ABSTRACT

The inadequate control of airflow in to, out of, and within multi-unit residential buildings (MURBs) has historically been associated with performance issues related to moisture damage, occupant comfort, and indoor air quality. Recently, in response to increasing societal concern and energy costs, airtightness is garnering more attention with respect to energy efficiency. Various jurisdictions in North America and worldwide have integrated or are considering integrating quantitative airtightness performance requirements in to their building regulations; however, the industry capacity to perform airtightness testing of MURBs and to adapt to meet a potential mandatory requirements is relatively unknown.

To gauge the state of the industry with respect to airtightness testing of MURBS, literature regarding airtightness testing was reviewed including various test standards. Also, while it is practical to set a quantitative airtightness requirement for MURBs, airtightness testing of MURBs is significantly less common than of detached houses and the resulting data is largely not compiled. To gain a better understanding of current MURB airtightness performance and aid in the selection of a regulatory airtightness requirement, a database was created of MURB airtightness testing results. Finally, a survey was distributed to members of industry to evaluate perception and preparedness with respect to airtightness testing. The paper will present the results of this review of testing techniques, airtightness performance, and industry perceptions and preparedness.

STATE OF THE ART OF MULTI-UNIT RESIDENTIAL BUILDING AIRTIGHTNESS: TEST PROCEDURES, PERFORMANCE, AND INDUSTRY INVOLVEMENT

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INTRODUCTION

The inadequate control of airflow in to, out of, and within multi-unit residential buildings (MURBs) has historically been associated with performance issues related to moisture damage, occupant comfort, and indoor air quality. Recently, in response to increasing societal concern and energy costs, airtightness is garnering more attention with respect to energy efficiency. Various jurisdictions in North America and worldwide have integrated or are considering integrating quantitative airtightness performance requirements in to their building regulations; however, the industry capacity to perform airtightness testing of MURBs and to adapt to meet a potential mandatory requirements is relatively unknown.

To gauge the state of the industry with respect to airtightness testing of MURBS, literature regarding airtightness testing was reviewed including test standards, procedures, and regulations. Also, airtightness testing of MURBs is significantly less common than of detached houses and the resulting data is largely not compiled, so to gain a better understanding of current MURB airtightness performance and potentially aid in the selection of a regulatory airtightness requirement, a database was created of MURB airtightness testing results. Airtightness testing data from the United States Army Corps of Engineers (USACE) was also assessed as a means of evaluating the potential airtightness performance that is achievable given performance and testing requirements. Finally, a survey was distributed to members of industry to evaluate perception and preparedness with respect to airtightness testing and potential implementation of regulatory testing and performance requirements.

This paper provides a summary of this research work and the full study is available in RDH (2013) and in Ricketts (2014).

AIRTIGHTNESS TEST PROCEDURES

Airtightness testing is commonly performed on houses as it is often required by energy efficient housing programs. The equipment and procedures for testing of houses are well developed and readily available. Airtightness testing of multi-unit residential buildings, however, is relatively rare due the complexity of the test methods, the invasiveness of the test on building occupants, the time required to conduct the test, budget considerations, and a lack of regulatory requirements. However, as jurisdictions and programs have begun to require airtightness testing, it has become more common. (2009 Seattle Energy Code, 2009; Washington State Energy Code 2009, 2011; USACE, 2009)

Airtightness testing is performed by pressurizing or depressurizing a building, or zone of a building, relative to outdoors and/or to adjacent zones. The pressure difference is created by forcing air in or out of the test volume using a fan and is intended to be of sufficient magnitude to overcome and significantly outweigh naturally occurring pressure differentials. The flow rate through the fan is measured at a given pressure difference, and, by conservation of mass, the same amount of airflow must be occurring through the zone pressure boundaries.

Test procedures have been developed and standardized by numerous organizations and a selection of these standard that are most commonly used in North America is provided below. There are also other test standards which are intended for laboratory testing of air barrier materials and assemblies rather than for field testing of whole buildings.

- CGSB 149.10-M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method (1986)
- CGSB 149.15-96 Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems (1996)
- ASTM E779-10 Standard test method for Determining Air Leakage Rate by Fan Pressurization (2010)
- ASTM E1827-96 Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door (2007)
- US Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes (developed in conjunction with the Air Barrier Association of America (ABAA)) (US Army Corps of Engineers, 2012)
- ISO Standard 9972 Thermal Insulation – Determination of Building Airtightness – Fan Pressurization Method (2006)
- ATTMA Technical Standard L1-2010: Measuring Air Permeability of Building Enclosures (Dwellings) (2010)

The standards identified in the list above are all similar in principle. The primary differences between them include:

- How the pressure difference is achieved (building mechanical system or test fan(s))
- How the airflow rate is measured (calibrated fan or orifice plate)
- Whether the test volume is pressurized, depressurized, or both
- How many flow and pressure measurements are made (number of test points) and how long a time period each is made over (one reading, average over 10 seconds, et cetera)

- How the mechanical ventilation system is prepared for testing (are the ducts sealed and which ones)
- The environmental conditions under which the test can be performed
- How the test results are reported, including bias and statistics

RDH (2013) provides a complete description of each test standard and identifies the differences between the various methods.

While the identified testing standards work well for small buildings and large buildings which have relatively open interior spaces (i.e. commercial buildings with open floors plans), in larger, more complicated building with many separate spaces (i.e. compartmentalized) such as multi-unit residential buildings, it is often impractical or impossible to pressurize or depressurize the entire building for the purposes of airtightness testing. To test large compartmentalized buildings such as MURBs, pressure neutralized fan depressurization/pressurization testing techniques have been developed to test individual spaces within a building. (Finch et al, 2009; Ricketts, 2014) This method permits the isolation of each side of a suite so that airtightness of the enclosure and of compartmentalizing elements (e.g. demising walls, floors, and ceilings) can be measured.

To measure the exterior enclosure airtightness of a specific zone (i.e. suite in a MURB) using the pressure neutralized fan depressurization/pressurization testing technique, blower-door fans such as those used in testing of single family homes are used. These fans are set-up to pressurize/depressurize the test zone, and then to equally pressurize/depressurize the zones adjacent to the test zone such that no air flows between the test zone and the adjacent zones. Once all of the adjacent zones are equalized, the airflow measured in to or out of the test suite is only through the exterior enclosure and can be used to determine the exterior enclosure airtightness.

Overall, while in some cases it is possible to airtightness test MURBs using whole building testing techniques, in many cases MURBs are compartmentalized such that achieving even pressurization/ depressurization of the entire building is difficult or impossible. Consequently, in many applications pressure neutralized pressurization/depressurization airtightness testing techniques may be the easiest or only appropriate test method for determining the airtightness of the exterior enclosure of a MURB. As this type of testing has not yet been formally standardized, development of a testing standard for this type of testing would greatly facilitate the widespread implementation of this type of testing and also would allow for its referencing within potential airtightness regulatory requirements.

MURB AIRTIGHTNESS DATABASE

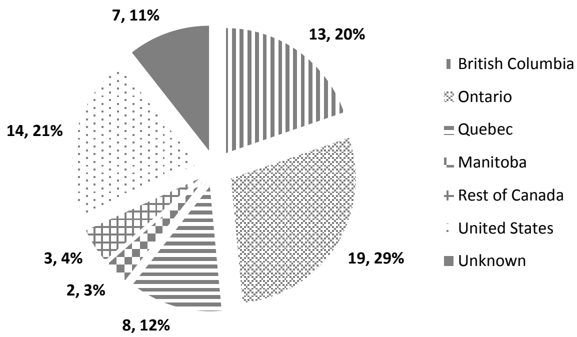
While testing of air barrier materials, components, and assemblies can provide some indication of the airtightness of actual completed buildings; the airtightness of buildings is largely dependent on workmanship and quality control, which is difficult to simulate. Consequently, airtightness testing of completed enclosure assemblies is most valuable, but for MURBs the results of this type of testing are limited and not compiled.

Airtightness testing data was compiled in to a database to provide an indication of MURB airtightness performance to allow for determination of appropriate regulatory performance targets. The database is populated with data collected from various literature sources and from test results provided directly to the author from unpublished sources. In many cases, the unpublished data is recorded in reports that are not available publicly. A complete list of references used in the development of the database is provided in RDH (2013) and Ricketts (2014). As much information about these buildings as was available was collected including height, number of storeys, age (year of construction), age of the air barrier, and wall and/or air barrier type. Results were converted to a normalized flow coefficient and/or flow coefficient using either an experimentally determined flow exponent or an assumed flow coefficient of 0.65 if insufficient information was available to calculate the value. (Straube & Burnett, 2005; Orne et al., 1998) Using these values, various common metrics were calculated to facilitate comparison.

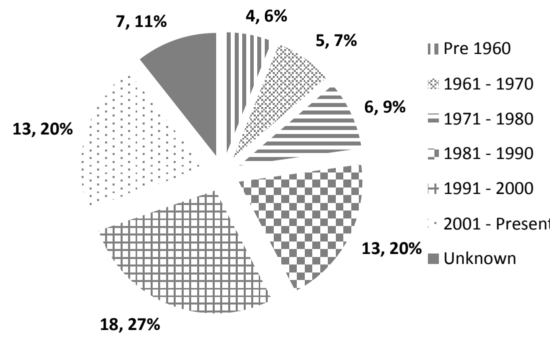
The database includes a total of 55 unique multi-unit residential buildings, and there are results from 170 individual tests, as in many cases buildings were tested multiple times (e.g. different suites in the same building, or before and after air sealing). Note that when air sealing was performed, the building was only counted once; however, results are included for both pre and post air sealing since the air barrier of these buildings changed significantly. When multiple tests were performed on the same building without any changes to the air barrier, the average of these results was used for analysis, but the results of each test are included in the database to allow for comparison if desired. Counting before and after air sealing as separate buildings, there are testing results for 66 unique multi-unit residential buildings; however normalized airtightness data was available for only 45 of these.

It is important to recognize that this database is likely not entirely representative of the existing building stock because buildings which are tested for airtightness are likely to be more airtight than the average building. Only in rare cases are buildings tested that are not associated with performance targets or air sealing work. Testing of buildings prior to air sealing work also provides a non-representative sample as these buildings are likely less airtight than an average building because they have been identified as candidates for the air sealing work.

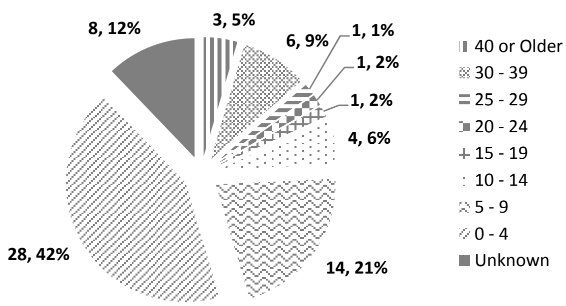
The MURBs in the database are primarily located in Canada, with some buildings also located in the United States as shown in and the majority of these buildings were constructed or significantly modified after 1990 as shown in FIGURE 1 a) and b) respectively. FIGURE 1 c) shows that over half of the buildings were tested when the air barrier was less than 10 years old (i.e. less than 10 years since original construction or subsequent air sealing work), and FIGURE 1 d) shows that most buildings in the database are between 1 and 14 storeys tall as shown in FIGURE 1.



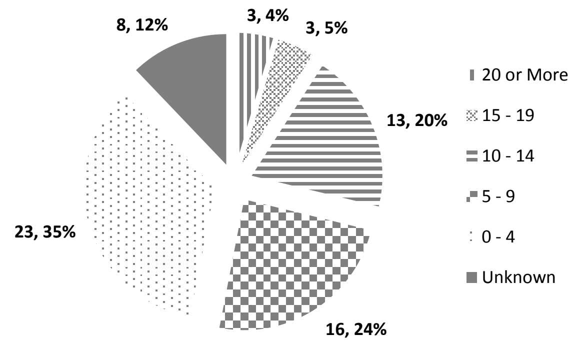
a) Geographical location



b) Air barrier construction or modification date



a) Air barrier age when tested



b) Building height

FIGURE 1: Charts of a) geographical location, b) air barrier construction or modification date, c) air barrier age when tested, and of d) building height for buildings in the multi-unit residential building airtightness database

The mean average normalized exterior enclosure airtightness of the buildings in the database is 3.81 L/s·m² (0.75 cfm/ft²) at 75 Pa based on data that was available for 45 buildings. The airtightness values (q_{75}, airflow at 75 Pa normalized by the enclosure area) for the buildings in the database are plotted in FIGURE 2, and the distribution of these values is shown in FIGURE 3. The median and standard deviation are 3.02 and 3.23 L/s·m² (0.59 and 0.64 cfm/ft²) respectively at 75 Pa. The airtightness values of the buildings in the database vary by orders of magnitude with minimum and maximum values 0.84 and 19 L/s·m² (0.17 and 3.74 cfm/ft²) at 75 Pa respectively.

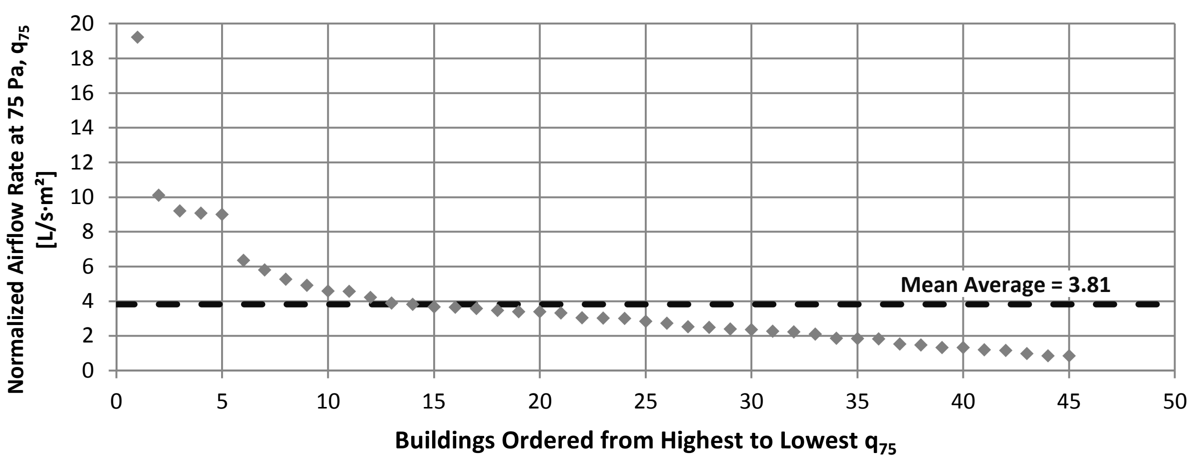


FIGURE 2: Graph of enclosure airtightness of MURBs in the database

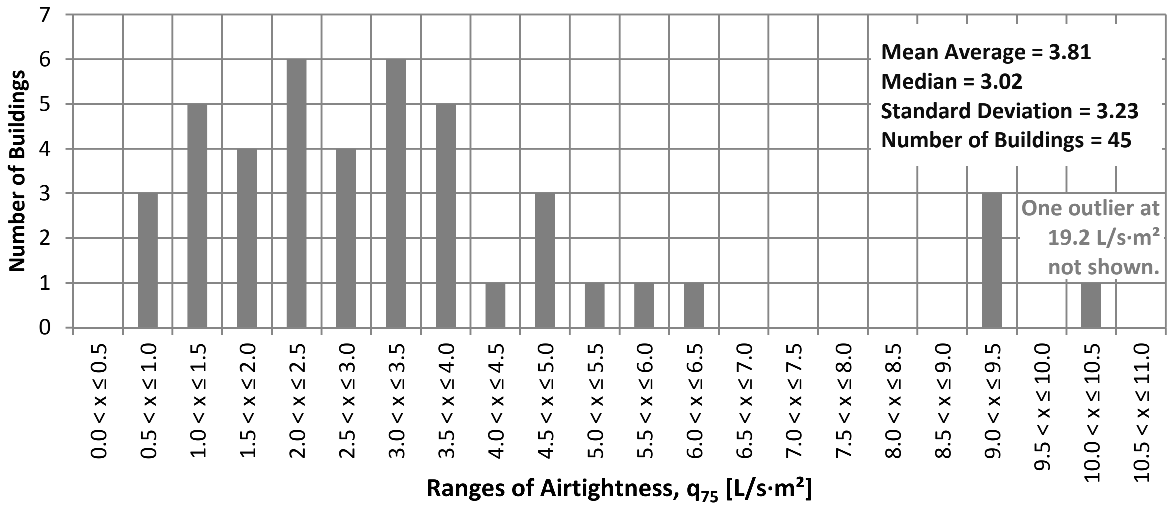


FIGURE 3: Chart showing distribution of enclosure airtightness of MURBs in the database

To evaluate the relationship of the exterior enclosure airtightness values with the date of air barrier construction or modification, the age of the air barrier when tested, and building height, these values were plotted against each other in FIGURE 4, FIGURE 5, and FIGURE 6 respectively.

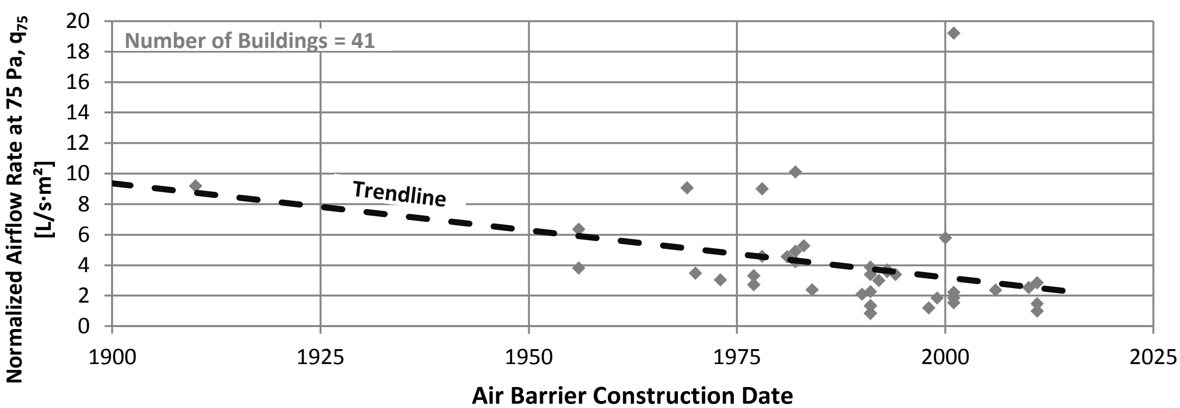


FIGURE 4: Graph of enclosure airtightness versus date of air barrier construction or modification

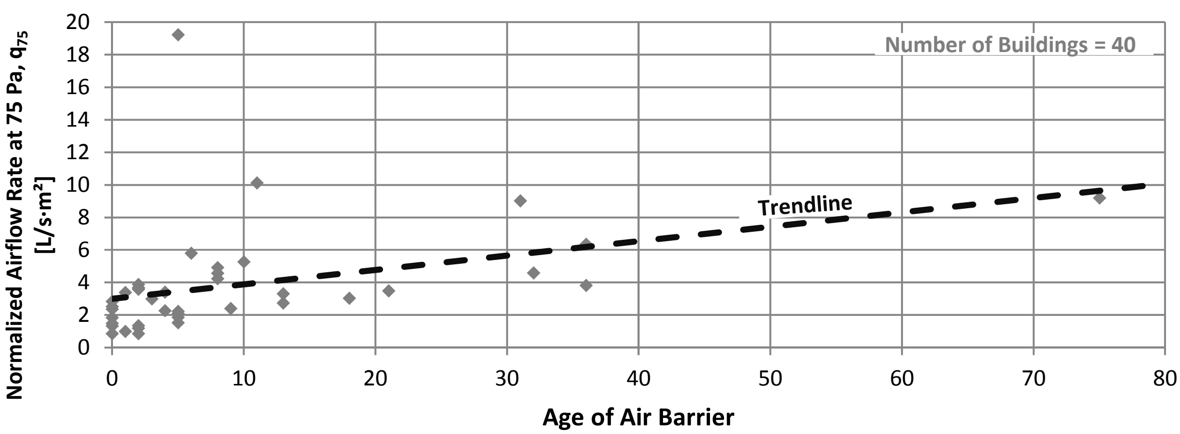


FIGURE 5: Graph of enclosure airtightness versus age of air barrier

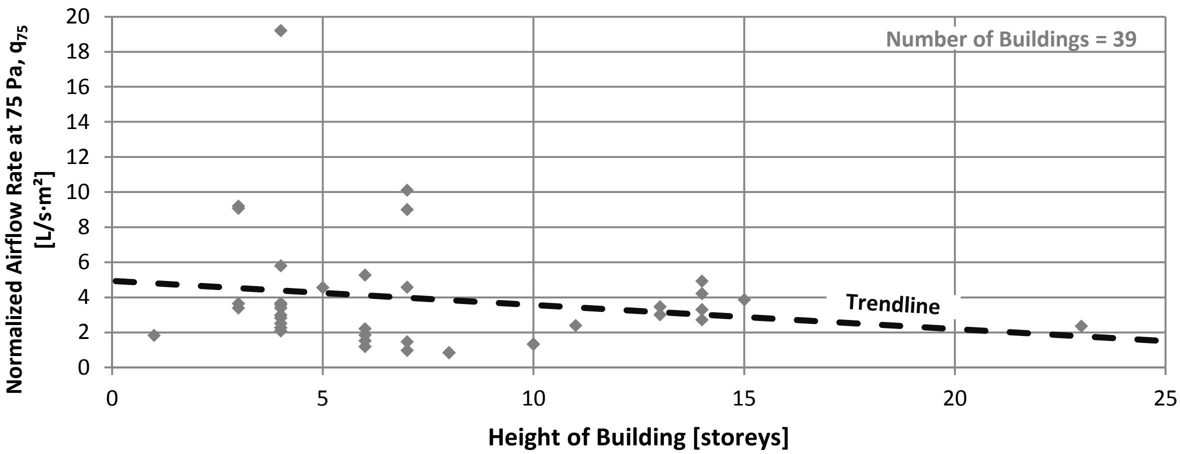


FIGURE 6: Graph of enclosure airtightness versus building height for buildings in the database

Generally, buildings where the air barrier was constructed more recently are more airtight (lower normalized airflow rate) than buildings where the air barrier is older. This finding applies both to overall age and age of the air barrier at testing which indicates that air sealing practices are improving over time, but may also indicate that air barrier systems tend to degrade over time. It should be noted that in many cases the age of the air barrier system is from original construction (i.e. no modifications to the air barrier were made), and consequently, the improved airtightness of younger air barrier systems when tested may not indicate degradation of the air barrier over time, but instead may simply indicate that older air barrier systems were less airtight when they were originally constructed.

A slight trend was found indicating that taller buildings are more airtight than shorter buildings. This may be as a result of typically more robust air barrier systems being used on taller buildings due to the higher wind speeds to which these buildings are often subjected.

For buildings where the flow exponent was found experimentally using multi-point testing, the mean average flow exponent value was found to be 0.63. This is consistent with literature values which suggest that the flow exponent typically ranges from 0.60 to 0.65. (Straube & Burnett, 2005; Orne et al., 1998) The distribution of the flow exponent values for buildings in the database is provided in FIGURE 7.

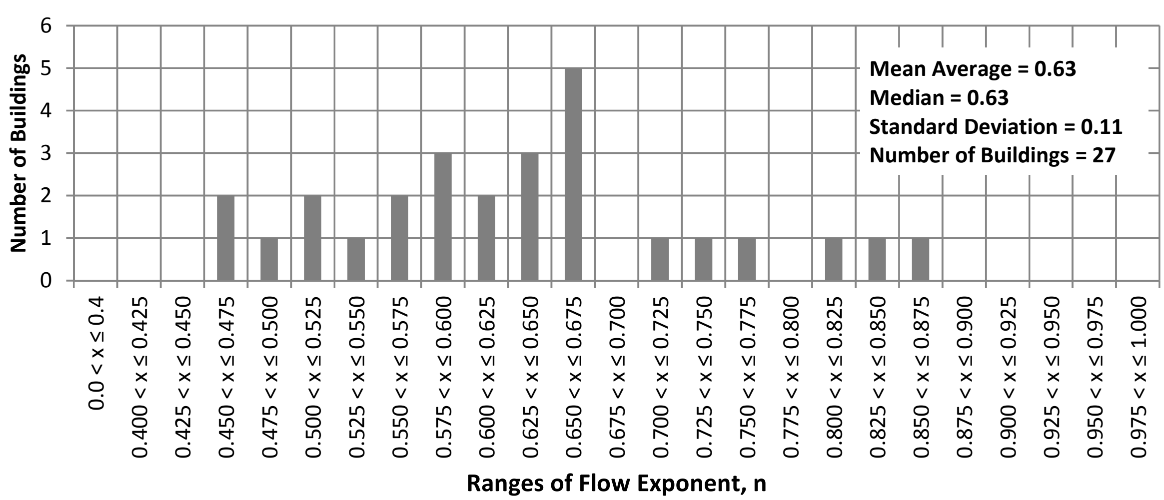


FIGURE 7: Chart showing distribution of flow coefficient values for MURBs in the database

US Army Corps of Engineers Airtightness Testing

A separate section of the airtightness database includes data from 52 USACE barracks type buildings which are similar in form to typical multi-unit residential buildings. USACE buildings are built to meet a target airtightness of 1.27 L/s·m² (0.25 cfm/ft²) at 75 Pa and are tested in accordance with the US Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes (USACE, 2013). These buildings provide a unique opportunity to assess the level of airtightness that is achievable when a performance target and required testing are implemented.

The airtightness of the exterior enclosures of these 52 buildings are graphed in descending order in FIGURE 8, and the distribution of airtightness values is shown in FIGURE 9. These figures show that despite the USACE setting a relatively airtight performance target, the vast majority of buildings were still able to the meet the target and many buildings were significantly more airtight than specified.

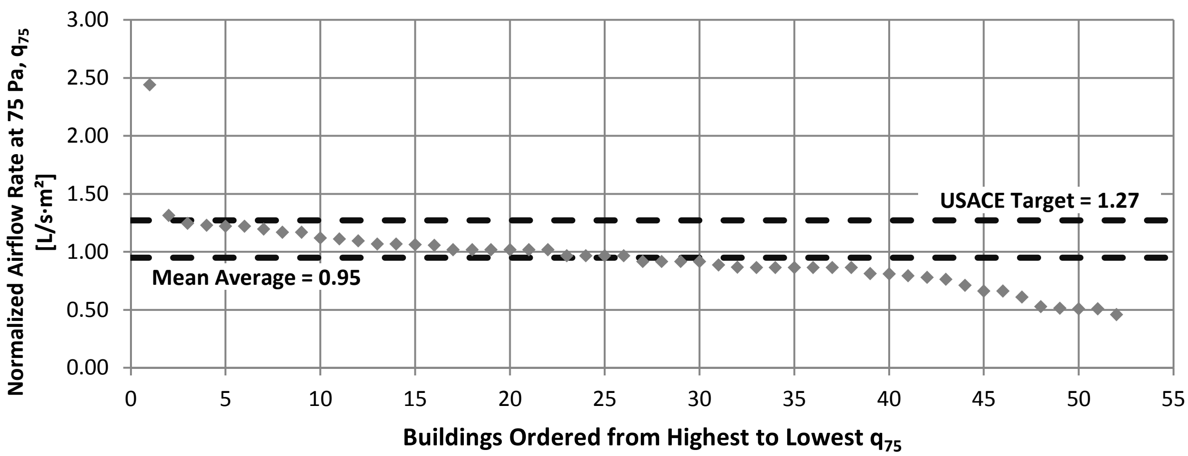


FIGURE 8: Graph of enclosure airtightness of USACE barracks buildings

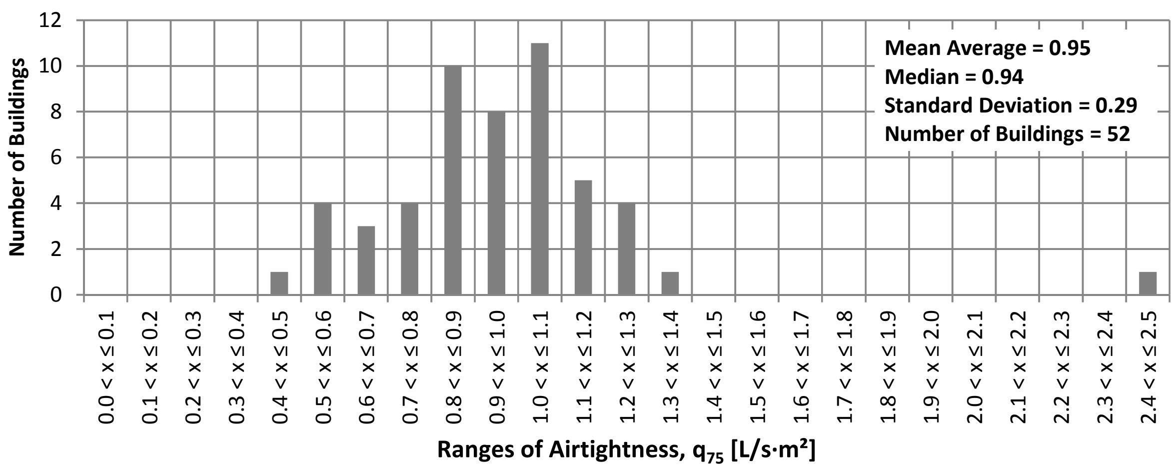
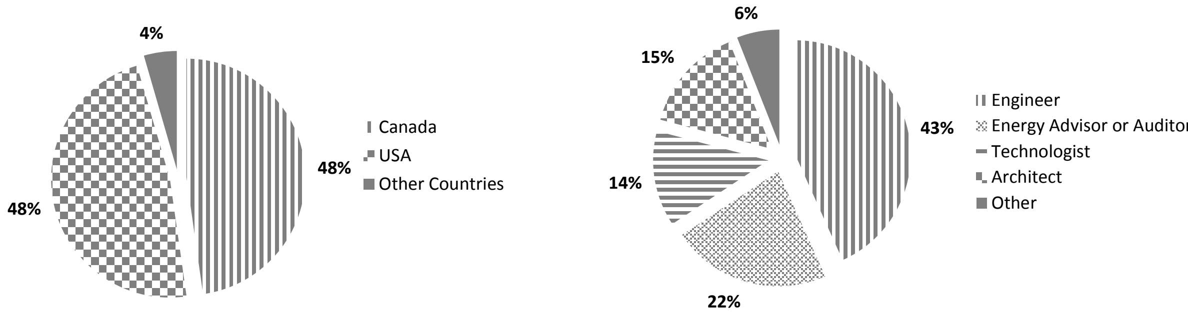


FIGURE 9: Chart showing distribution of enclosure airtightness of USACE barracks buildings

INDUSTRY PERCEPTION AND PREPAREDNESS SURVEY

To gauge the perception and preparedness of the industry with respect to airtightness a survey was distributed to architects, engineers, and others responsible for the design, implementation and testing of air barrier systems in large buildings, with particular attention to MURBs. While effort was made by this research group to reach as broad of a sample group as possible, it is likely that the respondents to this survey provide some bias that would not be present in the industry as a whole. For example, industry members that responded to this survey are likely more involved with airtightness of buildings than is the average industry member because those who are not involved with airtightness are less likely to have responded to the survey. While it is felt that the survey results provide a good indication of the state of the industry, the potential bias such as this should be considered when assessing the results.

Sixty-seven individuals responded to the survey and the distribution of their geographic locations and qualifications are shown in FIGURE 10.



a) Geographical location of respondents **b) Qualifications of respondents**

FIGURE 10: Charts of a) geographical location and b) qualifications of survey respondents

The survey respondents were asked to rank the reasons for which they would address airtightness in buildings. FIGURE 11 shows the percentage of respondents that ranked each response first, second, third, et cetera, with a rank of 1 being most important and a rank of 5 being least important. Note that not all categories total 100% because some respondents chose not to rank all of the options; additionally, it was possible to provide the same rank for multiple responses.

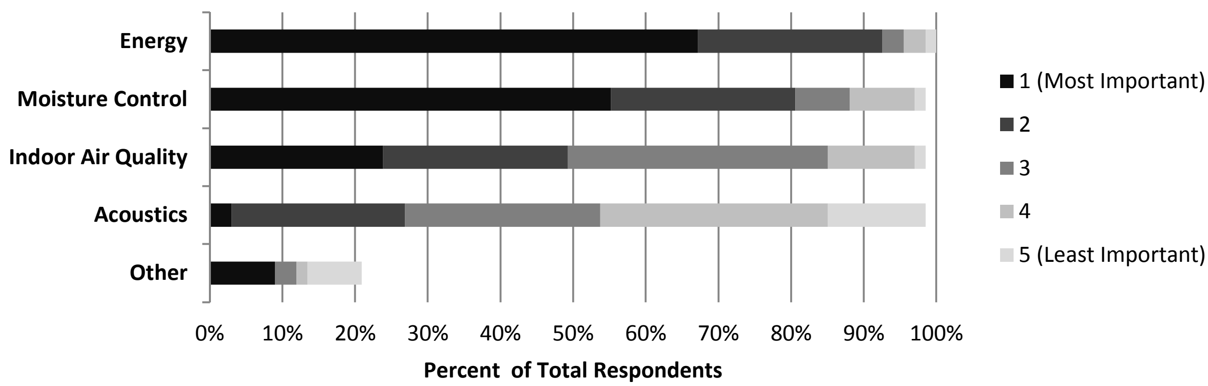


FIGURE 11: Chart showing respondents rankings of why to address airtightness

FIGURE 11 shows that most respondents felt that energy and moisture control were the most important reasons for controlling airtightness.

Nearly 80% of respondents indicated that they felt airtightness testing is necessary for the construction of airtight buildings. FIGURE 12 shows that a majority of respondents felt that both qualitative (i.e. thermographic scans or smoke testing) and quantitative airtightness testing should be implemented in building codes. 68% of respondents felt that quantitative testing is more effective that qualitative testing.

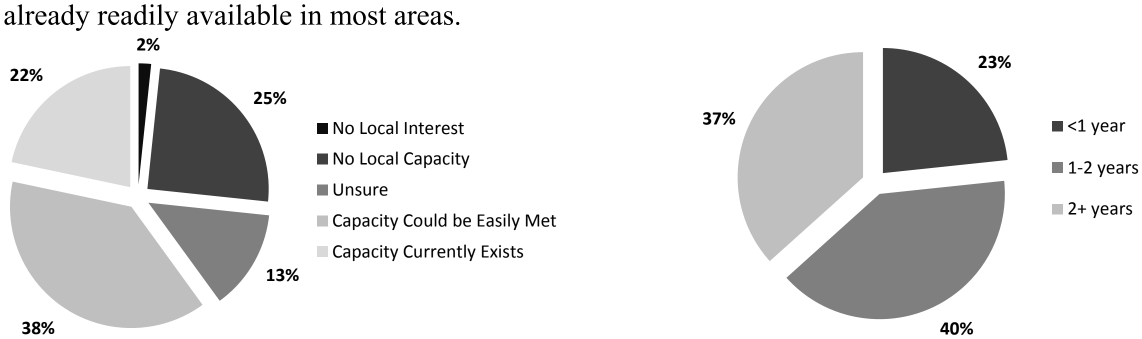
b) **Qualitative**

a) **Quantitative**

FIGURE 12: Charts showing percent of respondents that feel a) quantitative and b) qualitative airtightness testing is necessary for the construction of airtight buildings

Respondents were also asked to indicate what airtightness performance level they felt would be appropriate for implementation in building code. The average performance level is 1.5 $L/s \cdot m^2$ (0.30 cfm/ft^2) at 75 Pa with the range of suggested performance levels mostly falling between 1.25 $L/s \cdot m^2$ and 2.0 $L/s \cdot m^2$ (0.25 cfm/ft^2 and 0.4 cfm/ft^2) at 75 Pa.

Finally, respondents were asked to indicate their perception of industry preparedness to meet a potential code required airtightness performance level and associated airtightness testing. The majority of respondents felt that capacity already exists in their jurisdiction to accommodate potential airtightness requirements, or that capacity could be easily developed. The distribution of responses regarding industry capacity is shown in FIGURE 13 a). FIGURE 13 b) shows that the majority of respondents felt that it would take less than 2 years to develop the necessary industry capacity. Most respondents felt that the most important development activity is training and education for local companies, as testing equipment is already readily available in most areas.



c) **Capacity for Airtightness Testing** d) **Time to Develop Industry Capacity**

FIGURE 13: Charts showing respondents indication of a) industry capacity for airtightness testing and b) the time required for industry to develop the required capacity to accommodate building code airtightness requirements

Overall, the results of the industry survey indicate that generally industry in North America feels that airtightness is important to the performance of multi-unit residential buildings for a variety of reason including primarily energy consumption and moisture control. Furthermore, the survey results indicate that to construct airtight buildings, industry feels that airtightness testing is required and that a performance target should be implemented in building codes. On average the respondents suggest that a target of approximately 1.5 $L/s \cdot m^2$ (0.30 cfm/ft^2) would be appropriate. Finally, the majority of respondents felt that either industry capacity to accommodate an airtightness performance and testing requirement in code either already exists in their area, or that it could be developed within approximately two years.

CONCLUSIONS

To gauge the state of the industry with respect to airtightness testing of MURBs, literature regarding airtightness testing was reviewed, MURB airtightness test results were compiled into a database, and a survey was distributed to industry.

While numerous airtightness test procedures are available for whole building testing, no standardized technique exist for the testing of highly compartmentalized buildings such as MURBs. In many cases pressure neutralized pressurization/depressurization airtightness testing techniques are necessary to measure the exterior enclosure airtightness of MURBs, and a standardized technique should be developed. A standardized method could then be referenced in regulatory requirements and would facilitate the widespread implementation of this test method.

Analysis of the MURB airtightness testing database indicates that currently the airtightness of MURBs is highly variable. Newer MURBs are typically more airtight, and the average airtightness for MURBs in the database is 3.81 L/s·m² (0.75 cfm/ft²) at 75 Pa based on data that was available for 45 buildings. Data was also collected for 52 USACE barracks building which are similar in form to typical MURBs. These buildings were built to meet an airtightness requirement of 1.27 L/s·m² (0.25 cfm/ft²) at 75 Pa and are tested to ensure compliance. These buildings provide a unique opportunity to assess the level of airtightness that is achievable when a performance target and required testing are implemented. Despite this relatively demanding performance requirement, nearly all of the USACE barracks buildings met the requirement, and the average airtightness of these buildings is 0.95 L/s·m² (0.19 cfm/ft²). Furthermore, recent testing in Seattle has indicated that meeting the 2009 Seattle Energy Code requirement of 2.0 L/s·m² (0.4 cfm/ft²) is not prohibitively difficult. (Jones et al., 2014)

The results of the industry survey indicate that generally industry in North America feels that airtightness is important to the performance of multi-unit residential buildings for a variety of reason including primarily energy consumption and moisture control. Furthermore, the survey results indicate that a performance target should be implemented in building codes. A target of approximately 1.5 L/s·m² (0.30 cfm/ft²) was indicated as being appropriate, and the test data from USACE indicates that this target should be achievable. Finally, the majority of respondents felt that industry capacity to accommodate an airtightness performance and testing requirement in code either already exists in their area, or that it could be developed within approximately two years.

Overall, this study found that airtightness is generally held to be an important building performance metric, and has determined the state of the industry to facilitate the implementation of regulated airtightness performance and testing requirements.

ACKNOWLEDGMENTS

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REFERENCES

2009 Seattle Energy Code. Seattle: Seattle Department of Planning and Development, 2010.

Jones, D., Finch, G., Thompson, T., & Brown, B. 2014. Building Enclosure Airtightness Testing in Washington State – Lessons Learned about Air Barrier Systems and Large Buildings Testing Procedures. Proceedings of the ASHRAE 2014 Annual Conference. Seattle: ASHRAE.

Orne, M., Liddament, M., & Wilson, A. (1998). Numerical Data for Air Infiltration & Natural Ventilation Calculations. Coventry: Oscar Faber Group Ltd.

Finch, G., Straube, J, and Genge, C. 2009. Air Leakage within Multi-Unit Residential Buildings: Testing and Implications for Building Performance. Proceedings of the 12th Canadian Conference on Building Science and Technology. Montreal: Quebec Building Envelope Council.

Ricketts, L. 2014. A Field Study of Airflow in a High-rise Multi-unit Residential Building. MASc Thesis at University of Waterloo.

RDH Building Engineering Ltd. 2013. Air Leakage Control in Multi-Unit Residential Buildings – A Market Transformation Roadmap. Ottawa: Canada Mortgage and Housing Corporation.

Straube, J., & Burnett, E. (2005). Building Science for Building Enclosures. Westford: Building Science Press Inc.

USACE. 2009. U.S. Army Corps of Engineers Engineering and Construction Bulletin No. 2009-29.

USACE. 2012. U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes - Version 3. Champaign: U.S Army Corps of Engineers.

Washington State Energy Code - 2009 Edition. Olympia: Washington State Building Code Council, 2011.