AIR LEAKAGE: DIFFICULTIES IN MEASUREMENT, QUANTIFICATION AND ENERGY SIMULATION

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ABSTRACT

Air leakage through the building enclosure can have a significant impact on heating and cooling loads. Unfortunately, the measurement of air leakage through enclosure systems and components can be very difficult in practice. Inaccurate quantification of air leakage can affect building performance and may lead to incorrectly-sized mechanical systems and unreliable results from whole building energy simulations used during design. The relative impact of air leakage on energy use can negate the benefits of other enclosure systems (e.g. thermal resistance and glazing solar heat gain) predicted by an energy model. Therefore, for high performance buildings, the accurate prediction and measurement of air leakage is more important than for traditional construction.

This paper examines the difficulties of measuring air leakage through building enclosures on components, assemblies, systems, and whole-buildings. The authors discuss commonly specified air leakage criteria and testing requirements from a practical standpoint based on both theoretical and field testing experience. Energy simulation software is used to demonstrate the effect of air leakage on building energy use. The impact of inaccurate air leakage input values are compared to the predicted performance improvement attributed to common energy efficiency measures associated with the building enclosure (e.g. increased thermal insulation and glazing systems with reduced solar transmission). Readers will gain an understanding of both the need for, and difficulty of, air leakage testing in buildings. This understanding is fundamental to more accurately predicting building energy usage, evaluating material and component options, and designing more effective building enclosure systems for both new and remedial construction projects.

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INTRODUCTION

Although a part of the National Building Code of Canada since 1986, air barrier requirements are still in their infancy throughout much of the United States. Since Massachusetts added requirements for a continuous air barrier to their energy code in 2001, air barriers have been gaining popularity among design professionals and gradually making their way into a few other codes and design guides. However, as with most new technologies, much of the promotion of air barriers has taken place without a firm understanding of the benefits and limitations of air barrier systems in buildings.

The effectiveness of air barrier systems can be directly measured through field and laboratory testing, both of which are often included in building enclosure specifications. Measurements can be used both to verify the airtightness of an installation and to quantify air leakage for the purpose of calculating the heat losses and gains associated with uncontrolled airflow into and out of a building. As the thermal resistance of building enclosures improves, the relative contribution of air leakage to building energy use increases, particularly in heating-dominated climates. This effect makes air leakage control a top priority in high performance buildings. Reliable, accurate values for air leakage are required to create more realistic projections of building energy use, both for determining potential operating costs/savings and properly sizing mechanical systems.

AIR BARRIER SYSTEMS

The basic function of an air barrier system is to restrict air leakage through the building enclosure. To this end, an air barrier must be a complete system of materials and components that work together to provide a continuous barrier to airflow. Due to the nature of airflow, even small discontinuities in an air barrier can significantly reduce its performance. An air barrier system must resist the air pressure differential across it. As such, they are required to be structural and to withstand pressures caused by wind, stack effect, or mechanical pressurization of a building.

Unfortunately, the system approach is not widely understood and designers often expect the performance of an air barrier system when only specifying an air barrier material, such as a self-adhered or spray-applied membrane or spray-applied foam insulation. However, a continuous air barrier system or assembly can be composed of air barrier materials joined together at the interior or exterior surface of or within a building enclosure. The following definitions are presented to establish the difference between materials and systems/assemblies:

- An air barrier material is a single component of the building enclosure with a specific resistance to air leakage when tested by itself, without joints or seams. Examples include self-adhered and spray-applied membranes, spray-applied foam insulation, and gypsum wallboard. Measurement of air leakage through materials is described in ASTM E2178 - Standard Test Method for Air Permeance of Building Materials.

- An air barrier system/assembly is a collection of air barrier materials integrated together within the building enclosure. A typical example is an enclosure with self-adhered membrane containing seams and penetrations in opaque areas and transitions to glazing assemblies and other materials (e.g. roof-to-wall transitions). Measurement of air leakage through systems/assemblies is described in ASTM E2357 - Standard Test Method for Determining Air Leakage of Air Barrier Assemblies.

Regardless of the approach, air barriers are frequently applied to sheathing and other solid substrates to allow them to resist structural loads such as wind gust and pressure changes.

A common stumbling block to many designers has been determining the difference between air barriers and vapor retarders. This is made more difficult by the fact that many air barriers are also vapor retarders, such as the ubiquitous "peel-and-stick" membranes that are used in some way, shape, or form on nearly all new construction projects. The danger in confusing these two systems is that the proper location for a vapor retarder is dependent on both the interior and exterior climates, while an air barrier can be located anywhere within the building enclosure as long as it is continuous. Improper selection of either barrier can lead to moisture related problems within the building enclosure; however, this issue is outside the scope of this paper.

AIR BARRIER PERFORMANCE CRITERIA

Perhaps the most difficult aspect of air barrier design is determining what levels of air leakage are acceptable and expected. Established performance criteria exist for nearly all parts of the building enclosure, such as windows and doors, curtain walls, and roof systems, making it easy for designers to select performance criteria based on the local conditions at the building and to provide realistic, verifiable values for criteria such as deflection limits and allowable water leakage. This is the result of extensive efforts by designers, testing laboratories, and industry organizations (such as ASTM International and AAMA). Over the course of several decades, unrealistic or unverifiable performance criteria such as "windows shall not leak under any conditions" have gradually been replaced by criteria such as "windows shall not experience water leakage at a test pressure of 263 Pa (5.5 pounds per square foot, psf) when tested according to ASTM Standard E1105".

Although performance criteria for air barrier materials are relatively well established, problems with air barrier systems rarely develop as a result of air leakage through the field of an air barrier sheet or membrane, except at through fasteners (e.g. those used to secure masonry ties) or similar penetrations. Further, air barrier products such as spray-applied or self-adhered membranes often have leakage rates that are orders of magnitude lower than the generally accepted criteria of 0.02 $L/s{\cdot}m^2$ at 75 Pa (0.004 cfm/sf at 0.3 in. water) for air barrier materials (Canada 2005; Massachusetts 2008), making leakage through the field of the barrier much less likely. Therefore, the air permeance of the primary air barrier material(s) will typically have little to do with the overall air leakage through a building.

The Air Barrier Association of America (ABAA) recommends a maximum air leakage rate of 0.2 $L/s{\cdot}m^2$ at 75 Pa (0.04 cfm/sf at 0.3 in. water) for air barrier assemblies, which takes into account seams and penetrations of the material. The 2005 National Building Code of Canada recommends (but does not require) a slightly more stringent 0.1 $L/s{\cdot}m^2$ at 75 Pa (0.02 cfm/sf at 0.3 in. water) for buildings that maintain interior relative humidity levels between 27 and 55% -- typical of most buildings with the exception of cold storage facilities and natatoriums. Using the less stringent assembly value to calculate the approximately leakage through a 9.3 m^2 (100 sf) wall area yields an air leakage rate of 1.89 L/s (4 cfm), 10 times greater than if the material value were used. Since even the simplest systems will still have laps and penetrations, such as brick ties or other cladding attachments, using the material value as an indicator or predictor of overall performance is not realistic.

Windows, doors, and curtain walls (i.e., fenestration) and the transitions from these assemblies to opaque wall areas, are often not considered by designers when establishing air barrier system performance. This is a significant oversight as the majority of air leakage through a properly designed air barrier system often occurs through these components and, especially, the transition areas. Established values for air leakage through fenestration range from 0.3 $L/s{\cdot}m^2$ at 300 Pa (0.06 cfm/sf at 1.2 in. of water) for glazed curtain walls to 2 $L/s{\cdot}m^2$ at 300 Pa (0.4 cfm/sf at 1.2 in. of water) for operable windows, and can depend significantly on the standard referenced. Maximum air leakage rates are included in most building energy codes as well as industry standards from organizations such as ASHRAE and AAMA. Of some confusion to designers is the rapidly changing nature of many of these values as the various codes and standards attempt to reach a consensus. Air leakage values for air barrier assemblies account for seams and small penetrations, but do not account for large components such as windows or doors. Although the test procedures for air barrier assemblies include the air barrier connections at windows, the window opening is “blanked off” during the test so that only the perimeter is evaluated.

To account for the wide range of systems, details, and transitions in the air barrier of any particular building, it is more useful to speak in terms of whole envelope air leakage than material, assembly, or component leakage. This is especially true for the purpose of energy simulation or HVAC load calculation, where the global quantity of air leakage is the primary concern (as opposed to leakage through specific components). These values are typically reported as the average volumetric flow rate of air through a square unit of the entire air barrier surface (typically the same as the building surface area). Unfortunately, there are very few established standards for whole-building air leakage that designers can reference. The 2009 ASHRAE Handbook of Fundamentals, Chapter 16 (Ventilation and Infiltration) provides three “levels” of air leakage for typical buildings. These are 0.5 $L/s{\cdot}m^2$ (liters per second air leakage per square meter of exterior envelope area) at 75 Pa (0.1 cfm/sf at 0.3 in. water) interior/exterior pressure differential for “tight” buildings, 1.5 $L/s{\cdot}m^2$ at 75 Pa (0.3 cfm/sf) for “average” buildings, and 3 $L/s{\cdot}m^2$ at 75 Pa (0.6 cfm/sf) for “leaky” buildings. These general classes of air leakage were first presented in the results of a study of 8 commercial buildings in Canada, ranging in height from 11-22 stories, and clad with glazed aluminum curtain walls (Tamura and Shaw, 1976). These values are frequently cited when discussing whole-building air leakage despite being based on a small sample size and very specific building type. A more recent study (Emmerich and Persily, 2005) of approximately 200 low rise commercial and institutional buildings in the United States found an overall average leakage rate of 7.75 $L/s{\cdot}m^2$ at 75 Pa (1.55 cfm/sf at 0.3 in. water) – significantly higher than even the “leaky” value of 3 $L/s{\cdot}m^2$. Unfortunately, neither study contains any information on whether or not the design intent for the buildings included continuous air barriers. Considering this limitation, the average value of 7.75 $L/s{\cdot}m^2$ from the 2005 study could be seen as a reasonable expected maximum value for building air leakage, as a new building with a dedicated, continuous air barrier should provide greatly improved performance. That is not to say that buildings cannot or should not be designed to provide significantly better air leakage performance.

In 2006, the United Kingdom added criteria for whole building air leakage to their “Building Regulations” for commercial buildings greater than 500 m^2 (5380 sf) total floor area. The established value, which must also be verified through whole-building testing, is 2.74 $L/s \cdot m^2$ at 50 Pa (0.547 cfm/sf at 0.2 in. of water). Initial findings in the UK (Potter, 2007) have shown that more standardized building types, such as warehouses and large retail stores, have typically been able to meet this requirement, but buildings such as offices, schools, and hospitals, which are often of more unique design and have more transitions among envelope assemblies, often fail to meet the established leakage rate. This is indicative of designers not fully appreciating or understanding the need for air barrier detailing (i.e., air barriers require little detailing in standardized construction but are more difficulty to design for unique/custom building types).Given the results of recent studies in the United States, the average commercial building allows significantly more air leakage than this requirement; however, better performing buildings are possible and have been built (Emmerich and Persily, 2005). Although not a code-mandated value, ABAA currently recommends a maximum building air leakage rate of 2 $L/s \cdot m^2$ at 75 Pa (0.4 cfm/sf at 0.3 in. of water).

TEST PROCEDURES

Due to the relatively high sensitivity of air barrier systems to both design and workmanship quality, physical testing of air barrier systems is often the only way to verify an installation. For air barrier systems, the sensitivity to workmanship (sealing laps, making transitions, etc.) and potentially large impact on building energy use make in-place performance testing an important part of the construction process for buildings with continuous air barriers and for evaluating modifications to existing building enclosures. In addition to quantitative procedures, numerous qualitative measures exist to identify paths of air leakage; however, they are not the focus of this paper.

Quantitative air leakage testing involves the measurement of airflow through a given material, component, assembly, or whole building enclosure. For the purposes of this paper, laboratory testing is not reviewed in depth; examples below are for field testing/verification (although the general test procedures are similar to those used in laboratory testing). Further, testing of air barrier materials (by themselves) is not discussed, as this type of test is similar to the testing described below but rarely, if ever, performed in the field as performance values are often available for dedicated air barrier materials. For components and assemblies, testing typically involves the creation of a relatively airtight test chamber on one side of the specimen which is then pressurized or depressurized (Photo 1). A flow measuring device is attached to the chamber to measure airflow (Photo 2) and a pressure gage is used to determine the differential pressure across the specimen. Temperature and relative humidity measurements are also taken for use in calculating airflow and applying correction factors to readings from the flow measurement device.

Photo 1 – Test chamber on window specimen

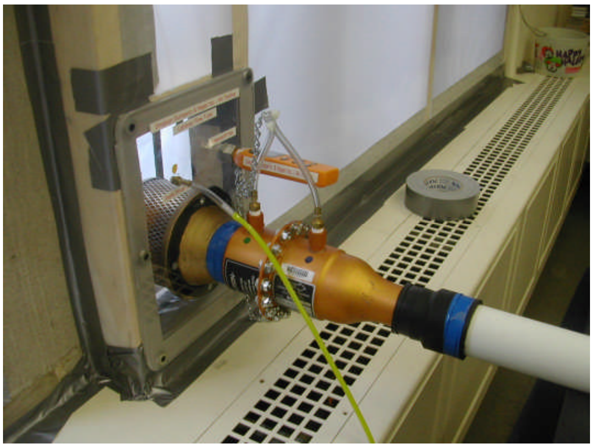

Photo 2 – Laminar flow element, pressure gage, and digital temperature/relative humidity meter installed in test chamber

The measured airflow in this arrangement is a combination of flow through the specimen and flow through the test chamber. To discern between the two, it is necessary to identify leakage through the chamber itself by sealing off the specimen during the initial test (Photo 3).

Photo 3 – Window from Photo 1 sealed on exterior for chamber air leakage measurement

A second set of measurements is taken with the exterior of the specimen unsealed, and the difference between the two tests is the air leakage through the specimen. This test can also be performed by installing the test chamber on the exterior and the specimen seal on the interior, but this is less common due to typical access difficulties. Measurements of air leakage through typical punched windows are on the order of several cfm, which can be measured with a fair degree of reliability with quality equipment.

Testing of air barrier assemblies can be done using the same general method described above, but presents several unique problems in addition to those described above:

- Air barrier assemblies are typically much larger than discrete components such as windows and doors (with the exception of large curtain walls).
- Air barrier assemblies may contain unique geometries that make construction of a tight test chamber difficult, such as structural members or slab edges that interrupt the test chamber. Exterior scaffolding may also interfere with the construction of the test chamber.
- Due to construction sequencing, testing of complete assemblies may not be practical due to the installation of different materials at different times.

An additional challenge with assembly testing is the need to eliminate extraneous air leakage around the edges of the area in question (this is not a problem when testing free-standing mockups, where the perimeter of the specimen can be sealed). Figure 1 shows extraneous leakage paths around an assembly that cannot be isolated or quantified when an interior test chamber is used. In this arrangement, the seal that is typically used to discern specimen from chamber leakage cannot account for all air leakage paths other than those through the chamber (blue arrows in Figure 1). When testing to meet the criteria of 0.2 L/s·m^2, even minor air leakage at the perimeter could significantly affect the accuracy of the test. For example, testing a 2.3 m^2 (5 ft x 5 ft) area to this level would require measurement of 0.47 L/s (1 cfm) of leakage. For a hollow concrete masonry unit (CMU) wall, it is likely that significantly more air would be drawn through the hollow cores of the CMU from air paths that extend into voids in the surrounding areas. Although these areas would likely be inboard of the air barrier assembly, they could result in the assembly failing the test based on measurement of greater than 1 cfm.

Constructing the test chamber on the exterior of the building will resolve some, but not all, of these issues. This configuration is shown in Figure 2. Although the use of an exterior chamber and seal eliminates leakage through the surrounding walls, it raises a new problem – how to remove the seal following the initial (chamber + specimen) test. As discussed above, even a small amount of uncertainty in the testing could render the results invalid. In most cases, if the chamber is removed in order to remove the seal, the initial measurement of chamber leakage cannot be re-used for the next stage of the test

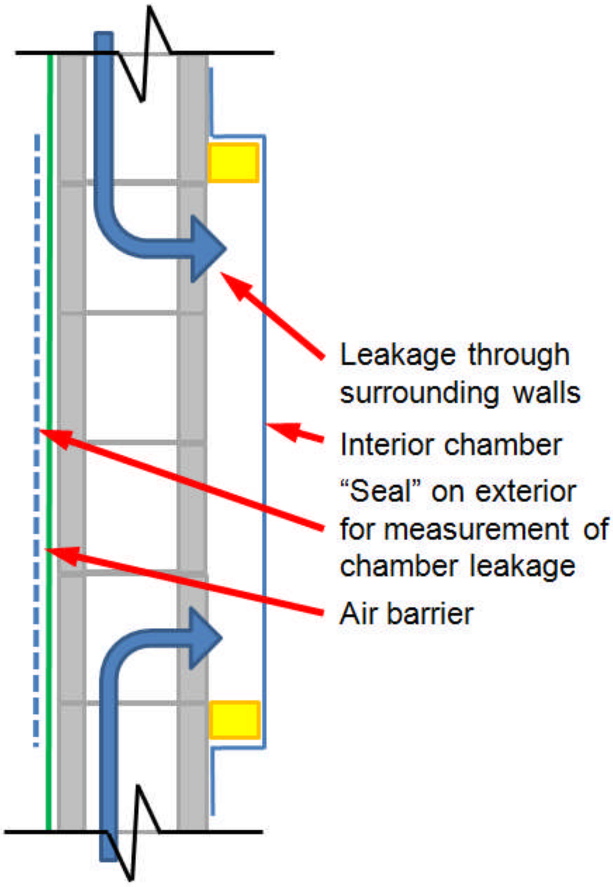

Figure 1 – Assembly test with interior chamber

due to the perimeter conditions being disturbed. One solution to this dilemma is a chamber with an operable panel through which the seal can be removed. For this to work, several chamber tests should be performed with the seal in place, operating the panel between tests to verify that air leakage through the chamber is not increased (or decreased) by the panel operation.

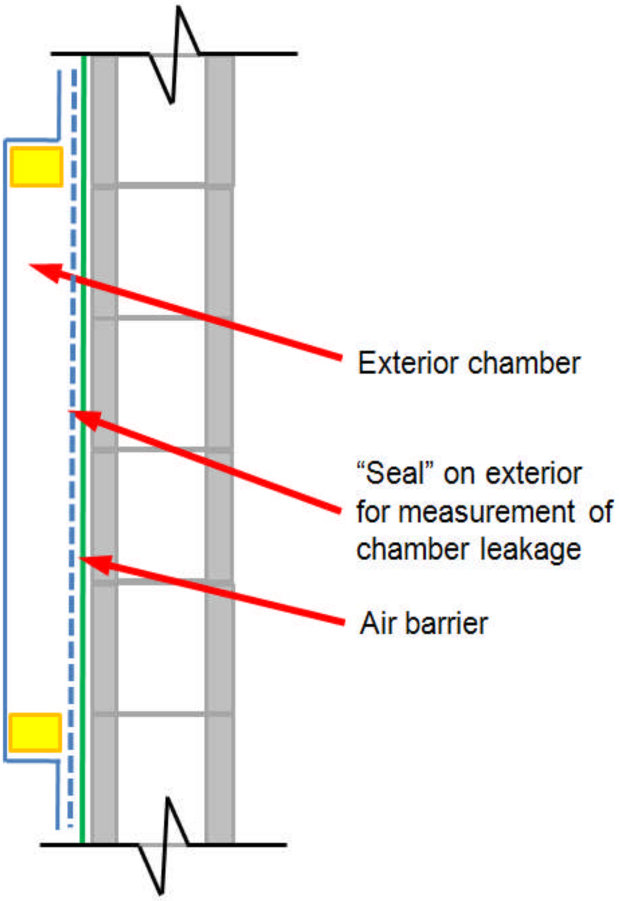

Figure 2 – Assembly test with exterior chamber

Measurement of air leakage on a building-wide scale requires similar basic equipment to component testing (fans, flow measurement devices, etc.), only on a much larger scale. Specialized equipment is available for this testing, including "blower doors" (Photo 4) and large, truck-mounted blowers for larger buildings. For certain building types, such as mid-to-high rise construction, additional fans may be required within the building to provide even pressure distribution throughout the full height of the space. Alternatively, buildings can be compartmentalized with differ rent portions tested at different times; however, this can extend the amount of time required to perform the tests considerably. As with component testing, engineers also often develop overall strategies specific to a particular project.

Photo 4 – Dual fan blower door used for whole-building airtightness test

Depending on the purpose of the test, it may be necessary to seal off certain openings in the building enclosure (such as air intakes) or to isolate ductwork from the occupied space to rule out the effects of duct leakage or leakage to the exterior through the mechanical system, which may not be a factor under typical operating conditions. Multiple data points are taken (airflow and differential pressure), from which air leakage at the test/target pressure – typically 50 Pa (0.2 in. of water) or 75 Pa (0.3 in. of water) – can be calculated. This value is normalized to the building surface area to produce a result in $L/s \cdot m^2$ (cfm/sf). Traditionally, normalization in North America has used the entire building enclosure area (including below-grade assemblies). However, recently the above-grade enclosure area has become more common in the U.S., becoming more consistent with European standards and more representative of the area through which air leakage will occur.

Qualitative testing can be performed using the same, or similar, test equipment described above, with the exception that no flow measurement device is required. For these tests, a pressure differential is created and visualization methods, such as the use of tracer smoke or infrared thermography, are used to identify air leakage paths. This type of testing is useful for identifying and locating air leakage sites, and is often performed in conjunction with quantitative testing to aid in the development of remedial strategies. Knowing where air leakage occurs is often far more useful than knowing how much leakage is actually occurring, especially in the case of high humidity buildings, such as museums and swimming pools, where even small air leaks can cause significant condensation. Qualitative testing has the advantage of providing installers with the locations of defects in the air barrier that require repairs in new construction and can inform a well-designed retrofit strategy in existing buildings

ENERGY ANALYSIS

To evaluate the effect of building enclosure air leakage on building energy use, whole building energy analyses were performed using EnergyPlus Version 3.1 (DOE 2009). EnergyPlus is building simulation software developed by the United States Department of Energy (DOE). It is capable of performing more complex heating and cooling analyses than many of the simulation programs commonly used in the industry, and it includes inputs for many building characteristics that affect energy use, including mechanical equipment, envelope construction, internal thermal mass, interior electrical loads, occupancy schedules, thermostat settings and external shading devices. EnergyPlus has been validated in accordance with ANSI/ASHRAE Standard 140-2007 (ASHRAE 2008; Henninger and Witte 2009-1; Henninger and Witte 2009-2; Henninger and Witte 2009-3; Henninger and Witte 2009-4) and ASHRAE Research Project 1052 (Henninger and Witte 2009-5). HVAC Component Comparative Tests (Henninger and Witte 2009-6), Global Energy Balance Tests (Henninger and Witte 2009-7) and IEA BESTEST In-Depth Ground Coupled Heat Transfer Tests (Henninger and Witte 2009-8) have also been performed for EnergyPlus.

The “Medium Office” Commercial Benchmark Building models (Figure 1) for Miami, Las Vegas and Chicago were used in performing comparative whole building energy analyses (Deru et al. 2008). These locations were selected to represent the range of climates typical of the contiguous United States. The Medium Office Benchmark by DOE, National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL) and Lawrence Berkeley

National Laboratory (LBNL) was developed to be representative of a typical mid-rise (3 story) commercial office building.

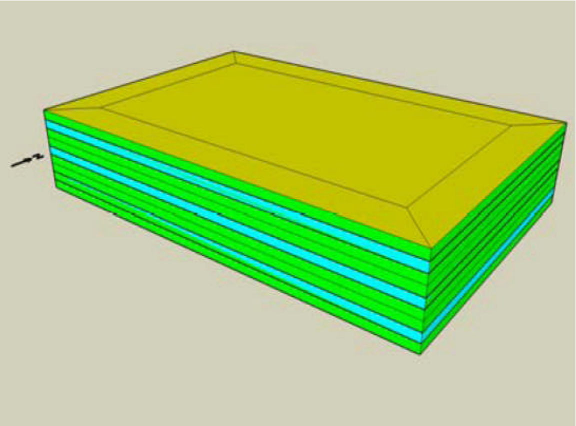

Figure 1: Medium Office Benchmark Building (Deru et al. 2008)

The Benchmark building systems meet the minimum prescriptive requirements of ASHRAE Standard 90.1-2004. The building is served by a variable air volume (VAV) HVAC system with electric cooling and natural gas heating. The exterior walls are steel-framed with insulation between the steel studs and, in some cases, continuous insulation outboard of the back-up wall. The roof contains continuous insulation installed entirely above the roof deck. Standard 90.1 allows north-facing glazing with a higher solar heat gain coefficient (SHGC) than on the other elevations; however, to simplify the analysis for this paper, we adjusted the north-facing glazing SHGC to match that of the other elevations. Table 1 summarizes the construction parameters in our baseline models that we later varied in our adjusted models. The table lists the glazing SHGC and the thermal resistance (R-value) of the opaque envelope areas.

TABLE 1: Baseline Construction Parameters

Location	SHGC	Roof Insulation[1]	Wall Insulation[2]
Miami	0.25	RSI-2.6	RSI-2.3
Las Vegas	0.25	RSI-2.6	RSI-2.3
Chicago	0.39	RSI-2.6	RSI-2.3 + RSI-0.67 c.i.

[1] Roof insulation is continuous across structural members

[2] The first listed R-value is for insulation between steel studs. The second R-value (denoted "c.i.") is for continuous insulation installed outboard of the steel studs.

For reference, RSI-2.6 (R-15) roof insulation represents 6.4 cm (2.5 in.) thick polyisocyanurate insulation, RSI-2.3 (R-13) insulation represents 8.9 cm (3.5 in.) thick fiberglass insulation, and RSI-0.67 (R-3.8) represents 2.5 cm (1 in.) thick expanded polystyrene (EPS).

This analysis compares the effect of reductions in enclosure air leakage to the effects of common envelope energy efficiency measures, such as additional insulation in opaque assemblies and reduced solar heat gain through glazing, and to determine what effect inaccurate air leakage inputs would have on predicted energy use. Table 2 summarizes the adjusted construction parameters included in our models.

TABLE 2: Adjusted Construction Parameters

Location	SHGC	Roof Insulation[1]	Wall Insulation[2]
Miami	0.20	RSI-3.5	RSI-2.3 + R-0.67 c.i.
Las Vegas	0.20	RSI-3.5	RSI-2.3 + R-0.67 c.i.
Chicago	0.34	RSI-3.5	RSI-2.3 + R-1.3 c.i.

[1] Roof insulation is continuous across structural members

[2] The first listed R-value is for insulation between steel studs. The second R-value (denoted "c.i.") is for continuous insulation installed outboard of the steel studs.

For each location, the adjusted SHGC is 0.05 lower than the 90.1-2004 prescriptive requirement and the opaque assemblies add 2.5 cm (1 in.) of continuous insulation. In our analysis, we considered these adjustments alone and in combination with air leakage reductions, but not in combination with each other.

We have assumed a baseline enclosure air leakage rate of 7.9 liters per second per square meter of exterior enclosure area (7.9 $L/s\cdot m^2$) at 75 Pa pressure differential between exterior and interior air (1.55 cfm/sf at 0.30 in. water). This is the average enclosure air leakage in a recent study of 203 commercial buildings in the U.S. (Emmerich and Persily 2005). We also developed models that assumed air leakage rates of 3.6 $L/s\cdot m^2$ (0.70 cfm/sf) and 0.76 $L/s\cdot m^2$ (0.15 cfm/sf) at a 75 Pa (0.30 in. water) pressure differential. These values are based on an approximation of the 2006 United Kingdom Building Regulations and a reasonable value for a well-detailed and constructed airtight building. In all cases, we assumed air leakage rates varied linearly with wind velocity. Though this will not reflect the exact relationship between wind velocity and enclosure air leakage – which typically scales with velocity raised to the power of approximately 1.2 – we worked within the constraints of the software to account for the dependence of air leakage on wind velocity. As wind velocities are typically much lower than what would cause a 75 Pa pressure differential, the air leakage rates are likely slightly lower in our simulations than in reality, providing a conservative analysis of their effect.

For all models, we calculated the source energy requirements based on the site requirements by fuel type and the conversion factors included in the DOE Benchmarks. For all locations, the site natural gas use is converted to source energy by multiplying by 1.092. The electricity site-to-source conversion factors are location-specific, as they depend on the fuel source used to produce electricity. The electricity conversion factors are 3.317, 3.577 and 3.546 for Miami, Las Vegas and Chicago, respectively.

Results

For clarity, we have limited the results included in this paper to the total source energy requirements for pertinent Miami, Las Vegas and Chicago simulations; Tables 3, 4 and 5, respectively, summarize these results. Parameters differing from the baseline condition are shown in boldface. The differences in the effects of SHGC, roof insulation and wall insulation adjustments at different air leakage rates were negligible. The results of these simulations are not included in Tables 3-5 for simplicity.

TABLE 3: Energy Simulation Results – Miami

Air Leakage ($L/s \cdot m^2$)	SHGC	Roof Insulation	Wall Insulation	Total (Source)	
				GJ	% Reduction
7.9	0.25	RSI-2.6	RSI-2.3	7150.7	N/A
7.9	**0.20**	RSI-2.6	RSI-2.3	7066.8	1.2%
7.9	0.25	**RSI-3.5**	RSI-2.3	7136.6	0.2%
7.9	0.25	RSI-2.6	**RSI-2.3 + RSI-0.67c.i.**	7106.5	0.6%
3.6	0.25	RSI-2.6	RSI-2.3	7084.1	0.9%
0.76	0.25	RSI-2.6	RSI-2.3	7036.3	1.6%

Our results indicate that substantial reductions in envelope air leakage provide comparable energy use reduction to lower SHGC. As would be expected in an insulated building in a cooling-dominated climate, additional roof insulation in Miami’s climate does not result in significant energy use reduction and additional wall insulation results in a less significant energy use reduction than air leakage reductions. Building enclosure air leakage generally has a much more significant effect on heating requirements.

TABLE 4: Energy Simulation Results – Las Vegas

Air Leakage (L/s·m^2)	SHGC	Roof Insulation	Wall Insulation	Total (Source)	
				GJ	% Reduction
7.9	0.25	RSI-2.6	RSI-2.3	7495.6	N/A
7.9	**0.20**	RSI-2.6	RSI-2.3	7463.1	0.4%
7.9	0.25	**RSI-3.5**	RSI-2.3	7473.6	0.3%
7.9	0.25	RSI-2.6	**RSI-2.3 + RSI-0.67c.i.**	7419.1	1.0%
3.6	0.25	RSI-2.6	RSI-2.3	7275.7	2.9%
0.76	0.25	RSI-2.6	RSI-2.3	7117.9	5.0%

The effect of reducing envelope air leakage is very significant in Las Vegas' climate compared to the other envelope modifications. The reduction in heating is more significant in terms of overall energy use in Las Vegas than in Miami. This suggests that except in the very warmest climates in the U.S., heating requirements are a significant enough percentage of total building energy use that buildings benefit from energy reductions associated with reduced enclosure air leakage.

TABLE 5: Energy Simulation Results – Chicago

Air Leakage (L/s·m^2)	SHGC	Roof Insulation	Wall Insulation	Total (Source)	
				GJ	% Reduction
7.9	0.39	RSI-2.6	RSI-2.3 + RSI-0.67c.i.	7864.8	N/A
7.9	**0.34**	RSI-2.6	RSI-2.3 + RSI-0.67c.i.	7832.7	0.4%
7.9	0.39	**RSI-3.5**	RSI-2.3 + RSI-0.67c.i.	7837.0	0.4%
7.9	0.39	RSI-2.6	**RSI-2.3 + RSI-1.3c.i.**	7803.4	0.8%
3.6	0.39	RSI-2.6	RSI-2.3 + RSI-0.67c.i.	7449.0	5.3%
0.76	0.39	RSI-2.6	RSI-2.3 + RSI-0.67c.i.	7122.1	9.4%

In our analyses, energy use reductions were much more substantial for the cases with reduced envelope air leakage than for the other enclosure modifications alone. The significant impact of building heating on total energy consumption in Chicago's climate and the influence of air leakage on heating requirements accounts for the notable reductions in total building energy consumption associated with increased enclosure airtightness.

In warmer climates, the effect of air leakage is less significant and, thus, incorrect air leakage inputs for energy simulations are less likely to produce erroneous results that will significantly affect a building's design. In heating-dominated climates, the effect of inaccurate air leakage modeling can have a significant impact on predicted energy use and a designer's understanding of the building's expected performance. Typically, input values are lower than actual envelope air leakage. This may result in significantly more energy use than predicted by energy models. Load calculations may also be inaccurate and mechanical system capacity may be too small to support the building's needs.

CONCLUSION

Design professionals are becoming more aware of the need for an airtight building enclosure; however, the industry as a whole is not yet focusing on high quality air barriers that form a continuous system across multiple envelope components. Furthermore, many designers cannot prescribe an acceptable overall building air leakage performance criterion and building codes containing these requirements are not yet widespread in the United States. Building enclosure air leakage testing – at both the assembly and building levels – is not yet standard in commissioning new buildings or in evaluating existing buildings. Despite this lack of quantification through measurement and verification, an accurate measure of air leakage through the building enclosure is essential to understanding and predicting building energy usage. The use of whole building energy analysis tools, such as those used in developing this paper, is becoming ubiquitous in high performance building design. As the analysis supporting this paper shows, the use of inaccurate enclosure air leakage models can produce energy simulation results that are significantly different than actual building performance and may result in improperly sized mechanical systems. This is particularly true in temperate and cold climates, where air leakage has a greater impact on building energy use, though safety factors in equipment sizing are generally sufficient to offset this effect. In “right sizing” mechanical systems for improved building performance, the factor of safety may be dropped considerably, making equipment sizing more sensitive to the assumed air leakage rate. A prudent approach to energy analysis is to evaluate a building design and alternate energy efficiency measures for a range of air leakage inputs.

In many areas of the United States, reduced air infiltration can produce significantly better results than common energy efficiency measures related to the building envelope. Designers need to treat air barriers as a system with multiple components and junctures, and pressurized testing of assemblies and whole buildings can be used to measure and verify performance of the system. As with thermal insulation and moisture migration through building materials, building codes and standards likely need to substantively address continuous air barriers in order for the industry to incorporate them into building construction on a large scale.

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