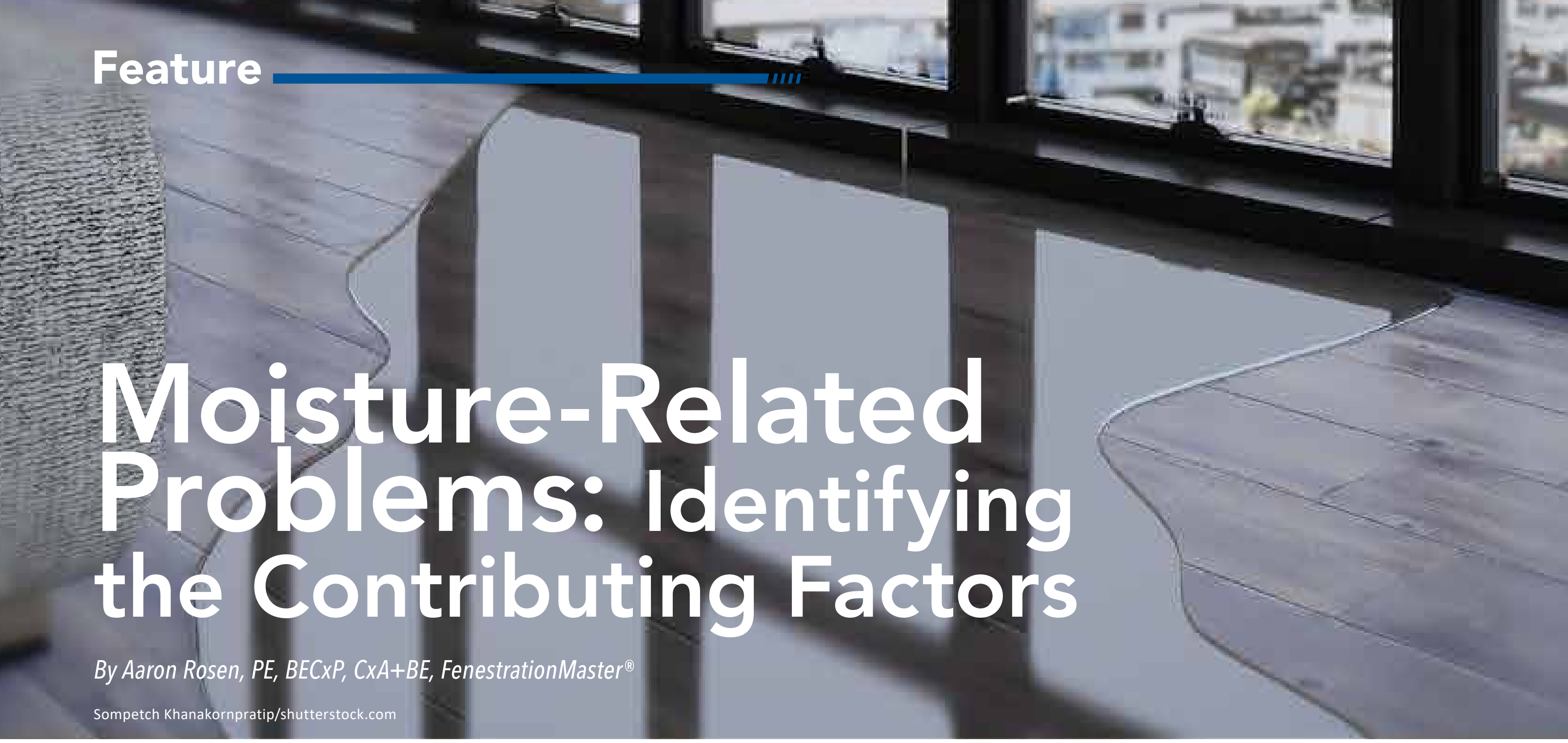

Moisture-Related Problems: Identifying the Contributing Factors

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WATER LEAKAGE WAS reported shortly after substantial completion of a three-story, Class A office building. The reported water leakage was limited to the south elevation of the building and occurred only on hot and sunny days that were preceded by rainfall. The owner notified the project team and asked them to resolve the issue at hand. The glazing contractor performed hose-water testing in accordance with AAMA 501.2, *Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls and Sloped Glazing Systems*,[1] which did not result in any water leakage. The general contractor did not offer another possible explanation. The owner then asked a third party to investigate and provide an objective technical opinion. Based on an extensive forensic investigation, it was determined that the reported water leakage was the result of summertime condensation. This conclusion was based on identifying a source of water vapor, a driving force, and unobstructed paths for the moisture-laden air to travel through the building enclosure.

A notable aspect of this case study is that other third-party experts appeared to have misinterpreted the findings from the investigation. One of them claimed that the condensation was the result of a negative building pressure, even though an independent test report indicated the HVAC system was operating at a positive pressure. Another expert proposed a repair approach that would not have properly contained the water vapor in the cavity behind the brick veneer.

This article provides a relatable way to evaluate the basic performance attributes of building enclosure products and systems by breaking down the technical concepts into source, path, and pressure. Assigning these items to an air- or water-leakage problem is straightforward. The same concept can also be applied to the flow of water vapor and heat, both of which have an impact on condensation and moisture accumulation.

This article is offered as a resource for forensic engineers who perform failure analyses of moisture-related building enclosure issues. It also serves as a cautionary reminder to design professionals that they should not arbitrarily incorporate/locate components in a wall assembly.

BUILDING ENCLOSURE PERFORMANCE ATTRIBUTES AND PROBLEMS

Building enclosures are designed to protect inside conditioned spaces from the outside environment. That might sound like a straightforward expectation, but there can be challenges in achieving an even basic level of performance.

Every building has distinctive physical features such as size, shape, and cladding materials, just to name a few. Then there is the geographic location, which dictates the environmental conditions such as outside temperature, wind, humidity, and rain. The team of designers, contractors, suppliers, and installers varies from project to project, meaning each building is constructed by different personnel. What could possibly go wrong? This question is asked facetiously because, unfortunately, building enclosure–related problems occur all the time.

The most common construction defect claims are moisture-related problems associated with the building enclosure.[2] These issues can be the result of excessive air leakage, water leakage, condensation, or moisture accumulation. In some circumstances, a building will experience multiple issues at the same time.

I have been hired numerous times as a third party to provide an objective technical evaluation for these enclosure-related issues, and the forensic investigation usually reveals a path for air or water leakage through the building enclosure. Sometimes, there are other contributing factors that might not have manifested into a noticeable problem on their own. Compared to an air- or water-leakage problem, investigating the root cause of a condensation or moisture accumulation problem can be a bit more complicated, and guidance for performing a failure analysis will be discussed later in this article.

THE LEAK TRIANGLE

A simple concept for evaluating an air or water leak through the building enclosure is the "leak triangle,"[3] which is composed of a source, path, and pressure (**Fig. 1**). Removing any one of the

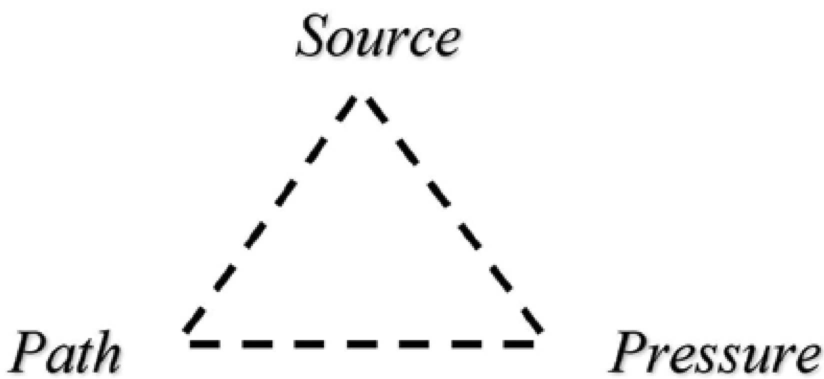

Figure 1. *The leak triangle.*

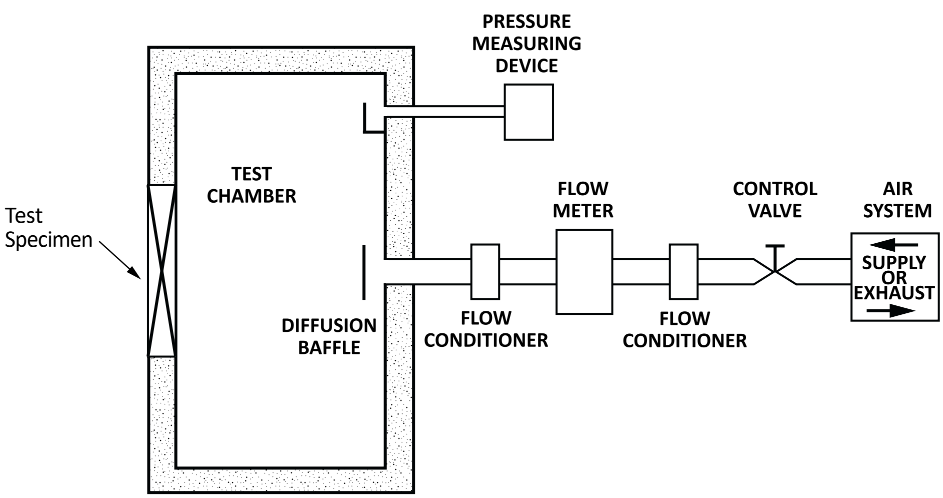

Figure 2. *Test apparatus for ASTM E283,* Standard Test Method for Determining Rate of Air Leakage through Exterior Windows, Skylights, Curtain Walls, and Doors under Specified Pressure Differences across the Specimen.

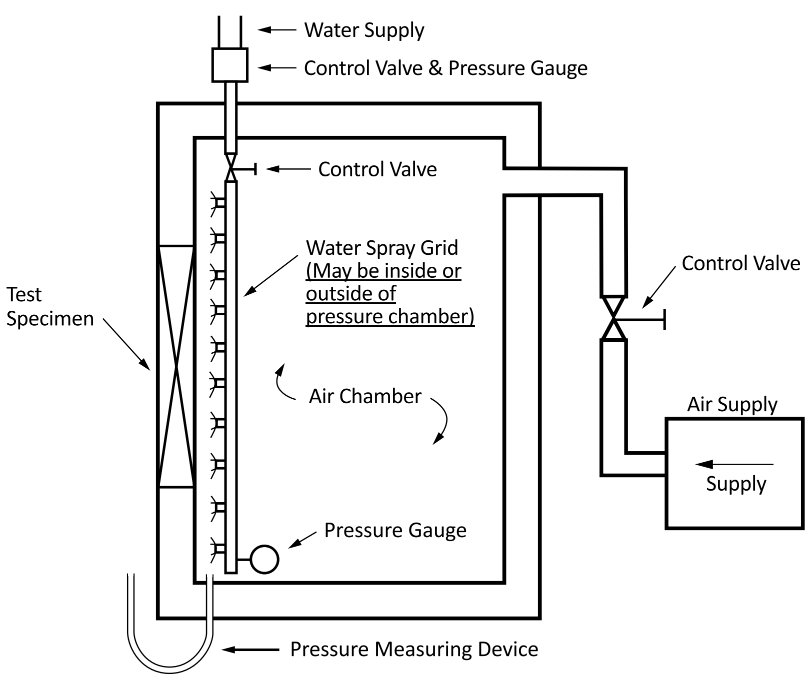

Figure 3. *Test apparatus for ASTM E331,* Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

three parts of the triangle will resolve a leakage issue. Therefore, as described in the following sections, both product performance validation for building enclosure components/systems and forensic investigations of leakage problems involve assessment of the leak triangle.

Air Performance Rating

Industry standards for determining the air performance rating of various building enclosure products and systems include ASTM E2178, *Standard Test Method for Determining Air Leakage Rate and Calculation of Air Permeance of Building Materials,*[4] and ASTM E283, *Standard Test Method for Determining Rate of Air Leakage through Exterior Windows, Skylights, Curtain Walls, and Doors under Specified Pressure Differences across the Specimen.*[5] To perform these tests, a static pressure differential is imposed across a test chamber, which either "pulls" or "pushes" air through the test specimen. The resulting air leakage is measured in units of ft^3/min (L/s). The air leakage rate, which is determined by dividing the amount of air leakage by the test specimen area, can then be used to evaluate and compare products. In terms of the leak triangle, the air is the source, the test specimen comprises the path, and the vacuum suction is the pressure (**Fig. 2**).

Air Leakage

There are unfavorable circumstances in which excessive air leakage occurs through the building enclosure. When such leakage happens, the amount of water in the air (water vapor) transported through the air (vapor transport) will be much greater than if it would be diffused through a material (vapor diffusion).[6] Thus, air leakage can be a significant contributing factor to moisture-related problems.

Unobstructed paths such as unsealed joints or holes will allow air to freely travel through the building enclosure. Investigators can use the test methodology described in ASTM E783, *Standard Test Method for Field Measurement of Air Leakage through Installed Exterior Windows and Doors,*[7] as a guide when looking to quantify the amount of air leakage through the building enclosure. Sometimes, the paths for air leakage can be identified by visual observation. However, temporary removal of cladding components to create exploratory openings is required if the deficient building conditions are concealed.

Revisiting the leak triangle, the earth's atmosphere is not a vacuum, and it would also be unusual for wind pressure to exceed the product performance rating for a sustained period of time. Thus, the source and pressure components of the

Table 1. *Leak triangle comparison between air performance rating and air leakage*

	Air Performance Rating	Air Leakage
Assessment method	Window system testing per ASTM E283	Common failure analysis
Source	Air leakage rate	Air
Path	Test specimen	Holes, joints, interface conditions
Pressure	Static pressure differential	Wind (+/-), HVAC (+/-), stack effect (+/-)

Table 2. *Leak triangle comparison between water performance rating and water leakage*

	Water Performance Rating	Water Leakage
Assessment method	Window system testing per ASTM E331	Common failure analysis
Source	Water spray rack	Rain
Path	Test specimen	Holes, joints, interface conditions
Pressure	Static pressure differential	Wind (+), HVAC (-), stack effect (-), gravity, hydrostatic pressure, surface tension, capillary suction

leak triangle are generally not the primary focus in an air leakage forensic investigation. Typically, it is the path or paths that need to be addressed to resolve an air leakage problem. Occasionally, adjustments to the HVAC system may be needed to help address a building pressure issue.

Water Performance Rating

A common test procedure for evaluating water performance is defined in ASTM E331, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*.[8] Assigning the components of the leak triangle to the procedure, the water is the source, the test specimen is the path, and the vacuum suction creates the pressure differential (**Fig. 3**). This test standard specifies a constant water flow for a certain amount of time. Upon completion of the test, and assuming water leakage is not observed, that product is then considered to be "rated" for the tested static pressure differential.

Water Leakage

For water leakage to occur through the building enclosure, there must be a source of water, a path, and a pressure. ASTM E2128, *Standard Guide for Evaluating Water Leakage of Building Walls*,[9] and AAMA 511, *Voluntary Guideline for Forensic Water Penetration Testing of Fenestration Products*,[10] are industry-recognized guidance for investigating water leakage through exterior walls and window systems, respectively.

Similar to air leakage problems, water-leakage problems typically involve a deficient building condition that provides a path for leakage through the enclosure. It is possible that a negative building pressure is also a contributing factor to the problem. On rare occasions, an extreme horizontal wind-driven rain event or flooding can exceed the capabilities of a rated product or system.

Summarizing the Leak Triangle

Tables 1 and **2** provide side-by-side comparisons of how the parts of the leak triangle apply to product performance ratings and in-service leakage problems. When evaluating the air performance of a building enclosure product or system, the key parameters are the air-leakage rate in units of $ft^3/min/ft^2$ ($L/s/m^2$) and the static pressure differential in units of lb/ft^2 (Pa). Product performance ratings used to evaluate water performance are described by the static pressure differential in units of lb/ft^2 (Pa).

When a building is experiencing an air- or water-leakage problem, the forensic engineer should investigate and analyze all three components of the leak triangle. In my experience, the failure analysis will generally indicate a deficient building condition that provided a path for the leakage to occur. Under this scenario, addressing the path of leakage would resolve the issue.

THE FLOW TRIANGLE

Using the same components as the leak triangle (source, path, and pressure), the "flow triangle" describes the flow of both water vapor and heat. The flow triangle can be helpful when analyzing moisture-related problems such as condensation and moisture accumulation. Before these issues are reviewed in further detail, a brief overview of some building enclosure components that control the flow of water vapor and heat is warranted.

Vapor Permeance Rating

There are several ways to quantify water vapor such as dew point temperature, humidity ratio, water vapor partial pressure, or water vapor concentration. When there is a difference in the amount of water vapor across the building enclosure, the water in the air will travel from areas with higher concentrations of water vapor to areas with lower concentrations. For many geographic

Table 3. *Water vapor flow triangle comparison between vapor permeance rating and moisture accumulation*

	Vapor Permeance Rating	Moisture Accumulation
Assessment method	Vapor retarder component testing per ASTM E96	Possible contributing factors
Source	Water vapor	Water leakage, air leakage, water vapor, condensation
Path	Test specimen	Location/placement and permeance rating of a vapor retarder
Pressure	Water vapor partial pressure differential	Water vapor partial pressure differential

Table 4. *Heat flow triangle comparison between thermal resistance rating and moisture accumulation*

	Thermal Resistance Rating	Moisture Accumulation
Assessment method	Thermal insulation component testing per ASTM C518	Possible contributing factors
Source	Hot plate	n/a
Path	Test specimen	Location/placement and resistance rating of thermal insulation
Pressure	Temperature differential (analogous comparison)	n/a

Note: n/a = not applicable.

locations, the direction of water vapor travel is typically from the outside to the inside of the building in the summer and from the inside to the outside in the winter.

One way to determine the rate of water vapor transmission through a material is to perform testing per ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials*.[11] There are two different methods in this test standard (wet cup and dry cup), the primary differences being the amount of water vapor and direction of the vapor flow (**Fig. 4**). With reference to the components of the flow triangle, the water vapor is the source (100% relative humidity [RH] for wet cup and 50% RH for dry cup) in this test scenario; the test specimen resists the flow of water vapor along the path; and the differences in water vapor provide the pressure (water vapor partial pressure).

This testing provides a vapor permeance rating in units of perms (ng/[Pa·s·m^2]). When comparing products, a lower vapor permeance rating indicates that the product will provide more resistance against the flow of water vapor.

Thermal Resistance Rating

Heat flows from hot areas to cold ones, and thermal insulation can be used to minimize heat loss across the building enclosure. A test for obtaining the thermal performance of a material is ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*.[12] This testing evaluates the thermal resistance of a product, stated as the *R*-value. The higher the *R*-value is, the more resistant the product is to heat flow.

Applying the flow triangle model to the test apparatus shown in **Fig. 5**, the hot plate is considered the source of heat, the test specimen resists the flow of heat along the path, and the temperature differential is analogous to the pressure component.

Condensation

Condensation occurs when the water in the air changes from the gaseous phase to the liquid phase. It will form when moisture-laden air comes into contact with a material having a surface temperature at (or below) the dew point temperature. When a condensation problem occurs, a rudimentary explanation likely involves a high amount of water vapor or a material surface that is too cold.

When performing a forensic investigation, the first step is to identify the source or sources of water vapor, and then the path or paths for vapor transport should be located. In cold climates, the forensic engineer will also want to determine whether materials with a low resistance to heat flow (such as steel or aluminum) comprise a continuous path through the building enclosure, creating what is known as a "thermal short circuit."

Moisture Accumulation

Moisture accumulation develops when the rate of wetting exceeds the rate of drying. In many instances, moisture accumulation within the building enclosure will accompany air- or water- leakage problems. Thus, a failure analysis for those potential problems should be performed when commencing a forensic investigation.

When analyzing a moisture accumulation problem, the forensic engineer will also have to consider the contribution of water vapor and heat. Unlike an air- or water-leakage problem, impeding the path component of the flow triangle might not necessarily address a moisture accumulation problem. This would entail decreasing the permeance of the vapor control layer or increasing resistance of the thermal control layer, which under certain conditions could inadvertently exacerbate the issue.

As previously mentioned in this article, there are industry guidelines that can be referenced when investigating air- or water-leakage issues. Dissecting and analyzing the components of a moisture accumulation problem, however, is not as straightforward. After developing a hypothesis about the potential components of the water vapor and heat flow triangles, a thorough and methodical investigation is necessary. It is important to keep in mind that air or water leakage, or both types of leakage, may be contributing factors to the moisture problem.

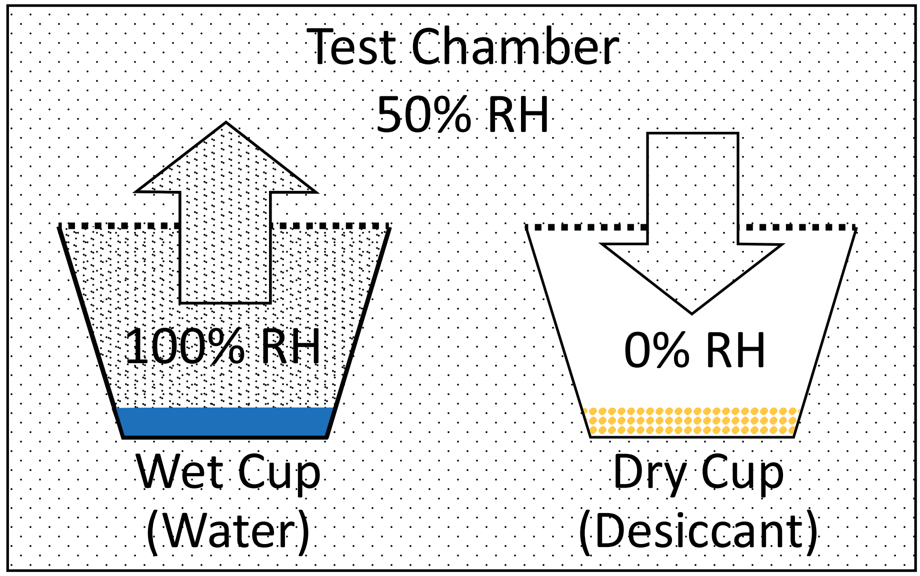

Figure 4. *Test apparatus for ASTM E96,* Standard Test Methods for Water Vapor Transmission of Materials.
Note: RH = relative humidity.

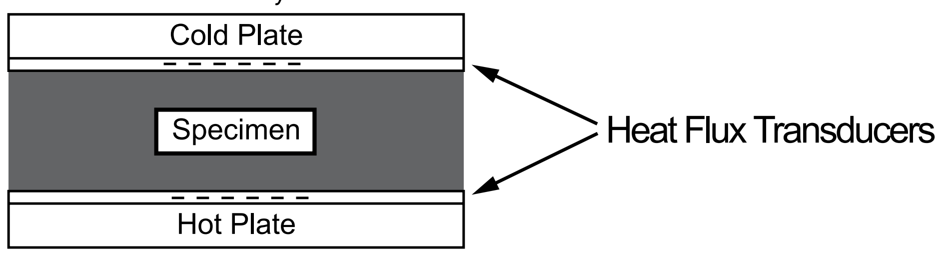

Figure 5. *Test apparatus for ASTM C518,* Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.

The location/placement of thermal insulation will influence both the water vapor pressure profile and temperature gradient, both of which have the potential to affect wetting and drying rates.

Summarizing the Flow Triangle

Tables 3 and **4** summarize how the parts of the flow triangle apply to the testing of building components and the investigation of a moisture accumulation problem. These tables can be used as a reference but should not be considered a comprehensive list of all possible contributing factors.

The *International Building Code*[13] has classifications for materials that impede the flow of water vapor (vapor retarders) as well as restrictions, based on climate zone, for their location/placement within a wall assembly. A potential consequence of improper usage of a vapor retarder is restricting the drying ability of an assembly, which could be a contributing factor to a moisture accumulation problem.

Incorporating a thermal control layer is an important design consideration for the building enclosure. The location/placement of thermal insulation will influence both the water vapor pressure profile and temperature gradient, both of which have the potential to affect wetting and drying rates. A hygrothermal analysis can serve as a useful tool to analyze different building enclosure assemblies and environmental conditions. Alternatively, the American Society of Heating, Refrigerating and Air-Conditioning Engineers provides a rather simple, steady-state, one-dimensional analysis called the dew-point or Glaser method, accompanied with a couple examples.[14]

SYSTEMS VERSUS COMPONENTS

Pre-engineered building enclosure systems, such as windows, typically have laboratory-tested air- and water-performance ratings. Assuming that the system is properly installed and coordinated with adjacent enclosure systems, the rating provides a reliable indication of in-service performance.

It should also be expected that the vapor- and thermal-control layers perform as indicated on their respective product data sheets. When these components are incorporated into an exterior wall or roof assembly, they have an impact on overall system performance, which must be carefully reviewed and considered during the design process. The use of a vapor retarder requires additional scrutiny and should not be arbitrarily integrated into the building enclosure.[15]

TAKEAWAY

There is no shortage of complex topics to discuss regarding today's high-performance buildings and their enclosures. Whether you are a design professional or forensic engineer, a simple way to evaluate the basic functional performance attributes of these systems is to delineate and analyze the components of the leak and flow triangles (*source*, *path*, and *pressure*).

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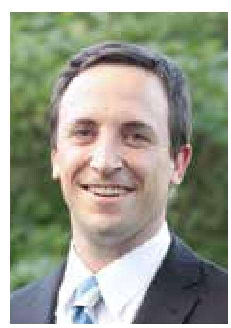

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