CONDENSATION IN THE BUILDING ENVELOPE: EXPECTATIONS AND REALITIES

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Abstract: Air leakage through building envelopes can cause condensation, mold growth and damage to building materials. It can increase heating and cooling loads, thereby increasing energy consumption and operating costs. In sufficient quantities, air leakage can compromise occupant comfort by creating drafts and allowing uncontrolled entry of dust and environmental pollutants into occupied space. These concerns are driving the development of government regulations and building code requirements for mandatory air barrier systems in commercial buildings. This paper reviews the mechanisms by which water vapor migrates through and condenses within the building envelope, and clarifies the difference between a vapor retarder and an air barrier. It summarizes design considerations for these systems and common reasons for failure.

INTRODUCTION

To build durable and healthful buildings, designers need to be concerned about moisture in the building envelope. Controlling rainwater penetration into roofs, walls, and windows should be a designer's primary concern because water leaks are usually the largest and most obvious moisture source. However, moisture problems can occur within wall and roofing assemblies due to concealed water vapor condensation. Hidden moisture accumulation can damage components and foster mold growth in an assembly without otherwise indicating a wetting problem. Repairing damage from long-term hidden condensation is costly.

Most building codes require a vapor retarder in the building envelope to address hidden condensation concerns. A vapor retarder can help mitigate the effects of vapor diffusion through building materials, but it typically does not address the primary cause of hidden condensation: moist air leakage through building envelope assemblies. Condensation due to air leakage is the next largest cause of moisture accumulation in building envelopes next to rainwater penetration. Most vapor retarder materials can be used to restrict the flow of air, but they are seldom designed and installed with the proper supports and seals to make them effective air barriers.

The following reviews the mechanisms by which water vapor migrates through and condenses within the building envelope, and explains the different performance requirements of vapor retarders and air barriers. Design considerations for these systems and common reasons for failure are also discussed.

AIRBORNE MOISTURE AND CONDENSATION – BASIC CONCEPTS

Water can exist as a solid, liquid, or vapor in our habitable environment. Moist air can be thought of as a binary mixture of dry air and water vapor. The total pressure of a moist air sample is the sum of the dry air pressure and the water vapor pressure. At constant atmospheric pressure, the total amount of water vapor that an air mass can hold is a function of its temperature, and warm air can hold more water vapor than cool air. *Relative humidity* (RH) is the ratio of actual water vapor in the air to the total amount of water vapor that the air can hold at a specific temperature. Expressed as a percentage, RH is commonly used to describe the water vapor condition of moist air, but it is not an absolute measure of the amount of water vapor in the air without a reference temperature. Two air masses with the same RH but at different temperatures, for example, will have different amounts of water vapor, with the warmer air mass holding more water vapor.

When we start to cool a moist air mass, the RH of the air will increase because we are reducing the air's ability to hold vapor, even though we have not added water vapor to the air. If we continue to cool the air we will eventually reach a point of 100% RH, where the air becomes saturated. At this point, the amount of water vapor in the air has not changed from the starting condition, but we have reached the limit of the air's ability to hold vapor. This temperature is called the *dewpoint* temperature. If we continue to cool the air below the dewpoint temperature, the air can no longer hold its water vapor and the excess vapor must revert back to its liquid form as condensation. Condensation will continue to form on surfaces that are below the dewpoint temperature of the air until sufficient moisture is discharged from the air or the surface is heated above the dewpoint temperature.

This is the phenomena by which condensation forms and accumulates within the layers of a building envelope assembly. In cold climates, water vapor from warm, moist indoor air migrates outwards across the building envelope during the winter, cools and condenses when it contacts surfaces that are below the dewpoint temperature. Conversely, water vapor from warm, moist exterior air in hot climates will cool and possibly condense as it migrates across the envelope towards conditioned indoor air spaces.

The prevention of hidden condensation requires an understanding of the mechanisms by which water vapor can migrate across the envelope, and the means by which it can be controlled. There are two mechanisms by which water vapor can migrate through the building envelope:

1) Vapor diffusion at a molecular level, and
2) Mass transport of vapor by air flow.

Vapor diffusion is conventionally controlled by means of a vapor retarder. Air leakage can be controlled by means of an air barrier system. The vapor retarder and air barrier can be combined into a single system, but combined systems are sometimes more complex to design and build.

MOLECULAR TRANSFER OF VAPOR BY DIFFUSION

Vapor diffusion is the process by which water vapor molecules migrate through the pore structure of other materials. The water vapor molecule is one of the smallest gas molecules. Some materials, such as glass and metal, have such small pores that the water vapor molecules and other gas molecules will not fit through. Other solid materials, such as gypsum board, stone, and concrete, have larger pores that the gas molecules can fit through with various amounts of resistance, depending on the molecule size.

The migration of water vapor by diffusion is driven by a difference in vapor pressure between one side of the material and the other. Vapor pressure is a force that water vapor exerts on its surroundings, and it increases with the amount of water vapor present in the air. Water vapor migrates from an area of higher vapor pressure to one of lower vapor pressure. The rate of migration depends upon the magnitude of the vapor pressure differential between the spaces and the permeability of the materials that vapor passes through. Although the forces that drive vapor can be relatively high, many common solid building materials are relatively impermeable to vapor compared to air.

The conventional means of controlling condensation by vapor diffusion is to install a vapor retarder, generally a sheet product that is relatively impermeable to vapor. Typical building codes define vapor retarders as materials with a perm value of 1 grain/sq ft · hr · in. Hg or less. Materials commonly used as vapor retarders include polyethylene films, aluminum foils, and low-permeability paints. However, other building materials used in the envelope fit the typical code definition of vapor retarder. Vinyl wall coverings, 1/2 in. plywood, EPDM rubber roofing membrane, and PVC roofing membrane are examples of materials that exceed the 1 Perm standard.

A vapor retarder need not be structurally rigid or firmly attached to a substrate to resist vapor diffusion. In addition, the vapor retarder need not be perfectly continuous or sealed to reduce the flow of water vapor across the assembly. Small holes, gaps or discontinuities in the vapor retarder generally will not significantly increase the amount of vapor transferred by diffusion.

Location of Vapor Retarder

Conventional wisdom places the vapor retarder on the "warm side" of the insulation during times of maximum vapor drive. Materials that retard water vapor flow and are located in cold parts of an assembly cause the local humidity to rise, increasing the moisture content of adjacent materials and promoting the formation of liquid condensate. The appropriate location of a vapor retarder within the wall assembly will vary depending on the climate type and building occupancy. The tendency in the United States has been to place the vapor retarder on the interior or exterior of the insulation layer based upon the type of climate as follows:

- Heating Climate: Areas in the north requiring significant heating of occupied spaces and with vapor drive primarily from interior to exterior in winter. Vapor retarder is placed on the interior side of the insulation.

- Mixed Climate: Areas in the middle to south requiring both significant heating in winter and cooling in summer of occupied spaces, with vapor drive in both directions needing to be considered. Vapor retarder is placed on either the interior or exterior side of the insulation, or omitted altogether (see following discussion).

- Cooling Climate: Areas in the southeast requiring significant cooling of occupied spaces with the vapor drive primarily from exterior to interior during summer. Vapor retarder is placed on the exterior side of the insulation.

This general practice for typical climate zones may be adequate for most buildings, but it does not perform well for all buildings, especially specialized building occupancies such as low temperature freezer and cold storage facilities, high temperature and high humidity spaces (such as industrial processes and natatoriums), and constant temperature/humidity spaces (such as museums, computer centers, clean rooms and containment spaces). In addition, the theory driving this practice is an oversimplification of the thermodynamic and hydroscopic properties of the envelope assembly. It does not account for the combined effect of multiple layers of building materials in the envelope or for the potential for reversal of the moisture drive at different times of the year.

In a multilayered wall system, it is the distribution of water vapor flow resistance of the various layers and the moisture storage potential that matters more than the location of a 1 Perm vapor retarder. It is possible to design a wall system with no strong vapor retarder in cold climates that will perform well if the design does not form a condensation plane in the wall system. It is also possible to place cold-side vapor retarders in wall systems if they have sufficient moisture storage capacity. Conversely, a strong vapor retarder placed on the warm side of the insulation in a cold climate can trap inbound vapor during warm weather, particularly if the wall is clad with moisture-absorptive materials such as wood or masonry, and the insulation is highly permeable.

Some envelope assemblies contain components that will naturally perform better as retarders than the materials identified by design as the barrier components. Failure to identify these components and to consider the moisture migration properties of the entire sequence of components can result in condensation and trapped moisture. Vinyl wall coverings, for example, have been the source of numerous problem projects in the southeast because their use places the vapor retarder on the cold side of the insulation and promotes condensation and growth of mold and mildew at the interface of the gypsum wallboard and vinyl wall paper. Similarly, metal siding and roofing can cause condensation and corrosion problems for humidified buildings in cold climates.

Another important consideration in the design of the building envelopes and the placement of the vapor retarder is the ability for the wall to dry out. Water that penetrates or forms within the building envelope can remain in the wall for prolonged periods and exacerbate the damage if it becomes trapped between two layers of vapor-impermeable building materials. The latest debate in the building science community is focused on this issue. While some argue that an effective vapor retarder should be stronger than the current standard (0.1 Perm in lieu of 1 Perm), others maintain that most wall systems should be designed without strong vapor retarders to avoid vapor traps and to allow the wall to dry out more quickly in both directions.

While the migration of vapor by diffusion is a steady process, the amount of vapor flow is relatively small, and the amount of condensation that can form within the envelope by vapor diffusion alone is limited, unless the building operates under elevated humidity levels. This process needs to be considered in the envelope design, but it is rarely the primary means for moisture transport.

MASS TRANSPORT OF VAPOR BY AIR FLOW

Air that is allowed to migrate across a building envelope either from the inside out (exfiltration) or from the outside in (infiltration) will carry with it the water vapor it holds. If, during its travels through an envelope assembly, it cools below its dewpoint temperature, condensation will occur. Unlike vapor diffusion, air flow occurs primarily at a macroscopic level through gaps, holes, cracks or other openings that form a path from one side of an enclosure to the other side.

The air path need not be direct. It is possible, for example, for air to flow into a stud wall cavity through an opening on the interior gypsum wallboard, flow within the stud wall cavity, and exit from an opening in the exterior sheathing at another location. In the process, moist air will sweep across the cold, inboard side of the exterior sheathing, depositing moisture on the surface on its way out.

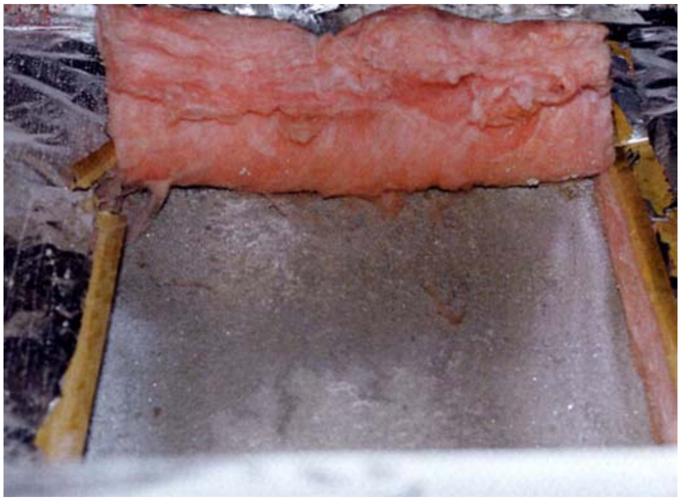


Figure 1. Wetting and frosting of concrete surface behind insulation due to air leakage.

Typical paths of air infiltration/exfiltration through walls include window and door perimeters, through-wall units and other utility penetrations, electrical boxes, and joints between walls and foundation walls, floors and roofs.

Air can also flow through very porous materials such as concrete block, expanded polystyrene insulation and fiberglass batts. The amount of air flow through solid materials is typically much less than that flowing through gaps and cavities.

Air Pressure Differential

Air leakage is driven by differences in absolute air pressure between spaces. These pressure differentials result from three mechanisms: wind pressure, stack effect and mechanical system operation (fans).

Wind Pressure: Wind (air flow) over and around a building creates positive pressure and infiltration on the windward side, and negative pressure and exfiltration on the leeward side. The pressures created on the roof will vary depending on the roof slope. Wind pressures produce the largest forces on the air barrier, and dictate its requirements for rigidity and structural attachment.

Stack Effect: Also known as the “chimney” effect, stack effect results from the thermal buoyancy of air, which becomes less dense with increasing temperature and therefore will tend to rise. Warm air rises in the building and exfiltrates through the upper levels, drawing cooler (denser) air into the building at lower levels. This produces outward (positive) pressure over the top half of the building and inward (negative) pressure over the lower half. In an air conditioned (cooled) building, the effect is reversed with negative pressure (infiltration) at the top of the building and positive pressure (exfiltration) at the bottom. The *neutral pressure plane* occurs where the direction of air flow is reversed. Air leakage due to stack effect can be very significant, particularly in high-rise buildings, because the resulting pressures are sustained for months.

Mechanical System Operation: Exhaust fans tend to induce negative pressure (infiltration) and supply air fans induce positive pressure (exfiltration). The fans of the HVAC system can significantly alter the pressure within the building, and because the pressure is sustained, it can have a dominating influence on the building's behavior.

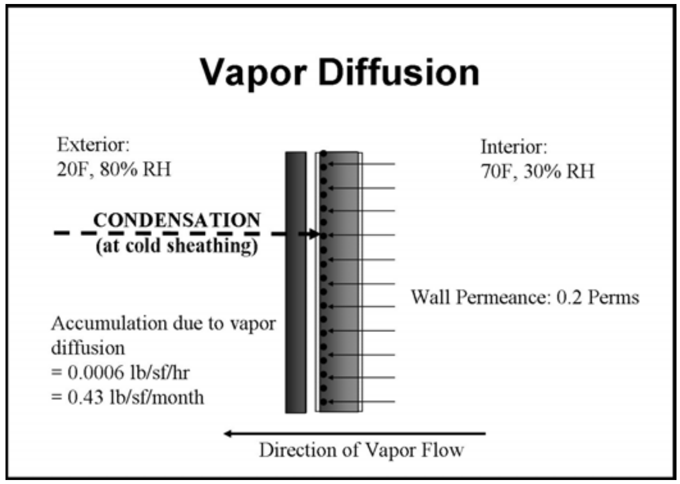
The net combined effect of wind, stack effect and HVAC system operation is to raise or lower the neutral pressure plane of the building. Building air pressure, and consequently air flow through the building envelope, can be controlled, in part, by using the mechanical systems. In heating climates it is more likely to find moisture-related problems higher in the building on the leeward side. Accordingly, the building's HVAC system should be balanced to obtain a slightly negative overall pressure to minimize detrimental moisture/air flow, though typical practice is to pressurize buildings to avoid cold air infiltration drafts. The effectiveness of this approach is dependent on the overall air-tightness of the envelope. Loose buildings are dominated by natural conditions of wind and temperature, while tight buildings respond to differences in outside ventilation and exhaust air flows.

The resistance of the flow path for air leakage is much less than the vapor diffusion resistance of typical building materials. Consequently, the amount of water vapor carried by air flow in a typical building is significantly more than that migrating by vapor diffusion. Adding that air can flow within an envelope assembly for long distances before exiting on the other side, the potential for hidden condensation is much greater from air leakage than it is for vapor diffusion. Generally, the accumulation of moisture from air flow through envelope construction is of the order of ten to hundreds of times that of vapor migration due to diffusion alone. As such this is the mechanism of greatest concern in design or in troubleshooting for condensation-related issues.

The flow of air can be controlled through the design and installation of an air barrier system. Air barriers need to be well sealed at perimeters and transitions to be effective, and thoughtful control of air pressure differences between spaces is required for complete moisture control.

Air Barrier Requirements

The function of an air barrier is to prevent the movement of air through the envelope in both directions, i.e., under positive and negative pressure differentials. Building codes in North America with mandatory air barrier requirements have set the limit for air leakage at 0.004 cfm/sq ft under a pressure differential of 0.3 in. of water. In addition to being impervious to air, the air barrier must resist the physical stress that air pressures will place on it, it must be durable so that it will not deteriorate under physical stress, and it must be continuous (i.e., all the openings in the envelope must be sealed).



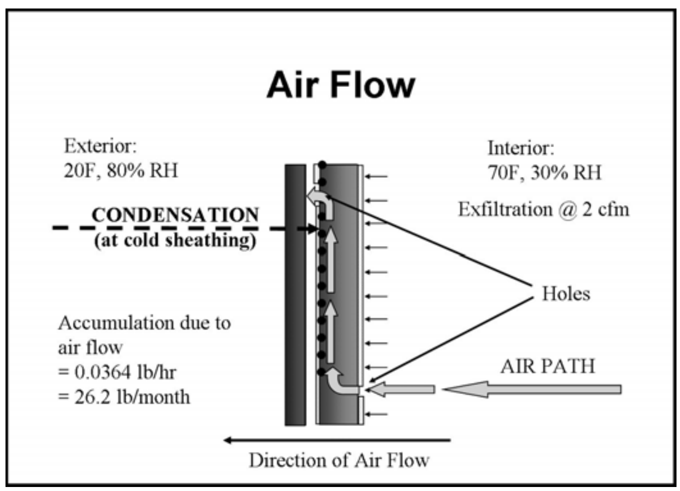


Figure 2. Comparison of moisture migration and accumulation by vapor diffusion and air leakage.

The total peak air pressures exerted on an air barrier are significantly greater than the vapor pressures exerted on the vapor retarder. They can range from sufficient to billow or flap an unsupported film to sufficient force to detach wall panels from structural supports. The air barrier must be able to resist peak pressures without tearing or displacement. Most vapor retarder materials can be used as air barriers if properly supported and sealed, but many air barrier materials are not particularly good vapor retarders (e.g., gypsum sheathing).

Unlike vapor retarders, the location of the air barrier within the envelope assembly is generally not considered particularly critical, and it is not governed by the particulars of climate. A more important consideration in the location of air barriers is the method of attachment, the ability to resist peak pressures without tearing or displacement, and a convenient location (plane) for achieving continuity and sealing to penetrations.

There are instances where air barriers are needed in more than one location. The adjustment of supply and return air dampers on registers within a room can cause room-to-room pressure differences even though overall air flow quantities are balanced. As such, buildings with large internal air pressure differences may require interior air barriers to control internal air movement in addition to external infiltration and exfiltration.

Continuity of the Air Barrier

An effective air barrier system must be continuous at all intersections and interfaces between different building systems and components, including the following:

- Intersections between the wall and the roof, floors and foundations, or between different wall or roof types.
- Interface of wall system and doors, windows and curtain walls.
- Penetrations where structural, mechanical or electrical components penetrate or otherwise interrupt the air barrier.
- Joints and seams between sheets or boards that make up the air barrier.

The air barrier is typically a system and not a single building material. An air barrier can be composed of a sequence of materials that are sealed to each other in an airtight manner. Various rigid board materials, such as gypsum board and plywood, make suitable air barrier components, but all fastener penetrations and joints between adjacent boards must be taped and/or sealed airtight. One common approach to making rigid board systems airtight is to install a self-adhering membrane or coating onto the boards.

Thin film vapor retarders with no support or one-sided support installed in locations where they ultimately become subject to significant air pressure differences are vulnerable to detachment, tearing or opening at the seams. Materials such as polyethylene or aluminum foil, installed between batt insulation and gypsum wallboard (in a stud wall) are not normally effective air barriers because they are not rigid and are difficult to seal permanently to components that penetrate the barrier.

CONSEQUENCES OF AIR LEAKAGE

As a carrier of vapor, heat and airborne particulates and pollutants, air flow across the building envelope can affect the building's durability, energy consumption, occupant comfort and indoor air quality.

Damage to Finishes and Structure

The primary consequence of air leakage is hidden condensation. Moisture accumulation within the building envelope can damage the structure and finishes and foster mold growth. Typical symptoms of air leakage include effloresced brick, damp patches on exterior claddings, blistering paints and water-stained finishes. Persistent condensation can corrode masonry wall ties and other structural wall elements, damage sheathing and insulation, and rot wood studs and blocking. The deterioration often progresses unnoticed because it is concealed, resulting in extensive and costly remediation once the problem is identified.

Energy Loss

Infiltrating air will increase heat load during the winter and cooling load during the summer. In addition, hidden condensation due to air leakage can wet and/or degrade some types of building insulation, reducing its thermal resistance and exacerbating the problem. Energy consumption due to air leakage can be a significant portion of the total energy consumption of a building.

Figure 3. Mold growth in roof insulation caused by air leakage.

Control of Pollutants and Indoor Comfort

In sufficient quantities, infiltrating air can carry outdoor environmental pollutants into the building, compromising the indoor air quality. Infiltration of outdoor air can also affect the thermal comfort of the building occupants. An airtight building improves the mechanical system's ability to control indoor temperature, RH and air quality.

Figure 4. Efflorescence on brick veneer caused by air leakage.

COMMON PITFALLS

The expectation that a vapor retarder, as it is typically designed and installed, will act as an effective and durable air barrier is misguided and often results in failure. A vapor retarder need not be completely continuous or structurally secure to be effective, while those same traits are essential for air barriers. The following common air barrier system conditions frequently result in building envelope problems.

Insufficient Detailing

The design of the air barrier system can be complex. It requires analysis and thought, and the resulting details are often intricate, involving the integration of multiple materials or building components into an airtight assembly. The most critical details are typically three-dimensional transitions that are best illustrated with isometric drawings. Construction documents that adopt the typical "fill in the blank" mentality, with generic requirements in the specifications such as "... seal to all adjacent construction ..." or "... provide continuous air barrier system" are simply inadequate. These projects often result in the last-minute, in-the-field recognition of special needs, under the pressures of time and money. The problematic air barrier detail is often compromised, if it is addressed at all.

Lack of Continuity

An effective air barrier system must be continuous. Every transition, interruption or termination of the designated air barrier component needs to be accounted for. Simply labeling the components on drawings that function as the air barrier system goes a long way toward promoting an understanding of what needs to be built and where critical seals are needed.

The following conditions can result in condensation and deterioration from air flow:

- Failure to detail seals and transitions to adjacent dissimilar materials, such as a wall/roof intersection where the roof and wall systems need to be connected. Insufficient consideration is given to making airtight, durable connections between dissimilar membrane materials that are intended air barrier components, such as EPDM roofing and rubberized asphalt wall membrane, or built-up asphalt roofing membranes and polyethylene.

- Failure to seal barriers at typical door and window penetrations, or failure to seal at an appropriate location on the door or window frame. The air barrier plane of a window or curtain wall system will vary from one manufacturer to another. Sealing the wall air barrier system to the interior surface of the frame will not provide an airtight seal if the plane of the glazing pocket is the manufacturer's intended air barrier plane. Similarly, sealing the wall air barrier to the exterior flange of a window system may not be appropriate if the sides of the window frame leak air.

- Overlooking pipe, electrical conduit, mechanical duct, chase, and structural penetrations. A fillet bead of sealant is typically inappropriate for sealing around such penetrations, as these seals are normally not durable and cannot reliably accommodate differential movement between the substrate and the penetrating component.

- Failure to recognize potential air leakage paths within a material that is designated as the air barrier. Lap and butt joints in the field of metal decks, for example, are not tight enough to make a metal deck assembly air tight unless additional sealing is installed. In addition, the numerous large gaps at flutes provide channels for air and vapor flow. Similarly, a CMU wall is permeable to air, normally contains gaps at terminations, and is likely to develop cracks in its serviceable life. It cannot be relied upon to perform as a component of the air barrier system unless it is covered or sealed with a suitable product.

- Using portions of the building envelope as ducts or plenums for the heating and ventilating systems. Special sealing may be required if significant air pressure differences exist in the air distribution systems. A corollary is failing to realize that portions of the structure (metal stud spaces) will act like conduits for air and vapor flow if there are air pressure differences through the cavity.

- Failure to design flexible seals for flexible joints such as midspan load deflections of beams.

Lack of Constructability and Durability

Air barriers located where numerous penetrations, special seals and transitions are required are difficult to install reliably and are prone to failure. The primary concern in the design of durable barriers is to locate them on a smooth plane surface where an uninterrupted barrier could be installed. The surface of exterior sheathings or the exterior surface of a back-up CMU wall normally provides a more continuous substrate for the air barrier than surfaces located on the interior of the wall.

Figure 5. A smoke pencil test shows how air is drawn into a perforated metal ceiling panel.

An example of a difficult air barrier installation is when the interior gypsum finishes are the intended air barrier system. Typical commercial construction frames and sheathes exterior walls first to make a reasonably weathertight structure to contain the remaining construction activities. Interiors are then fully framed for all partitions before interior gypsum finishes are installed. Unless specifically detailed and monitored, interior gypsum board is often discontinuous where interior partitions meet exterior walls, above the line of interior ceiling finishes, and around penetrations that have separate trims.

Reliance on Perfect Barriers

It is unreasonable to expect to design, construct and maintain perfect barriers. Envelope designs that employ a single line of defense against air and vapor migration are more prone to failure due to minor installation deficiencies. A more reliable design uses an integrated approach, which includes the following additional provisions:

Control Driving Forces: Control or reduce the forces that drive water vapor through the envelope. Unnecessarily high humidity levels in the ambient air should be reduced through dehumidification and/or mechanical ventilation. The mechanical system should be designed and balanced to provide complementary pressure control for the design conditions to minimize condensation potential.

Select Durable Materials: Building envelope materials located at potential condensation planes should not be susceptible to deterioration and mold growth if they become wet. Cement board, for example, is more tolerant of moisture than gypsum products, and glass fiber-faced gypsum is more mold resistant than paper-faced gypsum board.

Allow for Evacuation of Moisture: The design should allow any moisture entering or forming within the building envelope assembly to be evacuated. This requires that the wall or roof be able to dry out in one direction or the other. The installation of two materials that act as vapor retarders within the same wall or roof section will mitigate the assembly's ability to dry out.

A properly installed air barrier system can significantly reduce the potential for hidden envelope condensation and its consequences, but tight buildings must be provided with mechanical ventilation system to ensure that the interior spaces receive sufficient fresh air. Many residential buildings, including high-rise apartment complexes, are built using mechanical codes that allow infiltration and open windows to provide needed ventilation. Such buildings can have high occupancy moisture problems that could be avoided with proper mechanical ventilation.

BUILDING CODES AND REGULATIONS

Recognizing the potential for condensation due to air leakage and considering the benefits of an airtight building envelope, the Massachusetts State Building Code (MSBC) adopted a mandatory air barrier requirement in January 2001 for commercial and high-rise residential buildings. The MSBC requires that the building envelope be designed and constructed with an air barrier that is continuous; has an air permeability no greater than 0.004 cfm/sq ft at 0.3 in. H_2O; is capable of withstanding combined design wind, stack and HVAC pressures (positive and negative); and is durable or maintainable. The code also requires airtight and flexible connections at various junctures in the envelope and at all air barrier penetrations. It includes provisions for control of air flow at elevator and lobby doors, vestibules, dampers, and between indoor spaces with significantly different temperature/humidity levels. However, air flow testing in the code is still component-based, with no complete building test requirements.

Other states have begun to implement efforts to develop mandatory air barrier requirements, but no other state building code has yet adopted these requirements.

SUMMARY

Rainwater penetration into roofs, walls, and windows is usually the largest and most obvious moisture source in building envelopes, but moisture problems can occur within wall and roofing components due to concealed water vapor condensation. Condensation can be caused by vapor diffusion, but air leakage through building envelope assemblies typically transports more moisture.

Properly designed and installed vapor retarders can effectively control vapor diffusion through building envelope components. However, as they are typically specified, designed and installed, vapor retarders are not effective in mitigating the effects of air leakage.

An air barrier system needs to be impermeable to air, structurally rigid, continuous and durable. Air barriers need to be well sealed at perimeters and transitions to be effective, and thoughtful control of air pressure differences between spaces is required for complete moisture control.

As a carrier of vapor, heat, and airborne particulates and pollutants, air flow across the building envelope can affect the building's durability, energy consumption, occupant comfort and indoor air quality.

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