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Improving the characterization of infiltration parameters in whole-building energy models using component infiltration rate testing

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Abstract: *Infiltration parameters have some of the highest uncertainties among energy model inputs and greatly impact building energy consumption. These parameters are highly building specific, making them difficult to estimate from the literature. Reduction of parameter uncertainty using on-site measurements has traditionally been prohibitive, both from a cost and logistical standpoint. Window component infiltration rate testing was conducted at two buildings to develop component-weighted average infiltration rates, which were input into whole-building energy models and compared with models that used bulk infiltration rates estimated from the literature. The component-weighted infiltration rate approach reduced parameter uncertainty by incorporating building-specific measurements and accounted for variation in zone infiltration rates based on type and quantity of leakage paths. The discretization of the infiltration rate can also help during the modeling of energy retrofits that specifically target building infiltration by setting bounds on the maximum possible improvement.*

Keywords: *Energy modeling, calibration, infiltration, multi-unit residential building*

INTRODUCTION

Multi-unit residential buildings (MURBs) represent a significant portion of the world's housing stock, particularly in larger cities where more people are moving towards higher-density living. In Toronto, Canada's largest city, MURBs account for approximately 57 % of the total housing stock (Natural Resources Canada, 2014). In Canada, the majority of the MURB stock is aging and in need of building system retrofits and renewals to remain operational. These system retrofits and renewals provide the perfect opportunity to improve the building's energy efficiency. To maximize the return-on-investment, some MURB owners and operators rely on whole-building energy modeling to guide the retrofit process by determining which measures will yield the greatest energy savings; however, the reliability of these models is heavily dependent on the quality of the input parameters (Raftery, Keane, & O'Donnell, 2011; Touchie & Pressnail, 2014).

Air infiltration strongly influences energy consumption in buildings. Previous studies have shown that infiltration accounts for 15 % to 30 % of annual space heating energy consumption in single-family homes and up to 45 % in MURBs (Jokisalo, Kurnitski, Korpi, Kalamees, & Vinha, 2009; Scanada Consultants Ltd., 1997). Unfortunately, accurate quantification of infiltration in energy models has traditionally been problematic. Infiltration is dependent on the quantity and size of leakage paths across the pressure boundary, which is a factor of building age; building envelope assembly and component types; construction quality; and maintenance/operation practices. Previous studies have found that infiltration rate measurements varied considerably between buildings of the same construction type and even between different measurements from the same building (Proskiw & Phillips, 2001), making it difficult to generalize measurements from other studies. Infiltration testing in MURBs is also difficult. The sequential pressurization test procedure, a modified version of the blower door test used to measure infiltration at the suite- or floor-level in MURBs, is expensive and highly disruptive to residents. Apart from the financial and logistical concerns of completing infiltration testing in occupied MURBs, there is also debate as to whether we should be using fan pressurization tests to estimate in-service infiltration rates (Lstiburek, 2011). The results from a specific suite-level test are only valid for that configuration of building envelope components. Depending on the distribution of building envelope component types between building zones, suite-level infiltration rates may vary considerably. In addition, fan pressurization test results are idealized infiltration rates under test conditions, which vary from actual in-service conditions.

In the absence of site-specific measurements, the highly uncertain infiltration rates often become the default parameter used to calibrate energy models (Hanam, Finch, & Hepting, 2011; Touchie & Pressnail, 2014). This results

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in high uncertainty regarding the quality of the final model and provides no information on the potential reductions that can be expected from energy conservation measures (ECMs) targeting infiltration. If the building industry continues to rely on whole-building energy models to inform building retrofits, strategies need to be developed to improve parameter certainty of infiltration rates. These strategies need to be cost-effective and easily completed in occupied buildings.

It was hypothesized that the component-weighted approach could reduce parameter uncertainty and provide a more accurate characterization of zone infiltration rates using data from minimally-intrusive, on-site component infiltration tests.

This study investigated the feasibility of using window component infiltration rate testing to help characterize MURB whole-building infiltration rates in whole-building energy models developed for retrofit analysis. The analysis and results presented in the paper are part of a larger study completed by the authors (Lozinsky & Touchie, 2018).

METHODOLOGY

Building energy models were developed for two Toronto-area MURBs. For each model, the building infiltration rate was determined using two different approaches: The Traditional Calibration Method and the Component-Weighted Calibration Method. The Traditional Calibration Method assumed a single, building-level infiltration rate, which is consistent with how infiltration has traditionally been characterized in energy models. The Component-Weighted Calibration Method used a component-weighted infiltration rate, developed using component infiltration rate testing of the windows and window-wall interfaces at the two test buildings.

The base building model geometry and preliminary parameter definition for the energy models were completed using DesignBuilder, version 4.7.0.027, a graphical user interface for EnergyPlus. Final parameter definition and model calibration were completed using EnergyPlus, version 8.3.0. The energy models used the Canadian Weather for Energy Calculations (CWEC) weather file for Toronto, Canada.

Subject Buildings

Both test buildings are located in the North York suburb of Toronto, Canada, and are owned and operated by the local social housing provider. Basic building demographics are in Table 1. Both buildings are clad with a masonry veneer installed over concrete block back-up walls and have single-glazed, non-thermally-broken aluminum windows (fixed and operable units). Window-Wall Ratios (WWR) are 21 % and 17 % for Building A and B, respectively. Window operation was estimated in the models using a temperature set-point model. Both buildings are heated with natural gas-fired boilers connected to in-suite hot water radiators. The boilers also supply the domestic hot water (DHW) system. Neither building is equipped with central air conditioning. Both buildings have a pressurized-corridor ventilation system with gas-fired make-up air units installed on the roofs. Model parameters were collected from a variety of sources, including: long-term monitoring data (suite temperature and relative humidity); spot measurements (ventilation system air flow rates); operation and maintenance personnel (HVAC system operation schedules and DHW supply temperatures); energy audits and building condition assessments (HVAC equipment specifications, lighting and equipment inventories); and original building drawings.

Table 1: Subject Building Demographics

	Building A	**Building B**
Year Constructed (Age)	1974 (44 y/o)	1972 (46 y/o)
Gross Floor Area (m^2)	17,129	15,248
Number of Above-Grade Storeys	18	4
Below-Grade Levels	1	0
Occupant Type	Families	Seniors
Number of Suites	204 two-bedroom suites	397 bachelor/one-bedroom suites

Model Calibration

Energy models were calibrated using natural gas, electricity and water consumption data, provided by the building owner. The owners provided two to five years' worth of monthly utility data for each building.

Natural gas consumption data were calendarized and normalized using a linear regression analysis to reduce weather-related bias. The linear regression used monthly heating degree days at a base temperature of 18°C (HDD_{18}) as the independent variable. A single-variable linear regression model was selected over multi-variable regression models as previous studies have reported R^2 values between heating loads and HDD greater than 0.98,

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suggesting a high level of reliability (Huang, Ritschard, Bull, & Chang, 1986; Quayle & Diaz, 1979). HDD_{18} values for the months of June, July and August were forced to zero, to reflect that the heating systems are turned off in Buildings A and B between June 1st and September 15th.

Following weather-normalization of the utility data, energy model calibration was completed using a step-wise approach, similar to those described by others (Hanam et al., 2011; Hubler, Tupper, & Greensfelder, 2010; Touchie & Pressnail, 2014; Yoon, Lee, & Claridge, 2003) where input parameters are classified as low, medium and high uncertainty. High uncertainty parameters are assigned a range in which the calibrated value will likely fall. Energy end uses for each high uncertainty parameter are isolated, allowing for calibration of the high uncertainty parameters, one-by-one. We opted for a step-wise calibration procedure over more rigorous, Monte Carlo analysis calibration techniques, similar to those proposed by Reddy et al. (2007), to be consistent with typical industry practice. In the authors' experience, energy model calibration for the purposes of retrofit analysis is typically completed using heuristic methods similar to the step-wise approach. The limitations of heuristic calibration techniques, specifically with respect to calibrating building air infiltration rates, will be discussed in the *Limitations* section.

Models were considered calibrated when they met the acceptance thresholds from *ASHRAE Guideline 14 – Measurement of Energy and Demand Savings* (ASHRAE, 2002). *ASHRAE Guideline 14* was established to standardize the characterization of energy and demand savings associated with ECMs. In energy modeling applications, *ASHRAE Guideline 14* uses two metrics to determine when a model is sufficiently calibrated: the coefficient of variation of the root mean square error (CV(RMSE)) and the normalized mean biased error (NMBE). Under *ASHRAE Guideline 14*, the maximum allowable CV(RMSE) is 15 %, while the maximum allowable NMBE is +/- 5 %, when using monthly utility data for calibration.

Traditional Calibration Method

Suite plug loads, DHW consumption and building infiltration rate were identified as the high uncertainty parameters for both building energy models. Suite plug loads and DHW consumption were isolated and calibrated first. The infiltration rate for each model was then incrementally varied until modeled natural gas consumption converged with the weather-normalized natural gas consumption data.

Component-Weighted Calibration Method

The infiltration rate used for the Component-Weighted Method was based on a weighted value. The weighted infiltration rate was calculated on a zone-by-zone basis using building-specific quantities of building envelope components and normalized infiltration rates for each component, as shown in Equation (1):

$$I_i = \left[\left(q_{wall} \times A_{wall,i}\right) + \left(q_{roof} \times A_{roof,i}\right) + \left(q_{frame} \times L_{frame}\right) + \left(q_{interface} \times L_{interface,i}\right)\right]/1{,}000 \quad (1)$$

Where I_i in the infiltration rate for zone i (m^3/s); q_x is the normalized infiltration rate for component x ($L/s/m^2$, L/s/m); $A_{x,i}$ is the area of component x for zone i (m^2); and $L_{x,i}$ is the length of component x for zone i (m).

For this analysis, the building envelopes of Buildings A and B were broken down into four component types: opaque walls (m^2), roofs (m^2), fenestration assemblies (m of operable sash crack) and fenestration-to-wall interfaces (m of fenestration perimeter). It was assumed that these four components would account for the majority of building air infiltration. The validity of this assumption will be discussed in the *Limitations* section. Values for the fenestration-related infiltration rates were taken from field measurements. Opaque wall and roof infiltration rates were incrementally varied until the modeled energy consumption converged with the results of the Traditional Calibration Method. Final component infiltration rates for opaque wall and roof components were compared to values from the literature, to check that the test values were similar to previous research.

Window Component Infiltration Rate Testing

Two test procedures were used for the window component infiltration rate testing: the Frame Test and the Whole Installation Test. The Frame Test was completed in accordance with *ASTM E783 – Standard Test Method for Field Measurement of Air Leakage Through Windows and Doors* (American Society for Testing and Materials, 2010). The Frame Tests measured infiltration associated with the fenestration product only. The Whole Installation Tests were a modified version of the *ASTM E783* test procedure, similar to the procedure described by Shaw (1980). This modified procedure measured infiltration through both the frame and the fenestration-to-wall interface.

The general test configuration for the Frame Test is shown in Figure 1. Test chambers were constructed using 6-mil polyethylene sheeting, sealed using sheathing tape. For the Frame Tests, the test chambers were sealed directly to the window frame perimeter. For the Whole Installation Tests, the test chambers were sealed to the wall adjacent to the test specimen.

Within each test procedure (Frame or Whole Installation), two tests were completed: total infiltration, Q_t, and

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extraneous infiltration, Q_e. The final specimen infiltration rate, Q_s, was calculated as per Equation (2):

$$Q_s = Q_t - Q_e \quad (2)$$

Where extraneous infiltration can be taken as the error associated with the test chamber construction. Extraneous infiltration was measured by installing a second test chamber on the exterior of the test specimen and repeating the test procedure (see Figure 1). All testing was completed using the Minneapolis Duct Blaster outfitted with the Micro-Leakage Meter adaptor duct and the DG-500 digital pressure gauge, manufactured by The Energy Conservatory. Flow readings were taken at test chamber pressure differential readings of 10 Pa, 20 Pa, 30 Pa, 40 Pa, 50 Pa, 60 Pa and 75 Pa. Depressurization was used as the default for all tests, to limit stress on the chamber perimeter seals.

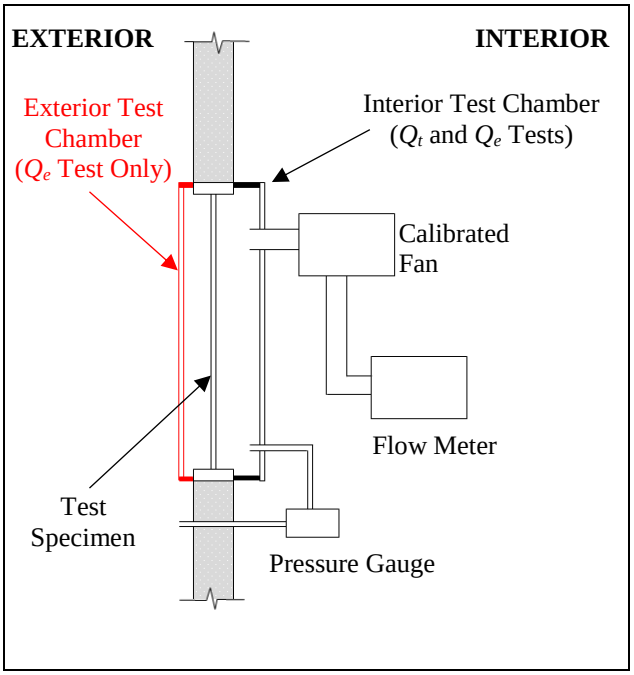

Figure 1: Schematic of Test Apparatus for Frame Test (adapted from ASTM, 2010)

Three flow readings were taken at each pressure interval. Each reading was based on a 10-second time average, to reduce noise in the data associated with pressure fluctuations induced by wind.

RESULTS

The following section summarizes the results from the Traditional Calibration Method; the window component infiltration rate tests; and the Component-Weighted Calibration Method, which incorporated the measurements from the window component infiltration rate testing. Benefits and limitations of this analysis in particular, as well as the Component-Weighted Method in general, will also be discussed.

Traditional Calibration Method

Step-wise calibration using a bulk infiltration rate resulted in calibrated models for both buildings. Figure 2 shows the calibrated monthly natural gas consumption for Buildings A and B, compared against the weather-normalized natural gas consumption data, computed using the regression equations developed from the building utility data. *ASHRAE Guideline 14* calibration statistics for Building A were optimized assuming an infiltration rate of 4.12 L/s/m^2 of building envelope surface area (q_{75}). Building B achieved optimized calibration assuming q_{75} equal to 1.58 L/s/m^2 of building envelope surface area. The bulk infiltration rates associated with the calibrated models fit within previously-published infiltration rates for buildings with similar construction types (Gulay, Stewart, & Foley, 1993; Proskiw & Phillips, 2001).

As predicted, infiltration had a large effect on energy consumption. Infiltration accounted for 53 % and 38 % of the total annual space heating load for Buildings A and B, respectively.

While *ASHRAE Guideline 14* helped in characterizing the "goodness of fit" between the weather normalized consumption data and the model results, the uncertainty statistics could not characterize the quality of the resulting calibrated model. A sensitivity analysis of the infiltration rate showed that a range of infiltration rates would yield a calibrated model that met *ASHRAE*'s uncertainty criteria. The annual natural gas consumptions associated with the "upper bound" infiltration rates were 8 % and 7 % higher than the "lower bound" infiltration rates for Buildings A and B, respectively.

This technique also exposes one of the major limitations of step-wise calibration techniques. Step-wise techniques are predicated upon the assumption that parameter uncertainty can be isolated to a small number of parameters and adjustment of those parameters will result in a calibrated model. In this analysis, the infiltration rate was adjusted indiscriminately to force calibration, under the assumption that all uncertainty related to weather-dependent natural gas consumption could be attributed to the infiltration rate.

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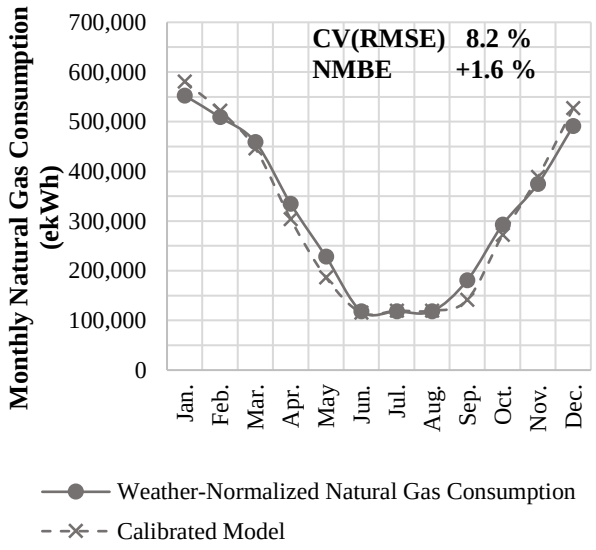
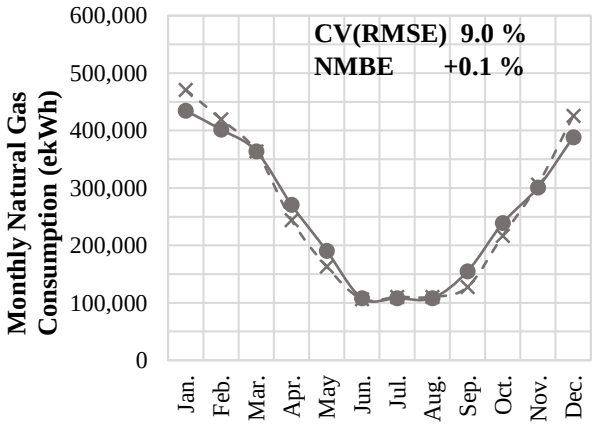


(a)



(b)

Figure 2: Monthly natural gas consumption for (a) Building A calibrated model and (b) Building B calibrated model

While the final models appear calibrated at the macro level and the final infiltration rates are consistent with previously-published data for similar building types, no new information was collected to guide or justify the parameter adjustment. Building and calibrating a model without adequate justification or evidence to support the input parameters is known as the *garbage in-garbage out principle* (Raftery et al., 2011; Reddy et al., 2007). This type of model is inappropriate for assessing ECMs, as the model is not an accurate representation of how the building performs. Problems may also arise when using this model to assess the effects of ECMs that specifically target infiltration. This model provides no guidance on the magnitude of infiltration rate reduction that could be reasonably achieved with ECMs, leaving the modeler to estimate the expected improvement based on professional judgment or on previously-published data. Over- or under-estimation of the expected reduction to air infiltration rates associated with specific ECMs, such as window replacements, will have a corresponding effect on the model-predicted energy savings. Depending on the magnitude of the error, this has the potential to greatly affect building owners and operators, either because a project is incorrectly classified as a poor investment or because the actual energy savings fall short of those predicted by the energy model, decreasing the return on investment.

Window Component Infiltration Rate Testing

Raw data from the window component infiltration rate tests were used to calculate test-specific flow coefficient, *C*, and flow exponent, *n*, values using the regression analysis procedure outlined in *CAN/CGSB 149.10-M86 - Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method* (Canadian General Standards Board, 1986). The calculated C and n values were then used to calculate average air flow rate curves using the power law equation.

The frame and whole-installation component infiltration rates were measured for five specimens, one in Building A and four in Building B. Due to access restrictions, the extraneous air leakage (Q_e), which requires access to the building exterior, could only be measured at one location. Q_e results from this test location ranged from 60 % to 70 % of the corresponding Q_t. Data collected from *ASTM E783* tests completed on other sites showed Q_e values ranging between 10 % and 80 % of the corresponding Q_t, while previous studies measuring window component infiltration rates have reported Q_e contributions between 47 % and 95 % (Louis and Nelson, 1995). To account for the large uncertainty in Q_e for each test $Q_{s,frame}$ and $Q_{s,wi}$ were calculated twice: once assuming a high Q_e component (80 % of Q_t) and once assuming a low Q_e component (10 % of Q_t). From these two calculations, an infiltration envelope was established, in which the actual specimen infiltration would likely reside. Descriptive statistics from the field tests are presented in Table 2.

The infiltration associated with the window-wall interface detailing ($q_{s,interface}$) was calculated by subtracting the frame infiltration rate from the whole installation infiltration rate. Previous studies measuring window component infiltration for comparable assemblies have reported mean frame infiltration rates ranging between 1.1 and 3.1 L/s/m and mean infiltration rates associated with window-wall interface detailing between 1.3 and 2.6 L/s/m (all values

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assuming ΔP = 75 Pa) (Colliver, Murphy, & Sun, 1994; Orme, Liddament, & Wilson, 1998; Shaw, 1980).

Table 2: Descriptive Statistics for Window Component Infiltration Rate Testing (at P = 75 Pa)

	(L/s/m)		
	Minimum	**Mean**	**Maximum**
$q_{s,frame}$ (per m of sash crack)	0.2	1.2	2.9
$q_{s,interface}$ (per m of fenestration unit perimeter)	0.3	1.5	2.2

In general, the infiltration rates from the field tests are within the same order of magnitude as other studies. Any discrepancies between the results of the field tests and those from previously-published sources can likely be attributed to the variation in age and condition of the components.

Component-Weighted Calibration Method

Applying the mean component infiltration rates obtained from the field testing to the building-specific quantities for each component yielded the component breakdowns shown in Figure 3. Fenestration-related component infiltration accounted for 41 % and 49 % of total infiltration for Buildings A and B, respectively. The remaining 59 % and 51 % was attributed to infiltration through opaque walls, roofs and miscellaneous penetrations not otherwise specified.

Building A's energy model reached convergence with the weather-normalized natural gas consumption profile (CV(RMSE) = 8.3 %; NMBE = +1.3 %) assuming an opaque wall component q_{75} equal to 3.0 L/s/m^2 and a roof component q_{75} of 2.53 L/s/m^2, which are consistent with previously-published component infiltration rates for similar construction types (Colliver et al., 1994; Persily & Ivy, 2001; Stanton, 2017). Figure 4 illustrates the effect of component infiltration on natural gas consumption for Buildings A and B. Infiltration associated with fenestration components (frames and interface detailing) account for 22 % of the annual space heating load for Building A.

The energy model for Building B reached convergence with the weather-normalized natural gas consumption profile (CV(RMSE) = 8.9 %; NMBE = +0.1 %) assuming a similar roof component infiltration rate as Building A and an opaque wall component infiltration rate of q_{75} = 0.32 L/s/m^2. While this is considerably lower than Building A, it is still within the range of typical values for the wall type. Fenestration component infiltration (frames and interface detailing) accounted for 14 % of Building B's annual space heating load.

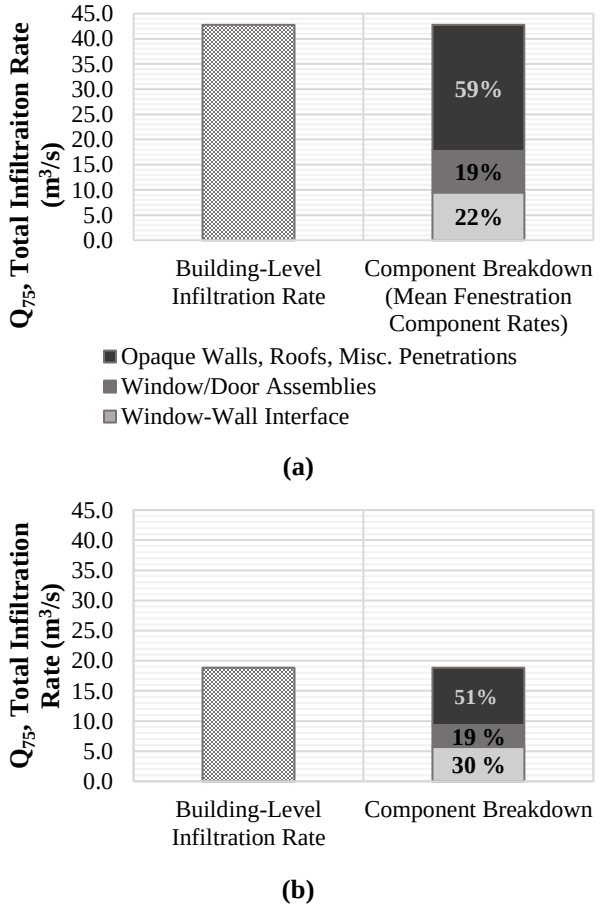
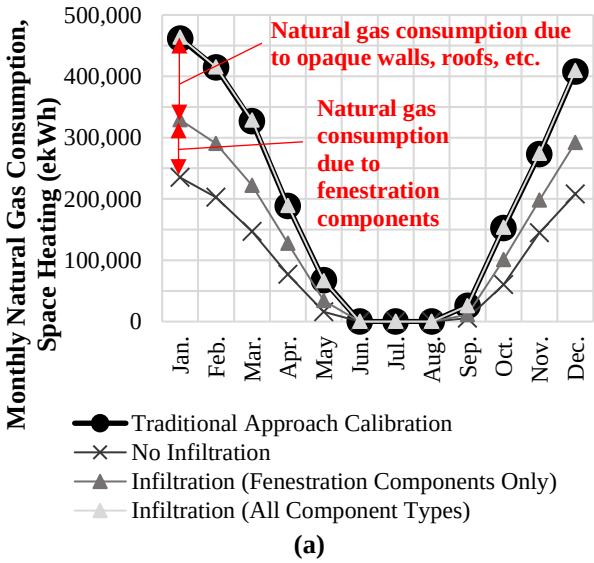


Figure 3: Building-level infiltration rates by component type for (a) Building A and (b) Building B



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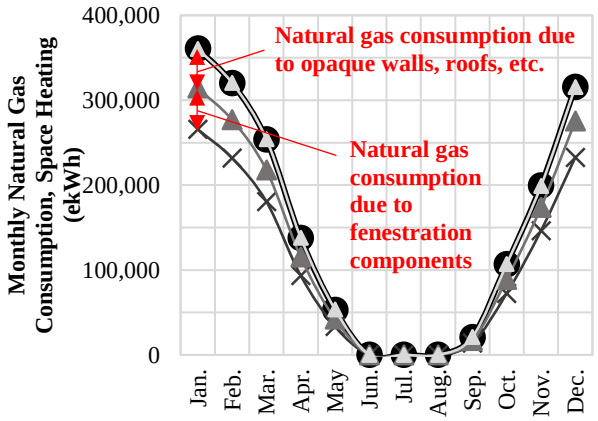

(b)

Figure 4: Monthly natural gas consumption for (a) Building A Calibrated Model and (b) Building B Calibrated Model

DISCUSSION

On a macro level, breaking the infiltration rate down by component type did not significantly affect the *ASHRAE Guideline 14* calibration statistics for either building; however, one of the main advantages of the component-weighted approach is its ability to properly account for uneven distributions of leakage paths between different zones. A review of the infiltration profiles at the zone-level revealed that the Traditional Calibration Method over-estimated zone infiltration in the corridor zone, compared to the component-weighted model. Conversely, the perimeter zones in the Traditional Method under-estimated zone infiltration compared to the Component-Weighted models. A similar trend was observed with the zone-level natural gas consumption profiles. For the 10th floor zones, the model calibrated using the Traditional Method over-estimated corridor zone annual natural gas consumption by 37 % and under-estimated perimeter-zone annual natural gas consumption by 4 %. Similar trends were noted in Building B. The daily average zone infiltration for the second-floor south perimeter zone and second floor corridor zone increased by 6 % and decreased by 67 %, respectively, compared against the Traditional Method calibrations.

For the two test buildings the uneven distribution of leakage paths was limited to the corridors, as all of the perimeter zones had similar WWRs; however, this effect could potentially result in large errors in buildings with an uneven distribution of building envelope component types between zones (e.g. operable vs. fixed windows). From a model accuracy perspective, this is important if heating and cooling set points vary between zones, which is often the case in MURBs where the corridor and suites are heated and cooled to different set points. In addition, energy costs for personal (i.e., suite) and communal (i.e., corridor) spaces are typically dispersed between different stakeholders in MURBs. Depending on the ownership structure, the zone locations projected to show energy savings may affect an owner or operator's decision to proceed with an energy retrofit, just as much as the actual magnitude of projected energy savings.

One of the major limitations of the Traditional Method was that it provided no guidance on the magnitude of infiltration rate reduction that could be achieved with ECMs that targeted infiltration. For example, decisions regarding window replacement or retrofit projects are typically made based on conduction losses alone, as accurate data on air infiltration rate improvements are rarely available. Unfortunately, the return on investment when only considering conduction losses are usually too small to justify the initial capital expenditure. As a result, window replacement is typically rejected as a viable energy retrofit. Only considering conduction losses when assessing window replacement projects represents a missed opportunity. In North America, fenestration system performance for most large-scale new construction projects falls under *AAMA/WDMA/CSA 101/I.S.2/A440-11*, also known as the *North American Fenestration Standard* (*NAFS*) (Canadian Standards Association, 2011). The maximum allowable specimen (frame) infiltration rate for operable windows that is permitted under *NAFS* is q_{75} = 1.5 L/s/m^2 of specimen area. The average frame infiltration rate, q_{75}, from the field tests completed as a part of this study was 3.26 L/s/m^2 – over double the *NAFS* maximum. In addition, these values do not account for possible airtightness improvements related to improved detailing at the window-to-wall interface. There is clearly a large potential for energy savings associated with improved airtightness of fenestration assemblies. The Component-Weighted Method, and by extension the on-site component infiltration rate testing, provided greater confidence when specifying base line building infiltration rates, as well as predicting the potential component-level improvements of retrofit measures.

Site-specific infiltration rate testing – and the potential for improving the characterization of ECMs – is not limited to windows. Component infiltration rate test procedures can be adapted to most building envelope components, giving modelers and designers additional evidence to improve model calibration and building owners and operators the information needed to make informed decisions about ECMs.

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LIMITATIONS

Despite the possible benefits associated with component infiltration rate testing and the Component-Weighted Method, several simplifying assumptions were made in the analysis regarding component type selection. In addition, adjustments and compromises were made during the window component infiltration rate testing to accommodate site conditions and access limitations, namely a reduced sample size and limited extraneous infiltration measurements. The results from this study should be viewed in context with these limitations.

Component Type Selection

The component-weighted analysis only included infiltration associated with four building envelope component types: opaque walls, roofs, fenestration assemblies and the interface detailing between fenestration units and walls. It was hypothesized that these four components were the largest contributors to total infiltration; however, this is not a comprehensive list of infiltration sources. Infiltration can occur at any discontinuity in the pressure boundary. In addition to the four components included in this analysis, previous studies on component infiltration rates have measured infiltration due to HVAC ductwork, vents, fireplaces, plumbing and electrical penetrations, wall-to-floor interfaces and air conditioning units (window and through-wall) (Colliver et al., 1994; Dickeroff, Grimsrud, & Lipschutz, 1982; Orme et al., 1998; Shaw, 1980; Zuluaga, Maxwell, Block, & Eisenberg, 2011). Inclusion of building envelope component types should be project-specific, depending on the building design. The validity of our component type selections could have been verified, at least in part, with a suite-level infiltration rate measurement. While we were able to conduct unguarded blower door tests in a few suites, these results were inflated by air flow rates through internal partitions, as we did not have full access to adjacent suites to neutralize the pressure differential across the internal partitions. Future development of component-weighted techniques would benefit from side-by-side comparisons with suite- or building-level infiltration rate testing, to refine component selection.

Extraneous Infiltration, Q_e

It was not possible to measure extraneous infiltration, Q_e, at four of the five test locations. The reliability of the component infiltration rate measurements is highly dependent on the control and quantification of extraneous infiltration. Extraneous infiltration includes not just errors associated with test chamber construction, but also bypass airflow into the interstitial space of the wall assemblies. While careful test chamber construction can usually limit the former, it is extremely difficult to control for the latter. Most studies discussing window component infiltration rate testing acknowledge that fully accounting for extraneous infiltration in field tests is fraught with difficulty (Gonçalves & Jutras, 2010; Proskiw, 1995; Waite & O'Brien, 2010), which is consistent with our experiences on site. When computing the specimen component infiltration rates a range of values were assumed to account for the high uncertainty associated with Qe; however, for ease of modeling the mean value for both the frame and interface component infiltration rate was used. To test the sensitivity of this assumption, the first quartile, mean and third quartile fenestration component infiltration rates were compared to the total infiltration at Building A. As shown in Figure 5, these three values yield a range of between 20% and 56% for fenestration-related infiltration.

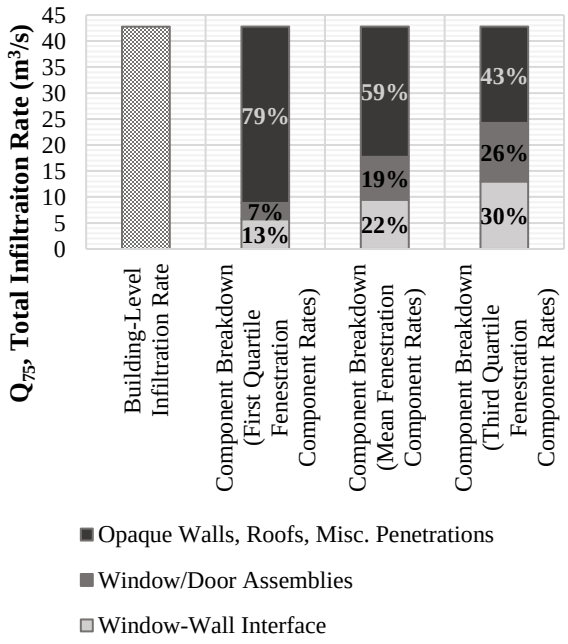

Figure 5: Building A building-level infiltration rates by component type assuming different ranges for fenestration component infiltration rates

Sample Size

Another limitation of this study is the relatively small sample size for the fenestration component infiltration rate testing. The fenestration component infiltration rates used in this analysis were estimated from a small sample and are thus susceptible to sampling errors. Building A contains 1,016 window/door assemblies, while Building B contains 522. For both buildings, the infiltration rate estimates were

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based on a sample size of five. The sampling uncertainty for both buildings was calculated at 19.2 %. Sampling uncertainty is inversely proportional to the square root of the sample size, q. Increasing the sample size by a factor of *x* will decrease the corresponding sampling uncertainty by $\sqrt{x}$, making it very difficult to cost-effectively reduce sampling uncertainty with large population sizes.

Traditional Method Model Inputs

Improving the characterization of air infiltration rates for building retrofit analysis is only one part of the puzzle. The validity of these results is also dependent on the accuracy of the base case model inputs, specifically those that affect building space heating loads and were initially classified as having high certainty (and thus were excluded from the step-wise calibration process). For the analyses, we relied on technical data supplied by the boiler manufacturers for the heating plant efficiencies; however, a recent study by Gestwick et al. (2014) found that in-situ heating plant efficiencies in two institutional buildings were either proportional to load, or did not vary at different load – contrary to typical efficiency load curves, which show plant efficiencies being inversely proportional to load. As most heating plants do not operate at peak loads for most of the year, improper characterization of plant efficiencies has the potential to greatly affect simulation results. The models also relied on a simple temperature set-point model to characterize natural ventilation. Temperature set-point models are limited, in that they do not accurately reflect human behaviour and often result in over- or under-estimation of ventilation rates as they cannot account for occupant interactions. Despite these limitations, a sensitivity analysis of the two models revealed that adjustment of the set-point temperature and the natural ventilation flow rate had a minimal effect on the optimized, calibrated infiltration rate.

CONCLUSION

Using a simple component infiltration rate test procedure modified from *ASTM E783*, building-specific infiltration rate measurements for both fenestration units and fenestration-to-wall interfaces were obtained in two occupied MURBs. The measurements were incorporated into component-weighted infiltration rates used to calibrate whole-building energy models for these two buildings.

Component infiltration rate testing was quick and easy to implement in a fully-occupied building by conducting the testing in vacant suites. Unlike suite-level, sequential fan pressurization testing, the test procedure did not require access to multiple suites at a time; did not require specialized training or equipment; and was easily completed by two people within a half-day. Window component infiltration rate testing is also considerably less expensive compared to suite-level, sequential fan pressurization testing. The cost to complete one window component infiltration rate test was approximately $750 CAD, while sequential fan pressurization testing in an occupied building is typically in the range of $5,000 to $6,000 CAD per test. The test data collected was used to reduce parameter uncertainty associated with building infiltration rates in the whole-building energy models. The reduction in parameter uncertainty using component infiltration rates helps not only with development of the baseline model, but also with retrofit analysis of potential ECMs by breaking infiltration rates down based on their source.

This analysis suffered from several limitations, namely a small sample size and an inability to accurately quantify extraneous infiltration, resulting in a large sampling uncertainty and a large range of possible component infiltration rates. This method also did not address the high uncertainty associated with wall and roof component infiltration rates. Despite these limitations, the overall method and procedure of both the window component infiltration rate testing and the Component-Weighted Calibration Method can be easily implemented and have the potential to improve model calibration practices during retrofit analysis.

The Component-Weighted Method is also not exclusively for use with window component infiltration rate testing. Any type of component testing could be incorporated in this analysis. Future research could focus on refining the Component-Weighted Method by measuring infiltration rates associated with different components and conducting a side-by-side comparison of the Component-Weighted Method with suite- or whole-building air infiltration test data.

The MURB housing stock in our cities is aging and these buildings are generally energy-inefficient. Improving energy efficiency through the implementation of ECMs that target uncontrolled air leakage in MURBs present a significant opportunity to reduce energy use in this sector and should be pursued. To make appropriate decisions about which retrofit measures are most effective for improving energy performance, more accurate modeling of uncontrolled is leakage is required. The Component-Weighted Calibration Method provides a practical means of improving parameter certainty associated with air infiltration that can be applied by researchers and practitioners alike.

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