Energy Impacts of Infiltration and Ventilation in U.S. Office Buildings Using Multizone Airflow Simulation

Steven J. Emmerich
Associate Member ASHRAE

Andrew K. Persily, Ph.D.
Member ASHRAE

ABSTRACT

With the exception of a few analyses of the impacts of ANSI/ASHRAE Standard 62-1989 and energy use in specific buildings, the energy use in commercial buildings due to infiltration and ventilation flows has received little attention. However, as improvements have been made in insulation, windows, etc., the relative importance of these airflows has increased. The energy impacts of infiltration and ventilation flows in U.S. office buildings was estimated based on the analysis of a set of 25 buildings developed to represent the U.S. office building stock. The energy calculation was performed by a bin method with infiltration flows determined by multizone airflow modeling. The results show that infiltration is responsible for about 13% of the heating load and 3% of the cooling load for U.S. office buildings. In newer buildings, infiltration is responsible for about 25% of the heating load and 4% of the cooling load due to the higher levels of insulation. The total annual energy impact of infiltration in U.S. office buildings is 60 PJ of heating energy (15% of the total heating energy) and 6 PJ of cooling energy (4% of the total cooling energy). It is also estimated that heating and cooling energy use due to ventilation is 17 PJ at a rate of 2.5 L/s (5 cfm) per person and 138 PJ at 10 L/s (20 cfm) per person. The results also show the potential energy savings due to tightening building envelopes and better control of ventilation system airflows. This calculation of the national energy impacts of infiltration and ventilation in office buildings is a rough estimate, with its accuracy limited by the calculation method and input data. This paper presents an intermediate step of this analysis, and an improved estimate will be calculated with a combined multizone airflow and building energy simulation model.

INTRODUCTION

As discussed in earlier papers, measurements have shown that office and other commercial buildings are subject to larger infiltration rates than commonly believed (Grot and Persily 1986; Persily and Grot 1986; Persily and Norford 1987; Persily 1999). VanBronkhorst et al. (1995) estimated the national impact of infiltration in office buildings using simple assumptions about building infiltration and a simplified bin method for calculating the building energy use due to those flows. The leakage characteristics of a given building were used, in conjunction with WYEC (Weather Year for Energy Calculation) hourly weather data, to estimate the volume of outdoor air that penetrates the building envelope during a given hour. The load associated with heating or cooling this air to the thermostat set point of the building was summed over every hour of the year in order to find annual loads for the building. Infiltration loads were calculated in this manner for a set of 25 buildings that represent the total office building stock of the United States. This set of buildings was created by researchers at Pacific Northwest Laboratories (PNL), such that each building represents a certain percentage of the total office building stock of the United States. Twenty of these buildings represent the existing office building stock as of 1979 (Briggs et al. 1992). The other five buildings represent construction between 1980 and 1995 (Crawley and Schliesing 1992). By basing the important parameters in the calculations of energy use due to infiltration on those used in the PNL analysis, it was possible to compare these results to the earlier predictions of total loads in order to estimate the percentage of the total annual load that is attributable to air infiltration. The initial estimate indicated that infiltration is responsible for 18% of

Steven J. Emmerich is a mechanical engineer and **Andrew K. Persily** is a group leader at the Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Md.

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the total heating energy use and 2% of the total cooling energy use in U.S. office buildings.

This paper updates the earlier estimate (VanBronkhorst et al. 1995) by improving the infiltration assumptions. The original work used crude guesses for infiltration rates that did not account for well-understood aspects of building airflow, such as the influence of temperature-driven flows (or stack effect) and the interaction of ventilation and infiltration airflows. This aspect of the energy estimate could be greatly improved by utilizing multizone airflow modeling to take advantage of the state of the art in modeling building airflow dynamics. Additionally, it was desired to use a similar method to estimate the national energy cost of ventilation flows in U.S. office buildings over a range of ventilation rates. Other researchers have reported on energy costs of ventilation for a limited number of buildings but have not considered the energy impacts on a national level (Eto 1990; Eto and Meyer 1988; Steele and Brown 1990; Zmeureanu et al. 1992; Mudarri and Hall 1993).

METHOD

Building Set

Researchers at PNL categorized the U.S. office building stock using a statistically valid sample of the nation's office building sector known as the Commercial Building Energy Consumption Survey (CBECS, previously called Nonresidential Building Energy Consumption Survey [EIA 1986, 1989]). This effort developed categories using a statistical technique known as cluster analysis based on attributes such as size, age, location, and building energy loads. Twenty of these buildings were described by Briggs et al. (1987) to represent the existing office building stock as of 1979. An additional five buildings were later described to represent expected construction between 1980 and 1995 (Crawley and Schliesing 1992). A summary of features of the 25 representative buildings is shown in Table 1, with all but the last column based on the

TABLE 1
Summary of Office Building Set

Bldg. No.	Floor Area (m^2)	No. of Floors	Year Built	Location	Floor Area Represented (10^6 m^2)	Effective Leakage Area at 10 Pa (cm^2/m^2)
1	576	1	1939	Indianapolis, IN	15.6	15
2	604	3	1920	Cleveland, OH	24.8	15
3	743	1	1954	El Paso, TX	21.5	10
4	929	2	1970	Washington, DC	26.5	7.5
5	1486	2	1969	Madison, WI	51.7	5
6	2044	2	1953	Lake Charles, LA	31	10
7	2601	4	1925	Des Moines, IA	68.2	10
8	3716	5	1908	St. Louis, MO	28.3	10
9	3902	2	1967	Las Vegas, NV	43.2	7.5
10	4273	3	1967	Salt Lake City, UT	35.5	5
11	13935	6	1968	Cheyenne, WY	28.6	5
12	16722	6	1918	Portland, OR	27.9	10
13	26941	11	1929	Pittsburgh, PA	58.5	10
14	26941	6	1948	Amarillo, TX	37.3	10
15	27870	12	1966	Raleigh, NC	32.7	5
16	28799	10	1964	Dallas, TX	22.9	5
17	53882	19	1965	Minneapolis, MN	27.6	3.33
18	67817	10	1957	Boston, MA	16.3	5
19	68746	28	1967	New York, NY	43.4	3.33
20	230392	45	1971	Los Angeles, CA	40.8	3.33
21	1022	2	1986	Raleigh, NC	117	5
22	1208	2	1986	Phoenix, AZ	92.2	5
23	1579	2	1986	Pittsburgh, PA	101	5
24	38089	9	1986	Pittsburgh, PA	64.5	3.33
25	46450	14	1986	Charleston, SC	54	3.33

PNL analysis. The envelope leakage values are discussed below. The PNL reports include an estimate of the total heating and cooling coil loads experienced annually in each of the 25 buildings, obtained using the DOE-2 building energy simulation program.

Since the PNL building set was defined several years ago and included projections for future construction, we attempted to determine if any dramatic changes have occurred to the U.S. office building stock and if the PNL projections for future construction were accurate. The building set, as shown in Table 1, was compared to the 1995 CBECS data (EIA 1997). The most significant difference noted between the building set and the new CBECS data is that the total floor space in the building set is about 14% greater than the total office floor space indicated in the survey, with the difference fairly equally distributed between pre-1980 construction (15% less than building set) and post-1980 construction (12% less than building set). Since these differences are fairly uniform across age, the average results reported for the energy impact calculations are not expected to be skewed but rather simply be a bit high. Also, the geographic breakdown of projected new construction per the building set vs. actual new construction per the 1995 CBECS data was examined. The projections were amazingly accurate, with 20% of the projected new floor space represented by Phoenix, Ariz., vs. 21% actually reported in the West Census region; 43% of the projected floor space represented by Raleigh, N.C., and Charleston, S.C., vs. 40% reported in the South Census region; and 37% of the projected floor space represented by Pittsburgh, Pa., vs. 38% reported for the Midwest and Northeast Census regions combined. Again, no skewing of the calculated results based on geographic differences is expected.

Infiltration Rate

The initial estimate reported by VanBronkhorst et al. (1995) used infiltration assumptions made by the PNL researchers. Air infiltration rates for each of the representative buildings were generated by Briggs et al. (1992) for a wind speed of 4.47 m/s (10 mph), using a formula that takes into account building age and height and an average annual indoor-outdoor temperature difference. For the infiltration load calculations, these values were scaled linearly with wind speed to generate a table of infiltration rates for each building for wind speeds between 0 m/s and 20 m/s. Because the PNL analysis did not account for the dependence of the air infiltration rate on the indoor-outdoor temperature difference, this dependency was not included in the initial estimate. During hours of fan operation, the resulting pressurization of the building may reduce the rate of air infiltration to some degree. Following Briggs et al. (1992), the amount of this reduction was based on the height of the building. For buildings of five stories or less, the air infiltration rate was reduced to 25% of the fans-off rate, and in taller buildings, it was reduced to 50% of the fans-off rate. Building number 2 has no mechanical ventilation, so the infiltration rate was not reduced.

For the present analysis, the PNL infiltration rate assumptions were replaced with infiltration flows calculated using the multizone airflow and pollutant transport program CONTAM96 (Walton 1997), which models a building as a network of well-mixed zones connected by various airflow paths. A CONTAM96 model was created for each of the 25 office buildings. Each building was modeled as three zones per floor—one for the main occupied area, one for the plenum, and one for the elevator and stairwell shafts combined.

The envelope airtightness values used in the simulations were based on an examination of the limited data that exist for U.S. office buildings (Persily 1999). The data in this reference include measurements of envelope airtightness using fan pressurization tests in 30 office buildings in the U.S., 8 in Canada, and 10 in the U.K. While this is an extremely small data set, it is the only published data set on office building airtightness that exists. The airtightness values ranged from about 1 cm^2 of effective leakage area (ASHRAE 1997) per m^2 of wall area at 10 Pa to about 40 cm^2/m^2. The mean value for all 30 U.S. office buildings is about 9 cm^2/m^2. These data were analyzed for relationships of airtightness to building age and wall construction, but essentially no correlation was seen. The only relationship that was observed was that taller buildings (more than 15 stories) tended to have tighter envelopes, while shorter buildings ranged from tight to loose.

Based on this data set, and a fair amount of engineering judgement, the airtightness values for the 25 simulated buildings were determined along the following guidelines. While the airtightness data examined do not necessarily support these assumptions, it was determined that some credit needed to be given for newer buildings, double-glazed windows, and tall buildings. Therefore, buildings constructed prior to about 1950, with essentially residential construction including single-glazed windows, were assumed to have a wall leakage value of 15 cm^2/m^2. Buildings of similar vintage, but nonresidential in construction, were assumed to have a leakage value of 10 cm^2/m^2. Buildings constructed between about 1950 and 1965 were also assumed to have a leakage value of 10 cm^2/m^2. Buildings built around 1965 or later, still with single-glazed windows, were set at 7.5 cm^2/m^2. Buildings of the same vintage with double-glazed windows were assumed to have a leakage value of 5 cm^2/m^2. Recent buildings of about ten stories or more, with double-glazed windows, were assumed to have a leakage value of 3.33 cm^2/m^2. For the simulations in which the impacts of tightening were examined, these leakage areas were reduced as follows: 15 to 7.5, 10 to 7.5 or 5 (the lower value in buildings constructed after 1950), 7.5 to 5, 5 to 3.33, and 3.33 to 2. Table 1 presents the envelope leakage values for all 25 buildings.

Loads Due to Infiltration

The algorithm for calculating infiltration loads for a given building consists of the following steps for each hour of the simulation:

1. Obtain weather conditions for the current hour: outdoor temperature, humidity, and wind speed.
2. Determine the air infiltration rate from CONTAM simulations based on current temperature, wind speed, and HVAC system flows.
3. Determine the thermostat set points of the HVAC system from the building operation schedule.
4. Compare the temperature of the outdoor air with the thermostat set points and balance point temperatures 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 loads using Equations 1 and 2 (derived from ASHRAE 1997).

$$Q_s = \rho \cdot C_p \cdot \Delta T \cdot I \cdot V \quad (1)$$

$$Q_l = \rho \cdot h_{fg} \cdot \Delta W \cdot I \cdot V \quad (2)$$

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

In Equations 1 and 2, 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 specific heat, ΔT is the indoor-outdoor temperature difference, h_{fg} is the enthalpy of vaporization, ΔW is the indoor-outdoor humidity ratio difference, I is the infiltration rate in h^{-1}, and V is the total volume of the building. $I \cdot V$, therefore, represents the volume of outdoor air that enters the building in one hour.

Application of this algorithm required some assumptions regarding the HVAC system parameters, most notably the operating schedule and the temperature and humidity set points. Whenever possible, the values of these parameters were taken directly from the input files for the DOE-2 analysis (Briggs et al. 1992). However, in the cases of indoor humidity levels and building balance point temperatures, no specific information was available, so additional assumptions were necessary as described below.

HVAC System Parameters

Due to the effect of building pressurization on the air infiltration rate, it was necessary to know whether or not the HVAC system fans were running during any given hour of the day. The PNL reports (Briggs et al. 1992; Crawley and Schliesing 1992) include descriptions of the HVAC system specified for each building and the average number of hours per day that the HVAC systems operate, which ranges between 9.2 h per day and 21 h per day. For each value of this variable, a detailed schedule is provided by PNL, indicating which hours the fans are considered to be running. Different schedules were utilized for weekdays and weekends.

The temperature set points were chosen to reflect the practice of changing thermostat settings in order to conserve energy at times when the building is unoccupied. Heating setbacks were 2.8°C (5°F) below the corresponding occupied-hours heating set points, which ranged from 21°C to 22°C (70°F to 72°F). Set points for cooling fell between 23°C and 25°C (74°F and 77°F). Cooling setups were fixed at 37°C (99°F) for every building, essentially ensuring that no cooling would occur during unoccupied hours. All of these values were taken directly from the DOE-2 input parameters as contained in the PNL reports. Schedules similar to those describing the hours of HVAC system operation were used to determine whether the high or low set point should be used for each hour's calculations. 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 set point, 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 a maximum allowed relative humidity of 60%. No latent loads were included when heating was required.

Another important impact of HVAC system operation is the (de)pressurization of the building based on the relative magnitudes of the supply and return flows. Most ventilation systems in U.S. commercial buildings are designed to operate with a smaller return flow than supply flow in order to positively pressurize the building. However, experience has indicated that many systems do not pressurize the building as intended (Persily and Norford 1987; Cummings et al. 1996). Schliesing et al. (1993) summarize literature reports that describe problems with HVAC system maintenance and operation, such as stuck dampers, blocked return vents, and disconnected controls. While anecdotal evidence of problems with system operation is plentiful, there is a lack of data to quantify the problem. Therefore, three different ventilation system operation conditions were defined for most of the buildings—pressurized (return flow = 90% of supply flow), balanced (return flow = supply flow), and depressurized (return flow = 110% of supply flow). The supply flow rate used was 5 L/s·m^2 (1 cfm/ft^2). For lack of better information, it was assumed that one-third of the floor space that each building represents operates at each of the three pressurization conditions with the following exceptions. Based on the PNL description of the building HVAC systems, some of the systems were judged not capable of pressurizing or depressurizing the buildings or unlikely to do so. Therefore, the pressurized condition was not applied to buildings 1, 2, 3, 6, 7, 8, 9, and 12, and the depressurized condition was not applied to buildings 1, 2, and 12. The balanced system flow condition was substituted for these exceptions. These HVAC system supply and return flows were used as inputs to the CONTAM simulations when calculating infiltration rates.

Balance Points

Another building parameter was introduced to account for the presence of internal heat sources, such as occupants, lighting, and electrical equipment. At times when the outdoor temperature is below the thermostat set point by a small amount, 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 simulate the "free" heating effect of a building's internal heat sources, a balance temperature was assigned to each of the representative buildings. If the temperature of infiltrating air fell between the balance temperature and the heating set point, no heating load was assessed during that hour. A balance temperature was estimated for each building based on properties provided in the DOE-2 input files, using the following equation (ASHRAE 1997):

$$t_{bal} = t_i - (q_{gain} / K_{tot}).$$

The total rate of heat gain, q_{gain}, includes internal sources such as occupants, lighting, and 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 (Btu/h·°F) due to infiltration, ventilation, and conduction. Assuming negligible heat transfer among the zones of a building, each zone will exhibit its own characteristic balance temperature. Since most heat loss occurs across the building envelope, the limiting balance temperature (the highest) will be that of the zones having exterior walls. For this reason, only the internal heat sources in the perimeter zones were included in the heat gain term when calculating the balance point for multizone buildings.

For each building, a separate balance point was calculated for unoccupied hours. These estimates assumed no solar or radiative heat gains since unoccupied hours generally occur at night. Receptacle loads were assumed to be 50% of their occupied-hours level and lighting loads 25%, while occupancy was at 5% of the maximum, based on the schedules created by Briggs et al. (1992). At both times, the interior temperature t_i was assumed to be equal to the current thermostat set point. Balance point temperatures for the 25 prototypical buildings ranged from -5.5°C to 15°C (22°F to 60°F) during the day and from 10°C to 17°C (50°F to 62°F) at night, with averages of 4.5°C (40°F) and 14°C (57°F), respectively.

Loads Due to Ventilation

For calculating the heating and cooling loads due to ventilation, the method described above was used with some slight modifications. For ventilation, the infiltration rates in Equations 1 and 2 of step 6 were replaced with the ventilation rates, and the balance points were recalculated for the different ventilation rates as described above. The ventilation rates used in the calculation were 2.5 L/s (5 cfm) per person and 10 L/s (20 cfm) per person based on a "design occupancy" of 7 people per 100 m^2 (1000 ft^2) from Standard 62 (ASHRAE 1989). At 2.5 L/s (5 cfm) per person, the balance points ranged from −16°C to 11°C (4°F to 52°F) during the day and from 6°C to 19°C (42°F to 66°F) at night. At 10 L/s (20 cfm) per person, the balance points ranged from −9°C to 12°C (16°F to 54°F) during the day and from 8°C to 19°C (47°F to 66°F) at night Also, all buildings including building 2, which is not mechanically ventilated, were included in the calculation, so the calculation should be considered an estimate of the impact on loads if the ventilation was at the specified levels, not an estimate of the energy impact of the ventilation rates expected to occur in these buildings. The two rates analyzed were selected based on the ventilation requirements for office buildings by ASHRAE Standard 62-1981 (ASHRAE 1981) and ANSI/ASHRAE Standard 62-1989 (ASHRAE 1989).

RESULTS

Energy Impact of Infiltration

The annual heating and cooling loads due to infiltration for the baseline envelope tightness case and all three building pressurization conditions are presented in Tables 2a and 2b. These tables also contain the average loads for the three pressurization conditions, the total heating and cooling loads as calculated by PNL (Briggs et al. 1992; Crawley and Schliesing 1992), the percent of this total due to infiltration, and the averages and totals for all buildings.

The heating load caused by infiltration in the individual buildings spans three orders of magnitude, ranging from 3 MJ/m^2 to 280 MJ/m^2 (300 Btu/ft^2 to 25,000 Btu/ft^2). As a portion of the total heating load, the range is from 3% to 42%. The floor space-weighted average over all of the buildings and conditions is 51 MJ/m^2 (4650 Btu/ft^2), which is 13% of the total average heating load. The range of the impact of infiltration on cooling loads is nearly as broad, ranging from less than 0.1 MJ/m^2 (9 Btu/ft^2) to almost 94 MJ/m^2 (8500 Btu/ft^2). However, as a portion of the total cooling load, the impact of infiltration is much less than for heating, ranging from 0% to 12%. The floor space-weighted average impact over all of the buildings is 15.9 MJ/m^2 (1440 Btu/ft^2), or 3% of the total average cooling load. The smaller impact of infiltration on cooling loads is attributable to several reasons including lower driving forces for infiltration, smaller indoor-outdoor temperature differences, and greater total cooling loads due to internal heat gains.

As found in the earlier report (VanBronkhorst et al. 1995), infiltration is responsible for a larger portion of the heating and cooling loads in newer buildings. On average, infiltration was responsible for 25% of the heating load and 4% of the cooling load in the five newest buildings (buildings 21 through 25). This larger relative impact for the newest buildings is due mainly to the lower total heating and cooling loads in the newer buildings, which were modeled as meeting the energy efficiency guidelines of ANSI/ASHRAE Standard 90.1-1989. This is particularly significant for the total heating load, which

TABLE 2a
Heating Loads Due to Infiltration

Building	Location	Heating Loads (MJ/m^2)					
		Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
1	Indianapolis, IN	[redacted]	205.7	[redacted]	205.7	656	31%
2	Cleveland, OH	[redacted]	284.0	[redacted]	284.0	2127	13%
3	El Paso, TX	[redacted]	18.0	34.7	26.4	162	16%
4	Washington, DC	22.5	29.5	44.3	32.1	341	9%
5	Madison, WI	34.5	42.8	62.3	46.5	313	15%
6	Lake Charles, LA	[redacted]	18.4	23.6	21.0	120	17%
7	Des Moines, IA	[redacted]	184.9	213.5	199.2	1087	18%
8	St. Louis, MO	[redacted]	69.3	89.2	79.3	745	11%
9	Las Vegas, NV	[redacted]	18.3	32.2	25.3	133	19%
10	Salt Lake City, UT	19.9	20.1	20.3	20.1	226	9%
11	Cheyenne, WY	39.8	44.2	54.7	46.2	382	12%
12	Portland, OR	[redacted]	39.0	[redacted]	39.0	724	5%
13	Pittsburgh, PA	52.0	94.0	153.6	99.9	1357	7%
14	Amarillo, TX	64.4	75.2	97.2	78.9	191	41%
15	Raleigh, NC	3.8	20.0	52.3	25.4	639	4%
16	Dallas, TX	13.6	20.3	37.2	23.7	185	13%
17	Minneapolis, MN	34.8	57.4	94.0	62.1	651	10%
18	Boston, MA	18.9	26.9	46.1	30.6	991	3%
19	New York, NY	36.3	47.5	66.1	50.0	233	21%
20	Los Angeles, CA	3.3	3.3	3.5	3.4	66	5%
21	Raleigh, NC	14.4	15.6	18.5	16.2	98	17%
22	Phoenix, AZ	5.3	5.5	6.2	5.7	49	12%
23	Pittsburgh, PA	23.9	28.4	39.9	30.7	155	20%
24	Pittsburgh, PA	8.7	14.5	38.6	20.6	49	42%
25	Charleston, SC	6.4	14.1	44.1	21.5	64	34%
All Buildings		**41.6**	**47.9**	**64**	**51.2**	**380**	**13%**

TABLE 2b
Cooling Loads Due to Infiltration

Building	Location	Cooling Loads (MJ/m^2)					
		Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
1	Indianapolis, IN	[redacted]	28.1	[redacted]	28.1	234	12%
2	Cleveland, OH	[redacted]	18.6	[redacted]	18.6	355	5%
3	El Paso, TX	[redacted]	11.9	26.8	19.4	429	5%
4	Washington, DC	0.8	10.1	36.4	15.8	355	4%
5	Madison, WI	1.1	4.6	16.6	7.4	254	3%
6	Lake Charles, LA	[redacted]	45.3	93.8	69.6	621	11%
7	Des Moines, IA	[redacted]	25.2	41.4	33.3	401	8%
8	St. Louis, MO	[redacted]	23.8	45.7	34.8	764	5%

TABLE 2b (Continued)
Cooling Loads Due to Infiltration

Building	Location	Cooling Loads (MJ/m^2) Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
9	Las Vegas, NV	[redacted]	15.0	40.8	27.9	420	7%
10	Salt Lake City, UT	3.1	3.6	4.2	3.6	547	1%
11	Cheyenne, WY	0.4	1.4	4.5	2.1	535	0%
12	Portland, OR	[redacted]	1.2	[redacted]	1.2	199	1%
13	Pittsburgh, PA	3.7	7.3	14.7	8.6	615	1%
14	Amarillo, TX	8.9	13.8	22.8	15.2	516	3%
15	Raleigh, NC	1.0	10.9	49.9	20.6	1209	2%
16	Dallas, TX	7.3	21.2	65.0	31.2	1087	3%
17	Minneapolis, MN	0.1	2.5	13.2	5.3	479	1%
18	Boston, MA	0.0	1.5	8.2	3.2	990	0%
19	New York, NY	1.1	4.9	17.0	7.7	292	3%
20	Los Angeles, CA	0.0	0.3	1.3	0.5	1000	0%
21	Raleigh, NC	1.6	9.6	34.8	15.3	565	3%
22	Phoenix, AZ	5.3	18.5	56.5	26.8	363	7%
23	Pittsburgh, PA	0.5	2.9	11.2	4.9	184	3%
24	Pittsburgh, PA	0.0	1.0	11.7	4.2	246	2%
25	Charleston, SC	0.4	10.5	67.1	26.0	444	6%
All Buildings		**6.6**	**11**	**30**	**15.9**	**494**	**3%**

averaged only 83 MJ/m^2 (7500 Btu/ft^2) for the newest buildings vs. 380 MJ/m^2 (34,000 Btu/ft^2) for the floor space-weighted average for all 25 buildings.

The load results in Tables 2a and 2b also demonstrate the significant impact of building pressurization on building heating and cooling loads due to infiltration. For heating, the floor space-weighted average load due to infiltration increases by over 50%, from 42 MJ/m^2 (3800 Btu/ft^2) for the pressurized condition to 64 MJ/m^2 (5600 Btu/ft^2) for the depressurized condition. This impact is even more significant for many individual buildings where the impact is an increase up to a factor of 14. For cooling, the impact is even larger, with the average load due to infiltration increasing by nearly a factor of 5 from 6.6 MJ/m^2 (600 Btu/ft^2) to 30 MJ/m^2 (2700 Btu/ft^2). For individual buildings, the impact on cooling loads was as great as a two order of magnitude increase. This large impact for cooling occurs because the pressurized buildings have very little infiltration during the day when temperatures are high, resulting in very small cooling loads due to infiltration. Depressurized buildings, on the other hand, can have much higher infiltration rates during the peak cooling hours.

The PNL analysis of these buildings (Briggs et al. 1992; Crawley and Schliesing 1992) estimated the annual energy use by modeling the heating and cooling equipment selected for the buildings. The total energy impact of infiltration in U.S. office buildings was estimated from the heating and cooling loads due to infiltration in Tables 2a and 2b by applying the energy to load ratios for each building from the PNL study. As presented in Table 3, infiltration is responsible for 60 PJ (or 15% of the total 410 PJ) of heating energy use annually in U.S. office buildings. For cooling, infiltration is responsible for 6 PJ (or 4% of the total 145 PJ) of energy use annually in U.S. office buildings.

Energy Impact of Ventilation

The estimated annual heating and cooling loads due to ventilation at 2.5 L/s (5 cfm) per person and 10 L/s (20 cfm) per person are presented in Tables 4 and 5, respectively. Increasing the ventilation by a factor of 4 results in a ninefold increase in the floor space-weighted average heating load due to ventilation, from 8 MJ/m^2 (700 Btu/ft^2) to 74 MJ/m^2 (6700 Btu/ft^2). The cooling load due to ventilation increases by a

TABLE 3
Total Annual Energy Use Due to Infiltration

	Heating	Cooling
PNL Total (PJ)	410	145
Infiltration (PJ)	60	6
% Due to Infiltration	15	4

TABLE 4
Heating and Cooling Loads Due to Ventilation at 2.5 L/s (5 cfm) per Person

Building	Location	Heating Loads (MJ/m²) Vent	Heating Loads (MJ/m²) PNL Total	Heating Loads % Vent	Cooling Loads (MJ/m²) Vent	Cooling Loads (MJ/m²) PNL Total	Cooling Loads % Vent
1	Indianapolis, IN	15.6	656	2%	14.9	234	6%
2	Cleveland, OH	14.9	2127	1%	2.1	355	1%
3	El Paso, TX	3.9	162	2%	16.9	429	4%
4	Washington, DC	3.3	341	1%	21.4	355	6%
5	Madison, WI	3.0	313	1%	9.5	254	4%
6	Lake Charles, LA	1.7	120	1%	53.1	621	9%
7	Des Moines, IA	51.5	1087	5%	14.8	401	4%
8	St. Louis, MO	18.5	745	2%	24.6	764	3%
9	Las Vegas, NV	3.3	133	2%	26.4	420	6%
10	Salt Lake City, UT	0.0	226	0%	10.4	547	2%
11	Cheyenne, WY	2.3	382	1%	3.0	535	1%
12	Portland, OR	2.2	724	0%	1.5	199	1%
13	Pittsburgh, PA	32.6	1357	2%	7.8	615	1%
14	Amarillo, TX	10.1	191	5%	12.3	516	2%
15	Raleigh, NC	10.1	639	2%	29.5	1209	2%
16	Dallas, TX	6.2	185	3%	38.0	1087	3%
17	Minneapolis, MN	10.6	651	2%	7.6	479	2%
18	Boston, MA	4.3	991	0%	4.7	990	0%
19	New York, NY	6.7	233	3%	9.8	292	3%
20	Los Angeles, CA	0.0	66	0%	0.9	1000	0%
21	Raleigh, NC	2.4	98	2%	25.6	565	5%
22	Phoenix, AZ	0.2	49	0%	37.2	363	10%
23	Pittsburgh, PA	1.8	155	1%	7.4	184	4%
24	Pittsburgh, PA	2.6	49	5%	7.8	246	3%
25	Charleston, SC	10.8	64	17%	44.5	444	10%
	All Buildings	**8.1**	**380**	**2%**	**18.2**	**494**	**4%**

TABLE 5
Heating and Cooling Loads Due to Infiltration at 10 L/s (20 cfm) per Person

Building	Location	Heating Loads (MJ/m²) Vent	Heating Loads (MJ/m²) PNL Total	Heating Loads % Vent	Cooling Loads (MJ/m²) Vent	Cooling Loads (MJ/m²) PNL Total	Cooling Loads % Vent
1	Indianapolis, IN	80.2	656	12%	59.3	234	25%
2	Cleveland, OH	86.7	2127	4%	8.5	355	2%
3	El Paso, TX	39.4	162	24%	66.0	429	15%
4	Washington, DC	126.2	341	37%	85.8	355	24%
5	Madison, WI	10.7	313	3%	1.8	254	1%
6	Lake Charles, LA	19.2	120	16%	212.3	621	34%
7	Des Moines, IA	271.6	1087	25%	59.2	401	15%

TABLE 5 (Continued)
Heating and Cooling Loads Due to Infiltration at 10 L/s (20 cfm) per Person

		Heating Loads			Cooling Loads		
		(MJ/m²)			(MJ/m²)		
Building	Location	Vent	PNL Total	% Vent	Vent	PNL Total	% Vent
8	St. Louis, MO	165.3	745	22%	98.6	764	13%
9	Las Vegas, NV	21.2	133	16%	105.6	420	25%
10	Salt Lake City, UT	4.7	226	2%	41.6	547	8%
11	Cheyenne, WY	23.3	382	6%	11.9	535	2%
12	Portland, OR	111.9	724	15%	6.2	199	3%
13	Pittsburgh, PA	359.5	1357	26%	31.1	615	5%
14	Amarillo, TX	55.1	191	29%	49.4	516	10%
15	Raleigh, NC	67.7	639	11%	117.9	1209	10%
16	Dallas, TX	32.8	185	18%	151.8	1087	14%
17	Minneapolis, MN	84.0	651	13%	30.5	479	6%
18	Boston, MA	39.6	991	4%	18.7	990	2%
19	New York, NY	46.9	233	20%	39.0	292	13%
20	Los Angeles, CA	0.4	66	1%	3.2	1000	0%
21	Raleigh, NC	74.8	98	77%	102.6	565	18%
22	Phoenix, AZ	15.6	49	32%	148.7	363	41%
23	Pittsburgh, PA	113.3	155	73%	29.9	184	16%
24	Pittsburgh, PA	41.5	49	85%	31.2	246	13%
25	Charleston, SC	46.4	64	73%	178.2	444	40%
All Buildings		**74.1**	**380**	**19%**	**71.3**	**494**	**14%**

factor of 4, from 18 MJ/m² (1600 Btu/ft²) to 71 MJ/m² (6400 Btu/ft²). The difference in impact on heating and cooling loads is due to the impact of the increased ventilation rate on the balance point temperature used in the calculation. This causes the impact on heating load to be nonlinear and to depend greatly on the climate and type of building. For example, there is almost no heating load in the Los Angeles building, even at 10 L/s (20 cfm) per person (the load due to ventilation is only 1% of the total heating load, which itself is small at 66 MJ/m² [6000 Btu/ft²]). At the other extreme, the average heating load due to ventilation for the five newest buildings increases by a factor of 16 as the ventilation is increased from 2.5 L/s (5 cfm) per person to 10 L/s (20 cfm) per person.

The estimated total energy impacts of ventilation in U.S. office buildings were calculated from the ventilation loads using the PNL energy to load ratios and are summarized in Table 6. The estimated annual energy use to ventilate U.S. office buildings at 2.5 L/s (5 cfm) per person is 10 PJ for heating and 7 PJ for cooling. Increasing the ventilation to 10 L/s (20 cfm) per person increases the annual energy use to 110 PJ or (27% of the total 410 PJ) for heating and 28 PJ (or 19% of the total 145 PJ) for cooling. (Note: The totals as calculated by PNL were not adjusted to reflect the different ventilation assumptions.)

TABLE 6
Total Annual Energy Use Due to Ventilation

Ventilation Rate (per Person)	Heating (PJ)	Heating: Fraction of PNL Total	Cooling (PJ)	Cooling: Fraction of PNL Total
2.5 L/s	10	2.4%	7	4.8
10 L/s	110	27%	28	19%

Potential Energy Savings from Tighter Building Envelopes and Building Pressurization

An estimate was also made of the potential energy savings that could be gained through the tightening of building envelopes. Each of the building envelope leakages listed in Table 1 for the baseline case was reduced by 25% to 50%, to the values listed in Tables 7a and 7b. All other parameters from the baseline case were retained.

The resulting heating and cooling loads for each of the buildings, along with averages for the three building pressurization conditions and floor space-weighted averages for all 25 buildings, are presented in Tables 7a and 7b. The average saving for all of the buildings is 26% for the heating load and 15% for the cooling load. The potential savings varies from case to case, but one important factor in determining the rela-

TABLE 7a
Heating Loads Due to Infiltration for Tightened Envelope

Building	Location	Envelope Leakage (cm^2/m^2)	Heating Loads (MJ/m^2) Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
1	Indianapolis, IN	7.5	[redacted]	107.7	[redacted]	107.7	656	16%
2	Cleveland, OH	7.5	[redacted]	144.9	[redacted]	144.9	2127	7%
3	El Paso, TX	5	[redacted]	8.3	26.4	17.4	162	11%
4	Washington, DC	5	15.3	21.1	37.5	24.6	341	7%
5	Madison, WI	3.33	23.7	30.8	52.9	35.8	313	11%
6	Lake Charles, LA	5	[redacted]	9.7	16.8	13.3	120	11%
7	Des Moines, IA	7.5	[redacted]	143.2	172.7	158.0	1087	15%
8	St. Louis, MO	7.5	[redacted]	56.8	77.5	67.2	745	9%
9	Las Vegas, NV	5	[redacted]	12.9	28.1	20.5	133	15%
10	Salt Lake City, UT	3.33	14.8	15.0	15.2	15.0	226	7%
11	Cheyenne, WY	3.33	27.7	31.6	43.3	34.2	382	9%
12	Portland, OR	7.5	[redacted]	30.5	[redacted]	30.5	724	4%
13	Pittsburgh, PA	7.5	36.2	78.8	140.4	85.1	1357	6%
14	Amarillo, TX	7.5	47.0	57.7	82.6	62.4	191	33%
15	Raleigh, NC	3.33	1.1	14.5	50.3	22.0	639	3%
16	Dallas, TX	3.33	8.5	14.4	33.6	18.8	185	10%
17	Minneapolis, MN	2	20.2	37.4	78.6	45.4	651	7%
18	Boston, MA	3.33	12.9	19.5	41.0	24.5	991	2%
19	New York, NY	2	20.0	29.6	50.4	33.3	233	14%
20	Los Angeles, CA	2	2.1	2.1	2.2	2.1	66	3%
21	Raleigh, NC	3.33	10.3	11.4	14.5	12.1	98	12%
22	Phoenix, AZ	3.33	3.8	3.9	4.7	4.1	49	8%
23	Pittsburgh, PA	3.33	16.6	20.5	33.7	23.6	155	15%
24	Pittsburgh, PA	2	6.4	10.7	36.4	17.8	49	37%
25	Charleston, SC	2	4.3	10.0	42.4	18.9	64	30%
All Buildings			**28.1**	**33.7**	**51.2**	**37.7**	**380**	**10%**

TABLE 7b
Cooling Loads Due to Infiltration for Tightened Envelope

Building	Location	Envelope Leakage (cm^2/m^2)	Cooling Loads (MJ/m^2) Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
1	Indianapolis, IN	7.5	[redacted]	15.6	[redacted]	15.6	234	7%
2	Cleveland, OH	7.5	[redacted]	9.3	[redacted]	9.3	355	3%
3	El Paso, TX	5	[redacted]	7.8	26.5	17.2	429	4%
4	Washington, DC	5	0.1	7.2	36.4	14.6	355	4%
5	Madison, WI	3.33	0.3	3.2	16.5	6.7	254	3%
6	Lake Charles, LA	5	[redacted]	24.0	88.7	56.4	621	9%
7	Des Moines, IA	7.5	[redacted]	20.1	38.4	29.3	401	7%
8	St. Louis, MO	7.5	[redacted]	18.3	42.8	30.6	764	4%

TABLE 7b (Continued)
Cooling Loads Due to Infiltration for Tightened Envelope

Building	Location	Envelope Leakage (cm^2/m^2)	Cooling Loads (MJ/m^2)					
			Pressurized	Balanced	Depressurized	Average	PNL Total	% Infiltration
9	Las Vegas, NV	5	[redacted]	10.4	40.2	25.3	420	6%
10	Salt Lake City, UT	3.33	2.0	2.5	3.1	2.5	547	0%
11	Cheyenne, WY	3.33	0.1	0.9	4.5	1.8	535	0%
12	Portland, OR	7.5	[redacted]	0.9	[redacted]	0.9	199	0%
13	Pittsburgh, PA	7.5	2.1	5.6	14.0	7.2	615	1%
14	Amarillo, TX	7.5	5.4	10.6	21.3	12.4	516	2%
15	Raleigh, NC	3.33	0.1	7.6	49.9	19.2	1209	2%
16	Dallas, TX	3.33	2.3	14.4	64.7	27.1	1087	2%
17	Minneapolis, MN	2		1.5	13.2	7.4	479	2%
18	Boston, MA	3.33		1.0	8.2	4.6	990	0%
19	New York, NY	2	0.1	3.0	17.0	6.7	292	2%
20	Los Angeles, CA	2		0.2	1.3	0.8	1000	0%
21	Raleigh, NC	3.33	0.4	6.8	34.8	14.0	565	2%
22	Phoenix, AZ	3.33	2.0	13.0	56.1	23.7	363	7%
23	Pittsburgh, PA	3.33	0.1	2.1	11.2	4.5	184	2%
24	Pittsburgh, PA	2		0.7	11.7	6.2	246	3%
25	Charleston, SC	2	0.1	7.2	67.0	24.8	444	6%
All Buildings			**4.0**	**7.5**	**29.0**	**13.5**	**494**	**3%**

tive savings is the ventilation system balance. For heating loads, the savings averaged 32% for pressurized buildings but only 20% for depressurized ones. The relative difference was even greater for cooling load savings at an average of 39% for pressurized buildings compared to only 3% for depressurized buildings. The estimated potential annual energy savings through tightening envelopes of U.S. office buildings is 16 PJ for heating and 0.8 PJ for cooling.

As indicated above, control of the building ventilation system's pressurization vs. depressurization has a large impact on heating and cooling loads. The potential reduction of heating and cooling loads was estimated by using the average loads as a baseline and assuming all buildings that could be pressurized were pressurized. This results in a reduction of the average heating load of 19% and a reduction of the average cooling load of 58%. The potential reductions in infiltration impacts on U.S. office building energy use are summarized in Table 8.

TABLE 8
Potential Reduction in Infiltration Impacts

Modification	Reduction in Heating Load from Infiltration	Reduction in Cooling Load from Infiltration
Reduce envelope leakage (25% to 50%)	26%	15%
Better ventilation system control	19%	58%

DISCUSSION

Many of the results presented above, such as the approximate average percent of heating and cooling loads caused by infiltration and the increased relative importance of infiltration in newer buildings, are not surprising and confirm the findings of the earlier analysis (VanBronkhorst et al. 1995). However, the significant impact of the balance between ventilation system supply and return flows on the heating and cooling loads due to infiltration could not be examined through the infiltration assumptions used in the earlier analysis (and typical of many building energy simulation efforts). Also, while the cruder assumptions gave a comparable estimate for the average results over the 25 buildings, the results for individual buildings varied by much more. For example, the earlier estimate of the heating load due to infiltration in building 21 was nearly three times greater than the new estimate in Table 3, while the earlier estimate for building 1 was only half of the new estimate. While these differences are for artificial prototypical buildings, the results indicate the potential value of using a multizone airflow model when performing building energy calculations.

As mentioned above, several studies on the energy impact of increased ventilation rates have been reported (Eto 1990; Eto and Meyer 1988; Steele and Brown 1990; Zmeureanu et al. 1992; Mudarri and Hall 1993). A detailed comparison to the results reported here has not been presented for several reasons. First, due to differing objectives, the other reports did not present the fraction of heating and cooling energy due to ventilation as reported here, nor did they report detailed results from which a comparable number could be calculated. Also, the other referenced works emphasized detailed simulation of one or very few buildings in a few climates, whereas this work focuses on the average impacts of a very diverse set of buildings with no single comparable building. As such, there is no comparable figure to our estimate of national impact. Furthermore, the results for any single building in this analysis should not be focused on too strongly, as each building in the PNL set is intended to represent the combined characteristics of a large number of buildings and not to be taken as the model of any single real building.

This calculation of the national energy impacts of infiltration and ventilation in office buildings is obviously a rough estimate, and its accuracy should not be overstated. The limitations on the accuracy of the calculation stem from two broad categories—calculation method and input data (or assumptions). The greatest shortcoming of the calculation method was the use of a "bin" type of energy calculation rather than a transient, energy balance method. However, there was no available simulation tool combining a building energy balance calculation with multizone airflow modeling until recently. Emmerich et al. (1995) describe plans for creating such a tool through a combination of the multizone airflow model CONTAM and the energy simulation program TRNSYS (Klein 1992). In fact, that simulation tool is now available and will be used in the next phase of this project to improve the energy estimates and to examine potential energy saving options in greater detail.

The other shortcoming is in the area of input data and assumptions. The envelope leakage data are drawn from a relatively small number of buildings that have been reported on in just a few studies. More envelope leakage data are needed from throughout the spectrum of building age, envelope type, and size to more adequately describe this important aspect of buildings. Also, the significant impact of building ventilation system operation on infiltration and, therefore, on heating and cooling energy use indicates a need for data on how buildings operate. There are few data on this important topic.

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