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Energy Impacts of Air Leakage in US Office Buildings

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SYNOPSIS

Airtightness and infiltration rate measurements in office and other commercial buildings have shown that these buildings can experience significant levels of air leakage [1,2]. The energy impact of air leakage in U.S. office buildings was estimated based on the analysis of a set of 25 buildings used in previous studies of energy consumption [3,4]. Each of these buildings represents a portion of the U.S. office building stock as of 1995. The energy impact of air leakage in each building was estimated by performing an hourly analysis over one year, with the infiltration rates varying linearly with the wind speed. The energy associated with each of the 25 buildings was then summed to estimate the national energy cost of air leakage. The results show that infiltration accounts for roughly 15% of the heating load in all office buildings nationwide, and a higher percentage in recently constructed buildings. A sensitivity analysis showed that the heating loads due to infiltration were particularly sensitive to uncertainty in the balance point temperature and nighttime thermostat setback. The results also show that infiltration has very little impact on cooling loads in office buildings. The results for office buildings are presented and discussed, along with the implications for the energy impacts of air leakage for the total commercial building stock in the U.S.

1. INTRODUCTION

Despite common assumptions that envelope air leakage is not significant in office and other commercial buildings, airtightness and infiltration rate measurements have shown that these buildings are subject to significant levels of air leakage [1,2]. Air leakage in commercial buildings can have several negative consequences, including reduced thermal comfort, interference with the proper operation of mechanical ventilation systems, degraded indoor air quality due to the infiltration of unfiltered outdoor air, moisture damage of building envelope components, and increased energy consumption. For these reasons, attention is being given to methods of improving airtightness both in existing buildings and new construction [5]. However, in order to evaluate the cost effectiveness of such measures, an estimate of the impact of air leakage on energy is needed. While there have been many studies of energy consumption in office and other commercial buildings using building energy simulation programs [3,6], these programs typically employ a simple approach to infiltration. For example, the DOE-2 program requires the user to specify an air change rate, which is then adjusted hourly depending on the wind speed [3]. However, outdoor infiltration in multizone, mechanically ventilated buildings is a complex phenomenon, with the infiltration rates depending on the indoor-outdoor temperature difference, wind speed and direction, the airtightness of exterior walls and interior partitions, and mechanical ventilation system airflow rates. In order to determine the impact of air leakage on energy consumption and to evaluate the benefits of various leakage mitigation strategies, a detailed multizone network airflow analysis, which calculates infiltration based on pressure distributions and effective leakage areas must be included in the energy simulation. While such an approach is currently being pursued at NIST, the objective of the current study is to make a preliminary estimate of the annual energy cost of infiltration in commercial buildings.

BUILDING SET

The calculations were performed for a set of 25 office buildings, each of which represents a portion of the office building stock in the U.S. Twenty of the buildings were developed by Briggs, Crawley, and Belzer [7] to represent the existing office building stock as of 1979; the other five buildings represent construction between 1980 and 1995 [4]. In both cases, cluster analysis was used to separate the total building population into several groups, within each of which certain physical characteristics and estimated annual loads of the buildings were relatively uniform. The characteristics on which the clusters were based were floor area, year of construction, number of floors, climate, and census region. For each group, a prototypical building was defined, using the mean values of the relevant properties of the member buildings. The source for the building characteristics was the Nonresidential Building Energy Consumption Survey database developed by the U.S. Energy Information Administration [8]. A summary of the salient features of the buildings appears in Table 1.

Bldg. No.	Floor Area (m^2)	No. of Floors	Year Built	Location	Floor Area Represented (10^6 m^2)	Air Change Rate w/ Fans Off (h^{-1})
1	576	1	1939	Indianapolis, IN	15.6	0.53
2	604	3	1920	Cleveland, OH	24.8	1.00
3	743	1	1954	El Paso, TX	21.5	0.43
4	929	2	1970	Washington, DC	26.5	0.33
5	1486	2	1969	Madison, WI	51.7	0.28
6	2044	2	1953	Lake Charles, LA	31.0	0.42
7	2601	4	1925	Des Moines, IA	68.2	0.65
8	3716	5	1908	St. Louis, MO	28.3	0.70
9	3902	2	1967	Las Vegas, NV	43.2	0.18
10	4273	3	1967	Salt Lake City, UT	35.5	0.21
11	13935	6	1968	Cheyenne, WY	28.6	0.19
12	16722	6	1918	Portland, OR	27.9	0.54
13	26941	11	1929	Pittsburgh, PA	58.5	0.62
14	26941	6	1948	Amarillo, TX	37.3	0.31
15	27870	12	1966	Raleigh, NC	32.7	0.22
16	28799	10	1964	Dallas, TX	22.9	0.18
17	53882	19	1965	Minneapolis, MN	27.6	0.26
18	67817	10	1957	Boston, MA	16.3	0.16
19	68746	28	1967	New York, NY	43.4	0.32
20	230392	45	1971	Los Angeles, CA	40.8	0.26
21	1022	2	1986[1]	Raleigh, NC	117.0	0.62
22	1208	2	1986[1]	Phoenix, AZ	92.2	0.58
23	1579	2	1986[1]	Pittsburgh, PA	101.0	0.53
24	38089	9	1986[1]	Pittsburgh, PA	64.5	0.21
25	46450	14	1986[1]	Charleston, SC	54.0	0.23

1. Each of buildings 21 - 25 represents a mix of construction in 1986 and 1995.

Table 1. Summary of Representative Building Set

This set of buildings has been the subject of previous studies of building energy consumption. The total heating and cooling coil loads experienced annually in each of the 25 buildings has been estimated using the DOE-2 building energy simulation program [3,4]. It was therefore possible to estimate the percentage of the total annual load that is attributable to infiltration.

3. DESCRIPTION OF APPROACH

The energy associated with infiltration in each of the buildings was estimated by summing the hourly infiltration load over one year. This analysis was performed with a program called AILOAD written in Microsoft® Visual Basic™. The algorithm for calculating infiltration loads for a given building consists of the following steps:

1. Obtain weather conditions for the current hour: outdoor temperature, humidity, and wind speed.

2. Determine the infiltration rate for the current hour, based on wind speed and HVAC system status.

3. Determine the appropriate thermostat setpoints of the HVAC system, based on the building occupancy schedule.

4. Compare the temperature of the outdoor air with the thermostat setpoints and building balance points to determine whether the infiltrating air needs to be heated or cooled.

5. If cooling is necessary, compare the humidity of the outdoor air to the desired humidity to determine whether latent cooling loads exist.

6. Calculate the hourly sensible and latent loads using equations (a) and (b).

   a) $Q_s = \rho * C_p * \Delta T * ACH * V$

   b) $Q_l = \rho * h_{fg} * \Delta W * ACH * V$

7. Add the hourly infiltration load to the cumulative total heating or cooling load.

In equations (a) and (b), Q_s is the sensible load due to infiltration, Q_l is the latent load, ρ is the density of the infiltrating air, C_p is the sensible heat capacity of air, h_{fg} is the latent heat capacity of air, ΔT is the indoor-outdoor temperature difference, ΔW is the indoor-outdoor humidity ratio difference, ACH is the infiltration rate in air changes per hour, and V is the total volume of the building. ACH * V is, therefore, the volume of outdoor air that enters the building in one hour. The specific data and other input parameters that are required at each of the steps are discussed in section 4.

The loads calculated in equations (a) and (b) are the space conditioning loads, indicating the amount of heat that must be added to or removed from the space to offset the heat loss or gain due to infiltration. In general, the total load on equipment is the sum of the conditioning loads for all the spaces it serves plus any losses in the air distribution system and any heat that must be added to or removed from ventilation air. Because the aim of this study is to assess the impact of infiltration only, the coil load is considered equivalent to the space heating load due to infiltration. Infiltration coil load intensities in MJ per m^2 of building floor area were calculated for each building. These values were compared to the total coil load intensities as predicted by the DOE-2 energy simulations in previous studies of these buildings. In order to convert the coil loads into energy use, some knowledge of the fuel types and efficiency of each building's HVAC system was needed. This information was drawn from the results of the previous studies [3,4], which calculated the energy use associated with the annual cooling and heating loads for each building. It was assumed that the energy required to meet the infiltration coil loads would be proportional to the energy required to meet the overall coil loads of the same building. Different ratios were used for heating and cooling energy estimates.

4. INPUT PARAMETERS

Implementation of this algorithm required specific information regarding the weather conditions, leakage characteristics of the buildings and HVAC system parameters. Much of the necessary information was provided by Briggs et al. [3] in the descriptions of the prototypical buildings and the input files for the DOE-2 energy simulations. Whenever possible, the parameter values for the infiltration load calculations were taken directly from the DOE-2 input files. However, in the cases of indoor humidity levels and building balance temperatures, no specific information was available, so additional assumptions were necessary. This section describes the important input parameters and the methods used to define their values.

4.1 Weather Data

Hourly weather data was provided by a WYEC (Weather Year for Energy Calculations) file for each of the 22 cities in which the prototypical buildings were located. Each file consists of a full year (8760 hours) of weather measurements, taken from U.S. Weather Service records for the month during which temperatures were closest to the long-term mean [9]. The specific data garnered from this source were the temperature, humidity, and wind speed for each hour of the typical year.

4.2 Infiltration Rates

Infiltration rates for each of the representative buildings were generated by Briggs et al. [3,4] for a wind speed of 4.5 m/s (10 m.p.h.) based on the age and height of the building and the average annual temperature difference. For the infiltration load calculations, as in the DOE-2 analysis, the baseline air change rates were adjusted hourly according to the current wind speed, assuming a linear relationship with zero infiltration in perfectly still conditions. No adjustment was made for the temperature difference across the building envelope; the baseline air change rates take into account the average influence of stack effects by including the building height and the average yearly temperature difference. However, the infiltration load estimation program used in this study allows specification of air change rates that vary with ΔT, and future analyses are planned to include this dependence.

The infiltration rates in Table 1 are valid when the HVAC system fans are off and at a wind speed of 4.5 m/s. During hours of system operation, the resulting pressurization of the building is assumed to limit the leakage of air through the building envelope. The previous DOE-2 analysis reflected this through reduced air change rates during the operating hours of the building. The amount of this reduction was based on the height of the building. For buildings of five stories or less, infiltration was reduced to 25% of the fans-off rate; in taller buildings, it was reduced to 50% of the fans-off rate.

4.3 Building Volume

Infiltration rates were multiplied by the building volume to calculate the amount of air entering the building during an hour. Building volumes contained a 90% correction factor that adjusted for the presence of unconditioned spaces, walls, and furniture within the building:

$$V = 0.90HA$$

A is the floor area represented by the building, and H is the floor-to-floor height.

4.4 HVAC System Parameters

Due to the effect of building pressurization on the infiltration rate, it was necessary to know whether or not the HVAC system fans were running during any given hour of the day. The operating hours for each building were derived from occupancy schedules developed by Briggs et al. [3], which were in turn based on hourly lighting and receptacle load data compiled during the End-Use Load and Consumer Assessment Program, a survey of electrical loads in commercial buildings in the Pacific Northwest [10]. The occupancy schedules used in the DOE-2 analysis contain hourly fractions of maximum occupant density, and the fans were assumed to be operating during all hours in which the scheduled occupancy was greater than 5% of the maximum. Each prototypical building was assigned one of five different schedules, which were scaled to reflect the average number of operating hours per weekday among the buildings represented, as reported in the NBECS [8]. On weekend days, the operating schedules were typically one hour shorter than during the work week.

The temperature setpoints reflected the common practice of changing thermostat settings in order to conserve energy at times when the building is unoccupied. Using the values as they appear in the DOE-2 input files, heating setbacks were 2.8 °C below the corresponding occupied-hours heating setpoint, which ranged from 21.1 °C to 22.2 °C. Setpoints for cooling fell between 23.3 °C and 25.0 °C. Cooling setups were fixed at 37 °C for every building, essentially ensuring that no cooling would occur during unoccupied hours. In general, setbacks and setups were in effect from the time the HVAC system fans cut off in the evening until one hour before they restarted in the morning. The existing building descriptions do not include a setpoint, per se, for the humidity of the indoor air. However, the input files for the system subprogram of DOE-2 include a listing for the maximum humidity of the system air. When calculating latent cooling loads, it was assumed that all infiltrating air that needed to be cooled was also dehumidified to the maximum level indicated for that building. The maximums were 70% relative humidity for the 20 original buildings, and 60% for the 5 buildings representing recent construction.

4.5 Balance Points

Another building parameter was introduced to account for the presence of internal heat sources, such as occupants, lighting, and electrical equipment. When the outdoor temperature is below the thermostat setpoint, infiltrating air may not need to be mechanically heated due to the heat generated by internal sources. The temperature above which this is true is called the balance temperature, or balance point, of the building. In order to account for the 'free' heating effect of a building's internal heat sources, a balance temperature was calculated for each of the representative buildings. If during any hour the temperature of infiltrating air fell between the balance temperature and the heating setpoint, no heating load was assessed. A balance temperature was estimated for each building, based on properties provided in the DOE-2 input files, using the following equation [11]:

$$t_{bal} = t_i - \frac{q_{gain}}{K_{tot}}$$

The total rate of heat gain, q_{gain}, includes internal sources such as occupants, lighting, equipment, solar gains through fenestration, and radiative gains through the walls and roof. K_{tot} is the total heat loss coefficient of the building (in W/K) due to infiltration, ventilation, and conduction. For the DOE-2 simulation, Briggs et al. [3] separated the representative buildings into distinct thermal zones. In general, each building comprised 5 zones: one interior zone and four perimeter zones, one facing each cardinal direction. If one assumes that heat transfer between the zones of a building is negligible, then each zone will exhibit its own characteristic balance temperature. Since most heat loss occurs across the building envelope, the limiting balance temperature (i.e., the highest) will be that of the zones having exterior walls. For this reason only the heat sources in the perimeter zones were included in the heat gain term when calculating the balance point for multizone buildings. For each building, separate balance points were calculated for occupied and unoccupied hours, based on the internal load intensities and schedules in Appendix C of reference [3]. Balance point temperatures for the 25 prototypical buildings ranged from -5.5 °C to 15 °C during the day, and from 10 °C to 17 °C at night, with averages of 4.5 °C and 14 °C, respectively. These ranges are comparable with the values of 1.1 °C and 11.1 °C calculated by Norford [12] for a modern, 3-story office building.

5. RESULTS

The results of the infiltration load calculations appear in Table 2. For each of the 25 buildings, the infiltration load estimates are shown, along with the total annual heating or cooling load predicted with DOE-2 [3,4] and the percentage of this total that is due to infiltration. Note that these values are the loads on the heating and cooling coils, and not the actual energy consumption, which depends on the source of energy.

The results indicate that, nationwide, infiltration is responsible for about 15% of the total annual heating load of the office building stock, but only 1% of the cooling load. The heating and cooling percentages are different because of the different extent to which these loads depend on ΔT. Heating loads arise from heat loss due to ventilation, conduction, and infiltration, all of which depend on ΔT. On the other hand, cooling loads have a substantial contribution from internal gains and solar gains, which do not depend on ΔT. Thus the portion of the total load that arises from ΔT-driven mechanisms, including infiltration, is smaller for cooling than for heating.

BLDG	LOCATION	HEATING LOADS (MJ/m^2)			COOLING LOADS (MJ/m^2)		
		Total	Inf.	% of Total Due to Inf.	Total	Inf.	% of Total Due to Inf.
1	Indianapolis, IN	656.0	104.6	16%	233.8	4.6	2%
2	Cleveland, OH	2127.0	345.9	16%	355.3	14.4	4%
3	El Paso, TX	162.3	25.5	16%	429.0	4.0	1%
4	Washington, DC	340.5	34.1	10%	355.3	3.7	1%
5	Madison, WI	313.3	44.8	14%	254.2	1.5	1%
6	Lake Charles, LA	120.3	19.5	16%	620.8	13.2	2%
7	Des Moines, IA	1087.3	151.2	14%	400.7	6.6	2%
8	St. Louis, MO	744.6	104.2	14%	763.9	24.3	3%
9	Las Vegas, NV	132.8	15.5	12%	420.0	4.0	1%
10	Salt Lake City, UT	225.9	24.7	11%	547.1	1.5	0%
11	Cheyenne, WY	382.5	64.7	17%	534.6	1.0	0%
12	Portland, OR	724.1	69.5	10%	198.6	1.3	1%
13	Pittsburgh, PA	1357.5	78.2	6%	615.2	5.2	1%
14	Amarillo, TX	190.7	72.9	38%	516.4	6.4	1%
15	Raleigh, NC	639.0	14.7	2%	1208.8	5.7	0%
16	Dallas, TX	185.0	20.3	11%	1087.3	11.0	1%
17	Minneapolis, MN	651.5	70.1	11%	479.0	3.0	1%
18	Boston, MA	990.9	45.7	5%	989.7	1.2	0%
19	New York City, NY	232.7	84.4	36%	291.7	4.3	1%
20	Los Angeles, CA	65.8	6.3	10%	999.9	0.2	0%
21	Raleigh, NC	97.6	42.7	44%	565.2	8.6	2%
22	Pheonix, AZ	48.8	12.9	26%	363.2	12.4	3%
23	Pittsburgh, PA	155.5	71.6	46%	184.4	2.7	1%
24	Pittsburgh, PA	48.8	41.6	85%	245.7	2.2	1%
25	Charlotte, SC	63.6	17.1	27%	443.8	14.3	3%
	All Buildings	380.2	58.5	15%	494.3	6.4	1%

Table 2. Annual Heating and Cooling Loads

A closer look at the results for individual building categories reveals that the percentage of the heating load due to infiltration varies from building to building. In particular, the estimated percentage for all five of the recent building classes (21 through 25) are significantly above the mean of 15%. In the DOE-2 analysis, these buildings were assumed to meet the building energy efficiency guidelines of ASHRAE Standard 90.1-1989. The more stringent envelope insulation values prescribed therein decrease conductive losses, making infiltration loads a higher percentage of the total. In buildings 13 and 15, infiltration causes a far smaller percentage of the heating load than average, partly because the HVAC systems of these buildings operate 24 hours per day. This has the dual effect of eliminating thermostat setbacks, thus increasing the total heating coil load, and reducing the infiltration loads because the building is pressurized day and night.

The results in Table 2 were calculated assuming that air exchange rates were reduced by one half or three quarters during hours of fan operation, depending on the height of the building. In actuality the relationship between HVAC system operation and infiltration is not nearly so simple. These reductions were intended to reflect the fact that in some buildings, the systems are designed to maintain positive pressure inside the building, eliminating infiltration entirely. Since, in reality, the ability of an HVAC system to maintain positive pressure varies from building to building, it is informative to look at two extreme cases. The first assumes that the buildings are completely pressurized while the system fans are running, eliminating any infiltration during occupied hours. In this case, the mean heating load due to infiltration drops to 9% of the total annual heating load, and the cooling load due to infiltration is effectively eliminated. On the other hand, if it is assumed that infiltration is unabated during hours of fan operation, the portion of the total heating load attributable to infiltration climbs to 20%; the portion of the cooling load increases to 4%.

6. Sensitivity Analysis

Given the approximate nature of many of the inputs to the infiltration load calculations, a sensitivity analysis was performed to determine how the uncertainty in the inputs affects the results.

6.1 Concept

Sensitivity analysis is a statistical technique which measures the relative importance of each input parameter in terms of its effect on the output. The importance of each variable x_i is represented by its 'main effect' - the percentage change in the output, y, as x_i changes from its lowest value to its highest value [13]. It is also possible to determine the effect of a nonlinear interaction between two or more variables. The effects are determined by running the simulation numerous times while systematically varying the values of the input parameters. In a factorial design, each input is assigned one low and one high value, or level, and with every run one variable is toggled between its low and high level. For n variables, this method requires 2^n runs to exhaust all combinations.

A fractional factorial design is a way to reduce the number of runs by varying more than one parameter with each run [14]. Reducing the number of runs introduces a certain amount of ambiguity to the results of the analysis: certain effects, as calculated, will actually represent the sum of the effects of more than one variable or interaction. The confounding pattern is known, however, so with some knowledge of the physical processes involved in the algorithm, reasonable conclusions can be drawn about which variable's effect is represented by each coefficient.

6.2 Experiment Design

The experiment measured the sensitivity of both the nationwide annual heating load and nationwide annual cooling load to eight different input parameters. The variables and their levels are listed in Table 3. The levels of the variables are given as a range above and below their nominal values, which vary from building to building. In some cases, the nominal values are different from the input values described in section 4, e.g., the cooling setup value. Therefore, the results of the sensitivity analysis provide insight only into the relative impact of the inputs and not into the uncertainty of the estimate of the energy use due to infiltration presented earlier.

The ranges are intended to be large enough to include all but the most extreme cases for each variable. By using a half factorial design when assigning variable levels for each simulation (a 2^{8-4}_{IV} design [14]), the number of runs was reduced to 16 (from 256 for a full factorial design). Interactions between three or more parameters were assumed to be negligible. By recognizing that certain variables could influence only the heating load and others only the cooling load, all two-factor interactions were isolated from their confounding effects

Number	Parameter	Nominal Value	Range
1	Heating Setpoint	21.1 °C - 22.2 °C	± .55 °C
2	Cooling Setpoint	23.3 °C - 25.0 °C	± .55 °C
3	Heating Setback	2.8 °C below setpoint	± 2.8 °C
4	Cooling Setup	2.8 °C above setpoint	± 2.8 °C
5	Balance Point	As calculated	± 2.8 °C
6	Maximum Humidity	60%	± 10%
7	Operating Hours/day	14 - 16 hours	± 2
8	Volume Correction	0.9	± 0.1

Table 3. Variables and Levels for Sensitivity Analysis

6.3 *Results*

Figure 1 summarizes the main effects of the variables listed in Table 3 with respect to the total annual infiltration loads for all 25 buildings. The values in Figure 1 are the percentage change in the output when each input is varied from its lowest to its highest level, as given in Table 3. The effect of each variable on the individual building loads varied widely from building to building, but in general the values of the heating setback and the balance point temperature had the greatest influence on heating loads. The largest changes in cooling loads were a result of varying the humidity setpoint and the thermostat setpoint and setback. The effect of the volume correction factor was nearly the same for all buildings; the 22% change in the output reflects a linear effect due to varying the effective volume of the building by ±11%. An overall level of uncertainty was estimated for the nationwide annual infiltration load estimates based on the nominal inputs in Table 3, by taking the square root of the sum of the squares of each of the main effects. This yielded an uncertainty of 44% for heating loads and 70% for cooling loads. As stated earlier, these uncertainty estimates do not apply to the infiltration loads presented in Section 5 due to some slight differences in the input values. Again, the overall uncertainty for individual building loads varied widely among buildings; between 36% and 83% for heating, and between 45% and 95% for cooling.

One important parameter was excluded from the sensitivity analysis - the infiltration rates. Based on equation (a) it is clear that if the air change rates were all adjusted by the same amount regardless of weather conditions, it would have a linear effect on the output, in the same way that the variation of the building volume does. Therefore the uncertainty in the output due to this parameter is the same as the uncertainty in the input parameter itself, which in the case of infiltration rates is relatively large.

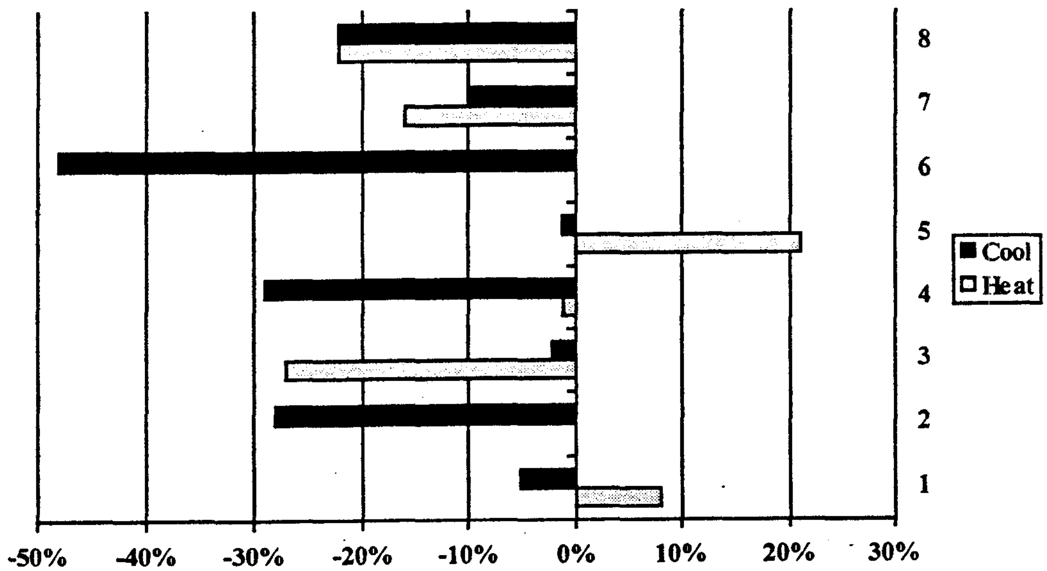

Figure 1. Main Effects of 8 Parameters on Nationwide Annual Infiltration Loads

7. Discussion

The earlier DOE-2 analysis of these buildings [3,4] includes an estimate of the annual energy use accounting for conversion efficiencies of HVAC system components and the source of energy. The energy used to cool and heat each building for a year was multiplied by the ratio of infiltration loads to total conditioning loads in order to estimate the annual energy cost of infiltration. For cooling, the total infiltration energy for all 25 buildings was 2.5 PJ (1 PJ = 10^{15} J), as compared to the total cooling usage of 145 PJ, i.e., infiltration was responsible for 2% of the cooling energy consumption. For heating, infiltration consumed 70 PJ or about 18% of the total of 410 PJ. Considering only the buildings constructed over the last 10 years (buildings 21 - 25), the portion due to infiltration is 45% of the heating energy, showing the increased impact of infiltration in newer, better insulated buildings. According to the Energy Information Administration [6], office buildings consumed a total of 1.3 EJ (1 EJ = 10^{18} J) of energy in 1989. Altogether, commercial buildings of all types consumed 6.1 EJ of site energy in 1989, 2.1 EJ of which went toward space heating. Assuming the portion of heating energy use due to infiltration is 18% for all commercial buildings, the nationwide cost of air leakage in commercial buildings is 0.38 EJ.

The accuracy of this estimate is limited by input uncertainty and the crude approach used to estimate infiltration rates. A sensitivity analysis of eight system parameters and building properties, detailed in section 6, revealed an overall uncertainty of 44% in the total heating load estimate. The assumptions made regarding infiltration rates are another source of uncertainty. The weather dependence of the air change rates was represented crudely, not taking into account the temperature difference across the building envelope. The interaction between air leakage and system operation was simplified to a constant reduction of infiltration during system operating hours.

Despite the large overall uncertainty of the infiltration energy estimates, they indicate that air leakage may be responsible for a significant portion of the energy used in U.S. office buildings. In order to estimate to what extent this energy usage could be reduced, more sophisticated methods of analyzing infiltration energy costs are necessary. The next phase of this project will involve using a building energy simulation program combined with network airflow analysis to account for the dependence of air change rates on weather conditions and on the interactions between system operation and infiltration.

8. Acknowledgments

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