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Impact of Air Leakage on the Building Envelope

Myths and facts about airtightness

by Maria Spinu, PhD, CSI, LEED AP, and Brian Erickson, MS, PE

All images courtesy Pie Forensic Consultants

UNCONTROLLED AIR LEAKAGE THROUGH THE BUILDING ENCLOSURE CAN HAVE A SIGNIFICANT IMPACT, AFFECTING ENERGY USE, ENVELOPE DURABILITY, OCCUPANTS' THERMAL COMFORT, AND INDOOR AIR QUALITY (IAQ).

Despite its myriad impacts on building performance, air leakage is generally regulated through energy codes because the effect on consumption is the one most readily quantified. While a continuous air barrier is a cost-effective strategy for leakage control, the energy codes have only recently developed quantitative requirements for these product systems.

Air leakage should not be confused with planned mechanical ventilation. It is never advisable to rely on holes in the building envelope to provide fresh air ventilation for the occupants. For one reason, the wind is not guaranteed to blow when fresh air is needed. Outdoor ventilation air is not intended to originate from cracks or holes in the building shell, but rather should be delivered through a well-designed and commissioned mechanical system that meets or exceeds the requirements set forth in American Society for Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) 62.1, *Ventilation for Acceptable Indoor Air Quality*.

Air leakage is unpredictable; its flow rate and pathways are random and change with air pressure difference patterns across the building envelope. The pressure differential across the building envelope is the sum of three main sources—wind pressure, mechanical pressure, and stack effect—with the resulting patterns becoming quite complex. For example, a building can experience both positive and negative pressure difference (*i.e.* infiltration/exfiltration) at different locations, at the same time.

Unintentional air leakage has both direct and indirect impacts on a building's energy performance. For the former, it is the result of infiltration of unconditioned air or exfiltration of conditioned air, both requiring the HVAC mechanical system to compensate for these losses. The direct impact of air leakage on the HVAC energy use can be estimated through energy simulations. A recent simulation study by the National Institute of Standards and Technology (NIST) has shown reducing air leakage can result in up to 35 percent heating energy cost savings in certain climates.[1]

The indirect impact of air leakage on thermal envelope performance is the result of loss of insulation R-value due to air movement and moisture transported by air currents (*e.g.* wind washing or forced convection, looping in air-permeable insulation, or through gaps around insulation).[2] Convection loops around batt insulation can still occur with an effective air barrier system in place. These effects can have a significant impact on the envelope loads, but they are more difficult to quantify in practice and are generally not taken into account.

Air and moisture

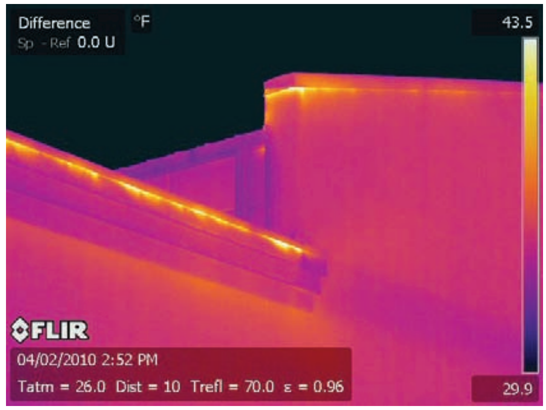
The impact of air leakage on building envelope durability is mostly due to air-transported moisture. Air can carry significant amounts of moisture that can be deposited on cooler interior surfaces, leading to interstitial condensation. Repeated condensation events, coupled with slow drying rates, could lead to significant moisture degradation of building materials (*e.g.* corroded metal and rotted wood). Reducing uncontrolled air movement through a building enclosure minimizes potential for condensation.

In heating climates, the focus is on interior moisture-laden air exfiltration. In humid, cooling climates, the concern is reversed and focuses on exterior moisture-laden air infiltration into air-conditioned structures. When one focuses strictly on energy impacts and subsequent payback analysis, the impact that air leakage has on moisture control can sometimes be overlooked.

Anyone involved with a project requiring remediation due to condensation within wall or roof cavities understands the time and cost involved far outweighs any upfront expenses to properly implement an air barrier design, construction, and measurement/verification program. Far too often, remediation is not only the cost of diagnostics and reconstruction, but also attorneys, expert witnesses, extensive testing, mold abatement, and the lost goodwill of the building owner or end-user.

In cooling climates, it is often assumed buildings can simply be 'pressurized' to avoid the humid outdoor air

Figure 1



This thermal Infrared image shows the air leakage (exfiltration) at parapet wall.

from migrating inward through the enclosure cavity. Not only does this operation carry an energy penalty, but it also assumes the enclosure and HVAC systems perfectly perform to maintain a 'slight positive pressure' throughout the building enclosure. This does not always occur. Further, buildings in heating climates are often designed to operate at a 'slight positive pressure,' which can have dire consequences as indoor air exfiltration is likely to lead to condensation of excess moisture on surfaces with temperatures below dewpoint during cold winters.

Infrared thermography (IRT) is becoming a common diagnostic tool for identifying potential air leakage areas in buildings. The infrared thermogram in Figure 1 was taken when the building was pressurized during a heating period and shows warm indoor air exfiltrating at the parapet due to lack of continuity of the air barrier.

As warm air can hold more moisture than cold air, the excess moisture in the exfiltration air can be deposited on interstitial surfaces with temperatures below the dewpoint temperature, leading to condensation. If there is a net accumulation of water within the cavity, building material deterioration and biological growth can occur (depending on the duration of condensation events and drying potential).

Air-transported moisture must not be confused with water vapor diffusion, and a vapor control layer (*i.e.* vapor barrier) must not be confused with an air control layer (*i.e.* air barrier). Water vapor diffusion is a much slower molecular movement driven by the difference in concentration across the building envelope. The amount of moisture that moves through air currents is two orders of magnitude higher than that transported by vapor diffusion. A recent reference gives an excellent comparison between air barriers/air leakage control and vapor barriers/vapor diffusion control.[3]

Figure 2

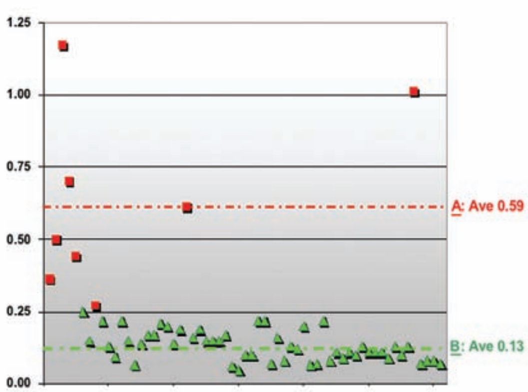
North American Air Barrier Codes and Standards

Codes & Standards/ Performance Requirements	Air Infiltration Resistance [cfm/sf @ 0.3 in w.g.] & Compliance Options		
	Material (ASTM E 2178)	Assembly (ASTM E 2357 or E 1677)	Whole Building (ASTM E 779)
1995 *National Building Code of Canada* (NBC)	0.004	--	--
2001 *Massachusetts Energy Code*	0.004	--	--
2009 *Minnesota Energy Code*	0.004	--	--
2009 *New Hampshire Energy Code*	0.004	--	--
2009 *Georgia Energy Code*	0.004	--	--
2009 *Rode Island Energy Code*	0.004	--	--
2009 *Oregon Energy Code*	0.004	--	--
2010 *Washington Energy Code*	0.004	--	--
ASHRAE 90.1* & 189.1P**	0.004	0.04	--
US Army Corps of Engineers (USACE)†	0.004	0.04	0.25
Washington State; Seattle, WA	0.004	--	0.25
IGCC††	--	--	0.25

* ASHRAE 90.1 2010 version includes a continuous air barrier mandatory requirement
** ASHRAE 189.1P, *Sustainable Buildings Standard*: 1st Published version, Jan. 22, 2010
† USACE's Building Envelope Airtightness Standard
†† International Code Council's (ICC's) *International Green Construction Code*; version 1 published March 2010; Final publication intended for 2012

Air leakage can negatively affect IAQ and occupant comfort, but its impact is often misunderstood. The authors believe statements such as "the more airtight our buildings are, the more polluted inside they may be" are misleading. In fact, the opposite is true—reducing the uncontrolled air leakage can improve the indoor environment by minimizing drafts (*i.e.* occupant comfort), reducing contaminant transport, and eliminating instances of water accumulation in the wall cavity and subsequent biological growth.

Figure 3



Impact of M & V Programs on Building Envelope Airtightness

Continuous air barriers and code regulations

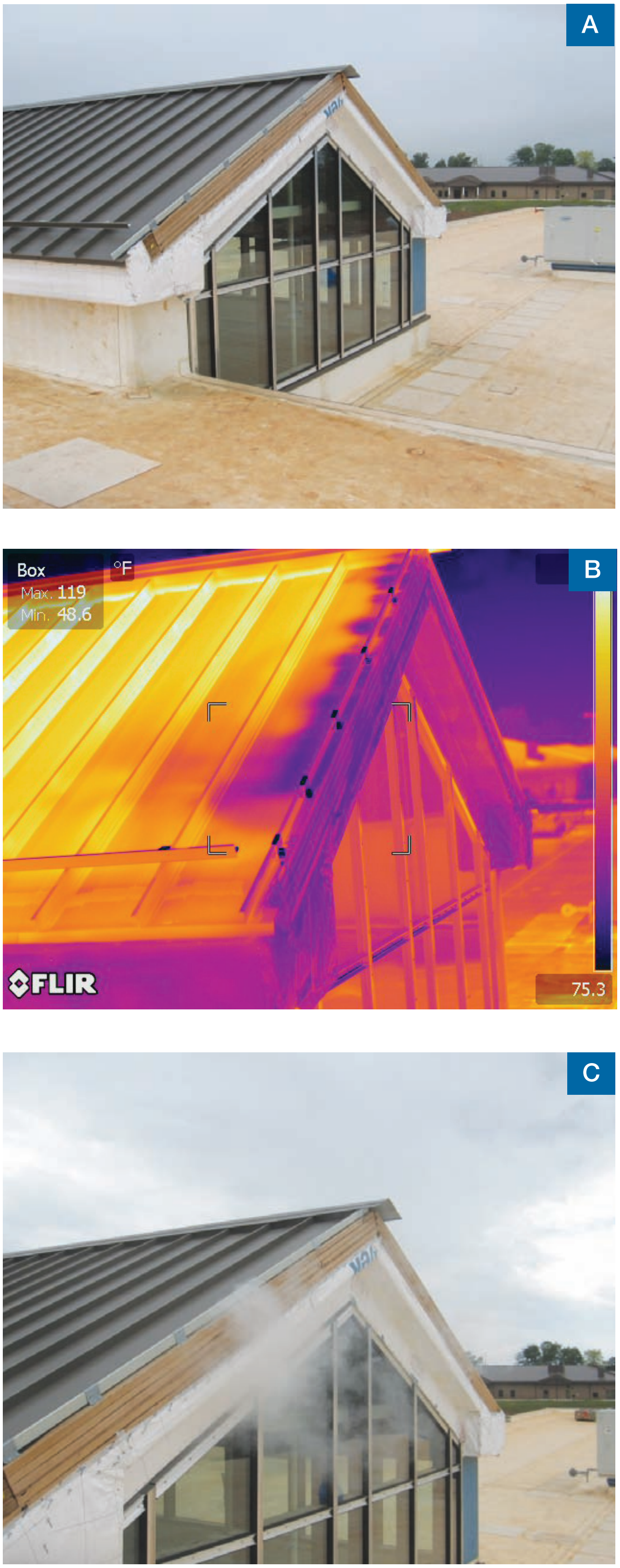
An air barrier system is a combination of air barrier materials and accessories (*i.e.* installation accessories and transitional components that provide continuity) that help achieve a continuous barrier to air movement through the building enclosure.

As mentioned, U.S. energy codes had no quantifiable and enforceable air leakage requirements until recently. For example, ASHRAE 90.1, *Energy Standard for Buildings Except Low-rise Residential Buildings*, required building envelope sealing, but included no acceptable air leakage rates for air barrier materials, assemblies, or whole buildings. Figure 2 summarizes the main air barrier codes adopted to date by different states or national code bodies. These include requirements for air barrier materials, assemblies, or whole buildings.

Air barrier materials

An air barrier material is a primary element within the wall or roof assembly that provides a continuous barrier to air movement. The current standard is an air permeance not to exceed 0.004 cfm/sf at a pressure difference of 0.3 in. w.g. (*i.e.* 0.02 L/s-m^2 at 75 Pa), when tested in accordance with ASTM E 2178, *Standard Test Method for Air Permeance of Building Materials.*

Figure 4



Non-continuous air barrier at roof-to-rake-wall interface. (A) Digital picture; (B) IRT scanning performed under building pressurization; (C) Large-scale smoke tracer generation test performed under building pressurization.

The most common material, the air barrier membrane, is specifically designed to achieve easy continuity with the various interfaces; depending on the manufacturer, they can be mechanically fastened, fluid-applied, or self-adhered.

Additionally, many common building materials such as plywood, oriented strandboard (OSB), closed-cell sprayed polyurethane foam (SPF) insulation, or extruded polystyrene (XPS) board insulation meet the air barrier materials requirements. The materials by themselves must be integrated together in an 'assembly' and, ultimately, a 'system' must be effective, as discussed later in this article.

The *National Building Code of Canada* (*NBC*) has had an air barrier material requirement since 1995. Six years later, Massachusetts became the first state to adopt the Canadian code for air barrier materials. Since then, many others have followed suit.

Air barrier assemblies

An air barrier assembly includes the air barrier materials and accessories that provide a continuous designated plane to the movement of air through portions of building enclosure assemblies. These assemblies must have an air permeance not to exceed 0.04 cfm/sf at 0.3 in. w.g. (0.2 L-s/m^2 at 75 Pa), when tested in accordance with ASTM E 2357, *Standard Test Method for Determining Air Leakage of Air Barrier Assemblies*, or ASTM E 1677, *Standard Specification for an Air Retarder Material or System for Low-rise Framed Building Walls*. ASHRAE 90.1-2010 includes a mandatory requirement for both air barrier materials and assemblies.

Whole buildings

A continuous air barrier system's ultimate goal is whole building airtightness. The country's measurement and verification standard for this attribute was introduced by the U.S. Army Corps of Engineers (USACE). USACE requires an air leakage rate that is not to exceed 0.25 cfm/sf of envelope @ 0.30 in. w.g. (*i.e.* 1.27 L/s-m^2 of envelope @ 75 Pa) when tested in accordance with the USACE air leakage test protocol, which was based on ASTM E 779, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.*

USACE and the building envelope airtightness program

The 2005 *Energy Independence Security Act* (*EISA*) set forth aggressive energy reduction requirements on all new construction and major rehabilitation projects. Three years later, the U.S. Army Corps of Engineers

Airtightness testing for a larger building. Multiple three-fan setups are typical for such sizable structures.

implemented a whole building air leakage measurement and verification program to address the potential energy savings and meet the act's requirements.

USACE mandates the building enclosure be designed, constructed, and tested to demonstrate the air leakage does not exceed 0.25 cfm/sf of envelope @ 0.3 in. w.g. (*i.e.* 1.27 L/s-m^2 envelope @ 75 Pa). To the authors' knowledge, this is the first performance measurement and verification (M&V) program for building enclosure airtightness that has been implemented by a governing agency in the United States.

The air leakage test uses portable, calibrated fans to supply a measured airflow into or out of the building while simultaneously measuring the pressure differential created. Tighter building enclosures require less airflow to achieve a certain pressure. The USACE protocol requires sufficient 'passing' airflow (which is based on the cfm/sf$_{envelope}$) to be supplied during the test and extensive verification of uniform pressure differential, which demands significant portable fan capacities and pressure monitoring equipment.

Testing a large commercial building is more complex than the residential 'blower door' test used successfully for many years by the Department of Energy's (DOE's) Energy Star program. For example, buildings with more than 27,870 m^2 (300,000 sf) of floor area have been successfully tested as a single zone, requiring over 47,000 L/s (99,600 cfm) worth of portable fan capacity and 15 pressure-monitoring stations to meet the USACE protocol.

While the codes and standards specify an acceptable air leakage rate for air barrier materials or assemblies, the lack of whole building airtightness measurement and verification lends skepticism about real benefits. Even the best design for a continuous air barrier is not always implemented as intended, particularly at junctions and interfaces where trade coordination issues arise.

A whole building M&V program is performance-based and is able to determine if the building enclosure meets the specified airtightness metric. Most importantly, an M&V program calls attention to detailing and interfacing during the construction phase. This is all but guaranteed to produce better results.

So far, all reports have indicated the USACE M&V program has been successful in terms of ensuring the building enclosure meets the specified air leakage rate. Pie Forensic Consultants conducted a review of more than 50 buildings tested per the protocol. The summary results are plotted in Figure 3 (page 32).

The buildings marked as 'A' were designed and constructed without a measurement and verification program, but met ASHRAE 90.1-2007, including the mandatory air sealing requirements. (One such building was even granted Platinum status under the U.S. Green Building Council's [USGBC's] Leadership in Energy and Environmental Design [LEED] program, tested at 0.7 cfm/sf, or 180 percent leakier than the USACE requirement.) The 'B' buildings were designed and constructed to USACE air barrier standards, including the M&V program. These buildings were also designed to comply with ASHRAE 90.1-2007.[4]

The A-buildings showed a lower leakage rate when compared to average existing buildings. For example, the average air leakage rate for the A-buildings was 0.6 cfm/sf of total envelope surface area at 0.30 w.g. (*i.e.* 3 L/s-m^2 @ 75 Pa), better than the 1.56 cfm/sf of above-grade envelope at 0.30 w.g. (*i.e.* 7.9L/s-m^2 @ 75 Pa) found for more than 200 existing U.S. buildings with available test data.[5]

Further, the B-buildings showed 77 percent improvement in airtightness when compared to their A-counterparts (*i.e.* 0.25 versus 0.6 cfm/sf at 0.30 w.g.). While this limited data does not represent all buildings, it suggests air barrier material standards, and more importantly the M&V programs, can have significant additional impact on air leakage reduction.

Debunking myths amd other challenges in implementing air leakage control

The introduction and implementation of USACE's air barrier program had challenges. While use of air and weather-resistive barrier (WRB) materials is a common industry practice, implementing the additional requirements for continuity (and especially the measurement and verification program) met some resistance.

The concerns were mainly from those tasked with producing building enclosures that meet the USACE air leakage requirements, mostly the prime contractor in design-build projects. These issues were extensively discussed among USACE, building scientists, testing experts, and project teams. The major objections are discussed in the following paragraphs.

It will increase the cost of the project through additional detailing, coordination, materials, and labor.

Many of the materials and details should already be specified to comply with ASHRAE 90.1 and moisture control requirements. Any additional increase in design time should only occur for the first one or two projects until designers understand how to achieve a continuous air barrier system. The material manufacturers already require proper application and interfacing of various materials and components of the air barrier system; the M&V only verifies that it was properly implemented.

It will increase the cost of the project due to the cost of the test.

This is true, but the cost of the test is negligible in comparison to the expense of building construction and potential repairs. If the building owner/developer is willing to pay the minor incremental cost of testing (ranging from five to 90 cents per square foot, based on building size, complexity, location, and testing agency), as is the case of the USACE, there is no cost increase to the actual design-build firm provided the building passes initially.

Overview of mechanically fastened sheet air barrier system installation.

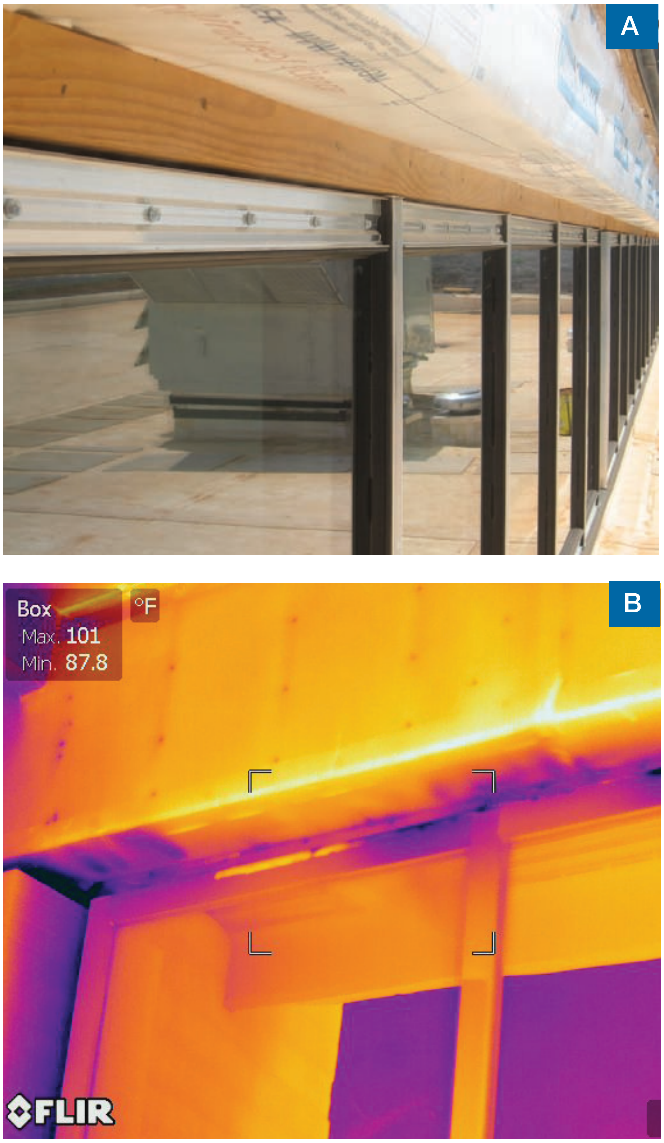
If a building fails, who is responsible for correcting the failed system in terms of cost and labor?

A failed building airtightness test likely involves discussions between the design team, prime contractor, relevant sub-trades, and even the material manufacturers, depending on where the failure occurred. The issues may be easily corrected or they may require cladding removal. A careful review of each party's contract responsibilities before undertaking the air barrier M&V program is strongly recommended to minimize the potential for failure.

When a building fails, does it need to be re-tested after repairs? If so, who pays for the re-test?

This is generally left up to the authority having jurisdiction (AHJ). If the failure was minor and the failure point(s) are clearly identified, re-testing may not be necessary. However, if gross failure occurs, a re-test is likely warranted.

Figure 5



Non-continuous air barrier window-wall interface. (A) Large-scale smoke tracer generation test performed under building pressurization; (B) IRT scanning performed under building pressurization.

Why implement a national standard when studies show the payback analysis varies depending on climate and region?
Based on energy savings simulations, different climates have different paybacks for air barrier implementation, which is typically because of temperature differentials between the outdoor and indoor air. For example, in heating climates, the outdoor air may be –18 C (–2 F) and indoor air 20 C (68 F), for a ΔT of 38 C (70 F). In a cooling climate, the outdoor air may be 32 C (90 F) and indoor air 24 C (75 F), for a ΔT of 8 C (15 F). It takes a greater amount of energy to condition the air per ΔT, not considering the latent load of the outdoor air. For example, cooling 'humid' air compared to 'dry' air requires more energy due to the increased latent load of the former.

However, strictly looking at the energy savings payback analysis ignores the other benefits of a continuous air barrier, as previously discussed in this article. Most importantly, it also ignores the significant role of air and water barriers in moisture control, both as liquid water or water vapor, where the cost to correct a failed system far exceeds any initial cost of implementation.

Are testing agencies sufficiently unbiased and able to perform an accurate test?
The issue of unbiased and competent testing agencies is significant and it has been continuously evaluated under the USACE program. Testing agencies must possess experience in building science and enclosure systems to effectively perform diagnostic evaluations and identify those areas of failure. For these reasons, there is a certification and review process that sets the minimum standards not only for those performing the test, but also for the test protocol itself.

USACE has written its own air leakage testing protocol to ensure all buildings are tested in the same manner. The process of ensuring the qualifications of the personnel performing the actual test is ongoing.

Can the building be too tight to make people sick?
Fresh air ventilation for the occupants should be delivered through a well-designed and commissioned mechanical system that meets or exceeds the requirements of ASHRAE 62.1, and not rely on holes in the building envelope. The "build tight, ventilate right" phrase coined by clever building scientists fully captures the concept of how the building envelope interacts with the mechanical system to provide a healthy environment for occupants.

Industry practices and common mistakes
The most common failures of air barrier systems occur at junctions and transitions. The 2010 edition of ASHRAE 90.1 specifies the following areas where special attention should be given to wrapping, sealing, caulking, gasketting, or taping to achieve a continuous air barrier and to minimize air leakage:

- joints around fenestration and door frames (both manufactured and site-built);
- junctions between walls and floors, between walls at building corners, and between walls and roofs or ceilings;
- penetrations through the air barrier in building envelope roofs, walls, and floors;
- building assemblies used as ducts or plenums; and
- joints, seams, connections between planes, and other changes in air barrier materials.

Even when details are provided for the most common interfaces, there is no guarantee they are constructed onsite per the design details.

This is due to the fact the interface involves multiple trade coordination, such as the roofing subcontractor, air/weather barrier installer, vertical wall framer, and fenestration installer. Too often, a single trade will leave and assume the next guy will finish the job.

It is the responsibility of the general contractor to conduct the necessary coordination meetings and visual oversight at critical junctures (*e.g.* wall-roof transitions, fenestration, and elevation changes) during construction to ensure the air barrier is continuous, and able to withstand loading per the project requirements. A building enclosure commissioning (BECx) program implemented in the project helps address these challenges.

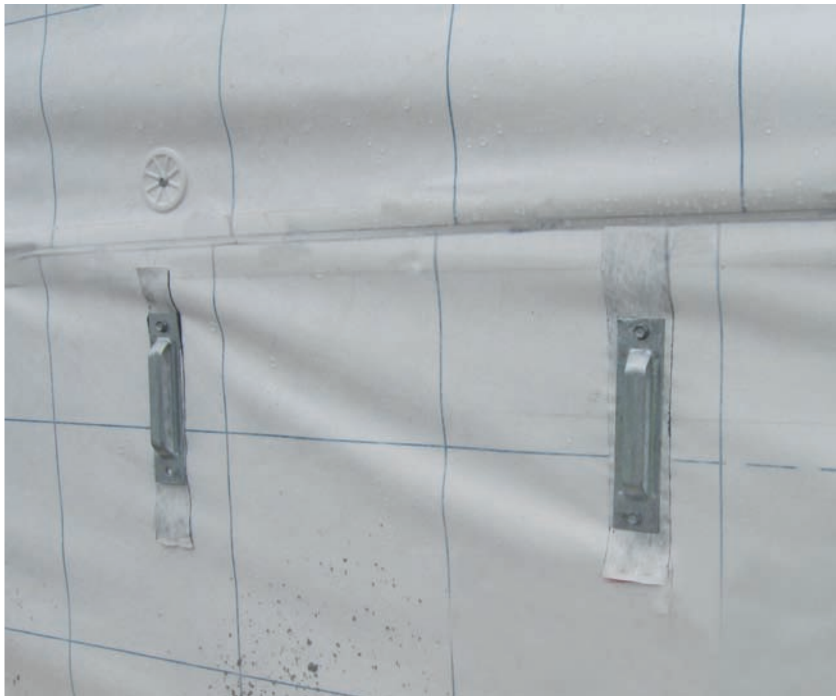
The authors have found the most important transitions for potential failures are the interface between the vertical wall and roof-ceiling air barrier system, and the wall-to-window interface. Figure 4a (page 34) illustrates the lack of integration of the rake wall and roof air barrier materials, as shown by IRT and verified by a smoke generation test.

The infrared thermogram and smoke test were performed with pressurized building during a warm day (*i.e.* cooler indoor air exfiltrating). The infrared thermogram (Figure 4b) highlights the gross failures that can occur when the air barrier materials are not properly tied in at interfaces. However, it is always prudent to verify the conditions observed with IRT are indeed due to air leakage and not a thermal bridge or differential solar loading. In this case, it was accomplished with a large-scale smoke tracer generation test (Figure 4c) that confirmed air leakage at the wall-roof interface. Figure 5 (page 38) shows a similar example for a wall-window interface.

In the authors' experience, penetrations through the air barrier due to mechanical attachments of different wall components (*e.g.* brick ties or metal panel façade clips, screws installed at 305 to 406 mm [12 to 16 in.] on center [oc] vertically and horizontally) were not a common source of air barrier failure.

Questions about mechanical penetrations are very common during pre-construction or site meetings by the design and construction team. It is important to note the requirements for air barrier materials, assemblies, and whole buildings allow for small imperfections and penetrations inherent to the construction process.

For example, air barrier materials must not exceed 0.004 cfm/sf @ 0.3 in w.g. (*i.e.* 0.02 L/s-m^2 @ 75 Pa) per



This photo shows a close-up of lap and fastener treatment in a mechanically fastened sheet air barrier.

ASTM E 2178, an order of magnitude tighter than the requirements for air barrier assemblies (not to exceed 0.04 cfm/sf @ 0.3 in. w.g [*i.e.* 0.2 L/s-m^2 @ 75 Pa] per ASTM E 2357), which is in turn an order of magnitude tighter than the requirements for whole building airtightness (0.25 cfm/sf @ 0.3 in. w.g [*i.e.* 1.27 L/s-m^2 of envelope @ 75 Pa] per USACE protocol).

Further, air barrier material manufacturers recommend mechanical penetrations be flashed and sealed, and peel-and-stick air barrier materials provide some level of 'self-sealing' around typical fasteners. It should also be noted that air barrier system failures during the air leakage test are rarely—if ever—attributed to small penetrations, fishmouths, wrinkles, pinholes, etc., even though these imperfections could affect the long-term air barrier durability and moisture control capabilities.

Rigorous quality assurance and field verification is beneficial and needs to address not only small defects, but also critical intersections and penetrations that contribute to the big holes often responsible for whole building air leakage test failures. Too often, the project team and building consultants do not see the forest for the trees.

Conclusion

In terms of energy reduction, the cost-effectiveness of air barrier systems varies by climate due to the temperature differentials between outdoor and indoor air, with colder regions experiencing greater energy savings. However, air barrier systems are beneficial in every climate when considering all other benefits that are not as easily quantified, and are beginning to be mandated by national codes and standards.

The lack of measurement and verification lowers the likelihood the building's air leakage will actually be reduced even if well-worded prescriptive requirements and material standards are in place. This is supported by the test data summary included herein as well as other studies. Implementation of an M&V system is not without hurdles, but many of those obstacles have been (or are in the process of being) addressed under the USACE program. It is the authors' hope other governing agencies and jurisdictions will look at the success the USACE program has had on minimizing building shell air leakage and consider implementation.

Common mistakes and failures of the air barrier systems are not a result of the material or small defects, but rather occur at junctions, transitions, and interfaces. Projects addressing these interfaces in the design phase and implement a strong quality assurance or BECx program during construction increase the likelihood of success in terms of meeting the USACE air barrier system requirements. **CS**

Notes

[1] See NISTIR 7238, *Investigation of the Impact of Commercial Building Envelope Airtightness on HVAC Energy Use*, by Steven J. Emmerich, Tim McDowell, and Wagdy Anis.

[2] For more, see the March 2009 paper, *Building America Special Research Project: High-R Walls Case Study Analysis, Research Report #0903*, by John Straube and Jonathan Smegal.

[3] Hear Joe Lstiburek's "Air Barrier or Vapor Barrier?" as part of *GBA Advisor*'s March 10, 2010 "Building Science Podcast." Visit www.greenbuildingadvisor.com/blogs/dept/building-science.

[4] Other than verification, are there significant differences between ASHRAE 90.1 and ASCE? If one considers the last published edition of the former, the answer is yes. While ASHRAE 90.1-2007 requires the building enveloped be "sealed and caulked," it does not have any specific air barrier requirements for materials, assemblies, or whole building. It is like requiring the building be insulated, without specifying an R-value for the insulation. The upcoming version of ASHRAE 90.1-2010 will have a mandatory requirement for air barrier materials and assemblies, even though it fell short of having a whole building requirement or a measurement and verification requirement. However, there is already work on including a measurement and verification under the performance option that could allow the earning of some LEED points for airtightness. However, this will not be part of the soon-to-be-published 2010 version, but rather an amendment to the standard.

[5] Emmerich and Andrew K. Persily's "Airtightness of Commercial Buildings in the U.S." was sponsored by DOE's Office of Building Technologies under Agreement No. DE-A01EE27615.

ADDITIONAL **INFORMATION**

Authors

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Abstract

U.S. codes and regulations have increased their focus on energy-efficient strategies for reducing a building's environmental impact. However, until recently the energy codes have been slow in passing prescriptive requirements for air leakage control and the industry has been lacking the knowledge to implement effective air leakage reduction measures. This article reviews the most recent changes in air barrier codes, industry practices, and examples of successful implementation of airtight building envelopes.

MasterFormat No.

07 27 00–Air Barriers

UniFormat No.

B2010–Exterior Wall Vapor Retarders, Air Barriers, and Insulation

Key Words

Division 07

Air barrier systems

Air leakage

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