The Path toward Net-Zero High-Rise Residential Buildings: Lessons Learned from Current Practice

Graham Finch
Associate Member ASHRAE

Dave Ricketts, PEng

Warren Knowles, PEng
Member ASHRAE

ABSTRACT

This paper presents some of the results of an ongoing research project that examines the relationship between current building practices and space heating in mid- to high-rise multiunit residential buildings (MURBs). The actual energy records and characteristics of the building enclosure are analyzed in detail for 39 mid- to high-rise residential buildings constructed over the past 40 years, located within the Lower Mainland of British Columbia. Several of the buildings in the study underwent complete building enclosure rehabilitations, primarily to address moisture damage, and this has provided an opportunity to examine the actual energy savings resulting from enclosure improvements. The effective R-value for all building enclosure assemblies have been calculated in detail and overall building R-values have been determined and compared to ASHRAE Standard 90.1 (ASHRAE 2007) and other performance criteria. The magnitude and significance of air leakage on space heating has also been assessed.

Significant conclusions include the following:

- *Space-heating and total energy consumption in high-rise condominium MURBs appears to have increased over the past 30 to 40 years despite perceived improvements in energy efficiency.*
- *Building enclosure rehabilitations to address moisture damage have demonstrated measurable reductions in space heating loads. Further reductions would be possible if incentives were available to improve energy efficiency at the time of necessary enclosure repairs.*
- *The overall effective R-values of high-rise MURBS have improved very little over the past 40 years, and current practice still remains significantly lower than current expectation for low-energy consumption buildings.*
- *Individual metering is an essential component of managing energy consumption in MURBs.*
- *Air leakage control has improved due to increased attention to wall and interface detailing; improved window performance, however, is still below expectations for current standards and low-energy consumption buildings.*
- *Airflow within the buildings is an issue for energy consumption and underscores the need for internal compartmentalization of suites in MURBs.*
- *A better understanding of occupant behavior and how buildings are actually operated is needed in order to design more efficient buildings.*

These conclusions also represent the best opportunities to improve building enclosure performance as part of achieving an overall net-zero energy goal in multiunit residential construction.

INTRODUCTION

The building industry is striving to reduce energy consumption and minimize the environmental impact of all buildings. This focus has gained momentum in recent years, and as with much of the evolution in building technology, this energy and environment focus has been led by the single-family housing sector. Houses have always represented a

Graham Finch *is a building science research engineer and* ***Dave Ricketts*** *and* ***Warren Knowles*** *are principals and senior building science specialists at RDH Building Engineering Ltd., Vancouver, BC, Canada.*

manageable opportunity for trying out new concepts and confirming performance. The concept of a house that generates as much power as it consumes, or "net-zero" energy is now well established, but this concept is now also gaining ground with respect to larger buildings and catching the attention of policymakers. The net-zero goal poses considerable challenges for houses, and when extended to include multiunit residential construction and other, larger buildings, additional complications are introduced.

ASHRAE Standard 189.1 (ASHRAE 2009) aims to be a net-zero-energy standard by 2030. The Government of British Columbia recently announced a mandate that by 2020 all new houses constructed in the province will be net-zero-energy ready. The City of Vancouver, known for being environmentally progressive, has set additional targets for all types of new buildings by 2020, including a 50% reduction in energy use from 2010 levels and a reduction of 20% in greenhouse gas emissions in all existing buildings. Therefore, in BC and particularly Vancouver, the prospect of drastically more energy-efficient multiunit residential buildings (MURBs) is possible and a current context for new and existing buildings.

A handful of net-zero houses have been built across Canada and the US, and we are now starting to receive feedback and performance results from these buildings (CMHC 2010). Net-zero homes built in the 1970s and 1980s are regaining attention and providing useful lessons. The Passivhaus standard is becoming popular in North America. Larger housing developments and small MURBs with community net-zero features have also been built recently and should become a good source of information in the future. The premise of this current research study and this paper is that we can also learn a lot from the performance of the existing MURB stock and that this information can help to establish priorities for net-zero design and construction of new MURBs, as well as retrofit of existing MURBs. This information can also be used for the design and construction of other buildings types.

The work in this study involves the assessment of the energy consumption data and, more specifically, the space-heating characteristics for 39 existing mid- and high-rise MURBs in the Lower Mainland of British Columbia. However, many of the building assemblies, as well as the analysis and conclusions arising from the study, are applicable to other geographic areas and building types.

Energy efficiency for any building begins with a highly insulated and air-tight building enclosure. The study is therefore focused on the identification of building enclosure issues that will need to be addressed in order to approach net-zero energy and emissions for MURBs. While specific net-zero strategies are not discussed within this paper, the holistic approach and consideration of fundamental energy efficiency issues that need to be addressed in existing and future MURBs are discussed. The paper also highlights where further field research is needed to improve the qualitative and quantitative understanding of certain building performance issues.

BACKGROUND

An industry sponsored research study was performed by the authors in conjunction with the local electricity and gas providers (BC Hydro, Terasen Gas, and Fortis BC), local municipality (City of Vancouver), and government agencies (Canada Mortgage and Housing Corporation [CMHC] and the Homeowner Protection Office) in a joint effort to look at and understand the energy consumption and energy efficiency of mid- to high-rise residential buildings. The study is unique in that it involves the analysis of a large number of in-service buildings with similar usage and exposure conditions.

For the study a total of sixty-four multiunit residential buildings (MURBs) of condominium ownership (i.e. strata title, home-owner association) were initially selected for analysis. Fifty-one of the buildings are 10 to 33 stories (high-rise) and thirteen of the buildings are 5 to 9 stories (mid-rise), and they were all constructed between 1974 and 2002. The buildings were selected to be representative of typical MURB housing stock and contain buildings of architectural form common to other mid- and high-rise residential buildings across North America. All of the buildings use both electricity and natural gas.

Though a population of over 60 buildings was initially chosen for the study, only 39 of the buildings had sufficient energy data. Data from the other buildings was unsuitable for this paper for a number of reasons, including missing or erroneous data, metering issues (i.e., single gas or electricity meters for several buildings grouped in complexes), difficulty in splitting consumption in buildings with mixed energy use (condominium plus commercial space on same meter), or lack of available data on the buildings at this time. All of the buildings use a combination of natural gas and electrical energy. Of the 39 buildings with data presented here, 5 are located in Victoria, BC, and 34 in the greater Vancouver, BC, area.

Both Vancouver and Victoria, BC, are in a temperate marine climate (IECC Zone 5C) and are considered two of Canada's warmest seasonal climates, with 2772 and 2853 annual average heating degree days (18°C), respectively, between 1998 and 2009 when the energy data was analyzed.

Approximately half of the buildings in the study also underwent complete building enclosure rehabilitations in the past decade, primarily to address moisture damage, which provides incidental pre- and post-rehabilitation energy savings as a result of well-documented enclosure improvements. Our firm is familiar with or has worked on the majority of study buildings in some capacity, commonly as the consultant responsible for assessing the existing conditions of the building enclosure assemblies and subsequently assisting with the design and implementing the enclosure rehabilitation, or in capital planning activities. In some cases, we were involved with the initial design and construction of the buildings as the building enclosure consultant. The detailed information from each of the buildings was utilized in the study to assess the MURBs in detail.

The principal objective of the study was to review and assess actual energy consumption of in-service mid- and high-rise MURBs, and the impacts of building enclosure rehabilitation improvements on the overall energy consumption. Additional objectives included development of strategies that take into account enclosure repairs, energy conservation, and greenhouse gas emissions. At the time the study was initiated, in-service combined gas and electricity data for MURBs was limited. Very few studies in the past have looked specifically at high-rise condominium MURB energy use. As a result, one of the primary objectives of the utility providers was to determine the contribution of both natural gas and electricity to overall energy consumption and space-heating in an effort to determine how to best allocate funding for possible energy efficiency incentive programs.

This paper presents a summary of the larger MURB energy study with a focus on some of the larger energy efficiency issues and key points. The complete literature review summarized for the project is provided in the full report (RDH 2010).

MURB ENERGY CONSUMPTION

Detailed energy consumption data were provided by the local gas and electric utility suppliers for the sample set of over 60 mid- to high-rise multiunit residential condominium buildings. For each of the MURBs, 10 to 11 years of data were provided to capture changes in energy consumption as the result of building enclosure upgrades in approximately half of the study buildings.

Electricity is individually metered for each suite and individually metered for the common and amenity areas. For confidentiality purposes in the study, the individual suite data was combined into an aggregate bill for analysis. Natural gas is metered at the supply inlet for the whole building (and sometimes a whole multibuilding complex). In all of the buildings, natural gas is used to heat domestic hot water and to heat ventilation air using gas-fired make-up air units (MAUs). In some buildings, natural gas is also used for gas fireplaces, and in a few buildings for stoves, but is not individually metered to the suites. The gas and electricity billing data were collected for the entire building and combined and calendarized into months for analysis along with climatic data. In a few of the buildings, daily consumption data were utilized to calibrate assumptions and refine the analysis.

As the primary goal of the study was to understand the influence of the building enclosure on energy consumption, it was of interest to isolate space-heat energy consumption. Space-heat energy was estimated by analyzing the seasonal variation in both gas and electrical energy consumption for each building. By analyzing average base-line summertime monthly consumption, the nonspace heat portion for each energy source was determined, allowing the space-heat energy (i.e., electric resistance baseboards or MAU gas for ventilation air) to be calculated as the monthly total energy minus the summertime baseline. This methodology is appropriate because cooling is not typically provided for the Vancouver study buildings (only one building incorporated cooling). This assumption was confirmed using daily gas data to improve the baseline estimates and calibrated energy modeling (RDH 2010).

Normalized site energy consumption data for the study buildings are presented in Figure 1, which shows the proportions of natural gas, suite electricity, and common electricity for each building. All energy consumption in this paper is site energy. With respect to this study, conversions to site energy were not performed, as site-to-source ratios for natural gas and electricity are approximately 1.10 and 1.11, respectively, in British Columbia (BC Hydro 2010). Electricity site-to-source ratios are very low compared to the rest of North America (3.0 to 3.5) due to the majority of electricity in BC coming from hydroelectric dams.

Average energy use intensity for the study MURBs is approximately 213 kWh/m^2/y and ranges from 144 to 299 kWh/m^2/y for the period from 1998 through 2009. On a per-suite basis, the average energy consumption is 21,926 kWh/y (combined gas, suite, and common electricity). This is lower on

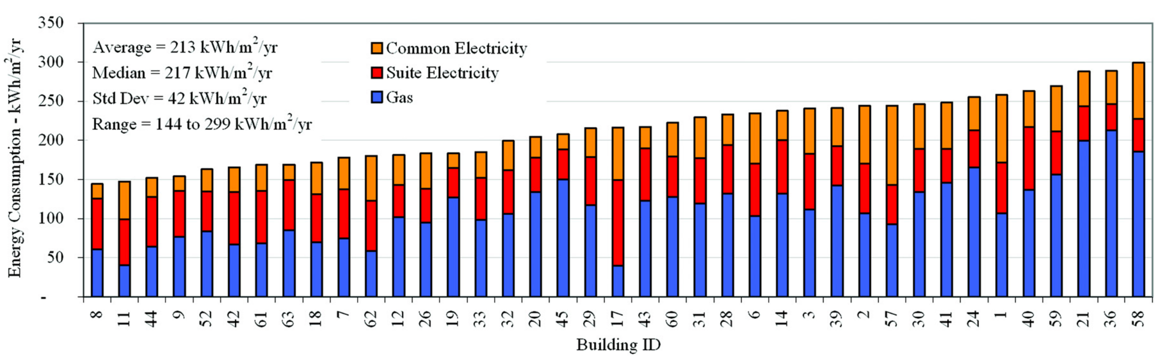


Figure 1 *Annual average energy consumption for 39 MURBs in the Lower Mainland and Victoria, BC—kWh/m^2/y of floor area.*

a per-dwelling unit than a local single-family house at 32,030 kWh/y (BC Hydro 2007).

On average, 49% of the energy is electricity, which breaks down to 28% electricity in suites and 21% electricity in common areas. Natural gas accounts for 51% of the energy used, which breaks down to approximately 25% for domestic hot water, with the remaining 26% used for make-up air ventilation heat and for gas-fireplaces (where present).

In terms of energy efficiency targets, a few twenty-to-thirty year old buildings have already demonstrated the ability to consume less than 150 kWh/m^2/y. There is also room for significant improvement in all of the study buildings to address mechanical system inefficiencies, ventilation strategies, lighting and equipment loads, building enclosure thermal performance, air-leakage, and occupant habits. If the target is to reduce energy consumption by 50% in the next ten years, a target of at most 100 kWh/m^2/y should be set for all new MURBs in the Lower Mainland. Energy modeling of MURBs with more efficient heating and ventilation systems, suite compartmentalization, a higher thermally performing building enclosure, and reductions in electrical base load suggests that it is both possible and economically feasible to drop MURB energy consumption below 100 kWh/m^2/y in the near term in this climate zone.

The billing analysis highlighted several metering and billing issues that further support the need to improve energy conservation by owners and occupants, which will in turn affect building energy efficiency.

- Natural gas accounts for approximately half of the energy consumption and the majority of purchased space-heat energy in a mid- to high-rise MURB yet is typically metered at only one location. Submetering of the MAU and domestic hot-water system is beneficial to assess actual consumption of each of these large appliances (instead of estimated) to develop individual strategies to reduce gas consumption.
- Submetering of individual suite gas fireplaces is necessary to properly allocate use and reduce gas consumption. Current practice in a strata building is for the total annual gas bill to be allocated based on strata lot-entitlement, regardless of fireplace use (and often even the presence of a fireplace). Suite occupants, therefore, have no incentive for reducing fireplace use and, in fact, may do the opposite and only use fireplaces for "free" heating (instead of electric baseboards, which they pay for). As monthly strata fees are fixed, the majority of occupants do not know what their individual fireplace use habits actually consume or cost. Similarly, domestic hot water would benefit from thermal submetering to fairly allocate energy costs and encourage conservation. Evidence of reductions in gas energy have been demonstrated within one of the study buildings where gas fireplace thermal meters were recently added by the building owners part way through this study. This building will continue to be monitored for a few years, and the results will be published in a later report.
- It would be of significant benefit to energy conservation if both natural gas and electrical meter information were made available electronically in real time to provide both occupants and building operators an indication of the actual energy use and cost. Numerous studies have shown that this encourages occupant behavior-related energy conservation. This information should also be made available to building designers and policy makers on which to base new and improved buildings and building construction requirements.

Space-Heat Energy

In the Lower Mainland of BC, the design space-heat system within most multiunit residential condominiums consists of electric resistance baseboard heaters within suites. Hydronic baseboard heat utilizing central gas boilers is less common in new condominiums but is fairly common in older apartment rental buildings. Gas fireplaces are also fairly common in condominiums and are present in several of the study MURBs constructed in the past 20 years. The suite space heat is supplemented by gas-heated ventilation air from a rooftop MAU supplied to the corridors and then to the suites through door undercuts (i.e., pressurized corridor approach). Ventilation air is typically provided to the corridors at a temperature between 15°C and 21°C, depending on the MAU setpoint. In the study buildings, a year-round setpoint of 20°C to 22°C was typically found in all of the buildings during the mechanical audits, with the owners setting the temperature near or above room temperature to reduce complaints of cold drafts in the corridors and through door undercuts. In a few buildings, up to a 25°C setpoint was found. As a result, ventilation air is heated even during the summer (a 20°C setpoint means that heat is provided for all but ~420 hours of the year in Vancouver). This is not typically assumed in the modeling of new buildings yet has a significant effect on gas consumption.

Analyzing the billing data from the 39 MURBs, the total energy consumed for space heating can be determined for both electricity and natural gas (MAU and fireplaces, where present). This is the total energy purchased for space heating; however, the conversion of gas burned by the MAU or fireplaces to provide useful space-heat is dependent on the seasonal efficiency of the equipment and distribution of heat to the suites.

The indirect gas-fired MAUs used on the MURBs in the study typically have a burner efficiency of 75% to 80%, depending on the age and manufacturer. Depending on the controls, turn-down ratio, low-burner setting, and heating load, the seasonal efficiency of a MAU system is estimated to be anywhere from less than 60% to up to 80%.

The types of gas fireplaces typically used in MURBs have efficiencies between 30% and 70%. The fireplaces installed in the study MURBs are direct-vent appliances and use exterior air for combustion (vented through side wall or vertical chimney at some penthouses). Pilot lights are controlled by occupants and in most buildings are not turned OFF during the summer. Fireplaces are often controlled only by ON/OFF switches and not thermostatically controlled, resulting in poor temperature control and thermal comfort and further reducing their useful space-heating efficiency.

The percentage of the total energy consumed for the purposes of space heating is shown in Figure 2 for the 39 MURBs, broken down by gas or electric source. Space-heat energy accounts for between 24% to 52% of the total energy consumption of the study buildings, with an average of 37% for a typical MURB.

All but the two hydronic heated MURBs (Buildings 19 and 45) incorporated electric baseboards to provide the space heat to the suites; however, the data indicates that on average 69% of purchased space-heat energy is from gas (even where gas fireplaces are not present). Figure 3 plots the percentage of total space-heating energy that is from gas sources. The two hydronic heated buildings and those buildings with gas fireplaces in the majority of suites are noted. Even in buildings without gas fireplaces, make-up-air gas accounts for greater than 60% of the space-heat energy consumed in the majority of the MURBs in the form of heated ventilation air.

The data show that while MURBs are being designed as electrically heated (with the exception of the two hydronic buildings) and have electric baseboards in suites, the majority of purchased space-heat energy is from gas. This is apparent for buildings containing gas fireplaces; however, this trend is shown even in MURBs without fireplaces, where heated ventilation air is the majority of space-heat energy consumed. Interestingly, Building 62, shown on the left side of the chart in Figure 3, has fireplaces within 10 of the 55 suites (18%) but has an older MAU providing minimal ventilation air and, as a result, appears more efficient. With the exception of the two older hydronic buildings, in general those buildings on the right side of the plot contain gas fireplaces, are of newer construction, and also have higher make-up airflow rates.

Figure 4 plots the normalized gas and electric space-heat energy versus the percentage of energy that is gas to demonstrate the impacts of inefficient gas fireplace consumption on electrical space heat, and total space-heating consumption. The gas (blue diamonds) and electric (red circles) space-heat consumption is plotted for each building, and for each building

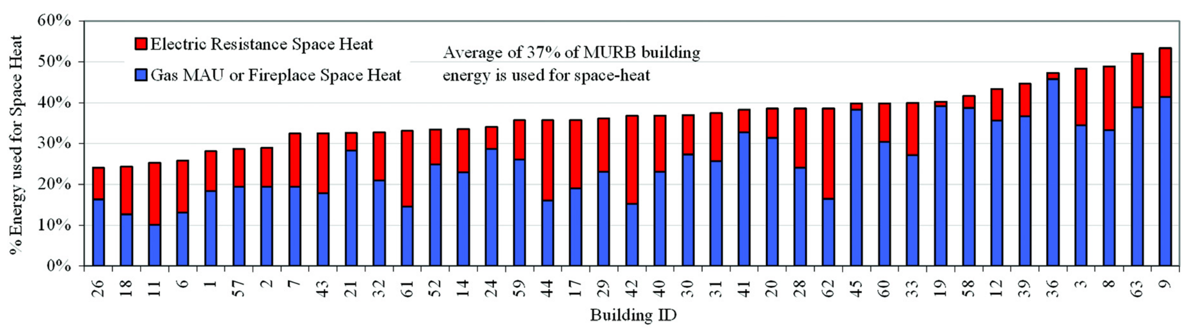


Figure 2 *Percentage of total energy used for space-heat, split by portion of gas and electricity.*

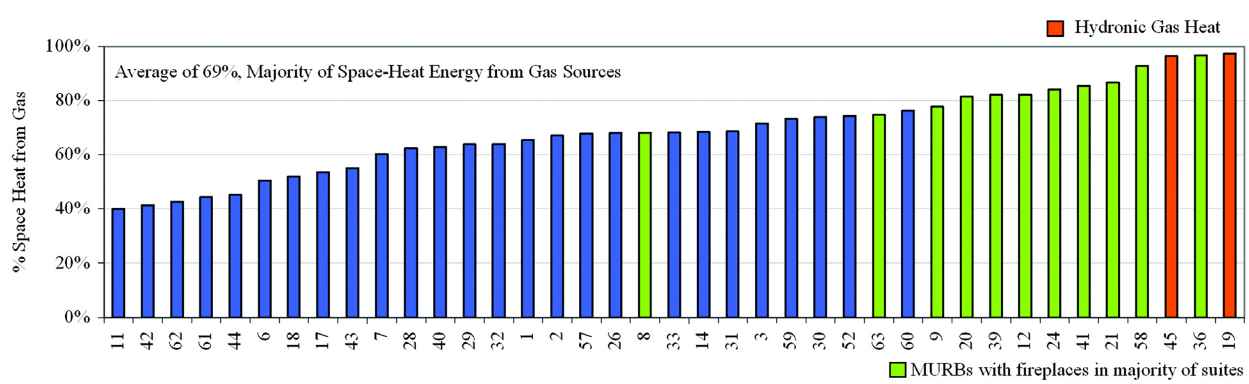


Figure 3 *Percentage of space heating energy that is from gas.*

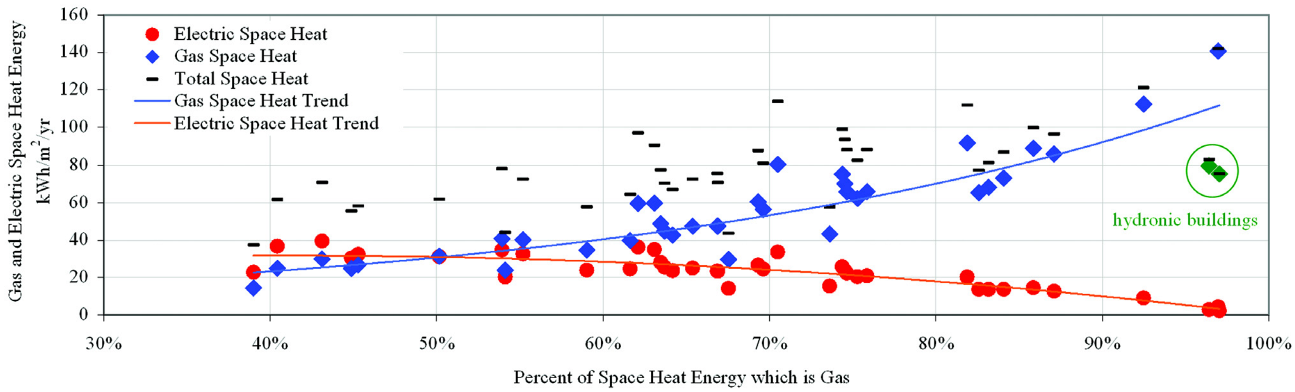


Figure 4 *Consumed gas and electric space-heat energy versus percent of space heat that is gas.*

lines up vertically. The total space-heat consumption for a specific building is the sum of both, as indicated by the small black dashed lines above.

The data indicates that on average, MURBs, which have 40%–70% of the space heat from gas, do not have gas-fireplaces and that an increasing trend in gas consumption in those buildings can be attributed to higher ventilation rates or MAU system inefficiency. Electric baseboard heat in these buildings remains on average between 20 and 40 kWh/m^2/y but slightly decreases as more make-up air heat is provided. The MURBs that have greater than 70% of the space heat from gas typically contain fireplaces, and the fireplace use (while inefficient) results in less electrical space-heat consumption (below 20 kWh/m^2/y). The increase in gas space-heat energy is higher than the reduction in electricity showing the effect of the lower fireplace efficiency. This is particularly apparent for building 36 (newer building with gas fireplaces) on the far right, where the gas space heat accounts for 140.7 kWh/m^2/y (97%) and electrical 4.4 kWh/m^2/y for a total space heat of 145.1 kWh/m^2/y. Compare this to a building at 50% gas heat without fireplaces, where both the gas and electrical space heat accounts for 31.4 kWh/m^2/y for a total space heat of 62.8 kWh/m^2/y, 82.3 kWh/m^2/y less than building 36. Even the older hydronic buildings only consumed a total of 80 kWh/m^2/y (both hydronic and MAU gas with <80% efficiencies). Considering the total average energy consumption is 213 kWh/m^2/y for a MURB, a space-heat consumption of 145 kWh/m^2/y appears to be excessively high.

The analysis demonstrates that gas fireplaces in MURBs are a hurdle in terms of energy efficiency, because of both occupant behavior in use and heating efficiency. Heating ventilation air using central MAUs also contributes to a large portion of the space-heat consumption of a MURB and higher ventilation rates as the result of design, and building code changes between 1980 and 2000 have resulted in a significant increase in gas consumption. This is further discussed in the following section.

For the 39 study buildings, on average 69% of the purchased energy for space heat is for gas, with a range from 40% to 97%.The remaining 31% of the space heat is used by electric baseboard heaters (the design heating system) with a range from 3% to 60%. This electrical space heat accounts for 38% of the suite electricity consumption (a range of 6% to 61%).

Gas fireplace heat partially offsets electric baseboard heat use; however, the inefficiency of gas fireplaces results in very high overall space-heating loads for those buildings with gas-fireplaces, which significantly affects total building energy use and compared efficiency. It is likely that the gas for fireplaces could be reduced by submetering and charging occupants for use; however, inefficiencies with commercially available residential fireplaces indicate that they are a poor choice as a space heating appliance compared to alternate systems.

Trends Affecting MURB Energy Consumption

Several trends became apparent in the analysis of the energy data. Discouragingly, the average energy consumption intensity (both natural gas and common electricity) within mid- to high-rise condominium MURBs appears to have increased over the past 20 to 40 years. This is illustrated in Figure 5, which plots the year of construction with each building's space heat and total energy consumption intensity.

The largest influence in the increase in total energy consumption appears to be an increase in energy for space heat. Interestingly, the average electricity consumption and electrical space heat has not significantly changed based on the age of building. In fact, the data would suggest a slight decrease in electrical space heat with the inclusion of gas fireplaces in newer buildings and higher MAU flow rates, as previously demonstrated. This indicates that the gas space heat for ventilation and fireplaces (and the efficiencies thereof) is one of the largest influences on the increase in MURB energy consumption, as shown in Figure 6.

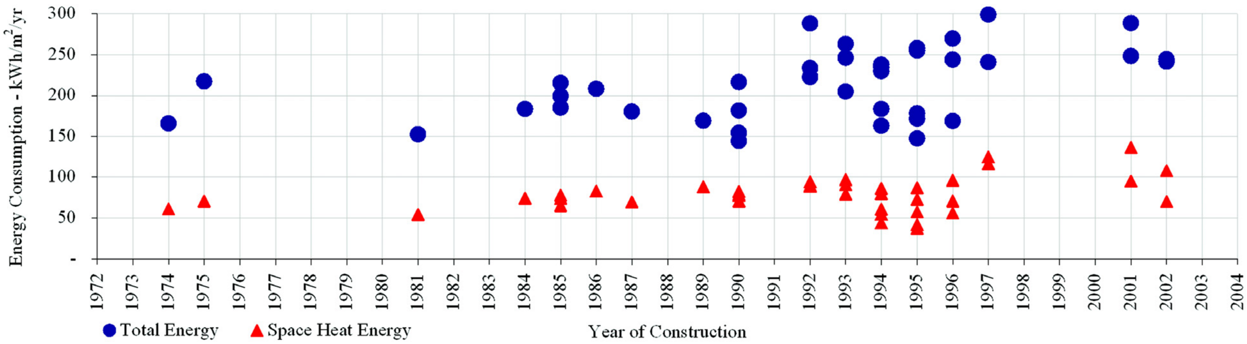


Figure 5 *Total and space-heat energy consumption of study MURBS by year of construction.*

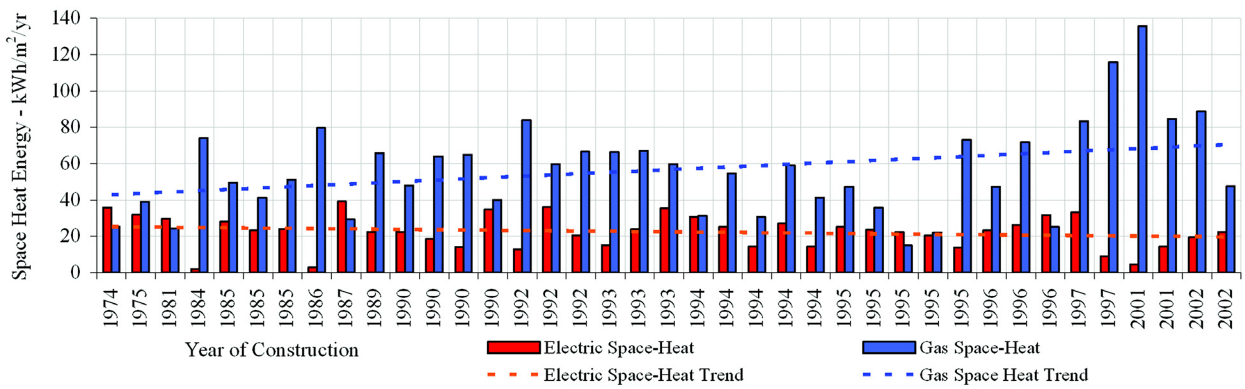


Figure 6 *Gas and electric space-heat energy by year of construction.*

The two hydronic buildings (19 and 45) that were originally constructed in 1984 and 1986 consume minimal electric space heat. Buildings with gas fireplaces are also anomalous since the ratio of gas to electric space heat is disproportionate. For example, the two buildings constructed in 1997 and 2001 include gas fireplaces and electric baseboard heaters; however, the data indicate the electric heat is rarely used compared to the fireplaces.

Other factors influencing higher energy consumption intensities in newer MURBs include the following:

- Increased common electricity from amenities such as larger lobbies, gyms, etc. in newer buildings.
- Increased mechanical loads from fans, pumps, elevators, etc. in more complex and taller buildings.
- The effective thermal performance of the study buildings has not significantly improved over the past 40 years. While the older buildings have lower glazing areas and less insulation within the walls, the newer buildings have higher glazing percentages and comparable effective insulation levels within the walls. Window-to-wall ratios range up to 80% in the study buildings. Effective overall R-values are discussed later in this paper.
- Increased natural gas consumption from increases in provided ventilation air (i.e., greater cfm per suite, translated to cfm/ft^2 of gross floor area), which requires larger MAUs burning more gas. Mechanical audits of the study buildings identified a range in designed and provided make-up air ventilation rates from 30 cfm/suite (0.025 cfm/ft^2) in buildings constructed in the 1980s to over 150 cfm/suite (0.140 cfm/ft^2) in buildings constructed after 2000. Figure 7 plots the total energy and total space-heat energy consumption within 13 of the study buildings versus the make-up air ventilation flow rate normalized to cfm/ft^2 of floor area.

Ventilation is provided for occupant health, and ventilation equipment is sized to provide a minimum cfm/person or cfm/ft^2 of floor area, depending on the code requirement. In a MURB, ventilation supply is provided by the MAU and a pressurized corridor to distribute to suites. In the past 40 years, minimum ventilation rates have increased in MURBs, resulting in larger MAUs and greater gas consumption proportional to the higher flow rates. This is the result of a design shift from using a pressurized corridor approach for only smoke and odor control to using the same system to intentionally provide

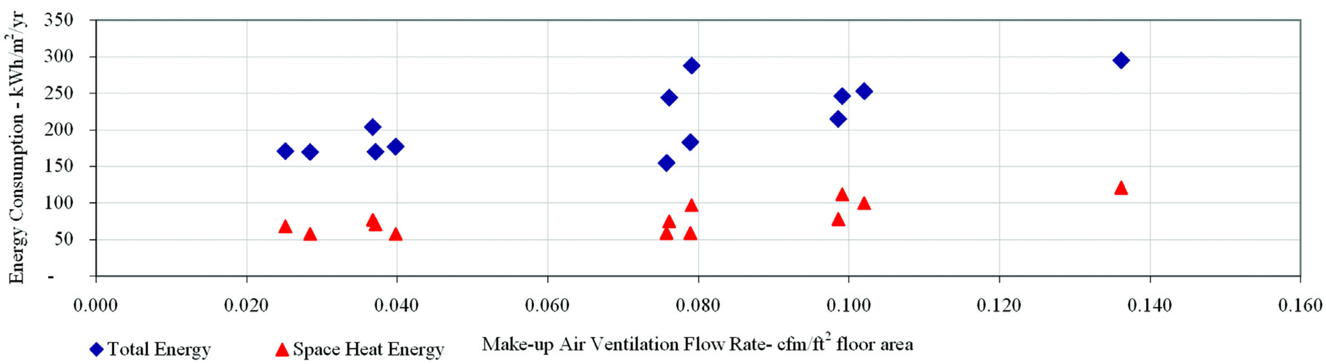


Figure 7 *Total and space-heat energy consumption versus designed make-up air ventilation flow rate.*

ventilation to suites in line with ASHRAE Standard 62.1 (ASHRAE 2010) requirements (in some jurisdictions of North America this is not allowed by building code). However, experience with MURBs has also shown that the pressurized corridor approach is less than 100% effective at providing sufficient ventilation air to suites, even in newer buildings. As a result, occupants often find it necessary to open windows for sufficient fresh air. This suggests that even higher pressurized corridor ventilation rates are required in some MURBs, which in turn would consume even more gas per suite.

Heated make-up air already constitutes a significant portion of a building's energy consumption, and the data would suggest that even more natural gas for ventilation heat if the industry continues to rely on a pressurized corridor approach for ventilation. In terms of energy efficiency, ventilation strategies should be decoupled from heating or, at very least, recover the heat from ventilation air through a centralized system.

As a more energy-efficient and effective ventilation strategy, it makes sense to compartmentalize suites and provide heating and ventilation directly to each suite. This can be done with either centralized mechanical equipment or in-suite mechanical equipment. Typically the in-suite approach is more economical, as the cost for ductwork, fire dampers, and odor control for a whole building ventilation approach (similar to a commercial building) is more expensive. In a temperate climate such as Vancouver, the use of in-suite balanced continuous supply and exhaust systems with option heat recovery ventilators (HRVs) can help provide ventilation air directly to the suites at a temperature that is acceptable for comfort year round. In colder climates, the use of small duct-mounted electric heaters may be necessary to temper ventilation air during the coldest months.

Disconnect between Energy Use and Payment

There exists a significant disconnect between energy use and payment for energy that currently influences and will continue to influence occupant behavior and energy conservation and efficiency measures in MURBs until properly addressed. The average total energy cost of the study buildings is $128,000 per year. This can be broken down into $49,000 for natural gas ($11/GJ) and $79,000 for all suite and common electricity ($0.07/kWh) for average 2008–2010 utility rates in BC. For the building as a whole, this represents a relatively significant amount of money; however, for each individual suite owner, this is on average only $1186/year ($3.25/day).

Individual occupants typically pay directly for the suite electricity and are invoiced on a monthly basis by the utility provider. On the other hand, the monthly invoices for gas and the common area electricity are paid directly by the collective owner group (strata corporation, home owner association, or condominium corporation). The monthly fee paid by the individual owners to the owner group includes the cost of this energy, but the majority of this fee typically includes a number of nonenergy costs, and the owners or occupants typically never see these energy bills. The average energy distribution and associated costs per suite are as follows:

- 28% for suite electricity, or $408/year paid by the suite owner or occupant
- 21% for common area electricity, or $323/year paid by the owner group
- 51% for gas (MAU space heat, DHW and fireplaces), or $455/year paid by the owner group

Of the per-suite total of $1186 paid per year, 36% ($34/mo) is paid by the owner or occupant, and 64% ($65/mo) is paid by the owner group. The actual amount paid by the occupant is relatively small, and they likely do not appreciate the total energy bill. This disconnect is a hurdle that must be overcome in order to effectively encourage conservation to reduce energy consumption in MURBs. It also shows that the central HVAC and electrical systems have the largest impact on total energy usage.

THE THERMAL PERFORMANCE OF MURBS

The effective U-factor of the building enclosure is directly related to the space-heating energy consumption and is an important variable in assessing the influence of the enclosure on the pre- to post-rehabilitation energy savings. The overall effective U-factors and R-values of several representative MURBs in the study were calculated in detail. This task involved thermally modeling each building enclosure assembly and detail (often over one-hundred wall, roof, and window models per building) using THERM 5.2 and WINDOW following National Fenestration Rating Council (NFRC) and ASHRAE procedures to determine component U-factors. Area-weighted U-factor calculations were then performed using detailed areas calculated for the building enclosure (derived from three-dimensional building models drawn in Sketch-up from original drawings and as-built conditions). The end results are U-factors and R-values for each of the building enclosure components and the whole building, which take into account actual construction details, thermal bridging, and window and door sizes and frame configurations.

For buildings that were rehabilitated, this process was performed for both the pre- and post-rehabilitation building enclosure assemblies. While the rehabilitation work was performed primarily to address moisture damage in the most cost-efficient manner, changes in window performance and insulation placement typically improved overall R-values. Table 1 presents calculated pre- and post-rehabilitation component and overall U-factors and R-values for three MURB archetypes selected from the rehabilitated study buildings.

The reduction in U-factor in conjunction with an improvement in airtightness resulted in a realized space-heat energy savings for each building as determined by a review of the actual energy bills. However, while some of the U-factor improvements were fairly significant, the resulting theoretical or modeled energy savings were not necessarily reflected in each of the study buildings. While not discussed in great detail here, there are several reasons for this finding, as discussed in the full study report (RDH 2010). These may include but are not limited to the following contributing factors.

- A reduction in solar heat gain through the windows post-rehabilitation.
- Occupant behavior with respect to window operation, primarily for ventilation. The rehabilitated buildings are more air tight; however, mechanical ventilation rates are insufficient.
- Lack of adequate control of airflow within the building.
- Occupant behavior with respect to fireplace use.
- Oversized heating equipment in the rehabilitated buildings.
- Operation of HVAC systems, including MAUs. A few-degree temperature change at the time of rehabilitation can negate a portion of the savings.

The overall enclosure R-value was improved in all of the study buildings as a result of improvements made to the building enclosure to more durable water-penetration resistant assemblies. Wall R-values notably increased pre- to post-rehabilitation in all cases, primarily from the change from insulating within the stud cavity to placing insulation to the exterior of the sheathing (exterior insulated). In most cases, the amount of exterior insulation was equal to or less than the insulation provided in the stud cavity due to wall thickness and cost limitations. In all cases the stud cavity insulation was removed, as an impermeable self-adhered membrane was installed on the exterior of the sheathing in the new wall assemblies. The improvement in wall R-values can be attributed to fewer framing members penetrating the insulation, and the insulation covering over the large thermal bridges, such as slab edges, and framing at wall corners and window perimeters. Even still, the thermal bridging at balconies, cladding girts and clips, brick-shelf angles, and other penetrations still result in relatively low overall wall R-values based on the detailed thermal calculations. While roof R-values tend to be higher due to fewer thermal bridges, the roof R-value does not significantly affect the overall enclosure R-value due to the low roof-to-wall area ratio of a high rise. The overall R-value is primarily influenced by the lowest thermally performing element, which tend to be the windows.

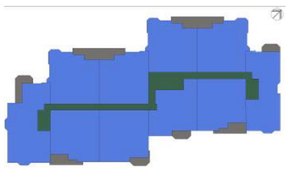
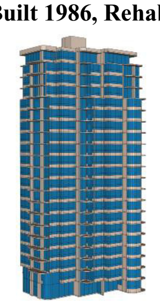
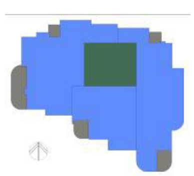
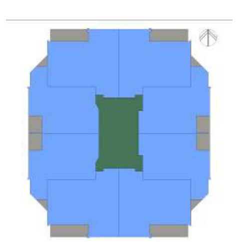
The overall effective enclosure R-values were found to be between R-2.1 and R-4.3 $h \cdot ft^2 \cdot °F/Btu$ for the study buildings where detailed thermal modeling was performed. Figure 8 compares the overall building enclosure pre- and post-rehabilitation R-values for ten of the study buildings. The average improvement pre- to post-rehabilitation for the eight rehabilitated buildings is a 38% improvement in R-value or 28% reduction in U-factor.

Window Thermal Performance Calculations

Window R- and U-factors were calculated for each window frame configuration of the selected study buildings, as previously shown in Table 1. NFRC-certified U-factors were not available for the windows in the study buildings nor does the NFRC standard window size represent typical high-rise window or window-wall configurations (i.e. coupled window lites with intermediate mullions and a combination of fixed and operable lites). NFRC standard sizes were developed for typical single-family dwelling windows sizes, and the standard does not currently have a more representative high-rise window or window-wall configuration. However, the calculation of window U-factors for actual frame dimensions and configurations were performed in general conformance with NFRC procedures, with modifications to consider actual window sizes and configurations and included intermediate mullions or coupled operable/fixed lites. Software written by the authors to compile THERM and WINDOW output was used for this purpose.

In lieu of detailed calculations for the purposes of preliminary energy modeling and analysis by others, it is of interest to simplify this tedious calculation procedure using published NFRC window U-factors area weighted to account for the mix of operable, fixed, and door assemblies on a building.

Table 1. Pre- and Post-Rehabilitation Enclosure R-Values for Selected MURBs

Building ID 3D Image and Floor-Plan	Pre-Rehabilitation Assembly Description	Pre-Rehabilitation R-value h·ft^2·°F/Btu	Post-Rehabilitation Assembly Description	Post-Rehabilitation R-value h·ft^2°F/Btu
#19 – Built 1984, Rehab 2004	**Walls (52% of enclosure):** Steel Stud w/ R-14 fiberglass. Slab edges uninsulated, balconies	3.94	**Walls:** Exterior insulated, R-9.5 mineral wool between steel z-girts. No stud cavity insulation. Slab edge insulated, balconies uninsulated.	5.25
	**Windows (27% of enclosure, 34% of wall area):** Non-thermally broken aluminum frames. Clear glass, air filled IGUs with aluminum spacers	1.37	**Windows:** High performance thermally broken aluminum frames. Soft-coat low-e, air filled IGUs with aluminum spacers	2.16
	**Roof (21% of enclosure):** Inverted assemblies with 3 in. extruded polystyrene	14.26	**Roof:** Inverted assemblies with 4 in. extruded polystyrene.	18.28
	Overall Building	**2.92**	**Overall Building**	**4.26**
	Rehabilitation improved R-value by 46% (31% reduction in U-factor) Rehabilitation resulted in a Space-Heat Savings of Approximately 10%			
#62, Built 1986, Rehab 2005 	**Walls (47% of enclosure):** Steel Stud w/ R-12 fiberglass. Exposed concrete. Slab edges un-insulated, balconies	3.49	**Walls:** Exterior insulated, R-9.5 mineral wool between steel z-girts. No stud cavity insulation. Slab edge insulated, balconies uninsulated.	4.55
	Windows (46% of enclosure, 50% of wall area): Non-thermally broken aluminum frames. Clear glass, air filled, IGUs with aluminum spacers	1.35	**Windows:** High performance thermally broken aluminum frames. Clear glass, air filled IGUs with aluminum spacers	1.67
	**Roof (7% of enclosure):** Inverted assemblies with 1.5 in. to 2 in. XPS	8.18	**Roof:** Inverted assemblies with 3 to 3.5 in. XPS. Improved detailing	12.53
	Overall Building	2.07	Overall Building	2.60
	Rehabilitation improved R-value by 26% (20% reduction in U-factor) Rehabilitation resulted in a Space-Heat Savings of Approximately 22%			
#32 (#33 similar), Built 1985, Rehab 2006–2007 	**Walls (47% of enclosure):** Steel Stud w/ R-12 fiberglass. Portions of exposed concrete. Slab edges uninsulated, balconies	3.81	**Walls:** Exterior insulated, R-13 mineral wool between steel z-girts. No stud cavity insulation. 3” EIFS over exposed concrete, slab edges insulated, balconies uninsulated.	7.09
	Windows (42% of enclosure, 47% of wall area): Non-thermally broken aluminum frames. Clear glass, air filled, IGUs with aluminum spacers	1.34	**Windows:** High performance thermally broken aluminum frames. Soft-coat low-e, air filled IGUs with aluminum spacers	2.02
	**Roof (12% of enclosure):** Uninsulated sloped assemblies, flat Inverted assemblies with 2 in. XPS	10.99	**Roof:** Insulated sloped assemblies, flat Inverted assemblies with 2 in. XPS. Improved detailing	12.79
	Overall Building	**2.26**	**Overall Building**	**3.56**
	Rehabilitation improved R-value by 58% (37% reduction in U-factor) Rehabilitation resulted in a Space-Heat Savings of approximately 17% in building 32 and 22% in building 33.			

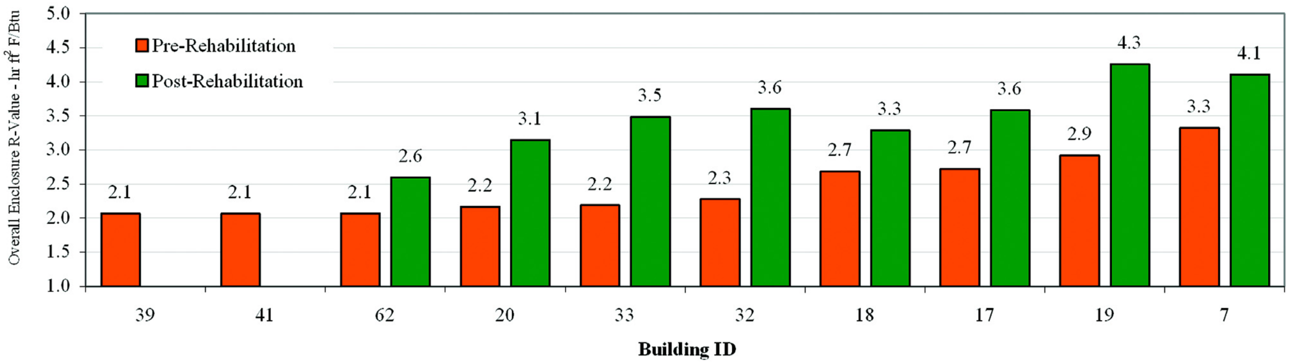


Figure 8 *Calculated overall building enclosure R-values (h·ft^2·°F/Btu) for typical study buildings.*

Table 2. Calculated Versus NFRC Procedure Estimated Overall High-Rise Window R-Values and U-Factors

Building	Frame/Glazing Type	Percentage of Fixed, Operable, and Sliding Door Assemblies	Actual—Calculated Overall	NFRC—Fixed Window	NFRC—Operable Window	NFRC—Sliding Door	Area Weighted NFRC
			R-value, h·ft^2°F/Btu (U-factor, Btu/h·ft^2°F)				
19 Pre-Rehab	Nonthermally broken aluminum, clear IGUs	59% fixed 20% operable 21% sliding doors	1.37 (0.73)	1.52 (0.66)	1.25 (0.80)	1.47 (0.68)	1.45 (0.69) 5% lower U-factor
19 Post-Rehab	Thermally broken aluminum, Low-e air IGUs	59% fixed 20% operable 21% sliding doors	2.16 (0.46)	2.44 (0.41)	1.75 (0.57)	2.10 (0.48)	2.19 (0.46) 2% lower U-factor
62 Pre-Rehab	Nonthermally broken aluminum, clear IGUs	58% fixed 15% operable 27% sliding doors	1.36 (0.74)	1.52 (0.66)	1.25 (0.80)	1.47 (0.68)	1.46 (0.69) 7% lower U-factor
62 Post-Rehab	Thermally broken aluminum clear air IGUs	58% fixed 15% operable 27% sliding doors	1.70 (0.59)	1.86 (0.54)	1.54 (0.65)	1.63 (0.62)	1.74 (0.58) 2% lower U-factor
32 Pre-Rehab	Nonthermally broken aluminum, clear IGUs	47% fixed 11% operable 42% sliding doors	1.36 (0.74)	1.52 (0.66)	1.25 (0.80)	1.47 (0.68)	1.47 (0.68) 7% lower U-factor
32 Post-Rehab	Thermally broken aluminum, low-e air IGUs	47% fixed 11% operable 42% sliding doors	2.16 (0.46)	2.44 (0.41)	1.75 (0.57)	2.10 (0.48)	2.20 (0.45) 6% lower U-factor

Published U-factors should represent the installation details for the window/door and include deflection headers and frame reinforcing (where needed). To check the validity of this simplification, the overall window U-factors as calculated from the actual window sizes and configurations are compared to an area weighted NFRC U-factor calculations for a typical floor of three of the selected study buildings (pre- and post-rehabilitation) in Table 2. The U-factors are slightly different than in Table 1, as the values in Table 2 are for a typical floor, whereas the U-factors in Table 1 account for all glazing in the building and nontypical floors (i.e., ground and penthouse levels).

Because NFRC factors were not published by the window manufacturers for the windows within the study buildings, these were also calculated using NFRC standard sizes (including deflection headers and other components where appropriate).

As shown for the three buildings in the table, the simplified window-type area weighted NFRC R-value calculation is generally accurate within 10%. The simplification tends to slightly underestimate the U-factor by up to 7% (overestimate the R-value by 8%). The largest differences occur in buildings where coupled window-wall type assemblies are utilized in non-NFRC standard sizes. The differences were found to be less where the majority of windows in a building are punched type and close to NFRC standard sizes. Larger differences also occur where there is a greater difference in performance between the framing and insulating glazing unit (IGU) U-factor, where thermal bridging through framing has more of a significant effect. The more detailed calculation procedure also accounts for the lower thermal performance of corners, couplers, and intermediate mullions not accounted for in the standard NFRC-sized window frame. However, there is a need to compare these modeled results and associated differences with actual testing results.

Window thermal performance is critical to building code compliance and energy efficiency. The window U-factor generally has the most significant impact on the overall U-factor of the building enclosure. Area weighted U-factor calculations demonstrate this where the U*A factor for the windows typically accounts for the majority of heat loss. The influence of window U-factor and percent glazing within an R-16 steel-framed wall (minimum ASHRAE Standard 90.1 [ASHRAE 2007] compliance for zone 5) is demonstrated in Figure 9.

Current Energy Standards

The overall effective building enclosure R-value of the study buildings ranges between R-2 and R-5 h·ft^2·°F/Btu (U-0.5 to U-0.2 Btu/h·ft^2·°F). This is barely better than the center of glass value of a typical IGU but is not surprising considering the effective wall and window R-values after accounting for thermal bridging through framing, slabs, and actual window sizes. These overall R-values commonly result in excessive heat-loss (and gain) through the building enclosure and need to be addressed to operate more energy efficient MURBs. Energy and Building Code Standards have the largest influence in addressing minimum thermal performance requirements which in turn affect space-heat energy consumption.

Figure 10 demonstrates an area weighted U-factor calculation to determine the overall enclosure R-value; by only assessing the wall R-value, window/door R-value and percent window/door area. Typical R-values for MURB wall assemblies are around R-5 effective; however, up to R-10 can be achieved by minimizing thermal bridging elements such as balconies. In comparison, an effective R-value of R-16 is the ASHRAE Standard 90.1 minimum prescriptive requirement for steel-framed wall assemblies in Climate Zone 5.

While current construction practice for wall and window assemblies results in overall R-values of R-2 to R-5, the impacts of higher performing windows (Figure 9) and walls (Figure 10) demonstrate how higher overall effective R-values of up to R-10 could readily be achieved using available technology.

Currently, effective window R-values range from R-1.3 h·ft^2·°F/Btu for nonthermally broken aluminum frames with clear IGUs to R-2.2 for thermally broken aluminum frames with low-e IGUs up to a maximum of R-2.5 for higher performance frames with good low-e coating(s) and argon filled IGUs. This R-value considers a typical mix of fixed, operable, and sliding-door assemblies.

Significantly higher overall window R-values of up to R-3 can be achieved with triple glazing and higher in aluminum frames, up to R-4 to R-6 when low-conductivity frames with double and triple IGUs are utilized. ASHRAE Standard 90.1 requires a minimum of R-2.2 (U-0.45) in climate zone 5 for aluminum framed fixed or operable windows. This is currently achievable with fixed aluminum windows but more difficult with operable windows and sliding doors (due to smaller thermal breaks for structural purposes and thermal bridging). As shown by the calculations of the three study

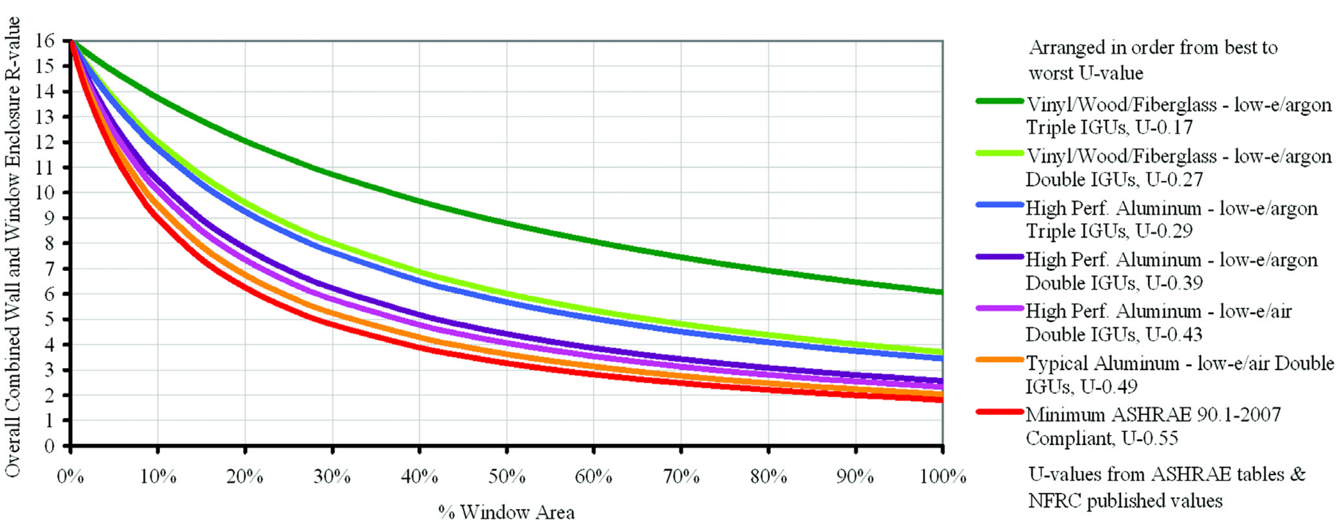


Figure 9 *Overall effective vertical enclosure R-value based on R-16 wall and various window U-factors.*

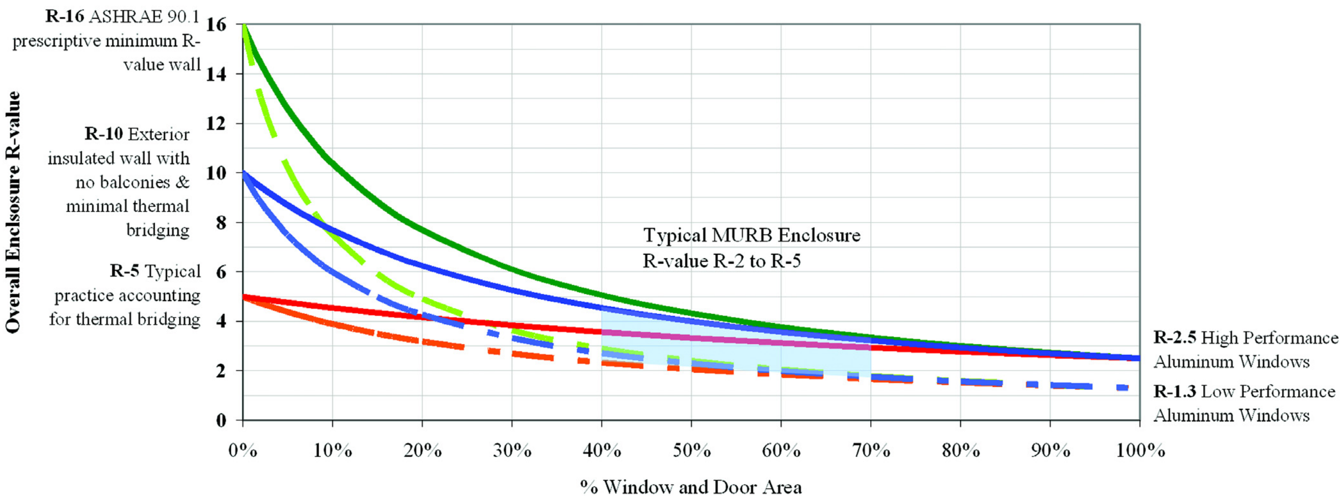


Figure 10 *Overall enclosure R-value (h·ft²·°F/Btu) for typical MURB wall and window assemblies.*

buildings, when all of the operable and fixed windows and sliding door assemblies are considered, an overall fenestration R-value of R-2.2 is just barely achieved and only when low-e IGUs are utilized within thermally broken aluminum frames. Looking forward, more stringent window performance criteria than R-2.2 will be needed to improve MURB energy efficiency.

To address the thermal performance of wall assemblies, significant changes to current common practice need to be made to achieve higher effective wall R-values. Strategies to build thermally efficient wall assemblies noncombustible construction focus around reducing thermal bridging through insulation. This can include thermally isolated balconies and projections, clip cladding supports, low-conductivity framing, and offset brick shelf angles among other strategies. Spandrel panels common in window-wall assemblies also need to be addressed, as the thermal performance of spandrel assemblies is only slightly better than the windows.

Currently, the prescriptive wall thermal resistance tables provided in ASHRAE 90.1-2007 do not account for thermal reductions from exposed slab edges, balconies, brick shelf-angles, or even alternate cladding support systems, and must be calculated on a case by case basis. Because this is a complicated task and becomes an iterative process for new construction, this is not typically undertaken when performing energy modeling calculations for determining code compliance, green building program points, and sizing mechanical equipment. While some thermal bridging is accounted for in the requirements of ASHRAE Standard 90.1, the overall thermal resistance of the building enclosure assemblies may still be overestimated compared to more detailed thermal modeling calculations, which account for actual construction practices and each thermal bridging element. It is suggested that tables developed from guarded hot-box testing and thermal modeling be incorporated within ASHRAE 90.1 and the Model National Energy Code for Buildings (MNECB) to simplify this task for building designers.

As a result of not considering all thermal bridging that occurs in buildings, the effective adoption of the ASHRAE 90.1 requirements, as well as the confirmation of compliance, is difficult. Unfortunately, this can result in an unfair disadvantage to those who properly consider actual thermal performance resulting from all thermal bridging elements. This becomes particularly apparent when energy simulation for LEED in Canada, where the baseline building R-values set out by the 1997 Model National Energy Code of Canada for Buildings (NRC 1997) do not appear to adequately consider the thermal bridging through the enclosure components (i.e., R-12.6 h·ft²·°F/Btu wall as a minimum). This R-12.6 stud insulated wall may have an effective R-value of R-3 to R-4 after considering the steel stud and track framing, exposed slab edges, and balconies typical with a MURB. Therefore, when detailed analysis is undertaken to determine actual R-values for spandrels and walls with balconies common with current construction practices, it is found that typical assemblies do not comply with R-12.6. Therefore, an actual R-value improvement over the baseline (for LEED points) is very difficult. Baseline building R-values should therefore be reconsidered and adjusted to minimum current practices as they were likely intended to be.

Baseline buildings for energy simulation comparisons should reflect current practice and be based on effective R-values so that designers are encouraged to really develop more thermally efficient assemblies in new buildings. These changes would better allow for future improvements to energy codes.

Looking forward, energy-efficient net-zero-ready building enclosures for high-rise MURBs will likely need to achieve an effective R-value in the order of R-15 to R-30 h·ft^2·°F/Btu, similar to single-family net-zero houses. This will mean significantly higher performing windows (i.e., R-6) and wall assemblies (i.e., better than R-30). This is a significant change in the design of current MURBs. Even if the target is not net-zero, there is a need to significantly improve the overall building enclosure R-values over current practice. Actual performance data is needed in order to allow for better calibration of models and improved future designs. Better means of evaluating in-service building performance characteristics are needed. Energy codes would then accordingly ramp up minimum realistic enclosure requirements towards an energy efficiency target.

AIR LEAKAGE CHARACTERISTICS OF MURBS

The reduction of enclosure air-leakage and intersuite/story airflow within a MURB is important for energy conservation. Air that exfiltrates the building results in a direct loss of heat energy, and the air that infiltrates the building requires heat energy to bring it to indoor conditions. In a MURB, the heat energy input required to offset air-leakage energy loss may not always be required in the suite in which it was lost. For example, under winter-time stack-effect, air will typically infiltrate lower floor suites, flow up the inside of the building and exfiltrate at the upper floor suites. This may result in extra heating required at lower floor suites, whereas upper floor suites will likely be too hot. Similarly, wind and mechanical pressurization will also effect infiltration and exfiltration through suites in the building and vary with time and season. Add in the compounding influence of operable windows and occupant behavior (such as opening windows to reduce heat at the upper floor suites) and the effective airtightness becomes very difficult to determine, as does the building pressurization (suite and whole building) used to predict the air-leakage rate of a MURB.

As an industry, we generally have an understanding of the qualitative airflows and air-leakage issues with high-rise buildings, including MURBs (Lstiburek 2000). However, a greater quantitative understanding is needed to determine the space-heat impacts from the service airflows, air-leakage (both internal and external), and suite ventilation rates over the course of a year under the influence of stack effect, wind, and mechanical pressures and occupant behavior. Energy modeling of air leakage relies on two main assumptions: enclosure airtightness and building pressure. *Airtightness* is the measure of the air porosity of the components and assemblies that make up the building enclosure at a certain pressure difference. *Air leakage* is defined as the uncontrolled flow of air through the building enclosure (i.e., infiltration or exfiltration) as the result of building pressure and the enclosure airtightness.

Enclosure airtightness can be measured but is expensive and a complicated task in a high-rise MURB. When measuring airtightness, windows are closed, so the usefulness of this measurement is questionable for an in-service MURB. Pressures across the enclosure of a high-rise building vary over time (from positive to negative) and with height due to stack effect, wind speed, building enclosure, interior airtightness, and mechanical system operation. As a result, it is difficult to determine an average net difference in pressure over the course of a year. Currently, energy models assume a fixed airtightness rate and an average building pressure, possibly with some consideration for wind. As a result, energy modeling of air-leakage and its impacts on space-heat loss in an MURB is problematic.

Air Pressures within MURBs

Normal operating pressure for a high-rise building varies over time (from positive to negative) with height due to stack effect, wind speed, building shell, interior airtightness, and mechanical system, and it is therefore difficult to determine an average net difference in pressure over the course of a year. For small one-to-two story buildings a pressure of 4 Pa is often assumed from empirical research but obviously varies between house types, sizes, climates etc. Pressures across the suite enclosure in high-rise buildings become increasingly more complex and less predictable. Pressure will vary with building height, wind exposure, season, and the relative airtightness of the interior and exterior components of the building. A more airtight building will typically be under a higher pressure than a leakier one. This pressure may be induced mechanically by an imbalanced ventilation system (i.e., MAU supplied air with occupant controlled intermittent exhaust) or passively by wind or stack effect. Uniformly opening windows will make the building enclosure less airtight and, hence, the building will be under a lower pressure. The pressures, airflow, and resulting air leakage for an MURB is shown schematically in Figure 11.

As an annual estimate, an average suite pressure difference of 5 or 10 Pa across a high-rise building enclosure is suggested in the reference literature. This accounts for higher stack effect pressures at the top and bottom of the building. As part of the study, stack effect measurements were taken on selected buildings and found average suite pressures were within this range for average Vancouver conditions. During these tests, it was found that the pressure measurements did not necessarily correspond with theoretical calculated stack pressures, and the neutral pressure plane was found to vary from the mid-height of the building toward the location of larger openings. The influence of exterior airtightness, window-operation, floor airtightness, and continuous shafts all influence the actual stack pressures and vary between MURBs in the study. The influence of stack effect on energy consumption on a suite-by-suite basis was also undertaken for selected study buildings, but no consistent correlation between electric heat and floor level can be found to support the influence of stack effect on higher suite space-heat consumption within suites at certain floors (RDH 2010).

A better understanding of the actual pressures in MURBs is needed to improve energy modeling estimates. Information on the in-situ pressures within different suites of various

MURB archetypes in different climates over the hours of an entire year is needed to improve energy modeling beyond assumptions of ideal case stack-effect scenarios.

Airtightness and Air Leakage Rates

Airtightness testing of whole or part of high-rise buildings has been performed primarily on a research basis since the 1970s and can assist with determining an expected airtightness range for an MURB. Air-leakage testing is not performed on a widespread basis in MURBs primarily due the lack of a building code requirement but also the high cost, risk, time, and equipment involved and logistics of such a large test. It is estimated that less than one-hundred high-rise buildings across Canada have been air-leakage tested in the past 40 years. These tests were primarily performed for research purposes. Fortunately, those buildings that have been tested and have published results provide useful data and insight into MURB enclosure airtightness under standard test pressures.

A literature review of published building enclosure airtightness data and airtightness studies from as far back as the early 1970s was performed (CMHC 1990; CMHC 1998; CMHC 2001; Dalgliesh 1988, Finch 2007, Gulay et al. 1993; Shaw et al. 1973, 1990, 1991; Sherman 1990, Sherman and Dickeroff 1998; Sherman and Chan 2004; Tamura et al. 1976). This data was compared with air-leakage testing performed on selected rehabilitated MURBs as part of the study. Interestingly the review of airtightness data across different high-rise enclosure types and different locations was surprisingly consistent and comparable to test data performed for the study. The airtightness of buildings in service was generally found to be higher than values recommended in the various standards or guidelines (ASHRAE, US Army Corps, ASTM, ABAA) but falls within a relatively small range of cfm/ft^2 at average building enclosure pressures of 5 to 10 Pa. Airtightness test results for MURB enclosures are compiled in common units of cfm/ft^2 of enclosure area at various pressures and provided in the full study report (RDH 2010). From this, a range of expected building airtightness values are provided in Table 3 at normal operating pressures. In units of cfm/ft^2, the airtightness can be converted into an air-exchange rate by multiplying by the enclosure area and dividing by the building volume.

While the airtightness of the enclosure is an important variable, open windows significantly alter the effective airtightness of the building enclosure. Open windows decrease the effective airtightness by an order of magnitude. Correspondingly, this reduced airtightness drops the building pressure and air-leakage rate. Consider the following example to demonstrate the influence of open windows on the air-leakage rate:

- The post-rehabilitation enclosure airtightness of Building 33 was measured and found to be 0.066 cfm/ft^2 at 5 Pa. This airtightness as measured is equivalent to a leakage area of 2.73 in.^{2}/100 ft^2 of enclosure at 5 Pa.

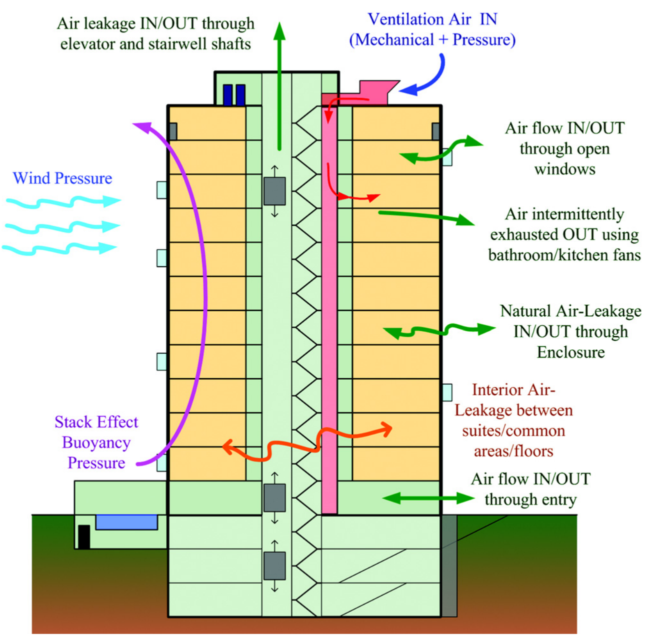


Figure 11 *Building pressures from wind, stack effect and mechanical equipment and the resulting airflow/leakage.*

Table 3. Expected Range of Airtightness for Noncombustible MURBs—Includes Exterior Walls, Windows, and Supply and Exhaust Duct as Normally Operated.

	cfm/ft^2 at 5 Pa (ach @ 5 Pa for Typical High-Rise MURB Layout)	**cfm/ft^2 at 10 Pa (ach @ 10 Pa for Typical High-Rise MURB Layout)**
Very Airtight—Lowest Recorded	0.02 (0.07)	0.03 (0.10)
Airtight—Low	0.05 (0.17)	0.08 (0.26)
Airtight—Average	0.10 (0.33)	0.16 (0.53)
Air Leaky	0.20 (0.66)	0.31 (1.02)
Very Air-Leaky, Open Windows	>0.40 (>1.32)	>0.63 (2.08)

- For this 20 story, 135-suite high-rise building with an enclosure area of 73,000 ft^2, the total leakage area of the building enclosure would be on in the order of 2000 in^2 (13.9 ft^2)
- For comparison, one of the 2 × 4 ft casement windows when fully open has an area of 1152 $in.^2$ and a 6 ft 6 in. tall sliding door cracked open by 6 in. has an area of 468 in^2.
- Estimating that at least one window per floor is open (which, based on observations of MURBs in Vancouver in winter, may be a conservatively low estimate), the total open window/door area is 23,040 $in.^2$, more than 11 times greater than the enclosure leakage area at 5 Pa. This demonstrates the importance of open windows on effective enclosure airtightness and as a potential input for energy modeling.

By inputting a range of probable airtightness into a utility bill calibrated DOE 2.1 energy model, the contribution of air-leakage, ventilation, and conduction to space-heat loss can be estimated for an older hydronic heated high-rise MURB (Building #19) and a newer electrically heated high-rise MURB (Building #32), as shown in Figure 12. Because the thermal performance of MURB building enclosures are generally poor, the majority of space-heat loss typically occurs by conduction; however, space-heat loss by air leakage and ventilation are significant and will proportionally increase as better insulated assemblies are adopted. Space-heat loss from ventilation air depends on the mechanical ventilation rate, which, as discussed, varies considerably with the MURBs in the study, so it is not surprising to see greater weighting on ventilation in better ventilated buildings (such as Building #32 vs. #19). Within most high-rise buildings, ventilation space-heating

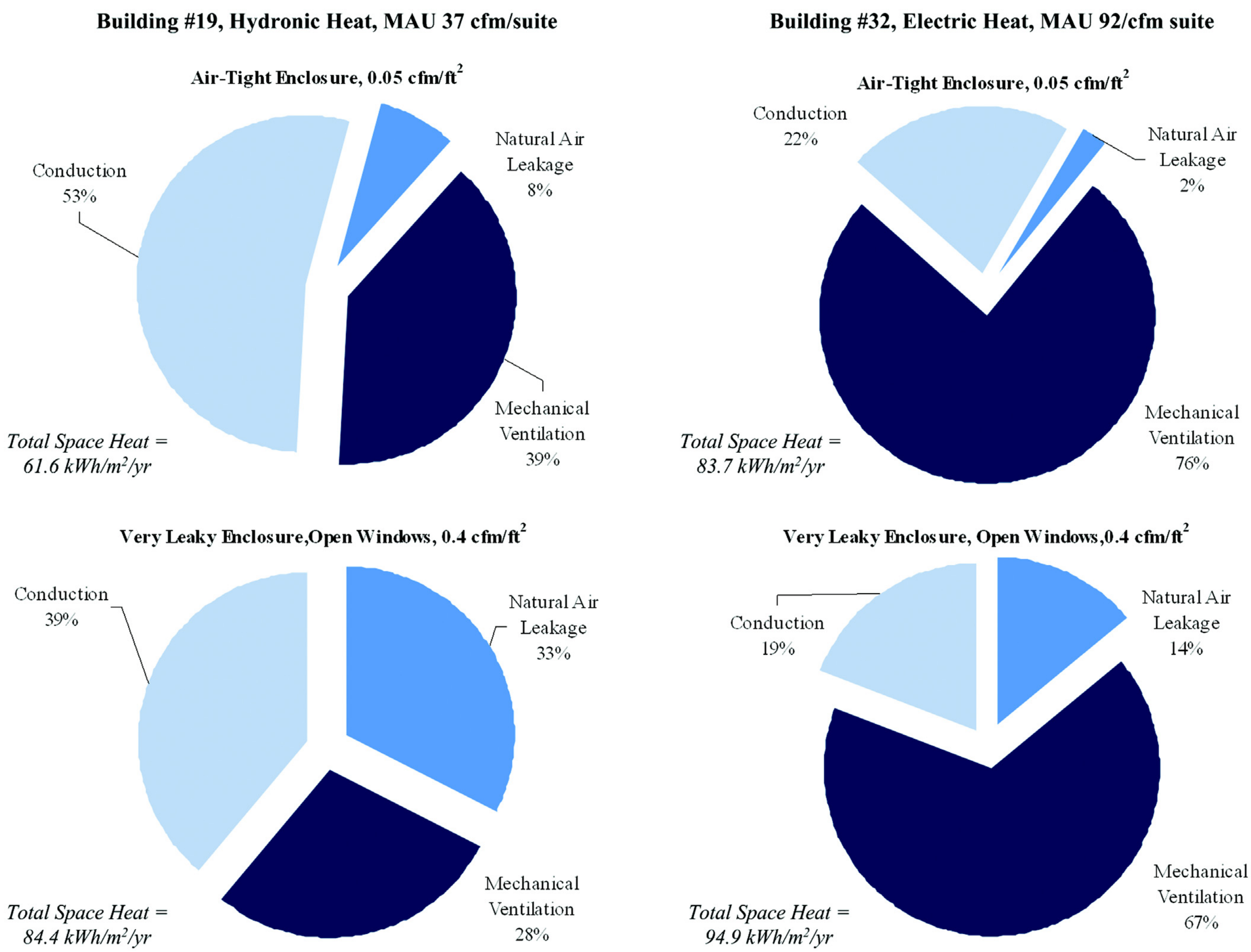


Figure 12 *Estimated distribution of space-heat loss in two typical high-rise MURBs (Buildings #19 and #32).*

systems need to be addressed first, as they are the dominant source of space-heat loss.

CONCLUSIONS AND RECOMMENDATIONS

The real time frame for the construction of very low-energy buildings is on the near horizon. To reach the ambitious energy efficiency targets for the next decade, significant changes in the design and construction practices will be required to reduce the energy consumption of and bring our new multiunit residential buildings toward a target of net-zero energy.

A review of a representative population of existing condominium MURBs in the Lower Mainland of BC has highlighted several issues related to the energy inefficiency of this housing type. Space heat and total energy consumption has apparently increased in the past 40 years. The energy consumption of the MURBs in the study ranged from 144 to 299 kWh/m^2/y and were on average 213 kWh/m^2/y. Approximately 50% of the energy is from gas and 50% is from electricity. On average, 37% of the energy is used for space heat and of this, 69% is from gas sources. Natural gas consumption for gas fireplaces is shown to be particularly inefficient and has a significant effect on the whole building energy consumption. The heating of ventilation air with gas-fired MAUs supplied using a pressurized corridor approach typically accounts for the majority of a building's purchased gas and space-heating energy and may account for the majority of space-heat loss.

Overall thermal resistance has not improved significantly, and new and existing MURBs typically have an overall R-value between R-2 and R-5 h·ft^2·°F/Btu. Enclosure airtightness has improved with more airtight windows and wall assemblies; however, the impact of open windows on effective airtightness likely masks much of this improvement.

To build more energy efficient MURBs, we need to address the thermal performance of the building enclosure, air-leakage and interior airflow, mechanical heating and ventilation systems, energy metering, billing disconnects, and better consider occupant use of the buildings.

To reduce space-heating loads, effective enclosure R-values need to improve significantly to at least meet current ASHRAE Standard 90.1 and, more ideally, ASHRAE Standard 189.1 minimums. To achieve higher effective R-values, thermal bridging must be minimized, and greater insulation thicknesses/configurations will be required in walls and roofs. Balconies, overhangs, and projections need to be better considered; however, strategies to thermally isolate protruding elements do exist. Window R-values have the most profound influence on the overall enclosure R-value, and significantly higher performing glazing assemblies will be necessary to reach more stringent energy efficiency targets.

To address ventilation and heating system effectiveness, suites within MURBs should be compartmentalized and heated/cooled and ventilated independent of the remainder of the building and controlled by the occupant. While mechanical systems can be shared between compartmentalized suites, it may be preferable for suites to have individual ventilation and heating/cooling systems (i.e., hotel approach). Compartmentalization addresses many of the larger issues addressed in MURBs with MAU gas consumption, air-leakage, building stack effect, airflow between suites, billing allocation, sound/odor control, fire separation, and occupant behavior and comfort. Code changes or incentives are necessary to change current practice.

Similar strategies for new construction could apply for the retrofit of existing buildings. While the focus of building energy retrofits is often only on the low-hanging fruit of mechanical system upgrades, the importance of the building enclosure is very significant and can have the largest impact on space-heat savings. The building enclosure has the longest lifecycle of all of the building components influencing space-heating and, like a boiler upgrade, also needs to be upgraded or replaced over the life of the building. Unfortunately, the cost to retrofit the building enclosure for an energy retrofit can be cost prohibitive if only immediate energy cost payback periods are considered as typically done.

It may be in the best interest for the long-term owners, utility providers, government agencies, and public at large to raise minimum energy efficiency standards for multiunit residential buildings to levels higher than single-family buildings.

The technology and understanding already exists to significantly improve the energy performance of high-rise MURBs. The implementation of these practices now, along with continuing analysis of actual performance, is needed to achieve efficient or net-zero MURBs in the near future.

ACKNOWLEDGMENTS

This industry-sponsored project was funded by a partnership of Canada Mortgage and Housing Corporation (CMHC), Homeowner Protection Office of BC (HPO), City of Vancouver, BC Hydro, Terasen Gas, Fortis BC, and RDH Building Engineering. Additional time and input was provided by Curt Hepting of Enersys Analytics and the property managers and owners of the buildings within the study.

REFERENCES

ASHRAE. 2007. *ANSI/ASHRAE/IESNA Standard 90.1-2007, Energy Standard for Buildings except Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2009. *ANSI/ASHRAE/USGBC/IES Standard 189.1-2009, Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2010. *ANSI/ASHRAE Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

BC Hydro. 2007. Residential End Use Energy Survey (REUS).

BC Hydro. 2010. Statistics on Energy Consumption for all Vancouver, BC Apartment Buildings.

CMHC 1990. Establishing the Protocol for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings.

CMHC 1998. TS 98-123, Establishing the Protocol for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings. Produced for CMHC by the NRC. Technical Series 1998-123

CMHC 2001. TS 01-123, Air Leakage Characteristics, Test Methods and Specifications for Large Buildings. Produced for CMHC by Proskiw Engineering and Unies Ltd. Technical Series 2001-123.

CMHC 2010. Equilibrium Sustainable Demonstration Initiative. Available Online: http://www.cmhc.ca/en/inpr/su/eqho/

Dalgliesh, W. 1988. Air Infiltration and Internal Pressure in Tall Buildings. From “Second Century of the Skyscraper” Council on Tall Buildings and Urban Habitat, 1988. NRCC-IRC Paper No. 1585.

Finch, G. 2007. The Performance of Rainscreen Walls in Coastal British Columbia. Masters thesis, Department of Civil Engineering, University of Waterloo, Waterloo. Ontario, Canada.

Gulay, B.W., Stewart, C.D., Foley, G.J., 1993. Field Investigation Survey of Air tightness, Air Movement and Indoor Air Quality in High-Rise Apartment Buildings: Summary Report. Canada Mortgage and Housing Corporation, Report 96-220.

Lstiburek, J. 2000. Towards an Understanding and Prediction of Air Flow in Buildings, PhD Dissertation. University of Toronto.

RDH, 2010. Energy Consumption and Conservation in Mid and High Rise Residential Buildings in British Columbia. Report: RDH Building Engineering Ltd. Report to Study Partners

Shaw, C., Sander, D., Tamura, G. 1973. Air Leakage Measurements of the Exterior Walls of Tall Buildings. ASHRAE Transactions, Vol. 79, Part 2, 1973, p.40-48. Reprinted by NRCC, Article 13951.

Shaw, C., Gasparetto, S., Reardon, J. 1990. Method for Measuring Air Leakage in High-Rise Apartments. ASTM STP 1067, Air Change Rate and Airtightness in Buildings, p. 222-230. NRCC-IRC Paper No. 1649.

Shaw, C.Y., Magee, R.J., Rousseau, J. 1991. Overall and Component Airtightness Values of a Five-Storey Apartment Building, ASHRAE Transactions, Vol. 97 (2), 1991, pp. 347-353.

Sherman, M. ed. 1990. Air Change Rate and Air Tightness in Buildings: ASTM STP: 1067. American Society for Testing and Materials.

Sherman, M.H., Dickerhoff, D. 1998. Airtightness of U.S. Dwellings. ASHRAE Transactions, 1998. V. 104 Part 2.

Sherman, M.H., Chan, R. 2004. Building Airtightness: Research and Practice. Lawrence Berkeley National Laboratory Report No. LBNL-53356. Draft, February 19, 2004.

Tamura, G.T., Shaw, C.Y. 1976. Studies on Exterior Wall Air Tightness and Air Infiltration of Tall Buildings. ASHRAE Transactions, Vol. 82, Part 1, 1976, p. 122-134. Reprinted by NRCC, Article 15732.