Air Leakage Control in Buildings: Importance of Reducing Air Leakage to Enhance Energy Efficiency and Comfort in Buildings

Good building construction practices should call for moisture-free and energy-economic performance of the building envelope, both in new construction and retrofits of multi-residential and commercial buildings. Air infiltration and ventilation has a profound influence on both the internal environment and on the energy needs of apartment buildings and commercial building 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 should result in significant improvements in the building airtightness. The increase in airtightness of the building shell reduces these problems and improves the thermal performance.

The air leakage rate in 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 the peak cold weather conditions, air leakage in the building also peaks, putting *additional* burden on the space-heating system. During these winter conditions, utilities also face greater power demand. Therefore, air leakage control offers a significant 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 buildings, a number of North American utilities are exploring air leakage control as an energy conservation measure in buildings.

This note summarizes the calculation procedures used for determining the potential reduction in peak heating demand and savings in energy consumption associated with air leakage control retrofits. The calculation procedures presented in this report have been used in the development of computerized energy savings model.

The importance of air leakage in building performance…

In buildings, the heating, ventilation and air-conditioning system maintains the indoor environment. The HVAC system provides the required conditioned air to different locations based on specific needs. The HVAC systems in commercial buildings are generally well pronounced and designed to satisfy the required ventilation as and when needed. In most buildings, the supply of fresh air ventilation is not dependent on the air leakage through the building envelope. In fact the mechanical ventilation system is generally designed to counteract the flow of air leakage through the envelope by keeping the indoor at slightly positive pressure. While counteracting the air leakage through the building envelope, a significant portion of conditioned air escapes through the envelope leakage paths. Leakage of conditioned air affects the building in two ways: (i) increases the moisture loading on the envelope; and (ii) incurs heat losses thereby affecting the operating costs.

There are four key factors, which affect air leakage in buildings:

- the overall tightness of the building (envelope construction and air leakage paths);
- the climatic influence (temperature driven stack and wind pressures);
- the interaction of building's HVAC system (mechanical pressures); and
- the topographic environment in which the building is located (shielding and exposure).

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. Elimination of uncontrolled air leakage through building envelope reduces the cold drafts, short-circuiting of conditioned air and thereby improves the indoor comfort and better control of indoor humidity.

Research and demonstration projects undertaken in last ten years have helped in the development of proper air leakage assessment field procedures and analysis tools. The following lists some of known demonstrations:

- A study undertaken at National Bureau of Standards (USA) measured the air change rates of eight office buildings and associated heat loads. The study showed that air leakage was a very significant part of the heating load. The average air infiltration rates measured in eight office buildings varied from 0.20 air changes per hour to 0.70 air changes per hour. The component of design heating load due to air leakage ranged from 23% to 61%. For four of these buildings, air leakage and make-up air heating constituted to over 50% of the heating loads. The study suggested solutions to improve the comfort and energy conservation aspects.
- In typical high-rise office buildings located in Ontario, the total energy consumption ranged from 250 to 450 kWh/m^2/year. The space heating energy component is about 39%, and the cooling energy component is approximately 13% of the total energy needs of the building. About 38% of the space heating and 8% of the cooling energy consumption is attributed to air leakage through the building envelope. In other words, air leakage represents about 15.9% (ranging from 40 to 72 kWh/m^2/year) of the annual energy needs of the building. On the basis of results of many field studies, it is established that the cost-effective air-sealing measures can reduce the air leakage component by 30% to 55%. Using this conservative practically achievable potential, air sealing retrofit measures can reduce the total annual energy consumption from 4.8% to 9.0%. This represents an annual energy savings of approximately 17 to 32 kWh/m^2/year for the building. The air-sealing measures can also reduce the peak heating demand in the electrically heated buildings by 3 to 8 W/m^2. Air leakage control (ALC) retrofit measures in high-rise buildings can have an average cost payback of 3 to 6 years.

- A recent study published by PWGSC showed that for a 17-storey office building (Brooke Claxton, Tunney's Pasture, Ottawa), 19,730 m^2 floor area, the whole building airtightness test results showed an improvement of airtightness of 37% after implementing window weatherstripping and caulking, and the sealing of vertical columns from the inside. A detailed hourly energy analysis showed that the rate of air leakage heat losses substantially increased with the increase in the indoor/outdoor temperature difference as shown in Figure 1. This figure emphasises the advantage of air-leakage control measures in curtailing the peak heating demand for electrically heated buildings.
- Another study by PWGSC showed that the exterior metal panel of a 20-storey, 12,800 m^2 floor area, high-rise office building (Davidson Dunton Tower) was replaced with a curtain-wall cladding system. This re-modelling improved the airtightness by 43% and reduced the annual space heating energy consumption by more than 11%.
- A survey of four electrically heated high-rise residential buildings (eight storeys or higher -- approximately 20 m and higher) in Ontario showed that the peak heating demand varied from 35 to 70 W/m^2 of floor space. During the peak winter conditions (below -18^oC ambient temperature and wind velocity of more than 5 m/s), the air infiltration component contributed to the heating load by 12 to 25 W/m^2 - roughly 25 to 40% of peak heating demand or approximately 12 to 16% of the total energy demand. The decrease in heating demand due to reduced air leakage also affected the annual energy consumption of the building. For the above four buildings, it was shown that the space heating energy consumption was reduced by 8 to 11.5 $kWh/year/m^2$ of heated floor space. This represented approximately 9 to 13% of the space heating energy consumption for the building.
- During 1990/91, a simplified assessment method was developed to estimate the impact of air leakage in high-rise building for Ontario Hydro. Scanada Consultants and Canam Buildings Specialist jointly developed the method. The assessment method was validated using the utility monitoring data and actual airtightness tests in two high-rise residential buildings. Based on the reliable air leakage control assessment procedure, Ontario Hydro' Non-Profit Housing Retrofit (NPHR) Program successfully completed air leakage retrofits of about 14,000 units comprising in about 320 electrically heated buildings. The impact evaluation credited the NPHR Program for reducing Ontario Hydro's system coincidence peak electrical demand by about 3.7 MW.

Based on our field and research experience, we have developed simplified assessment methods which can are used by energy services professionals. The simplified methods provide an acceptable confidence in engineering estimates of potential impact of air-sealing measures for a variety of buildings.

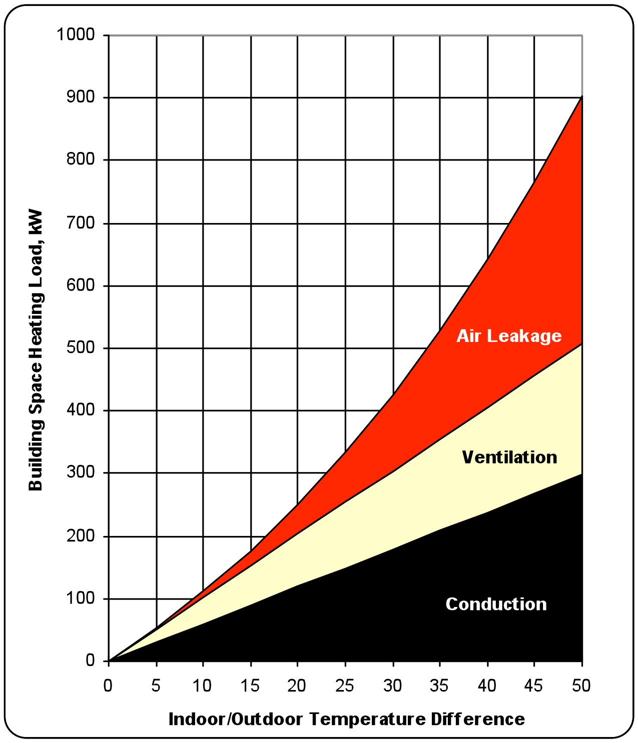

Figure 1: Heat loss components established for a 17-storey office building located in Ottawa.

Air Leakage Control Assessment Procedure

There are four components associated with each of the above calculation procedure:

- *Determination of air leakage paths*: the quantity measurements and qualitative assessments are used to determine the equivalent leakage area and the quantity measurements for the ALC work. This involves field walk-through audit.
- *Estimation of air-leakage flow rate*: air leakage flow rate is determined using the peak weather conditions for the location and the leakage area distribution. This involves detailed airflow modeling and developing airflow projections based on ambient conditions.
- *Calculation of potential energy savings*: heat flow calculations are performed to determine the potential benefits in the reduction of peak heating demand and savings in annual energy consumption. This involves location and building specific heat loads and estimation of energy impacts.
- *Assessment of cost-benefit*: Pre-determined unit ALC measures cost are used to determine the cost of ALC work. The reduction in peak demand is compared that of cost of a measure.

Calculation Procedures

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 and operation procedures;
- building dimensions, exposure, shielding, orientation, typology, 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 types, 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.

By applying the mass balance equation, the component of air infiltration that would be occurring during the peak winter condition can be determined. This airflow rate is responsible for the space-heating load due to uncontrolled air leakage. Any reduction in this air leakage 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 field auditors and practitioners.

Stack Pressure: In apartment buildings, the significance of the stack effect must be considered for a number of configurations. These are: (i) buildings with isolated floors, (ii) buildings with semi-isolated floors, (iii) uniform internal temperature distribution, and (iv) non uniform 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

$$P_s = \rho * g * TDC*(h_1-h_2)*(T_i-T_o)/(T_o)$$

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; and

TDC = thermal draft coefficient; for apartment 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 Fundamentals Handbook 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:

$$P_w = ((\rho\, C_{pw})/2)[(V_h)^2]_h$$

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.

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

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).

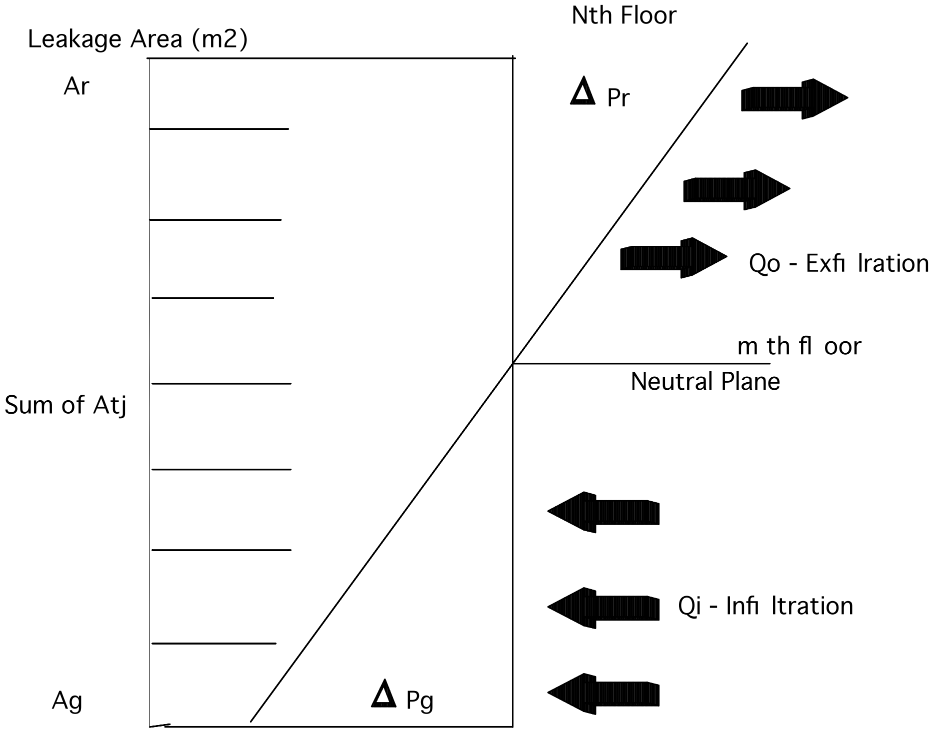

Figure 1: Initial assumptions for air infiltration and exfiltration flows.

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 DP (Pa) and local leakage area **A** (m^2), as follows:

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

and

$$Q_i = \sum_{j=M}^{N} A_{Tj}\sqrt{2|\Delta P_j|/\rho} + A_R\sqrt{2|\Delta P_R|/\rho}$$

The airflow balance is

$$Q_i = Q_o$$

where, Q = airflow rate, m^3/s; *i* = in-flow, *o* = out-flow;
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 (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 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.

Estimation of air-leakage flow rate

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. A schematic flow chart of the implementation of air-sealing measures in apartment buildings is shown in Figure 2.

The following presents a brief summary of the field assessment undertaken for apartment buildings.

- 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.
- 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 pencilling," and infrared thermographic examination aided in data collection.
- Estimation of air leakage flow rate: Determination of the air leakage flow rate during the winter design condition was undertaken using the method described as above. The potential reduction in peak heating demand and energy savings is determined using the air-leakage rates for different window components.
- 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.

Identification and Assessment of Air Leaks

The airtightness or air leakage distribution in apartment 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(s), 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[1]. 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: (i) full access to all suites (apartments) in the building; (ii) closing of all windows, exterior doors, air-supply dampers, and elevator shafts during the test; (iii) favourable weather conditions; and (iv) 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.

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[1] Shaw C.Y., S. Gasparetto, and J.T. Reardon. 1990. Methods for measuring air leakage in high-rise apartments. *Air Change Rate and Airtightness in Buildings*, ASTM STP 1067, M.H. Sherman, ed., pp. 222-230. Philadelphia: American Society for Testing and Materials.

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, to obtain a high ratio of kW saved to the cost of air sealing. The building components are divided into five different groups:

- Windows: In most apartment 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 and 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 operable 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).
- External Doors: In most apartment 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.

- 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;
  - plumbing and piping holes; and
  - accessible joints in attic in low-rise buildings; party wall and partition wall joints.
- Elevator Shafts and Service Shafts: In apartment buildings, elevators, stairwells, garbage chutes, service shafts, and vertical plumbing or electrical stacks comprise 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.
- 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.

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; attic; 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 pencilling" of envelope leaks. Once the air leakage path is located the assessor measures the size of this air leakage path.

- 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 need for considering the building component for air sealing. Chapter 26 of the 2001 ASHRAE Handbook of Fundamentals and other references provide detailed tables showing typical ranges of effective leakage area for different building components.

Determination of Savings in Annual Energy Consumption

There are two levels of calculations: (i) the energy savings model determines the reduction in heating demand for the building at the peak winter design conditions; and (ii) using the combined factor of demand diversity and the effectiveness of air sealing measures, the energy savings model further determines the reduction in space heating demand for the building.

The following briefly describes the energy-benefit calculations:

1. The air leakage rate is determined using the field information of leakage distribution and the driving forces due to stack pressure and wind pressure.

2. The energy savings model calculates the peak space heating demand due to uncontrolled air leakage in the building using the following information: (i) the air leakage rate, and (ii) the temperature difference between outdoor design temperature (2.5% winter design temperature for the location) and an assumed "balance point" temperature for the building. The balance point temperature of the building takes into account the effects of internal loads (lighting, people and appliances), solar gains and the diversity of heating equipment. The value of the peak space heating demand is a net space heating requirement that will occur for the building during the cold winter days.

3. A *combined factor* inclusive of the demand diversity factor (DDF) and the effectiveness of air sealing measures is being used to determine the "generation level" peak demand savings. The air leakage control remedial measures are approximately 40 to 50% effective in reducing the air-change related space

heating demand for the building. The demand diversity factor of 80%, obtained from Ontario Hydro, is assumed. This DDF factor is believed to closely match with the coincidental space heating loads on cold winter design days for most locations in Ontario. The *combined factor* varies from 32% to 40%. The energy savings model uses the *combined factor* to determine the generation level reductions in peak heating demand due to air leakage control measures.

The determination of demand diversity factor (DDF) is a complex procedure and is beyond the scope of the energy savings model. Therefore, a single value of DDF equals to 0.80 is being used to determine the "generation level" reductions in peak demand due to air leakage control in multi-unit residential buildings. This value of DDF was obtained from Ontario Hydro and is believed to closely match with the coincidental space heating loads on <u>cold day of the month</u> for most locations in Ontario.

During the coldest day of the month the DDF value varies from 0.80 to 0.90. However, during the <u>average day of the month</u> in the winter season, the DDF value will be lower than 0.80. During the <u>average day of the month</u>, the buildings' heating equipment cycling factor is low. (The cycling factor on the coldest day of the month is about 0.70 to 1.00 depending on the design of the heating equipment; while during the average day of the month the cycling factor may be 0.30 to 0.60.) The overall generation level demand is also lower on the average day. The combined effects of these two factors will lower the DDF. What value this DDF will have during the average day of the month is a stimulating question. It is assumed on the basis of cycling factor that the DDF may vary from 0.40 to 0.60. The above values of DDF are based on the engineering judgment.

4. The ALC model determines the potential savings in the energy consumption for the whole heating season. The ALC energy savings model uses a *combined factor* inclusive of the demand diversity factor and the effectiveness of air sealing measures to determine the "generation level" peak demand savings. The air leakage control remedial measures are approximately 40 to 50% effective in reducing the air-change related space heating demand for the building.

5. Calculations of Savings in Annual Energy Consumption. The peak demand saving for a design day (kW_{peak}) is calculated using the ALC model using daily average weather data for each month. The reduction in energy consumption ($kWh_{heating}$) is calculated for the whole heating season that may vary from the month of September to May depending on the location.

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