Controlling Air Leakage In Tall Buildings

By Colin Genge

For years, people have talked about setting a standard for air leakage in high-rise buildings, but no one has done anything about it—until now. The U.S. Army Corps of Engineers has mandated that all of its buildings have less than 0.25 cfm75/ft^2 (cfm of air leakage per square foot based on a test pressure of 75 Pa). This article outlines how this test is to be conducted and why the detailed testing protocol was established the way it was. This could be the start of a widespread adoption of an air leakage control standard to achieve higher levels of energy conservation, comfort and safety.

Pass/Fail Criteria for Air Leakage

Several groups are trying to assess air leakage control in high-rise buildings for different reasons. The National Fire Protection Association's NFPA92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*, and the International Building Code are concerned about the air leakage of smoke barriers at 12.5 Pa. LEED® apartment testing requires the measurement of the air leakage of interior and exterior surfaces with the results extrapolated to 4 Pa for the purpose of interior pollutant control. Envelope control measures and the *2005 ASHRAE Handbook—Fundamentals* refer to the air leakage at 75 Pa for the purpose of energy conservation and rain penetration testing. To make matters more confusing, different units make it difficult to convert from one standard to another (*Tables 1* and *2*).*

It would be convenient to measure air leakage in all instances with the same procedure, using the same units. A com-

About the Author

Colin Genge is president and CEO at Retrotec Energy Innovations in Vancouver, BC, Canada, and Retrotec Inc., Wash.

Unit Conversions for 0.25 cfm75/ft^2 to Other Common Units for a Building, 120 × 110 × 8 ft, Four Stories ($n = 0.65$)	
Used by ASHRAE and U.S. Army Corps	0.25 cfm/ft^2 at 75 Pa
"Setting Airtightness Standards" ASHRAE Journal, September 2005	0.19 cfm/ft^2 at 50 Pa
Used by U.S. Building Scientists to Calculate Natural Air Exchange in Houses	1.06 in^2 EfLA/100 ft^2 at 4 Pa
Used in Canada and Other Countries	1.98 in^2 EqLA/100 ft^2 at 10 Pa
Used in Finland But Is Compromised in High-Rise Buildings Because Volume to Area Ratios Change So Much	1.12 ACH at 50 Pa
Used in U.K. to Rate Commercial Buildings	3.51 m^3/h·m^2 at 50 Pa
Used by Researchers in U.S., Canada, and Europe	1.27 L/s·m^2 at 75 Pa

***Table 1:** Various unit conversions that appear in the industry.*

Conversions Made for a Building, 120 × 110 × 8 ft, Four Stories ($n = 0.65$)	cfm75/ft^2
ASHRAE Handbook—Fundamentals, Leaky	0.60
Part L or U.K. Building Code Requires 5 m^3/h·m^2 at 50 Pa Normal, Offices and Homes	0.36
NFPA 92A Smoke Control Standard, 0.1 cfm/ft^2 at 0.05 in. w.c.	0.32
ASHRAE Handbook—Fundamentals, Average	0.30
LEED,1.25 in^2 EfLA at 4 Pa/100 ft^2 Envelope	0.30
U.S. Army Corps Standard is 0.25 cfm/ft^2 at 75 Pa	0.25
Part L of U.K. Building Code Requires 3 m^3/h·m^2 at 50 Pa Best Practice, Homes	0.21
Part L of U.K. Building Code Requires 2 m^3/h·m^2 at 50 Pa Best Practice, Offices	0.14
Canadian R-2000 1.0 in^2 EqLA at 10 Pa/100 ft^2 Envelope	0.13
ASHRAE Handbook—Fundamentals, Tight	0.10

***Table 2:** Various definitions of amounts of acceptable air leakage.*

mon pass/fail air leakage criterion could be established for all compartmentation boundaries for energy conservation, smoke control in fires, and pollutant control, so that all three benefits could be achieved simultaneously.

Universal Air Leakage Procedure and Units

Specifications for high-rise building tests often cite ASTM E779-03, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, but it is not suitable for high-rise building testing without modifications. It was originated to test houses where one of the required results was "effective leakage area at 4 Pa." Since ambient pressure fluctuations on a house, due to stack and wind, can be close to 4 Pa, making measurements inaccurate, the standard states that preferred test conditions are "4 mph wind or less and a temperature range of 41°F to 95°F." Since these requirements make testing prohibitively expensive due to the meteorological restrictions, field testing evolved into testing at 50 Pa, which has the advantage of being repeatable.

If the ASTM test needs to be modified for houses, more robust protocol is required for high-rise buildings. As height increases, the pressures on the building due to wind and stack increase in a complex way. As height doubles, the increased pressures experienced due to wind roughly double. As height quadruples, stack pressures double. Combining these two pressures to any existing HVAC imbalance creates a bias pressure experienced by

---

* For the purposes of this article, units are expressed in cfm/ft^2 at 75 Pa, recognizing the units are a mixture of I-P and SI. This was done because units in the industry have evolved to this odd mixture out of convenience, and it is the expected practice.

Measuring Air Leakage

The procedure incorporates the door-fan-pressurization method and is intended to characterize the airtightness of any building enclosure, or part of that enclosure (i.e., wall, floor, and roof). It's intended to be a measure of the entire exterior enclosure leakage, where individual apartments or offices (units) face into an interior hallway. Or, where individual units face the exterior, this procedure is a measure of the individual enclosure's leakage to outdoors and to adjacent units.

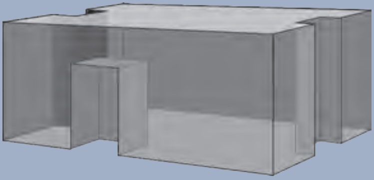
The door fan equipment used in this procedure is also useful in locating air leakage sources by using it in conjunction with visual aids including smoke or infrared.

Any style of door fan equipment may be used for this test, and this test may be performed under any reasonable weather condition, provided that a test pressure of 75 Pa is established, testing can be performed in both directions and the bias pressure does not exceed 15 Pa. If only 50 Pa can be achieved then the maximum bias pressure must not exceed 7.5 Pa. If testing in both directions is not possible, then a test pressure of 75 Pa must be achieved, and the maximum bias pressure must not exceed 5 Pa.

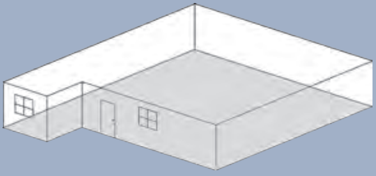
Zones to Be Tested (also see boxes at right). In general, a test should be made of the largest zone where the air barrier is continuous. For buildings where doorways of each apartment lead to a common internal hallway, the building shell must be tested as a whole. Mechanical rooms and laundry rooms that are open to the outdoors, and areas with large overhead doors, should be considered to be outside the enclosure to be tested since the leakage of these components will cause the building to fail. The enclosure must be sealed from the mechanical rooms, loading docks, and laundry room walls inward.

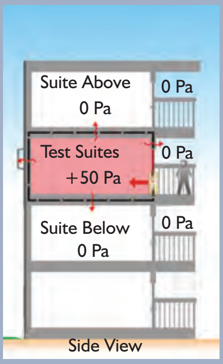
Enclosure Area. The architect or design engineer is responsible for defining the enclosure and for supplying the enclosure area to be used in the results calculation. The enclosure area is an important value because results are directly and inversely proportional to the value used in calculations; if the area doubles, the result in cfm/ft^2 is halved.

Set Up the Building and Record Conditions. Because results are dependent on setup conditions, they must be recorded in detail and photographed to provide a record of exactly what was done so that repeat tests can evaluate the building under the same conditions, or if setup conditions are different, at least different results can be explained. It is important to understand the location of the air barrier, so that openings outside of the air barrier are not sealed. For example, in a ventilated attic space, the vents from this attic space to the outdoors must not be sealed, because they are not part of the air barrier. Sealing these openings will make the building appear tighter than it really is in some cases, and have no effect in other cases.



This four-story building (*photo*) has an enclosure shown at bottom left. It is accessed by an exterior stairway with no direct interior connection between floors and must be tested with four door fans simultaneously (*right figure*) to measure the total enclosure leakage.





In buildings where individual units have doors to the outside (*photo*), the test must be performed on the individual unit (*bottom left*) with the adjacent units open to the outdoors so the leakage of the unit, whether it is to the outdoors or to the adjacent unit, is measured (*right figure*). It is sufficient to perform door fan tests on 20% of these zones. If they all pass, then it can be assumed the rest are acceptable. Should any fail, the number of zones to be tested should be increased.

Uniform Test Pressure. A uniform test pressure must be maintained within the conditioned space to within ±10% of the measured inside/outside pressure difference. Typically, pressures tend to be constant throughout the enclosure, unless large airflows are going from one zone to another through small openings such as doorways. As a rule of thumb,

there must be at least one pressure pickup point per 50,000 ft^2 (4645 m^2) of enclosure area, inside and outside. Exterior pressures must be manifolded and then used by each gauge as its reference pressure. Interior pressures must be measured on each gauge. The readings are recorded and averaged mathematically.

Perform a Single-Point Door Fan Test. The purpose of this step is to get a quick ±25% reading of the building leakage. It is possible that the building is much leakier than the standard and does not warrant an accurate test. In that case, knowing that it fails by a wide margin may be all that is necessary since the test must be repeated. In other cases, the building may fail this single-point test because a door or window or other intentional hole has been accidentally left open. In that case, this is an opportunity to find the problem and set it right before repeating this step.

Perform a 12-Point Door Fan Test, in Both Directions, Starting at +50 Pa to +75 Pa. This test can be performed with bias pressures up to 30% of the lowest test pressure and still deliver acceptable results. When both pressurizing and depressurizing, errors due to large bias pressures cancel out, making this procedure the most accurate way to test.

Perform a 12-Point Door Fan Test in One Direction Starting at +75 Pa. This test can be performed with bias pressures up to 10% of the lowest test pressure and still deliver acceptable results. This option acknowledges that super large buildings may require truck or trailer-mounted equipment that will not easily test in both directions. Because bias pressures will have a greater impact on single-direction tests, the maximum allowable bias pressure under these circumstances is reduced to 5 Pa. However, the test pressure achieved must be 75 Pa. At these pressures, the bias pressure is somewhat masked by the high test pressure, and extrapolation is no longer an issue. Because buildings often leak more in one direction versus the other, testing in only one direction must be considered less accurate.

When setting up the building, seal continuous ventilation inlets, but leave intermittent ventilation open.

the building before any additional test pressures are applied. It is difficult to remove the effect of a bias pressure when applying a test pressure with a door fan apparatus. These bias pressures are created by an unpredictable combination of effects and cannot be subtracted. ASTM E779-03 merely subtracts these bias pressures, which works if they are small when compared to the test pressure. Houses typically experience bias pressures of 2 Pa to 5 Pa whereas larger buildings can experience 10 Pa to 20 Pa. Taking results at higher pressures helps achieve a more consistent result.

A practical limit to the test pressure is about 75 Pa because above that test pressure, door fan power must be substantially increased, and the risk of damage due to higher test fan wind velocities, and test pressures, increases. A test pressure of 75 Pa is about the maximum pressure that a well-built suspended ceiling can withstand without tearing it down during depressurization or blowing the tiles out while pressurizing.

Recommended adjustments to the ASTM standard to achieve meaningful and repeatable results on high-rise buildings are as follows:

Test Procedure 1. Test in both directions from 50 Pa to 25 Pa to neutralize the effect of bias pressure and to cancel out temperature and barometric effects. Maximum bias pressure must not exceed 30% of the test pressure.

Test Procedure 2. Test in one direction from a higher starting pressure of +75 Pa to 50 Pa. Since the test is in one direction only, bias pressure must be recorded and additional corrections must be made for temperature and barometric pressure. Maximum bias pressure must not exceed 10% of the test pressure.

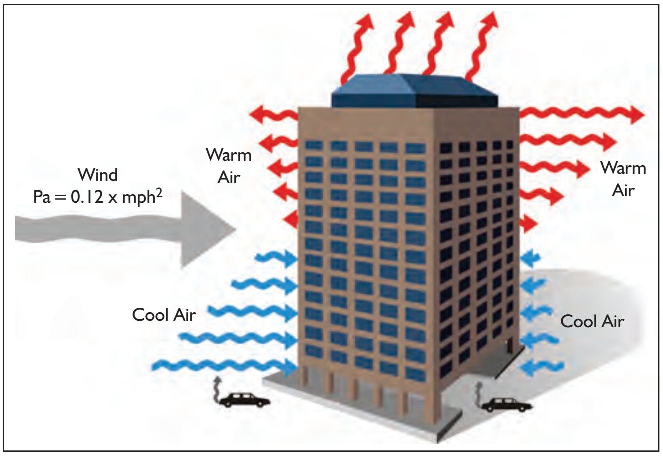


Figure 1: Driving forces on air leakage control.

Both of these procedures will achieve approximately the same accuracy but Test Procedure 1 requires less fan power and causes less air velocity disturbance in the building and can be performed in a wider range of weather conditions.

High-rise building test results have focused on airflow at 75 Pa, which is the lowest reference pressure that yields stable results. Reporting airflow in cfm at 75 Pa per square

Test Direction With and Without Correction For Bias Pressure	Test Pressure Range	No Wind cfm75		Windy cfm75	
		Deviation	Error Range	Deviation	Error Range
Depressurize With Bias	–60 to –12.5 Pa	2%	–2.5% to +1.5%	17%	–24% to –10%
Depressurize With Bias	–50 to –25 Pa	2%	–2.5% to +1.5%	10%	–13% to –6%
Depressurize With Bias	–75 to –50 Pa	1.4%	–2% to +0.5%	5.3%	–7% to –3%
Both Directions With Bias	±75 to ±50 Pa	1.1%	–1.1% to +1.5%	4.9%	–6% to –3%
Both Directions Without Bias	±75 to ±50 Pa	1.5%	–1.8% to +1.5%	3%	–6% to –1%
Both Directions Without Bias	±50 to ±25 Pa	1.5%	–1.8% to +1.9%	4.9%	–8% to –3%

Table 3: Error and deviations resulting from adjusting for bias pressure, test pressure range, and testing in one or both directions.

Observing Test Pressures

Static pressures in high-rise buildings are commonly above 12.5 Pa, which makes obtaining results at 12.5 Pa difficult, if not impossible. *Table 3* indicates the average error that can be expected when testing a high-rise under a range of weather conditions, but stopping well short of storm conditions.

Bias pressure is the pressure created by wind and stack pressures, averaged over 30 seconds, that is measured with all HVAC equipment shut down.

Observations

- Under windy conditions, the classic ASTM test procedure—measuring the before and after bias pressure and only testing in one direction from 60 to 12.5 Pa—produced the most unacceptable results. Variations in flow readings from one minute to the next, even with time averaging in place, varied as much as 25% for one reading. Conclusion: The classic ASTM set of test points from 60 to 12.5 Pa was unacceptable under windy conditions.
- If testing was to be completed in only one direction, reasonable results could be achieved by measuring the before and after bias pressures and testing at higher test pressures, from 75 to 50 Pa. Conclusion: The preferred test method is to test in both directions, from 75 to 50 Pa, and to disregard bias pressures.
- Testing in both directions and averaging the results always yielded results with less deviation than only testing in one direction. Conclusion: If testing in both directions is not possible, then it is preferable to measure the bias pressure before and after the test, and to test from 75 to 50 Pa.
- The best results were obtained from testing in both directions without taking the bias pressure into account. It was observed that any bias pressure reading before and/or after the test was peculiar to that small time period only. When bias pressures were remeasured they would be different causing all results to be corrected differently. Testing in both directions and averaging the results tend to cause the bias pressure effects to cancel out. Conclusion: If establishing 75 Pa in both directions is not possible, then testing in both directions from at least 50 Pa down to 25 Pa should be very similar.

When testing in both directions, the effects of bias pressures tend to cancel out, and better results are achieved by not attempting to measure and correct for them. The ASTM method of subtraction of bias pressures from test pressures introduces large errors. The ideal ASTM approach would be to require bias pressures to be so low that there would be little or no effect. That approach, however, is not practical because it makes test scheduling extremely difficult and waiting for perfect conditions is costly. Measuring the bias pressures before and after the test, averaging them, and then subtracting that average from each test pressure (per ASTM), is a poor solution. The true test pressure is then just a guess, because there is no way of knowing what the bias pressure was at the time a particular test point was taken. The bias pressure before, after, or the average of both, is no indication of what the bias pressure is at any given point in time and adds virtually no value.

The effect of temperature, barometric, and elevation corrections are all small. One might be fooled into thinking that because a standard takes these particular small corrections into account, it is more accurate—it is not. In this type of testing, the overriding source of accuracy and repeatability is due to bias pressure.

Practical Applications for Testing

By Graham Finch

Airtight buildings place higher demands on mechanical systems and place a higher demand on the mechanical ventilation systems to perform in service. Unintended air leakage, either through the enclosure or through interior partitions (between adjacent suites and common areas), can have serious ramifications on the in-service mechanical system performance.

The interaction between enclosure airtightness and mechanical system performance is an important consideration when rehabilitating the building enclosure of existing buildings. In older buildings, relatively high levels of air leakage typically have been allowed through and around window and wall assemblies, resulting in passive ventilation. As a result of those construction practices, mechanical designers could safely assume that a significant portion of a building's overall ventilation requirements would take care of itself.

When an older building needs rehabilitation to reduce water infiltration and repair damage to underlying wall components, modern wall assemblies are typically constructed more airtight. The existing windows often are replaced with higher performance air and watertight windows and sealant is used around all penetrations and joints, resulting in a tighter exterior enclosure.

Air leakage testing of rehabilitated residential buildings, using the methods described in this article, typically find that the exterior enclosure air leakage has been reduced so significantly that the relative percentage of intersuite stale air leakage becomes a factor in the mechanical system performance. In typical residential construction this results in drawing in "fresh" air from adjacent suites instead of the outdoors (when exhaust-only systems are used).

In several buildings where the building enclosure was rehabilitated, this has resulted in indoor relative humidity and air-quality issues, which did not exist before. As part of any building enclosure rehabilitation program, the HVAC system should be checked to confirm it will still function adequately once the new airtight cladding and glazing assemblies are installed. As part of this process the air leakage of the exterior enclosure and relative airtightness of adjacent suites can be measured using the methodology described here. With this information, airtightness can be improved between suites where needed, and ventilation systems can be properly designed and commissioned.

Graham Finch is a building science research engineer with RDH Building Engineering in Vancouver, BC, Canada.

foot of envelope (cfm75/ft^2) would be an ideal universal air leakage unit to apply to all high-rise building testing for the purpose of testing the quality of construction. It is recognized that results expressed at around 10 Pa are more suitable for calculating air leakage losses, but that is not the purpose of this proposed universal air leakage unit. The endgame for high-rise buildings is to eventually make their leakage so low that it becomes a minor contributor to overall building energy loss, and can essentially be ignored in load calculations. To get builders involved in reducing air leakage losses, these tests must be simple and repeatable.

Universal Pass/Fail Criteria for Air Leakage

The U.S. Army Corps of Engineers has adopted 0.25 cfm75/ft^2 for all new buildings and for all major renovations. It must be measured using Test Procedure 1 or 2. Intermittent exhaust must be left open and continuous ventilation openings sealed. Its criterion applies to the total exposed enclosure.

The U.S. Army Corps' commitment should be recognized as a great starting point. The next logical step is to require that each compartment of a building pass the same criterion. Each apartment, stairwell, shaft or hallway could easily be tested to ensure that compartmentation extends throughout the structure. Next, interstitial floor slabs could be isolated by pressurizing floors above and below a slab to ensure there is a smoke- and stack-effect seal between floors. This type of compartmentation provides a building that contains energy within the exterior enclosure, and also stops stack pressures at each floor, stops wind driven infiltration across vertical boundaries, and stops HVAC imbalances from drawing in polluted air from parking garages, garbage chutes and neighbors.

In the future, new buildings could be designed to have no more than 0.10 cfm75/ft^2 for all surfaces and 0.01 cfm75/ft^2 for all internal floor slabs. This would make the accidental ingress and egress of outdoor air so low that this type of loss could be considered to be near zero for design purposes, and the mechanical systems would then be called upon to supply all the needed fresh air. These airtightness levels can be found in the best of existing buildings,[1] where no special efforts were undertaken to create a tight building. This suggests that good quality design and construction, with testing, is all that is needed to accomplish these tightness levels.

Achieving Low Air Leakage Levels

For existing buildings, an air leakage diagnosis starts with interviews to uncover comfort or energy complaints. This is followed up by an inspection of the envelope and mechanical systems. The envelope can be door-fan tested to measure the existing leakage. If the entire building is not available, building sections or even one apartment can be tested to quantify the existing air leakage levels. Interior walls may be neutralized

Advertisement formerly in this space.

Building Science Perspective

By Lee Durston

The U.S. Army Corps of Engineers has adopted an airtightness level of performance into its requirements for new building and renovation work to reduce energy use and provide for an all-around better building enclosure. They are requiring building commissioning to include air barrier testing that show building envelope leakage rates of no more than 0.25 cfm/ft^2 of building envelope, when tested at 75 Pa.

Unfortunately, failure rates of air barriers systems are high when actual performance testing is carried out, and systems evaluated. It was quickly realized that the typical design and construction methods, implemented prior to this requirement, must include the design, installation and testing of an effective continuous air barrier system. To prevent failure, it is necessary to implement into the design/build process an education program for the design and construction teams, advising them of the pitfalls of the continuous air barrier component in the design/build process. If continuous air barrier requirements are not addressed in the design phase, and properly tested in the commissioning phase, the success rates of building envelopes meeting the air leakage specifications are low.

With the complex nature of building types being developed, a knowledgeable consultant team must provide predesign, design, preconstruction consulting, as well as observation during construction, pretest visits, airtightness testing, air leakage investigation, and consulting on effective remedial works should the building fail to achieve the required standard. Consultants should have experience that includes a comprehensive database of "best practice" guidance documents, including details and specifications that provide practical advice for builders, architects, developers and building owners.

Peer review of the proposed construction methods and materials should be undertaken by analyzing drawings and specifications and providing feedback where warranted. Site visits should be undertaken to observe construction quality and detailing, and to confirm that an effective airtight barrier is being provided. Airtightness tests can be preceded by the issuing of a pretest inspection list. In the event of a failed performance verification test, a forensic building science consultant should be hired to use infrared thermography, smoke testing, and invasive measures to best understand the failed airflow pathways before moving towards remedial actions.

Lee Durston is the director of the Building Science Group for BCRA Inc., in Tacoma, Wash.

with additional door fans to isolate one section of envelope for analysis. A subjective estimation of the air leakage reduction can be made, along with a subjective analysis of the effects that reduction may have on ventilation rates.

Airtightness for a new building starts with a good design. Leakage rates of wall sections, windows and doors are important, but most problems occur where walls or floors meet. This detailing is most important. When the air leakage target is set, the ventilation system can be designed to match the load. Consider that the envelope may not supply much accidental ventilation or exhaust, and if possible, specify a balanced ventilation system for each unit.

Unless the building is fitted with windows that cannot be opened, assume that windows will be open, and place more emphasis on the internal barriers to airflow: the partition walls, hallway walls, floor slabs, elevator shafts, elevator hoist rooms, elevator lobbies, stairwells, chases, and garbage chutes. Many of these features can be door-fan tested separately to discover what parts of the building are responsible for the largest portions of air leakage.

Timely measurement and sealing is essential while the building is under construction to ensure that airtightness detailing is accomplished at the right stages. Methods may be altered early in the process to ensure that problems are not repeated. This may be done best by companies or community action agencies with air leakage testing and air sealing experience. Witnessing compliance with the air leakage specification is the responsibility of the mechanical engineer.

Builders can constantly monitor results for any completed section with easy to use door fan equipment that gives them the results they need.

Sealing Air Leakage Sites

Spray foam and a sprayable water-based elastomeric fire-rated rubber coating are the two most effective ways to seal the vast expanses that must be made tight in high-rise buildings. Several makes of rubber provide a fire rating but must be sprayed over a backing of rock-wool or foam. The advantage of both is that they move with the building and adhere well to dusty, irregular, surfaces. An essential element of air sealing is using a door-fan air leakage measurement device that provides instantaneous feedback for installers as work progresses.

In some cases, effective air sealing can only be accomplished when the schedules of construction are taken into account. It is not possible to come in after drywall installers are finished to attempt to air seal. The air sealing must be done as they proceed since successive steps often cover up the opportunity to create effective seals in key locations.

Conclusion

It is essential to begin fixing existing buildings and designing high performance new buildings now. It is unnecessary to

wait for all the groups to establish specifications, when we can, with a marginal increase in cost, produce buildings where air leakage is properly controlled. Builders may fear the unknown costs of this type of specification, making their training key to getting this work done. Many of the top architectural firms are capable of providing this type of training.

Air leakage control to 0.30 cfm75/ft^2 is often achieved in buildings where no special effort was made to make the building tight, and should be considered as a minimum for all buildings. With better design details, 0.1 cfm75/ft^2 is easily achievable, and should be the level expected by 2010.

References

1. Finch, G. 2007. "The Performance of Rainscreen Walls in Coastal British Columbia," Chapter 7, "Air Leakage Testing of Multiunit Residential Buildings in Vancouver, BC," (master's thesis, Department of Civil Engineering, University of Waterloo).

Bibliography

Finch, G., C. Genge, J. Straube. 2009. Air leakage within multi-unit residential buildings—Testing and implications for building performance. To be published in the *Proceedings from the 12th Canadian Conference on Building Science and Technology*.

Genge, C. 2008. "Airtightness Specification Guide for U.S. Army Corps Buildings." U.S. Army Corps of Engineers Workshop on Mold Control and Energy Use Reduction in Army Barracks. http://retrotec.com/file_drop.php.

Genge, C. 2003. "Measuring smoke and toxic gas pathways in tall buildings." *Proceedings of the CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre.*

Genge, C. 2008. "Technical Background for Airtightness Testing U.S. Army Corps Buildings." U.S. Army Corps of Engineers Workshop on Mold Control and Energy Use Reduction in Army Barracks. http://retrotec.com/file_drop.php.

Genge, C. 2008. "Test Form Guide for Airtightness Testing U.S. Army Corp Buildings." U.S. Army Corps of Engineers Workshop on Mold Control and Energy Use Reduction in Army Barracks. http://retrotec.com/file_drop.php.

Hubbs, B., R. Bombino. 2005. "Integration of occupant lifestyle, building enclosure, architectural and HVAC design on the performance of exterior walls in multi-unit residential buildings." *Proceedings from 10th Canadian Conference on Building Science and Technology.* ●