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Ventilation-Energy Liabilities in US Dwellings

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VENTILATION-ENERGY LIABILITIES IN U.S. DWELLINGS[1]

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The role of ventilation in the housing stock is to provide fresh air and to dilute internally-generated pollutants in order to assure adequate indoor air quality. Providing this ventilation service requires energy either directly for moving the air or indirectly for conditioning the outdoor air for thermal comfort. Different kinds of ventilation systems have different energy requirements. Existing dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by mechanical ventilation systems. The purpose of this report is to ascertain, from best available data, the energy liability associated with providing the current levels of ventilation and to estimate the energy savings or penalties associated with tightening or loosening the building envelope. Various ASHRAE Standards (e.g., 62, 119, and 136) are used to determine acceptable ventilation levels and energy requirements. Building characteristics, energy use, and building tightness data are combined to estimate both the energy liabilities of ventilation and its dependance on building stock characteristics. The average annual ventilation energy use for a typical dwelling is about 46 GJ (roughly 50% of total energy usage); the cost-effective savings potential is about 28 GJ. The associated total annual ventilation energy use for the residential stock is about 3 EJ (ExaJoules).

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LIST OF SYMBOLS

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

INTRODUCTION

Infiltration and ventilation in dwellings is conventionally believed to account for 1/3 to 1/2 of the space conditioning energy. There is not a great deal of measurement data or analysis to substantiate this assumption. As energy conservation improvements to the thermal envelope continue, the fraction of energy consumed by the conditioning of air may increase. Air-tightening programs, while decreasing energy requirements, have the tendency to decrease ventilation and its associated energy penalty at the possible expense of adequate indoor air quality.

In evaluating energy efficiency opportunities, the United States Department of Energy and others need to put into perspective the energy and indoor air quality liabilities associated with residential ventilation. The purpose of this report is to use existing data to estimate these liabilities in the current U.S. housing stock as well as scenarios based on energy conservation and ventilation strategies.

Because of the lack of direct measurements, we cannot approach this as a direct data analysis task. Rather, we approach this objective as a simplified modeling task using the existing sources of data as inputs to the model. The LBL infiltration model[14] and its derivatives will be used as the basis for the calculation.

DATA SOURCES

For any one house, a straightforward modeling approach can be used to determine the heating and cooling demand as well as the effective air change rate. Applying this to each of the almost 75 million single-family households in the U.S. would require more data and manpower resources than currently exist. The approach we use instead, is to take the sources of data available and combine them at an appropriate level of detail using database management tools.

Putting all of the data sources together we can determine for each county the number of houses (from the U.S. Census[7]), the type and sizes of houses (from the Residential Energy Consumption Survey, RECS[18]), the leakage properties (from the AIVC Leakage Database[10]) and the representative weather conditions.[2,8] From the analysis of this data, data average and aggregate quantities are developed for the nation as a whole. Following are descriptions of each of the data sources.

CENSUS DATA

The Constitution of the United States[19] requires that a complete population census be completed every decade. The results of the 1990 Census[7] have recently become available. Among other information, the data contains information on the number, type (single-family detached, single-family attached, etc.) and location of each building. The data is broken down into nine census divisions as well as down to the state, county and, eventually, the block level. We can use this data to determine the number of each type of buildings on any geographic scale we desire; however, the data does not contain information about specific building characteristics.

As the census dataset contains more geographic detail than could profitably be used in this project, we decided to use the county-level of detail as our finest detail. There are 3413 counties which span the U.S. having an average of 33,000 residential buildings (23,000 single family buildings). For each county we use the census data to determine the building stock and the number of buildings broken down by the number of units in each building. We will only be using single-family buildings (single family detached, single family attached and mobile homes) for this study, which make up 86% of the total U.S. residential building floor area.

RECS DATA

The Residential Energy Consumption Survey[18] 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 5100 observations, each of which has approximately 1000 reported survey values regarding energy conservation and building characteristics. The survey contains information on building size and shape, the type, details, and use of heating and cooling systems, indications of the level of air tightness, as well as age and geographic location of each representative building.

We have broken the dataset up into 32 different types of houses: old vs. new (using 1970 as a dividing point); single-story vs. multistory; poor condition vs. good condition; duct systems vs. none; and floor leakage vs. no floor leakage. The RECS data is used to determine, for each census division, the floor area and percentage of air conditioning use for each of the 32 house types. The smallest, statistically significant geographical breakdown in the RECS data is the census division. Therefore the properties of the housing stock are separately determined for each of the nine census divisions. Every county within a given division is assumed to have the same relative distribution of housetypes, where the number of houses in each county is determined from the Census data.

LEAKAGE DATA

While the RECS data contains some indications of air tightness, it does not contain quantitative values which could be used as part of this modeling effort. Several years ago LBL compiled a database on measured air tightness for the U.S.[17] which has since been included in the AIVC numerical database[10]. The dataset contains the measured air tightness, *NL*, as well as a general description of the building which allows estimates of leakage distribution, *R* & *X*, and condition.

In contrast to the census data, the leakage data is very sparse. The current database consists of approximately 500 measured U.S. single-family houses. This sample was a sample of convenience and therefore cannot be said to be statistically representative. Although more measurements have been made, this data set represents the best available compilation. Of the complete dataset, 242 houses meet the criteria of the 32 house types and are used to estimate national average leakage characteristics for each house type.

WEATHER DATA

Representative weather data is necessary to run any infiltration model. LBL has a library of approximately 240 representative weather sites across the country. These weather files have been selected to be representative of typical years for each site and are derived from the WYEC (Weather Year for Energy Calculations), TMY (Typical Meteorological Year), TRY (Typical Reference Year)[2] and CTZ (California Climate Zones)[8] weather tapes. For each county, the most representative weather site was chosen, based primarily on geography. Each weather file contain outside temperature and humidity, wind speed and direction and barometric pressure.

MODELING TOOLS

In order to use this information we must have a way of predicting instantaneous ventilation rates and deriving the corresponding seasonal and annual air change rates and ventilation energy requirements. The fundamental relationship between the infiltration and the house and climate properties is expressed by the LBL infiltration model[15], which is incorporated into the ASHRAE Handbook of Fundamentals[1]. The LBL infiltration model is used to generate, on an hourly basis, specific infiltration and air flow rates. From these hourly results, seasonal average air change rates and corresponding energy consumption, as well as overall measures of tightness (ASHRAE Standard 119)[5] and rates for adequate ventilation (ASHRAE Standard 62)[4] are determined.

LBL INFILTRATION MODEL

The LBL infiltration model[15] calculates specific infiltration rate, *s[h]*, as:

$$s[h] = \sqrt{f_s^2 \cdot \Delta T[h] + f_w^2 \cdot v^2[h]} \qquad \text{(EQ 1)}$$

where the stack and wind factors (f_s and f_w respectively) are a function of building properties and are calculated as shown in Equation 2 and Equation 3.

$$f_s = \left(\frac{1+\frac{R}{2}}{3}\right)\left(1-\frac{X^2}{(2-R)^2}\right)^{\frac{3}{2}}\left(\frac{g \cdot H}{T_o}\right)^{\frac{1}{2}} \qquad \text{(EQ 2)}$$

where R and X are measures of leakage distribution, H is the height of the building and T_o is the outside drybulb temperature.

$$f_w = C'(1-R)^{\frac{1}{3}} A \left(\frac{H}{10m}\right)^{B} \qquad \text{(EQ 3)}$$

where C′ can be found from Table 1, "Shielding Parameters," as a function of shielding class, and A and B can be found from Table 2, "Terrain Parameters," as a function of terrain class.

Table 1: Terrain Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
A	1.30	1.00	0.85	0.67	0.47
B	0.10	0.15	0.20	0.25	0.35

Table 2: Shielding Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
C'	0.34	0.30	0.25	0.19	0.11

The hourly infiltration rate is calculated using the following relationship:

$$Q[h] = ELA \cdot s[h] \qquad \text{(EQ 4)}$$

The effective leakage area, *ELA*, quantifies the absolute size of the openings in the building and for the LBL infiltration model is determined by summing the respective component leakage areas of a specific building. A better measure of the relative tightness, however, is the normalized leakage as defined in ASHRAE Standard 119[5]:

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3} \qquad \text{(EQ 5)}$$

Effective Air Change Rate

The equations above allow the calculation of instantaneous air change rates. A simple average of these values has, unfortunately, no physical significance whatsoever[16]. The effective air change rate is calculated by a process similar to that used in ASHRAE Standard 136-93[6]:

$$ACH = 1.44 \cdot w \cdot NL \qquad \text{(EQ 6)}$$

where:

$$w = \frac{N}{\sum_{h=1}^{N} \frac{1}{s[h]}} \qquad \text{(EQ 7)}$$

Seasonal Energy Use

The energy used to condition air depends on the temperature or enthalpy difference between the infiltrating and exfiltrating air. Since the driving forces for infiltration also depend on the temperature difference, the relationship is non-linear.

A simplified method for treating this non-linearity is to create a statistic that quantifies the infiltration-related climate. One method[13] creates such a statistic, called Infiltration Degree-Days(*IDD*). During the heating season the IDDs can be calculated by summing over each heating hour:

$$IDD_{heating}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (TH - T[h]) \quad \text{(EQ 8)}$$

where TH is the indoor heating temperature setpoint (19 °C), $T[h]$ is the outside dry-bulb temperature and s_o=0.71 m/s.

For the cooling season, as latent cooling loads may be quite important, both latent and sensible cooling loads must be considered. The IDDs for each hour should be taken as the larger of the two values:

$$IDD_{cooling\,(sensible)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (T[h] - TC) \quad \text{(EQ 9)}$$

where TC is the cooling setpoint temperature (25°C).

$$IDD_{cooling\,(latent)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot \frac{HO[h] - HI}{C_p} \quad \text{(EQ 10)}$$

where HO is the enthalpy of the outside air and HI is the enthalpy of the indoor air (set to a default for each census division, based on DOE-2[9] modeling results).

Hours of heating, cooling and ventilation are determined based on outside temperature conditions. The building is modeled in heating mode when the outside temperature is below 19 °C and in cooling mode when the outside temperature is greater than 25°C. When the external conditions meet the ASHRAE comfort requirements[3], it is assumed that the occupants open their windows. When in ventilation mode, the effective leakage area is increased by a factor of 100 to reflect the opening of windows.

The total number of IDDs (both heating and cooling) is a good estimate of the energy intensity of the climate with respect to infiltration. The annual energy intensity, reflecting heating and cooling energy consumption, can be calculated from the normalized leakage and the number of infiltration degree days:

$$E/(Af) = 86.4 \cdot s_o \cdot \rho C_p \cdot NL \cdot IDD \quad \text{(EQ 11)}$$

where the coefficient 86.4 has the units of s/day. Ventilation mode, as modeled with natural ventilation, does not carry any energy liabilities.

Compliance with ASHRAE Standards

Compliance is checked with two ASHRAE standards: Standard 119[5], the tightness standard, and Standard 62[4], the ventilation standard.

ASHRAE Standard 119 relates normalized leakage to infiltration degree-days. The standard can be expressed[12] in the following form:

$$NL \leq \frac{2000}{IDD} \tag{EQ 12}$$

where the denominator is the total number of IDDs for heating and cooling. A building is considered to be in compliance with the tightness standard when the above relationship is true.

The effective air change rate, as calculated using Equation 6, is the value of the air change rate that should be used in determining compliance with minimum ventilation requirements. ASHRAE Standard 62 sets minimum air change rate requirements, for residences, of 0.35 air changes per hour. If we use Equation 6 to represent the effective minimum air change rate then the requirement becomes:

$$w \cdot NL \geq 0.24 \tag{EQ 13}$$

A building is considered to be in compliance with the ventilation standard when the above relationship is true. It should be noted, for smaller residences, that the additional requirement of a minimum of 7.5 l/s per occupant must also be met in order to meet compliance.

RESULTS

The houses used in this analysis are selected to reflect the current U.S. single family housing stock, including almost 75 million households (86% of the total U.S. residential housing floor area). Thirty-two housetypes are developed based on the RECS data for each of the nine census divisions. House floor areas range from 92 to 335 m^2 with a national average of 193 m^2. The percentage of houses having air conditioning varies from housetype to housetype and from division to division. By division, average percentage of houses with air conditioning ranges from 22% to 72%. Nationally, the average percentage of houses with air conditioning is 50%. Normalized leakage factors (*NL*) range from 0.24 to 1.70 for the 32 housetypes. Shielding and terrain classes of III are assumed for all locations.

The scenario described above can be considered as the base case in that it represents our best estimate of the housing stock. The same approach can be used to consider alternative scenarios to consider either policy options or the impact of various technologies on indoor air quality and energy consumption.

In developing a national infiltration energy picture, we have explored two additional scenarios: the "119 Case" and the "62 Case". For the "119 Case," any houses that do not meet the tightness standard are tightened to meet the standard.

Conversely, for the "62 Case," any houses that do not meet the ventilation standard are loosened unit they meet the standard.

Using the characteristics of the housing stock described above, for each of the three scenarios, we have derived corresponding infiltration energy consumption, ventilation rates and percent of houses complying with ASHRAE standards 119 and 62. The results from our three scenarios follow:

Base Case: Current U.S. Single Family Housing Stock

Our results would indicate that the national average effective annual air change rate is 0.83 ACH with a 19% standard deviation, based on county-averaged air change rates. Of real importance, however, is the compliance with the tightness and ventilation standards, Standards 119 and 62 respectively. Table 3, "Percent of U.S. Houses Meeting ASHRAE Standards," shows the percentages of houses which comply with these Standards.

TABLE 3. Percent of U.S. Houses Meeting ASHRAE Standards

Standard	% of Houses
Standard 62 Only	50.2
Both Standards	37.6
Standard 119 Only	12.1
Neither Standard	0.1

} 88houses% Meet 62

} 50% Meet 119

Due to the looseness of the U.S. housing stock, 88% of the base case houses meet Standard 62, the standard for adequate ventilation. Conversely, 50% of the houses meet Standard 119, the tightness standard. Of interest is the 38% of houses which meet both standards, implying that some balance between lower energy consumption and increased indoor air quality has been achieved for certain climates. Only a small portion of houses meet neither standard, being too loose to meet the tightness standard but not loose enough to meet the ventilation standard.

The map in Figure 1, shows the geographic distribution of the percentages of houses which meet Standard 119, based on county-wide averages. In colder climates, less than 20 percent of the houses meet the tightness standard, driven by the higher number of infiltration degree days in the cooler climates. In the warmer climates over 80 percent of the houses meet the tightness standard, reflecting the milder climate and hence lower infiltration degree days.

There is very little variation in the geographic distribution of the percent of houses meeting Standard 62 is relatively flat and, thus, shows no obvious trends.

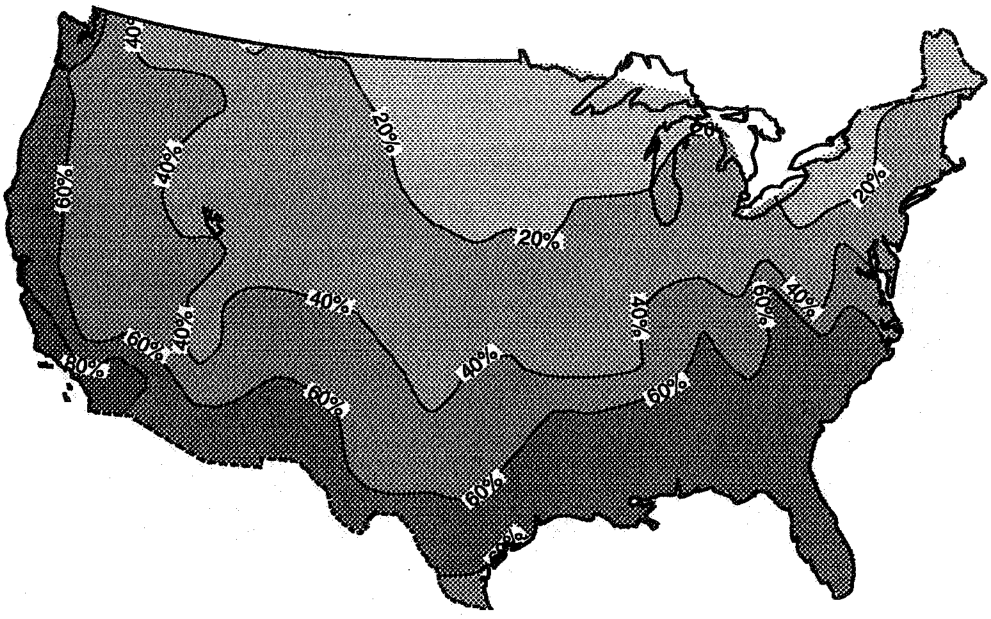

FIGURE 1: Base Case - Percent of Houses Meeting ASHRAE Standard 119

By determining infiltration energy consumption on a county-by-county basis, we are able to evaluate trends in distribution and magnitudes of energy consumption. By mapping the energy density, in GJ/house/year, as shown in Figure 2, we see that county-averaged infiltration energy consumption ranges from less than 20 GJ/house/year in the milder climates to over 100 GJ/house/year in more severe climates. On average, infiltration energy consumption is 46 GJ/Year/House.

119 Case: Tighten Houses to Meet ASHRAE Standard 119

The "119 Case" assumes that ASHRAE Standard 119 is instantaneously implemented in any house in the current stock that needs it. In this case any house that was leakier than Standard 119 would have to be tightened until it met the standard. This is an energy savings strategy, but may compromise indoor air quality. The national average effective annual air change rate is smaller than that of the base case, at 0.34 ACH with a 20% standard deviation. The percentage of houses that meet Standard 119 increases from less than 50% to 100% (of course). The corresponding percentage of houses which meet Standard 62 drops from 88% to 49%, which is not surprising. As can be seen from the map in Figure 3, less than 20% of the houses in the colder climates meet Standard 62. In the warmer climates, over 80% of the houses are in compliance. This finding suggests that natural ventilation will be adequate in mild climates, but infiltration alone will not be adequate in more severe climates.

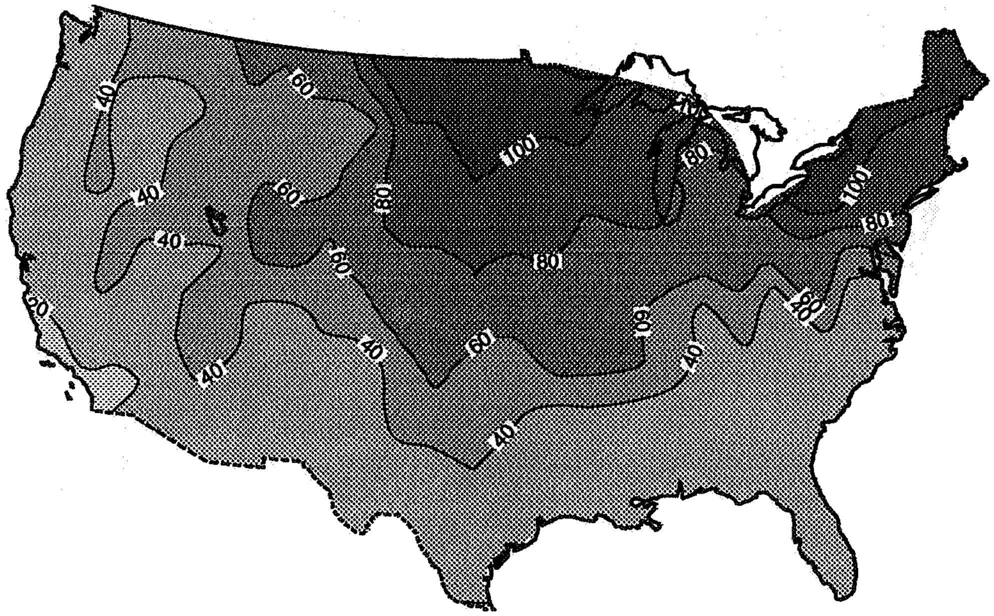

FIGURE 2: Base Case - Infiltration Energy Consumption (GJ/house/year)

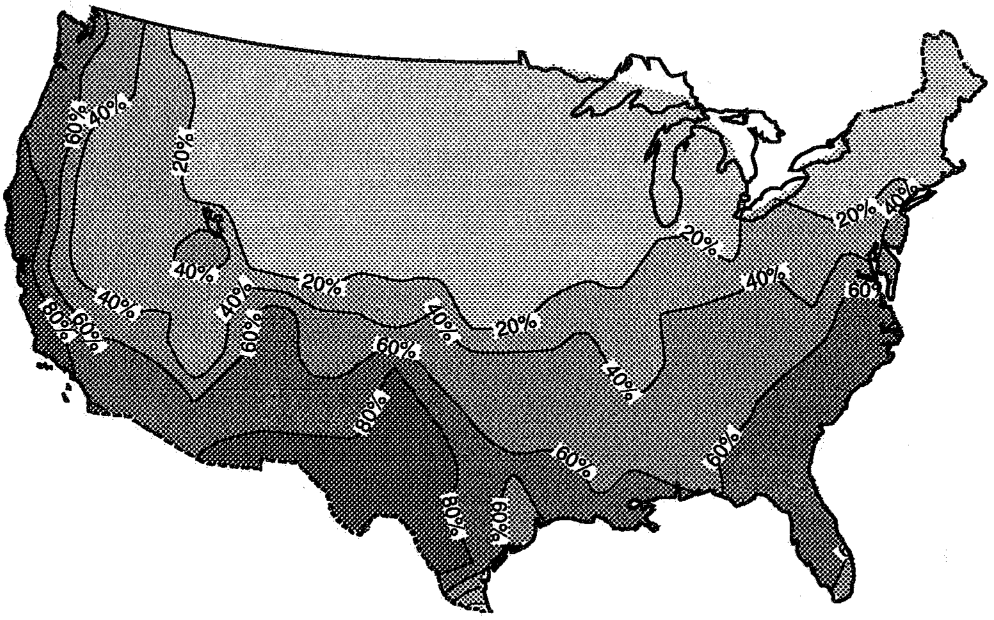

FIGURE 3: 119 Case - Percent of Houses Meeting ASHRAE Standard 62

When houses are tightened to meet ASHRAE Standard 119, national infiltration energy consumption drops sharply, from a total of 3.4 EJ/Year (an average of 46 GJ/house/year) to 1.3 EJ/Year (18 GJ/house/year). The distribution of county-averaged infiltration energy consumption, as shown in Figure 4, ranges from less than 15 to more than 25 GJ/house/year.

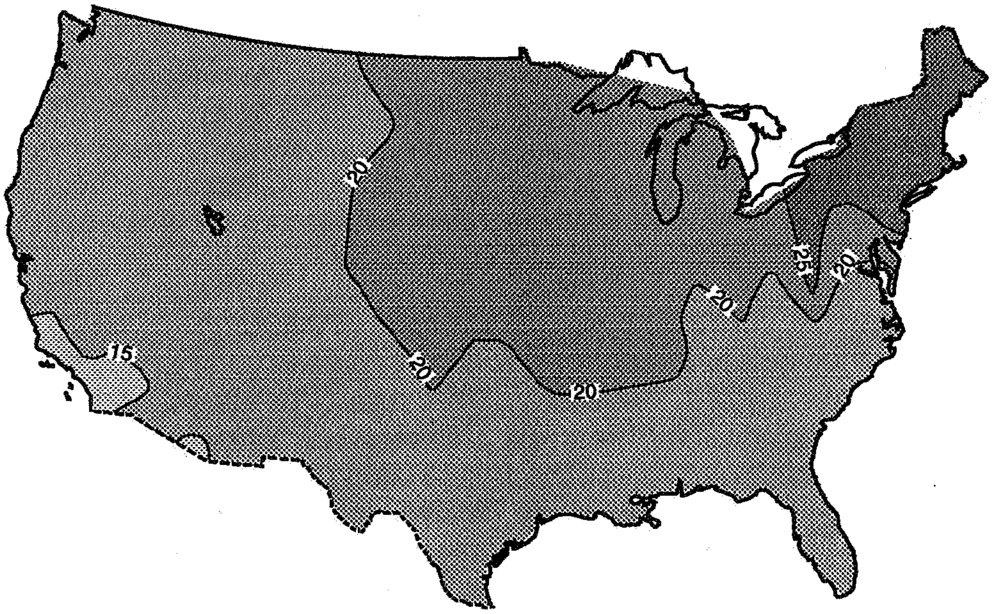

FIGURE 4: 119 Case - Infiltration Energy Consumption (GJ/house/year)

62 Case: Loosen Houses to Meet ASHRAE Standard 62

The "62 Case" assumes that any house that did not meet the ASHRAE ventilation standard would be loosened until it did. This strategy should provide adequate ventilation but at an increased energy cost. In the "62 Case," all houses which do not already meet Standard 62 are loosened to meet the ventilation standard. The national average effective annual air change rates is slightly higher than that of the base case, at 0.87 ACH with a standard deviation of 16%. When the houses are loosened, the corresponding percentage of houses that meet Standard 119 drops slightly from 50% to 47%. This small drop is due to the fact that so many of the houses already met Standard 62 in the base case scenario, so there is very little change in the number of houses which meet standard 119 when the remaining houses are loosened to meet the ventilation standard.

When houses are loosened to meet ASHRAE Standard 62, national infiltration energy consumption rises only slightly, from 3.4 EJ/Year (46 GJ/house/year) to 3.5 EJ/Year (49 GJ/house/year). This slight change in energy consumption when loosening the houses to meet Standard 62 is due to the fact that most of the houses are already loose enough to meet Standard 62.

Analysis of Errors

Data from four sources (U.S. Census, RECS, AIVC leakage database and weather files) is used to determine the effective infiltration rates and related energy consumption and compliance with ASHRAE tightness and ventilation standards. Inherent in these data sources is a certain level of uncertainty, the largest of which is related to the leakage database.

As the U.S. Census tries to sample each and every household in the United States, the related sampling errors are very low. Our interpretation of the RECS data has an estimated maximum error of less than five percent for individual averages. The weather data approximates a typical or an average weather year for a specific weather site, with some level of error as to its accuracy in modeling any specific year. While the weather data may have biases in it for various purposes, it can be considered as representative to some degree.

The estimated error in the use of the data from the AIVC leakage database is of more importance due to the potentially large sampling bias. Of the 243 houses, there is a limited range of construction styles, age of buildings, and a large geographic bias (most of the houses in the database are located in the Pacific and Northwest regions of the country). The results also do not include houses built in the last decade. Our Bayesian estimate for the error in the mean is 40%. Clearly, the leakage data is the largest driving force in the level of uncertainty of these results.

The relatively poor data quality of the leakage data implies uncertainty in the base case results, but the difference between the "119 Case" and the "62 Case" is not materially affected by this uncertainty. Thus, if we assume that U.S. homeowners will be motivated to meet ventilation requirements by infiltration, there exists 2 EJ potential savings in infiltration load reduction by meeting Standard 119.

SUMMARY

Our analysis is based on housing and leakage data available on hand at the time of our analysis. This analysis provides a preliminary view of the distribution and magnitude of infiltration-related energy consumption in the U.S. single- family building sector. We have found that, based on our analysis, the current U.S. housing stock is relatively loose, signifying that most of the houses (88%) meet the ASHRAE ventilation standard. Of equal interest, however, is the potential for further energy conservation as reflected by the large number of houses not meeting ASHRAE Standard 119. While 88% of the total base case houses meet or exceed the ventilation requirements of Standard 62, 50% of the total houses meet the tightness requirements of Standard 119, with an overlap of 38% meeting both standards.

Table 4 summarizes, on a national basis, annual heating, cooling and total infiltration energy consumption for the base case and each of the two scenarios. By tightening up the housing stock to meet Standard 119, the potential national energy savings are projected to be up to 2.1 EJ/Year (28 GJ/house/year). However, at the same time, the number of houses which meet the ventilation standard drop from

88% to 49%. The converse case, loosening the housing stock to meet Standard 62, results in a potential national increase in energy consumption of 0.1 EJ/Year (1.3 GJ/house/year).

TABLE 4. Annual Infiltration Energy - U.S. Single Family Houses

Scenario	Heating (EJ/Year)	Cooling (EJ/Year)	Total (EJ/Year)
Base Case	3.0	0.4	3.4
119 Case	1.1	0.2	1.3
62 Case	3.1	0.4	3.5

From an indoor air quality perspective, it is tempting to propose that existing houses should be loosened to meet Standard 62. From an energy perspective, however, knowing that it is possible to save up to 28 GJ/house/year by tightening the houses, it suggests that another tack be taken. For much of the country, strategies such as mechanical ventilation and heat recovery, could be utilized to create a middle ground and insure maximizing energy savings as well as providing adequate ventilation.

The 2 EJ potential infiltration savings cannot be tapped without accounting for the addition of mechanical ventilation systems in some climates. A true economic analysis requires fuel prices, heat recovery option efficiencies as well as the standard economic data requirements. The huge potential savings, however, justifies an increased emphasis on residential ventilation.

FUTURE WORK PROGRAM

Although the efforts reported here have begun to address the problem, it is only a beginning. The level of detail in key databases and the range of options considered are somewhat limited. Future work will focus on three main issues: the leakage database, scenario evaluation and expansion to include analysis of the multifamily building sector.

The current leakage database needs to be greatly expanded. It is not geographically representative; it does not cover much recent construction; and it has far too few entries to be able to draw conclusions regionally or by house type. The appropriate level of detail for the leakage database should be approximately that of the RECS database. Thus the number of entries should be increased by approximately an order of magnitude and they should be selected to be representative at least on the divisional level. Also the number and kind of leakage measurements need to be improved to match the needs of the modeling program.

The second area of future work is the inclusion of scenarios that consider mechanical ventilation options. Exhaust, supply, and balanced ventilation systems can all be used to augment infiltration and each can have a variety of control strategies. When coupled with various heat recover options (e.g., heat exchangers, heat pumps, etc.), such mechanical ventilation options have the potential to save more energy and provide better air quality than any tightening- or loosening-only strategy.

This report has dealt exclusively with thermal loads. To convert thermal loads to resource energy or life-cycle costs it is necessary to have appropriate information on system efficiencies and appropriate economic factors. Proper evaluation of mechanical options requires that this data be incorporated into the analysis procedure.

This analysis covers only single-family buildings. It is tempting to say that we would use the same energy intensity for multifamily buildings, which represent only 14% of the U.S. residential floor area, and scale up our values. Future work will attempt to ascertain the accuracy of such an assumption.

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