Chapter 1: Moisture Control in Buildings

Introduction

Moisture control is fundamental to the proper functioning of any building. Controlling moisture is important to protect occupants from adverse health effects and to protect the building, its mechanical systems and its contents from physical or chemical damage. Yet, moisture problems are so common in buildings, many people consider them inevitable.

Excessive moisture accumulation plagues buildings throughout the United States, from tropical Hawaii to arctic Alaska and from the hot, humid Gulf Coast to the hot, dry Sonoran Desert. Between 1994 and 1998, the U.S. Environmental Protection Agency (EPA) Building Assessment Survey and Evaluation (BASE) study collected information about the indoor air quality of 100 randomly selected public and private office buildings in the 10 U.S. climatic regions. The BASE study found that 85 percent of the buildings had been damaged by water at some time and 45 percent had leaks at the time the data were collected.[2]

Moisture causes problems for building owners, maintenance personnel and occupants. Many common moisture problems can be traced to poor decisions in design, construction or maintenance. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) notes that, more often than not, the more serious problems are caused by decisions made by members of any of a number of different professions.[3] However, such problems can be avoided with techniques that are based on a solid understanding of how water behaves in buildings.

Moisture control consists of:

- Preventing water intrusion and condensation in areas of a building that must remain dry.
- Limiting the areas of a building that are routinely wet because of their use (e.g., bathrooms, spas, kitchens and janitorial closets) and drying them out when they do get wet.

To be successful, moisture control does not require everything be kept completely dry. Moisture control is adequate as long as vulnerable materials are kept *dry enough* to avoid problems. That means the building must be designed, constructed and operated so that vulnerable materials do not get wet. It also means that when materials do get wet, the building needs to be managed in such a way that the damp materials dry out quickly.

Health Implications of Dampness in Buildings

At the request of the U.S. Centers for Disease Control and Prevention (CDC), the Institute of Medicine (IOM) of the National Academy of Sciences convened a committee of experts to conduct a comprehensive review of the scientific literature concerning the relationship between damp or moldy indoor environments and the appearance of adverse health effects in exposed populations. Based on their review, the members of the Committee on Damp Indoor Spaces and Health concluded that the epidemiologic evidence shows an association between exposure to damp indoor environments and adverse health effects, including:

- Upper respiratory (nasal and throat) symptoms.
- Cough.
- Wheeze.
- Asthma symptoms in sensitized persons with asthma.

The committee also determined that there is limited or suggestive evidence of an association between exposure to damp indoor environments and:

- Dyspnea (shortness of breath).
- Lower respiratory illness in otherwise healthy children.
- Asthma development.

[2] http://www.epa.gov/iaq/base/. Accessed November 6, 2013.

[3] Limiting Indoor Mold and Dampness in Buildings. 2013 (PDF) at https://www.ashrae.org/about-ashrae/position-documents. Accessed November 6, 2013.

Details of the results of this review were published in a 2004 report, *Damp Indoor Spaces and Health.*[4] It is also important to note that immuno-compromised individuals, such as some categories of hospital patients, are at increased risk for fungal colonization and opportunistic infections.[5]

After the publication of the IOM report, a study by Lawrence Berkeley National Laboratory concluded that building dampness and mold raise the risk of a variety of respiratory and asthma-related health effects by 30 to 50 percent.[6] A companion study by EPA and Berkeley Lab estimated that 4.6 million cases of asthma, 21 percent of the 21.8 million cases of asthma in the U.S. at that time, could be attributed to exposure to dampness and mold in homes.[7]

Moisture Damage in Buildings

In addition to causing health problems, moisture can damage building materials and components. For example:

- Prolonged damp conditions can lead to the colonization of building materials and HVAC systems by molds, bacteria, wood-decaying molds and insect pests (e.g., termites and carpenter ants).
- Chemical reactions with building materials and components can cause, for example, structural fasteners, wiring, metal roofing and conditioning coils to corrode and flooring or roofing adhesives to fail.
- Water-soluble building materials (e.g., gypsum board) can return to solution.
- Wooden materials can warp, swell or rot.
- Brick or concrete can be damaged during freeze-thaw cycles and by sub-surface salt deposition.
- Paints and varnishes can be damaged.
- The insulating value (R-value) of thermal insulation can be reduced.

The following photos show some of the damage that can result from moisture problems in buildings.

Figure 1-1 Mold growing on the surface of painted gypsum board and trim. Long-term high humidity is the source of the moisture that allowed the mold growth. All of the walls experienced similar near-condensation conditions. Consequently, the mold growth is widespread rather than concentrated in a single damp area.

[4] Institute of Medicine (2004) *Damp Indoor Spaces and Health.* http://www.iom.edu/Reports/2004/Damp-Indoor-Spaces-and-Health.aspx. Accessed November 6, 2013.

[5] Institute of Medicine (2004) *Damp Indoor Spaces and Health.* http://www.iom.edu/Reports/2004/Damp-Indoor-Spaces-and-Health.aspx. Accessed November 6, 2013.

[6] W. J. Fisk, Q. Lei-Gomez, M. J. Mendell (2007) Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. *Indoor Air* 17(4), 284-295. doi:10.1111 /j.1600-0668.2007.00475.x

[7] D. Mudarri, W. J. Fisk (2007) Public health and economic impact of dampness and mold. *Indoor Air* 17 (3), 226–235. doi:10.1111 /j.1600-0668.2007.00474.x

Figure 1-2 Mold growth on painted concrete masonry. The cool masonry wall separates a classroom from an ice rink. Humid air in the classroom provides moisture that condenses on the painted surface of the masonry. That moisture allows mold to grow on the paint film.

Figure 1-3 Mold growth on vinyl floor tile. Long-term high humidity provided moisture that was absorbed into the cool vinyl tile and supported mold growth. Also note that the high humidity caused the adhesive attaching the tile to the floor to fail, allowing the tile to become loose.

Figure 1-4 Corrosion of galvanized fluted steel floor deck. The floor is at grade level. The source of the water is rainwater seepage.

Figure 1-5 Corrosion of structural steel in a ceiling cavity in a cold climate. The steel extends into the exterior wall assembly. During cold weather, the steel near the wall is chilled by cold outdoor air. The building is humidified, and condensation from high indoor humidity provides the moisture that rusts the cold steel.

Figure 1-6 Blistering paint on split face concrete block. Wind-driven rain is the source of moisture contributing to the damage. Water wicks into the concrete masonry unit (CMU) through pin holes in the paint. The sun drives water vapor through the CMU. The assembly cannot dry to the interior because low-vapor-permeability foam board, taped at the joints, insulates the interior surface of the wall. The wall remains saturated throughout the spring, summer and fall. The same paint on areas of the wall sheltered from sun and rain shows no damage.

Figure 1-7 Condensation behind vinyl wallpaper in a warm, humid climate. Condensation and mold growth occurs behind the vinyl wallpaper on both exterior and interior walls. Air leaks in the return plenum of the air handler depressurizes the interior and exterior wall cavities. Warm, humid exterior air is drawn from outside through air leaks in a heavy masonry wall.

Figure 1-8 Rainwater leaks in a rooftop parapet wall result in damaged plaster and peeling paint. Rainwater is drawn into this brick assembly by capillary action, and the moisture is aided in its downward migration by gravity. The peeling paint contains lead and results in an environmental hazard as well as physical damage to the plaster.

Figure 1-9 Interior plaster damaged by rain seeping around a window in a brick building. The inside of the exterior wall is insulated with closed-cell spray foam. Consequently, the wall cannot dry to the interior, so it retains excessive amounts of moisture. At the point where the plaster on the window return meets the brick wall, rainwater wicks into the plaster causing the damage seen in this photo.

Figure 1-10 Further rain damage to interior plaster. At another location on an office window in the building shown in Figure 1-8, rain seepage turns gypsum board joint compound to a fluid, causing the gypsum to bubble and lift.

Figure 1-11 Gypsum board on the lower edge of a basement wall dissolved by seasonal flood waters. The water table is just below the basement floor during dry weather and rises several inches above the floor during heavy spring rains.

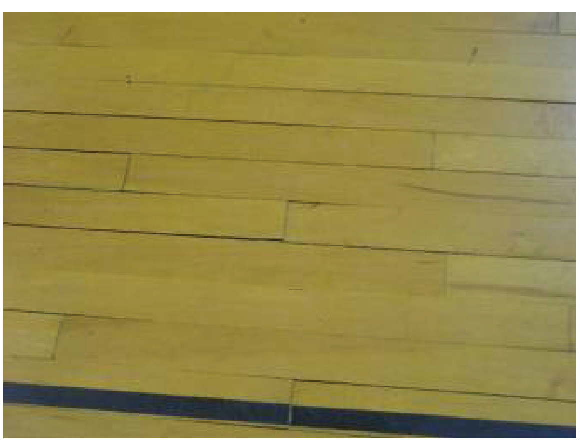


Figure 1-12 Hardwood gymnasium floor warped by moisture in the cavity below it. Water rises through the concrete sub-floor. The source of the moisture is rainwater that has not been drained away from the foundation of the building.

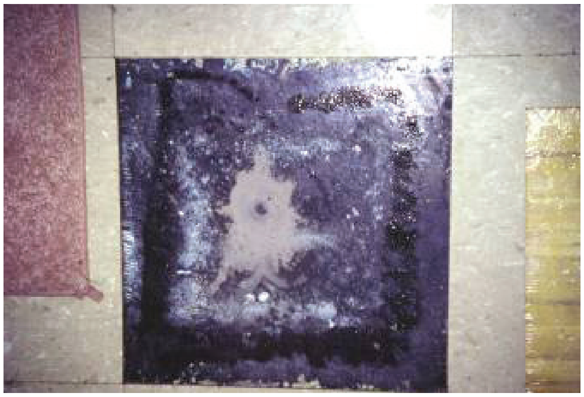


Figure 1-13 Tile adhesive that failed to cure because of water in the concrete and high pH. The tile can be removed by hand. The floor is a concrete slab-on-grade. The water visible in the photo evaporates into the room after several minutes. Its source may be liquid water wicking up from the sub-slab fill or water vapor migrating through the slab.

Figure 1-14 Damage to bricks caused by the migration of soluble salt through them. Salts in the brick or mortar dissolve in rainwater that wicks through the brick. The water evaporates in the building's interior, and the salt left behind crystalizes and splits the surface layer off the brick, exposing its interior. This process is called sub-fluorescence.

Moisture Problems are Expensive

Health problems and building damage due to moisture can be extremely expensive. Berkeley Lab estimates that the annual asthma-related medical costs attributable to exposures to dampness and mold total approximately $3.5 billion in the U.S.[8] But many more adverse health outcomes due to damp buildings have been reported, each with associated costs of its own. And damage to the building itself is also costly. Building owners and tenants bear a significant proportion of these costs, including:

- Absenteeism due to illnesses such as asthma.
- Reduced productivity due to moisture-related health and comfort problems.
- Increased insurance risk, repair and replacement costs associated with corroded structural fasteners, wiring and damaged moisture-sensitive materials.
- Repair and replacement costs associated with damaged furniture, products and supplies.
- Loss of use of building spaces after damage and during repairs.
- Increased insurance and litigation costs related to moisture damage claims.

How Water Causes Problems in Buildings

Mention water damage and the first image that comes to mind for most people is liquid water in the form of rain, plumbing leaks or floods. Many water leaks are easy to detect. When it rains, water may drip around skylights, or a crawl space may fill with water. If a toilet supply line breaks, the floor will likely be flooded.

On the other hand, many water-related problems are less obvious and can be difficult to detect or diagnose. For example, the adhesive that secures flooring to a concrete slab may not cure properly if the slab is damp, resulting in loose flooring and microbial growth in the adhesive. Or, humid indoor air may condense on the cool backside of vinyl wallpaper that covers an exterior wall, providing ideal conditions for mold to grow. These problems are less obvious than a leak because water is not running across the floor, and the real damage is being done out of sight under flooring or behind wallpaper.

Moisture problems are preventable. They do not happen until water moves from a source into some part of a building that should be dry. The actual

[8] D. Mudarri, W. J. Fisk (2007) Public health and economic impact of dampness and mold. *Indoor Air* 17 (3), 226–235. doi:10.1111 /j.1600-0668.2007.00474.x

damage begins after enough moisture accumulates to exceed the safe moisture content limit of moisture-sensitive materials.

To diagnose or prevent a moisture problem, keep in mind **four key elements** of moisture behavior in buildings:

1. **Typical symptoms of moisture problems.** They include corrosion of metals, the growth of surface mold or wood-decaying molds, insect infestations, spalling exterior brick or concrete, peeling paint, failing floor adhesives, stained finishes and health symptoms.
2. **Sources of moisture.** Among them are rainwater, surface water, ground water, plumbing water, indoor and outdoor sources of humidity and sewer water.
3. **Transport mechanisms.** They include liquid water leaking through holes, wicking through porous materials, or running along the top or bottom of building assemblies and water vapor carried by warm, humid air leaking through assemblies and by diffusion through vapor-permeable materials.
4. **Common failures of moisture control elements and systems.** Moisture controls include site drainage, gutter systems, above- and below-grade drainage planes, effective flashing, condensate drainage and humidity controls. Failures can occur during any phase of a building's life and may include poor site selection or design, poor material or equipment selection, improper installation or sequence of building materials and equipment, insufficient coordination between trades during construction and insufficient or improper maintenance of materials or equipment.

Moisture Control Principles for Design

To control moisture for long building life and good indoor air quality, follow these three principles:

1. Control liquid water.
2. Prevent excessive indoor humidity and water vapor migration by air flow and diffusion in order to limit condensation and moisture absorption into cool materials and surfaces.
3. Select moisture-resistant materials for unavoidably wet locations.

Armed with an elementary understanding of these principles, readers will be prepared to control moisture and prevent the vast majority of moisture problems that are common in buildings.

Moisture Control Principle #1: Control Liquid Water

The first principle of moisture control is to keep liquid water out of the building. Sheltering occupants from water is a primary purpose of building assemblies including roofs, walls and foundations. Among the sources of water from outside a building are:

- Rain and melting snow, ice or frost.
- Groundwater and surface runoff.
- Water brought into the building by plumbing.
- Wet materials enclosed in building assemblies during construction.

Problem: Building Assemblies and Materials Get Wet

Moisture problems are common. By their very nature, buildings and the construction process are almost certain to encounter moisture problems that could lead to poor indoor air quality and other negative impacts. The most common liquid water problems include:

- **Rain and snow get inside.** Rainwater, surface water and ground water, including snowmelt, may enter a building through leaks in roofs, walls, windows, doors or foundations. In most climates, rain is the largest source of water in buildings. Rainwater intrusion can cause great damage to the building itself and to its contents.
- **Plumbing leaks.** We intentionally bring water into buildings for cleaning, bathing and cooking, and we intentionally drain wastewater out of buildings. Any water brought in and drained out is contained in pipes, vessels and fixtures that can tolerate being wet all or most of the time. However, leaks in plumbing supply lines, drain lines, sinks, showers and tubs may cause problems. Although model plumbing codes require both the supply side and drain/vent side of plumbing systems to be tested for leaks, these tests are sometimes performed poorly or not at all. Large plumbing leaks are immediately obvious, but small leaks inside walls and ceiling cavities may continue unnoticed for some time.
- **Water during construction causes problems.** Some materials are installed wet because they were exposed to rain or plumbing leaks during construction. Wet concrete masonry units (CMUs), poured or pre-cast concrete, lumber and the exposed earth of a crawl space floor have all been sources of problems in new buildings.

- **Some materials are installed wet because water is part of the process.** Poured concrete, floor levelers, wet-spray insulation and water-based finishes all contain water. Porous materials that appear dry may contain enough water to cause problems if they come in contact with moisture-sensitive materials or if they humidify a cavity after they are enclosed. Flooring, wall coverings and coatings will fail if they are applied before surfaces are dry enough. Water from these materials may indirectly cause problems by raising the humidity indoors during a building's first year of use, leading to condensation problems.

Solution: Control Liquid Water Movement

Effectively controlling liquid water intrusion requires all of the following:

- **Drain rain, irrigation water and snowmelt away from the building.** The first step in water control is to locate the building in dry or well-drained soil and use or change the landscape to divert water away from the structure. In other words, drain the site. This includes sloping the grade away from the building to divert surface water and keep subsurface water away from the foundation below grade. After the site is prepared to effectively drain water away from the building, the building needs a storm water runoff system to divert rain from the roof into the site drainage system.
- **Keep rain and irrigation water from leaking into the walls and roof.** Leaking rainwater can cause great damage to a building and to the materials inside. In successful systems, rainwater that falls on the building is controlled by:
  - Exterior cladding, roofing and storm-water management systems to intercept most of the rain and drain it away from the building.
  - Capillary breaks, which keep rainwater from wicking through porous building materials or through cracks between materials. A capillary break is either an air gap between adjacent layers or a material such as rubber sheeting that does not absorb or pass liquid water. A few rain control systems consist of a single moisture-impermeable material, sealed at the seams, that both intercepts rainwater and provides a capillary break. Membrane roofing and some glass panel claddings for walls work in this way.
- **Keep water from wicking into the building** by using capillary breaks in the building enclosure. Moisture migration by capillary action can be interrupted using an air space or water-impermeable material.
- **Prevent plumbing leaks** by locating plumbing lines and components where they are easy to inspect and repair, are unlikely to freeze, and are not in contact with porous cavity insulation.
- **Avoid enclosing wet materials in new construction** by protecting moisture-sensitive and porous materials during transport and on-site storage and by drying wet materials before they are enclosed inside building assemblies or covered by finish materials.

Drained Roofing and Wall Cladding

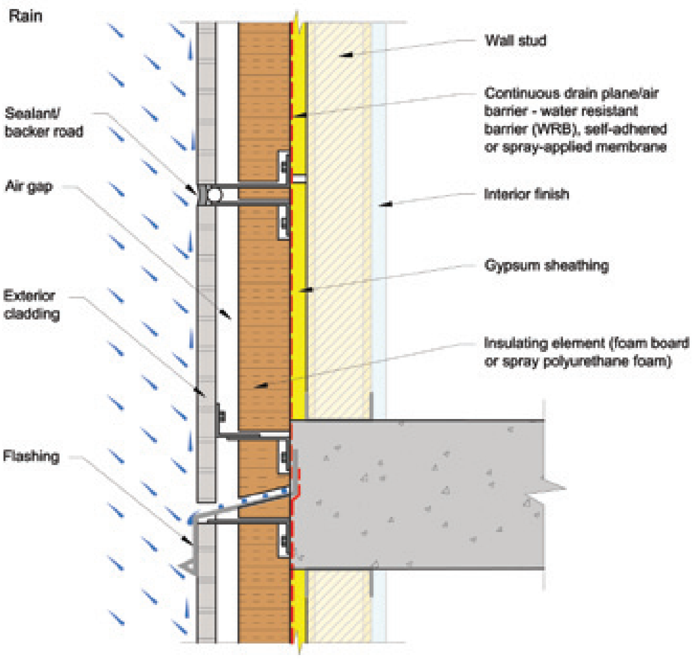
Roofing and cladding systems are frequently backed by an air gap and a moisture-resistant material that forms the drainage plane. Most of the water that seeps, wicks or is blown past the cladding will drain out of the assembly. The drainage plane prevents any water that might bridge the air gap from wetting the inner portions of the assembly. Some examples are:

- **Roofs.** Asphalt or wooden shingles, metal panels and elastomeric membranes are common outer layers for roofs.
- **Walls.** Wooden and vinyl siding, stucco, concrete panels, brick, concrete masonry units and stone veneers are common outer layers for walls.
- **Drainage planes.** Building felt, tar paper and water-resistant barriers are commonly used as drainage planes beneath roofing and wall cladding systems. Single- and multi-ply roofing combine the drainage plane with the outer layers of the roof—there is no inner drainage plane material.

Figure 1-15 illustrates the concept of a drained wall assembly. Although the cladding intercepts most of the rainwater, some liquid will seep inward. The air gap acts as a capillary break, and seepage cannot jump that gap. Instead, seepage runs down the back of the cladding until it is drained out by the flashing. Some of the seepage may run to the drainage plane along materials that bridge the gap, for example, mortar droppings or cladding fasteners. The impermeable surface of the drainage plane keeps water out of the backup sheathing, CMU or concrete, protecting the inner wall. Water flows down the drainage plane and over the flashing, which diverts it back outside.

Some roofing or siding materials absorb water (e.g., wooden shingles or siding, fiber cement siding, traditional stucco and masonry veneers), while others do not (e.g., roofing membranes, vinyl siding and metal or glass panels). Historically, the porous

Figure 1-15 Drained Wall Assembly



materials were backed by an air gap. Examples include wooden shingles on skip sheathing, masonry veneers and heavy masonry walls with 1- to 2-inch cavities separating brick walls and beveled siding installed shingle style. The air gap between the siding and the interior of the wall enables wet porous materials to dry out to either the outdoor air or into the air gap.

In either case, the drainage plane must be watertight at all joints and penetrations. Table 1-1 lists penetrations commonly found in roofs and walls and presents ways to maintain the watertight integrity of the drainage plane. This list is not comprehensive. Any and all penetrations through roofing and exterior cladding must be detailed to prevent rainwater intrusion.

Windows, curtain walls and storefronts are all used in wall assemblies and are among the more complex penetrations to detail. Typically, standard details for window head, jamb and sill flashing are provided by the manufacturers of these components. Figure 1-16 illustrates a method of providing pan sill and jamb flashings for walls constructed with an exterior insulation and finish system (EIFS). Note that the sill flashing protects the wall assembly from seepage at the corners of windows and at the joints between windows. Dams on the sides and back of the sill pan flashing stop any seepage from running into the building or into the wall beneath the window.

Foundations

The building foundation must be detailed to protect the building from rainwater. The above-grade portions of a foundation are often masonry or concrete. Much of the rainwater that wets the above-grade wall simply drains off the surface to the soil below. Masonry walls are often protected below grade using Portland cement-based capillary breaks (e.g., traditional parging or proprietary coatings). Concrete walls may be treated with additives that provide an integral capillary break or may be so massive that absorbed water is more likely to be safely stored in the wall—drying out between storms—than to wick through to the interior.

Landscape surfaces immediately surrounding the foundation perform the same function for the walls below grade as the roofing and cladding in the walls above grade: they intercept rain and drain it away from the building.

The damp-proof or waterproof coatings on below-grade walls serve the same purpose as the drainage plane in the above-grade walls. These coatings provide a capillary break that excludes the rainwater that saturates the surrounding fill. An additional capillary break is formed by free-draining gravel or geotechnical drainage mats placed against the below-grade walls. These materials provide an air gap that allows water to drain freely down the foundation wall.

At the bottom of the below-grade wall, a footing drain system carries rainwater and ground water away from the footing and the floor slab. Paint formulated for use on concrete can be applied to the topside of the footing to provide a capillary break between the damp footing and the foundation wall. A layer of clean coarse gravel, with no fines, can provide an air-gap-style capillary break between the earth and the concrete floor slab. Plastic film beneath the floor slab provides a vapor barrier as well as a capillary break beneath the slab. These drainage layers and the vapor barriers beneath foundation slabs are often required by building codes.

Table 1-1 Maintaining Drainage Plane Water-Tightness in Roofs and Walls

Penetrations Commonly Found in Roofs	How to Maintain Drainage Plane Water-Tightness
Joints between pieces of roofing	Shingling or sealing provides continuity
Roof edges	Overhangs, copings and drip edges provide capillary breaks
Roof intersections with adjoining, taller walls	Through-flashing provides continuity where a lower story roof intersects the wall of the higher level and where any roof meets a dormer wall. Flashing and counter-flashing of veneers and low-slope roof membranes keep water out of joints between materials
Skylights and roof hatches	Flashing, curbs and counter-flashing provide continuity
Chimneys	Flashing, crickets and counter-flashing provide continuity
Air handlers and exhaust fans	Flashing, curbs and counter-flashing provide continuity
Plumbing vents	Flashing and counter-flashing provide continuity
Penetrations Commonly Found in Walls	**How to Maintain Drainage Plane Water-Tightness**
Windows	Head flashing, jamb flashing and panned sill flashing provide continuity
Doors	Head flashing, jamb flashing and panned sill flashing provide continuity
Outdoor air intakes	Head flashing, jamb flashing and panned sill flashing provide continuity
Exhaust outlets and fans	Head flashing, jamb flashing and panned sill flashing provide continuity
Fasteners	Sealants provide continuity
Utility entrances	Sealants provide continuity

The "Pen Test"

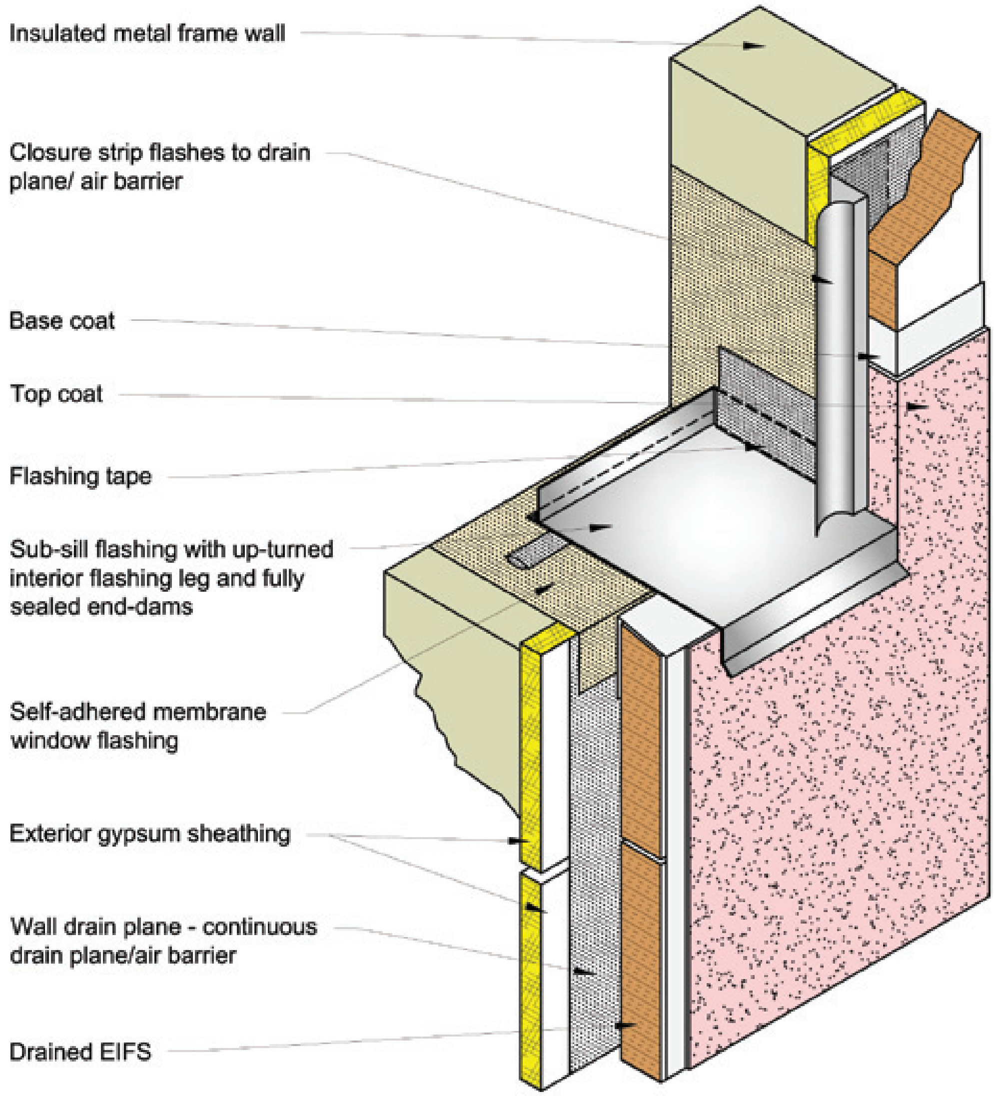
The waterproof layers of the walls, roof and foundation must form a continuous, six-sided box with no gaps, no cracks and no holes. It is difficult to achieve this degree of integrity, especially at the long edges where the walls meet the roof and the foundation. The pen test is used before the architectural design is complete to help make sure these continuous water barriers, when installed according to the design, will not leak.

When rainwater control has been well designed, it should be possible to trace the waterproof layers that form a capillary break around a sectional view of the building without lifting pen from paper. This simple test can be performed not only for the rainwater control, but also for the thermal insulation layer and the air barrier. The methods for all three are outlined in Appendix A and are part of the requirements for documenting compliance with the guidance in Chapters 2, 3 and 4.

Figure 1-17 illustrates tracing the capillary break in a sample section. Starting at the center of the roof:

- The roofing membrane is the first line of defense, protecting the water-sensitive inner materials from rain and snowmelt.
- Tracing the roofing membrane from the center of the roof to the edge of the roof, the roofing membrane flashes beneath a metal coping, which in turn flashes to a metal fascia.
- The fascia forms a drip edge, channeling water away from the cladding.
- An air gap between the drip edge and the brick veneer forms a capillary break, protecting the materials beneath the coping from rainwater wicking into them.

Figure 1-16 Pan Sill and Jamb Flashings for EIFS Walls

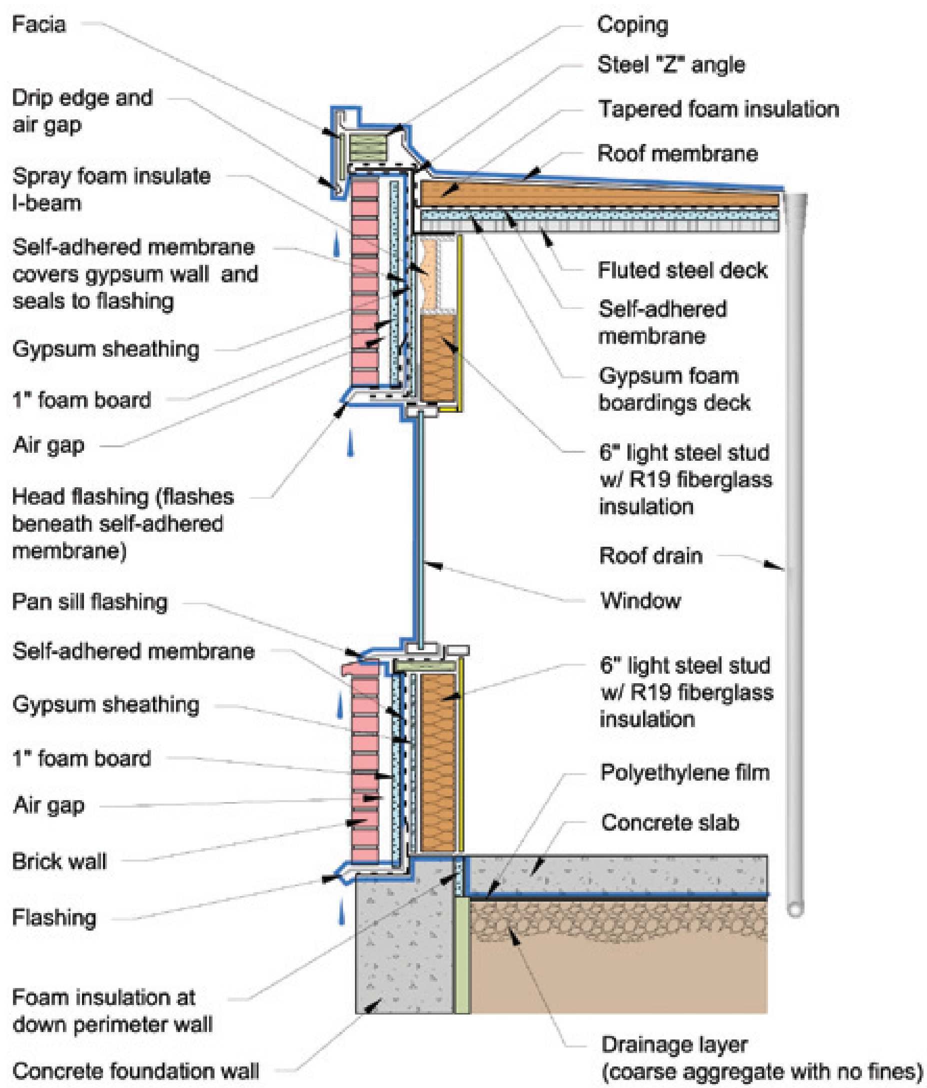


- Behind the brick veneer, air gap and foam board, a water-resistant barrier (WRB) applied to the gypsum sheathing forms a capillary break between the damp brick and the inner wall assembly.
- The WRB laps over the vertical leg of a head flashing, protecting the window from rainwater with a drip edge and an air gap.
- The window frame, sash and glazing form a capillary break system that sits in a pan sill flashing at the bottom of the window.
- The pan sill flashing forms a capillary break protecting the wall beneath from seepage through the window system.
- The pan sill flashing shingles over the WRB in the wall beneath, which shingles over a flashing that protects the bottom of the wall system.
- A polyethylene foam sill seal makes a capillary break between the foundation and the bottom of the framed wall, connecting with an inch of extruded polystyrene insulation that makes a capillary break between the top of the foundation wall and the edge of the floor slab. Polyethylene film immediately beneath the slab provides the code-required water vapor retarder and forms a capillary break between the bottom of the slab and the fill below. NOTE: If the bed of fill beneath the slab consists of crushed stone greater than ¼ inch in diameter (and if it contains no fines), the bed also forms a capillary break between the soil and the slab.

Note the critical role of flashing in excluding water and in diverting water out of the building if it leaks in. Applying the pen test to the building design shows

Figure 1-17 Tracing the Capillary Break in a Sample Section

The blue line traces the elements of the capillary break in the rainwater control system for a section through a building.



the importance of flashing that is both well designed and well installed. There are no certification programs for the proper installation of flashing; however, the following trade associations offer educational materials and training programs for flashing design and installation:

- Sheet Metal and Air Conditioning Contractors' National Association (SMACNA), http://www.smacna.org.
- National Roofing Contractors Association, http://www.nrca.net/.
- National Concrete Masonry Association, http://www.ncma.org.
- Brick Industry Association, http://www.bia.org.
- Spray Polyurethane Foam Alliance, http://www.sprayfoam.org.

Prevent Plumbing Leaks

To avoid plumbing leaks, new plumbing systems must be pressure tested at a stage of construction when the plumbing lines are easily inspected and leaks can be readily repaired. This is a code requirement in many jurisdictions.

Supply lines must be pressurized to design values, and drain lines must hold standing water. Plumbing must be designed not only to prevent initial problems, but also to permit easy maintenance to avoid future problems.

Further, plumbing should be located where:

- Leaks will be noticed quickly.
- Leaking water will not wet easily damaged materials.
- Water inside the plumbing will not freeze in cold weather.

Plumbing access panels allow critical maintenance over the life of the building. They should be located anywhere concealed valves or traps will need to be inspected for leaks or accessed for adjustment, maintenance or replacement.

No matter the climate, avoid placing plumbing lines, valves and drain lines in exterior walls and ceilings that have porous insulation. If the plumbing leaks, insulation in those walls or ceilings will get wet. Once wet, porous insulation takes a long time to dry (or may never dry). This situation can lead to mold growth, corrosion of structural fasteners and needless energy consumption. Also, in climates with cold winters, any plumbing located in exterior walls or above ceiling insulation is more prone to freezing and bursting.

Avoid Enclosing Wet Materials in Building Assemblies

Moisture-sensitive materials and equipment should be kept dry during construction. In particular, gypsum board, finished woodwork, cabinets and virtually all mechanical equipment should be stored in a weather-protected shelter or installed in their final, weather-protected locations immediately upon delivery to the site.

If moisture-sensitive or porous materials get wet, dry them quickly before mold grows or physical damage occurs. Masonry walls and concrete floor slabs, for example, are very porous and can hold a great deal of water. Masonry block and concrete must be thoroughly dry before being coated or covered by water-sensitive materials such as floor tile, carpeting, paint or paper-faced gypsum board.

Water is added to some materials during installation (e.g., concrete, water-based coatings, wet-spray fire-proofing and wet-spray insulation). These materials must be allowed to dry naturally, or force-dried using specialized equipment before being enclosed in building assemblies. These intentionally wet materials may not suffer from long exposure to moisture, but as they dry, they will transfer their moisture to nearby materials that can support mold growth or change dimension.

Moisture Control Principle #2: Manage Condensation

Limit indoor condensation and make sure condensation dries out when and where it occurs.

Problem: Condensation Happens—Keep Track of the Dew Point

Both indoor air and outdoor air contains water vapor. Wherever air goes, water vapor goes. When humid air contacts a surface that is cold enough, the water vapor in the air will condense onto that cold surface. The concept of the air dew-point temperature is very useful in understanding when, why and how much condensation will occur—and how to avoid it.

The dew point is the temperature of the air at which condensation occurs. The higher the dew point, the greater the risk of condensation on cold surfaces. The dew point depends on how much water vapor the air contains. If the air is very dry and has few water molecules, the dew point is low and surfaces must be much cooler than the air for condensation to occur. If the air is very humid and contains many water molecules, the dew point is high and condensation can occur on surfaces that are only a few degrees cooler than the air.[9]

Consider hot weather condensation inside a building. Condensation can be prevented as long as the indoor air dew point is *below* the temperature of surfaces that are likely to be cold. If the dew point rises, moisture will begin to condense on cold surfaces. For example, humid outdoor air leaking into a building in Miami will have a dew point above 70°F throughout most of a typical year. During normal operation of an air-conditioned building, there are *many* surfaces that have a temperature below 70°F. For example, a supply air duct carrying air at 55°F will have a surface temperature near 55°F. If the infiltrating outdoor air has a dew point of 70°F, its moisture will condense on the outside of that cold duct, and possibly on the supply air diffuser.

Dew Point vs. Relative Humidity

When most people think of humidity, they think of relative humidity (RH) rather than dew point. But

[9] Dew point can be measured by cooling a mirrored surface until condensation just begins to appear. Monitors that measure dew point directly in this way are called chilled mirror devices.

relative humidity is just that, a relative measurement and not one that expresses the absolute amount of water vapor in the air. In simple terms, RH is the amount of water vapor in the air compared to the maximum amount the air can hold at its current temperature.[10] Change the air temperature and the relative humidity also changes, even if the absolute amount of water vapor in the air stays the same. So knowing only the RH of the air is not much help in predicting condensation.

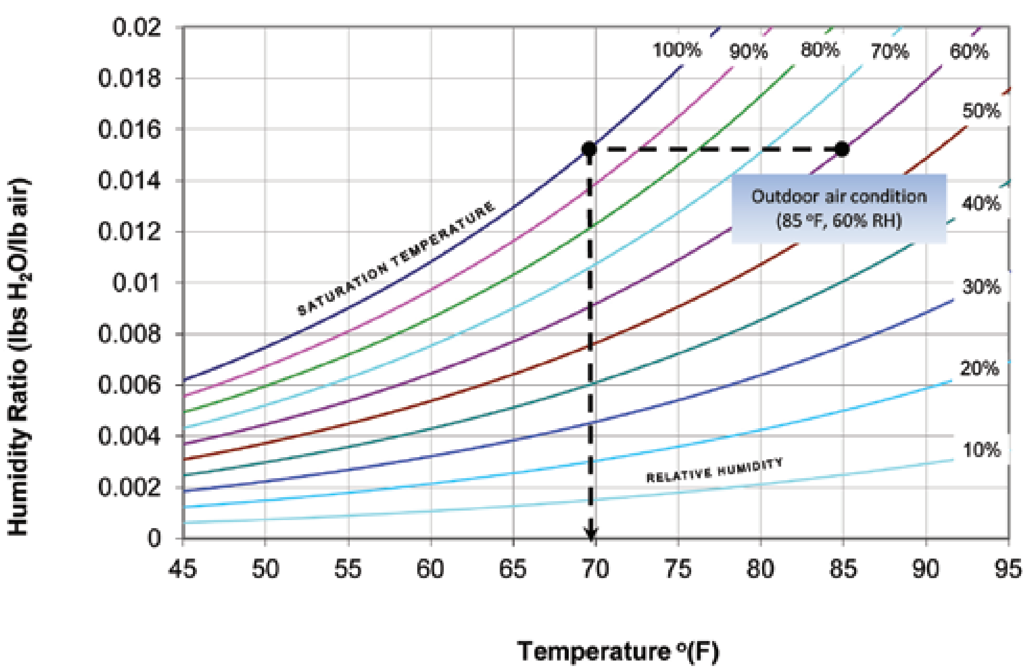
Unlike RH, the dew point does not change with air temperature. In that sense it is an "absolute" measurement of the amount of water vapor in the air. When you know the dew point of the air and the temperature of a surface, you can predict condensation. If the dew point is *above* the temperature of the surface, water vapor will condense onto that cold surface. If the dew point is *below* the surface temperature, moisture will not condense. So it is simple to predict condensation, as long as you know the dew point of the air surrounding the surface.

To be sure, knowing the dew point is not always easy because many humidity instruments measure and read only air temperature and relative humidity. So if the instrument you are using does not display the air dew point, you will need a psychrometric chart to find the dew point based on the temperature and RH of the air. A psychrometric chart graphs the physical and thermal properties of moist air.[11] A simplified psychrometric chart relating the air's temperature and RH to its dew point at sea level is shown in Figure 1-18. With this chart and the readings from a low-cost monitor to measure air temperature and RH, one can determine the more useful value of air dew point in a few seconds.

For example, assume an instrument shows the outdoor air is 85°F and its RH is 60 percent. Plot that point on the chart. Then, beginning at that point move horizontally to the left until your line intersects the saturation curve (i.e., the 100 percent RH curve that forms the left edge of the chart). From that intersection, read straight down to the bottom of the chart to determine the dew point. As shown in Figure 1-18, the dew point of air at 85°F and 60 percent RH is 70°F. In other words, air at those conditions will begin to condense moisture when it contacts any surface that has a temperature of 70°F or below.

The psychrometric chart reveals an important dynamic between surface temperature, dew point and RH. Notice that if the RH is 90 percent, a surface only

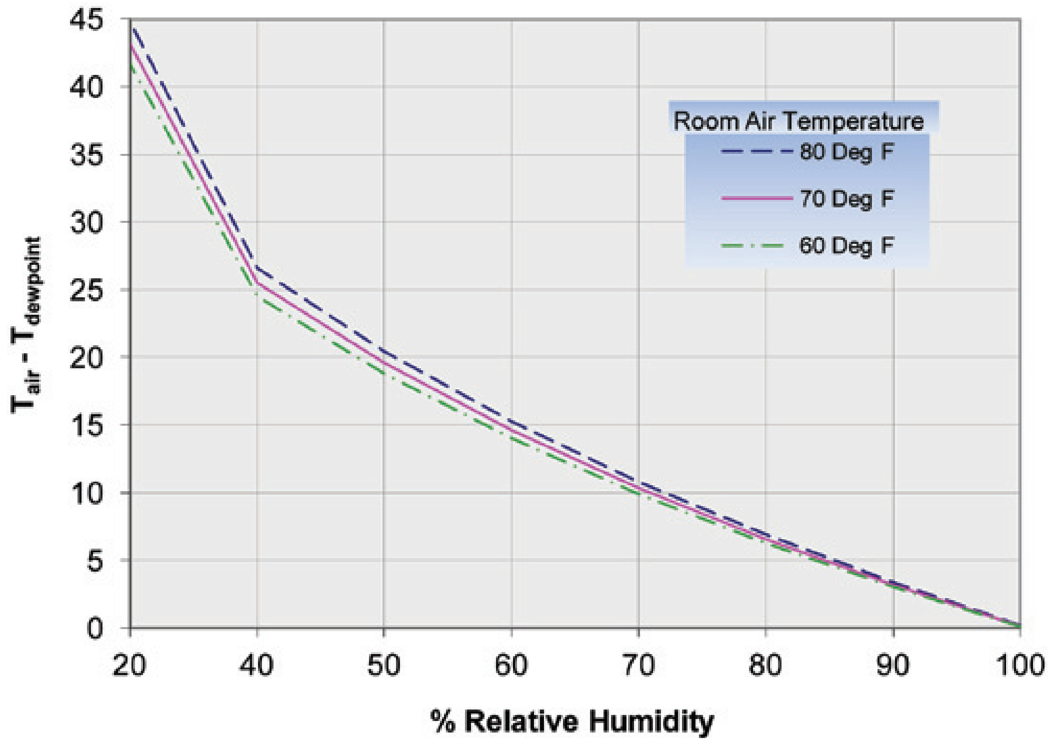
Figure 1-18 A Simplified Psychrometric Chart Relates Air Temperature, RH and Dew Point.



[10] The technically more accurate definition of relative humidity is the ratio of vapor pressure in the air sample compared to the vapor pressure of that air if it were completely saturated at the same temperature, expressed as a percentage. But the definition provided above is sufficiently accurate, easier to understand and useful for managing moisture in buildings.

[11] The psychrometric chart is a powerful tool for understanding the water vapor characteristics of air and the effects of heating and cooling moist air. Its history and use are fully explained in the ASHRAE publication *Understanding Psychrometrics* by Donald Gatley.

Figure 1-19 The Difference Between Room Air Temperature and the Dew Point as a Function of RH



has to be 3°F cooler than the air for condensation to occur. It is very likely that during normal operation in many seasons there will be surfaces in buildings that are 3°F colder than room temperature.

At high temperatures, high RH may also mean there is a strong risk of condensation. Figure 1-19 shows the relationship between RH and the number of degrees cooler a surface must be for condensation to appear when the RH is between 25 percent and 100 percent. This graph provides a way to think about dew point in terms of RH. At 50 percent RH, a surface must be around 20°F cooler than the room air for condensation to occur. Under ordinary circumstances, few surfaces in a building are 20°F cooler than room air.

Causes of Condensation in Buildings

Condensation may be the result of excessively high dew point, unusually cold surfaces, or a combination of the two.

The indoor dew point is a balance between the addition and subtraction of water vapor from the air. A building has both indoor and outdoor sources that add water vapor, and its mechanical systems must have adequate dehumidification capacity to remove it, in order to keep the dew point within reasonable limits.

Inside residential buildings, people and their activities, especially cooking and washing of floors and clothes, are usually the leading sources of humidity.

In humidified commercial and institutional buildings such as hospitals, museums and swimming pool enclosures, indoor humidity is very high by design or necessity.

In low-rise buildings of all types, damp basements or crawlspaces may add as much water vapor to the air in a day as all the other internal sources combined.

During the cooling season, humidity loads from outdoor air are far larger than loads generated inside commercial and institutional buildings. The largest sources of humidity are the ventilation air, the makeup air that compensates for exhaust air, and the air that infiltrates into the building through air leaks in the enclosure. If the ventilation and makeup air is kept dry and the building is tight so that it does not allow much leakage, the contributions from outdoor air will be low.

Water vapor may be removed from indoor air by dehumidification (e.g., air conditioners or dehumidifiers) or by ventilation air when the outdoor air is dry. Ventilating air only dehumidifies the indoors when the outdoor air dew point is lower than the indoor air dew point.

Exhaust air is a special case. When an exhaust fan rids a building of highly humid air, from showers or cooking, for example, the indoor humidity loads are reduced. On the other hand, if the outdoor air that replaces that exhaust air has a dew point above the indoor dew point, the incoming outdoor air represents a humidity load that must be removed by the mechanical system.

Condensation Problems During Cold Weather

In cold weather, condensation is most likely to occur on the inside of exterior walls or roof assemblies. The temperature of sheathing and cladding on the outside of the insulation and air barrier will be near the temperature of the outdoor air. Indoor window surfaces are often cooler than surrounding walls and are typically the first sites of condensation during cold weather. If the surface temperature of an indoor wall is below the indoor dew point at a void in the insulation or at an uninsulated framing member, enough water may accumulate to support mold growth. If there is a hole in the air barrier and the building is under negative pressure at that location, cold infiltrating air may bypass the insulation layer and chill indoor surfaces to temperatures below the dew point.

Condensation may occur within an assembly. For example, a steel beam that passes through an exterior wall will be much colder than the adjoining inner surfaces of the wall because the beam conducts heat from inside to outside hundreds of times faster than an insulated portion of the wall. If the building is under positive pressure, the warmer, more humid indoor air will be forced into the enclosure through holes in the air barrier and condensation within the assembly may result.

Condensation problems within wall or roof assemblies are hidden and may be mistaken for rainwater or plumbing leaks. For example, warm air from a humidified space, such as a swimming pool area, may leak past the air barrier and insulation layers into an attic during freezing weather. The water vapor in the indoor air may form frost on the bottom of the roof deck, accumulating there until a warm day when it melts and leaks back through the ceiling. If it happens to be raining the day the condensation problem is found, it might be mistaken for a rainwater problem.

Figure 1-20 Condensation on Uninsulated Metal Framing in a Cold Climate

Condensation occurs on a C-channel at the top of a parapet wall located in a cold climate. The building is humidified and pressurized with filtered outdoor air to maintain specified interior conditions.

Air pressure can be higher inside a building than outside for two reasons. First, the upper floors of a building are usually under positive pressure during cold weather due to the stack effect. Buoyant warm air rises from the lower to the upper floors and then flows out near the top of the building. As a result, cold outdoor air is pulled into the building at its base. During cold weather, condensation usually occurs on the upper floors. Any gaps, cracks or holes through the upper floors of the enclosure receive a constant flow of warm, humid air exiting the building. Condensation occurs where the warm humid air leaves the cold enclosure.

The second reason air pressure can be higher inside is that, to avoid uncomfortable drafts and freezing pipes, the mechanical ventilation system generally brings in more air from outdoors than is exhausted to the outside. Condensation may occur when warm, humid air is forced out of the building through cold walls. In addition, portions of a building may be pressurized by mechanical system fans if the supply air side of the air distribution system has more air than the return air side. For example, a room that has two supply diffusers but no dedicated return will be under positive pressure when the windows and doors are closed. If the interior surfaces of the exterior walls near that room have gaps, cracks or holes, humid indoor air under positive pressure will be forced into the cold exterior wall.

Condensation Problems During Hot Weather

Condensation can sometimes be a problem in hot weather. Hot weather condensation is more common in buildings equipped with air conditioning (AC) systems that are very large and difficult to control and in buildings located in climates that have thousands of hours of humid weather. Six factors contribute to problems in buildings that have air conditioning systems:

1. Air conditioning chills all the indoor surfaces—some surfaces more than others.
2. When air conditioners do not run long enough to dehumidify, they cool the air in the building without removing moisture from the air, raising the indoor dew point and increasing the chances of condensation on cool surfaces.
3. Supply air ducts, diffusers and refrigerant or chilled water lines are much colder than the room air.
4. When a building's exhaust air exceeds the amount of its makeup air, the building will draw in unconditioned, moisture-laden outdoor air through gaps, cracks and holes in the building enclosure. That outdoor air will come into contact with surfaces chilled by the AC systems.
5. Sun shining on wet masonry, stucco or wood will raise the temperature of that material, evaporating some of the stored water and "driving" a portion of the evaporated water further into the assembly, and sometimes into contact with colder indoor surfaces.
6. Intentional or accidental vapor barriers on the inside surfaces of exterior walls may cause condensation during cooling conditions. For example, water vapor driven in from outdoors may condense when it encounters a vinyl wall covering on the cool, inside surface of an exterior wall.

   A similar dynamic occurs in below-grade walls. Water vapor migrating into a basement from the ground beneath may condense when it encounters a vapor barrier on the inside of a finished basement wall.

Solution: Control Condensation

Effective condensation control requires keeping the dew point below the temperature of surfaces indoors and within building cavities. The dew point can be lowered by designing, installing and maintaining HVAC systems to control indoor humidity in both heating and cooling mode. Building enclosures can be designed and constructed so surface temperatures within the assemblies are above the dew point regardless of season. Neither of these design elements can succeed by itself. They must work together as a system.

Use airtight HVAC systems to keep indoor dew points low. To prevent condensation on indoor surfaces during cooling mode, keep the indoor dew point below 55°F (e.g., maximum 50 percent RH when the indoor air temperature is 75°F). This can be done by designing air conditioning systems that dehumidify even when there is no need for cooling, or by using dedicated dehumidifiers to dry the ventilation air whenever the outdoor dew point is above 55°F. See references below and in Chapter 2 for more details on designing HVAC systems to manage indoor humidity.

The most important job of the air conditioning system is to remove the large and nearly continuous humidity load from the incoming ventilation and makeup air. After that load is removed, the much smaller water vapor loads from indoor sources may be removed by:

- **Exhaust systems** designed to remove water vapor from known sources of humidity such as showers, cooking areas and indoor pools.
- **Ventilation** with outdoor air in non-air-conditioned buildings.
- **Air conditioning systems** equipped with dedicated dehumidification components and controls that activate them when the dew point rises above 55°F.

Design building enclosures to prevent condensation. At minimum the exterior enclosure must:

- Be made airtight by using continuous air barrier systems around the entire enclosure. These systems must greatly reduce leakage of inside air into the exterior enclosure assemblies during cold weather and leakage of outdoor air into the exterior enclosure or interior wall, ceiling and floor cavities during warm weather.[12] Air sealing an enclosure makes it easier to manage indoor-outdoor air pressure relationships with practical airflow rates.

- Meet minimum R-values in accordance with the 2012 International Energy Code.
- Manage the flow of heat and water vapor through all enclosure assemblies to avoid condensation on materials inboard of the drainage plane.

Insulating materials must be used to manage heat flow in order to keep the surface temperature of low-permeability materials inside the enclosure above the expected dew point. A continuous thermal barrier is also necessary to prevent condensation on the interior surfaces of exterior walls and ceilings during heating conditions. The insulation layer must be continuous to prevent condensation in low R-value components of the enclosure (e.g., metal framing, concrete slab edges and angle iron ledgers). The pen test can be conducted to trace the thermal barrier's continuity.

To manage water vapor migration by diffusion, select materials with appropriate water vapor permeability. The materials in the wall or roof assembly must be layered to keep low-perm materials above the dew point during the heating and cooling seasons and to allow the assembly to dry out if it gets wet. This protection must be provided in all above- and below-grade walls, floors, ceilings, plaza and roof assemblies, including opaque walls and roofs, glazed fenestration and skylights, curtain wall systems and exterior doors.

Condensation control must be provided for typical sections and at thermal bridges. Many standard designs in published work detail assemblies that provide condensation control for various assemblies in many climates. For example, the International Building Code covers condensation control for a variety of wall types and all North American climates. Straube (2011) includes systematic guidance for four fundamental wall and roof assemblies in all North American climates, plus a discussion of underlying moisture dynamics. (See references below and in Chapter 2. For designs and climates not covered in published guidance, and for buildings with high humidity levels indoors [e.g., swimming pools, hospitals, knitting mills and museums], analyses should be performed by a knowledgeable person using one of several computer simulations such as WUFI or hygIRC. For more information on managing condensation in the enclosure and hygrothermal modeling, see references in Chapter 2).

It is important to note that a layer of porous material which can safely store moisture may be used as a buffer to improve the condensation resistance of an assembly. For example, a fibrous cover board beneath a fully adhered low-slope roofing membrane reduces the risk of condensation that can damage the adhesive layer. A concrete masonry backup wall behind a fluid-applied drainage plane can safely store moisture in the event of minor seepage.

Design HVAC systems to manage air flow and control condensation. HVAC system pressurization may be used to manage the direction in which air flows through an enclosure. Controlling pressure in air-conditioned buildings in hot, humid climates is crucial to controlling condensation in the enclosure. Buildings in those climates must be positively pressurized to prevent warm, humid outdoor air from entering building cavities and the building itself.

In climates with a significant cold season, humidified buildings—such as swimming pools, hospitals and museums—must not be positively pressurized, otherwise humid air will be forced into cold building cavities. In cold climates, slight depressurization is a better strategy for humidified buildings.

Moisture Control Principle #3: Use Moisture-Tolerent Materials

The final moisture control principle is to use building materials that can withstand repeated wetting in areas that are expected to get wet. Adequate control can be achieved by using moisture-tolerant materials and by designing assemblies that dry quickly. Moisture-tolerant materials should be used in areas that:

- Will get wet by design.
- Are likely to get wet by accident.

Areas that Get Wet by Design

Some locations and materials in buildings are designed specifically to be wet from time to time.

[12] The U.S. Army Corps of Engineers (USACE), for example, has chosen a maximum allowable air leakage rate of 0.25 cubic feet per minute per square foot of total enclosure area at a pressure difference of 75 Pascals when tested in accordance with the USACE test protocol. *U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes Version 3* May 11, 2012.

They include custodial closets, laundry rooms, kitchens, baths, indoor pools, spas, locker rooms, entryway floors and floors that are regularly mopped or hosed down.

Areas Likely to Get Wet by Accident

Some areas are likely to experience water leaks over the course of time. For example, spaces that contain plumbing equipment, such as laundry, lavatory, bath and utility rooms, are prone to water leaks and spills. Below-grade wall and floor assemblies are at the bottom of the building. Water from leaks below grade, on the surface, or above grade is likely to end up on the lowest floor. In these areas, use moisture tolerant materials and assemblies that dry quickly.

Many materials can safely get wet as long as they dry quickly enough. Stainless steel, copper, some stones, china and porcelain tile contain no nutrients to support the growth of molds or bacteria, do not absorb water and are stable when wet. These characteristics are why these materials have long been used in bathrooms, kitchens and entryways.

In areas that may get wet from time to time, it is best to avoid building materials that have proven to be vulnerable to moisture damage. Among these moisture-sensitive materials are untreated paper-faced gypsum board, medium density fiberboard (MDF) and oriented strand board (OSB). Moisture-sensitive materials are vulnerable because they may:

- Contain nutrients that are digestible by molds, bacteria or wood-decaying molds.
- Quickly and easily absorb liquid water and, once wet, take longer to dry than materials that are impermeable to liquid water.
- Have no anti-microbial characteristics.
- Delaminate, crumble, dissolve or deform when wet or while drying.

Substitutes for vulnerable materials are now commonly available at only a modest increase in cost. For example, mold- and moisture-resistant gypsum board, fiber cement board tile backers and sub-floors are available in home improvement stores in addition to builders' supply yards.

If in doubt, the moisture-resistant properties of a building material can be determined by testing according to ASTM D3273-00 (2005) *Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber*. Designers can ask the manufacturer for the results of these tests.

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