Building Enclosure Air Leakage in Commercial Buildings: Energy Codes, Testing and Practical Limitations

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ABSTRACT

While the importance of air barrier systems in buildings has been understood for decades, it is only in the past decade or so that they have been given appropriate attention in the energy codes of most countries. While at least one country has had air barrier requirements in their codes since the mid-1980s, the "model energy codes" of others have largely ignored the issue until recently. Studies in the United States in the early 2000s that showed the potential for significant energy savings due to airtightness improvements in buildings were instrumental in getting air barriers incorporated into both the ASHRAE 90.1 standard and the International Energy Conservation Code (IECC), both of which form the basis for almost every energy code in the country.

As many in the buildings industry have discovered, getting air barriers into the energy codes was only the first step. Airtightness in buildings is an extremely complicated issue, as it spans so many aspects of both design and construction. If a designer specifies a maximum U-factor for a window system or a minimum R-value for wall insulation, the chances of installed systems varying significantly from those performance levels are relatively small. With air barriers, however, simply specifying a material with a certain air permeance is nowhere near sufficient to achieve that performance on the whole-building scale. The material needs to be properly integrated with all aspects of the enclosure, from below-grade waterproofing to roofing to fenestration. The overall impact on building airtightness now depends on the thoroughness of the detailing, the performance of the adjacent systems, and the quality of installation. This is in sharp contrast to thermal insulation, where the R-value is the R-value regardless of how the material is installed, and performance can be reliably calculated as opposed to requiring field testing.

To account for these concerns, many codes and building rating systems (such as Passive House) have started to include requirements for whole-building air leakage testing to confirm the effectiveness of the air barrier system. Again, this is a good first step, but the practical difficulties of air leakage testing are not widely understood. This paper reviews the development of air barrier requirements in model energy codes, including whole building testing, and discusses the practical limitations of current codes. The authors present strategies for both improving building airtightness through thorough design documentation and construction

monitoring and for performing field testing to confirm execution and verify performance. We discuss how both designers and builders can meet these code requirements while considering the practical limitations of the construction process, from constructability to scheduling.

1. INTRODUCTION

In the early half of the 20th century, much of the research into building enclosures focused on water vapor control. Work by Dr. Frank Rowley in the 1930s and 40s focused on evaluating water vapor flow to prevent condensation within exterior wall insulation. This largely overshadowed work by Leonard Barret who was evaluating how airflows could produce similar condensation impacts (and who turned out to be correct about the problems associated with moisture migration via moving air). A 1942 United States Federal Housing Authority publication titled "Property Standards and Minimum Construction Requirements for Dwellings" required low permeance materials on the inside of insulated walls with impermeable coverings on the exterior – and the vapor barrier was born. Although it quickly spread to building codes and standards around the country, some researchers still observed condensation issues in these walls despite the low-permeance interior barriers.

Condensation due to air leakage was occasionally studied in the latter half of the 20th century, but it was not until the energy crisis of the 1970s that research focused more on the impact of air leakage on heating and cooling loads in buildings. The 1986 National Building Code of Canada was the first code to include a specific requirement for air leakage control. Where a building assembly would be subjected to a temperature differential, a differential in water vapor pressure and a differential in air pressure due to stack effect, mechanical systems or wind, the code required that assemblies be designed to provide an effective barrier to air exfiltration and infiltration, at a location that would prevent condensation within the assembly through the materials of the assembly, joints in the assembly, joints in components of the assembly, and junctions with other building elements.

In the U.S., ASHRAE 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings has helped to define energy efficiency for commercial buildings since the first version was published in 1975. ASHRAE 90.1 had a clause addressing air leakage as far back as 1989, but only in very generic terms (i.e., "All exterior joints, cracks, and holes in the building envelope shall be caulked, gasketed, weather stripped, or otherwise sealed."). The U.S. did not see any well-defined requirements for air barriers until 2001 when Massachusetts added continuous air barriers to the 6th edition of their building code. It wasn't until 2010 that the 90.1 standard began requiring that "The entire building envelope shall be designed and constructed with a continuous air barrier." This requirement was included in the 2013 version as well and then updated in 2016 to include field testing to prove effectiveness of the air barrier installation. The International Energy Conservation Code followed a similar path to ASHRAE 90.1, with loose language on sealing of the enclosure up through the 2009 version and then more specific language on air barrier systems beginning in 2012.

While most standards and codes now require continuity, testing to quantify air leakage and confirm that installed systems meet quantitative performance targets is relatively new and brings with it challenges that are sometimes equal to or greater than the challenges associated with effectively installing the air barrier system. When evaluating air infiltration on a manufactured component such as a window or a door, you can be relatively confident that you are going to get what is advertised because one contractor is responsible for building it exactly the way the fabrication instructions describe. A building-wide air barrier system, however, crosses trades and requires a heavy focus on detailing during design as well as coordination between contractors during construction.

The process of successfully installing an air barrier is somewhat similar to an automotive assembly line, where a highly complex assembly process is broken down into many smaller steps. Each of these steps must be performed in sequence and according to a global design plan in order for the finished product to function. For air barriers installed in the field, a similar level of quality is required but now half the assembly steps are performed out of order and everyone on the "assembly line" is working from a different set of drawings. Looking at it from this perspective, it is not surprising that continuity of air barrier is extremely difficult to achieve. As we will discuss in the following sections, this difficulty has not been well understood because until very recently, testing has not been required and is rarely done voluntarily.

2. DESIGN VS. PERFORMANCE

When a design team is designing a building, they can choose most products to meet the performance requirements that match their code or project goals. A window or curtain wall's thermal performance can be confirmed with analyses or physical testing. Placing that window within a wall opening, where it may be surrounded by thermal bridges, will reduce its effective performance, but through analysis or testing that reduction is quantifiable with a reasonable degree of accuracy. The same is true for insulation materials – knowing the R-value of the material and the specific method of installation (between studs, interrupted by façade anchors, etc.), a designer can calculate the in-situ assembly performance using software tools or data from manufacturers or other industry sources.

Shifting to air barriers, while manufacturers can provide testing results for the airtightness of individual components (air leakage rates, typically expressed in L/s*m^2 [CFM/ft^2] at a specific pressure differential [in Pa or lb/ft^2]), the assembly of multiple materials into the finished air barrier system can result in greatly different values in the field. This fact is clearly reflected in typical building code requirements, where the maximum air leakage rate for air barrier assemblies, which include opening perimeters, penetrations, etc. is typically 10 times higher than the rate for the primary air barrier (membrane) materials (0.2 L/s*m^2 at 75 Pa [0.04 CFM/ft^2 at 1.57 ft^2] vs. 0.02 L/s*m^2 at 75 Pa [0.004 CFM/ft^2 at 1.57 ft^2]). For whole buildings, leakage is another 10 times higher than for assemblies (2.0 L/s*m^2 at 75 Pa [0.4 CFM/ft^2 at 1.57 ft^2], or now 100 times higher than for primary materials. Performance is heavily dependent on installation, detailing configurations, construction practices, and sequencing. Unlike thermal performance, where the performance impacts of thermal bridges and other discontinuities can be quantified, both the level of discontinuity and the impact of those discontinuities on air barrier system performance cannot be reasonably estimated during the design of a project, whether to evaluate actual energy impact or to simply confirm that the installation meets the above-mentioned code limits on air leakage.

While designers can, and must, be thorough in air barrier design and fully detail transitions, intersections, joints, and related details, the execution of that design is significantly more difficult to accomplish. Execution is also a process over which typical designers have very little control. Some typical installation concerns include:

- Does the membrane tie in with adjacent trades with shingle laps that consider both chemical compatibility and adhesion? The air barrier is often also the water barrier in an assembly, so it needs to be designed in accordance with good waterproofing practice as well as being airtight. Compatibility is a common concern, as many common air barrier and enclosure materials are either physically or chemically incompatible (e.g., asphaltic materials will embrittle PVC membranes over time, very few materials will successfully adhere to silicone, etc.). Complicating matters, for primary systems like roofing, manufacturers may make warranty exceptions if detailing requires tie-in with some types of adjacent materials – even if those materials are critical to air barrier performance. The authors have worked on many projects where detailing was compromised because "it will void the roof warranty" and manufacturers would not accommodate any changes. Warranty aside, the issue of trade coordination is a frequent cause of problems, where even with a third party (general contractor) managing the process, it is difficult to get separate trades to agree on transition details and then perform their work in a manner to allow those details to get built.
- Who is checking if other trades damage the membrane after it has been installed? As noted above, even small gaps (or in this case, punched holes/damage) in an air barrier can significantly degrade performance. Air barriers are often one of the first components installed after the structure is in place and will experience both construction traffic and subsequent trades (framing for rainscreens, mechanical attachment of roofing, etc.). This provides no shortage of opportunities for damage (Figure 1).

Figure 1 - Large cut in air barrier at soffit made to pass through temporary utilities and not repaired.

- Is the air barrier continuously supported? Air barriers need to resist both internal building pressure and external applied pressure (due to both wind and changing environmental conditions). Extending air barrier materials across large gaps can result in failure over time as the material is stressed or as seams pull open. This often comes down to coordination, as the air barrier installer who is being pressured to finish their work may not take the time to work with the framer to address gaps in the backup wall – they simply conceal the issue with their membrane and move on.
- Is the general contractor coordinating between trades to make sure the initial trade left conditions to accommodate the next trade in such a way that allows for continuity? Sequencing of air barrier systems, especially when they are also functioning as water barriers, is critical to performance. Installing materials out of sequence may prevent proper shingling of materials, connection to fenestration, or integration with other elements of the enclosure. This is typically a problem where cladding systems change or abut adjacent elements such as roofing. If the air barrier simply ends at the edge of the cladding, there is no practical way to make the air barrier connection without removing materials (Figure 2).

Figure 2 - Wall (green arrow) and roof (red arrows) air barriers installed but never joined together at a roof eave condition. Remedial membrane installation was simple but required significant exterior finish removal.

- Have changes or "value engineering" decisions affected the design in a way that prevents certain details from being implemented? We have discussed the importance of thorough detailing, but what happens when detailing is based around a specific system or system type which gets changed before or during construction? We have often provided detailed drawings for integrating air barriers with curtain wall framing systems only to have that framing "value engineered" to a lesser system, requiring either expensive changes to the design, compromises in performance, or both.

3. MEASUREMENT AND VERIFICATION

Breaches in the air barrier are not always obvious, or even visible, and physical testing is the most reliable way to both identify these breaches and to determine how tight the envelope is. Such testing should include a combination of whole building testing and localized chamber testing, both qualitative and quantitative.

3.1 Quantitative Testing

There are two primary reasons that one would test the air barrier system to evaluate actual air leakage rate. The first is to establish whether the installed system (or individual component, such as a window or door), meets the specified and code-required level of performance. This is a simple comparison of a tested value to a referenced standard and is essentially pass/fail. The second reason would be evaluating the performance of the enclosure and estimate heating and cooling losses associated with air leakage – either to determine mechanical system parameters for an upgrade or to evaluate potential causes of heating and cooling issues. Test procedures for windows and doors are well-established and included in almost all new construction and many retrofit projects as a quality assurance measure. While whole-building testing of single-family residential buildings has been well understood for decades, testing of larger commercial buildings (as well as regulation of overall leakage rates) is a much more recent development.

The first obstacle to implementing maximum air leakage rates in building codes is developing a reasonable value or target – not an easy task, since there was very little data in the industry to suggest what air leakage rates were reasonable, and achievable, for commercial buildings. Early studies in the U.S. found that existing buildings had very high leakage rates, with averages 3 to 4 times greater than current code limits. However, the body of knowledge in that area was limited, with only a few studies sampling a small number of existing buildings, and even less information was available for new construction. In 2009, the Washington State Energy Code began requiring most new buildings to perform a whole-building air leakage test. Interestingly, there was no performance target given, just a requirement to complete the test and report findings. This was, in effect, an information gathering exercise to help inform future code changes. It was not until 2012 that the same code established an actual target (the now-standard 2.0 L/s*m^2 at 75 Pa [0.4 CFM/ft^2 at 1.57 ft^2], likely based on collected data which showed that to be an achievable requirement. Around this same time, in 2010, the U.S. Army Corp of Engineers began requiring all their buildings, including renovation projects, meet a whole-building leakage rate of 1.26 L/s*m^2 at 75 Pa [0.25 CFM/ft^2 at 1.57 ft^2]. This is lower than current code values, but with careful design and increased focus on airtightness, many of their buildings were able to achieve this value as designers and installers became more familiar with the steps necessary to improve airtightness. While confusion over targets was a frequent topic of discussion over the past 10+ years, typical codes are now in agreement on reasonable targets, with many advanced standards (such as the Passive House and similar low-energy guidelines) pushing the envelope to produce even tighter buildings.

Perhaps in recognition of the difficulty of testing (which will be discussed in more detail below), most codes include whole-building testing as an optional path, but allow for other, less quantitative compliance paths (such as the use of materials or assemblies with tested performance levels). However, some U.S. jurisdictions have started moving towards whole-building testing as a hard requirement for some building types. For example, the 2020 New York City code requires quantitative testing to show that the building envelope does not exceed 2.0 L/s*m^2 at 75 Pa [0.4 CFM/ft^2 at 1.57 ft^{2}for all new buildings between 929 m^2 (10,000 ft^2) and 4645 m^2 (50,000 ft^2) and less than or equal to 23 m (75 ft) in height. And while many designers and builders do not yet have the experience required to both meet that air tightness target and successfully demonstrate compliance via testing, seeing how codes have developed in the last 10 years, it is only a matter of time before those requirements become the standard and not the exception.

The following sections discuss the various issues associated with whole building air leakage testing of large and increasingly complex buildings.

3.2 Qualitative Testing

While this paper primarily deals with the difficulties of quantifying air leakage, it is important to note that qualitative testing can often be just as critical, and in many ways a simpler approach to testing. Telling a contractor that the whole-building leakage rate was 4.0 $L/s*m^2$ at 75 Pa (0.79 CFM/ft^2 at 1.57 $ft)^2$ gives them no real direction on how to implement repairs, other than the very general “make the building tighter”. Qualitative testing is needed to locate the actual breaches in the air barrier so that they can be exposed and repaired. Qualitative testing may include smoke testing and/or infrared (IR) scans when the building is pressurized, using visual (or in the case of IR, detectable) methods to identify leakage sites. IR scans work under a similar mechanism but require a temperature differential between the building interior and exterior so that air leakage is “visible” to an IR camera that detects the resulting temperature differential near the leakage site (Figure 3). Smoke testing when the building is pressurized will lead to smoke exiting the building where there is a breach (Figure 4). These types of tests can be highly beneficial since they can be performed in any size space, can be done in small sections rather than needing the entire air barrier to be complete, and provide immediate guidance to the installers on where and how to make repairs.

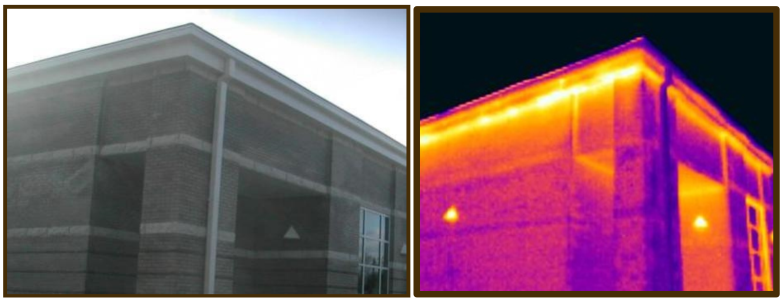

Figure 3 - Visual (left) and IR (right) images of a building with air leakage at roof-to-wall interface. IR image visualized temperature differential associated with leaking interior air.

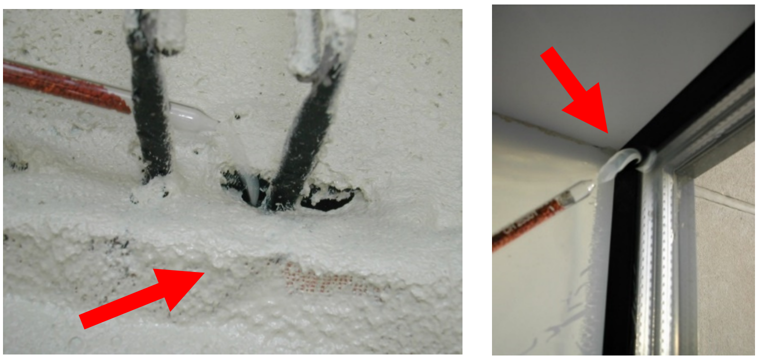

Figure 4 - Testing of air barrier details using tracer smoke.

4. CHALLENGES OF WHOLE-BUILDING TESTING

Whole-building testing of a completed single-family home is a relatively simple process, requiring small fans, minimal preparatory work, and in many cases a single technician (Figure 5). The chances of passing that test are relatively high due to the simple construction and limited number of contractors involved in construction of the building, simplifying many of the coordination issues discussed above for larger commercial buildings. This is part of the reason why single-family residential airtightness testing has been well-established and predates testing of larger buildings by decades in some locations. Below we discuss the major issues associated with testing of the latter building type, primarily focusing on the "when" and the "how" of testing.

Figure 5 - Dual-fan blower door for small building air leakage test.

The primary elements of the air barrier system in a large commercial building are the wall air barrier membrane, the roof system, and fenestration. In an ideal world, all those systems would be installed building-wide, but left exposed to allow for inspection or repair. A whole-building test would be performed, and if it failed, qualitative testing would identify any breaches in, or damage to, the air barrier which could then be repaired for a re-test. The actual process of constructing a large building is a very different story. By the time all the included systems in the air barrier are completed, most air barrier components are likely already concealed due to schedule pressure to complete the building. For many projects, scheduling the work to allow for the entire air barrier system to be exposed for testing would make those projects financially unfeasible. Projects may also experience out-of-sequence work, where the wall air barrier may be completed and exposed for weeks or months before fenestration is installed, further delaying a potential test. This means that for buildings where testing is the only option, the project team may be faced with a difficult scenario of failing to meet the required leakage rate but needing to find breaches in a partially or fully concealed air barrier. While some of the methods described above, particularly IR scanning, can help to located concealed air leaks, removal of brand-new cladding, materials, etc. will be required to access those locations for repair.

In many cases, partial testing of buildings (e.g., one completed floor at a time) can be a useful method of dealing with sequence and schedule issues, as it is more likely that a single floor or localized area can be made airtight prior to the installation of exterior finishes. The challenge with this approach, however, is isolating air leakage through the enclosure systems from air leakage into adjacent/incomplete spaces. This challenge can be significant due to the large number of penetrations through walls and floors in a modern building, many of which will not be sealed or isolated until much later in the construction process. Such communication between spaces may require temporary sealing for the test, or in some cases, limit the size of the area that can reasonably be tested. In addition to sealing air paths into and out of the test area, it is also necessary to “pressure balance” the surrounding spaces with the test area, maintaining the same pressure (either negative or positive, depending on the test) in both spaces to prevent airflow between them. While a “brute force” approach of using multiple fans to maintain pressure balancing without sealing air paths may work for small spaces, the fan power required to overcome leakage through large openings is impractical for most applications. For partial testing, a qualitative approach can also be used which is much simpler, as the required pressure differential may not be as high as for quantitative testing, and there is no need to prevent leakage into adjacent spaces as long as the required differential can be maintained.

Building on the “how” of testing, one of the primary challenges of testing a large building is simply its size. While most single-family residential buildings can be tested with a single fan, large buildings may require multiple fans (dozens in some cases) or specialized high-capacity fans which greatly limit the availability of testing agencies. For a moderate to complex building, fans must also be well-distributed throughout the space to provide consistent pressure control. This is especially important for taller buildings during temperature extremes. For example, in a 75m (246 ft) tall building under a temperature differential of 15C (27F), the magnitude of potential stack pressure is almost 50 Pa (1.0 lb/ft^2). For a test that is typically performed at 75 Pa (1.57 lb/ft$^{2)}$, failure to balance out such high stack pressures internally could result in significant pressure variations throughout the building and produce misleading air leakage results. Especially in taller buildings, fans must often be installed in stairwells and on multiple floors to provide internal pressure balancing both vertically and horizontally. While these approaches can be used successfully to quantify air leakage, they require both equipment and expertise currently beyond that of the typical design professional or testing agency.

5. SUMMARY

As airtightness requirements become more stringent and expectations of proving installed performance increase, coordination between members of the design and construction teams must also increase. Designers will need to develop detailing and specify materials that can accommodate transitions between trades accounting for compatibility and anticipating potential sequencing. They will also need to consider the building parameters (heights, floorplans, use, etc.) in developing testing plans. Additional materials may need to be specified for testing plans that require compartmentalization and incremental testing to ensure floors and/or areas of the building can be effectively tested. Some of these provisions may fall into means and methods for contractors but, regardless, there will need to be coordination with the general contractor to understand anticipated schedules and sequencing. Specifications will also need to include recourse and direction for failed tests to help all parties navigate a changing construction landscape and to help resolve potential disputes. In many cases, performing a whole-building air leakage test on a project may just not be practical. In these cases, it will be important for the design and construction teams to establish alternate testing criteria (such as partial or incremental testing) as well as to work with the local authority having jurisdiction (AHJ) to confirm that such alternate paths will be acceptable.

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