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Power Demand and Energy Savings Through Air Leakage Control in High-Rise Residential Buildings in Cold Climates

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ABSTRACT

The air leakage rate in high-rise residential buildings predominantly depends on the stack and wind forces acting on the envelope, the operation of mechanical equipment, and the characteristics of leakage paths. During peak cold weather conditions, air leakage in the buildings also peaks, putting an additional burden on the space-heating system. Air leakage control has the potential to reduce electric space-heating loads. A method has been developed to determine the air leakage rate for high-rise residential buildings. Visual inspection of air leakage paths, aided by simple field tests, and assigning components airtightness characteristics are important parts of the air leakage control assessment procedure (ALCAP). This assessment procedure was applied and field-demonstrated in two high-rise residential buildings. The field comparison was accomplished by undertaking proven whole-building airtightness tests and monitoring energy and power demands. The results for two high-rise buildings can be summarized as follows: (1) air leakage control offered a reduction in peak space-heating demand by 4 to 7 W/m^2 of floor space, depending on the location and building characteristics; (2) the air leakage assessment procedure was found to be reliable within 10% in predicting the potential reduction in peak space-heating demand; and (3) the indoor air quality tests performed before and after the air sealing showed that there was no negative impact on the general conditions of comfort and air quality in both buildings.

INTRODUCTION

Good building construction practices should call for moisture-free and energy-saving performance of the building envelope, both in new construction and retrofits of multi-residential high-rise buildings. Air infiltration and ventilation have a profound influence on both the internal environment and on the energy needs of high-rise buildings in cold climates. On the basis of long-term performance, air leakage outward through the building envelope (exfiltration) has long been recognized as a contributor to concealed condensation. Excessive air infiltration causes cold drafts and reduces the indoor relative humidity levels, which results in comfort problems. Air sealing the building envelope from the interior will result in significant improvements in the building's airtightness. The increase in airtightness of the building shell reduces these problems and improves the thermal performance.

The air leakage rate in high-rise buildings predominantly depends on the stack and wind forces acting on the envelope, the operation of HVAC equipment, and the characteristics of leakage paths. During peak cold weather conditions, air leakage in the building also peaks, putting an additional burden on the space-heating system. During these winter conditions, utilities also face greater power demand. Therefore, air leakage control has the potential to reduce peak winter electric space-heating loads in cold climates. Concerned especially with reducing peak power demand and improving the energy efficiency of electrically heated high-rise buildings, various utilities across North America are exploring air leakage control as an energy conservation measure in high-rise residential buildings.

A survey of four high-rise residential buildings in Ontario showed that air leakage is indeed a major component contributing to peak demand during winter months. Energy audits of these four buildings showed that the peak space-heating demand in high-rise residential buildings (eight stories and higher) varies from 35 to 65 W/m^2 of floor space. During peak winter conditions, the air leakage component contributes to the heating load by 12 to 25 W/m^2—roughly 25% to 40% of the peak heating demand (SCL 1990). Therefore, control of air leakage in high-rise buildings has been recognized as a key element in conserving electrical demand and energy.

Despite the importance of the process of air leakage in high-rise buildings, it is still an aspect of building science about which there is considerable uncertainty. In part, this problem has been made difficult by the diverse range of buildings, each built according to widely varying construction practices. The quantification of air leakage flows is difficult due to the complexities in flow mechanisms. Field practitioners, consulting engineers, and utility energy conservation program managers have long felt the need for an inexpensive assessment procedure to evaluate the importance of air leakage control in high-rise buildings.

This paper briefly describes (1) the field procedures necessary to identify and assess the air leakage rate in buildings of eight stories and higher and an estimation

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procedure to evaluate the various air leakage control strategies with respect to potential cost benefits and (2) a demonstration of air leakage control in two high-rise residential buildings including the impact on peak power demand, energy conservation, indoor air quality, and, of course, the building's airtightness.

METHOD

The theoretical airflow model is based on the network method. The following components are included:

- inside/outside temperature difference to determine the stack pressure distribution;
- design wind speed and directions to determine the wind pressure distribution;
- characteristics of the mechanical ventilation system;
- building dimensions, exposure, shielding, orientation, type, and construction details; and
- flow path distribution and air leakage characteristics.

The air leakage rate at a given location depends on the driving forces (stack, wind, and mechanical ventilation) and the characteristics of the opening in the building envelope. A simplified network of airflow paths can be established using the following information: climate and exposure, building type, building form, building dimensions, surface-to-volume ratios, shafts, envelope types, windows and doors, envelope crack lengths, openings, and make-up air strategies. The algebraic sum of airflow through these paths must always be equal to zero (SCL 1991a).

By applying the mass balance equation, the component of air infiltration that would occur during peak winter conditions can be determined. This airflow rate is responsible for the space-heating load due to uncontrolled infiltration. Any reduction in this infiltration flow should decrease the heating requirements for the building. The procedure has been simplified and developed into a practical application tool that is being utilized by assessors and air leakage control contractors (SCL 1991b).

Stack Pressure

In high-rise buildings, the significance of the stack effect must be considered for a number of configurations. These are (1) buildings with isolated floors, (2) buildings with semi-isolated floors, (3) uniform internal temperature distribution, and (4) nonuniform internal temperature distribution. The pressure difference due to stack effect at height h_2, with respect to the pressure at h_1, is given as

$$P_s = \rho * g * TDC * (h_1 - h_2) \frac{(T_i - T_o)}{T_o} \qquad (1)$$

where

P_s = pressure difference at height h_2 due to stack effect, Pa;
ρ = air density, kg/m^3 (about 1.2 at an average of indoor and outdoor temperature);
T_i = indoor temperature, K;
T_o = outdoor temperature, K;
h = building height, m; h_1 is height measured from the ground; h_2 is height of neutral pressure plane from ground;
TDC = thermal draft coefficient; for high-rise residential buildings, TDC varies from 0.7 to 0.9.

The location of the neutral pressure plane at zero wind speed depends on the vertical distribution of openings in the building envelope, the resistance of the openings to airflow, and the resistance to vertical airflow within the building. Internal partitions, stairwells, elevator shafts, utility ducts, vents, and mechanical supply and exhaust systems should be considered in estimating the local stack pressure. Maintaining airtightness between floors and from floors to vertical shafts is a means of controlling indoor-outdoor pressure differences and, therefore, air leakage.

Wind Pressure

Wind pressure is a function of height, terrain, and local shielding. On impinging the surface of an exposed building, wind deflection induces positive pressure on the windward side and negative pressure on the leeward side. The *1989* ASHRAE *Handbook—Fundamentals* (ASHRAE 1989) provides a method for determining the wind pressure. The time-averaged wind pressure at any height of the building can be expressed by the following equation:

$$P_w = \frac{(\rho C_{pw})}{2} \int_h (V_h^2) \qquad (2)$$

where

P_w = pressure due to wind, Pa;
C_{pw} = wind pressure coefficient;
V_h = wind speed at height h, m/s.

Mechanical Ventilation

The effect of mechanical ventilation on envelope pressure differences depends on the direction of the ventilation flow (exhaust or supply) and differences in these ventilation flows among the zones of the building. The mechanical ventilation in most high-rise buildings is designed to provide uniform fresh airflow to each floor. Mechanical ventilation may exert a constant pressure of 0.5 to 3 Pa, depending on the airtightness of the building shell and balancing of the ventilation system.

Combined Air Leakage Driving Forces

The total airflow rate is proportional to the square root of the pressure difference. The separate stack, Q_s, wind, Q_w, and mechanical ventilation, Q_v, airflows are added in quadrature to obtain the total air leakage rate due to combined pressures.

$$Q_{total}=(Q_s^2+Q_w^2+Q_v^2)^{1/2} \tag{3}$$

Determination of Air Leakage Rate

The air leakage paths in the building envelope and shafts are classified as follows (Figure 1):

- the area of the air leakage path occurring at the basement and ground floor level (A_G),
- the area of the air leakage path occurring at typical floor(s) (A_T), and
- the area of the air leakage path occurring at the top floor and penthouse (A_R).

Assuming that there is a neutral zone at the *m*th floor, as shown in Figure 1, the infiltration rate (Q_i) and the exfiltration rate (Q_o) through the exterior wall can be expressed given the local inner/outer pressure differential ΔP (Pa) and local leakage area A (m^2), as follows:

$$Q_i=A_G\sqrt{(2|\Delta P_G|/\rho)}+\sum_{j=2}^{M-1} A_{TJ}\sqrt{2|\Delta P_j|/\rho)} \tag{4}$$

and

$$Q_o=\sum_{j=M}^{N} A_{TJ}\sqrt{2|\Delta P_j|/\rho)}+A_R\sqrt{(2|\Delta P_R|/\rho)}\ . \tag{5}$$

The airflow balance is

$$Q_i=Q_o \tag{6}$$

where

Q = airflow rate, m^3/s;
i = inflow,
o = outflow;
A = leakage area, m^2;
ρ = air density, kg/m^3;
ΔP = pressure difference across building envelope, Pa.

The solution to the above three equations can be obtained using the following steps:

Step 1: Determine the leakage paths at each floor and assign the leakage class (by visual inspection, thermography, and simple tests—the method is described in the following section).

Step 2: Establish the stack pressure, wind pressure, and pressure due to mechanical ventilation and determine the net indoor/outdoor pressure difference (ΔP) at each floor as shown above.

Step 3: Calculate the airflows at each floor using the above equations by assuming first that the neutral pressure plane (NPP) occurs at the mid-height of the building.

Step 4: Equate the air inflow and outflow (Q_i = Q_o). If inflow is greater than outflow, then move the NPP one floor below and repeat the calculations as in step 3. If the inflow is lower than the outflow, then move the NPP one floor above and repeat the calculations. These steps should be repeated until

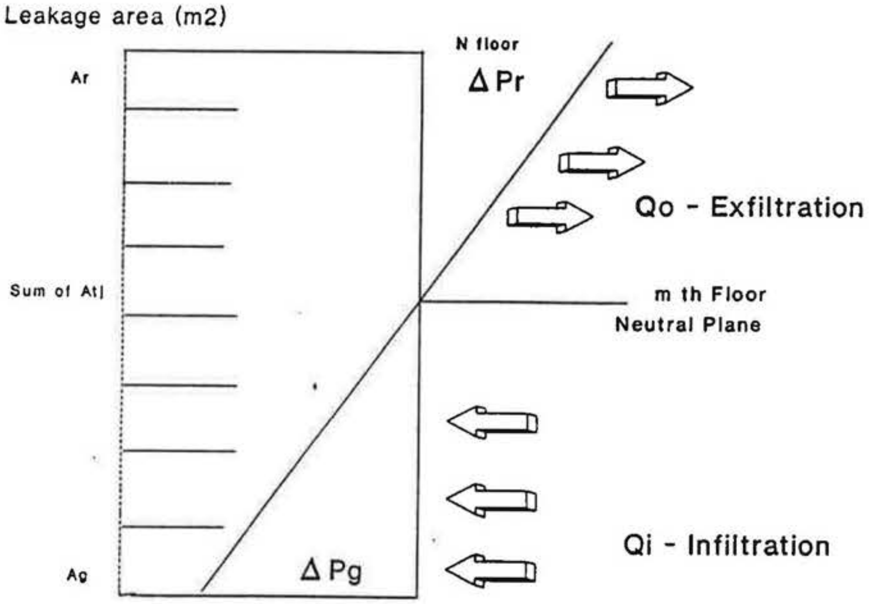


Figure 1 Initial assumptions for air infiltration and exfiltration flows.

at most a 3% difference between inflow (Q_i) and outflow (Q_o) is obtained.

The air inflow (Q_i) to the building is the uncontrolled air infiltration. Reduction of this component will result in reducing the peak heating demand and energy consumption.

The calculation procedure requires a detailed "picturing" of air leakage paths in the building. Identification and assessment of leakage paths and effective leakage area are the most important components of the calculation procedure and are described in the next section.

Based on the above method of determining the air leakage rate, a detailed field inspection procedure was developed to assess the potential reductions in peak heating demand. The air leakage assessment procedure addresses four concerns: (1) What is the air leakage in the building? (2) How much reduction in peak demand is possible with air leakage control? (3) What will be the air-sealing priorities and effectiveness for achieving the maximum ratio of reduction in kW to the air sealing costs? (4) How tight can buildings be and still supply adequate ventilation, maintain indoor air quality, and reduce moisture problems? A flow chart of the implementation of air-sealing measures in high-rise buildings has been suggested and is shown in Figure 2.

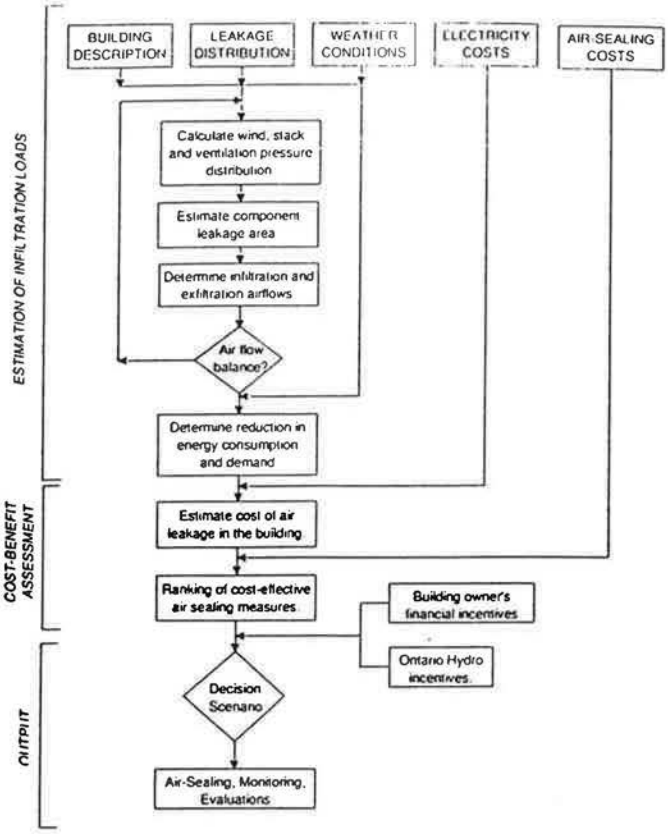


Figure 2 *Procedure for air leakage assessment and control in high-rise residential buildings.*

IDENTIFICATION AND ASSESSMENT OF AIR LEAKS

The airtightness or air leakage distribution in high-rise buildings can be assessed in two ways: (1) by the whole-building airtightness test using a calibrated fan and (2) the qualitative assessment of air leakage paths and characteristics using visual inspection, thermography, smoke pencils, draft meters, and suite depressurization.

The whole-building airtightness test, using a large axial fan or fans, is a more accurate and reliable method for determining the air leakage characteristics of the building envelope. Literature review shows that this method has been extensively developed and practiced in the field for research purposes (Shaw et al. 1990). Several field tests were conducted for developing the knowledge base and understanding air infiltration and exfiltration in high-rise buildings. However, such whole-building fan testing is costly for general commercial applications due to the need for (1) full access to all suites (apartments) in the building; (2) closing of all windows, exterior doors, air-supply dampers, and elevator shafts during the test; (3) favorable weather conditions; and (4) skilled rigging and operation of the fan and many associated accessories. Nevertheless, the whole-building test is both a research tool and a very good verification or quality control tool.

The qualitative visual assessment method is approximate; however, it is potentially much less costly and more broadly useful for commercial application to much of the high-rise building stock. The air infiltration or exfiltration flows in the building can be estimated by evaluating various leakage paths in the building. The leakage distribution in buildings is a function of the style of construction, which, in turn, is a response to the climatic conditions, the prevailing architectural fashion, and the building code requirements at the time of construction. The leakage distribution, being largely accidental, differs substantially in each building. The amount of the envelope leak that is not attributed to components such as windows, doors, and shafts (also known as background leakage) depends to a degree on prevailing construction practices.

It is also important to identify the relative air leakage importance of different components of the building. Such a ranking of air leakage through different components will assist in a cost-effective selection of air-sealing priorities, which should result in a maximum reduction in peak heating demands (i.e., to obtain a high ratio of kW saved to the cost of air sealing). The building components are divided into five different groups.

1. Windows

In most high-rise buildings, windows account for 15% to 70% of the total perimeter wall area. Air leaks through the perimeter of operable windows, and window sashes and glazing units contribute substantially to uncontrolled air infiltration. The wall and window junction is also a prime source of air leakage. The operable windows exert wear and tear on weatherstripping and sliding rails, which increases the air leakage drastically. The window leakage differs widely among different types. Windows that seal by compressing the weatherstrip (casements, awnings) have significantly lower leakage than windows with sliding seals. For implementing air leakage control measures, windows that are characterized as average or loose should be considered. Windows that are "airtight" should not be considered for retrofit measures.

Portable window-testing equipment can be used to determine the airtightness of openable windows. The airflow rate at the pressure difference of 50 Pa is recorded. This airflow rate is compared with the design value for the type of window. If the airtightness value of the existing window is within ±15% of the design value, the window is considered "tight." However, if it exhibits more than ±15%, the window is considered for air sealing (weatherstripping and/or caulking). ASTM Standard E 783-84 provides a method for field measurement of air leakage through windows (ASTM 1984).

2. External Doors

In most high-rise residential buildings, exterior doors account for 6% to 12% of the total perimeter wall area. Air leaks through the perimeter of operable doors and the door frame and glazing unit contribute to uncontrolled air infiltration. The wall and door junction is also a source of air leakage. The doors exert wear and tear on weatherstripping and sliding rails, which increases the air leakage drastically. Leakage characteristics are determined using visual inspection techniques. ASTM Standard E 783-84 provides a method for field measurement of air leakage through doors.

3. Building Envelope

Building component junctions contribute to air infiltration. These are

- basement and first-floor junction;
- corridors connecting the underground parking garage to the building;
- pipe, duct, and conduit penetrations from the basement to upper floors;
- perimeter wall and floor interface for the bottom and top zones of the building;
- roof and wall gap;
- baseboard heater wiring where it penetrates wall and floor zones;
- partition-into-wall junctions;
- wall and window or door junctions;
- interior partitions that provide pathways into each floor space and to exterior wall space;
- exterior light fixtures;
- basement walls and slab floor junctions; and
- plumbing and piping holes.

4. Elevator Shafts and Service Shafts

In high-rise buildings, elevators, stairwells, garbage chutes, service shafts, and vertical plumbing or electrical stacks constitute a significant part of the total air leakage. These components allow free airflow patterns due to stack effect. It has been shown that sealing or isolation of these shafts reduces the air leakage in the building by 10% to 25%. The air sealing can be done around cables and chain drives, the perimeter of the penthouse, stairwells, fire doors, the penthouse at the roof, and garbage chute hatches.

5. Miscellaneous

There are several smaller components in the building that contribute to air leakage. If these components are not properly sealed, they may contribute to a large proportion of air leakage in the building. These components are

- backdraft dampers on suite exhaust fans,
- ducting for suite exhaust fans behind grilles,
- inspection hatches,
- laundry chute exit, and
- ducting for exhaust fans in kitchen and bathrooms.

Figure 3 shows typical air leakage paths. The field inspection of various air leakage paths involves the following steps.

Examining the Air Leakage Paths Any crack or opening in the building envelope that allows the transfer of outdoor air to indoors, or indoor air to outdoors, is considered a clear air leakage path. The air leakage path may be straightforward or through torturous windings. The field survey covers the following locations in the building: exterior survey of the building; basement and underground parking garage; ground floor; common areas such as service rooms, corridors, meeting rooms, and laundry and utility rooms; at least 10% to 15% of suites; penthouse and mechanical room; and roof. During the field visit, the assessor identifies air leakage paths through visual inspection. The visual inspection is aided by simple in-situ tests such as window airtightness tests and suite depressurization and "smoke penciling" of envelope leaks. Once the air leakage path is located, the assessor measures its size.

Determining the Class of Air Leakage The severity of air leakage is classified into three groups: tight, average, and loose. Visual inspection, smoke pencilling, suite fan depressurization tests, and in-situ window tests assist in determining the class of air leakage. The relative significance of air leakage classification is important. If the air leakage path is classified as "tight," there is no need to implement air sealing. "Average" and "loose" signify the

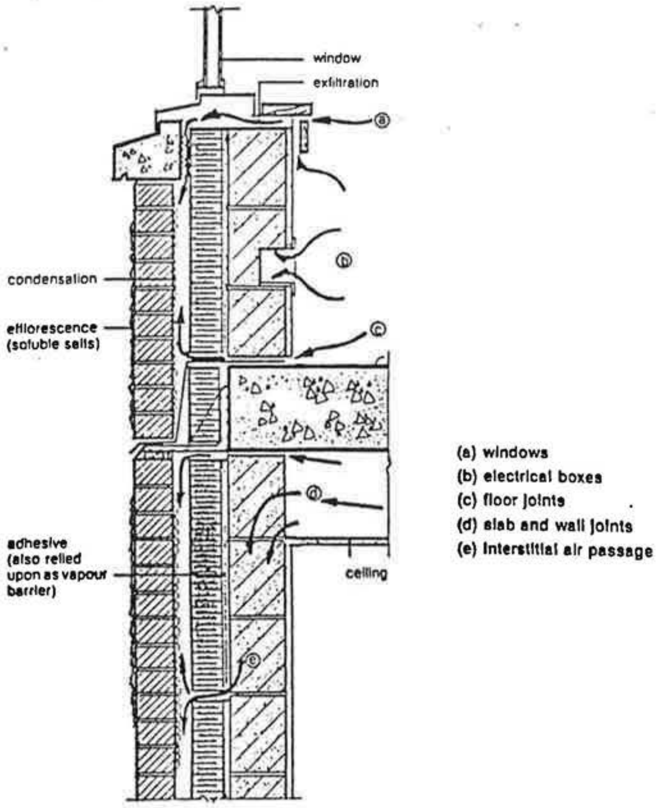


Figure 3 *Air leakage paths.*

need for considering the building component for air sealing. Chapter 23 of the *1989 ASHRAE Handbook—Fundamentals* and other references (ASHRAE 1989; SCL 1991a, 1991b) provide detailed tables showing typical ranges of effective leakage area for different building components.

FIELD DEMONSTRATION AND SUMMARY OF RESULTS

Two buildings were selected for the demonstration of air leakage control. The following tests were conducted to characterize these buildings before and after the air-sealing work: visual inspection and assessment of air leakage paths, whole-building airtightness tests, indoor air quality, and monitoring of energy and power consumption. The buildings are as follows.

Building A: It is a fairly well-maintained 21-story apartment tower located in Ottawa on open and flat terrain. Its 240 suites are fully occupied. The total heated floor space is 14,290 m^2 and the heated volume is 43,515 m^3. The exposed building envelope area is 7,470 m^2. A detailed energy audit of the building showed that the average annual space-heating energy consumption was 105 kWh/m^2 a year. The peak space-heating demand during the winter months was 42 W/m^2. Ottawa has 4,634 heating degree-days, a winter design temperature of -23°C, and a design wind speed of 12.5 m/s.

Building B: It is a 10-story, 95-suite apartment building located in a suburb of Toronto. The total heated floor space is 9,825 m^2 and the volume is 25,455 m^3. A detailed energy audit showed that the average annual space-heating energy consumption was 98.6 kWh/m^2 a year. The peak space-heating demand during the winter months was 46 W/m^2. Toronto has 3,646 heating degree-days, the winter design temperature is -18°C, and the design wind speed is 11.5 m/s.

Airtightness Tests Before and After Air Sealing

A test procedure described in Magee and Shaw (1990) was used to conduct the airtightness tests in both buildings. The airtightness tests were used to compare the network model used in the air leakage control assessment procedure (ALCAP).

Building A: A large axial vane fan with maximum capacity of 23,600 L/s was used to depressurize the building. The fan inlet was connected by 12 m of 0.9-m-diameter ducting to a plywood panel temporarily installed in the double doors. All windows, exterior doors, fan grilles, and elevators were shut off during the test. Airflow rates were measured upstream of the fan intake using a pair of total averaging tubes. Flow rates were accurate within 5% of the measured values. The airtightness results for Building A showed the following profiles, as shown in Figure 4.

Before air sealing,

$$Q=0.0983(\Delta P)^{0.809}. \tag{7}$$

After air sealing,

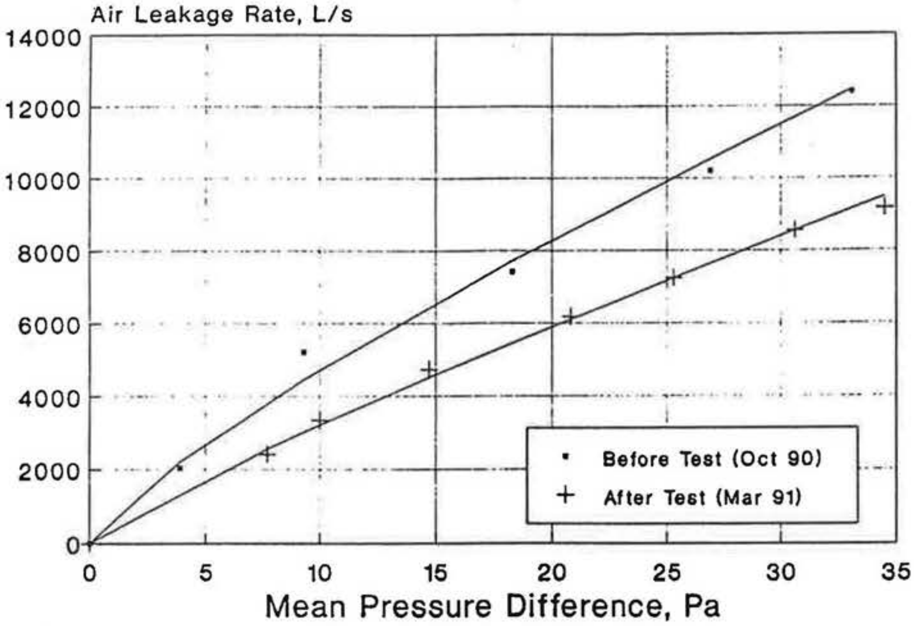
$$Q=0.0580(\Delta P)^{0.872} \tag{8}$$

where

Q = air leakage rate, $L/s{\cdot}m^2$ of envelope area, and
ΔP = mean pressure difference across the envelope, Pa.

Building A had a net uncontrolled air leakage rate of 4,740 L/s at 10 Pa pressure difference before the air-sealing retrofit. The equivalent leakage area is 2.13 m^2. The second test conducted after the air-sealing retrofit showed that the air leakage rate was reduced to 3,220 L/s at 10 Pa pressure difference. The improvement in airtightness was approximately 32% ([4,740-3,220]/4,740) after air sealing.

Building B: A floor-by-floor method was used to determine the airtightness of this building (Magee and Shaw 1990). The airtightness results showed that the air leakage rate was 1,885 L/s at 7 Pa pressure difference before the air-sealing retrofit. The air sealing of the building envelope reduced the air leakage rate to 1,165 L/s at 7 Pa pressure difference. The improvement in airtightness was 38% after the air sealing.



Before Test: Q = 734.23 (Delta P)^0.809
After Test: Q = 433.43 (Delta P)^0.872

Figure 4 *Effect of air sealing on measured airtightness of building A.*

Estimation of Potential for Air Leakage Control

The air leakage assessment procedure was used to determine the potential for air leakage control in these buildings (SCL 1991b; Parekh et. al. 1991). The following presents a brief summary of the field assessment undertaken for high-rise buildings.

1. *Pre-screening*. Energy audits were undertaken to determine the performance of buildings. Pre-screening tests showed that both these buildings did not have any moisture or indoor air quality related problems.
2. *Building inspection, audit of air leakage paths, and data collection*. A field inspection and building envelope audit were undertaken to assess the air leakage paths. In-situ window and door tests, suite depressurization with "smoke penciling," and infrared thermographic examination aided in data collection.
3. *Estimation of air leakage flow rate*. Determination of the air leakage flow rate during the winter design condition was undertaken using the method described above. The potential reduction in peak heating demand and energy savings is determined using the air leakage rates for different window components.
4. *Assessment of cost benefits*. Air-sealing costs were obtained from various air-sealing contractors. These costs were used to determine the cost benefit of various air-sealing measures. Depending on the ratio of cost ($) to potential reduction in peak demand (kW), the air-sealing measures were prioritized.

The assessment of Building A showed that the building envelope's air leakage area was approximately 2.72 m^2. The air leakage rate at the peak winter conditions, calculated using the procedure described above, was 5,390 L/s. Figure 5 shows the calculated profile of air leakage rates at the peak winter design condition for Building A. Energy analysis showed that the uncontrolled air leakage in the building contributed an additional heating demand of 265 kW— approximately 42% of peak space-heating load. As observed in the whole-building airtightness test, the air sealing of Building A reduced the air leakage by 32%. With the use of these field data, it can be determined that the air sealing has reduced the peak heating demand by 92 kW (6.4 W/m^2 of floor area).

A similar method was used to assess Building B. The air leakage control reduced the peak demand by approximately 42 kW (4.3 W/m^2 of floor area) in this building.

Indoor Air Quality

Air quality in residential buildings is an area of great concern. With the trend toward conserving energy, the effects on air quality need to be evaluated to avoid potential health problems that may result from the drastic reduction in air change. Therefore, during this study, air quality tests to monitor the effects of air-sealing work were done before and after the air sealing using a test protocol (CMHC 1990). The following air quality indicators were chosen for these buildings: formaldehyde, radon, carbon dioxide, relative humidity, and indoor temperature. In Building B, carbon monoxide samples were taken at the ground and

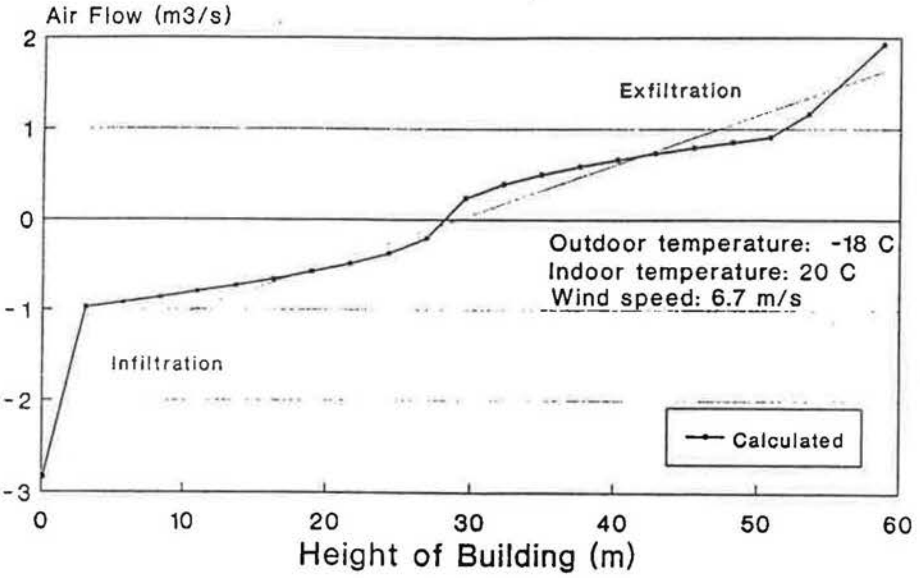


Figure 5 *Estimated profile of air leakage flow rate at peak winter design conditions for building A.*

underground parking levels. The following briefly summarizes the IAQ results of both buildings.

Formaldehyde The formaldehyde readings did increase slightly in some apartments while remaining relatively the same in others. However, the upper levels of formaldehyde concentration were well below the acceptable limit of 0.1 ppm for residential occupancies (HWC 1987). Table 1 shows a partial list of formaldehyde sampling in Building A.

Radon Radon samples were taken at the basement, ground, and first-floor levels. There was no significant change in the radon level after the air-sealing retrofit. The maximum level recorded in these buildings was 20 Bq/m^3 (0.54 pCi/L), which is well below the acceptable level of 148 Bq/m^3 (4 pCi/L).

Carbon Dioxide The carbon dioxide levels either remained the same or increased in some apartments after the air sealing. However, the upper levels of CO_2 were less

TABLE 1

Average Measurements of Formaldehyde Concentration in Building A

(Two samples were installed in each suite. Testing Method: AQR, PF-1 formaldehyde monitors)

Sampling Location Suite Number	Before Air Sealing Jan. 4 - 11, 1991 (ppm)	After Air Sealing Feb. 15 - 22, 1991 (ppm)	Degree of Change
103	0.016	0.031	slight increase
107	0.028	0.043	slight increase
207	0.016	0.031	slight increase
210	0.016	0.034	slight increase
402	0.022	0.028	slight increase
406	0.018	0.021	unchanged
807	0.027	0.021	relatively unchanged
810	0.013	0.008	unchanged
1507	0.019	0.020	unchanged
1510	0.062	0.062	unchanged
1703	0.028	0.038	slight increase
1710	0.034	0.040	slight increase
2207	0.030	0.032	unchanged
2210	0.010	0.020	slight increase

than the acceptable 1,000 ppm as recommended by *ASHRAE Standard 62-1989* (ASHRAE 1989c).

Relative Humidity The relative humidity levels increased in the lower-floor apartments and decreased in the upper stories. The average RH was 29% before and 32% after the air sealing. The measured RH readings were within the human comfort zone.

Carbon Monoxide CO samples were taken at the underground parking and ground-floor levels of Building B. Comparison of the samples showed no significant difference. The CO levels were well below the accepted limit of 11 ppm (HWC 1987).

In both these buildings, it was also observed that the air sealing had reduced the movement of stale odors. In fact, the sealing allowed for more consistent adjustment of air supply to the apartments. The air sealing had no negative impact on the general indoor air quality in the test buildings.

Monitoring of Energy Consumption Before and After Air Sealing

Energy consumption in both buildings was continuously monitored at 15-minute intervals. The total electric supply to the building and the hot water loads were monitored from November 1990 to June 1991. Similar weather periods, before and after air sealing, were selected to compare the energy consumption. The analysis was performed using an hourly energy simulation program to develop appropriate correction factors to account for solar gains, weather effects, and occupancy using the building description (CR 1988). The results are summarized below and in Table 2.

Building A The comparison of similar weather periods showed that the difference in electric load before and after air sealing was 64 to 84 kW depending on the ambient conditions. Using the building characteristics and an assumed weather profile for a peak day (ambient temperature varying from -18°C to -21°C and an average wind speed of 12.5 m/s), a simulation was performed to predict the potential reductions in heating load. Results showed that the reduction in heating load due to air sealing would be 85 kW on a peak day—a reduction of 14% of the peak space-heating demand. The space-heating energy consumption during the heating season was reduced by 165 MWh, or 12% of the total. Figure 6 shows a comparison of electric demand data taken before and after air sealing.

Building B The comparison of similar weather periods showed that the difference in electric load before and after air sealing was 33 to 42 kW depending on the ambient conditions. Analyses using the building characteristics and an assumed weather profile for a peak day (ambient temperature varying from -15°C to -18°C and an average wind speed of 11.5 m/s) were performed to predict the potential reductions in heating load. The reduction in heating load due to air sealing was 42 kW on a peak day—18% of the peak space-heating demand. This reduction in space-heating load represents 8.5% of the total electric load for the building. The energy consumption during the heating season was reduced by 63.3 MWh, or 6.5% of total. Figure 7 shows the load profiles measured on two similar weather days before and after air sealing.

Comparison of Predictions of ALCAP with Field Tests and Energy Monitoring Data

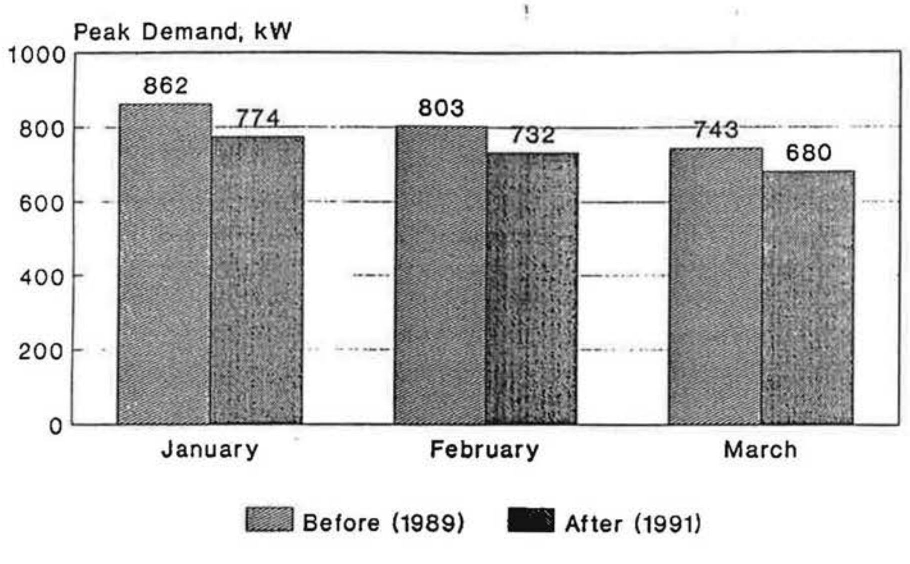
Building A The assessment procedure predicted an airtightness of 0.712 $L/s \cdot m^2$ of building envelope. The whole-building airtightness test showed an airtightness of 0.635 $L/s \cdot m^2$ at 10 Pa mean pressure difference. The predicted airtightness value was approximately 12% higher than what was actually measured. The measured difference in the peak heating load was 5.95 W/m^2 of floor area. The predicted reduction in space-heating load at winter design conditions was 6.44 W/m^2. Predicted savings in peak heating demand were approximately 8% higher than the measured data.

Building B The assessment procedure predicted an airtightness of 0.842 $L/s \cdot m^2$ of envelope area. The measured airtightness of the building was 0.893 $L/s \cdot m^2$. The predicted value was 6% lower than the measured. Similarly, the predicted savings in peak space-heating demand was about 5% lower than the measured savings.

TABLE 2

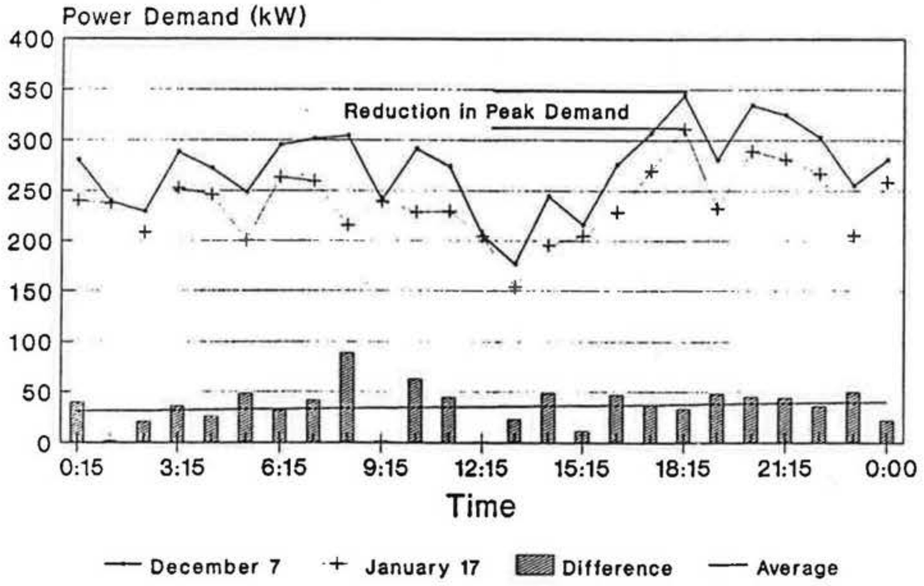
Summary of Measured Energy Consumption Before and After Air Sealing

	Peak Demand				**Energy Consumption During Heating Season (kWh)**	
	Before Air Sealing (kW)	**After Air Sealing (kW)**	**Difference in Demand (kW)**	**Percentage Reduction**	**Difference in Energy (MWh)**	**Percentage Reduction**
Building A (Ottawa)	772	687	85	11.0%	165	12.0%
Building B (Toronto)	496	454	42	8.5%	63.3	6.5%



Peak demand data normalized for temperature difference and degree days

Figure 6 Effect of air sealing on monthly peak power demand for building A.



Similar weather patterns for both days

Figure 7 Effect of air sealing on peak power demand on similar weather days for building B.

The demonstration of air leakage control in the above two buildings has shown remarkable savings in peak electric demand and space-heating energy consumption. However, on the basis of these two sets of results, it is difficult to generalize the potential benefits of air leakage control. Nevertheless, the above results do provide a higher degree of confidence in predicting the potential savings in demand and energy through air sealing of high-rise buildings. The project team is currently undertaking a field implementation of air leakage control of more than 250 high-rise residential buildings across Ontario. Results of this "weatherization" program will provide valuable data regarding the impact of air leakage control on high-rise buildings.

CONCLUSIONS

- A method has been developed to determine the air leakage rate for high-rise buildings. Visual inspection of air leakage paths, aided by simple tests, and assigning the components airtightness characteristics are important parts of the air leakage control assessment procedure (ALCAP). This predictive assessment procedure was compared with the results of field demonstration of air leakage control in two high-rise buildings. The field comparison was accomplished by undertaking proven whole-building airtightness tests and monitoring of energy and power demand.

- Based on the successful demonstration of air-sealing work and the use of the assessment procedure, it can be concluded that air leakage control has the potential to reduce peak electric demand by 4 to 7 W/m^2 of floor space depending on the location and building characteristics in cold climates.
- Indoor air quality tests showed that air sealing of the building had no negative impact on the general conditions of comfort and air quality in both buildings. It was also observed that the air sealing had reduced the movement of stale odors. In fact, the sealing allowed for more consistent adjustment of air supply to the apartments.

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