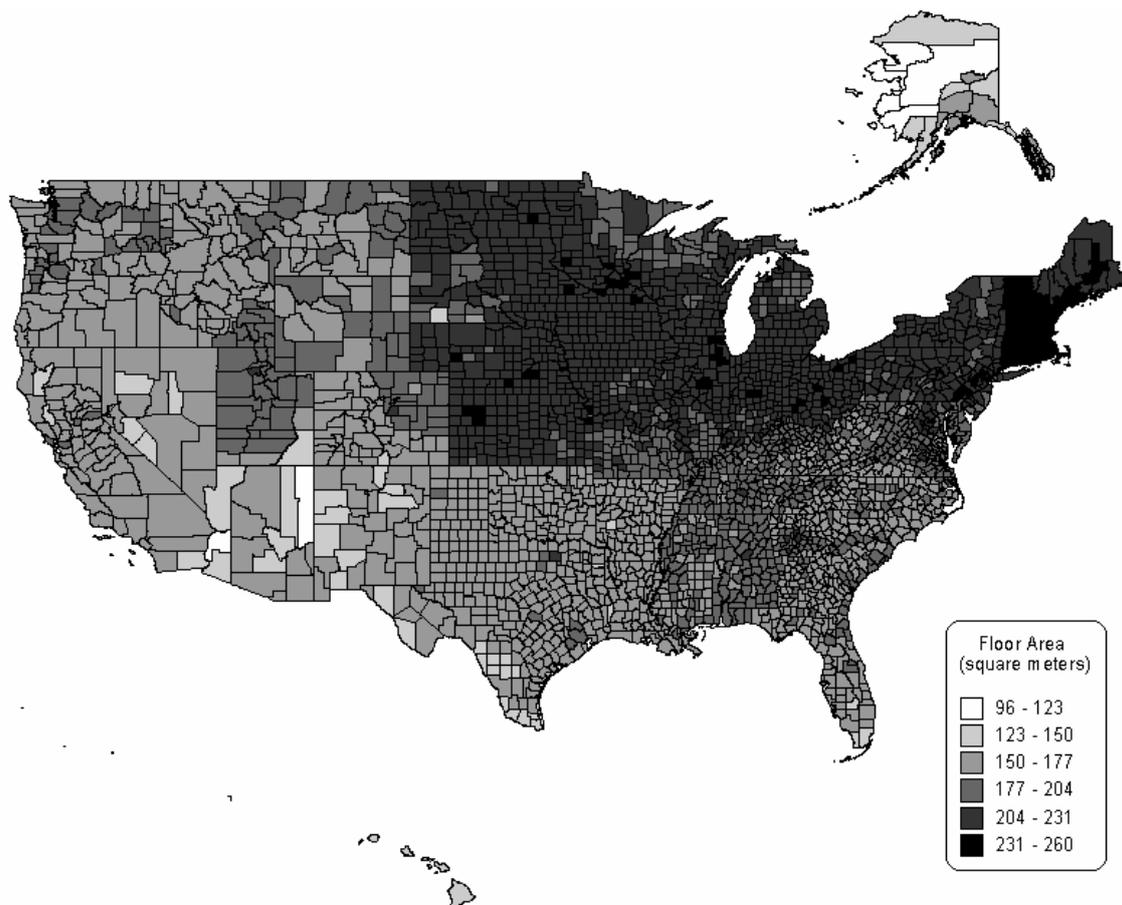
Dwelling floor area was also determined from a combination of Census and RECS data. Census data provided a distribution of the number of rooms in each county. Average floor area per room was calculated for each census division from “total floorspace” and “number of rooms per house” given in RECS data.

Figure 6 shows that larger dwellings are concentrated in the Northeast and Midwest while smaller homes are concentrated in the West and Southwest. The Southeast has larger homes in Mississippi, Alabama and Tennessee and smaller homes from Appalachia to Florida. The estimate of floor area is a bit crude because it is based on the number of rooms, but it was the best we could do with the data available. It is unfortunate for such a poorly defined/known

parameter that NL has a strong dependence (16% decrease in NL for every 100m<sup>2</sup> increase in floor area) on floor area in the model developed by McWilliams and Jung (2006).

No data was available in either Census or RECS data regarding participation of households in an energy efficiency program. The Energy Star Homes webpage states that currently 10% of newly constructed homes participate in the Energy Star program, and that there are approximately 500,000 Energy Star homes existing in the United States. The total number of single family dwellings in the United States is 73.7 million according to the RECS. Since the energy program variable is used to describe not only houses that participated in new construction energy programs, but retrofit programs as well, we assumed that 1% of houses nationwide had participated in an energy efficiency program. This assumption could be fine tuned as more data becomes available.

**Figure 6: Dwelling Floor Area by County [m<sup>2</sup>]**



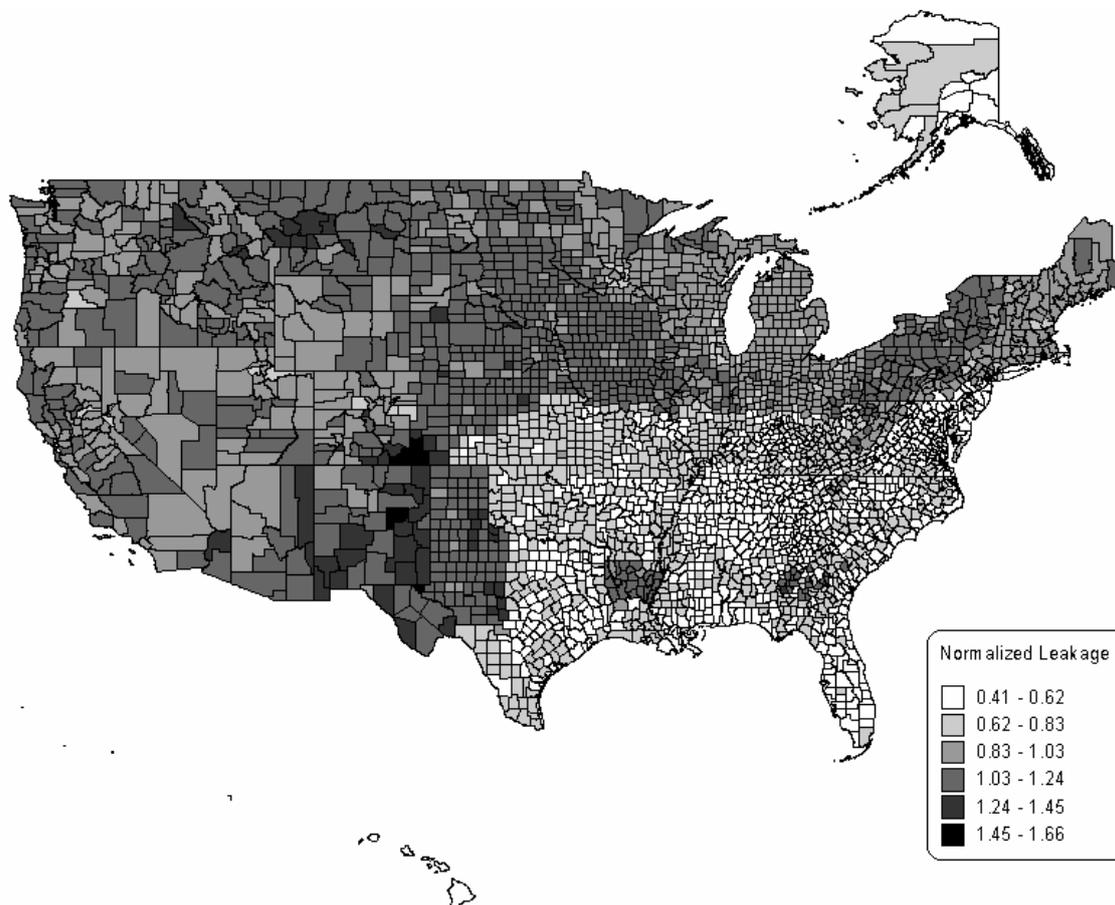
## **Discussion**

The input parameters were used to predict the ventilation for houses in each county. First, the empirical model is used to predict normalized leakage in each county. Figure 7 shows the normalized leakage across the United States. Immediately visible is the lower normalized leakage in the south east of the country and in Alaska. The boundary of this lower leakage area almost exactly follows the boundary of the humid climate zone. The climate coefficient of 0.35 for the humid climate is similar to the climate coefficient of 0.36 for Alaska. In contrast, the climate coefficients for the cold climate (0.53) and the dry climate (0.61) are much higher.

Another feature of this map that is initially apparent are the two areas of higher normalized leakage, one in northern Louisiana and the other in mid-southern Georgia. These pockets of leaky houses can be attributed to the fact that the houses in these areas are smaller, slightly older, and have a higher percentage of low-income residents than the surrounding counties. Households in Mississippi and Alabama are similar in income, but they are on the order of 50 square meters larger, which decreases NL by 8% according to the model. The higher probability of floor leaks in

Mississippi and Alabama increases the NL by 2-3%, which counteracts, but does not negate, the effect of their larger size.

**Figure 7: Normalized Leakage by County**



The air exchange rate is calculated using the LBL Ventilation model, which predicts flow through the building envelope based on the leakage area of the house and the weather conditions in that location. The shielding class and terrain parameters were both assumed to be moderate, or class III. The leakage distribution parameters,  $X$  and  $R$  were set according to the floor leakage parameter. Houses with floor leakage were assumed to have one quarter of the leakage in the ceiling, one quarter of the leakage in the floor, and one half in the walls, as in ASHRAE Fundamentals, Chapter 27. Houses with no floor leakage have one third of the leakage in the ceiling and two thirds in the walls. Model predictions are only weakly sensitive to the values of  $X$  and  $R$  (0-15%, Reinhold and Sonderegger, 1983) so precise determination of these variables is not necessary.

The simulation was performed for each hour over a year of typical weather conditions, and the mean air change rate is shown in Figure 8. The same pattern can be seen as in Figure 7 with lower air change rate in the tight houses of the Southeast.

Ventilation efficiency was calculated using the Sherman-Wilson model. It is clearly visible that the milder climates on the west coast and in the south east have ventilation efficiencies closer to 1, indicating that the infiltration is close to steady state over the course of the year. Climates with low ventilation efficiency--as those in the mountainous regions and in the northern part of the country--have increased infiltration variation over the course of the year.

Figure 8: Yearly Average Natural Air Exchange Rate by County

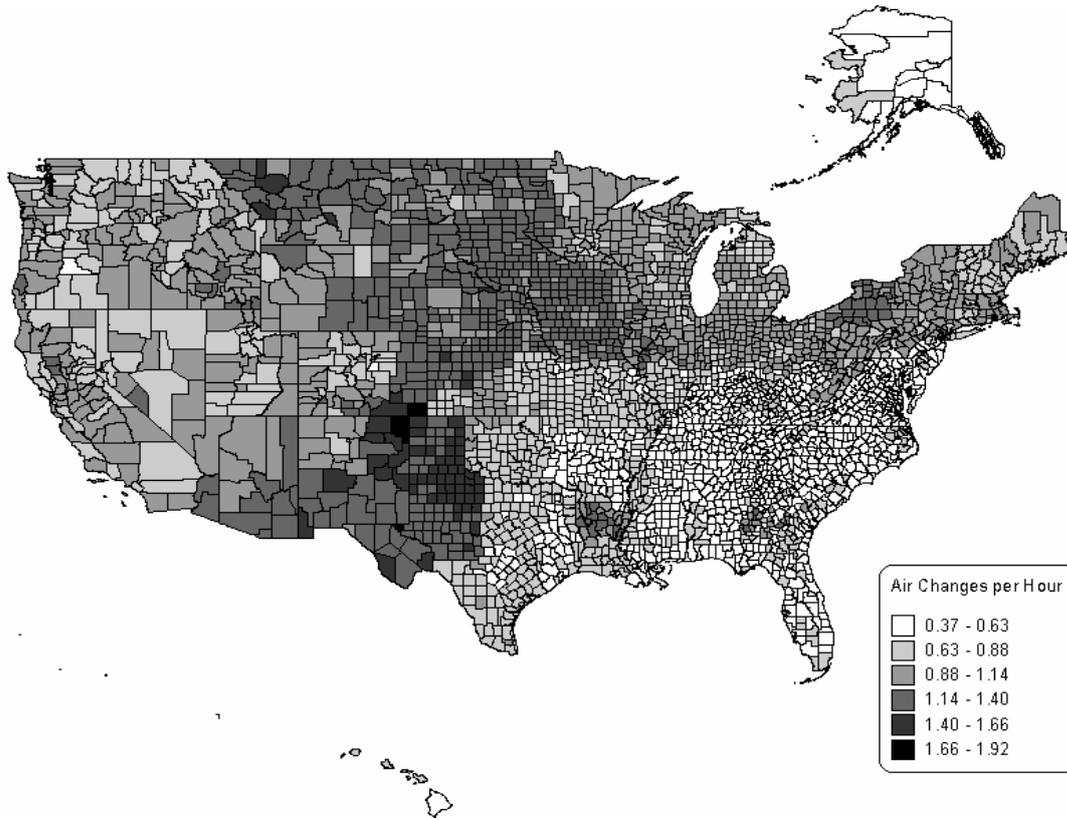
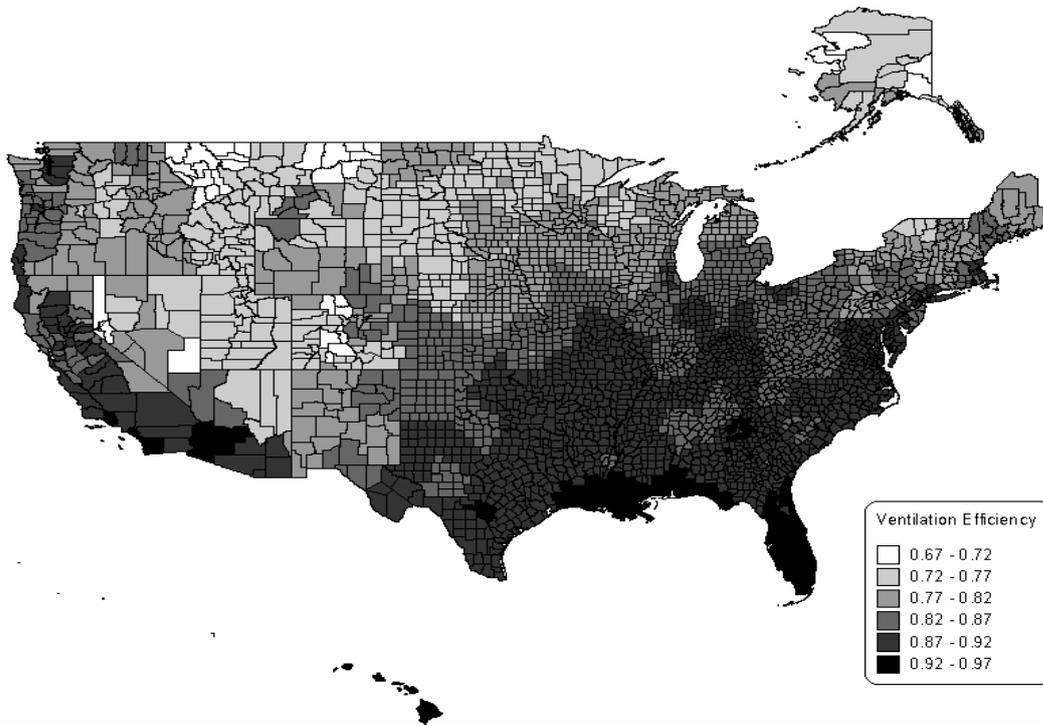


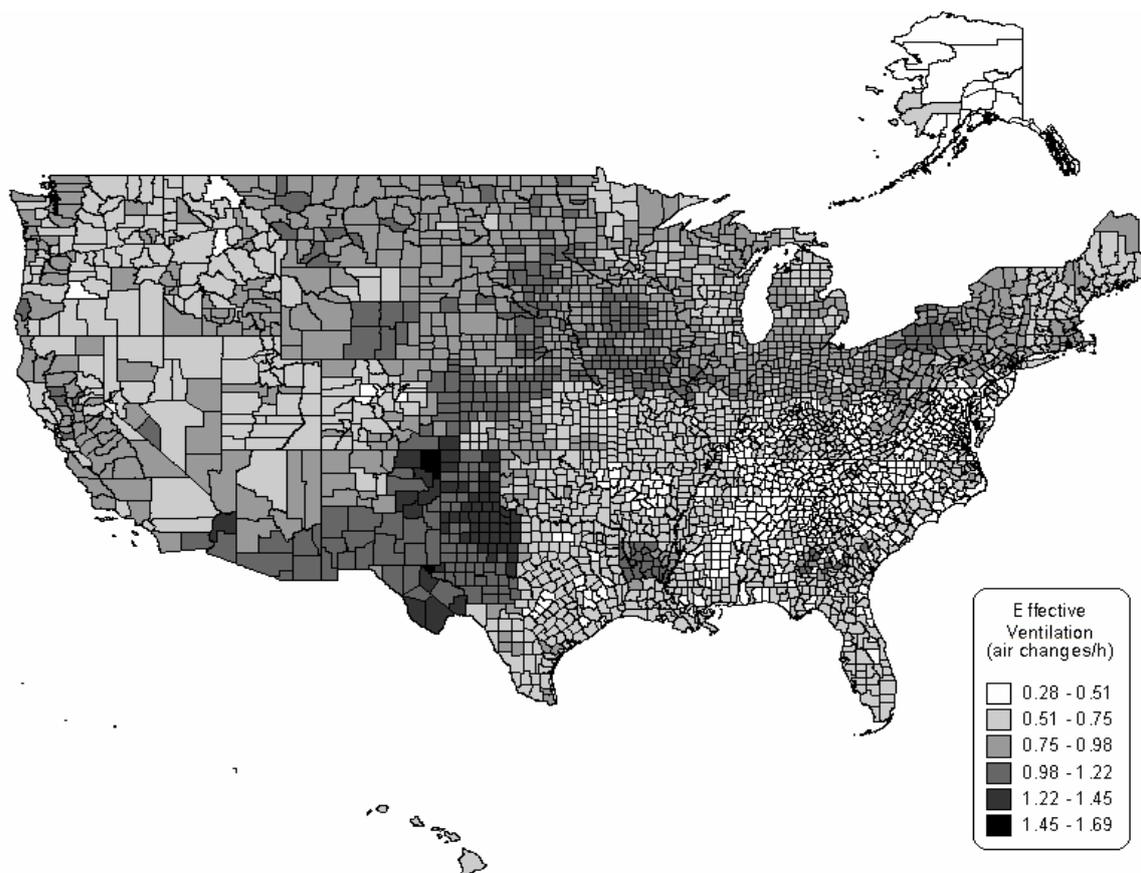
Figure 9: Ventilation Efficiency by County



Effective entilation shows how much ventilation is going towards reducing exposure for human occupants to pollutants. Figure 10 presents this data in air change rates and shows that Alaska and the Southeast have the lowest effective ventilation.

When effective ventilation is calculated for each month of the year, we find most of the country experiences the highest ventilation rate during the summer months. Some parts of the Midwest and areas on the Gulf of Mexico experience the highest ventilation in the spring, contrastingly the east coast of Florida and Seattle experience the highest ventilation in October. Only the interior of Alaska experiences the highest ventilation rate in the winter, although the maximum effective ventilation values are very similar in Alaska in summer and winter.

**Figure 10: Effective Ventilation by County**



## **Summary and Conclusions**

This report has presented and used a statistical model for predicting the air tightness of any U.S. home based on location, age, size and configuration. While this model is expected to have an uncertainty of approximately 50% for an individual prediction it can be used on larger populations to predict regional and other trends.

The housing stock in the U. S. contains a negligible number of houses with mechanical ventilation systems therefore infiltration provides the ventilation in these houses. Our results indicate that the vast majority of the residential building stock has effective air change rates above 0.35 air changer per hour and therefore gets sufficient ventilation from infiltrations when looked at on an annual basis.

Our analysis can help to select which regions may be particularly good candidates for saving energy through air tightening, such as through weatherization programs. The data containend herein has been used to estimate leakage trends, but could , in the future, be used to estimate potential energy savings.

Because there can be a substantial veariation between individual houses, many tighter homes—including most new construction—will likely not be sufficiently ventilated by infiltration alone. In these cases both energy and IAQ gains can be made through a combination of air tightening and designed ventilation systems.

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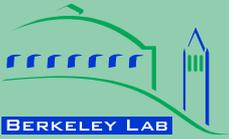
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## ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

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# Development of a Mathematical Air-Leakage Model from Measured Data

Jennifer McWilliams and Melanie Jung

**January 2006**

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# **Development of a Mathematical Air-Leakage Model from Measured Data**

**Jennifer McWilliams and Melanie Jung**

March, 2006

## **Abstract**

A statistical model was developed to relate residential building shell leakage to building characteristics such as building height, floor area, floor leakage, duct leakage, and year built or the age of the house. Statistical regression techniques were used to determine which of the potential building characteristics best described the data. Seven preliminary regressions were performed to investigate the influence of each variable. The results of the eighth and last multivariable linear regression form the predictive model. The major factors that influence the tightness of a residential building are participation in an energy efficiency program (40% tighter than ordinary homes), having low-income occupants (145% leakier than ordinary) and the age of a house (1% increase in Normalized Leakage per year). This predictive model may be applied to data within the range of the data that was used to develop the model.

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## List of Symbols

Symbol	Definition
NL	Normalized Leakage
Area	Floor area of the house in meters squared
H	Building height in meters
AT	Age of the house when it was tested
YB	Year when the house was built
FL	Existence of foundation leakage (0 or 1)
DL	Existence of duct leakage (0 or 1)
$\varepsilon$	Participation of the house in an energy-efficiency program (0 or 1)
$\beta_x$	Generic coefficient that in the regression
$\beta_{Area}$	The area coefficient
$\beta_H$	The height coefficient
$\beta_{AT}$	The age-tested coefficient
$\beta_{YB}$	The year built coefficient
$\beta_{FL}$	The floor leakage coefficient
$\beta_{DL}$	The duct leakage coefficient
$\beta_\varepsilon$	The e-program coefficient
$\beta_{x(std)}$	Generic standardized coefficient
$I_{cz}$	Vector of indicator variables for all the climates
$I_{cold}$	Indicator variable for the cold climate
$I_{mixed-humid}$	Indicator variable for the mixed humid climate
$I_x$	Generic indicator variable
$\beta_{cz}$	Vector coefficient corresponding to the climate vector
$\beta_{cold}$	Climate Coefficient for the cold climate
$\beta_{mixed-humid}$	Climate Coefficient for the mixed humid climate
$I_{AT}$	Indicator variable for age tested
$I_{YB}$	Indicator variable for year built
$I_{FL}$	Indicator variable for floor leakage
$I_{DL}$	Indicator variable for duct leakage
$\beta_{IAT}$	Coefficient of the age tested indicator variable
$\beta_{IYB}$	Coefficient of the year built indicator variable
$\beta_{IFL}$	Coefficient of the floor leakage indicator variable
$\beta_{IDL}$	Coefficient of the duct leakage indicator variable
$\beta_{adj. AT}$	Vector of coefficients corresponding to the climate vector, and adjusted for the age tested term
$\beta_{adj.}$	Vector of coefficients corresponding to the climate vector, and adjusted for multiple terms
$\phi_{Area}$	Area factor in the predictive model for NL

$\phi_H$	Height factor in the predictive model for NL
$\phi_{Age}$	Age factor in the predictive model for NL
$\phi_\varepsilon$	Energy efficiency program factor in the predictive model for NL (0 or 1)
$\phi_{Floor}$	Floor leakage factor in the predictive model for NL (0 or 1)
$\phi_{LI}$	Low-income occupant factor in the predictive model for NL
$\phi_{LI, Age}$	Low-income age adjustment factor in the predictive model for NL
$\phi_{LI, Area}$	Low-income area adjustment factor in the predictive model for NL
$NL_{CZ}$	A vector of constant terms, one for each climate, used in the predictive model for NL
size	Ratio of the floor area of a house to a reference area of 100 m <sup>2</sup>
Age	Age of a house when it was tested ( in years)
$P^{Eff}$	Percentage of houses in a dataset that participated in an energy efficiency program
$P^{Floor}$	Percentage of houses that have floor leakage (Floor leakage is defined as 1 if there is a possibility of leakage through the floor of the conditioned space as in a vented crawlspace or unconditioned basement, and 0 if there is no possibility of such leakage such as in a slab on grade house or a conditioned basement.
$P^{LI}$	Percentage of houses in a dataset that have low income residents

## **Introduction**

The goal of this research was to create a model to relate residential building shell leakage to building characteristics such as building height, floor area, floor or duct leakage and the age of the house or the year it was built. A model was developed and statistical regression techniques were used to determine which of the potential building characteristics best described the data. The data used for the this project were from the residential leakage database compiled and maintained by the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory. Seven preliminary regressions were performed to investigate the influence of each variable. The results of the eighth and last multivariable linear regression form the predictive model.

## **Description of the database**

The analysed database contains approximately 100,000 blower-door measurements<sup>1</sup> at single-family houses. The data were assembled from many different source organizations, therefore the building characteristics available for each house are not consistent throughout the database. The list of source organizations can be found in Appendix A. Most of the observations in the database contain the following core information: house floor area, test date, year built, participation in an energy efficiency program, and the shell leakage. A small number of houses have additional information such as the existence of a duct system, the type of floor or foundation construction, and the number of stories the house contains.

### *Quality of the data*

The database does not contain equally distributed data that is representative of the U.S. housing stock because it was compiled from data that had already been collected in various research, certification and weatherization programs. By default the data contained in the database comes from houses that were chosen to be in one of these three types of programs. This means that we have a much higher percentage houses that participated in an energy efficiency program than there are in the housing stock at large. Our data are also not geographically uniform because each data source generally collected data from local houses so our data are somewhat clumped around our source sites. This paper will discuss the limiting characteristics of the database, and the model results will be applicable to the American housing stock within the limits defined by our data sources.

### *Non-Homogeneity of Data*

The nature of the different sources leads to different information available for buildings in different parts of the country as well as geographical, construction quality, maintenance and operational differences between the buildings. The three largest contributors to the database are the Ohio Weatherization Program with more than 52,000 measurements, Alaska Housing Finance Corporation with almost 19,000 measurements, Energy Rated Homes with about 8,000 measurements and AKWarm (an energy-efficiency program in Alaska) with more than 5,000

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<sup>1</sup> The leakage data from one of our sources, Energy Rated Homes with 8047 observations, were determined using both measurements of some houses and visual inspections of others. There was no indication in the dataset of which leakage values had been determined visually. We were assured by Energy Rated Homes that the fraction of visual inspections was small. In a more recent dataset from the same source the fraction of visual inspections was 4.6%. The visual inspection observations from the newer dataset were not included in the database. By applying the fraction of visual inspections from the new data set to the old data set, we approximate that the database contains 400 visual approximations of shell leakage.

measurements. More than 20 other organizations contributed the remaining measurements covering more than 30 states. We know that all the houses from the biggest contributor have low-income residents, since that was a requirement of participating in the Ohio Weatherization Program. That means the occupants of these houses earn below 125% of the poverty level. For the rest of the observations we don't have any information about the income of the occupants. Additionally, we have about 14,000 observations that we know were involved in an energy-efficiency program (e-program). That means some changes were made, either during the design phase or post-construction, to save energy. Some datasets did not offer information about energy efficiency programs so for these houses we don't know if they were involved in an e-program. For purposes of our regression we combined houses that were not in an e-program with those houses for which we didn't know their involvement with an e-program. There are also a significant number of observations that are missing other information such as year built, basement type, climate zone, etc.

### *Geographical Data Distribution*

The data has a very significant regional bias since two thirds of the data are from Ohio and one quarter of it is from Alaska. Most of the Ohio data also come from low-income households since the major data source in Ohio is the Ohio Weatherization Program. In order to deal with this problem we separated the Ohio Weatherization Program from the rest of the data, and analyzed the two parts separately.

The bulk of the Alaska data was given to us after the analysis for this project was already finished. We ran the final regression (8) with and without the new data, and the results were not significantly changed, so we reported the results using all of the data. The preliminary regressions (1-7), however, do not include the new data.

Excluding the Ohio Weatherization Program data, the majority of the measurements are from houses located in Alaska, Rhode Island and Wisconsin. The abundance of data in Alaska is the main reason that the West Pacific Census Division is best represented. Data are also concentrated in Arizona, California and Washington, which are also in this Region. Rhode Island and Vermont together make up the second most sampled division, the New England Census Division. This is followed by the West Mountain Census Division, which consists of data from New Mexico, Arizona and Nevada. The South East Central Division is the worst represented division with fewer than 50 observations.

The U.S. Census Bureau collects U.S. housing stock data in a survey called the American Housing Survey (AHS). To create current statistics the Department of Housing and Urban Development interviewed 58,400 house owners in 1999. Chan et al. [2003] compared the database with these results. They pointed out that the floor areas of houses in the leakage database are generally smaller than those reported in the AHS. Also, the houses in the air leakage database are slightly older than houses in the AHS dataset.

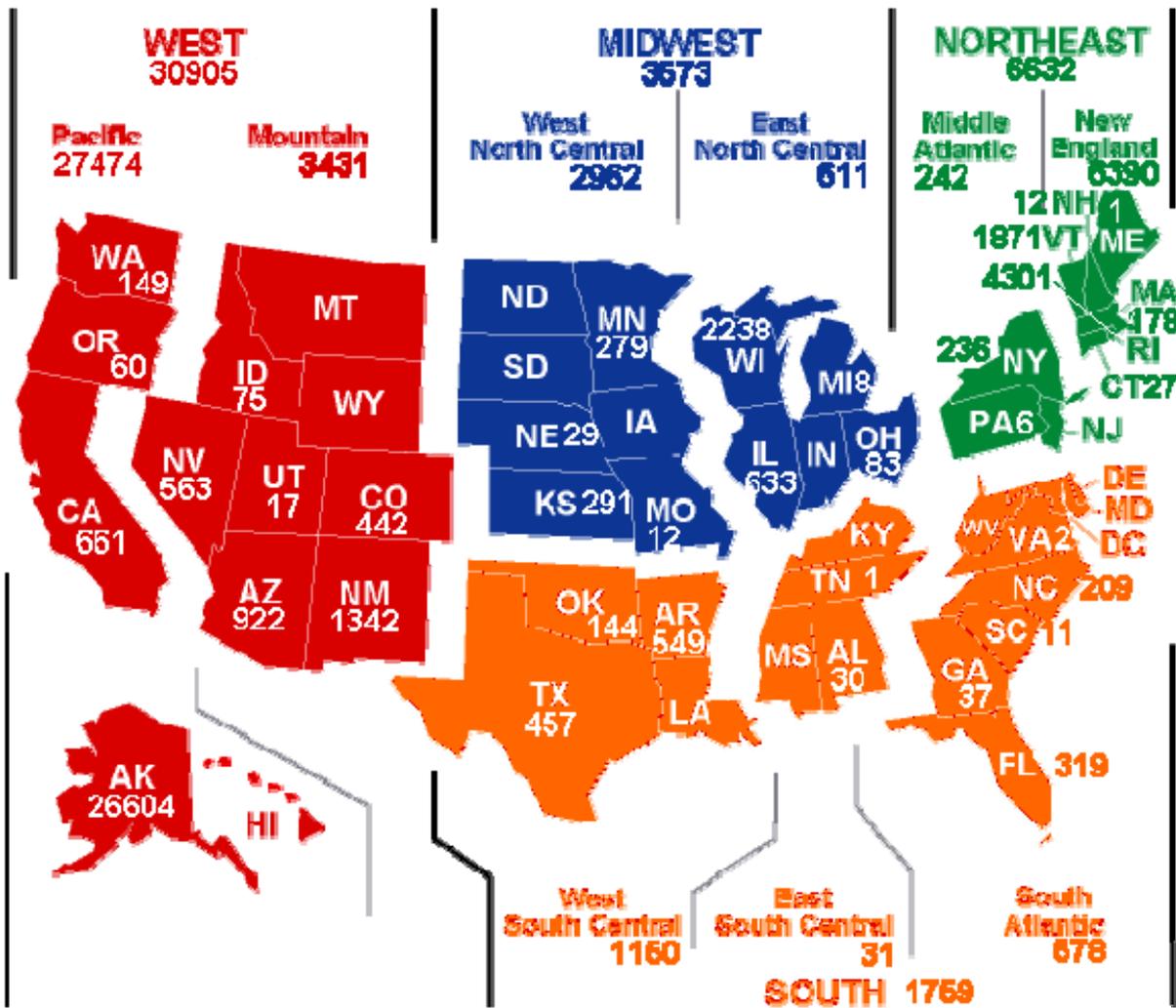


Figure 1: Geographic Distribution of Leakage Measurements in Database (2006) excluding the data from the Ohio Weatherization Program

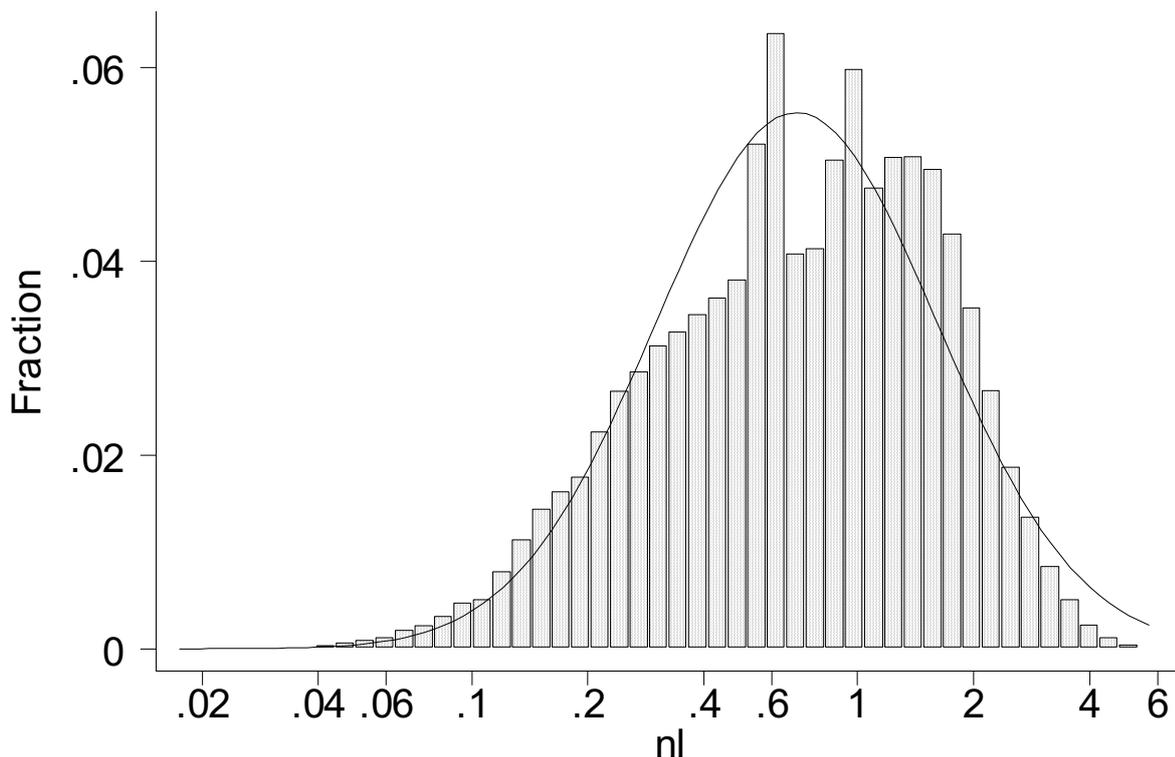
### Regression

Regression analysis is a statistical method where the mean of one or more random variables is predicted, based on other (measured) random variables. The leakage of a building is generally measured with a fan, and the data that is collected is the flow through the fan at a specific pressure, generally 50 Pascals. With this raw data it is difficult to compare differently sized houses with each other because there is usually more flow through a large house than a small one. Often, the raw data are normalized by converting the flow to an Equivalent Leakage Area [Sherman, 1995], and then normalizing the leakage area by floor area and height according to Equation 1, for Normalized Leakage as defined by ASHRAE [1988, 2005].

$$NL = 1000 \left( \frac{ELA}{Area} \right) \left( \frac{H}{2.5m} \right)^{0.3}$$

Equation 1

When we look at the distribution of the Normalized Leakage in our database we see that it is not normally distributed, but that the distribution is closer to log-normal. This is expected because the Normalized Leakage is always a positive number. Regression analysis assumes that the data will be normally distributed so instead of regressing the normalized leakage, we regress the natural log of the normalized leakage. Figure 2 shows the distribution of our data on a log scale and a curve of a normal distribution with the same mean and standard distribution as our data. We can see that the distribution of NL is slightly skewed toward higher leakage values. After the regression we will transpose the equation and fitted parameters from log-space back into normal-space.



**Figure 2: Distribution of the Normalized Leakage on a log scale**

In analyzing the results of the regressions we look not only at the R squared of the regression as a whole, but also at the confidence interval which shows the ranges in which 95% of the values lie. Adding independent variables to a linear regression model will increase the value of R-squared for the regression unless the added variable is multicollinear with the existing variables. The effect can be accounted for by using the adjusted coefficient of determination (adjusted R-squared), which is always smaller than R-squared and can also be negative. The adjusted R-squared increases only if the new term improves the model more than would be expected by chance, and is used in this analysis whenever R-squared is referred to.

The individual coefficients can be examined by using the t-value and P-value. The t-test (yielding the t-value) is a statistical test of whether the slope of a regression line differs significantly from 0. In statistics, a result is significant if it is unlikely to have occurred by chance, where, in reality, the independent variable being examined has no effect. Thus, the larger the t-value for a particular coefficient, the larger the statistical difference between that slope and zero.

The P-value is the significance level of the t-test or the maximum probability of accidentally rejecting a true null hypothesis. (The null hypothesis in this case is the hypothesis that the particular coefficient is equal to zero.) The smaller the P-value, the more significant the result is said to be.

In the analysis we compare the significance of the variables, one to another. In order to do this it is first necessary to standardize the variables by subtracting the mean from each value and then dividing by the standard deviation of the distribution. In this way the units of each variable are removed, and the distribution of each variable is centred on zero, with a standard deviation of one.

### **Data analysis and processing**

Data processing was initiated by verifying the plausibility of each data point. This means unrealistic data values (such as building year earlier than 1600) were deleted from the database. Afterwards the available information was investigated to see which independent variables are qualified for the regressions. Each of the variables is described in the later part of this section.

### **Error Correction**

The following acceptable data ranges were applied to the data:

- floor area                      from 30 to 1,000 square meters
- building height                taller than 1.79 meters
- year built                        1,600 or newer
- cfm50                            from 100 to 20,000
- year tested                      1980 or more recent,

The minimum year tested date was set at 1980 because both big companies which manufacture blower door testing equipment in the United States were founded in the early 1980's.

We identified and fixed a mistake that had been made in the data entry of the shell leakage of approximately 8,000 data points that had been noticed in previous investigations of this database.

Another data challenge was to assign climate zones (since we thought leakage might vary with climate). Many of our data had spelling errors in the location information, or inconsistencies between the city, state and zip code. These errors were fixed where possible and then a climate zone was assigned to each record based on the Building Science Corporation's climate map, see Figure 3.



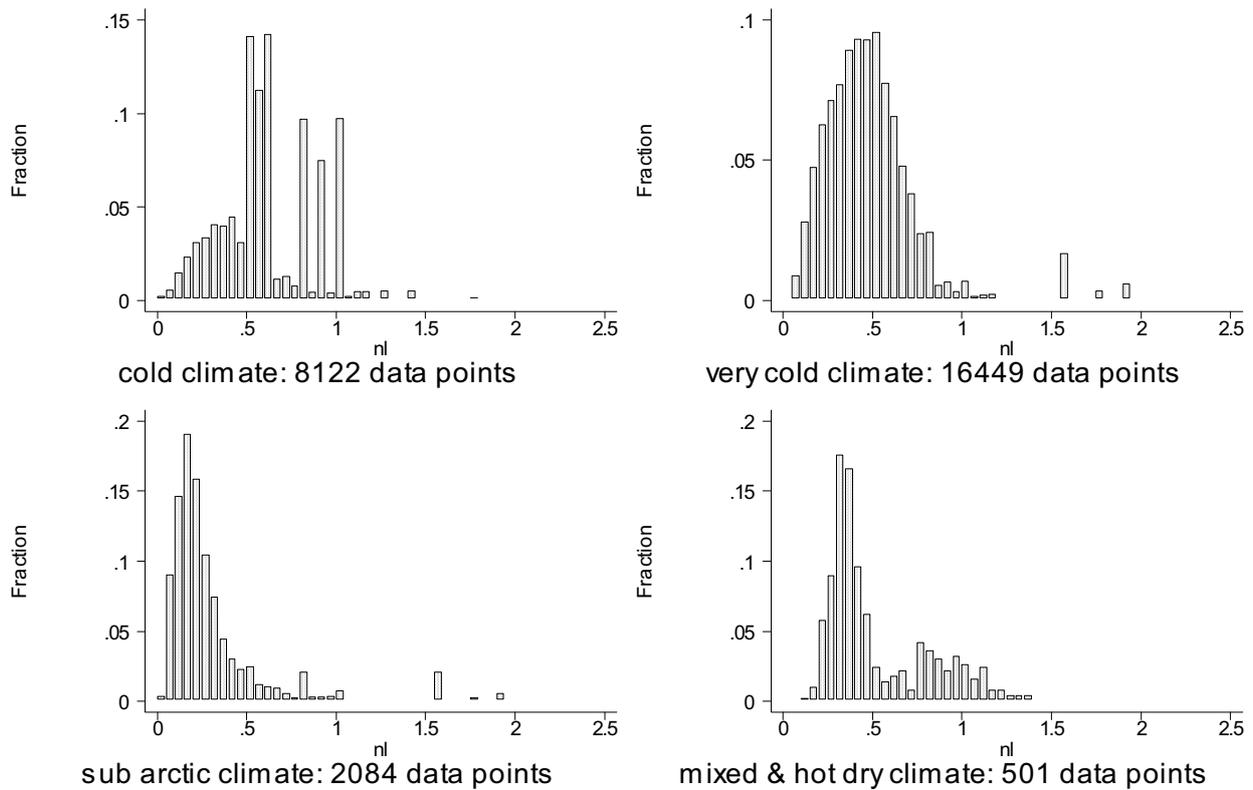
**Figure 3: Climate Zones defined by Building Science Corporation**

### **Uneven Data Distribution**

Houses in the leakage database do not statistically represent the characteristics of the housing in the US as a whole because of two main reasons.

1. Data were contributed voluntarily by home weatherization contractors and research organizations from around the country, and some contractors contributed much more data than others.
2. Most of the data were gathered as part of programs to target particular classes of homes, for example, “low-income” homes that were tested as part of a weatherization program, and “energy-efficient” homes that were tested to check compliance with air infiltration targets of the energy programs.

The Normalized Leakage distribution is shown in Figure 4 for the four best represented climate zones, excluding houses with low-income residents and e-program houses. The tail of the cold data with NL greater than 2.5 was not visible on the graph when all data was shown together. The tail consists of 13 data points with NL greater than 2.5 and less than 4.5. The very cold climate also has a tail of 4 data points with NL greater than 2.5 and less than 3.0. Data from a particular data source<sup>2</sup> is visible in the cold and very cold climates where we see a few discrete values of NL for a portion of the data. In this particular data set we were not able to obtain raw data, but only data that had already been categorized into leakage classes. The cold climate, with median NL of 0.59, has leakier houses than the other three climates with median NL values of 0.46, 0.22, and 0.40 for the very cold, sub arctic and mixed & hot dry climates respectively. Quartile values are summarized in Table 1.



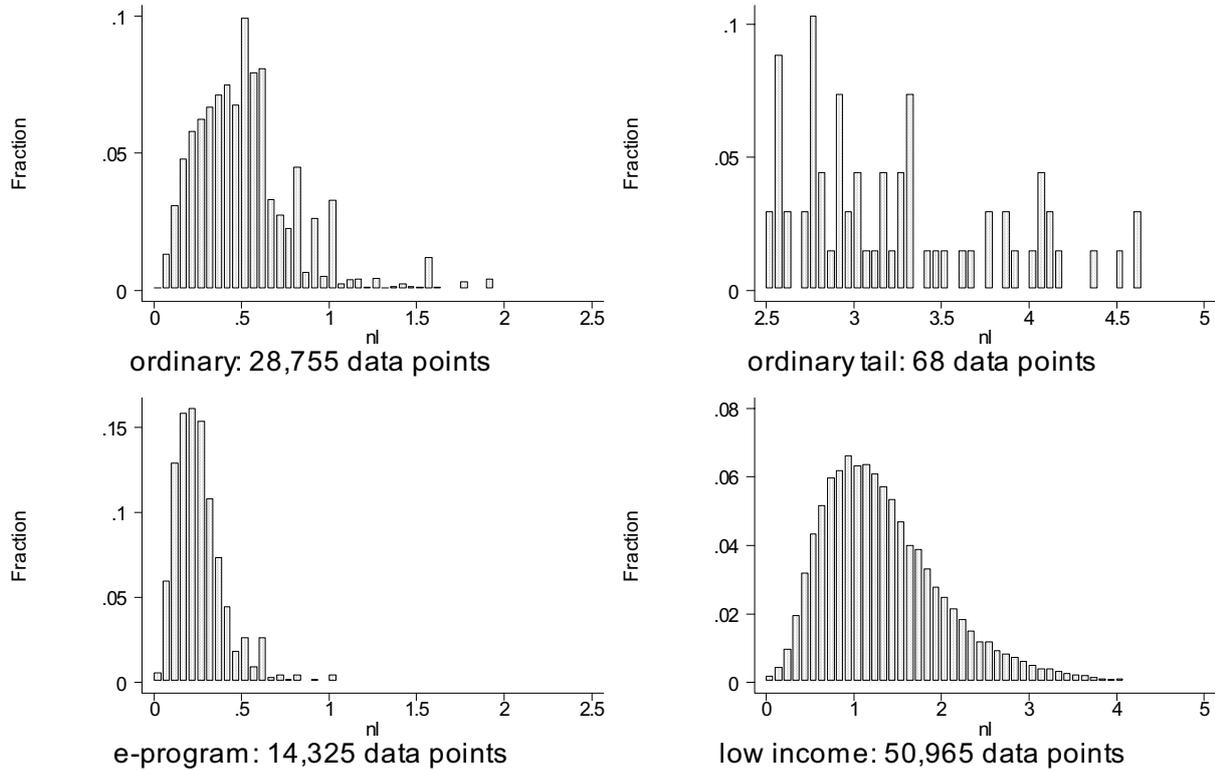
**Figure 4: Normalized Leakage distribution for the best represented climates, excluding houses with low-income residents and e-program houses**

Climate	25 <sup>th</sup> Percentile	50 <sup>th</sup> Percentile	75 <sup>th</sup> Percentile
Cold	0.48	0.59	0.83
Very Cold	0.32	0.46	0.61
Sub Arctic	0.15	0.22	0.34
Mixed & Hot Dry	0.33	0.40	0.75

**Table 1: Normalized Leakage quartiles for the best represented climates, excluding houses with low-income residents and e-program houses**

<sup>2</sup> Energy Rated Homes containing 8047 observations, all tested prior to 1994.

More than half of the data comes from a low-income weatherization program in Ohio, making this type of house over-represented in our dataset. Figure 5 shows the distribution of normalized leakage values in ordinary, e-program and low-income houses. The tail of the ordinary data has been graphed separately because it was not visible when all the data was shown together. The e-program data also has a tail of 2 data points with NL greater than 2.5 and less than 2.7.



**Figure 5: Normalized Leakage distribution for all ordinary houses, e-program houses, and houses with low-income residents**

We can see from the graph, and also from the quartile values in Table 2 that e-program houses with a median NL of 0.25 are tighter than ordinary houses with median NL of 0.50 and low income houses with a median NL of 1.24. We have a nice distribution of low income houses because of the huge volume of data.

House Type	25 <sup>th</sup> Percentile	50 <sup>th</sup> Percentile	75 <sup>th</sup> Percentile
E-Program	0.17	0.25	0.34
Ordinary	0.33	0.50	0.65
Low-Income	0.85	1.24	1.74

**Table 2: Normalized Leakage quartiles for three types of housing: e-program houses, houses with low-income residents and ordinary houses (those which are not part of either of the previous groups)**

The ordinary data are much less uniform due to the discrete values from the Energy Rated Homes source. We have fewer e-program houses than ordinary houses in our database, therefore we believe that the additional tightness of the e-program houses can be captured in an e-program variable. We will try the same approach with the low-income data in regression 5, but

do not anticipate success since there is so much data from the Ohio Weatherization Program. As part of the exploratory analysis we divide the houses into two broad classes, “low income” and “ordinary”, and analyze the two classes separately. We will examine each of the regression variables to see if it has a different trend in the low-income versus ordinary data. However, since all of our “low income” houses are in Ohio we have to assume that “low income” houses in Ohio differ from the Ohio housing stock in the same way that “low income” houses in other states differ from the housing stock in those states. This may or may not be a good assumption.

### **Variables Investigated**

Eight variables were investigated: foundation type, year built, house age when tested, low-income residents, participation in energy efficiency program, floor area, climate zone and the existence of a duct system. Six of these variables were included in the final model. Each of the variables is described below.

#### *Foundation Type*

Sherman and Dickerhoff [1998] point out that the Normalized Leakage of houses with a slab-on-grade foundation is significantly less than for houses with a crawlspace or an unconditioned basement. Unfortunately, we know the under floor construction for fewer than 10% of the houses in the database. The 2003 AHS reports the presence of a slab, basement, or crawlspace to be about 29%, 43%, and 27% in the US housing stock. However, the survey did not differentiate between conditioned and unconditioned basements. The leakage database, in comparison, reports about 9%, 53%, and 34% of the houses having a slab, basement, or crawlspace, respectively.

#### *House year-built and testing age*

New homes tend to be much tighter than old homes because of improved materials (e.g. weather-stripped windows), better building and design techniques, and lack of age-induced deterioration (e.g. settling of foundation). This trend has been reported by Sherman and Dickerhoff [1998] who observed substantial reduction in leakage in homes built after 1980. We attempted to determine separately the reduction in leakage due to improvements in building technologies, and the aging effect due to deterioration by using a “year built” variable to capture the change in construction techniques over time, and an “age tested” variable to capture the effect of aging on building leakage. Because all the houses were tested within a span of 20 years (1981 to 2004), these two variables are not completely independent. Houses that are less than 10 years old are very likely to be built after 1980, and houses that are older than 20 years old are very likely to be built before 1980. Because of this it is very difficult to separate the effect of materials or construction technique improvement which experienced a sharp reduction in leakage around 1980 and a deterioration effect due to aging. Most of the observations in the database include information about testing year and year built but not all. The age tested data are calculated by subtracting year built from testing year. These two variables were found to be correlated so only one could be used in the final model. Testing age was used in the model and year built was discarded.

#### *Low-Income*

Chan et al. [2003] point out that low-income houses have much higher leakage areas than ordinary houses, regardless of year built and floor area, and we also see this in Figure 5. We examine this in the analysis. As previously mentioned, all of our low-income data comes from a source called Ohio Weatherization Program, and all of this data are located in Ohio.

### *Energy-Efficiency Programs*

Houses that are participants in energy-efficiency programs are designed to be especially air tight to save thermal conditioning costs. Nearly fifty percent of the non low-income data are from energy-efficiency programs in 31 different states. All of the data from New Mexico, Kansas and Pennsylvania are from energy-efficiency programs. The fraction of houses in an energy-efficiency program in the database is much higher than observed nationally. This is because blower-door measurements are often used for the energy analysis that is commonly performed on houses participating in energy-efficiency programs.

### *Floor Area*

Normalized Leakage is normalized by floor area, so we don't expect a relationship between Normalized Leakage and floor area, but Chan et al. [2003] identified that Normalized Leakage is a function of floor area among houses that were built before 1995 so we investigate this variable. A relationship between NL and floor area would suggest that ELA should be normalized not by 1/Area, but by something more complicated.

### *Climate zones*

We expect that the climate has an important influence on the leakage area of residential buildings. Houses in harsh climates should be tighter because increased infiltration due to stack effect will result in more discomfort since the infiltrating air is cold in winter. In milder climates we expect more leakage because there is a lower monetary and comfort incentive to build tight houses.

The International Energy Conservation Code (IECC) defines 17 Climate Zones [ICC, 2003]. When our data are classified into these climate zones some zones contain very few or no data points. We need to group some climate zones together in order to do a meaningful climate analysis. Building Science Corporation uses a simplified set of 7 climate zones which can be directly mapped to the 17 IECC climate zones [BSC 2005]. See Figure 3 for a map of the climate zones and Table 3 for a listing of the number of observations that our dataset has in each zone. Although the marine climate still has a small number of data points, the other climates seem to have sufficient data so we begin our climate analysis with these climate zones, and we will later combine them if necessary.

<b>Climate</b>	<b>Total Number of Observations</b>	<b>Observations from Ohio Weatherization Program</b>
sub arctic	3,736	
very cold	23,202	
cold	55,154	44,956
dry	3,362	
mixed-humid	7,285	6,009
hot-humid	810	
marine	293	
unknown	276	

**Table 3: Number of Observations in each Climate Zone**

### *Duct system*

The presence of a thermal distribution system can add significant leakage. Sherman and Dickerhoff [1998] report that leaks measured separately from duct systems account for almost 30% of the total leakage of the house. The American Housing Survey classifies heating equipment into several types, but the two that use ducts as part of the system are warm-air furnaces and electric heat pumps. They represent 60% and 10% of the total housing stock respectively, meaning that 70% of the housing stock contains a duct system. In the air leakage database, there are approximately 5000 data points that record the presence or absence of duct systems, with 74% of those reporting the presence of duct systems. In the end this variable was not used in the model.

### **Result of data analysis and processing**

Based on these exploratory analyses, we conclude that house type (low-income, ordinary or energy-efficient), year built, age, climate, foundation construction and floor area all potentially influence the leakage of a house. As these factors are not completely independent of one another, more detailed analysis is required to determine how each one is associated with leakage. This more detailed analysis will be done in the next section by separating the data into categories (low-income and ordinary data) and carrying out the regression analysis.

### **Regression Analysis**

Eight sets of regressions were run in this analysis. Each set consisted of one regression of the low-income dataset and another regression of the ordinary house data set until the two datasets are combined for the later regressions. We started with a basic model and made changes in each successive regression until we arrived at the final regression, which we think best describes the data. Regression 8 was performed with and without the new data, and is described in detail in the Predictive Model section.

The first regression used only those variables for which each observation had a value. The low-income data and ordinary data are analyzed separately for all regressions until Regression 5. In the second regression we develop a method for including observations with missing data. Regression 3 adds the duct leakage and floor leakage variables. Regression 4 adds the energy efficiency program variable. Regression 5 combines the low income and ordinary house data into one model. In Regression 6 several variables are removed in turn to see if they are necessary to include in the model. Regression 7 examines the climate zones in detail.

As described in the Regression section of the Introduction, our data shows that the Normalized Leakage has logarithmic distribution. Therefore, instead of creating a linear model for NL, we will develop a linear model for the natural logarithm of NL, which then becomes an exponential model for NL as we will see in the Predictive Model section.

Results of the regressions using standardized variables can be found in Appendix B. The results of non-standardized regressions are summarized in Appendix C, and the full information on each regression (including the t and P-values) can be found in Appendix D. In general, the magnitude of the t-values are large (the sign always follows the sign of the coefficient) and the P-values are zero. Where this is not the case it is noted in the text.

## Regression 1

We start with a basic model which uses only observations where all the parameters are known: floor area, building height, age the house was when tested and the year it was built. We regress the low-income house data and the ordinary house data separately.

### *Low Income Data*

The Ohio Weatherization Program data come exclusively from low-income households. There are more than 50,000 observations in this dataset that contain values for each of the necessary parameters. All the observations are in only two climate zones. The indicator variables for each of the climate zones is set to 1 if the observation is in that particular climate zone and zero if it is not. There were no observations with unknown climate in this dataset. The model for these data is then the following:

$$\ln(\text{NL}) = (\beta_{\text{cold}} \cdot I_{\text{cold}} + \beta_{\text{mixed-humid}} \cdot I_{\text{mixed-humid}}) + \beta_{\text{Area}} \cdot \text{Area} + \beta_{\text{H}} \cdot \text{H} + \beta_{\text{AT}} \cdot \text{AT} + \beta_{\text{YB}} \cdot \text{YB}$$

**Equation 2**

As previously stated, in order to compare the variables, one to another, it is first necessary to standardize the variables by subtracting the mean from each value and then dividing by the standard deviation of the distribution. In this way the units of each variable are removed, and the distribution of each variable is centred on zero, with a standard deviation of one.

Aside from the two constants for the climate, the standardized age coefficient, 0.98, has the largest magnitude of the coefficients in this first regression showing that age has the most influence on the leakage of a building. The algebraic sign is positive indicating that the older the building is the leakier it is like expected to be.

The second biggest coefficient is the year the house was built with a value of 0.8. The positive algebraic sign means a positive relationship between the year a house was built and its leakage area. The later the building was built the leakier it is. This is in contrast to what we expect. The coefficient of house age when tested indicates that older houses are leakier, which is what we expect. This leads us to look at these parameters in more detail.

The correlation matrix shows a correlation of 94% between the influences that each of these variables have on the Normalized Leakage. Since all houses in our database were tested more recently than 1980 there is a strong correlation between date the house was built and the age of the house when it was tested. Because of this, only one of these variables should be used in the final regression. We will investigate which is the better variable to use in regression 6.

We expect that the floor area will have a relatively small influence on the Normalized Leakage since the leakage is normalized by floor area, as well as by building height. The standardized floor area coefficient is  $-0.24$ , which is the second smallest coefficient, confirming our expectations. The non-standardized floor area coefficient is  $-0.0044$  [ $1/\text{m}^2$ ], which means that the logarithm of NL actually decreases by 0.0044 for each additional square meter of building floor area.

The coefficient for the building height ( $-0.002$ ) is the smallest in regression 1, and has a standard deviation larger than the value of the variable (0.003). The t-value is small, and the P-value is 0.572, indicating low statistical significance for this variable in this regression.

An examination of the building height data reveals that it has only two discrete values (2.5m and 3.75m) in this part of the dataset because no data on building height or number of stories were given from the Ohio Weatherization Program directly. The floor area was assigned according to the following assumptions: Single-family buildings with a floor area smaller than 92 m<sup>2</sup> were assigned the height of a 1-story building (2.5 meters). Buildings with floor area 92 m<sup>2</sup> and bigger were assigned the height of 1.5-stories (3.75 meters). These assumptions are permissible because the Normalized Leakage is only weakly dependent on building height due to the height term's exponent of 0.3. The area for the low-income data set varies between 46 m<sup>2</sup> and 1,030 m<sup>2</sup>. This results in a distribution of 40% 1-story buildings and 60% 1.5-story buildings. Because this coefficient has a standard error that is bigger than the coefficient itself, the building height will not be included as one of the variables in the next regression.

We calculated the constants separately for the two climate zones containing data in Ohio, cold and mixed-humid. The P- and t-value of both coefficients point out significance for both constants. As expected the constant term for the cold climate is smaller. That means the Normalized Leakage is smaller in the colder climate indicating tighter houses. Each of the individual climate zones (cold and mixed humid) has a higher adjusted R-squared and smaller root mean square error (MSE) than the two climate zones together.

The R-squared for this regression indicates that this model only describes 21.5% of the data variability.

### *Ordinary Data*

For the houses that are not part of the Ohio Weatherization Program, the model becomes slightly more complicated because we have a wider range of climates so we replace the two constant terms with a sum of eight constant terms:

$$\ln(\text{NL}) = \sum(\beta_{\text{cz}} \cdot I_{\text{cz}}) + \beta_{\text{Area}} \cdot \text{Area} + \beta_{\text{H}} \cdot \text{H} + \beta_{\text{AT}} \cdot \text{AT} + \beta_{\text{YB}} \cdot \text{YB}$$

**Equation 3**

$I_{\text{climate}}$  is a set of climate indicator variables, where,  $I_x$  is equal to 1 for the x<sup>th</sup> climate and 0 for all the others. There are seven climates in this dataset, plus an additional climate variable for those where the climate is unknown.

All of the coefficients change when we use this new dataset. The height coefficient (0.14) is two orders of magnitude bigger than it is in the low-income-data and is the second biggest coefficient in this regression. The standard error is less than 2% of the coefficient. This is probably because we have real data for this variable instead of discrete data correlated with floor area. The algebraic sign is positive that means the higher the building the bigger the Normalized Leakage area.

The coefficients of all the other variables, floor area, “age tested”, and “year built”, decrease using the new dataset showing that the dependence of the Normalized Leakage on these variables decreases in the ordinary data.

The climate coefficients are the same order of magnitude as in the regression of the low-income data (low-income data:  $I_{\text{cold}} = -57.22$  and  $I_{\text{mixed humid}} = -57.05$ ; ordinary data:  $I_{\text{cold}} = -20.4$  and  $I_{\text{mixed humid}} = -20.1$ ).

The adjusted R-squared in this regression shows that nearly 36% of the variability in the data is described by the model. It is almost twice that of the low-income data but it still describes less than a half of the variability. Although separate regressions for each climate zone were investigated, a separate equation for each climate zone is not an option because of the vastly different number of observations across the climate zones. Moreover we want to have one model, which is as simple as possible, so we continue with the combined model, but modify it in the next regression to include observations with missing information for some of the variables. (In regression 1 these observations were dropped from the regression.)

## Regression 2

In regression 2 we remove building height when we regress the low-income data and we include observations with missing values by adding an indicator variable for each of the problem variables. The indicator variables ( $I_x$ ) are 1 if the data are known and 0 if the data are unknown, just as for the climate variables. The following term is substituted for each term in the previous equation that contained missing data:

$$\dots + \beta_x \cdot X \cdot I_x + \beta_{Ix} \cdot (1 - I_x) + \dots$$

**Equation 4**

### *Low Income Data*

In the low income data we use indicator variables for the year built and age tested terms. The building height variable is dropped, and the floor area variable contains no missing data. This regression uses about 250 more observations than were used in regression 1. Because the age tested variable is calculated by subtracting year built from year tested, and in this dataset the year tested variable was complete, all observations where year built is missing are also missing the age tested. Therefore, we need only one indicator variable for both variables ( $I_{AT} = I_{YB}$ ).

$$\ln(NL) = (\beta_{cold} + \beta_{mixed-humid}) + \beta_{Area} \cdot Area + \beta_{AT} \cdot AT \cdot I_{AT} + \beta_{IAT} \cdot (1 - I_{AT}) + \beta_{YB} \cdot YB \cdot I_{YB} + \beta_{IYB} \cdot (1 - I_{YB})$$

**Equation 5**

The fit is nearly the same for this regression as it was for regression 1 when we removed the building height variable from the regression. This means the assumptions about the indicator variables that we made were good.

### *Ordinary Data*

Many observations in the ordinary data set have missing values for year the house was built and testing year. We can include these observations in the regression by using indicator variables as shown in Equation 6. Here the indicator variables  $I_{AT}$  and  $I_{YB}$  are not equal to each other.

$$\ln(NL) = \Sigma(\beta_{cz} \cdot I_{cz}) + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_{AT} \cdot AT \cdot I_{AT} + \beta_{IAT} \cdot (1 - I_{AT}) + \beta_{YB} \cdot YB \cdot I_{YB} + \beta_{IYB} \cdot (1 - I_{YB})$$

**Equation 6**

The ratio of the parameters coupled to each variable can be used to estimate the average value of the missing data. If we assume that there is no inherent difference in the missing and non-missing data with respect to the variable, i.e.  $\beta_{x(missing)} = \beta_x$ , then  $\beta_{Ix}$  is equal to the product of  $\beta_x$

and the average of the missing values, and we can calculate the average of the missing variables as follows:

$$\frac{\beta_{Ix}}{\beta_x} = \bar{x}_{missing}$$

**Equation 7**

The average of the missing values, calculated in this way, is 128 years for the age of the house when it was tested and 1987 for the year built. These numbers are different from the average of the known ones ( $\overline{AT}=10$  and  $\overline{YB}=1993$ ). The difference between the known and missing values for both of these variables intuitively makes sense because an occupant is less likely to know the year a house was built the older it is. What is surprising is that there are 118 years of difference between the values of age tested, and only 6 year of difference between the values of year built. The averages of the low-income-data show a similar behavior. The calculated averages for testing age and year built are 116 years and 1857. The averages of the known values are 52 for age tested and 1942 for year built. In this dataset the two variables have closer to the same number of years difference between known values and missing values (64 years for the age tested variable, and 85 years for the year built variable). These results do not have any relationship to how the age of the house affects the Normalized Leakage, and it is possible that the results are skewed by the correlation between the age variables, but the result is interesting nonetheless.

The number of observations is 50% larger in this dataset by using all observations. Also the adjusted R-squared increased by nearly 5%.

### Regression 3

In this step we added the variables and indicator variables for duct and floor leakage. The data from the Ohio Weatherization Program contained no information about existing ducts or basement type. So we only look at the ordinary data.

Including these new variables, the model becomes:

$$\ln(NL) = \Sigma(\beta_{cz} \cdot I_{cz}) + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_{AT} \cdot AT \cdot I_{AT} + \beta_{IAT} \cdot (1-I_{AT}) + \beta_{YB} \cdot YB \cdot I_{YB} + \beta_{IYB} \cdot (1-I_{YB}) \\ + \beta_{FL} \cdot FL \cdot I_{FL} + \beta_{IFL} \cdot (1-I_{FL}) + \beta_{DL} \cdot DL \cdot I_{DL} + \beta_{IDL} \cdot (1-I_{DL})$$

**Equation 8**

Both variables are assigned a value of 1 if there is known leakage from the designated area (through the floor or through the duct system) and a value of 0 if there is no leakage through this area. There is no floor leakage in a slab on grade house or a house with a conditioned basement. Similarly, a house with no duct system cannot have duct leakage. Numbers between 0 and 1 may be assigned to these variables to denote a probability of duct or floor leakage when analyzing a large homogeneous dataset, or a percentage of full leakage on a case by case basis. In our dataset the variable FL is assigned the value 1 if the foundation type is crawlspace or unconditioned basement, 0 if the house is slab on grade or has a conditioned basement, and FL gets the value 0.5 if the foundation type is unknown or is a combination of foundation types. Similarly, the duct leakage variable has a value of 1 if the house has a duct system, 0 if it does not have a duct system.

Compared to Regression 2, the adjusted R-squared increases and the root mean square error goes down. This is expected since we have added two additional degrees of freedom to the

model. The climate and year built variables change slightly. The three variables for the floor area, the building height and the indicator variable of the age are become closer to zero.

Only the coefficient for the age tested,  $\beta_{AT}$ , changes significantly. Again, this could be caused by the correlation of the age variables which will be investigated later.

The new floor leak variable has P- and t-values (t-value = -2.65 and P-value = 0.8%) that show it to be not well defined in this regression. This is probably because the presence or absence of floor leaks is known for just under 25% of the data.

The variable for the duct leakage is shown as significant by the P- and t-values. The negative algebraic sign of the coefficient (- 0.139) is surprising. It means that buildings without duct systems are leakier than buildings with duct systems. This is opposite to what is expected. Ducts often run through an opening in the building shell to an air handling unit that is located outside of the conditioned space. Therefore, the result that houses with ducts are tighter than those without is unbelievable. 85% of the buildings with duct information are from energy efficiency programs. The e-program variable was not considered in this regression so it is likely that building tightness due to e-program shell improvements is ascribed to the duct variable in this regression.

#### Regression 4

In this regression we introduce another variable which will capture the effect of participation in an energy efficiency program on the Normalized Leakage. The e-program parameter has a slightly different form because in the data we cannot tell the difference between a house that is truly ordinary from one in which the participation in an energy efficiency program is unknown. Therefore we only have one set of input values not two.

$$\ln(NL) = \Sigma(\beta_{climate} \cdot I_{climate}) + \beta_{area} \cdot area + \beta_H \cdot H + \beta_{AT} \cdot AT \cdot I_{AT} + \beta_{IAT} \cdot (1-I_{AT}) + \beta_{YB} \cdot YB \cdot I_{YB} + \beta_{IYB} \cdot (1-I_{YB}) + \beta_{FL} \cdot FL \cdot I_{FL} + \beta_{IFL} \cdot (1-I_{FL}) + \beta_{DL} \cdot DL \cdot I_{DL} + \beta_{IDL} \cdot (1-I_{DL}) + \beta_\epsilon \cdot \epsilon$$

**Equation 9**

In this model there are 19 independent variables and 19 fitted parameters ( $\beta_x$ ). Eight parameters for the climate zones; one each for area, building height and energy programs and two each for age tested, year built, foundation type and ducts.

Compared to Regression 3 the adjusted R-squared goes up and the root mean square error goes down, as they must because an additional variable was added. The coefficient for the e-program variable is negative (-0.22) so the Normalized Leakage for houses participating energy efficiency programs is smaller, all other variables being equal. It is not surprising that energy program houses are tighter since they are built to save energy.

The duct leak coefficient is still negative, but a slightly higher t-value shows a bit more significance in this regression than in regression 3. The natural logarithm of NL for buildings with duct system ( $\overline{\ln(NL)}_{DL=1} = -1.36$ ) is smaller than the logarithm of NL for buildings without ducts ( $\overline{\ln(NL)}_{DL=0} = -0.94$ ). Apparently the tightness of these particular houses that have a duct system is not sufficiently accounted for in the e-program variable, and the regression assigns the additional tightness to duct leakage, although we know this to be impossible. It follows that the variable is not qualified to be used in our mode because our data are skewed with respect to this variable.

The variables for the floor area, the year built (including indicator variables), the duct variable, and climate variables don't change much from the previous regressions. They all become slightly closer to zero, as we expect when we add more degrees of freedom to the model.

In this regression the coefficient for the variable of the house age when tested is negative. This is probably due to the 92% correlation between the age tested and the year built variables. The P-value of the age tested coefficient is 0.3% in this regression compared to 0 in the last regression which indicates that it was better defined in the previous regression.

The floor leakage variable in this regression has an even larger P- value (17%) and a smaller t-value (-1.37) than in regression 3 indicating even lower significance. We drop this variable from the model, but will revisit it again in Regression 8 when we use a different method for including variables with many missing data points.

## Regression 5

In this regression we develop a way of combining the low-income data and the ordinary data into one model. The fitted parameters relating to floor area, building height, year built and age tested are dissimilar between the ordinary dataset and the Ohio Weatherization Program dataset. We combine the two datasets into one regression in the simplest way possible, by adding a single parameter (LI) to the model of regression 4 as shown in Equation 10.

$$\ln(\text{NL}) = \Sigma(\beta_{\text{CZ}} \cdot I_{\text{CZ}}) + \beta_{\text{Area}} \cdot \text{Area} + \beta_{\text{H}} \cdot \text{H} + \beta_{\text{AT}} \cdot \text{AT} \cdot I_{\text{AT}} + \beta_{\text{IAT}} \cdot (1-I_{\text{AT}}) + \beta_{\text{YB}} \cdot \text{YB} \cdot I_{\text{YB}} + \beta_{\text{IYB}} \cdot (1-I_{\text{YB}}) \\ + \beta_{\text{FL}} \cdot \text{FL} \cdot I_{\text{FL}} + \beta_{\text{IFL}} \cdot (1-I_{\text{FL}}) + \beta_{\text{DL}} \cdot \text{DL} \cdot I_{\text{DL}} + \beta_{\text{IDL}} \cdot (1-I_{\text{DL}}) + \beta_{\epsilon} \cdot \epsilon + \beta_{\text{LI}} \cdot \text{LI}$$

**Equation 10**

The LI variable is 1 or 0 depending on whether or not the data comes from the Ohio Weatherization Program dataset. Like the energy program issue, we only have one variable. It is known that those in the Ohio Weatherization Program are low-income houses, but the ordinary dataset may also contain some low-income houses.

In this regression the adjusted R-squared increases to 64% from 51% in regression 4. It seems that this is an acceptable way to combine the two datasets. After closer examination we see that all of the climate variables and the year built variables have P-values greater than zero and t-values smaller than 1. We decide to continue analyzing the data from the two datasets separately and find another way to combine them for the predictive model at the end.

## Regression 6

In previous regressions we saw that the age tested variable and the year built variable are correlated, so only one of them is appropriate to use in the model. In this regression we remove the year built variable and age tested variable in turn to see which of these variables better describes the data. We remove the floor leakage variable in this regression because regression 4 indicated that it was not significant.

The adjusted R-squares of the two regressions (.49 using age tested and .50 using year built) are very similar, and are very close to the adjusted R-squared of regression 4 (.51) so the model works just as well without the variable for the floor leaks and without one of the age variables. The standardized coefficients in these two regressions are very similar to each other, and are not much different from the coefficients in regression 4, except for the age tested coefficient and the climate coefficient in the regression that uses age tested variable. In this regression the

leakage is explained by the age tested, rather than the climate. The correlation matrix for this regression does not show a correlation between age tested and climate, whereas the correlation matrix of the next regression shows a high correlation between the year built variable and the climate coefficients. It makes sense that the climates are related to the year the house was built because different areas of the country experienced building booms at different times. For this reason we choose to use age tested as the variable that we will continue to use in the following regressions. It is important to remember, however, that this coefficient really describes both an aging effect, and an improved design and materials effect so the predictive model should not be used to predict into the future, but only to back-forecast the leakage of existing houses.

## Regression 7

Now the developed model fits the data fairly well. There is no variable with a t-value smaller than twenty. All the P-values are zero. Now we turn our attention to the climate zones. Some of the climates have very few observations compared to the other climates. The coefficient values are shown in Table 4 with the tightest houses at the top of the table, and the leakiest at the end.

Climate Zone	Number of Observations	Coefficient Value
sub arctic climate	3736	-1.39 ± .02
marine climate	293	-1.14 ± .03
mixed and hot dry climate	3362	-1.05 ± .02
cold climate	10,198	-0.99 ± .02
very cold climate	23198	-0.88 ± .02
mixed humid	1276	-0.66 ± .02
unknown climate	276	-0.54 ± .03
hot humid climate	811	-0.46 ± .03

**Table 4: Number of observations and coefficient value per climate zone from regression 6 using the age tested variable.**

In regression 7 we combine the climate zones to eliminate some of the climate zones with low numbers of observations, and to align the climate zone boundaries with areas that have similar building practices. This is particularly important for Alaska, which we know to have different building practices, for instance, the garage is conditioned. We create a new climate called Alaska containing all the observations from this state. These observations are a subset of the former sub arctic and very cold climates.

The second new climate is the cold climate. Because of the large number of observations the cold climate is representative enough to stay alone. The few observations from the sub arctic (279 observations) and very cold (52 observations) climate that are not situated in Alaska fit in this climate too.

The new humid climate includes the former hot and mixed humid climates. This climate is located in the south east of the country.

The remaining climates are summarized in the dry climate. The dry climate covers the west and south west of the country. Although the marine climate is not particularly dry, the building practices in this climate are similar to building practices all over the west of the country.

We expect the houses in more severe climates to be tighter than those in mild climates, and this is the case with the tightest houses in Alaska as shown in Table 5. We found that the climates that the model predicts to be tighter are those climates where a higher proportion of our data comes from e-program houses. We will look at the climate coefficients in more detail when we do the final regression, because it may change.

Climate Zone	Number of Observations	Coefficient Value
Alaska climate	26,603	-1.31 ± .02
dry climate	3,655	-1.10 ± .02
cold climate	10,529	-1.03 ± .02
humid climate	2,087	-0.62 ± .02
unknown climate	276	-0.59 ± .04

**Table 5: Number of observations and coefficient value per climate zone from regression 7**

### Results of the preliminary regression analysis

Regression 7 describes 45% of the data by using five constant terms (climate coefficients), five variables and two indicator variables. The logarithm of Normalized Leakage decreases by 0.0014 per added square meter. If the building height increases by one meter the ln(NL) increases by 0.08. This value is plausible since the surface of the building shell increases with increasing height.

The leakage expressed in ln(NL) increases by 0.011 per year. This effect contains both aging and improvements in the quality of construction. Since the age and year built data are correlated it is not possible to separate these effects.

Our model shows that houses with ducts are tighter than those without ducts. This is counter-intuitive and physically unrealistic so we look for another explanation. 85% of the houses in our database that have ducts are also e-program houses. Perhaps these e-program houses with ducts are slightly tighter than the average e-program house, and that tightness is erroneously explained by the ducts variable although it has nothing to do with the ducts. Therefore, the duct variable will not be used to form the predictive model.

### Predictive Model

The intended purpose of this model is to predict the Normalized Leakage of a set of houses in the U. S. If we had statistically representative and complete data we would simply fit our model to the data and get the parameters of interest. Unfortunately we have missing data and we have unrepresentative data. We will therefore try to stratify the analysis procedure to maximize the value of the data: We will develop a core model and then regress the residuals of the model to fit the other parameters. Indicator variables are no longer necessary with this new strategy.

### Development of the Predictive Model

Since we have so much data in Alaska, we ran the analysis on the Alaska data and the continental US separately to see if there was a difference between the data that we have for these regions. (Results of these regressions are shown in Table 6.) There was not a significant difference so we decided that no stratification was required for Alaska in the regression 8 analysis.

### Regression 8: The Core

For all the data we are using we have information on the leakage, the climate, the area and height of the house and whether it is in an e-program. We therefore will use all of the *non-low income* data and fit it to what we call our core model:

$$\ln(NL) = \overline{\beta}_{cz} + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_\varepsilon \cdot \varepsilon \quad \text{Equation 11}$$

We have excluded the low-income data from the core because the low-income data we have comes only from one state and therefore may be biased for a variety of reasons. We have excluded age from the core because only about half the non-low income data has appropriate age information *and* the leakage of houses where the age is known is different from the leakage of houses where the age is not known.

### Regression 8a: Adjustment for age

To estimate the age parameters we will first consider the non-low income data for which we have age information. We will regress the residuals of regression 8 against the age variable. Specifically,

$$\ln(NL) - (\overline{\beta}_{cz} + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_\varepsilon \cdot \varepsilon) = const + \beta_{AT} \cdot AT \quad \text{Equation 12}$$

The age coefficient is, in fact, the one we wish to use in our predictive model, but in order to keep the mean leakage unchanged between the core and this expression it is necessary to subtract off the impact that this new parameter has from the climate term which is the parameter times the average age of the homes in the dataset:

$$\overline{\beta}_{adj.AT} = \overline{\beta}_{cz} - \beta_{AT} \cdot \overline{AT}$$

If the data that was missing age information were drawn from the same population as the data with age information, we would expect this last term to be equal to the constant term in the Equation 12. These terms are not the same and we can see from the data that the houses where we do not know the age are substantially leakier than those that we do—all other things being equal.

### Regression 8b: Adjustment for floor leakage

The floor leakage variable also had the missing data problem that the age variable had. By repeating the age analysis using the floor leakage variable and using the results to adjust the equation it will be:

$$\ln(NL) = \overline{\beta}_{adj.} + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_\varepsilon \cdot \varepsilon + \beta_{AT} \cdot AT + \beta_{FL} \cdot FL$$
$$\text{with: } \overline{\beta}_{adj.} = \overline{\beta}_{cz} - \beta_{AT} \cdot \overline{AT} - \beta_{FL} \cdot \overline{FL} \quad \text{Equation 13}$$

### Regression 8c: Adjustment for Low-income

To determine the low-income parameters we will use just the low-income data with the core model (plus age) and regress:

$$\begin{aligned}\ln(NL) - (\overline{\beta_{adj}} + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_\varepsilon \cdot \varepsilon + \beta_{AT} \cdot AT) \\ = \beta_{LI,AT} \cdot AT + \beta_{LI,Area} \cdot Area + \beta_{LI}\end{aligned}$$

**Equation 14**

This determines the last of the parameters we are concerned with. The coefficients describe the difference between the low-income and the ordinary data.

### Interpretation of the Results

The full predictive model can be written in the following form:

$$\begin{aligned}\ln(NL) = \overline{\beta_{adj}} + \beta_{Area} \cdot Area + \beta_H \cdot H + \beta_\varepsilon \cdot \varepsilon + \beta_{AT} \cdot AT + \beta_{FL} \cdot FL \\ + (\beta_{LI} + \beta_{LI,Area} \cdot Area_{LI} + \beta_{LI,AT} \cdot AT_{LI}) \cdot LI\end{aligned}$$

**Equation 15**

Since, ultimately, we are interested in the Normalized Leakage we manipulate the equation by taking the exponent of both sides. To make the equation more meaningful we create a term,  $NL_{cz}$ , which is the Normalized Leakage in a particular climate zone of a building with a floor area of 100 m<sup>2</sup> and one story high with unknown age, basement type, energy program participation and occupant income. This core is then modified by six parameters, any of which can be dropped if the information is unknown. Three of the parameters (participation in an energy efficiency program, presence of floor leakage, and occupants in a low-income bracket) have an exponent that is a probability so that the average NL can be calculated for a group of houses that have a known distribution of these factors. Equation 16 shows the final version of the predictive model. The values for each of the parameters can be found in Table 6. The predicted values based on the Alaska data only are also included in this table for comparison. The only value that changed significantly was the e-program coefficient. The dataset from the Alaska Housing Finance Corporation used the EPA Energy Star rating system, so a house that was modelled to use 30% less energy than the base case was defined as an e-program house. As we might expect, our model shows that these Energy Star houses also have 30% less leakage than the average house. The e-program houses in our database as a whole generally participated in programs with more stringent requirements, and therefore the leakage of e-program houses in the overall database is lower.

$$NL = NL_{cz} \cdot \phi_{Area}^{size-1} \cdot \phi_{Height}^{N_{story}-1} \cdot \phi_\varepsilon^{PEff} \cdot \phi_{Age}^{Age} \cdot \phi_{Floor}^{PFloor} \cdot (\phi_{LI,Age}^{Age} \cdot \phi_{LI,Area}^{size-1} \cdot \phi_{LI})^{PLI}$$

**Equation 16**

Where  $NL_{cz} = e^{\overline{\beta_{adj}} + \beta_{Area} \cdot Area_{ref} + \beta_H \cdot H_{single-story}}$

**Equation 17**

$$Area_{ref} = 100m^2 \quad H_{single-story} = 2.5m$$

And

$$size = \frac{Area}{Area_{ref}}$$

Equation 18

Parameter	Defined as:	Value (AK only)	Value (all data)
$\phi_{Area}$	$\phi_{Area} = e^{\beta_{Area} \cdot Area_{ref}}$	0.867 ± 0.003	0.841 ± 0.003
$\phi_H$	$\phi_H = e^{\beta_H \cdot H_{Single-Story}}$	1.158 ± 0.005	1.156 ± 0.005
$\phi_\varepsilon$	$\phi_\varepsilon = e^{\beta_\varepsilon}$	0.680 ± 0.006	0.598 ± 0.004
$\phi_{Age}$	$\phi_{Age} = e^{\beta_{AT}}$	1.0162 ± 0.0002	1.0118 ± 0.0002
$\phi_{Floor}$	$\phi_{Floor} = e^{\beta_{FL}}$	n/a	1.08 ± 0.02
$\phi_{LI}$	$\phi_{LI} = e^{\beta_{LI}}$	n/a	2.45 ± 0.01
$\phi_{AgeLI}$	$\phi_{LI, Age} = e^{\beta_{LI, Age}}$	n/a	0.9942 ± 0.0001
$\phi_{AreaLI}$	$\phi_{LI, Area} = e^{\beta_{LI, Area} \cdot Area_{ref}}$	n/a	0.775 ± 0.003
NL <sub>CZ(Alaska)</sub>	Equation 17	0.33 ± 0.01	0.36 ± 0.01
NL <sub>CZ(Cold)</sub>	Equation 17	n/a	0.53 ± 0.01
NL <sub>CZ(Humid)</sub>	Equation 17	n/a	0.35 ± 0.01
NL <sub>CZ(Dry)</sub>	Equation 17	n/a	0.61 ± 0.01

Table 6: Values of parameters for predictive model

### Influence of Floor area

The value of 0.84 for the floor area parameter means that for every 100m<sup>2</sup> (1,000ft<sup>2</sup>) of floor area added the house's Normalized Leakage gets about 16% lower. It is important to note the limitations of our model here. The Normalized Leakage is normalized by floor area and building height. When we look at the Equivalent Leakage Area (non-Normalized Leakage) predicted by this model we find that the shape of the curve is such that it increases to a point and then decreases at higher areas. Physically, it doesn't make sense for the ELA to decrease with increasing building size so the model shouldn't be used to predict the Normalized Leakage of houses above the inflection point. The regression has set this inflection point at about 400 m<sup>2</sup>, and only 1% of our data are larger than this. In the data we see a flat relationship between area and ELA when houses are larger than 400 m<sup>2</sup>.

### Building Height

The building height parameter,  $\phi_H$ , has a value of 1.16 which means that for a given house the Normalized Leakage increases by 16% if you go from one to two stories, keeping the floor area the same. Because height is one of the parameters used to normalize the leakage it is useful to examine the effect that our model predicts for non-Normalized Leakage. ELA decreases by about 6 % from a 1-story- to a 2-story-building. This makes sense because for the same size of house a two story house will have less surface area, and more of that surface area will be walls.

Leakage often occurs through plumbing and other penetrations through the attic plane, so with smaller attic area we would expect fewer of these penetrations and a relatively tighter building shell. Again, when applying the model to predict Normalized Leakage we need to stay within the range of data used for development of the model. Our dataset contained only ten observations that had more than two stories, thus the predictive model is only applicable to one and two story residences.

### *Energy Efficient Houses*

This result indicates that a house that is part of an energy efficiency program has roughly 60% the leakage of a similar house that is not. For a group of houses,  $P_{Eff}$  can be treated as the probability that a house is part of an energy efficiency program. This result shows that the efforts to make buildings tighter have an effect. Both building types (e-program and non e-program) are represented sufficiently in the database. So the conclusion can be applied to the American housing stock.

### *Testing Age*

For non-low income houses, the age-adjustment factor of 1.01 means that houses get on average a bit over 1% leakier every year. Although this effect looks small it can be quite substantial over the life of the house.

### *Floor leakage*

The floor leakage parameter of 1.08 implies that the buildings in this database are 8% leakier if the building has a crawlspace or an unconditioned basement as opposed to a conditioned basement or slab-on-grade construction.

### *Climate*

The variation from climate zone to climate zone is not very big and shown in Table 6. Buildings in the humid climate are the tightest, explained perhaps because houses in the south east tend to be more often built of concrete block which is generally much tighter than wood frame construction. In the other three climates house tightness varies with climate severity as we expect: Alaska houses are the tightest, followed by houses in the cold climate, and houses in the dry climate are the leakiest.

### *Low Income*

For low-income houses, we use the weatherization dataset to modify the coefficients for climate constants and the coefficients for the age and floor area for low-income-buildings. The values,  $\phi_{LI}$ ,  $\phi_{AgeLI}$ , and  $\phi_{AreaLI}$  (see Table 6) show how an ordinary building differs from a building with low-income residents.

These three terms are raised to the power of  $P_{LI}$  in Equation 16 where  $P_{LI}$  is the probability of the building being low-income or, equivalently, the fraction of similar houses that are low-income. The expression for the constant term of 2.45 is a correction of the constant coefficient  $NL_{cz}$ . This means houses with low-income residents are about 145% leakier than the same house with non-low income residents.

The low income age coefficient is very slightly less than 1 (0.9942) which indicates that houses with low-income residents become slightly less leaky with age than their counterparts with non-low income residents.

The area coefficient, however, shows a marked difference between houses with low-income residents where the Normalized Leakage decreases by 39% per added 100m<sup>2</sup> opposed to houses with non-low income residents where the Normalized Leakage decreases only 16% per added 100m<sup>2</sup>. This shows us that the size of a house makes less difference to it's leakage if it is occupied by low income residents than if it is occupied by non low income residents.

### Comparison to previous work

The R-squared of the core regression is 30%. This is lower than some of our preliminary regressions, but we have added additional data for this regression. In order to compare this model to the previous model described Chan et. al. [2003] which uses only floor area and year built variables to describe the data we needed to run both models on the same data set. So we re-calculated her parameters (shown in Table 7) based on the new data. The new values are very similar to the values that Chan published. In order to compare the two models we calculated the root mean square of the residuals for Chan's model (147.45) and our model (147.02). The values are so similar that we conclude that both models describe the data equally well.

Type	Coefficient	Estimate	Std. Error	t-value	R-squared
<b>Low-income</b>	(Intercept)	$1.09 \times 10^{+1}$	$0.02 \times 10^{+1}$	66.1	0.18
	Year Built	$-5.27 \times 10^{-3}$	$0.08 \times 10^{-3}$	-62.7	
	Floor Area	$-4.25 \times 10^{-3}$	$0.04 \times 10^{-3}$	-98.5	
<b>Ordinary</b>	(Intercept)	$1.75 \times 10^{+1}$	$0.04 \times 10^{+1}$	47.6	0.14
	Year Built	$-9.12 \times 10^{-3}$	$0.18 \times 10^{-3}$	-49.5	
	Floor Area	$-1.67 \times 10^{-3}$	$0.05 \times 10^{-3}$	-35.8	
<b>Energy Program</b>	(Intercept)	$4.13 \times 10^{+1}$	$0.15 \times 10^{+1}$	27.9	0.09
	Year Built	$-2.14 \times 10^{-2}$	$0.07 \times 10^{-2}$	-28.9	
	Floor Area	$-3.22 \times 10^{-4}$	$0.60 \times 10^{-4}$	-5.3	

Table 7: Coefficients of Chan's Model calculated using the new dataset

### Conclusion

Within the scope of this paper a mathematical model to predict the leakage of single-family-buildings was developed. After various regressions to analyze the data a model was fitted which is applicable to the American housing stock within the range of our dataset, defined in Table 8. The model should only be applied to data within these ranges, and it should only be applied to a group of data, and never to just one house.

Variable	# of obs.	Mean	Std. Dev.	Min	Max
<b>Floor Area [m<sup>2</sup>]</b>	97222	143	75	31	1035
<b>Height [m]</b>	97512	3.7	1.3	1.7	12.5
<b>Age Tested</b>	79952	35	33	0	370

Table 8: range of the variables in the model

The most significant building characteristic in determining Normalized Leakage was income of the occupants. Buildings where occupants earn less than 125% of the poverty level differ from

ordinary buildings in being about 145% leakier. It is important to remember that this conclusion is based on data from only the state of Ohio. We assume that the difference between ordinary and low-income houses in that state can be applied to all other states.

The second most significant characteristic is being part of an energy efficiency program. Buildings that are part of such programs are 40% tighter, on average, than their ordinary counterparts. Although the definition has recently changed, the US EPA Energy Star program has historically defined an energy efficient home as one that is 30% more energy efficient than homes built to the 1993 national Model Energy Code [EPA 2006.] The result shows that the efforts to seal building shells in new construction are successful.

Other significant building characteristics are the building age and floor area of the building. The age of the building has what looks like a small effect of 1% increase in Normalized Leakage per year. But since buildings are used on the order of 100 years the influence grows with the time. This is, in fact, a combined effect of aging and of newer houses having more air tight design and construction materials. As we mentioned, it is impossible, given our data, to separate these effects. The Normalized Leakage decreases by 16% for every additional 100 m<sup>2</sup> of floor area in an ordinary house, and by 39% for each additional 100 m<sup>2</sup> in a house occupied by low-income residents.

When all the exponents in the model are set to zero, the Normalized Leakage is predicted in a particular climate zone for a building with a floor area of 100 m<sup>2</sup> and one story high with unknown age, basement type, energy program participation and occupant income. A more precise prediction can be made if information is available for the floor area, building height, building age, basement type, positive confirmation of participation in an energy efficiency program or the income status of the residents.

The regression method requires that the known variables are random, and that the predicted variable be normally distributed. We know that our data are not randomly sampled, because they come from research programs, weatherization programs and energy rating programs, which all have particular criteria for selecting houses. The predicted variable, the logarithm of Normalized Leakage, is close to normally distributed, but is slightly skewed as we saw in Figure 2. The model could be improved by collecting more data in order to make the database more representative. It would also be possible to weight the representative data and un-weight less representative data for the regression. But in order to do this we need to know which data are representative and which are not.

A next step with this model could be the prediction of Normalized Leakage using U. S. Census Bureau Data to find housing characteristics on a county by county basis. The leakage could then be determined on a county by county basis across the United States.

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## **Appendix A - List of sources for the database**

The contributions of the leakage data and the appropriate data were provided by the following organisations and persons:

- 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 Reiler (Sitka, Ak)
- Florida Solar Energy Center
- Guaranteed Wattsavers
- Kansas Energy-Star
- Lawrence Berkeley National Laboratory
- Ohio Home Energy Rating System
- Ohio Weatherization Program
- Vermont Energy Investment Corporation
- Energy Rated Homes of Vermont
- Daran Wastchak, L.L.C.
- Wisconsin Energy Conservation Corporation
- Wisconsin Energy Star Homes

## Appendix B - Table with the standardized results of the regressions 1 to 7

This table shows the normalized results of regressions 1-7. The results of regression 8 were not normalized. We standardized the variables by subtracting the mean from each value and then dividing by the standard deviation of the distribution. In this way the units of each variable are removed, and the distribution of each variable is centred on zero, with a standard deviation of one.

#	Area	$\sigma$	H	$\sigma$	AT	$\sigma$	YB	$\sigma$	FL	$\sigma$	DL	$\sigma$	e-prog.	$\sigma$	LI	$\sigma$
	ln(NL) per m <sup>2</sup>		ln(NL) per m		ln(NL) per year		ln(NL) per year						ln(NL)		ln(NL)	
1	-0.239	0.003	-0.002	0.003	0.978	0.023	0.8	0.2								
	-0.171	0.004	0.114	0.002	0.527	0.026	0.21	0.03								
2	-0.240	0.002			9.292	0.022	0.77	0.02								
	-0.167	0.003	0.134	0.002	0.085	0.013	-0.22	0.01								
3	-0.161	0.003	0.140	0.002	0.119	0.013	-0.19	0.01	-0.014	0.005	-0.139	0.008				
4	-0.116	0.003	0.088	0.002	-0.037	0.012	-0.29	0.01	-0.007	0.005	-0.174	0.007	-0.216	0.003		
5	-0.185	0.002	0.043	0.001	0.170	0.014	0.00	0.01	-0.012	0.003	-0.076	0.005	-0.158	0.002	0.322	0.004
6	-0.116	0.003	0.085	0.002	0.253	0.004					-0.280	0.007	-0.195	0.003		
	-0.121	0.003	0.091	0.002			-0.290	0.004			-0.284	0.007	-0.205	0.003		
7	-0.118	0.003	0.096	0.002	0.243	0.005					-0.259	0.006	-0.202	0.003		

## Appendix C - Table of the non-standardized results of the regressions

This table shows the results of regressions 1-8. The underlined coefficients have a p-test value that is not equal to zero. See Appendix D for P-test and t-test results. The regressions in bold were used in the final result.

#	dataset	description	adj. R <sup>2</sup>	obs.	Root MSE	Area	$\sigma$	H	$\sigma$	AT	$\sigma$	YB	$\sigma$
		units	%		%	ln(NL) per m <sup>2</sup>		ln(NL) per m		ln(NL) per year		ln(NL) per year	
1	ohio	all information known	21.5	50,722	49.82	-0.0044	4.96E-05	<u>-0.003</u>	0.005	0.0349	0.0008	0.029	0.008
	non-o	all information known	36.33	28,908	47.8	-0.0018	3.67E-05	0.130	0.002	0.024	0.001	0.010	0.001
2	ohio	with indicator var.	19.57	50,965	49.88	-0.0044	4.22E-05			0.3312	0.0008	0.0271	0.0008
	non-o	with indicator var.	40.69	43,150	51.39	-0.0020	3.25E-05	0.115	0.002	0.0039	0.0006	-0.0094	0.0006
3	non-o	with floor and duct leakage info	45.72	43,150	49.16	-0.0019	3.14E-05	0.120	0.002	0.0054	0.0006	-0.0080	0.0005
4	non-o	with eprog info	51.38	43,150	46.54	-0.0014	3.07E-05	0.076	0.002	-0.0017	0.0006	-0.0127	0.0005
5	all	together	64.38	94,115	50.24	-0.0025	2.69E-05	0.052	0.002	0.0054	0.0004	0.0001	0.0004
6	non-o	without year built without floor leak.	49.34	43,150	47.50	-0.0014	3.10E-05	0.073	0.002	0.0116	0.0002		
	non-o	without age tested without floor leak.	49.75	43,150	47.32	-0.0014	3.07E-05	0.078	0.002			-0.0125	0.0002
7	non-o	summarized climates	44.96	43,150	49.51	-0.0014	3.25E-05	0.082	0.002	0.0111	0.0002		
<b>8</b>	<b>core</b>	<b>without indicator variables (everyth. known)</b>	<b>30.53</b>	<b>42,874</b>	<b>52.66</b>	<b>-0.0017</b>	<b>3.54E-04</b>	<b>0.058</b>	<b>0.002</b>				
a	non-o	to create the age tested coefficient	30.68	28,908	49.88	-0.0016	3.88E-05	0.113	0.002	<b>0.0117</b>	<b>0.0002</b>		
b	non-o	to create the floor leakage coefficient	49.12	5,646	45.88	-0.0011	7.86E-05	0.102	0.006				
c	ohio	adjusted by low income	19.23	50,722	50.45	<b>-0.0026</b>	<b>4.28E-05</b>			<b>-0.0059</b>	<b>0.0001</b>		

#	dataset	description	FL	$\sigma$	DL	$\sigma$	e-prog.	$\sigma$	LI	$\sigma$	climate		avg. $\sigma$
											average	$\ln(NL)$	
		units					$\ln(NL)$		$\ln(NL)$				
1	ohio	all information known										-55.5	1.6
	non-o	all information known										-17.9	2.4
2	ohio	with indicator var.										-52.1	1.6
	non-o	with indicator var.										18.4	1.1
3	non-o	with floor and duct leakage info	-0.04	0.01	-0.41	0.02						16.6	2.3
4	non-o	with eprog info	-0.02	0.01	-0.51	0.02	-0.432	0.006				25.5	1.1
5	all	together	-0.05	0.01	-0.34	0.02	-0.422	0.006	0.689	0.009	0.3		0.9
6	non-o	without year built without floor leak.			-0.83	0.02	-0.390	0.006				-0.87	0.02
	non-o	without age tested without floor leak.			-0.84	0.02	-0.410	0.006				24.5	0.4
7	non-o	summarized climates			-0.76	0.02	-0.404	0.006				-0.85	0.02
8	core	without indicator variables (everyth. known)					-0.514	0.006				-0.64	0.01
a	non-o	to create the age tested coefficient					-0.285	0.007				0.00	
b	non-o	to create the floor leakage coefficient	0.08	0.01			-0.73	0.01				0.00	
c	ohio	adjusted by low income											

## Appendix D – Complete Regression Results

log:  
 Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression1.log  
 log type: text  
 opened on: 14 Mar 2006, 12:09:11  
 (43150 observations deleted)

Source	SS	df	MS	Number of obs =
Model	3448.78711	5	689.757421	50722
Residual	12587.555	50716	.24819692	F( 5, 50716) = 2779.07
Total	16036.3421	50721	.316167704	Prob > F = 0.0000

R-squared = 0.2151  
 Adj R-squared = 0.2150  
 Root MSE = .49819

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0043536	.0000496	-87.70	0.000	-.0044509 -.0042563
h	-.002629	.0046492	-0.57	0.572	-.0117415 .0064835
age_tested	.0348813	.0008195	42.56	0.000	.033275 .0364876
yrbuilt	.0288605	.0008135	35.48	0.000	.027266 .030455
I_c	-57.22326	1.622429	-35.27	0.000	-60.40324 -54.04328
I_mh	-57.04524	1.622432	-35.16	0.000	-60.22523 -53.86526

(6009 observations deleted)

Source	SS	df	MS	Number of obs =
Model	2994.91187	4	748.727968	44855
Residual	11234.8065	44850	.250497358	F( 4, 44850) = 2988.97
Total	14229.7184	44854	.317245248	Prob > F = 0.0000

R-squared = 0.2105  
 Adj R-squared = 0.2104  
 Root MSE = .5005

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0043383	.0000525	-82.66	0.000	-.0044412 -.0042354
h	-.0032378	.0049888	-0.65	0.516	-.013016 .0065404
age_tested	.0379683	.0008744	43.42	0.000	.0362545 .039682
yrbuilt	.0320809	.0008681	36.96	0.000	.0303795 .0337824
I_c	-63.63869	1.731292	-36.76	0.000	-67.03205 -60.24533

(43150 observations deleted)

(44956 observations deleted)

Source	SS	df	MS	Number of obs =
Model	369.51028	4	92.37757	5867
Residual	1316.56742	5862	.224593554	F( 4, 5862) = 411.31
Total	1686.0777	5866	.28743227	Prob > F = 0.0000

R-squared = 0.2192  
 Adj R-squared = 0.2186  
 Root MSE = .47391

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
------	-------	-----------	---	------	----------------------

area		-.0044507	.0001518	-29.32	0.000	-.0047483	-.0041531
h		.0082592	.0126579	0.65	0.514	-.016555	.0330735
age_tested		.0107333	.0023182	4.63	0.000	.0061886	.0152779
yrbuilt		.0037013	.0022989	1.61	0.107	-.0008053	.0082079
I_mh		-6.932204	4.583573	-1.51	0.130	-15.9177	2.05329

(50965 observations deleted)

Source		SS	df	MS		Number of obs =	28908
Model		3771.53622	10	377.153622		F( 10, 28897) =	1650.43
Residual		6603.51501	28897	.228519051		Prob > F =	0.0000
						R-squared =	0.3635
						Adj R-squared =	0.3633
Total		10375.0512	28907	.358911379		Root MSE =	.47804

lnNL		Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area		-.0017819	.0000367	-48.56	0.000	-.0018538	-.00171
h		.129987	.0017621	73.77	0.000	.1265332	.1334407
age_tested		.0241451	.0012027	20.08	0.000	.0217878	.0265024
yrbuilt		.0095019	.0011771	8.07	0.000	.0071948	.011809
I_sa		-21.02226	2.353686	-8.93	0.000	-25.63559	-16.40893
I_vc		-20.42233	2.353467	-8.68	0.000	-25.03523	-15.80942
I_c		-20.40901	2.352278	-8.68	0.000	-25.01958	-15.79843
I_mhd		-20.27306	2.351621	-8.62	0.000	-24.88235	-15.66378
I_mh		-20.0786	2.350691	-8.54	0.000	-24.68606	-15.47114
I_hh		-20.02156	2.350912	-8.52	0.000	-24.62946	-15.41367
I_m		-19.75631	2.343056	-8.43	0.000	-24.3488	-15.16381
I_unkn		(dropped)					

(39414 observations deleted)

Source		SS	df	MS		Number of obs =	3052
Model		438.680611	4	109.670153		F( 4, 3047) =	426.64
Residual		783.250573	3047	.257056309		Prob > F =	0.0000
						R-squared =	0.3590
						Adj R-squared =	0.3582
Total		1221.93118	3051	.400501863		Root MSE =	.50701

lnNL		Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area		-.0019145	.0001345	-14.23	0.000	-.0021783	-.0016507
h		.1170668	.0061106	19.16	0.000	.1050854	.1290482
age_tested		.0274868	.0038523	7.14	0.000	.0199334	.0350403
yrbuilt		-.0020756	.0036379	-0.57	0.568	-.0092085	.0050574
I_sa		2.138296	7.277123	0.29	0.769	-12.13027	16.40686

(50965 observations deleted)

(19952 observations deleted)

Source		SS	df	MS		Number of obs =	20860
Model		1849.84083	4	462.460208		F( 4, 20855) =	1997.78
Residual		4827.65227	20855	.231486563		Prob > F =	0.0000
						R-squared =	0.2770

```
-----+-----
Total | 6677.4931 20859 .320125275
Adj R-squared = 0.2769
Root MSE = .48113
```

```
-----+-----
lnNL | Coef. Std. Err. t P>|t| [95% Conf. Interval]
-----+-----
area | -.0020843 .0000474 -44.01 0.000 -.0021771 -.0019914
h | .1350201 .0019723 68.46 0.000 .1311541 .1388861
age_tested | .0306998 .0013873 22.13 0.000 .0279807 .033419
yrbuilt | .0152002 .0013397 11.35 0.000 .0125742 .0178261
I_vc | -31.79712 2.678665 -11.87 0.000 -37.04751 -26.54672
```

(50965 observations deleted)

(32952 observations deleted)

```
-----+-----
Source | SS df MS Number of obs = 3548
-----+-----
Model | 456.853345 4 114.213336 F( 4, 3543) = 653.91
Residual | 618.823616 3543 .174660913 Prob > F = 0.0000
-----+-----
Total | 1075.67696 3547 .303263874 R-squared = 0.4247
Adj R-squared = 0.4241
Root MSE = .41792
```

```
-----+-----
lnNL | Coef. Std. Err. t P>|t| [95% Conf. Interval]
-----+-----
area | -.001123 .0000674 -16.67 0.000 -.001255 -.0009909
h | .1150702 .0074686 15.41 0.000 .1004269 .1297134
age_tested | -.0433324 .0074556 -5.81 0.000 -.0579501 -.0287148
yrbuilt | -.0547123 .0074059 -7.39 0.000 -.0692325 -.0401921
I_c | 107.8811 14.79541 7.29 0.000 78.87275 136.8895
```

(50965 observations deleted)

(39788 observations deleted)

```
-----+-----
Source | SS df MS Number of obs = 716
-----+-----
Model | 18.6477544 4 4.66193861 F( 4, 711) = 72.70
Residual | 45.5913897 711 .064122911 Prob > F = 0.0000
-----+-----
Total | 64.2391441 715 .089844957 R-squared = 0.2903
Adj R-squared = 0.2863
Root MSE = .25323
```

```
-----+-----
lnNL | Coef. Std. Err. t P>|t| [95% Conf. Interval]
-----+-----
area | .0000191 .0001919 0.10 0.921 -.0003577 .0003959
h | -.1118513 .0113271 -9.87 0.000 -.1340898 -.0896128
age_tested | -.056733 .0073568 -7.71 0.000 -.0711766 -.0422895
yrbuilt | -.0609028 .0045984 -13.24 0.000 -.0699309 -.0518747
I_mhd | 120.8679 9.196544 13.14 0.000 102.8122 138.9235
```

(50965 observations deleted)

(41874 observations deleted)

Source	SS	df	MS	Number of obs =	386
Model	48.7605944	4	12.1901486	F( 4, 381) =	79.23
Residual	58.6185489	381	.153854459	Prob > F =	0.0000
				R-squared =	0.4541
				Adj R-squared =	0.4484
Total	107.379143	385	.278906866	Root MSE =	.39224

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0020813	.0001578	-13.19	0.000	-.0023915	-.0017711
h	.2067471	.0176369	11.72	0.000	.1720692	.241425
age_tested	.0832178	.0630579	1.32	0.188	-.0407673	.2072029
yrbuilt	-.0330728	.0124179	-2.66	0.008	-.057489	-.0086566
I_mh	64.76293	24.82295	2.61	0.009	15.95581	113.57

(50965 observations deleted)  
(42339 observations deleted)

Source	SS	df	MS	Number of obs =	325
Model	15.2745524	4	3.81863811	F( 4, 320) =	54.37
Residual	22.474522	320	.070232881	Prob > F =	0.0000
				R-squared =	0.4046
				Adj R-squared =	0.3972
Total	37.7490744	324	.116509489	Root MSE =	.26501

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	.0005094	.0001989	2.56	0.011	.000118	.0009008
h	.2674455	.0250376	10.68	0.000	.2181864	.3167046
age_tested	.1519625	.0290334	5.23	0.000	.094842	.209083
yrbuilt	.0142722	.0065784	2.17	0.031	.0013299	.0272145
I_hh	-30.45296	13.1608	-2.31	0.021	-56.34559	-4.56034

(50965 observations deleted)  
(42857 observations deleted)

Source	SS	df	MS	Number of obs =	21
Model	.759679726	4	.189919932	F( 4, 16) =	2.69
Residual	1.12779093	16	.070486933	Prob > F =	0.0686
				R-squared =	0.4025
				Adj R-squared =	0.2531
Total	1.88747065	20	.094373533	Root MSE =	.26549

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0012261	.0010517	-1.17	0.261	-.0034556	.0010034
h	.0261567	.0613708	0.43	0.676	-.1039435	.1562569
age_tested	.0323883	.085135	0.38	0.709	-.1480898	.2128664
yrbuilt	.024657	.0863204	0.29	0.779	-.158334	.2076479
I_m	-49.50859	171.6604	-0.29	0.777	-413.4125	314.3953

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression1.log  
log type: text

closed on: 14 Mar 2006, 12:09:40

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression2.log

log type: text

opened on: 14 Mar 2006, 12:09:44

-> OWP = 1

Source	SS	df	MS	Number of obs		
Model	3446.3439	6	574.39065	50965	F( 6, 50958)	= 2308.35
Residual	12679.9541	50958	.248831471		Prob > F	= 0.0000
Total	16126.298	50964	.31642528		R-squared	= 0.2137
					Adj R-squared	= 0.2136
					Root MSE	= .49883

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0043588	.0000422	-103.29	0.000	-.0044415	-.0042761
AT	.0331244	.0007959	41.62	0.000	.0315643	.0346844
I_at	3.844229	.1679291	22.89	0.000	3.515086	4.173372
I_YB	.027131	.0007901	34.34	0.000	.0255824	.0286796
I_yb	50.39544	1.480275	34.04	0.000	47.49408	53.29679
I_c	-53.7801	1.575603	-34.13	0.000	-56.8683	-50.69191
I_mh	-53.60571	1.575624	-34.02	0.000	-56.69395	-50.51747

(50965 observations deleted)

Source	SS	df	MS	Number of obs		
Model	7822.96895	13	601.766842	43150	F( 13, 43136)	= 2278.28
Residual	11393.5779	43136	.264131534		Prob > F	= 0.0000
Total	19216.5468	43149	.445353237		R-squared	= 0.4071
					Adj R-squared	= 0.4069
					Root MSE	= .51394

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0019596	.0000325	-60.28	0.000	-.0020233	-.0018959
h	.1150814	.0016383	70.24	0.000	.1118702	.1182926
AT	.0038824	.0006124	6.34	0.000	.0026821	.0050828
I_at	.4988667	.0257162	19.40	0.000	.4484624	.5492709
I_YB	-.0094152	.0005686	-16.56	0.000	-.0105298	-.0083007
I_yb	-18.708	1.11831	-16.73	0.000	-20.89991	-16.51609
I_sa	16.9926	1.136984	14.95	0.000	14.76409	19.22111
I_vc	17.54838	1.136923	15.43	0.000	15.31999	19.77677
I_c	17.55038	1.136494	15.44	0.000	15.32283	19.77793
I_mhd	16.84194	1.136895	14.81	0.000	14.6136	19.07027
I_mh	17.74662	1.134337	15.64	0.000	15.52329	19.96994
I_hh	17.46194	1.136314	15.37	0.000	15.23474	19.68914
I_m	17.2574	1.13638	15.19	0.000	15.03007	19.48472
I_unkn	18.05388	1.136812	15.88	0.000	15.82571	20.28205

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression2.log

log type: text  
 closed on: 14 Mar 2006, 12:09:45

log:  
 Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression3.log  
 log type: text  
 opened on: 14 Mar 2006, 12:09:49  
 (50965 observations deleted)

Source	SS	df	MS	Number of obs =	43150
Model	8790.73553	17	517.10209	F( 17, 43132) =	2139.27
Residual	10425.8113	43132	.241718707	Prob > F =	0.0000
				R-squared =	0.4575
				Adj R-squared =	0.4572
Total	19216.5468	43149	.445353237	Root MSE =	.49165

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0018864	.0000314	-60.00	0.000	-.0019481 - .0018248
h	.1199073	.0015742	76.17	0.000	.1168219 .1229927
AT	.0054419	.0005903	9.22	0.000	.0042849 .006599
I_at	.4745373	.0246488	19.25	0.000	.4262252 .5228495
I_YB	-.0080197	.0005485	-14.62	0.000	-.0090948 -.0069447
I_yb	-15.8965	1.078615	-14.74	0.000	-18.01061 -13.7824
FL	-.0394595	.0148887	-2.65	0.008	-.0686416 -.0102774
I_f	-.2605137	.0145842	-17.86	0.000	-.2890991 -.2319284
DL	-.4099247	.0229058	-17.90	0.000	-.4548206 -.3650288
I_d	.2905532	.0174694	16.63	0.000	.2563128 .3247937
I_sa	14.12794	1.097545	12.87	0.000	11.97673 16.27915
I_vc	14.67355	1.09747	13.37	0.000	12.52249 16.82462
I_c	14.7045	1.096873	13.41	0.000	12.5546 16.85439
I_mhd	14.49288	1.097219	13.21	0.000	12.34231 16.64346
I_mh	14.91683	1.095049	13.62	0.000	12.77051 17.06315
I_hh	15.13261	1.096763	13.80	0.000	12.98294 17.28229
I_m	14.46662	1.096551	13.19	0.000	12.31736 16.61588
I_unkn	15.20704	1.09689	13.86	0.000	13.05711 17.35696

log:  
 Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression3.log  
 log type: text  
 closed on: 14 Mar 2006, 12:09:50

log:  
 Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression4.log  
 log type: text  
 opened on: 14 Mar 2006, 12:09:54  
 (50965 observations deleted)

Source	SS	df	MS	Number of obs =	43150
Model	9876.61184	18	548.700658	F( 18, 43131) =	2533.85
Residual	9339.93498	43131	.216548074	Prob > F =	0.0000
				R-squared =	0.5140
				Adj R-squared =	0.5138
Total	19216.5468	43149	.445353237	Root MSE =	.46535

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
------	-------	-----------	---	------	----------------------

area	-.0013535	.0000307	-44.09	0.000	-.0014137	-.0012933
h	.0755294	.0016164	46.73	0.000	.0723612	.0786975
AT	-.0016929	.0005678	-2.98	0.003	-.0028057	-.0005801
I_at	.2117575	.0236235	8.96	0.000	.1654551	.25806
YB	-.0126997	.0005233	-24.27	0.000	-.0137254	-.0116739
I_yb	-25.02264	1.029015	-24.32	0.000	-27.03953	-23.00575
FL	-.0192556	.0140951	-1.37	0.172	-.0468822	.008371
I_f	-.3082791	.0138205	-22.31	0.000	-.3353675	-.2811907
DL	-.5113452	.0217277	-23.53	0.000	-.5539319	-.4687584
I_d	.0124606	.0169948	0.73	0.463	-.0208496	.0457708
eprog	-.4321517	.0061027	-70.81	0.000	-.4441132	-.4201903
I_sa	24.09063	1.048314	22.98	0.000	22.03591	26.14534
I_vc	24.60848	1.048191	23.48	0.000	22.554	26.66295
I_c	24.5273	1.047419	23.42	0.000	22.47434	26.58027
I_mhd	24.494	1.048081	23.37	0.000	22.43974	26.54826
I_mh	24.64762	1.045537	23.57	0.000	22.59835	26.6969
I_hh	25.03695	1.04747	23.90	0.000	22.98389	27.09001
I_m	24.4073	1.04734	23.30	0.000	22.3545	26.46011
I_unkn	25.05098	1.047475	23.92	0.000	22.99791	27.10405

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression4.log

log type: text

closed on: 14 Mar 2006, 12:09:55

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression5.log

log type: text

opened on: 14 Mar 2006, 12:09:59

Source	SS	df	MS	Number of obs =	94115
Model	42953.4689	19	2260.70889	F( 19, 94095) =	8955.19
Residual	23753.9869	94095	.252446855	Prob > F =	0.0000
				R-squared =	0.6439
				Adj R-squared =	0.6438
Total	66707.4558	94114	.708794183	Root MSE =	.50244

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0025023	.0000269	-93.09	0.000	-.002555 - .0024496
h	.0519382	.0015865	32.74	0.000	.0488288 .0550477
AT	.0054197	.0004436	12.22	0.000	.0045502 .0062892
I_at	.4610627	.022625	20.38	0.000	.4167179 .5054075
YB	.0001015	.0004353	0.23	0.816	-.0007517 .0009547
I_yb	.1757688	.8550894	0.21	0.837	-1.500197 1.851735
FL	-.0543379	.0149671	-3.63	0.000	-.0836732 -.0250025
I_f	-.3626044	.0141717	-25.59	0.000	-.3903807 -.3348281
DL	-.3443546	.0229151	-15.03	0.000	-.3892681 -.2994412
I_d	.126643	.0181193	6.99	0.000	.0911293 .1621567
eprog	-.4218036	.0063925	-65.98	0.000	-.4343329 -.4092743
OWP	.6893771	.0085315	80.80	0.000	.6726555 .7060987
I_sa	-1.24745	.8716789	-1.43	0.152	-2.955931 .4610316
I_vc	-.7280879	.871558	-0.84	0.404	-2.436332 .9801562
I_c	-.6716203	.8707128	-0.77	0.441	-2.378208 1.034967
I_mhd	-.8473643	.871601	-0.97	0.331	-2.555693 .8609642

I_mh		-.498568	.8705385	-0.57	0.567	-2.204814	1.207678
I_hh		-.2702527	.8711514	-0.31	0.756	-1.9777	1.437195
I_m		-.8122206	.8716544	-0.93	0.351	-2.520654	.8962126
I_unkn		-.2176131	.8709985	-0.25	0.803	-1.924761	1.489535

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression5.log  
log type: text  
closed on: 14 Mar 2006, 12:10:00

log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression6.log  
log type: text  
opened on: 14 Mar 2006, 12:10:04  
(50965 observations deleted)

Source	SS	df	MS	Number of obs =	43150
Model	9484.09625	14	677.435447	F( 14, 43135) =	3002.45
Residual	9732.45056	43135	.225627694	Prob > F =	0.0000
				R-squared =	0.4935
				Adj R-squared =	0.4934
				Root MSE =	.475
Total	19216.5468	43149	.445353237		

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.001354	.000031	-43.63	0.000	-.0014148 - .0012931
h	.0730916	.0016453	44.43	0.000	.0698669 .0763164
AT	.0115873	.0002002	57.87	0.000	.0111948 .0119797
I_at	.7098758	.0070239	101.07	0.000	.6961088 .7236429
DL	-.825268	.0192796	-42.81	0.000	-.8630564 -.7874797
I_d	-.2057197	.0153738	-13.38	0.000	-.2358527 -.1755868
eprog	-.389691	.0061196	-63.68	0.000	-.4016855 -.3776966
I_sa	-1.392192	.020066	-69.38	0.000	-1.431521 -1.352862
I_vc	-.880287	.0190594	-46.19	0.000	-.9176438 -.8429301
I_c	-.990322	.0175133	-56.55	0.000	-1.024648 -.9559955
I_mhd	-1.054638	.0210255	-50.16	0.000	-1.095849 -1.013428
I_mh	-.6636532	.019602	-33.86	0.000	-.7020734 -.6252329
I_hh	-.458584	.0255108	-17.98	0.000	-.5085858 -.4085823
I_m	-1.139075	.0331251	-34.39	0.000	-1.204001 -1.07415
I_unkn	-.5492496	.0337859	-16.26	0.000	-.6154706 -.4830286

Source	SS	df	MS	Number of obs =	43150
Model	9556.76745	14	682.626246	F( 14, 43135) =	3048.21
Residual	9659.77937	43135	.223942955	Prob > F =	0.0000
				R-squared =	0.4973
				Adj R-squared =	0.4972
				Root MSE =	.47323
Total	19216.5468	43149	.445353237		

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0014213	.0000307	-46.32	0.000	-.0014815 - .0013612
h	.0778014	.0016342	47.61	0.000	.0745983 .0810045
YB	-.0125191	.0001788	-70.03	0.000	-.0128695 -.0121687

I_yb		-24.34148	.3549566	-68.58	0.000	-25.0372	-23.64576
DL		-.8378601	.0193099	-43.39	0.000	-.8757079	-.8000122
I_d		-.2182162	.0153402	-14.23	0.000	-.2482833	-.1881491
eprog		-.410248	.0060629	-67.67	0.000	-.4221314	-.3983646
I_sa		23.66479	.3573766	66.22	0.000	22.96433	24.36526
I_vc		24.17206	.3576374	67.59	0.000	23.47108	24.87303
I_c		24.0717	.3550929	67.79	0.000	23.37571	24.76769
I_mhd		24.03704	.3568936	67.35	0.000	23.33752	24.73656
I_mh		24.40183	.3551675	68.71	0.000	23.7057	25.09797
I_hh		24.59992	.3576326	68.79	0.000	23.89896	25.30089
I_m		24.13155	.3541066	68.15	0.000	23.43749	24.8256
I_unkn		24.50218	.3570192	68.63	0.000	23.80242	25.20195

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log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression6.log  
log type: text  
closed on: 14 Mar 2006, 12:10:05

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log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression7.log  
log type: text  
opened on: 14 Mar 2006, 12:10:09  
(50965 observations deleted)

Source	SS	df	MS	Number of obs =	43150
Model	8641.57304	11	785.597549	F( 11, 43138) =	3204.65
Residual	10574.9738	43138	.245142885	Prob > F =	0.0000
Total	19216.5468	43149	.445353237	R-squared =	0.4497
				Adj R-squared =	0.4496
				Root MSE =	.49512

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0013796	.0000325	-42.48	0.000	-.0014432 - .0013159
h	.0821337	.0017073	48.11	0.000	.0787875 .08548
AT	.0111427	.0002091	53.28	0.000	.0107328 .0115526
I_at	.677965	.0072154	93.96	0.000	.6638227 .6921072
DL	-.7644717	.0185183	-41.28	0.000	-.800768 -.7281755
I_d	-.1735259	.0157953	-10.99	0.000	-.2044849 -.1425668
eprog	-.4038536	.0063232	-63.87	0.000	-.4162471 -.39146
I_humid	-.6185201	.0195148	-31.69	0.000	-.6567694 -.5802708
I_dry	-1.097901	.0208282	-52.71	0.000	-1.138725 -1.057077
I_alaska	-1.009366	.019543	-51.65	0.000	-1.047671 -.9710616
I_cold	-1.025855	.0181341	-56.57	0.000	-1.061399 -.9903124
I_unkn	-.5857182	.0351498	-16.66	0.000	-.6546126 -.5168239

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log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression7.log  
log type: text  
closed on: 14 Mar 2006, 12:10:09

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log:

Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression8.log  
log type: text  
opened on: 14 Mar 2006, 12:10:14  
(276 observations deleted)

-> nonO = 1

Source	SS	df	MS	Number of obs =	42874
Model	5740.04571	6	956.674285	F( 6, 42867) =	3142.68
Residual	13049.3066	42867	.304413807	Prob > F =	0.0000
				R-squared =	0.3055
				Adj R-squared =	0.3054
Total	18789.3524	42873	.438256067	Root MSE =	.55174

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0017372	.0000354	-49.12	0.000	-.0018065	-.0016679
h	.058066	.0018152	31.99	0.000	.0545081	.0616238
eprog	-.5143286	.0064425	-79.83	0.000	-.526956	-.5017012
I_humid	-.3560121	.0146004	-24.38	0.000	-.3846291	-.3273951
I_dry	-.8943106	.0125962	-71.00	0.000	-.9189994	-.8696217
I_alaska	-.8730227	.0100414	-86.94	0.000	-.8927041	-.8533413
I_cold	-.49782	.0102282	-48.67	0.000	-.5178675	-.4777725

Variable	Obs	Mean	Std. Dev.	Min	Max
age_tested	28908	5.548914	15.38079	0	170

Variable	Obs	Mean	Std. Dev.	Min	Max
DL	4996	.7345877	.4415967	0	1

Variable	Obs	Mean	Std. Dev.	Min	Max
FL	5646	.6710946	.4590827	0	1

-> nonO = 1

Source	SS	df	MS	Number of obs =	28908
Model	3185.20489	7	455.029269	F( 7, 28900) =	1829.02
Residual	7189.84634	28900	.24878361	Prob > F =	0.0000
				R-squared =	0.3070
				Adj R-squared =	0.3068
Total	10375.0512	28907	.358911379	Root MSE =	.49878

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
area	-.0016008	.0000388	-41.26	0.000	-.0016769	-.0015248
h	.1130956	.0019851	56.97	0.000	.1092047	.1169865
eprog	-.2852972	.0073955	-38.58	0.000	-.2997927	-.2708017
age_tested	.0117431	.0002251	52.17	0.000	.0113019	.0121842
I_humid	-.8288597	.0220569	-37.58	0.000	-.8720923	-.7856271
I_dry	-1.055095	.0210624	-50.09	0.000	-1.096379	-1.013812
I_alaska	-1.350404	.0115028	-117.40	0.000	-1.37295	-1.327858
I_cold	-1.234993	.0156512	-78.91	0.000	-1.26567	-1.204316

Source	SS	df	MS	Number of obs =	4996
Model	593.31362	6	98.8856034	F( 6, 4989) =	724.42
Residual	681.018109	4989	.13650393	Prob > F =	0.0000
-----				R-squared =	0.4656
-----				Adj R-squared =	0.4649
Total	1274.33173	4995	.255121467	Root MSE =	.36946

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0010278	.0000695	-14.79	0.000	-.0011641 - .0008915
h	.0760192	.0055779	13.63	0.000	.0650841 .0869543
eprog	-.5824843	.0160669	-36.25	0.000	-.6139824 -.5509862
DL	-.1470902	.0157145	-9.36	0.000	-.1778976 -.1162829
I_humid	-.5684585	.0281667	-20.18	0.000	-.6236776 -.5132395
I_dry	-.9951699	.0294188	-33.83	0.000	-1.052844 -.9374961
I_alaska	(dropped)				
I_cold	-.7514015	.0304725	-24.66	0.000	-.811141 -.6916621

Source	SS	df	MS	Number of obs =	5646
Model	1148.66866	7	164.095523	F( 7, 5638) =	779.54
Residual	1186.81459	5638	.210502765	Prob > F =	0.0000
-----				R-squared =	0.4918
-----				Adj R-squared =	0.4912
Total	2335.48325	5645	.413725997	Root MSE =	.45881

lnNL	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0011218	.0000786	-14.28	0.000	-.0012758 -.0009677
h	.1019827	.0057688	17.68	0.000	.0906735 .1132918
eprog	-.7327949	.0132403	-55.35	0.000	-.7587509 -.7068389
FL	.0756503	.0144094	5.25	0.000	.0474025 .1038982
I_humid	-.4126376	.0250786	-16.45	0.000	-.4618013 -.363474
I_dry	-.6279918	.2058411	-3.05	0.002	-1.03152 -.224464
I_alaska	-.1914362	.0250512	-7.64	0.000	-.2405463 -.1423262
I_cold	-.7946466	.0283261	-28.05	0.000	-.8501767 -.7391164

-> Oh = 1

Source	SS	df	MS	Number of obs =	50722
Model	3074.46473	2	1537.23236	F( 2, 50719) =	6040.79
Residual	12906.742	50719	.254475482	Prob > F =	0.0000
-----				R-squared =	0.1924
-----				Adj R-squared =	0.1923
Total	15981.2067	50721	.315080671	Root MSE =	.50446

dif	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
area	-.0025546	.0000428	-59.73	0.000	-.0026384 -.0024708
age_tested	-.0058538	.0000838	-69.87	0.000	-.006018 -.0056896
_cons	.8291634	.005906	140.39	0.000	.8175876 .8407392

log:  
Y:\Residential\Leakage\_Database\2005\_melanie\new\_analysis\_2006\Regression8.log  
log type: text  
closed on: 14 Mar 2006, 12:10:18



**The Air Infiltration and Ventilation Centre** was inaugurated through the International Energy Agency and is funded by the following countries:

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The Centre provides technical support in air infiltration and ventilation research and application. The aim is to provide an understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

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