AN EXAMINATION OF AIR PRESSURE AND AIR MOVEMENT PATTERNS IN MULTI-UNIT RESIDENTIAL BUILDINGS

Gary Proskiw and Bert Phillips

ABSTRACT
A protocol was developed for characterizing air pressure regimes and air movement patterns in Multi-Unit Residential Buildings (MURB’s) and then applied to two MURB’s in Winnipeg, Canada. Using the data collected, a number of interesting observations were made and conclusions developed.

First, measured envelope pressure regimes were significantly different from those anticipated, especially during the winter. Occupant-controlled window operation was found to have a major impact on both building airtightness and the overall performance of the structure. Window utilization was found to be significant in even the coldest periods of winter (−40 °C). This resulted in erratic behaviour of both the Neutral Pressure Plane (NPP) and the Thermal Draft Coefficient (TDC). Basically, the “effective airtightness” of the buildings was controlled by the occupants and their use of the windows, not by the designers or builders.

Likewise, the NPP was found to be far less predictable than anticipated, particularly during the summer and shoulder seasons. During the winter, it tended to stay within the range of 0.70 to 0.90 times the height of the building, although large excursions were observed. This meant that potentially damaging exfiltration forces were moderated by the prevalence of open windows. The TDC also behaved in a very dynamic fashion and not in the relatively constant manner which had been anticipated. Again, much of this variation was attributed to occupant-controlled window operation. A procedure was also developed for estimating the leakage area attributable to screened windows which resulted in a very surprising re-evaluation of the true airtightness of buildings equipped with operable windows.

INTRODUCTION
Air leakage can be defined as the uncontrolled, and often unintentional, movement of air across the building envelope and is a critical factor affecting a building’s long-term durability and energy performance. Air leakage also has a major influence on comfort, health, noise transmission and the overall quality of the indoor space. In smaller structures, such as detached houses, air leakage is a relatively well understood phenomenon for which there is a good qualitative understanding of the processes involved as well as a decent quantitative appreciation of how much air leakage occurs, where it takes place, etc. However, houses are fairly simple buildings which can usually be treated as one or two zone structures.

The situation for Multi-Unit Residential Buildings (MURB’s), and other large structures, is considerably more complex and less well understood. Although the physical
processes which cause air leakage are identical, MURB’s are usually large, multi-storey buildings which can not be treated as simple one or two zone structures - in fact, many consist of hundreds of individual, interconnected zones. Further, their mechanical systems are usually larger and more powerful than those found in houses. Also, their sheer size makes it difficult and expensive to perform airtightness tests on the building envelope, measure mechanically delivered air flow rates and generally quantify the behaviour of the structure. Tests which can easily be performed in a house for a few hundred dollars may be difficult or impossible to carry out in a MURB - even with the expenditure of tens of thousands of dollars. For example, data bases now exist which contain measured airtightness results on literally hundreds of thousands of Canadian and American houses. In contrast, the total equivalent data base for large buildings, including MURB’s as well as commercial, institutional and industrial buildings, numbers a few hundred - worldwide. The air leakage behaviour of MURB’s is further complicated by the fact that they often contain hundreds of occupants, all of whom influence the performance of the building through such actions as opening and closing windows and doors, operating exhaust devices, producing water vapour and other activities which are often difficult or impossible to predict.

Despite the inherent complexities of large buildings, relative to detached houses, it has been argued that envelope pressure differentials could be used as a surrogate to provide useful information about air leakage and air movement patterns in such large, complex structures. Unfortunately, while the theoretical knowledge base on the behaviour of envelope pressure differentials is good, the observational evidence to support this understanding is relatively limited.

OBJECTIVES

The objective of the work described in this paper was to study building envelope pressure differentials on typical Multi-Unit Residential Buildings under winter, summer and shoulder season conditions and to better assess whether such measurements could provide useful information on the behaviour of this type of building.

AIRTIGHTNESS OF MULTI-UNIT RESIDENTIAL BUILDINGS

The term “airtightness” is used to describe the resistance to air movement of the building envelope. It is affected by the size of the structure as well as the number and characteristics of the various cracks, holes and other leakage pathways which exist through the envelope. Leakage path characteristics include such factors as the flow geometry, path length, as well as entrance and exit effects.

Understanding the behaviour of any building, including MURB’s, requires information on the overall airtightness of the structure. This is normally determined by mechanically pressurizing or depressurizing the structure while measuring the indoor-to-outdoor pressure differential and the corresponding air flow rates. This process is then repeated at a number of different pressure differentials. Mathematically, the relationship between air leakage and the imposed pressure differential can be represented by the classic power law function shown in Eq. (1).
\[ Q = C \Delta P^n \]  

where

- \( Q \) = air leakage, (l/s)
- \( C \) = flow coefficient (L/s\( \cdot \)Pa\(^n\))
- \( \Delta P \) = indoor-to-outdoor pressure differential (Pa)
- \( n \) = flow exponent (dimensionless)

The absolute flow rate in Eq. (1) is, by itself, of limited value since building size has to be factored into the analysis. For that reason, airtightness data are normally expressed using metrics based on either the surface area of the building envelope or the volume of the structure. Perhaps the two most common parameters used for large buildings are the “Normalized Leakage Rate at 75 Pascals” (NLR\(_{75}\)) and the “air change rate at 50 Pascals (ac/hr\(_{50}\))”. It has been shown that the area-based parameters, such as the NLR\(_{75}\), are better indicators of air leakage-induced moisture transport capability while volumetric-based air leakage parameters, such as the air change rate at 50 Pa, are better indicators of the energy liability which air leakage creates since the energy load is directly proportional to the volume of air which has to be conditioned (Proskiw, 2004).

For larger structures such as MURB’s, air leakage-induced moisture transport is normally the major concern and airtightness data is usually expressed using the Normalized Leakage Rate at 75 Pa.

\[ \text{NLR}_{75} = \frac{\text{Total leakage at 75 Pa}}{\text{Envelope area}} \]  

Compared to detached houses, the existing knowledge base on MURB airtightness is tiny - although some does exist. Table 1 summarizes airtightness data on 23 MURB’s located in eight different cities across Canada and ranging in height from single-storey structures to 21-storey apartment blocks (Proskiw and Phillips, 2001). As a benchmark for viewing these results, the Appendix of the 2005 National Building Code of Canada (NRC) recommends a maximum NLR\(_{75}\) of 0.10 L/s\( \cdot \)m\(^2\) (for buildings with average relative humidity levels), although these recommendations only apply to the opaque, insulated portions of the envelope and are not strictly intended to apply to the entire building. Further, these requirements are not mandatory parts of the code but simply recommendations for good building practice. Nonetheless, they do provide a general sense of what level of airtightness is considered desirable. Although none of the 23 reported buildings were designed or constructed to meet these contemporary guidelines, it is obvious that the existing MURB stock in Canada appears to far exceed what is now considered desirable, typically by a factor of 30 to 40.

Table 1

<p>| Summary of Airtightness Data - MURB’s (from Proskiw and Phillips, 2001) | | |</p>
<table>
<thead>
<tr>
<th>Number of Buildings</th>
<th>NLR&lt;sub&gt;75&lt;/sub&gt; (L/s·m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>12</td>
<td>3.19</td>
<td>1.18 to 6.37</td>
</tr>
<tr>
<td>3</td>
<td>4.00</td>
<td>3.15 to 4.50</td>
</tr>
<tr>
<td>8</td>
<td>4.30</td>
<td>0.83 to 10.00</td>
</tr>
</tbody>
</table>

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR<sub>75</sub>.  
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR<sub>75</sub>.  
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR<sub>75</sub>.

**BUILDING DESCRIPTIONS**

The field portion of this project was performed on two MURB's located in Winnipeg, Canada. Both were publically owned facilities, constructed in the early 1970's and used for social housing. Building #1 was 15 floors high and was equipped with electric baseboard heating and a corridor pressurization system to provide ventilation. It used masonry construction for the exterior walls with double-glazed PVC awning and fixed window units. Building #2 was 17 floors high and also used electric baseboard heating with a corridor pressurization system. The exterior wall system consisted of precast concrete panels with double-glazed, horizontal aluminum slider windows. Both buildings used individual suite exhausts which drew air from the bathrooms or bathrooms and kitchens. Both the suite exhaust and corridor ventilation systems operated continuously and were not under the control of the building occupants. Neither building contained combustion appliances in the suites.

**MONITORING PROGRAM - OVERVIEW**

Each building was visited during the winter, summer and shoulder seasons (spring or fall) and a variety of performance variables measured. These included instantaneous measurements of: interior and exterior environmental conditions (e.g. temperatures, relative humidity, etc.), instantaneous and continuous building envelope pressure differentials, various interior pressure differentials (e.g. suite-to-corridor, suite-to-suite, corridor-to-elevator shaft, etc.) and mechanical ventilation rates.

**PRESSURE DIFFERENTIALS**

The key monitoring variable (for this paper) was the indoor-to-outdoor pressure differential. This was measured at various locations on the building envelope using Setra Model 264 portable pressure transducers and ACR data loggers. The pressure transducers have a range of ±62.3 Pa with an accuracy of ±1% of full scale. The transducers and data loggers were installed for one week periods in unoccupied suites and recorded the indoor-to-outdoor pressure differential using copper capillary tubes routed to the outdoors through operable windows which were then taped shut. For each set of
measurements, the instrumentation was installed in two suites - one located near the top of the building and another near the bottom on the same side of the structure. The data loggers were then synchronized with each other and programmed to measure and record the indoor-to-outdoor pressure differential during the week. Between 10,000 and 22,000 individual measurements were recorded by each data logger for each monitoring session. These were subsequently processed down to mean, hourly data. This information was further processed to show the behaviour of the Neutral Pressure Plane (NPP) and the Thermal Draft Coefficient (TDC).

As previously stated, most high-rise buildings of the type studied in this project are relatively complex, multi-zoned structures with significant internal partitioning and complicated mechanical systems (compared to, say, houses). Developing a full understanding of their pressure behaviour would require extensive and detailed monitoring of envelope pressure differentials at numerous locations on the envelope as well as information on other parameters such as wind speed and direction, mechanical system operation, etc. One of the underlying objectives of this project was to evaluate the utility of monitoring pressure regimes using only a few monitoring locations since this would offer a fairly economical tool for such field investigations. The main assumption used in the development of this protocol was that two locations, at different elevations on the building envelope, would provide representative information on the pressure behaviour of the structures.

NEUTRAL PRESSURE PLANE

The Neutral Pressure Plane (NPP) is defined as the locus of points on the building envelope at which the indoor-to-outdoor pressure differential is zero. Since the stack effect is often the dominant driving force for air leakage, the NPP is typically assumed to be located along a horizontal plane at the mid-height of the structure - at least under winter conditions and in the absence of wind and mechanically induced pressure differentials. In practice, the NPP does not have to be horizontal (since the driving forces vary over the building's surface), nor at the mid-height of the building (since this assumes an equal distribution of leakage pathways over the building's height), nor is its location static (since the driving forces can vary on a second-by-second basis). In fact, the location of the NPP is highly variable. A building can even have several Neutral Pressure Planes.

Assuming uniform temperatures, the stack-induced pressure differential will vary linearly with the building height (ASHRAE, 2005). In the absence of wind and mechanical system action, those locations below the NPP will, under winter conditions, experience infiltration while those above the NPP will be exposed to exfiltration. This behaviour of the NPP explains why many buildings located in heating climates suffer the greatest envelope damage over the upper portions of the structure since that part of the building receives the greatest amount of air exfiltration and hence moisture deposition due to interstitial condensation. Under summer conditions, the stack effect will be reversed if the building air is at a lower temperature than ambient due to air-conditioning or thermal lag although leakage-induced damage will still predominate at the top of the structure.

OBSERVED BEHAVIOUR OF THE NEUTRAL PRESSURE PLANE POSITION
In the absence of wind and mechanical action, the indoor-to-outdoor pressure differential should vary linearly with height due to the influence of the stack effect. If we assume that wind and mechanical action do not significantly alter this assumption (at least over extended periods of time), then using the nomenclature shown in Fig. 1, the variation in the pressure differential can be expressed as...

\[ G = \frac{(P_2 - P_1)}{(H_2 - H_1)} \]  

where:
\( G \) = vertical pressure gradient (Pa/m)
\( P \) = pressure (Pa)
\( H \) = height at which the pressure differential is measured (m)

The y-intercept of this curve (the pressure differential at grade) is then equal to...

\[ \Delta P_{\text{int}} = P_1 - G(H_1) \]

In general,

\[ \Delta P = \Delta P_{\text{int}} + G(H) \]

\[ = [P_1 - G(H_1)] + G(H) \]

By definition, the Neutral Pressure Plane occurs where \( \Delta P = 0 \), so...

\[ \Delta P = [P_1 - G(H_1)] + G(H_{npp}) = 0 \]  

where:
\( H_{npp} \) = height of the Neutral Pressure Plane (m)

Therefore,

\[ G(H_{npp}) = G(H_1) - P_1 \]

\[ H_{npp} = \frac{[G(H_1) - P_1]}{G} \]

\[ H_{npp} = H_1 - \frac{P_1}{G} \]  

Thus, by measuring the indoor-to-outdoor pressure differentials at two different vertical locations on the building envelope, and knowing the heights above grade of these two locations, the height of the NPP can be calculated.

Using Eq. (5) and the corresponding pressure differential data, the height of the NPP was plotted for each monitoring period. These results are shown in Figs. 2 and 3 which plot
the NPP location normalized as a function of the building’s height. Examining the winter data first (when the NPP location has the greatest impact on building performance), the height of the NPP typically varied from about 0.70 to 0.90 times the building height for the two structures. As previously noted, the classical interpretation of NPP behaviour (in the absence of wind and mechanical action) is that it will be located at the mid-height of the structure - assuming an even distribution of leakage area over the vertical plane of the building.

One of the key observations made in this project was the influence which occupant-controlled window operation had on the operation of the two buildings. A window is a comparatively large hole in the envelope and having several dozen of them open will obviously play a major role in defining the overall leakage characteristics of the building. Experience (with this project and others) has shown that MURB occupants tend to open windows to a much greater extent on the upper portions of the building than on the lower floors to cool or ventilate their suites. Above the NPP, this usually produces air exfiltration, which means the utility of window operation for providing these two functions is severely compromised - which leads to increased window operation. However, one effect of opening a large hole is that it causes the NPP to move towards the hole, the larger the hole the greater its influence. Figs. 2 and 3 illustrate this effect since the NPP stayed well above the mid-height of the building during both winter monitoring periods.

The summer season results show even more extreme behaviour. Both buildings exhibited wildly erratic NPP behaviour due to large-scale window operation by the occupants. It should also be noted that the only air-conditioning in the two buildings was that provided by the corridor pressurization system (which had a cooling coil in the inlet ducts) and that many of the occupants were home during the day and thus able to open windows whenever desired. The corridor pressurization system would also have been more significant during summer operation because the stack effect was weaker relative to winter operation. Although summer operation is of much less concern from a building envelope perspective, these results illustrate the difficulty of predicting NPP behaviour in warm weather conditions for buildings with operable windows.

During the shoulder seasons, the behaviour of the NPP was somewhat different. In Building #1, the height of the NPP varied wildly since the driving force temperature differential was relatively weak. The average outdoor temperature during this period was 8.6 °C. Essentially, the NPP height was unstable for much of the period. In Building #2, the average temperature was slightly lower, 6.6 °C, with the result that the NPP behaviour was much closer to the classical model. However, the average NPP height was lower than experienced during winter conditions, likely because of increased window operation over the lower portions of the envelope. Wind would have also introduced some randomness into the buildings’ behaviour although the wind was also present during the winter when the position of the NPP was more stable.

There are several signification implications of this behaviour (i.e. operating the building with a large open window area). First, it provides significant protection to the
building envelope by reducing moisture transport into the envelope. Not only is a larger percentage of the envelope exposed to infiltration, rather than exfiltration forces, but the magnitude of the exfiltration forces on the upper portion of the building is reduced. Presumably in a building without operable windows (such as an office building), this effect would not be possible and the threat to the envelope would be greater. It also means that comfort issues would be more pronounced as the infiltration-inducing forces on the lower portion will be larger increasing the possibility of comfort-related complaints through non-window leakage sources. Smoke transport would also be different than would occur if the NPP were at mid-height.

It should be remembered that the two buildings used in this project were both equipped with operable windows which were frequently left open by the occupants. Buildings equipped with non-operating windows would not be subject to these influences and may exhibit behaviour which is significantly different from that observed on the two project buildings.

THERMAL DRAFT COEFFICIENT

One of the major differences between low-rise and high-rise buildings is that while the former are usually single-zone structures, high-rise buildings are multi-zone structures with complex arrangements of interior partitions, floors, etc. which can create a significant resistance to air flow relative to the building envelope. For this reason, the concept of the Thermal Draft Coefficient (TDC) was developed. The ASHRAE Handbook of Fundamentals (2005) defines the TDC as the actual pressure difference across the exterior walls of the building divided by the theoretical draft which would be created if there were no internal floors, partitions or other obstructions to air flow. The difference between the theoretical and actual pressure differentials provides a measure of the internal flow resistance created by the internal partitioning. As issues such as compartmentalization become more significant in the design of MURB’s, the TDC represents a valuable tool for assessing the degree to which it has been achieved. As a building is compartmentalized (i.e. sub-divided into separate physical zones which have appreciable levels of airtightness between them), the TDC decreases. Successful compartmentalization reduces the pressure differential which the exterior envelope experiences since a greater portion of the total stack effect is assumed by the interior partitions, floors, etc. Again however, the knowledge base of measured TDC values is extremely limited. Tamura and Shaw reported TDC values for tall office buildings ranging from 0.8 to 0.9 but few, if any, other references are available (1976).

OBSERVED BEHAVIOUR OF THE THERMAL DRAFT COEFFICIENT

Thermal Draft Coefficients were calculated for the two project buildings during each of the three seasonal monitoring periods. Using the continuously monitored, indoor-to-outdoor pressure differential data recorded on the upper and lower floors along with the hourly outdoor temperature, TDC values were calculated for each hour during each week-long monitoring session. These are shown in Figs. 4 and 5.

Contrary to what was anticipated, the TDC exhibited very unstable behaviour with significant variations appearing on an hour-by-hour basis. This behaviour raises some
important issues. Perhaps the most significant effect is that for buildings similar to the two used in this project, the TDC can behave in a very dynamic manner and not in a quasi-static fashion which a cursory review of the theory might suggest. However, it is believed that this behaviour can also be explained by the tenant’s operation of the building’s windows. As previously discussed, it appears that opening even a small percentage of the operable windows in a building can completely alter the airtightness characteristics of the structure. In fact, the leakage due to these open windows can completely swamp the “natural” air leakage pathways in the envelope, even during the coldest parts of winter.

The thermal draft coefficient is, in theory, a very valuable tool for describing certain aspects of a building’s air leakage behaviour and could become a very useful metric as the trend grows towards improved compartmentalization of MURB’s and other large buildings. However, the experiences with this project have suggested that using the TDC for this purpose may only be practical when the building’s airtightness is not subject to random modifications - such as in structures which do not have operable windows or other features which can alter the airtightness of the structure.

<table>
<thead>
<tr>
<th>Outdoor Temperature (°C)</th>
<th>Percent Open Window Area</th>
<th>Increase In NLR(_{75}) (L/s m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>8.8%</td>
<td>39.4</td>
</tr>
<tr>
<td>4</td>
<td>7.0%</td>
<td>31.3</td>
</tr>
<tr>
<td>-25</td>
<td>2.3%</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Typical Range Of NLR\(_{75}\) Values For Canadian MURB’s 1.18 to 6.37

THE UNEXPECTED ISSUE

One of the more significant (albeit, in hindsight, obvious) observations emerging from this project was the impact which occupant-controlled window operation had on the pressure regimes and overall performance of the buildings. Most modern large structures, particularly those which are relatively tall, have few (if any) operable windows. Commercial, industrial and institutional buildings are usually constructed with non-operating units to provide better control on the indoor environment. This limits the impact which the occupants can exert over the building, simplifies building operations and makes the structure’s behaviour more predictable. Among large, tall buildings, MURB’s are one of the few types normally equipped with operable windows - both in existing as well as new construction.

DISCUSSION
If the results of this project are representative of the general MURB population, it is apparent that many occupants routinely used their windows for comfort purposes during a significant portion of the year - even during bitterly cold weather. However, this strategy tends to only be modestly effective on floors above the NPP since, in the absence of significant wind action, air exfiltration will dominate through open windows during the heating season. These suites would basically be ventilated with corridor air provided by the pressurization system and by air leakage from lower floors.

During some site visits, photographs were taken of Building #2 and used to estimate the extent to which the windows were open - since it used slider windows whose positions were relatively easy to assess from a distance. Unfortunately, Building #1 used awning windows whose relative openness was more difficult to estimate. Using digital photographs from these visits, window operation was assessed for Building #2 for three different outdoor temperatures (20 °C, 4 °C and -25 °C). As shown in Table 2, the extent of window operation was quite significant even under winter conditions. This may seem surprising, but such behaviour was routinely observed with both structures. For example, on one occasion, Building #1 was visited at approximately 10:00 p.m. when the outdoor temperature was hovering around -40 °C. A number of windows, on both sides of the building, were observed to be partially or fully open.

Although interesting, these observations should be viewed cautiously since the data set is quite limited. Also, all of these observations were based on photographs taken during the day. An attempt was made to photograph one of the buildings at night but this was unsuccessful due to inadequate lighting although casual observation suggested that nighttime window operation was similar to that observed during daylight hours.

ESTIMATING AIR FLOW THROUGH SCREENED WINDOWS

Window operation not only affects the pressure regimes experienced by the building but can also have a profound impact on the effective airtightness of the structure. As previously mentioned, published airtightness data for MURB’s indicates that typical NLR75 values range from 1.18 L/s•m² to 6.37 L/s•m² (although the sample size for this data was only 12 buildings, i.e. Type 1 data in Table 1). All of this data was generated with the windows closed.

An open slider window (of the type found in Building #2) represents a large, rectangular orifice-like obstruction to air leakage. Its behaviour is somewhat complicated by the presence of insect screening which reduces the air flow rate since the screening has a comparatively high pressure drop relative to an open window. Insect screens are almost always present on operable windows in Winnipeg buildings.

Although the impact of occupant-controlled window operation on the airtightness, pressure regimes and overall behaviour of a building can never be completely predicted, the effect of an individual open window can be estimated. Then with knowledge of the overall utilization of the building’s windows, a general approximation can be made of their
effect on certain performance variables - most notably airtightness. Airflow through a large intentional opening can be estimated using Eq. (6)

\[ Q = C_D A \left( 2 \frac{\Delta P}{\rho} \right)^{0.5} \]  

where:
- \( Q \) = airflow rate, m\(^3\)/s
- \( \Delta P \) = pressure drop across the screen (N/m\(^2\) or Pa)
- \( A \) = area of the opening (m\(^2\))
- \( C_D \) = discharge coefficient for the opening (dimensionless)
- \( \rho \) = air density (kg/m\(^3\))

The primary unknown in Eq. (6) is the discharge coefficient, \( C_D \), which depends on the geometry of the opening and the Reynolds number of the flow. For unidirectional flow through the opening (i.e. where the flow is either completely infiltration or completely exfiltration), and where no screens are present, ASHRAE recommends a value for \( C_D \) of 0.65 (2005). The effect of screens on the airflow rate is primarily a function of their porosity, defined as the percentage of screen area which is open and unobstructed. Perez Parra et al (2004) have suggested that the airflow rate through a screened opening can be related to the flow rate through an equivalent unscreened opening by Eq. (7)...

\[ \frac{Q_s}{Q_{u/s}} = \varepsilon (2 - \varepsilon) \]  

where:
- \( Q_s \) = airflow rate through a screen opening (m\(^3\)/s)
- \( Q_{u/s} \) = airflow rate through an unscreened opening (m\(^3\)/s)
- \( \varepsilon \) = screen porosity

For this analysis, it was estimated that the screen had a 20 x 20 mesh with a wire diameter of 0.33 mm (typical values). This translates into a screen porosity of 0.548. Substituting into Eq. (7),

\[ \frac{Q_s}{Q_{u/s}} = \varepsilon (2 - \varepsilon) = (0.548) x (2 - 0.548) = 0.80 \]

Therefore, the impact of the screens would be to reduce the airflow rate by about 20% relative to that for an unscreened opening. Using this information along with Eq. (6) and an assumed air temperature of 10 °C (since both infiltration and exfiltration have to be considered) and an air density of 1.25 kg/m\(^3\), the airflow rate through an open, screened window can be estimated as...

\[ Q_s = (0.80) C_D A \left( 2 \frac{\Delta P}{\rho} \right)^{0.5} = (0.80) (0.65) \left( \frac{2}{1.25} \right)^{0.5} A \Delta p^{0.5} \]
The area \( A \) in Eq. (8) represents the total, open window area. For simplicity, this can be expressed as the total area of operable windows in the building multiplied by the percentage which are open. In Building #2 there were 272 operable windows, each with an area of 2.30 m\(^2\) thereby giving a total operable window area of 625.6 m\(^2\).

If we use the observed, estimated percentage area of open windows for 20 °C, 8.8\%, then \( A \) in Eq. (8) will equal 625.6 x 0.088 = 55.1 m\(^2\). The significance of this begins to emerge if we calculate the air flow which would occur through the open windows at an indoor-to-outdoor pressure differential of 75 Pa since this is the condition used to express airtightness results...

\[
Q = (0.66 \times 55.1) (75)^{0.5}
\]

\[
= 315 \text{ m}^3/\text{s}
\]

\[
= 315,000 \text{ L/s}
\]

While this may seem like a large flow rate, remember that it is an artificially imposed test condition and is calculated at a comparatively large indoor-to-outdoor pressure differential (75 Pa). Further, it assumes the windows (along with the rest of the building envelope) would be subject to infiltration, as opposed to a mix of infiltration and exfiltration.

The significance of Eq. (8) is that it allows the air flow rate to be estimated simply with knowledge of the open window area. Using Eq. (8) in concert with the temperature-dependent window usage characteristics summarized in Table 2, we can estimate the impact of window usage on the building’s overall airtightness (as determined under standardized test conditions). Although no measured NLR\(_{75}\) data was available for Building #2, we can use the range of typical NLR\(_{75}\) results reported for Canadian MURB’s - 1.18 to 6.37 L/s•m\(^2\). Using the total envelope area for Building #2 of 8,005 m\(^2\), the additional NLR\(_{75}\) created by the open windows at 20 °C would be...

\[
\text{NLR\(_{75}\)windows} = (315,000) / 8,005
\]

\[
= 39.4 \text{ L/s} \bullet \text{m}^2
\]

Parallel calculations were performed for the two other temperatures at which the window operation had been observed. These results are also shown in Table 2 which clearly illustrates that the presence of open windows in a MURB (or other building) has a major impact on the overall airtightness of the structure. In fact, for Building #2, the “effective airtightness” was largely defined by window utilization. Assuming that Building #2’s airtightness was within the range shown in Table 2, then even at -25 C, the major source of air leakage would be that which occurs through the open windows. At milder
temperatures, the non-window leakage becomes minor - even trivial.

Figure 6 shows the vertical distribution of open window area for Building #2 at an outdoor temperature of -25 °C. A very asymmetric pattern is evident with the open window area occurring predominately over the upper portions of the envelope. Assuming that the building's measured airtightness was within the range shown in Table 2, then the dominate source of leakage would be the open windows. For example, using the calculated NLR\textsubscript{75} value of 10.3 L/s\textbullet{}m\textsuperscript{2} for the windows at -25 °C, along with the published NLR\textsubscript{75} range of 1.18 to 6.37 L/s\textbullet{}m\textsuperscript{2}, the windows would represent between 62% and 90% of the total, effective leakage area, while at higher temperatures these values would increase significantly. Since the effect of a large hole is to cause the NPP to move towards the hole, the observed window usage shown in Fig. 6 suggests that the NPP should be located at some point well above the mid-height of the building. This corresponds quite well with the measured NPP behaviour shown in Fig. 3 c). Further, it adds support to the underlying assumption that long-term monitoring of envelope pressure differentials at two elevations in a multi-zone building can provide useful information on its behaviour.

Could the elevated neutral plane behaviour have resulted from a severe, asymmetric distribution of leakage area over the building envelope, specifically a preponderance of large holes near the top of the building (say the tops of elevator shafts, garbage chutes, etc)? Given that the total area of open windows in Building #2 ranged from 10.3 m\textsuperscript{2} to 39.4 m\textsuperscript{2} (depending on the outdoor temperature), this suggestion seems highly unlikely since it would have required holes of roughly comparable size to exist on the roof or elsewhere. The observed behaviour would have required not simply a very leaky elevator penthouse (for example), but a missing penthouse.

Could the elevated neutral plane position have been the result of mechanical depressurization? During each of the seasonal visits, the delivered air flow rates provided by the corridor pressurization system, along with the main floor supply system in Building #2, were measured using an Alnor APM151 flow hood. Bathroom and kitchen exhaust flow rates from a sample of three suites were measured during each visit using a TSI Model 1650 heated probe anemometer. The results, summarized in Table 3, show that the net flow imbalance during the winter for Building #2 was -2869 l/s (i.e. creating depressurization). If we again assume the building's NLR\textsubscript{75} was within the range of 1.18 to 6.37 L/s\textbullet{}m\textsuperscript{2}, and assume a flow exponent of 0.65 for n in Eq. (1) (a common assumption when n is unknown), then with knowledge of the building's envelope area (8005 m\textsuperscript{2}), we can use Eqs. (1) and (2) to estimate the pressure differential which this amount of flow imbalance would create...

\[
\text{With } \text{NLR}\textsubscript{75} = \frac{Q\textsubscript{75}}{A} = \frac{(C \Delta P^n)}{A} = 1.18 \text{ L/s}\textbullet{}m\textsuperscript{2}
\]

\[
\text{And } \Delta P = 75 \text{ Pa}, A = 8005 \text{ m}\textsuperscript{2}
\]

\[
1.18 = (C \times 75^{0.65}) / 8005 \text{ and}
\]

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C = 571 L / s•Pa^n.

Likewise, with NLR_{75} = 6.37 L/s•m^2, C = 3081 L / s•Pa^n

Then, using Q = C Δp^n with C = 571 L / s•Pa^n

2869 = 571 ΔP^{0.65} and

ΔP = 12 Pa

With C = 3081 L / s•Pa^n

ΔP = 0.9 Pa

In other words, the impact of the building’s mechanical system under worst-case conditions would have been to depressurize the structure between 0.9 and 12 Pa, during the winter with the windows closed. If we factor in window usage (i.e. increase the NLR_{75} by 10.3 L/s•m^2, then the impact of the mechanical system is further reduced. Repeating the preceding calculations, with the windows open to their observed winter condition, produces a mechanically generated pressure differential of between 0.2 and 0.4 Pa.

It should also be noted that during non-winter conditions, the mechanical flow imbalance was much less pronounced while window utilization increased significantly - all of which would have further mitigated the mechanically induced pressure differential. Likewise, flow imbalances in Building #1 were less pronounced than in Building #2. Therefore, assuming the two buildings’ airtightness were within the published range for comparable structures, then it appears the influence of mechanical systems on the overall pressure behaviour of the buildings would have been minimal.

**Table 3**

Ventilation System Flow Rates (L/s)

<table>
<thead>
<tr>
<th></th>
<th>Building #1</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Spring/Fall</td>
<td>Winter</td>
<td></td>
</tr>
<tr>
<td>Exhaust</td>
<td>-1768</td>
<td>-988</td>
<td>-1820</td>
<td></td>
</tr>
<tr>
<td>Supply</td>
<td>826</td>
<td>1048</td>
<td>1370</td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>-942</td>
<td>60</td>
<td>-450</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Building #2</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Spring/Fall</td>
<td>Winter</td>
<td></td>
</tr>
</tbody>
</table>

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Perhaps the most interesting result from this analysis is that since Eq. (8) is not building-specific, any structure which has significant numbers of operable windows that are used on a regular basis will basically have its airtightness dominated by air leakage through open windows. As the trend towards tighter building envelopes continues, the impact of window operation will become even more significant. For example, if judged by contemporary standards, the NLR$_{75}$ values in Table 2 actually represent fairly leaky buildings. One implication is that if MURB’s, and other structures, are to operate with low levels of natural air leakage, then improved ventilation, heating and cooling strategies will be required. In the absence of these measures, building occupants can be expected to open windows with such frequency, and to such an extent, that the effective airtightness of the structure will be controlled by the open windows and not by the air barrier - no matter how well the latter is designed and installed.

Frequent window operation in a MURB also means that compartmentalization becomes a more significant issue. When a window is open, the suite-to-outdoor pressure differential effectively drops to zero and the suite door, interior partitions, floor and ceiling assume the full indoor-to-outdoor pressure differential. If the building has been properly compartmentalized, the leakage between the suite and the rest of the structure will be minimized thereby negating much of the negative impact of the open window. In the absence of effective compartmentalization, an open window will be able to influence both the suite in which it is located as well as the rest of the building to a much greater extent.

Window operation can have other effects on a building. As long as the window is open, no appreciable amounts of air exfiltration will occur through the envelope in that suite and hence no moisture deposition will take place. In essence, open windows can protect the envelope from moisture damage. One of the authors encountered this phenomenon in a MURB which had a long history of water damage due to air exfiltration. The building was over 40 years old and had extensive, moisture-related damage to its wall system. Several suites suffered water and mould damage which required significant remedial work. However, one suite was found to be virtually damage-free. The tenant reported that she kept all of her widows (horizontal sliders) cracked open 5 cm to 10 cm at all times - even during the middle of winter. This neutralized the pressure differentials across the envelope in that suite and prevented significant air exfiltration and moisture deposition.

The results of this project have shown that window operation can seriously distort the anticipated pressure regimes which the building envelope experiences. And, the behaviour of the Neutral Pressure Plane and the Thermal Draft Coefficient for the two buildings was predictable in only a general sense as the result of window operation.
CONCLUSIONS

Behaviour Of The Neutral Pressure Plane - A procedure was developed for determining the long-term behaviour of a building's Neutral Pressure Plane (NPP) based on continuously monitored indoor-to-outdoor pressure differentials recorded at two locations on the building envelope. Using this method, the height of the NPP in the two project buildings was found to be far less predictable than anticipated. Under winter conditions, it tended to stay within the range of 0.70 to 0.90 times the height of the building, rather than at mid-height (as anticipated) although large excursions were frequently observed. However, during the summer and shoulder seasons, the position of the NPP became much more erratic. It is believed that the NPP's instability was largely the result of significant use of open windows by the buildings' occupants - even during periods of bitter cold.

Behaviour Of The Thermal Draft Coefficient - Using the continuously monitored indoor-to-outdoor pressure differentials, the Thermal Draft Coefficient was also found to behave in a very dynamic manner and not in a quasi-static fashion which a cursory review of the theory might suggest. It is believed that this behaviour can also be explained by the tenant's operation of the building's windows. It appears that opening even a small percentage of the operable windows in a building can completely alter the airtightness characteristics of the building.

Occupant-Controlled Window Operation - The occupant-controlled use of windows in the two test buildings had a major impact on the overall airtightness and performance of the structures. For example, in Building #2 the “effective airtightness” was shown to be largely dictated by window operation. Assuming that this structure's airtightness was representative of most MURB's, then even at -25 °C the major source of air leakage was through the open windows - not through the rest of the envelope. At milder temperatures, the non-window leakage became minor - even trivial - in comparison. One implication of this is that if MURB's, and other structures, are to operate with low levels of natural air leakage, then improved ventilation, heating and cooling strategies will be required. In the absence of these measures, building occupants can be expected to open windows with such frequency, and to such an extent, that the effective airtightness of the structure will be controlled by the open windows and not by the air barrier - no matter how well the latter is designed and installed.

COMPARTMENTALIZATION

Frequent window operation means that building compartmentalization becomes a more significant issue. With an open window, the suite-to-outdoor pressure differential approaches zero and the suite door, interior partitions, floor and ceiling assume the full indoor-to-outdoor pressure differential. If the building has been properly compartmentalized, the leakage between the suite and the rest of the building will be minimized thereby negating much of the potentially negative impact of the open window. In the absence of effective compartmentalization, an open window will influence both the suite in which it is located as well as the rest of the building.
REFERENCES


Fig. 2c) - Bldg. #1, Winter
Hnpp / (Building Height)

Fig. 3a) - Bldg. #2, Summer
Hnpp / (Building Height)
Fig. 6
Building #2, Window Usage

Conditions:
Outdoor Temp. -25°C
Wind: 15 km/hr
Sunny