It’s Not Raining—Where is the Water Coming From? Moisture Movement in Building Enclosures

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ABSTRACT

Water damage is the most common reason for lawsuits against builders. In the springtime, the roof leaks, even though it has not rained for months. Where is the water coming from? I used high-permeable materials in the building construction, so why do I have moisture problems? I have been constructing buildings for decades, and I never had moisture problems in the past—why am I facing them now? This presentation explores the ways that moisture moves in buildings and why moisture problems are showing up in today's construction. The energy and moisture transport calculator is used to provide answers to these questions.

SPEAKER

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Laverne Dalgleish has spent most of his life in the construction business. As the executive director of the Air Barrier Association of America (ABBA), he has been involved in all their research projects, starting with a major initiative to demonstrate the energy savings of airtight buildings. Dalgleish is the coordinator for developing material specifications for air and water-resistive barriers as well as test methods to determine material properties. As the developer of ABAA's Site Quality Assurance Program, he saw the problems caused by water intrusion and poor workmanship.

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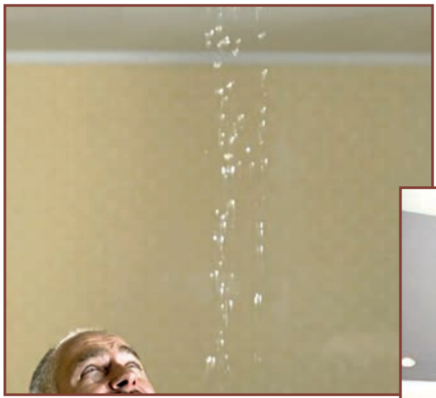

Figure 1. Water coming from roof.

Figure 2. Water damage.

Ceilings can be a problem in cold climates, in both new and existing homes. One specific conundrum is water damage to raised cathedral and nonvaulted ceilings that is evident in the spring but not in the summer (**Fig. 1**). Roofing contractors who installed new roofs in the fall would be called back in the spring to fix roof leaks, even if the water leaks do not correlate to a rain event and the leaks no longer occur in the subsequent summer months. The contractor is always to blame, as “it didn’t leak before you installed the new roof.”

Sometimes it is the roofer’s fault because of installation deficiencies, but in many cases, water intrusion resulted even where proper installation in accordance with the design intent is confirmed (**Fig. 2**). And it is not just roofs that have issues: —basements would have water “leaks” in the spring, which are speculated to be the result of a crack in the foundation until it is discovered that there are no cracks in the foundation, nor any rusting form ties that could leak.

In both cases, the moisture inside the building does not come from outside; it is caused by warm, moist air inside the building that leaks into unconditioned spaces and condenses, even turning to frost. In cold climates, the frost builds up over time and when the weather warms up and the sun shines brightly, the temperature in the unconditioned space would warm and the frost melts. The now-liquid water would show staining on the interior of the ceiling and water would show on the floor of the basement.

The moisture did not come from the outside, it is interior water vapor that condensed.

MOISTURE MOVEMENT IN BUILDINGS

Building physics tells us the answer. The nice thing about building physics is that it does not change, no matter where the building is located or what materials are used.

Moisture always moves from wet to dry and high water vapor pressure to low water vapor pressure. Water is all around us in the form of a solid, liquid, or gas. Moisture moves by gravity, capillary action, diffusion, and air transport.

In many cases—but not all—water in the form of a solid or gas does not lead to problems in buildings that cause lawsuits and unhappy building owners and tenants. Instead, solid water melting to a liquid and water as a gas condensing to a liquid is where we get the problems in our buildings.

For example, a snowstorm in a northern climate can blow snow into the attic of a building with a peaked roof and gable-end vents. At that time, there is no problem; snow can be a good insulator. The problem with snow is that it does not stay snow, it melts (**Fig. 3**).

Figure 3. Snow in attic.

Water as a gas, can lead to high humidity in a building. The humidity can be quite high and not cause a problem if the building enclosure has been properly designed and constructed. The problem is when warm, moist air touches a cold surface; this lowers the air temperature to the dew point where water vapor condenses to liquid water. The cold surface can be caused by cold temperatures outside or by an air-conditioning system inside.

Bulk (liquid) water is handled by roofing materials, shingles, water-resistive barriers, and flashing. The purpose of all these materials is to direct water down and away from the building. Gravity then does its part, as long as the right materials have been installed in the right way. This is priority number one: if liquid water is not kept out of the building, nothing else matters.

In some parts of the country where there are high water tables, water can be wicked up the foundation by capillary action if the foundation is made of a porous material. The same occurs with many materials if part of the material is in liquid water: water will move up the material by capillary action.

Water vapor transmission or diffusion is when water vapor moves through a material. This is an important property to know, but this is where we get off track. Many designers feel that this is the most important property of a material. They design their building around permeable materials, so that the building "breathes." Keep in mind these are molecules of water working their way through a material and for some materials, it can take months for enough water to work its way through to be able to measure the flow and assign a water vapor transmission rate. The permeability of a material is measured in perms. One perm is 57 ng per $(m^2 \cdot s \cdot Pa)$ of water and a nanogram is one billionth of a gram. A drop of water is approximately 0.05 mL, so its mass would be 0.05 g. No matter how you look at this, it is not a lot of water; there are many nanograms of water in one drop.

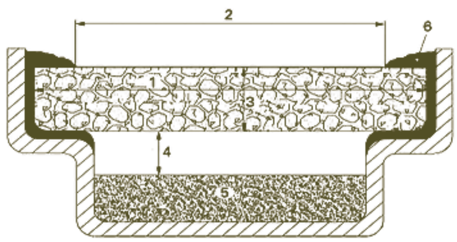

Figure 4. Specimen cup.

Many design professionals focus on the water vapor transmission of a single material and they want a material that can "breathe." Materials that have a water vapor transmission rate of 10 perms (570 ng) or 30 perms (1710 ng) do not have a lot of drying potential. Characteristics of current materials allow water vapor transmission both ways: in and out. Water will always move from wet to dry, so whether moisture goes into or out of a building assembly depends on which side has a higher moisture content, not the material used.

Much of the water damage in buildings is not caused by a material having a water vapor transmission rate that is too high or too low. Moisture movement by air transport is often overlooked because the result is liquid water. When you see liquid water, you expect there is a leak, so you look for a breach or you may feel the material you used is not permeable enough to allow drying. It is important to understand the comparison of moisture movement by water vapor transmission rate through materials and moisture transported by air.

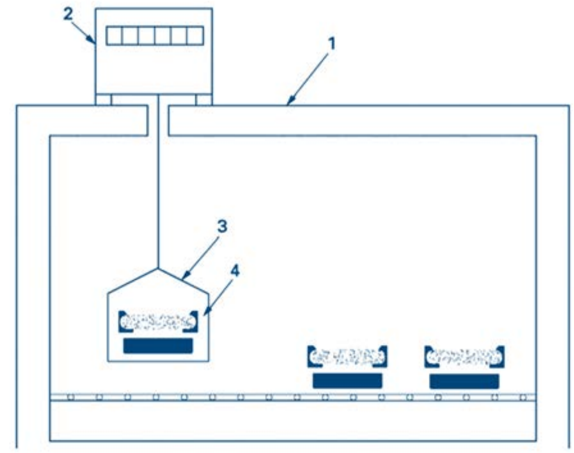

Figure 5. Oven.

Self-Adhered	Desiccant method, ng	Water method, ng	Difference
Minimum water vapor transmission rate	0.572	0.572	0%
Maximum water vapor transmission rate	1763	2830	61%
Mean water vapor transmission rate	1.01	2697	5789%
Minimum percent difference	0	0	4%
Maximum percent difference	1.15	1.26	10%
Mean percent difference	1763	2380	65%

Source: Air Barrier Association of America website.

Table 1. Sampling of water vapor transmission rates for self-adhered sheet membranes; n = 59

Fluid-applied membranes	Desiccant method, ng	Water method, ng	Difference
Minimum water vapor transmission rate	0.572	0.572	0%
Maximum water vapor transmission rate	1763	2830	61%
Mean water vapor transmission rate	0.89	1.8	102%
Minimum percent difference	4.96	5.15	4%
Maximum percent difference	4.3	2034	47202%
Mean percent difference	418	870	108%

Source: Air Barrier Association of America website.

Table 2. Sampling of water vapor transmission rates for fluid-applied membranes; n = 11

WATER VAPOR TRANSMISSION RATE OF MATERIALS

In simple terms, the water vapor transmission rate is how fast water can go through a material and exit on the other side. ASTM E96[1] defines the water vapor transmission rate as "the steady water vapor flow in unit time through [a] unit area of a body, normal to specific parallel surfaces, under specific conditions on temperature and humidity at each surface." This definition is important because it means that a published water vapor transmission rate is only applicable to steady-state conditions at specific atmospheres. It also means that for thicker materials, it does not account for water that enters the material but does not go out the other side.

Understanding what this means requires understanding the test method. The basics are simple. There are two test methods: the desiccant (dry cup) method and the water (wet cup) method (**Fig. 4**). In the desiccant test method, a specimen is prepared with anhydrous calcium chloride in the bottom of a glass dish. The material being tested is then placed over the dish and sealed so that the only way for water vapor to get into the dish is through the material.

The water test method is almost the same preparation for the specimen, except that water is in the bottom of the dish instead of anhydrous calcium chloride. The water molecules then have to work their way through the material to exit the dish.

This creates the driest and the wettest conditions possible inside the glass dish: for practical purposes, 100% relative humidity (RH) and 0% RH. For both the desiccant and water test methods, the specimens are then placed in an oven that is held at 23°C and 50% RH (**Fig. 5**).

For the desiccant method, the conditions are essentially 25% RH as there is 0% RH on one surface and 50% RH on the other surface. For the water method, the conditions are 75% RH as there is 100% RH on one surface and 50% RH on the other surface.

If the atmosphere changes on either side of the material, the water vapor transmission rate changes. The *International Building Code*[2] and the *International Residential Code*[3] require that you meet a water vapor transmission rate using the desiccant method and the code and then identify three classes of vapor retarders.

Here is where the problem comes in. If the vapor retarder is installed in a wall assembly, how often during the year will the material be subjected to an atmosphere of 23°C and 25% RH? If it is installed on the interior, there may be times when the material is subjected to that atmosphere, but if it is installed on the exterior of the sheathing and under the cladding, the amount of time the material will be subjected to this environment will be minimal.

The water test method essentially involves an atmosphere of 23°C and 75% RH. These values are high for an interior application but probably better aligned with the atmosphere when installed on the exterior of a building under the cladding.

However, the point of a standardized test method is not to estimate the performance of a material in situ. It is to determine "the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions on temperature and humidity at each surface." A standard test method is simply a means of comparing materials under a specific set of conditions. An architect asked which test method should be used when designing a building: desiccant or water? It does not matter, as the test method is simply a way of comparing material and has nothing to do with installed performance of the material itself, nor the performance of the building assembly.

It is not possible to determine the difference between the desiccant and water test methods and apply that percentage to materials that only have desiccant method results to determine the water method results. Every material will have different percentages according to the two methods.

The Air Barrier Association of America (ABAA)[4] website provides accredited laboratory results for materials tested according to ASTM E96 using both the desiccant and water methods (**Tables 1** to **5**). The results are surprising.

The website lists the following materials under the heading of assemblies as both the material to be tested and as the material installed in a wall assembly and tested.

- self-adhered sheet membranes
- fluid-applied membranes
- sprayed polyurethane foam (medium-density closed cell)
- mechanically fastened commercial building wrap

Sprayed polyurethane foam (medium-density closed cell)	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	1.13	56	4856%
Maximum water vapor transmission rate	68.9	241	250%
Mean water vapor transmission rate	49	90	84%
Minimum percent difference	68.9	74	7%
Maximum percent difference	24.87	217.36	774%
Mean percent difference	56	1021.13	1723%

Source: Air Barrier Association of America website.

Table 3. Sampling of water vapor transmission rates for sprayed polyurethane foam (medium-density closed cell); n = 16

Factory-bonded membrane	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	1.22	1.1	10%
Maximum water vapor transmission rate	1459	1850	27%
Mean water vapor transmission rate	105.24	279.7	166%
Minimum percent difference	105.24	279.7	166%
Maximum percent difference	1.22	1.1	10%
Mean percent difference	1459	1850	27%

Source: Air Barrier Association of America website.

Table 4. Sampling of water vapor transmission rates for factory-bonded membranes to sheathing; n = 3

Adhesive-backed commercial building wrap	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	6.68	8	20%
Maximum water vapor transmission rate	1763	2030	15%
Mean water vapor transmission rate	614	978	59%
Minimum percent difference	1600	3630	127%
Maximum percent difference	6.86	8	17%
Mean percent difference	614	978	59%

Source: Air Barrier Association of America website.

Table 5. Sampling of water vapor transmission rates for adhesive-backed commercial building wrap; n = 6

The performance of the building assembly needs to be determined based on the total assembly and under the conditions the building assembly will be subjected to.

- boardstock (rigid cellular thermal insulation board)
- factory-bonded membranes to sheathing
- adhesive-backed commercial building wrap

Each of these materials has different water transmission rates when tested according to the desiccant and water method. The minimum, maximum, and mean water vapor transmission rates are listed for all materials. The percent differences listed are the results for the same material.

The data shown in Tables 1 to 5 help to understand two things. First, the results of the ASTM E96 desiccant test method used to determine the water vapor transmission rates of a material cannot be used to indicate the performance of a building assembly. Second, the amount of water that comes through a material or a building assembly is minimal in the big picture and in many cases can be ignored. In cold climates, when the outside air is heated, the RH drops and the air is very dry. In humid climates, if the outside air goes through the heating, ventilation, and air-conditioning (HVAC) system, the amount of water vapor in the air is normally reduced by the equipment.

The performance of the building assembly needs to be determined based on the total assembly and under the conditions the building assembly will be subjected to. If the building assembly will be subjected to high humidity most or all of the time (for example, an indoor swimming pool), or if the building assembly will always have a moisture drive in one direction (for example, a freezer), a vapor barrier can be critical.

Water vapor transmission needs to be determined for the whole building assembly and not just a single material. Each material layer has a different water vapor transmission rate, so the placement of each material is important and will affect the overall building assembly performance. For example, in cold climates, a polyethylene sheet installed on the inside of a building over a fibrous insulation will have a very small amount of water vapor transmission through the material, while the fibrous insulation and all the other materials outboard of the polyethylene material will be kept dry. But if the same polyethylene film is placed on the cold side of the insulation, there can be condensation on the polyethylene sheet if the temperature is at or below the dew point.

The water vapor transmission rate of a whole building assembly can be tested for water vapor transmission in a climate chamber, where a different atmosphere is placed on each side of the assembly. However, changing the construction of the assembly or changing the atmosphere on either side of the specimen will change the results. Testing a whole building assembly gives the overall performance of an assembly, but only at the atmospheres tested.

THE BIG MOISTURE PROBLEMS

Liquid Water

The measures to prevent big water problems in a building should be obvious. First, keep liquid water out. That applies both during and after construction. Correctly install the shingles, avoid holes in a roofing membrane, cover the complete exterior with a water-resistive barrier (do not use an 8 ft sheet on a 10 ft wall), water drainage does not work that way. If the water-resistive barrier comes in rolls, overlap the top sheet over the bottom sheet. Flash every opening properly and have the flashing material direct the water to the outside of the exterior cladding, not just onto the water-resistive barrier. Avoid gaps between pieces of flashing; flashing should be continuous. Direct all water to the outside of the exterior cladding.

These measures are very basic, but many buildings have required hundreds of thousands of dollars' worth of repairs because the basics were not done.

Water Vapor Transmission

When it is determined that the water in the building is not the result of a leak, many people believe that the building assembly has not been allowed to dry out because the water vapor transmission rates of the material were too low. The tendency is therefore to use materials with increasingly higher water vapor transmission rates to solve the problem. Water damage may be blamed on a material with a low water vapor transmission rate and the solution is to use a material with a high water vapor transmission rate.

Materials available in the construction market allow moisture to move in both directions. A material with a high water vapor transmission rate allows water vapor to escape and also allows it to enter the building assembly. A good example is reservoir cladding, such as brick or stucco, where moisture can stay in the material for some time after a rainstorm. The cladding becomes saturated during a rain

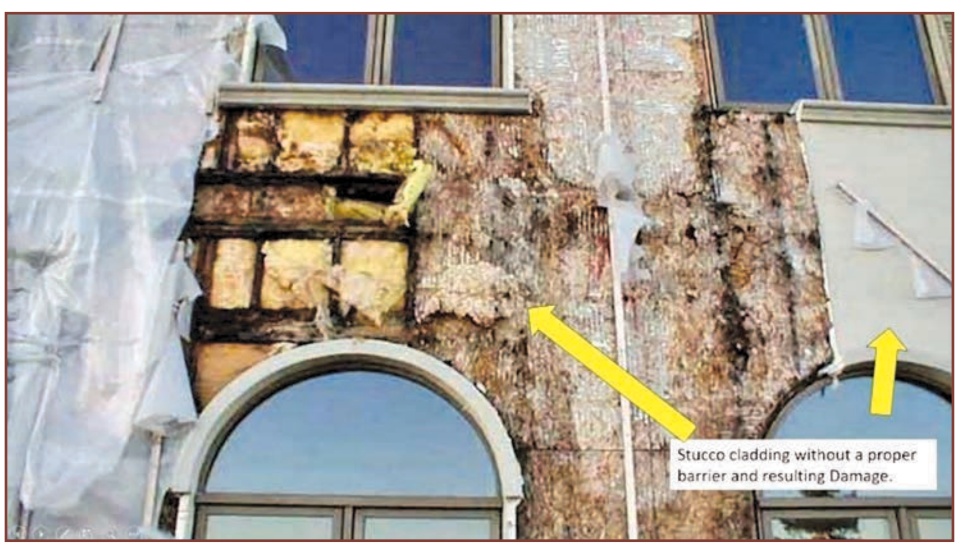

Figure 6. Wall damage.

event and then the sun comes out. The solar energy hitting the wall moves the moisture from wet to dry and from high to low humidity (**Fig. 6**). Moisture moves into the building assembly more rapidly than the drying rate. This will result in an increase in the moisture content of the building assembly. This can lead to mold, mildew, rot, or corrosion. The two-way movement of water vapor through the material needs to be considered when choosing materials for construction.

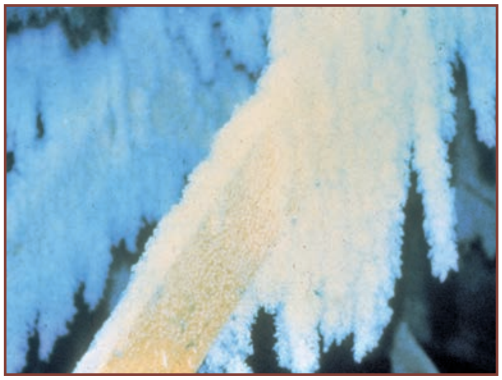

Figure 7. Frost in attic.

Water Vapor by Air Transport

Many people do not equate liquid water or frost can be caused by water vapor. When liquid water is evident in a building or in a building assembly, people look for a water leaks in the assembly or feel that the materials used should have a high water vapor transmission rate to allow the moisture to escape. The amount of water transported by air through the holes and cracks in the building assemblies is not considered (**Fig. 7**).

The ABAA website[5] has an air and water transport calculator that provides this information. Many presentations have included a comparison of the amount of water vapor that goes through 1 m² of drywall in a heating season and the amount that goes through a 2 cm² hole. The National Research Council calculated this over a full heating season for a home in Ottawa, Ontario, Canada. These results are applicable to a single type of building in a single location.

The calculator allows the determination of moisture movement by air leakage for 52 cities the United States and five cities in Canada. The amount of water vapor going through a 1 in.² hole by air movement is compared with a material subjected to conditions in the ASTM E96 desiccant test method. The test is conducted under steady-state conditions and the building is subjected to dynamic, continually changing conditions. The material performs differently in a building than it does in a laboratory. The water vapor transmission amounts in **Table 6** do not indicate field performance. Programs such as WUFI that calculate heat and moisture transport in multilayer building components provide realistic numbers of water vapor transmission of a building assembly.

Table 6 compares the amount of water that moves through a 1 in.² hole in four cities representing different regions and atmospheres in the United States, based on water vapor pressure differences created for each city. The water vapor transmission through a material was calculated using ASTM E96 desiccant test method. This is not an apples-to-apples comparison, but it provides an approximation of the amount of water that moves by air transport compared with the amount of water that works its way through a material over a period of one year. Neither method indicates which way the moisture moves nor how much of the moisture remains in the building assembly.

The difference in air leakage from a mid-rise to a high-rise building is due to stack effect (and reverse stack effect) caused by the height of the building and the temperature difference between inside and outside the building.

When water is observed in a building assembly, there could be more than a single cause of water damage. Each potential cause should be evaluated and its significance determined.

When basic building physics is used when water or water damage is observed, a workable solution can be found. Every building is different, but if it is not raining outside and there are no water leaks from a pipe, it's probably caused by water vapor movement (**Fig. 8**).

When the ceiling of a building leaks in the spring with no rain, it is caused by warm, moist air leaking into the ceiling or attic and condensing on the underside of the sheathing or on framing members in the attic in cold climates or ducts and pipes in the ceiling in warm and humid climates.

In cold climates, the solution normally used is to add attic ventilation. There are requirements in the code for ventilation and if problems occur, the solution is thought to be to add more ventilation. In many cases, that can aggravate the problem. The problem in most buildings is warm, moist air from inside the building leaking into the attic and condensing. There is an air-pressure difference between inside the building and the unconditioned attic caused by wind, stack, and mechanical effects. There can also be a pressure difference between the attic and outside. When we add more holes between the outside and the attic, we reduce the pressure different between the two spaces, but it could increase the air-

Figure 8. Mold on sheathing.

Location	Water vapor by air transport through a 1 in.-square hole, oz/gal.		Water vapor transmission through 39 × 39 in. of material,* oz/gal.		
	Mid-rise	High-rise	5.7 ng (0.1 perm)	57 ng (1.0 perm)	570 ng (10 perm)
Seattle, WA	5,543/34.64	18,120/113.25	0.166	1.66	16.6
San Francisco, CA	6,812/42.57	20,738/129.61	0.166	1.66	16.6
Chicago, IL	5,612/35.07	16,285/1010.78	0.166	1.66	16.6
Miami, FL	7941/49.63	17,577/109.86	0.166	1.66	16.6

* According to ASTM E96 desiccant test method

Table 6. Moisture movement: water vapor transmission through a material compared with air transport

Figure 9. Rotten, five-year-old walls.

pressure difference between the interior of the building and the attic space, which is now close to the outside pressure. This increase in pressure difference results in more moisture being drawn into the attic space.

When the problem is air leakage from the interior into the attic, rather than adding more ventilation, it makes more sense to fix the leaks. Fixing a boat with leaks by adding increasingly bigger pumps is not logical. The leaks should simply be sealed. The same applies to our attic: adding more ventilation does not seal the holes that are the root cause of the problem. The floor of every attic should be air sealed before any insulation is added to the attic.

THE PROBLEM WILL GROW

These problems have been around for decades. They became more pronounced in the 1960s and 1970s, when we started to add more insulation to our buildings. Up to that point, most buildings had little insulation and leaked like a sieve. That meant that the moisture created inside our buildings had an easy way to escape to the exterior. The moisture was not around long enough to cause damage. As we add insulation, the insulation performs as intended: it slows down heat flow. That means there is not the same amount of energy to move the moisture from the building assembly to the exterior. The warm, moist air stays in the building assembly longer, where it is more likely to condense. When some of the holes in the building are sealed, the warm, moist air travels to the next hole where the path through the building assembly may be longer (**Fig. 9**).

Low-energy homes are being constructed and this means more insulation is being added (as high as *R*-40 to *R*-50), making the building assemblies thicker. Any warm, moist air, either outside the building or inside the building, depending on the climate, will have a longer time to work its way through the building assembly and may reach the dew point temperature before it exits the building assembly.

Air barriers are required by many local codes, but they may not be installed continuously. This results in a smaller number of holes, which will result in a greater airflow through them. These concentrated leaks will introduce more water vapor to a small area, which may condense before it exits the building assembly.

Building as a system means nothing is simple: any change can affect other functions, either for the good or to the detriment of a building. Both residential and commercial buildings need to have balanced supply and exhaust air to function properly. Unbalanced systems can increase pressure differences in parts of the building, resulting in greater air leakage in that part of the building. A properly sized air conditioner can remove a lot of moisture from the air, but an oversized air condition will not run long enough to dry the air out, which will affect the amount of moisture in the air.

Building performance is affected by the building enclosure, the HVAC system, the occupants, and the exterior environment. Getting them all to work together is not easy, but it is building science.

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