

CHAPTER 64. AVOIDING MOISTURE AND MOLD PROBLEMS

INDOORS, buildings should always be dry. When building interiors get damp and stay damp, problems often emerge for their occupants and for the building's structure, materials, and furnishings.

Persistent indoor dampness has been associated with human health problems, increased risk to buildings' structural fasteners and exterior enclosure, shortened useful life of furnishings, and reduced acceptability to occupants because of odors and stains. These and related problems can be costly and disruptive, as well as annoying to all concerned (ASHRAE 2013).

HUMAN HEALTH

The U.S. National Academy of Medicine and the World Health Organization determined that there is a clear association between damp buildings and negative health effects (NIM 2004). The U.S. Department of Energy's Lawrence Berkeley National Laboratory estimated the cost of documented dampness-specific health effects to be more than \$3.5 billion each year (Mudari and Fisk 2007), and health hazard evaluations of buildings around the world have repeatedly shown that indoor dampness is neither normal nor desirable from a health perspective (e.g., NIOSH [2013]). Although not all of the mechanisms are well understood at this time, cognizant public health authorities agree that damp buildings can lead to health problems.

ENERGY CONSERVATION

Insulation can be compromised when rain and snow melt water leaks into roofs or exterior walls, and when indoor humidity condenses inside walls. When insulation gets wet, it allows more heat to pass through the building enclosure. The increased heat flow wastes energy, increases the difficulty of meeting energy reduction goals, and adds needless costs to building operation.

SUSTAINABILITY

Damp buildings generate corrosion, rot, and mold, which damage structural fasteners (Zelinka 2013), materials, and finishes. Therefore, a building and its furnishings are not sustainable (because their useful lives are shortened) unless they are designed and constructed to prevent moisture accumulation.

COSTS

Fixing a moisture problem after construction is roughly 10 times as expensive as correcting a drawing at the design stage, and remediating a mold problem is roughly 100 times as expensive as correcting that drawing. Thus, it is far more cost effective (and more sustainable) to avoid problems at the design stage than to repair problems caused by moisture-risky design.

AVOIDING LITIGATION RISK

Humidity and moisture-related problems in buildings have been the single largest category of claims against the errors and omissions insurance of architects and engineers (84%). Also, moisture-related damage is the single most-litigated construction defect against contractors (NAIC 2008).

1. COMPLEX CAUSES

Based on investigations of problem buildings, dampness sufficient to cause problems seldom has a single cause. More often, a series of events, including decisions in many areas of professional and personal responsibility, combine in complex ways to cause a problem. Therefore, it is not appropriate to assign responsibility for building dryness to any single group, because it is not likely that any one group acting alone, can prevent a problematic level of dampness, mold, or microbial growth.

The interactions that lead to the amount and duration of moisture accumulation that creates problems are similarly complex. [Figure 1](#) shows an example: the classic and problematic practice of installing vinyl wallpaper on the indoor surfaces of exterior walls in a mechanically cooled building in hot, humid climates.

High-dew-point outdoor air infiltrates through exterior walls. Its moisture is then absorbed into hidden cool surfaces of interior gypsum wallboard. Because the vinyl wallpaper is relatively impervious to water vapor transport, moisture accumulates in the gypsum board, resulting in mold growth and eventually decay, rot, or corrosion of structural members or their fasteners.

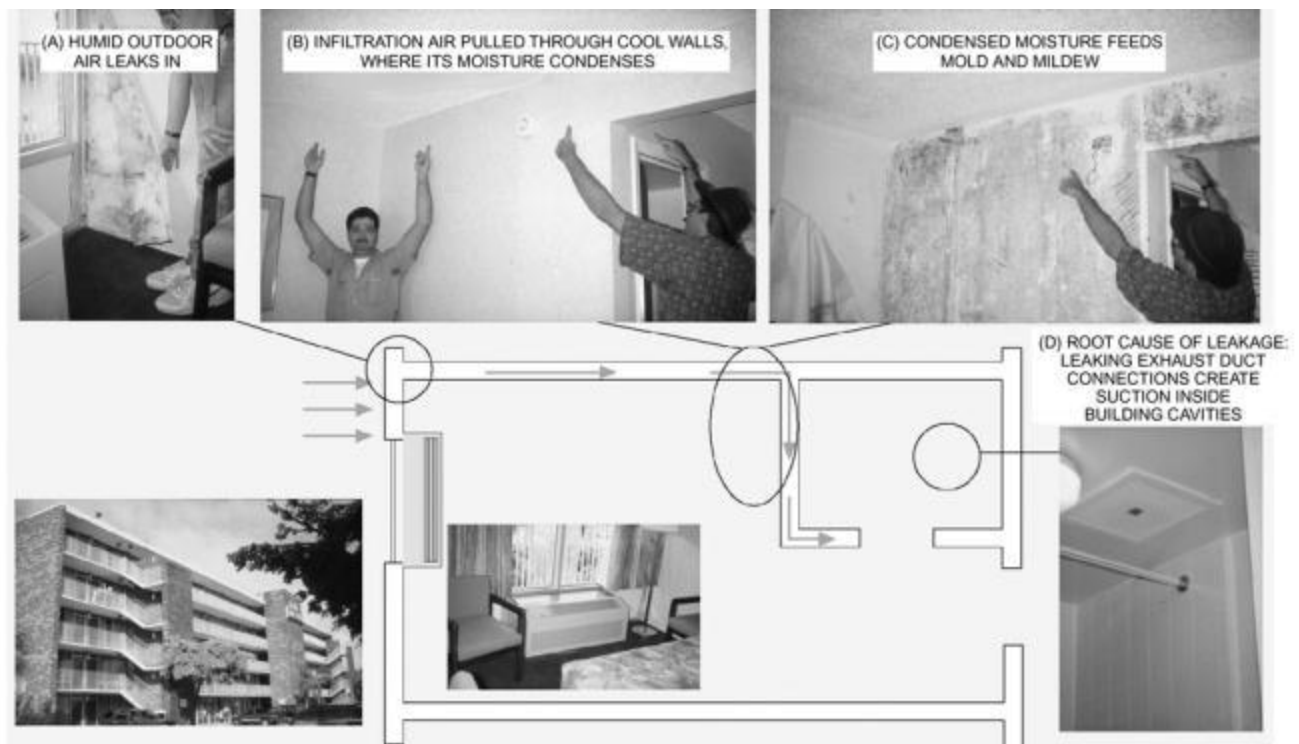


Figure 1. Mold Caused by Complex Combination of Factors

Note that the problems illustrated by [Figure 1](#) resulted from more than one element: high outdoor dew point for many days or weeks, extensive humid air infiltration into the enclosure, chilled indoor surfaces, vinyl wallpaper, and untreated paper-faced gypsum board. If any one of those elements were absent, little or no mold growth might have occurred. In this example,

- The owner or interior designer decided to install vinyl wall covering rather than a more permeable wall covering.
- The architectural designer designed and/or the contractor built a building that allows extensive humid air infiltration, and also selected untreated gypsum wall board for a location likely to experience high humidity in a climate where high humidity continues for many months.
- The HVAC system was apparently designed and/or installed such that it overcools wall surfaces. The toilet exhaust duct system was also either designed, installed, or operated such that it extracts air from building cavities as well as from the bathroom, thereby increasing humid air infiltration and leading to high relative humidity inside the cavities. High relative humidity inside cooled walls leads to moisture absorption and high water activity in vulnerable paper-based backing of the wall board.

This example illustrates that risks from multiple decisions made by many different professionals usually act in combination to produce enough moisture accumulation in the wall cavities, for a long-enough period, to create a microbial growth problem.

Further, the risk of excess moisture accumulation can be either increased or reduced by occupants as they use the building. For example, if the occupants of an apartment generate a significant amount of moisture from cooking and cleaning activities without opening windows or using exhaust fans, excess moisture accumulation and mold growth may occur, most commonly on the inside surfaces of exterior walls during cold weather. A building is a complex and dynamic system, and the actions of its occupants are an integral and constantly changing component of that system.

Finally, with respect to health issues, people in the same building are often quite different in their individual sensitivities to airborne microbial contaminants. A low level of contamination that causes adverse health effects for one sensitive individual often causes no health effects for others.

Consequently, the prudent course of action is to keep all of the materials that make up a building and its HVAC systems as dry as possible, consistent with their normal functions. Building professionals and building occupants can

reduce risks by

- Remembering that the risk factors for microbial contamination and corrosion are excessive long-term moisture accumulation in materials, repeated wetting, or catastrophic water damage.
- Making decisions and taking actions to keep the building and its systems, furnishings, and finishes as dry as possible, given the function of the component in question and the available resources. To help establish threshold levels of concern for material dampness, microbiologists and building investigators observe that mold growth is rarely a problem when the water activity of interior building materials and furnishings is held consistently below 0.8 (below an equilibrium relative humidity of 80% rh in the surface layers of a material, as opposed to 80% in the nearby air) (*ASHRAE Standard 160*).
- Being aware that, if adequate resources are not made available to keep the building, systems, and contents dry, the risk of microbial growth (including mold) will increase.
- Addressing persistent dampness inside a building; stagnant water in condensate drain pans; or constantly damp insulation, filters, or sound lining of HVAC systems.

2. ELEMENTS OF MOISTURE MANAGEMENT

Numerous pathways exist for moisture migration into and out of a building, both its spaces and its construction assemblies, as depicted in Figure 2. Other chapters of the *ASHRAE Handbook* that provide broad insight into these avenues and mechanisms, as well as engineered systems for dealing with them, are noted in the figure. A more complete listing of other Handbook topics related to moisture management can be found in [Chapter 37 of the 2021 ASHRAE Handbook—Fundamentals](#).

The largest contributors of liquid moisture are water from wind-driven rain in building envelopes with insufficient drainage, leaks from roof or gutters, and leaks from internal plumbing. These sources must be addressed and resolved for the building envelope to succeed.

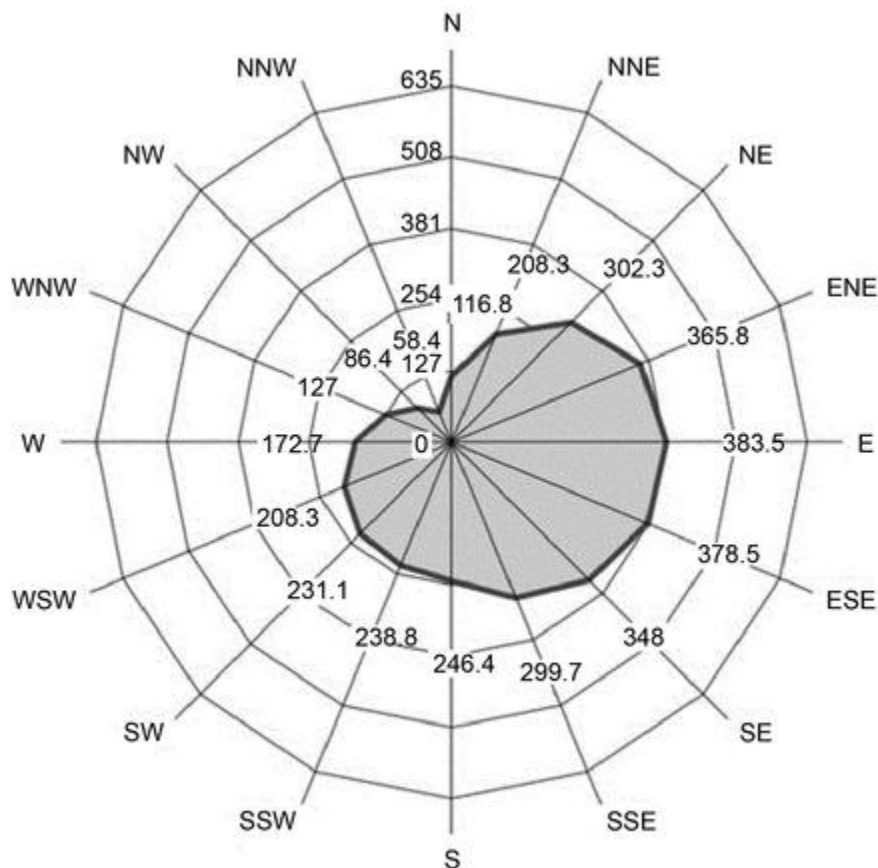


Figure 3. Rain Loads Versus Wind Speed and Direction (mm per year (Straub and Schumacher 2010))

Once liquid water is addressed, the next factors to consider are vapor pressure and relative humidity. The driving forces responsible for water vapor movement within buildings and across the envelope are air pressure differences that move air and vapor together, and vapor pressure differences that activate vapor diffusion. Temperature-, wind-, and fan-induced air-pressure differentials typically overwhelm diffusion in terms of total vapor flux displaced. However, in

hot, humid climates or in buildings with high indoor/outdoor vapor pressure differences, pure diffusion may nevertheless cause problems.

Designing for moisture and humidity management includes the choice of building materials and the layering of the envelope as well as the design and component selection of the HVAC system. For information on the building envelope, refer to [Chapter 15](#); for details on building assemblies, see [Chapters 25, 26, and 27](#). [Chapters 16 and 20](#) contain information on air movement in buildings. [Chapter 13](#) gives information on intrazone airflow, multizone network airflow, and contaminant transport, included vapor; and [Chapter 24](#) discusses airflow around buildings. ANSI/ASHRAE *Standard* 160-2021 provides criteria to evaluate the transient hygrothermal performance of envelopes. This analysis may be used to evaluate moisture tolerance in cases where, besides vapor, liquid water is a primary factor.

3. MOISTURE TOLERANCE AND LOADS

Concrete, masonry, stone, and heavy wood timbers are much less moisture sensitive than untreated paper-faced gypsum board, light gage steel studs, and carpet adhesives. That is why the traditional heavy construction assemblies typical of buildings built before the twentieth century sometimes tolerated rainwater loads and moisture accumulation in exterior walls with fewer problems than the lighter construction of most modern buildings.

Consequently, it is useful to recognize that not all buildings have the same risks, and each type responds differently to equal amounts of humidity and moisture accumulation. When building materials and finishes tolerate moisture exposure, as in the case of a ceramic tile-lined shower room, there is less risk of mold and microbial growth than if that same shower room were lined with painted gypsum wall board.

Similarly, not all exterior surfaces of the same building are subject to the same level of environmental moisture stress. Risks from rain exposure and moisture accumulation are quite different on each face of the building. Beginning with the matter of moisture loading, [Figure 3](#) shows an example of the fact that the volume of rain often depends on the predominant direction of wind-driven rain. In Toronto, Canada, the majority of the rain comes from the east (Straube and Schumacher 2010). In other locations, most of the wind-driven rain can come from quite different directions, varying by season of the year .

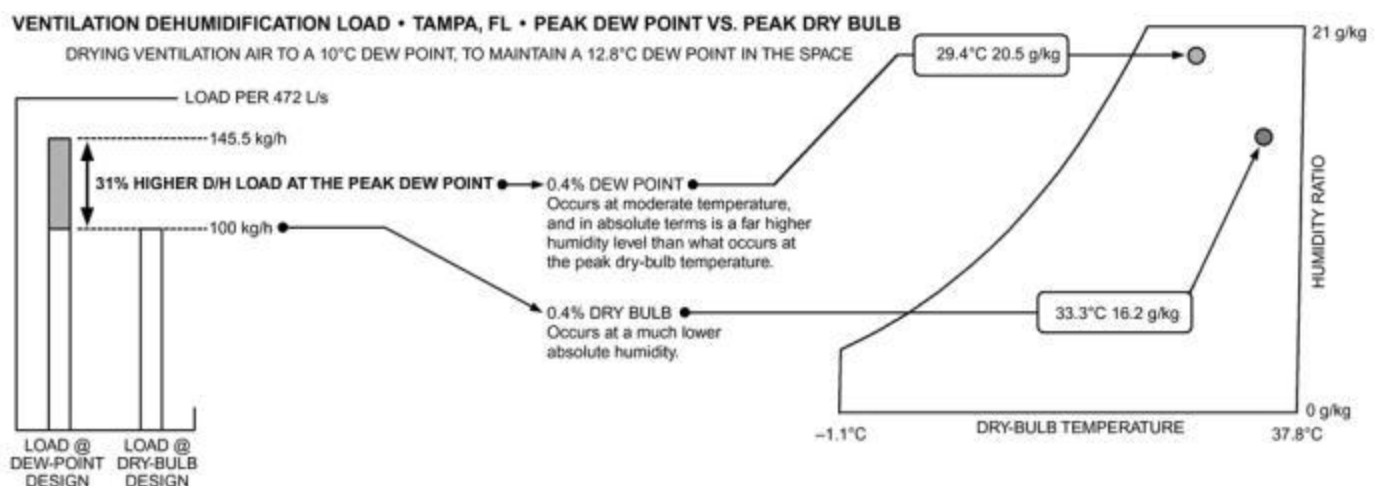


Figure 4. Dehumidification Load Versus Peak Outdoor Dew Point Design and Peak Dry Bulb

Also, the drying potential of the building varies according to building orientation. For example, in the northern hemisphere, the northern side of a building is shaded from direct solar radiation, reducing the annual drying potential on the north wall to far less on the south and west sides of the same building. In the northern hemisphere, the risks of equal amounts of rain are much higher on the north side than on the southern and western elevations.

Therefore, when designing any building enclosure, it is useful to recognize differences in moisture tolerance of materials and to remain aware of differences in moisture loading and drying potential both outside and inside the building. [Chapter 45](#) outlines useful suggestions for architectural designers to limit the potential for problems in building enclosures.

The concern continues after construction is complete. An owner of an existing building should recognize that some types of construction and some systems and assemblies in a building are more subject to problems from moisture accumulation than others. Building operations become more economical and the building itself becomes more sustainable when designers avoid moisture-sensitive materials and assemblies in parts of the building where annual water exposure is high and drying potential low, rather than treating all parts of all buildings equally. In both design and operation, an appropriate hierarchy of concern will be based on how much water a given problem can potentially add to moisture-sensitive indoor materials and furnishings.

Construction planners and building owners should be aware that at every stage of design, construction, and operation, the owner's program requirements (OPR) need to clearly define the key moisture management decisions, who will make them, and who will ensure each decision is carried out in practice (EPA 2013). For example, if there is

no requirement to design and operate the HVAC system to keep the building dry during unoccupied, as well as occupied, hours, the HVAC designer and building operator might well assume that mold protection in a school during summer vacation is not a measure that the owner is willing to pay for.

Architects should keep in mind that the side of the building that has the greatest annual wind and rain exposure needs the most water-resistant materials and the most effective building enclosure design details.

Engineers should remember that buildings in hot and humid climates experience thousands of hours at high outdoor dew points, so the ventilation and makeup air systems must be sure to dry incoming air with more certainty than buildings in dry climates.

Building owners and operators should remember that, no matter what the construction age or type, rainwater leaks are a bigger concern than high humidity, and plumbing leaks are a bigger concern than air leakage from ducts.

All of these problems can cause mold growth, but a simple rule applies to all circumstances: more moisture exposure means a higher potential for problems in a shorter amount of time. Therefore, designers and owners benefit from understanding some of the specific factors that have historically been most influential in dampness problems.

4. RISK FACTORS AND MITIGATION

Each area of professional and occupant activity involves decisions and actions that either increase or reduce the risk of problems related to moisture, mold, and other microbial growth. In most cases, the individuals involved are not aware they are making fateful decisions. When reviewing these factors, it is important to remember that moisture and mold problems can develop for different reasons in cold and hot climates, and can also occur through mechanisms caused by regionally specific building designs, material selections, and construction practices in different parts of the world. Therefore, recommendations based on local conditions are often needed to avoid dampness-related problems.

4.1 HVAC SYSTEMS

Risk Factors

- Failing to dry the ventilation air, and failing to measure and limit the ventilation and exhaust air to the amounts needed for the use of the building and for the number of people actually occupying the building at any given time. Needless amounts of exhaust and ventilation, and ventilation without dehumidification during humid outdoor conditions, have been responsible for major and widespread mold growth problems in hot and humid climates. Whenever any building (in any climate) is mechanically cooled and ventilated, the indoor dew point must remain low enough to keep the indoor surface relative humidity below 80%, even on hidden cool surfaces. Keeping the indoor air dew point below 15°C is a reliable means of avoiding high surface relative humidity (Harriman and Lstiburek 2009).
- Failing to ensure that system operation during unoccupied periods keeps the indoor dew point low enough to maintain a water activity below 0.8 in building materials and furnishings (30-day average surface relative humidity below 80% in surfaces cooled by air-conditioning systems). Mold and microbial growth accelerate when the indoor dew point stays high while surfaces are intermittently chilled by cooling systems. Moisture accumulation and mold have often been observed in unoccupied schools, vacation homes, hotel rooms, institutional dormitories, and military barracks; this happens when there is no independent dehumidification that keeps indoor dew points low when cooling systems are reset to higher temperatures (Harriman and Lstiburek 2009).
- Failing to make air distribution components and joints in return plenums and supply and exhaust ducts sufficiently airtight. Joints and connections must be tight enough to prevent suction that otherwise pulls humid outdoor air into the building, and/or leakage that allows cold supply air to chill surfaces inside humid building cavities (Harriman and Lstiburek 2009; Harriman et al. 2001).
- Failing to keep the long-term average indoor air pressure positive with respect to the outdoors when the outdoor dew point is higher than indoor surface temperatures (Harriman et al. 2001).
- Failing to prevent dirt and dust accumulation on cooling coils and on duct surfaces and sound lining downstream of cooling coils. Accumulating a damp layer of dust can lead to microbial growth. Install access panels that allow inspection and cleaning of the condensate pans and areas upstream and downstream of cooling coils to ensure the condensate pan is not accumulating water, that coils are clean, and that upstream and downstream surfaces are clean and dry. Regular cleaning and ultraviolet lamps can reduce the impact of occasional lapses in filtration. Over time, however, effective filtration is the most important factor in preventing microbial growth in parts of the system likely to accumulate moisture during normal operation.
- Failing to keep air velocity through cooling coils low enough to prevent droplet carryover into downstream duct work and filters, leading to microbial growth in those locations (Harriman and Lstiburek 2009).

- Failing to install condensate drain traps deep enough to allow free-flowing drainage of normal cooling coil condensate, and failing to install traps and condensate drain lines with a diameter large enough to allow maintenance personnel to both observe clogs and clean out anything that obstructs free-flowing drainage (Harriman et al. 2001).
- Failing to install accessible cleanouts in condensate drain lines to allow periodic removal of algae and the particulate, feathers, sticks, and leaves that typically wash off the coil. Note also that copper piping has been effective in limiting biological accumulation in condensate drain lines (Harriman et al. 2001).
- Failing to ensure that the temperature of chilled-water systems stays low enough, and water flow rates through the coils stay high enough, to effectively dry the air. Note that this problem is most common when a building or a system is not equipped with a separate dehumidifier (Harriman and Lstiburek 2009).
- Redistributing microbial air contaminants, including mold, from a contaminated space into occupied areas. Examples of contaminated spaces can include parts of the building under construction or renovation, hidden building assemblies (e.g., damp crawlspaces or attics), or spaces above dropped ceilings or below raised floors (Harriman and Lstiburek 2009).

Risk Mitigation

- Ensure that all ventilation air is dried to a dew point below the dew point maintained inside the building when the building is being mechanically cooled (Harriman and Lstiburek 2009; Harriman et al. 2001).
- Design ventilation dehumidification components based on the humidity loads at peak outdoor dew point, rather than the loads at the peak outdoor dry-bulb temperature. [Figure 4](#) shows the large difference between these conditions in Tampa, FL; [Figure 8](#) provides more detailed examples in other climates (Harriman and Lstiburek 2009; Harriman et al. 2001).
- Ensure that there are HVAC systems and controls that keep the indoor air dew point below 15°C when the building is unoccupied, such as during summer vacations of schools and universities, long-term remote deployments of personnel who occupy military barracks and dormitories, and off-season vacancy of vacation homes, apartments, and condominiums.
- Ensure that all condensation inside HVAC components and air distribution ductwork is drained away to an appropriate sanitary drain or condensate collection system (Harriman et al. 2001).
- Ensure that indoor surfaces of both occupied and unoccupied spaces are not cooled to temperatures so low as to create an average surface relative humidity of over 80% lasting for more than 30 days, or surfaces cold enough to allow condensation (ASHRAE *Standard* 160).
- Note that the relative humidity of air measured in the occupied space or return air does not indicate the relative humidity in the thin boundary layer of air in contact with cool surfaces. Monitoring and controlling indoor dew point compared to indoor surface temperatures is the more useful metric for preventing persistent dampness. For example, in buildings that are mechanically cooled during hot or humid weather, drying the ventilation air to an air dew point below 12.8°C nearly always ensures that surface relative humidity stays below 80%, even on cool surfaces. In contrast, if the indoor air relative humidity were 55% at 25.6°C, any surface cooled below 18.9°C would have a relative humidity above 80% (Harriman and Lstiburek 2009).
- Keep the indoor dew point low enough to ensure that there is no condensation on the exposed surfaces of cool HVAC components or on moisture-sensitive building materials or furnishings. Note that the caution against condensation and long-term average surface relative humidity above 80% applies not only to visible surfaces in occupied spaces but also to any moisture-sensitive materials inside hidden building cavities and unconditioned spaces (Harriman et al. 2001).
- Ensure that large-capacity humidifiers are installed as multiple modular stages rather than a single large units, and controlled so they do not overload the air with humidity, reducing the risk of condensation inside air distribution systems or inside exterior walls and roofing assemblies (Harriman et al. 2001).
- Ensure that cold HVAC and plumbing components and systems such as chilled-water pipes and valves, supply air ducts, cold domestic water lines, and cold condensate drain piping are sufficiently insulated to keep the temperature of all of their surfaces at least 4 K above the dew point of the surrounding air. Note that pipes often pass through unconditioned spaces such as basements, crawlspaces, and attics. Any insulation on chilled piping must be continuous and complete, and also be equipped with an effective vapor retarder, or be itself a vapor retarder to limit high surface relative humidity on cold pipes as they pass through high-dew-point spaces and building cavities (Harriman and Lstiburek 2009).

4.2 ARCHITECTURAL FACTORS

Risk Factors

- Vinyl wall covering on exterior and demising walls of buildings in hot and humid climates. Problems have frequently occurred behind vinyl wall covering when the building lacks a continuous, sealed air barrier that effectively keeps humid outdoor air out of the cavities inside the exterior and interior walls (Harriman and Lstiburek 2009).
- Damp basements and crawl spaces (DOE 2005). In residences in cold climates, humid air from damp basements and crawlspaces is often carried upward into a cold attic by stack effect. The moisture condenses into the roof sheathing and supports mold growth. In hot climates, the water vapor may condense or be absorbed into the flooring of the first floor, because that surface has been cooled by air conditioning in the occupied space.
- Water accumulating next to or under the building's foundation, often because of exterior grading that has compacted, sloping inward toward the foundation after freeze/thaw cycles in cold climates, or because of decorative edging around shrubbery that creates a pond near the foundation (ASTM 2009; Rose 2005).
- Rain leaks through joints around windows, doors, or other wall penetrations such as through-wall air-conditioning units, electrical fixtures, exhaust ducts, or structural fasteners, or leakage through joints where different types of exterior cladding come together (Harriman and Lstiburek 2009).
- Absence of effective flashing around windows, doors, skylights, and other penetrations of the building's walls or roof (ASTM 2007).
- Absence of an effective, continuously sealed air barrier covering all six sides of the building envelope, allowing leakage of humid air from either indoors or outdoors into cool exterior walls, crawlspaces, roof assemblies, or attics (see [Chapter 45](#)) (ASHRAE *Standard* 90.1).
- Absorptive exterior cladding such as brick veneer, stucco, or masonry, which retains rainwater but is not backed by a free-draining and vented air gap in front of a water-resistant vapor barrier equipped with effective flashing (Derome and Saneinejad 2009).

Risk Mitigation

- Roof overhangs of at least 600 mm or more (CMHC 1998). In both tall and low-rise buildings, a roof overhang greatly reduces the volume of rainwater that ends up on the wall.
- Sill pan flashing under windows and doors to force any water leakage outward onto an effective water barrier and then out of the building wall (ASTM *Standards* D7338, E2112; Harriman and Lstiburek 2009; JLC 2007).
- Crawlspaces lined with water and vapor barriers that are sufficiently sealed to prevent infiltration into the building from surface water and moisture from the soil and humid air (DOE 2005).

4.3 BUILDING OPERATIONAL DECISIONS

Risk Factors

- Failing to turn off exhaust fans and close ventilation air dampers when the building is unoccupied (to reduce humid air infiltration when systems are not providing dehumidification).
- Failing to effectively exhaust humid air from showers, spas, decorative water fountains, indoor landscaping irrigation, and swimming pools.
- Failing to dry outdoor air brought into the building for ventilation or to replace exhaust air, when the outdoor air dew point is above 15°C.
- In cold weather, humidifying indoor air to dew points high enough to create condensation or surface relative humidity above 80% or water activity above 0.8 at the surface of moisture-sensitive surfaces inside walls, above insulated ceilings, or in attics for extended periods (e.g., days, weeks).
- Failing to ensure that the temperature of chilled-water systems stays low enough, and that flow rates through the coils stay high enough, to effectively dry the air when the chilled-water systems are the only means of removing excess humidity from the building. This problem often occurs when chilled-water temperatures are reset to save

energy when the building is unoccupied during hot and humid weather; under these circumstances, a separate dehumidification system may be necessary to prevent problems associated with persistent dampness (Harriman et al. 2001).

Risk Mitigation

- Mop and dry up spilled liquids or wash water promptly, limiting the amount of water that soaks into walls, carpeting, or flooring materials.
- Repair plumbing leaks quickly, and dry up any water leakage that resulted from such leaks within 24 to 48 h.
- Keep irrigation spray heads aimed carefully away from the building, preventing the frequent soaking of exterior walls and foundation.
- Maintain the slope of exterior landscaping so that rainwater and irrigation spray flows away from the foundation rather than accumulating there.
- Keep rainwater runoff from the roof at least 1 m away from the foundation.
- Prevent microbial growth in HVAC components and air distribution systems, and remove mold and other microbial contaminants from air flowing through HVAC systems, to prevent contaminants from being distributed throughout the building (ACGIH 1999; AIHA 2008; EPA 2001).
- In hot and humid weather, operate systems so they limit the dew point of the indoor air to less than 15°C, when the building is not occupied.

4.4 OCCUPANT DECISIONS

Risk Factors

- Failing to operate exhaust fans or open windows to effectively remove humid air from cooking or from baths and showers, especially in small homes or apartments with many people or long cooking operations that lead to a large percentage of hours per week or month at a high indoor dew point.
- Failing to exhaust humid air from clothes driers or drying clothes on racks indoors without effective exhaust of the resulting humidity. The problems associated with this error are especially severe during cold weather, when exterior walls and attics are cold, creating large condensing surfaces.
- Growing an unusually large number of live plants indoors, without exhausting or using dehumidifiers to remove the humidity they respire. Problems created by this oversight have been seen to be especially severe in cold climates and indoor spaces used to grow medicinal or recreational cannabis.
- In cold weather, humidifying the indoor air to dew points high enough to create condensation or surface relative humidity above 80% or surface water activity or materials inside cooled walls and attics for days or weeks at a time.
- Storing large amounts of documents, furniture, or cardboard boxes in damp basements or crawlspaces, or in contact with cool walls or foundations.

Risk Mitigation

- Keep shower or tub splash within the tub enclosure, limiting the amount of water that can soak the floor or walls.
- Install and operate quiet, humidity-activated exhaust fans in bathrooms and in spaces used for growing large numbers of plants. Set the fan to start operating when humidity in the space rises above 70% rh.
- Mop and dry spilled liquids or wash water promptly, limiting the amount of water that soaks into walls, carpets, or flooring materials during cleaning operations, and dry any water that remains within 24 to 48 h.
- Repair plumbing leaks quickly, and dry any water accumulation within 24 to 48 h.
- Keep irrigation spray heads aimed carefully, preventing repeated soaking of exterior walls and foundation.
- Maintain the slope of the landscaping so that rainwater and irrigation runoff flows away from the foundation rather than accumulating there.

- Keep rainwater runoff from the roof at least 1 m away from the foundation.
- Remove mold and other microbial contaminants from the residence promptly, using appropriate engineering controls such as high-efficiency particulate air (HEPA) filtration and temporary negative pressure containments to keep contaminants from becoming airborne and distributed throughout the building (ACGIH 1999; AIHA 2008; EPA 2001; IICRC *Standard S520*).

5. SOLUTIONS

5.1 ARCHITECTURE AND DESIGN

Suggestions in this section are traditionally within the control of the owner, architect, and general contractor. These can help accomplish three tasks that reduce the risk of indoor dampness: (1) keep rain off and away from the building envelope, (2) help materials drain water and resist its effects when leaks eventually occur, and (3) keep humid air from infiltrating into the building envelope (especially through the historically problematic large gaps in the long joints where the roof meets the walls).

Roof Overhang

Ideally, the roof should project at least 600 mm beyond the walls all around the building. This greatly reduces the risks of water leakage, because much less rainwater ends up on the walls over the life of the building.

The baseline risk of mold and moisture problems depends on how much water contacts the exterior walls. More hours of contact and a higher volume of water generates more risk when gaps and cracks occur (by design, during construction, or over the building's lifetime). The further the roof extends beyond the walls, the less rainwater will flow down those walls to challenge every joint and seam.

A roof projection of about 600 mm is likely to cut the annual rain volume flowing down the walls and windows by roughly 50% in both tall and low-rise buildings. The exact reduction depends on many factors, but 50% is a reasonable approximation of the load reduction value of an overhang. Longer projections are even better because they reduce the rain volume still further, but studies of moisture problems in buildings indicate that even in very rainy climates, very few major moisture problems occur where the roof projection is at least 600 mm beyond the exterior walls (CMHC 1998). As a side benefit, the wider the overhang, the greater the reduction in solar-driven cooling load, which reduces energy consumption in air-conditioned buildings.

A useful option for taller buildings is to increase the length of the overhang. Interestingly, in high-rise buildings, most of the annual rain load reaches the building as it blows in from the sides during periods of wind-driven rain; the building's 600 mm overhang catches the approaching wind and forces it to roll into a protective cylindrical air mass near the roof line. That rolling cylinder of air acts as a sort of dry protective bumper, forcing most of the oncoming rain-laden wind up, over, and around. Consequently, most of the rainwater never reaches the surface of the building.

Waterproof Drainage Plane

To further reduce risks, exterior walls can be designed with a three-part drainage plane behind the exterior cladding. An effective drainage plane consists of three components:

- Waterproof drainage layer with flashing at its base that forces any water leakage back out of the wall assembly.
- Air gap to allow smooth flow of any leakage water down the surface of that waterproof layer.
- Flashing that prevents water from entering the wall above and around penetrations (e.g., windows, doors, air-conditioning unit sleeves). The flashing is integrated with the waterproof layer such that any leakage water is eventually redirected back out of the wall to the weather side of the cladding.

In theory, exterior cladding can be designed as a barrier system, so that no water ever gets into the exterior wall. However, in practice, whether due to extreme weather, oversight during construction, or aging of materials, some water usually gets in.

In some cases, the wraparound air barrier described in the following section can also act as the waterproof layer, if (1) both design and installation of the joinery are done carefully, and (2) the air barrier is adequately supported to minimize flexing. There is no inherent conflict between the functions of air barrier and water barrier; both are vapor permeable. However, keep in mind that an air barrier must be structurally strong enough to resist the full design wind load, and a waterproof membrane needs to remain waterproof. If an air barrier flexes and stretches over time under wind loading, its seams may not remain waterproof. With sheets, it is also important to remember that the waterproof layers must overlap shingle style, so that each seam sheds water rather than traps it.

Combining the functions of water barrier and air barrier is less complex when using spray-applied, vapor-permeable but waterproof membranes. In contrast, when the sheets are assembled into a combined air barrier/waterproof layer, all joinery must resist wind loads over time, and it must be detailed to ensure that all its joints and seams shed water.

In addition to the air barrier and waterproof layer, buildings clad with brick, stone, or stucco need vapor barriers on the exterior side of the wall insulation because these materials act as moisture reservoirs: unless equipped with specialized coatings, they soak up rainwater. This is not always a problem for the material itself, but it often creates problems for more moisture-sensitive sheathing behind that cladding. Solar heat drives large amounts of hot water vapor out of the cladding and inward into the sheathing. In hot, humid, and mixed climates, it is important to line the drainage gap for brick or stucco with a vapor barrier, and that layer may act as the waterproof layer and air barrier as well.

Keep in mind that although exterior waterproof layers and air barriers are needed in all buildings, vapor barriers are needed in a much smaller percentage of buildings and must be thoughtfully located to avoid problems. Walls must be able to dry, ideally both inwards and outwards. Exterior vapor barriers have often prevented this necessary drying. Except behind the claddings described previously, it is usually best to avoid exterior vapor barriers in hot and mixed climates. In cold climates, if any vapor barrier is needed, it should be located toward the inboard of the insulation. In cold weather, the vapor flows become more complex. For example, a vapor barrier outside of the insulation could lead to accumulation of moisture that would freeze during the winter.

The basic goal is to keep humid air out of any cold wall. In cold climates, the humid air is on the indoor side, so a combination vapor barrier/air barrier is useful in that location. In hot climates, an air barrier (not a vapor barrier) located near the outside of the wall is usually the best way to keep humid air out of exterior walls that are chilled by the indoor air conditioning. However, the optimal location for a vapor barrier is complex and depends on many other factors that are beyond the scope of this chapter. For more about the different functions and locations for vapor barriers, air barriers, and waterproof layers, see [Chapters 25, 26, and 27 of the 2017 ASHRAE Handbook—Fundamentals](#) and [Chapter 45](#) of this volume. Also, consider using an hourly hygrothermal modeling program to analyze the behavior of the proposed enclosure over a full year, rather than a single-point analysis that looks only at extreme conditions.

Sill Pans and Flashing

To be effective, flashing must extend around the entire perimeter of windows and doors. It must be designed and installed so that any water leak above, beside, or through the window framing or door is caught by a watertight pan under the window or door, and redirected back out of the wall and onto the waterproof drainage plane (ASTM 2016).

In commercial and institutional buildings, sill pans are often made of metal for maximum durability. It is important to ensure that a metal sill pan does not form a thermal bridge that allows heat leakage. This is important from an energy perspective in all seasons, and also from a moisture management perspective during cold weather. If the indoor edge of the sill pan is cold in the winter, it could lead to condensation and moisture accumulation inside the wall.

The architectural designer (as opposed to the craftsperson installing the flashing) is in the best position to select the sill pan material and to define how all the layers in the wall must be integrated with this flashing. For best results, the architectural plans should show the layer integration in isometric projection, with each layer and its installation sequence defined and illustrated. Most importantly, the architectural drawings need to clearly show how these layers all come together in the corners.

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Many designers assume that flashing integration is a question of means and methods, and therefore a contractor responsibility. Depending on the contracts, this may sometimes be the case. But in most situations, designing and detailing the exterior walls with all their complex layers and corners is better left to the architectural designer. This is especially true of the complex inside and outside corner details. It is rarely sufficient to design the layers in section drawings and then hope that the contractor will be able to guess how they are supposed to meet in the corners and still be watertight. The three-dimensional integration of the flashing layers, especially the sill pan flashing, is usually the responsibility of an architectural designer.

When there are no drawings to three-dimensionally show the sill pans, the window flashing at the head and jambs, and how all the layers go together in the corners, the architectural design of the flashing is effectively assigned to the installer. That may not always be the person who is best equipped to make complex decisions that involve both form and function as well as material compatibility, construction sequencing, economics, and long-term durability. Additionally, even very capable craftspeople are rarely compensated financially for absorbing responsibility for such design decisions.

Wrap-Around Air Barrier

Continuous exterior air barriers reduce the risk of indoor moisture problems. Air leakage into or out of wall assemblies has been one of the most common sources of moisture accumulation and mold problems in all climates. In a heating-dominated climate, humidified air that leaks outward through the building envelope may encounter

temperatures low enough to cause condensation inside the assembly. A similar problem can occur in a cooling-dominated climate: when warm, humid air enters through cracks and gaps, the moisture it carries can condense or be absorbed when the air contacts the cooler surfaces inside the building.

Consequently, air barriers must be continuous, without gaps, cracks, or open seams. In short, the ideal air barrier is continuously sealed around all penetrations and fasteners, and it must wrap around all six sides of the entire building. From a moisture control perspective, pay special attention to air barrier continuity at the roof/wall joint; most air leakage occurs where the walls meet the roof. In traditional designs, this roof/wall joint was sometimes designed to leak (e.g., vented soffits). However, air leakage has proven highly problematic for humidity control, moisture control, and energy consumption. The state of the art is to design and construct buildings that do not leak air, as reflected in the guidance of ASHRAE *Standard* 90.1 and the requirements of building codes in Canada and standards for U.S. government buildings.

Mold-Resistant Gypsum Board

When gypsum board is used on or inside exterior walls, or installed over interior concrete or masonry walls, it is prudent to specify products certified by the manufacturer to be resistant to mold growth and moisture damage. Although cement board is generally the preferred material for the lining of showers and bathtubs, any additional gypsum wall board installed in the walls or ceilings of bathrooms, shower rooms, or laundry rooms should also be resistant to moisture and mold growth.

In parts of the building which can often be moist, it is wise to use moisture-tolerant and mold-resistant wall board. These products provide a useful degree of tolerance for common shortcomings of conventional construction, which begin with construction moisture. Excess construction moisture and plumbing leaks have been responsible for mold and moisture problems in buildings in all climates. In hot and humid regions, rain is a constant challenge on construction sites; in cold climates, the construction season is so short that the building must often be closed in before the concrete and block have had enough time to dry out with ambient air circulation alone.

Mold and moisture problems do not happen in the concrete or masonry block itself, because those materials are moisture tolerant. Problems arise when flooring adhesives are applied over damp concrete, or when untreated, paper-faced gypsum wall board covers damp masonry block. Therefore, it is useful to specify that any masonry or concrete covered by gypsum board must be dried before gypsum board is installed. Further, manufacturers typically recommend against mounting gypsum board in direct contact with masonry block, even when masonry appears to be dry. Instead, install gypsum board over furring strips that allow an air gap between the masonry and the gypsum board, or install the board over a layer of low-permeability foam insulation board that is in direct contact with the masonry.

Exterior walls also benefit from moisture-tolerant wall board. Water leakage and humid air infiltration are probable at some point during the life of the building, no matter how well built it is at the beginning.

Permeable Interior Wall Finish for Exterior Walls

To reduce risks of trapping moisture inside walls in hot climates, specify that any paint or other wall finish for the indoor surface of an exterior wall must have a net value above $860 \text{ ng}/(\text{Pa} \cdot \text{s} \cdot \text{m}^2)$, including the effect of any adhesive.

Impermeable vinyl wall covering on the indoor surface of exterior walls has proven to be frequently problematic, especially in hot and humid climates. In tens of thousands of buildings, vinyl wall covering has been largely responsible for massive mold growth inside exterior walls. [Figure 5](#) shows an example of the problems frequently seen on vinyl-covered exterior walls. The same problems can occur with certain types of paint, notably the epoxies and high-durability latex paints. The vinyl or impermeable paint acts as a vapor barrier, preventing effective drying of moisture that often collects inside exterior walls. Moisture can accumulate through many mechanisms, including leaks in the drainage plane, aging of joints, or humid outdoor air infiltrating and condensing moisture in the material behind the vinyl. There is no practical way to prevent 100% of occasional episodes of moisture accumulation, so it is imperative that moisture not remain trapped inside the wall, as happens when vinyl wall covering is adhered to exterior walls.

In recent years, manufacturers have developed permeable or semipermeable vinyl wall covering. Quantified permeability of these products is often uncertain. Risks of moisture accumulation can be reduced by specifying that the system as a whole (wall covering plus its adhesive) must have a value (ASTM *Standard* E96-16) above $860 \text{ ng}/(\text{Pa} \cdot \text{s} \cdot \text{m}^2)$.



Figure 5. Impermeable Vinyl Wall Covering on Exterior Wall

5.2 HVAC SYSTEMS

Suggestions provided here are traditionally under the control of the HVAC designer, installer, and the building operations staff. These steps can reduce risks by ensuring that the indoor dew point stays below the typical surface temperatures of an air-conditioned building and its HVAC components. They also save energy and reduce the risk of moisture accumulation by preventing cold air from escaping from ducts to chill indoor surfaces, and by avoiding the problems created when humid outdoor air is pulled through walls and through attics instead of through the HVAC system.

Dedicated Outdoor Air Systems (DOAS)

There are many reasons to separate a building's ventilation air system from its heating and cooling systems by using a DOAS, but from the perspective of reducing risk of moisture accumulation, the most important reason is to ensure that incoming outdoor air is always dried below the indoor dew point, typically to a dew point of 12.8°C or lower. Additionally, if the DOAS units are equipped with return air connections, as shown in [Figure 6](#), they can act as effective whole-building dehumidifiers when the building is unoccupied or when the ventilation air flow requirement is reduced.

If incoming ventilation and makeup air is not dried out before it enters the building, it is very difficult to keep excess humidity from being absorbed into the building's interior finishes and building materials. Incoming ventilation and makeup air typically carries more than 80% of the building's annual dehumidification load; if this load is not intercepted and removed by a dedicated dehumidification component such as that typically included in a DOAS system, the cooling equipment will struggle to remove the humidity load and often overcools the building as a result. Overcooling leads to discomfort, energy waste, and cooler surfaces. [Figure 7](#) illustrates the consequences in a building that was overcooled instead of dehumidified, resulting in moisture absorption by those cold surfaces and subsequent mold growth. (Note that this level of mold growth occurred in spite of hospital-grade, nonabsorptive epoxy wall paint.)

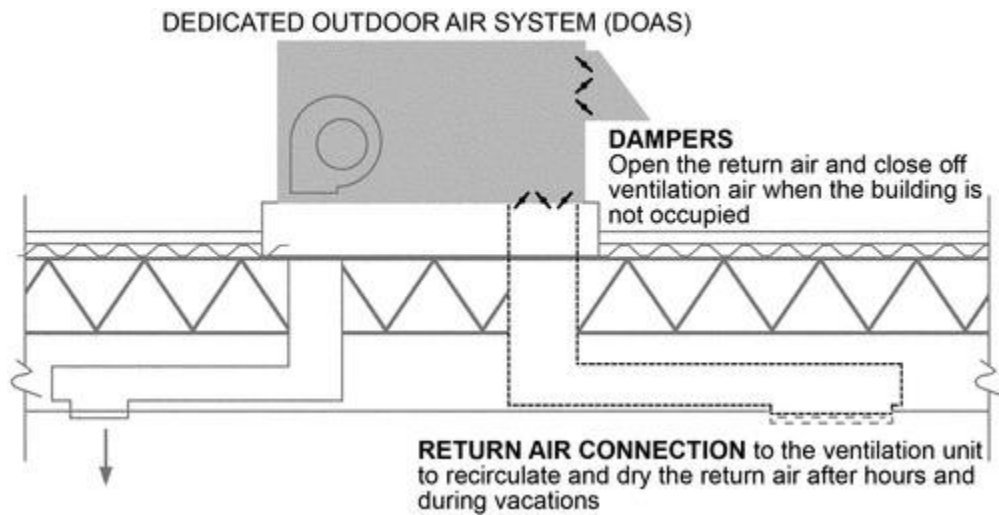


Figure 6. Dedicated Outdoor Air System (DOAS) with Return Air Connection for Drying After Hours

Maximum 12.8°C Indoor Dew Point for Mechanically Cooled Buildings in Hot or Humid Climates

Another way to reduce the risk of building moisture problem is to design the HVAC systems so they remove enough humidity to keep the indoor dew point below 12.8°C during occupied periods and below 15°C during unoccupied periods.



Figure 7. Mold Resulting from Humid Air Infiltration in Overcooled Health Clinic

Support for this maximum is documented in ASHRAE publications based on the collective experience and judgment of the authors and reviewers of those publications (Fischer and Bayer 2003; Harriman and Lstiburek 2009; Harriman et al. 2001; Spears and Judge 1997). Note, however, that the 12.8°C control level is not yet incorporated in an ASHRAE standard and has therefore not been subjected to public review. Consequently, each owner and designer must decide what indoor dew point maximum is prudent given the climate, the needs of the building, and the risks for that building and its occupants from any moisture or microbial growth problem. Following is the logic behind this control level, which should help readers use their own judgment about the prudent maximum dew point for different types of buildings, occupancies, and climates.

Keeping the dew point below 12.8°C protects the building from indoor condensation and excessive moisture absorption into cool surfaces. The 12.8°C dew point also allows comfort at higher dry-bulb temperatures, which reduces cooling energy consumption and provides comfort for a wider variety of activity levels and body types. At or below a 12.8°C dew point, occupants rarely need to overcool the space in order to achieve comfort (Fischer and Bayer 2003; Spears and Judge 1997).

Another reason for specifying a dew point maximum in place of a relative humidity maximum is that, in the past, guidance based on relative humidity has been ineffective in preventing moisture accumulation and the associated problems. A maximum 65% rh has been a traditional criterion, and some standards and codes still suggest that as a limit, but building failures have shown that this criterion is not always effective in preventing mold. Consequently, recent publications from ASHRAE, the U.S. Environmental Protection Agency (EPA), and U.S. General Services Administration (GSA) recommend a maximum dew point as a reasonable compromise between the competing goals of energy consumption, comfort, and mold avoidance during both occupied and unoccupied hours (EPA 2013; GSA 2014; Harriman and Lstiburek 2009; Harriman et al. 2001).

The basic problem with the 65% rh maximum is that it does not address what happens at the surface of cool materials, which is where problems occur. For example, consider 65% rh in an unoccupied office or day care center closed at night, or on weekends. The building's thermostat is often reset to 29°C to save energy. At that temperature, 65% means air has a dew point of 23°C. When the air-conditioning system begins to chill the building back down for occupied operation, any surface now cooled to 23°C has a surface relative humidity of 100%, not the 65% value shown by the HVAC control sensors (which measure the air). Air-conditioning systems' humidity sensors cannot measure the surface relative humidity on all of the cold surfaces on and behind the walls and above the ceilings.

Keeping the indoor air at or below a 12.8°C dew point avoids such confusion and provides an effective margin of safety for keeping building materials dry. At that dew point, the relative humidity at cool surfaces is very unlikely to rise to levels that promote the amount of mold growth shown in [Figure 6](#).

Holding a building below a 12.8°C dew point is a conservative suggestion for standard operation, representing the collective experience of many who have investigated moisture problems in buildings. This limit will almost certainly reduce the risks of moisture problems caused by HVAC issues to a negligible level, and also reduce the risks of minor water leakage associated with architectural design and construction. Although the lower dew-point limit may also save energy, cost increases in terms of equipment and operating expense are possible. Many buildings all over the world have exceeded this criterion for a significant portion of their operating hours without any documented moisture or mold problems. Whether problems arise depends on many factors, including the sensitivity of the building material and of the furnishings and finishes, and (perhaps most importantly) the number of hours that interior surfaces are able to absorb moisture from the indoor air. The number of high-dew-point hours varies with climate, and often varies according to the design and operation of the HVAC system. More hours at high dew point increase risks, but do not guarantee failure.

Experience (e.g., Harriman and Lstiburek [2009]; Harriman et al. [2001]) also shows that, at high indoor dew points, occupants are very likely to turn down the thermostat to gain comfort, which increases energy consumption. Again, these difficulties will be more problematic as the number of humid hours outdoors increases.

Climate. In cool climates or high-altitude locations with only a few hundred hours of outdoor dew points above 12.8°C and a few hundred hours of air conditioning, the risk of higher indoor dew points above may be relatively low. Any problems would usually take many years to develop, if they indeed ever happen. But in mixed or humid climates where there are many thousands of hours when the outdoor dew point is above 12.8°C and where the air-conditioning season (i.e., when building surfaces are chilled) is long, problems may develop in a few months or a few years.

Drying During Unoccupied Periods

When a building is unoccupied and the weather outdoors is humid, keep the air inside the building dry, so that in turn, the surfaces of walls, floors, ceilings, carpets, furnishings, and contents remain dry enough to prevent mold growth.

Until recently, humidity control during unoccupied periods has often been ignored, because the HVAC design and its operation are, logically, focused on providing the lowest-cost system that will maintain comfortable temperatures with acceptable humidity levels when people are in the building. However, it has become increasingly apparent that moisture and mold problems are associated with unoccupied periods during the summer in schools, military barracks, and university dormitories and also in seasonally occupied buildings such as vacation apartments and condominiums (Light 2017; Light et al. 2015; McMillan and Block 2005).

To avoid growing mold in buildings that are not occupied constantly, the HVAC designer (and the system operators) need to make decisions that keep the indoor air dry during unoccupied periods. As a minimum, design and operate the HVAC systems so that humid outdoor air does not flood into the building.

First, ensure that when the building is not occupied, toilet exhaust fans turn off, so that exhaust fan suction does not pull humid outdoor air into the building. Next, make sure that all outdoor air dampers close tightly (ideally automatically) during unoccupied periods, so that these do not act as holes that allow infiltration of humid outdoor air. Finally, provide equipment and controls that continue drying the indoor air, independent of the cooling set point. This last point is important, but is often not addressed because most HVAC designs rely on cooling equipment to remove humidity as well as removing sensible heat. Although most cooling systems are adequate to keep humidity under

control when they are in full operation, it is important to keep in mind that during intermittent operation, cooling systems may not actually remove any humidity.

During unoccupied periods, the thermostat set point is generally raised to reduce energy costs. At the higher set point, the thermostat calls for cooling only rarely, because sensible cooling loads are much reduced. Also as a result of the lower loads, the sensible cooling is accomplished so quickly that the cooling equipment turns off before any significant amount of moisture is removed from the air (Shirey and Henderson 2004). There are several strategies available that can address this limitation of cooling systems while still keeping operational costs low when a building is not occupied.

First, make sure that the dehumidification loads are kept low, by halting ventilation and exhaust fans and closing dampers to keep outdoor air out of the building as discussed above. After those measures have been implemented, either add a separate dedicated dehumidifier to the system to recirculate dry air during unoccupied periods, or operate the cooling system components towards the goal of limiting the indoor air dew point rather than keeping the air cool.

Drying during unoccupied periods can be partly accomplished in existing buildings that do not have dedicated dehumidifiers by ensuring that operation of cooling equipment is restricted in two respects: raise the cooling set point temperature to 27°C or above, and only allow cooling equipment to operate between the hours of 12:00 noon and 3:00 pm. This strategy has two beneficial effects. It keeps indoor surfaces warm, which discourages moisture accumulation. Then, by restricting the number of hours the cooling equipment can operate to the hottest hours of the day, the system is forced to operate for long periods to drop the indoor air to the thermostat set point. Long periods of continuous cooling provide some amount of dehumidification, even without dedicated dehumidifiers.

When designing new buildings, a much more robust dehumidification design strategy is to provide the building with dedicated outdoor air systems (DOAS) so that all the outdoor air is dried and filtered before it enters the building. Then the DOAS unit can be converted to a dedicated, recirculating dehumidifier during unoccupied periods. This can be accomplished at very modest first cost by providing the DOAS unit with two additional components: a return air connection and dampers that can close off the ventilation air when the building is not occupied. With that arrangement, air from the space can be dried by the DOAS in response to a dew point controller. As the indoor space rises towards a dew point of 15°C, the DOAS unit turns on to dry and recirculate the indoor air. [Figure 5](#) shows a diagram of such a configuration.

The suggestion to control the indoor air dew point, rather than its relative humidity, is based on the fact that at high dry-bulb temperatures, a relative humidity setting that might otherwise seem reasonable could allow an excessive amount of moisture to accumulate in surfaces. For example, at 30°C, a relative humidity of 65% represents a dew point of 22°C. At that level of absolute humidity, the relative humidity at the surface is above 80% for any material that has a temperature of 25°C or below. Chances are good that, in any building that has mechanical cooling, some surface will often be below 25°C, due to leaking cold supply air duct connections and less-than-optimal placement of supply air diffusers. In contrast, controlling the indoor air dew point to less than 15°C when the building is unoccupied provides more certain avoidance of moisture absorption into surfaces, especially if the indoor air temperature stays above 27°C.

Design for Dehumidification Based on Loads at Peak Outdoor Dew Point

Peak dehumidification loads occur when the outdoor dew point is at its highest level—not when the outdoor dry bulb temperature is at its peak. In absolute terms, the outdoor humidity is 30 to 35% higher at the peak dew point condition compared to the humidity load at the peak dry bulb condition.

[Figure 8](#) shows the effect of this difference on the humidity loads of a medium-sized retail building that complies with the requirements of ASHRAE *Standard* 62.1-2016. When the humidity loads are calculated at peak outdoor dry-bulb temperature, the load calculation grossly understates the humidity load occurring when the outdoor air is at its local peak dew point. Note also that magnitude of this unexpected difference in humidity loads is usually greatest in continental climates (e.g., Beijing, Cincinnati) rather than coastal climates (e.g., Miami, Hong Kong). To avoid the risk of major shortcomings in the design of the dehumidification components, the designer should use the peak dew point values for dehumidification load calculations. Peak dew-point design values for more than 6000 weather locations are provided in [Chapter 14 of the 2021 ASHRAE Handbook—Fundamentals](#) and on the CD accompanying that volume.

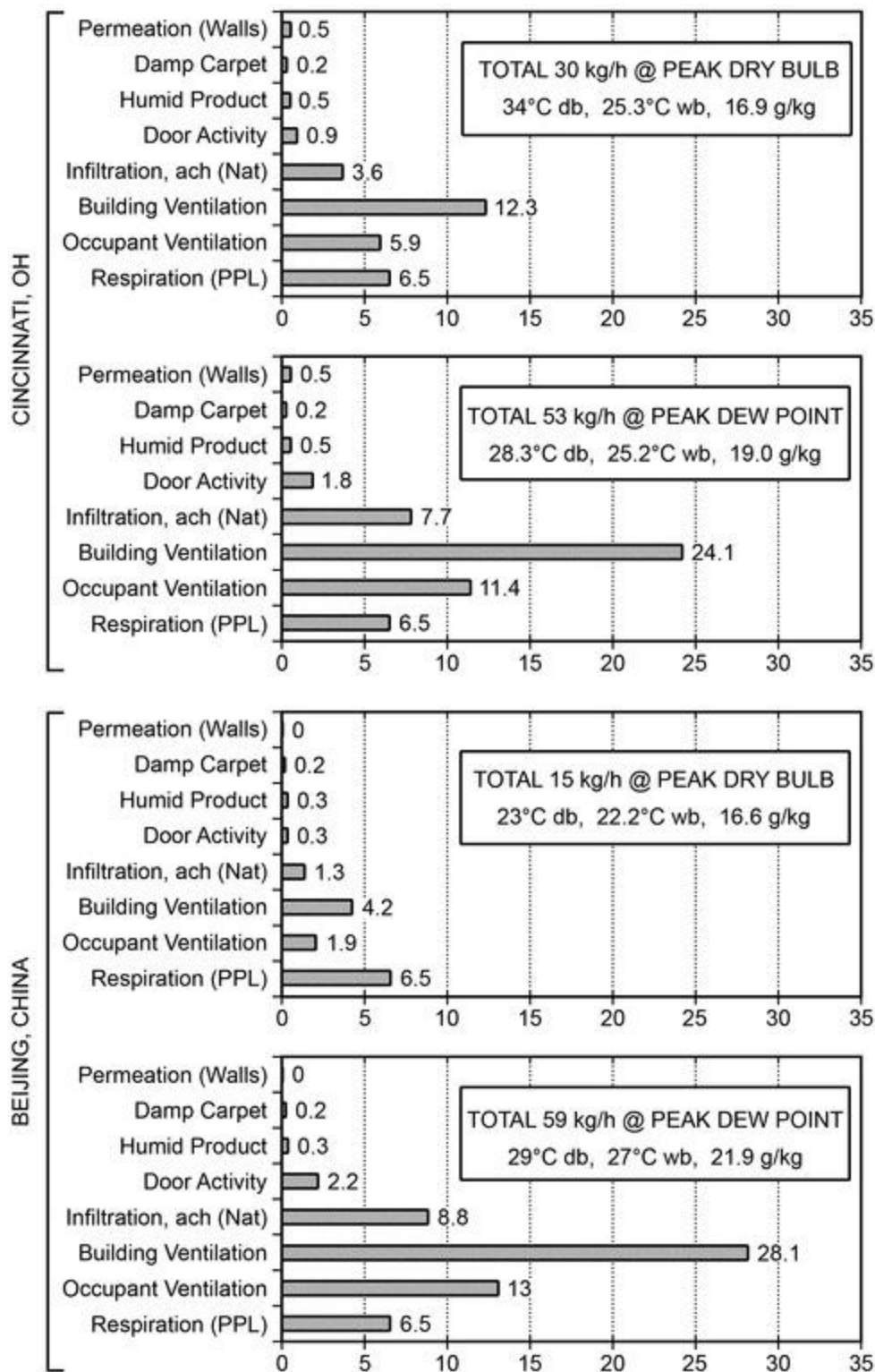


Figure 8. Peak Dry-Bulb Versus Dew-Point Design: Retail Store Humidity Loads Based on ASHRAE Standard 62.1-2016

Mastic-Sealed Duct Connections

To reduce the risk of problems from humid air infiltration into the building and the risks of problems from chilling hidden surfaces in building cavities, specify that all air system connections must be both mechanically fastened and covered with mastic that has been reinforced for long-term durability. Air sealing is equally important for all connections to air handlers and to air distribution components such as filter boxes, fans, cooling and heating coils, and variable-air-volume (VAV) boxes. Less obviously, the requirement to seal duct connections also extends to all joints in exhaust air duct work.

Air leakage into and out of duct connections has been responsible for many of the most expensive and difficult-to-repair mold problems in buildings. Leaking exhaust duct connections pull air from interstitial spaces, much of which is replaced by untreated outdoor air leaking in through construction joints in the exterior wall. The suction created by the exhaust fan ensures that this humid air infiltration is large, and in many cases, continuous. See [Figure 1](#) for the results of this shortcoming in HVAC and architectural design.

The same thing happens when return air duct connections or plenums leak. The suction of the system creates local negative pressures, which lead to humid air infiltration and subsequent moisture absorption by cool indoor surfaces.

On the positive-pressure side of the fan, any leaks mean that cold air escapes the duct, cooling surfaces behind walls, under floors, and above ceilings. Those cold surfaces can either condense moisture from humid air, or absorb moisture because their surface relative humidity is very high. Both problems result in mold.

The other problem with leaking connections and plenums is that they waste energy. In theory, if the leak is inside the thermal boundary, all the cooling energy stays indoors; in fact, if the cooling capacity is where it is not needed (e.g., in the attic, above the ceiling), the air-conditioning system must work harder and longer to get the needed cooling to the occupied zones. Thus, any air leaks waste fan capacity, fan power, and compressor energy.

In the past, vinyl or fabric-backed "duct tape" has often been used to satisfy a duct sealing requirement, but these materials have often proven inadequate over time. Field experience does not usually match the expectations set by the warranty of fabric or vinyl-based duct tape. Durability warranties are only for "properly applied" material in "properly designed" and "properly installed" joints. Apparently, it is more difficult to properly apply the duct tape than might be expected, because over time duct tape has proven to be unreliable. Connections that are mechanically fastened and sealed with either reinforced liquid-applied mastic or pressure-sensitive mastic carried on metal foil tape have not shown the same number or degree of problems.

According to measured data from field studies in California, Florida, New York, and Iowa, air leaks from duct connections waste between 25 and 40% of the annual energy needed to heat and cool the building (Cummings et al. 1996; Henderson et al. 2007; Wray 2006). Consequently, without airtight duct connections, the building is not likely to meet energy reduction targets no matter how efficient the heating and cooling equipment might appear from its ratings. Solving this problem is critical for reaching energy reduction targets: all air-side connections must be sealed with mastic, and unsealed plenums must not be used for either supply or return air systems.

Positive Building Pressure When Outdoor Dew Point Is Above 12.8°C

During occupied hours in the cooling season, risks of humid air infiltration can be reduced by providing more dry outdoor air to the building than the sum of the exhaust air. To reduce the risk of moisture problems during hot and humid weather, it is better to have any air leaks going out of the building. By providing a slight excess of dry ventilation and makeup air, most of the leakage will be from indoors to outdoors, so that air inside the exterior walls will be dry instead of humid. This keeps the building's materials from absorbing moisture, and the slight outward flow of dry air helps dry out rain leakage that sometimes finds its way into exterior walls.

In most buildings, it is not necessary maintain a specific, defined pressure difference between indoors and outdoors to reduce risks of moisture problems. It is usually enough to design and commission the system so that more air enters the building than is being exhausted. In the real world, it is nearly impossible to maintain a defined pressure difference at all points across the exterior wall at all times. The wind outdoors changes pressures on the exterior wall many times per second, and any system attempting to maintain a fixed difference across an exterior wall is likely to waste cooling, dehumidification, and fan energy by keeping the building overpressurized much of the time.

The purpose of the slight positive pressure is simply to keep most of the leakage going out rather than going in, most of the time. As long as that modest goal is achieved, and provided that the other risk reduction measures are installed, the exact amount of positive pressure does not really matter, and less is better. For example, 10% more air makeup than the total exhaust air is a long-standing rule of thumb, but with modern airtight buildings and airtight duct connections, 5% excess outdoor air is often sufficient.

To minimize energy waste, modern designs sometimes reduce both exhaust and ventilation air streams according to occupancy. The preferred way to do this is to interlock the DOAS system with the exhaust fans. As the exhaust fans reduce speed or turn off, reduce the airflow through the DOAS system, keeping the total outdoor air higher than the total exhaust air. This is often a more practical method than using pressure control. With a very small pressure difference as the target, the system would be constantly hunting (i.e., running the fan speeds up and down, attempting to provide just the right pressure difference).

Winter weather presents a different problem. In cold climates, major moisture and mold problems happen when humid indoor air is pushed into cold exterior walls. During the heating season, the humid air is now on the inside of the building rather than the outside. It is counterproductive to keep blowing warm, humid indoor air outward through the cold exterior enclosure, where it is likely to condense and create problems. Also, a great deal of energy is wasted by heating excess outdoor air to keep buildings under an arbitrary positive pressure during cold weather. Therefore, during the heating season, the airflow balance should target neutral building pressure with respect to the outdoors.

5.3 CONSTRUCTION

The objective of moisture management during construction is to produce a dry building, free of mold growth by completion. Flexibility is needed to integrate steps taken into the construction process.

Risk Factors

- Wetting of interior surfaces and stored materials by intrusion of rain, snow melt, surface runoff or groundwater.
- Trapping moisture behind surfaces which is not allowed to dry.
- Letting mechanical insulation become wet.
- Leaking from plumbing systems.
- Condensing on surfaces.
- Allowing dew point or relative humidity to become excessive.
- Insufficient drying after wet product application (i.e., fireproofing, gypcrete).

Mitigation

- Identify potential moisture issues during the design and preconstruction phases and specify the necessary steps to prevent or minimize.
- Implement temporary measures or expedite construction to minimize water infiltration
- Delay installation of susceptible materials or take steps to ensure their protection
- Continuously inspect for wet conditions and effectiveness of moisture controls
- Identify and resolve trapped moisture and visible growth
- Fully seal mechanical insulation before operating HVAC
- Ensure interior of HVAC equipment is protected from dust and moisture if operated.
- Operate HVAC systems to facilitate moisture control and mold prevention

6. RESPONDING TO WATER DAMAGE

6.1 MOLD GROWTH

Mold may grow on either organic material, or surface dust or grease on inert materials which remain wet for more than a few days. In most cases, mold is visible to the unaided eye as powdery deposits or discolored spots. These can generally be distinguished from stains or material due to non-moisture sources (i.e., construction products, occupant activities). Mold testing is generally not necessary for confirmation and observations likely to be moisture-related can be considered suspect growth. The presence of mold or suspect growth is considered an action level to be eliminated. In cases where the distinction between discoloration originating from moisture and non-moisture sources is not clear, these surfaces can simply be treated as suspect for response purposes. It is not necessary to determine the type of mold (i.e., species) (ASTM *Standard* C1789). However, it is important to identify the source of moisture, which can be categorized as either water related (i.e., direct contact with water from leaks) or humidity related (i.e., surface discoloration on the surface only caused by sustained high dew point or condensation on cool surfaces). It is also important to distinguish between growth that is wet (likely to continue spreading and release spores into the air) or dry (stable unless disturbed).

Although potential for growth depends on a variety of factors, duration of moisture is critical. In Light (2018), triggering of growth was best predicted by the number of days that relative humidity was elevated (time of wetness).

6.2 INVESTIGATION

For purposes of establishing an effective response to mold growth, an overall investigation of site moisture is necessary. The moisture evaluation process should identify mold locations (including hidden surfaces) and sources. This investigation should include not only visual observations and moisture measurements, but also site history and an understanding of site conditions and activities. In some cases, additional access will be necessary (i.e., cutting inspection holes) to identify moisture pathways and the extent of damage. Mold testing is not needed to establish a response plan and can be misleading. Details for conducting mold/moisture investigations can be found in ASTM *Standard* D7338-14.

6.3 DRYING

Wet surfaces should be returned to background moisture content to prevent additional mold growth and prevent ongoing structural Damage. This can be accomplished in various ways, depending on site conditions. In some cases, wet surfaces will dry without intervention, which may be sufficient if accomplished rapidly enough for the circumstances. HVAC adjustments may facilitate this. In other cases, mechanical drying with portable equipment (i.e., fans and dehumidifiers) is necessary. The fastest resolution of wet material may be to simply remove it for disposal. Detailed information on drying wet surfaces can be found in IICRC *Standard* 500/530.

6.4 REMEDIATION

Although there are no mandatory requirements for remediating mold growth, guidelines are available from the U.S. EPA, New York City Department of Health, IICRC, etc. These can be followed, where applicable, but deviations may be considered acceptable if the process achieves the following performance objectives:

- The source of moisture is identified and resolved.
- Impacted surfaces and materials are located, dried, and cleared of suspect growth.
- Occupants are not exposed to dust and debris during the drying, removal, and treatment process or after reoccupancy.

Mold can be remediated by either surface treatment or removal. Effective surface treatment, where applicable, can often be achieved by application of a sanitizing solution. Verification should include visual determination that specified work practices have been followed and that all impacted surfaces are dry, clean, and free of suspect growth.

7. HEALTH-RELEVANT INDOOR DAMPNESS

Epidemiological investigators have shown clear and consistent associations between occupancy of damp indoor spaces and increased probability of significant adverse health effects such as development of new asthma, exacerbation of existing asthma, allergic rhinitis, and respiratory infections (Institute of Medicine 2004; Kanchongkittiphon et al. 2015; Kennedy and Grimes 2013; Mendell et al. 2011; Miller 2011; Miller and McMullin 2014; WHO 2009). Unlike some other health complications, illnesses triggered by damp indoor spaces are preventable.

7.1 HEALTH-RELATED STANDARDS AND GUIDELINES

There are no mandatory requirements related to moisture in buildings. Guidelines are generally based on maximum moisture content and relative humidity. However, these are not predictors of mold growth. The de facto standard for dampness in buildings is that indoor mold growth is not acceptable and should be eliminated (CDC).

7.2 DAMPNESS INDICATORS

Indicators of health-relevant indoor dampness in a building or space include either visible mold growth, damage from water or moisture, or musty/moldy/earthy odors. These indicators have each been clearly and strongly associated with increased probability of negative health effects for occupants, although no specific dampness thresholds have been established, and not all individuals are equally affected.

The term *mold growth* here refers to fungal colonization of building assemblies, finishing materials and coatings, or building contents. Growth reflects the fact that fungal spores have encountered adequate surface moisture on a suitable substrate to induce germination, and sufficient metabolic activity to develop colonies that can be seen with the unaided eye. Such visual evidence can include past growth that is currently dormant or dead, as well as currently active growth. Note that the presence of airborne fungal spores is not by itself evidence of growth in the space in question, nor is the presence of spores accumulated in surface dust. Fungal particles are quite common on indoor surfaces and air, even in well-maintained buildings. For example, one study quantified the number of discrete organisms that had characteristic DNA sequences of either bacteria or fungi in active, undamaged, and well-maintained university classrooms. (Qian et al. 2012). The researchers concluded that the typical bioburden imposed on the indoor air by the presence and movement of students resulted in resuspension and/or shedding of 37 million bacteria and 7 million fungi per person, per hour.

Quantitative metrics that can provide early warning of possible health risks from dampness include

- Persistent water activity levels above 0.85 at the surfaces of organic materials or coatings.
- Persistent moisture content above 15% wood moisture equivalent (WME) in organic materials, coatings, and untreated paper-faced gypsum board.

- Persistent moisture content above 80% equilibrium rh in concrete or masonry that is either coated or in contact with organic materials.
- Persistent indoor humidity above a dew point temperature of 15°C in buildings that are being mechanically cooled, or above a dew point temperature of 7°C in buildings that are being heated.

In this context, *persistent* means that the condition has become typical, extending for days or weeks at a time, rather than consisting of infrequent excursions of a few hours per week above these suggested thresholds, followed by a return to normal levels of dryness.

These thresholds are indicators of abnormal conditions that can ultimately lead to moisture accumulation and health-relevant indoor dampness. *Abnormal* here describes conditions that, although they may occur with some regularity in many buildings, are seldom (if ever) the basis of design for durable buildings and energy-efficient climate control systems.

Finally, keep in mind that these four suggested metrics and thresholds have not been documented to be indicators of health-relevant indoor dampness. They should be considered *early warnings* of possible health-relevant dampness at some future date. They do not provide quantitative validation of *current* health-relevant dampness.

8. MEASURING BUILDING DAMPNESS

8.1 WATER ACTIVITY

When moisture in a material is loosely bound, the moisture is more easily accessible to mold. Given equal temperature and nutrient value for any given mold type, the factor that most governs growth is not material moisture content, but rather how tightly that moisture is bound into the material's molecular structure. The concept of **water activity** provides a means of quantifying the biological growth potential of a damp material by measuring how tightly moisture is bound in a material. Consequently, it is the metric used by biophysicists and mycologists to define mold growth potential. It is the ratio of the water vapor pressure in the material to the water vapor pressure in the surrounding air, if that air were to be fully saturated at the same temperature as the material. (A useful engineering shorthand description is that water activity provides a measure of the bioavailability of water in a material. High values mean that water in the material is more easily accessible to bacteria and fungi. Lower water activity values mean that the material's moisture is more tightly bound and therefore less available to support fungal and bacterial growth.)

Water activity is measured most accurately by sealing the material in question into a small container, and then allowing the air inside that container to come into complete hygrothermal equilibrium with the material. The temperature of both air and material must be identical, and the air in the sealed container must have the same relative humidity as the air inside the pores of the material. After the hours or days necessary for both variables to reach simultaneous equilibrium, water activity of the material is measured by reading the relative humidity inside the sealed container. Water activity is reported as the decimal equivalent of the equilibrium relative humidity. For example, relative humidity measured at 80% after complete hygrothermal equilibrium inside the sealed container is reported as a material water activity of 0.80.

Water activity as low as 0.75 has allowed slow mold growth in an ideal laboratory environment of constant temperature and moisture, in a nutrient-rich and biologically accessible growth medium such as a Petri dish filled with malt extract agar. However, building materials are typically formulated to avoid mold growth. Also, in a building environment, damp areas usually benefit from a small amount of drying through normal HVAC system operation. Consequently, measured values of water activity below 0.75 usually indicate a low risk of mold growth, even in the most nutrient-rich building materials and coatings.

Measuring water activity in buildings can never be identical to measurements in a sealed container in a lab environment, because nothing is ever at complete hygrothermal equilibrium in buildings. Materials are always gaining and losing small amounts of both heat and moisture, even when there is no excessive dampness. Also, it is not practical to seal up entire installed building components into a tightly sealed small container, much less wait the days, weeks, or months necessary for such a sealed container's air and the material to reach identical temperature and relative humidity. When water activity measurements are made in a building, they are more accurately described as the **near-equilibrium surface water activity** rather than as the biophysically defined term of water activity. Given that water activity is abbreviated as A_w , to avoid confusion with the microbiological literature of the late twentieth century the building-relevant near-equilibrium surface water activity should be abbreviated as A_{ws} .

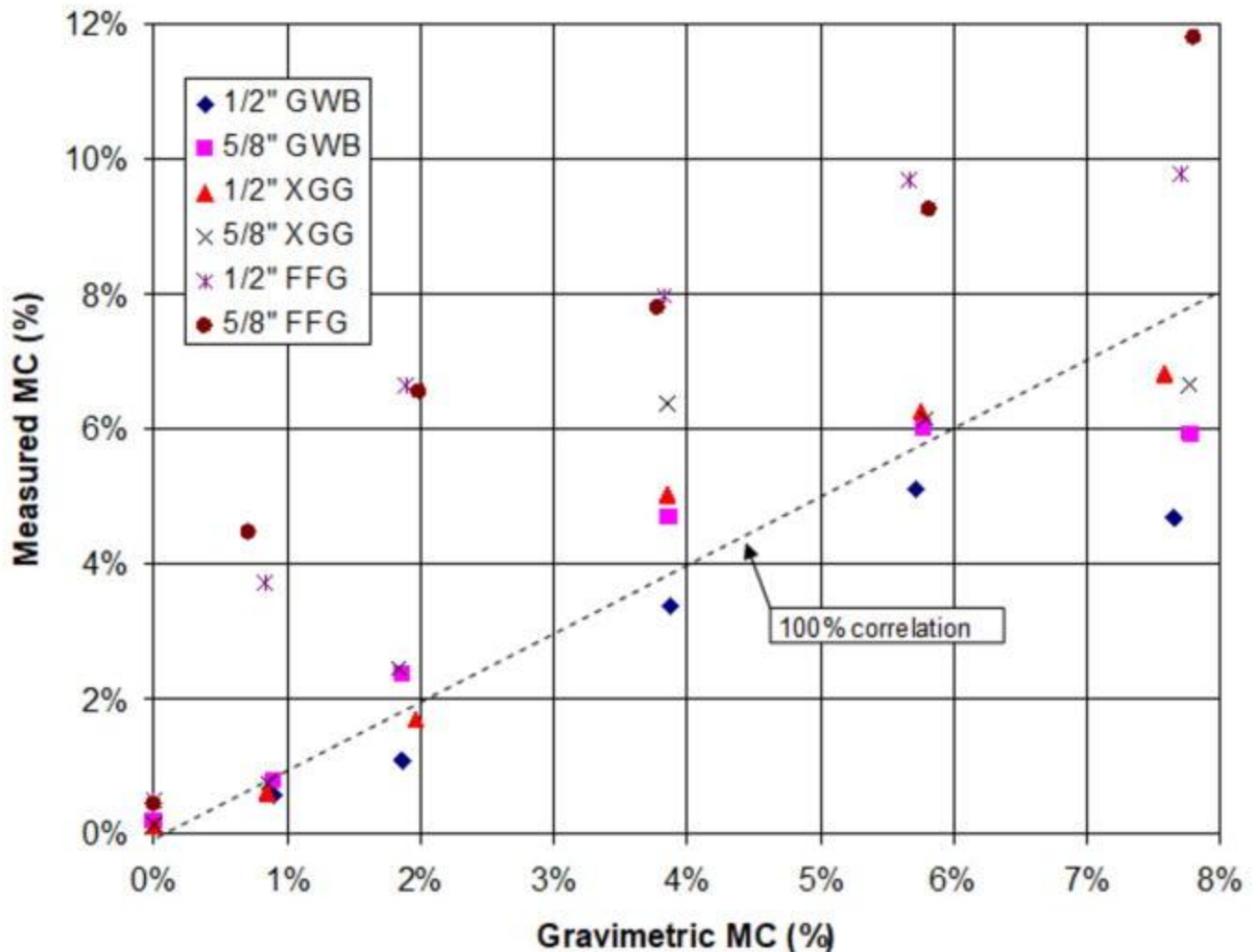


Figure 9. Moisture-Meter Accuracy

Surface water activity measurements are made in buildings by attaching a relative humidity sensor within a few millimetres of a target surface, and then covering both sensor and target location with a shield that isolates the two from direct contact with the surrounding air and any air movement. An ideal sensor attachment and shielding approximates the environment of the sealed container used in laboratory measurements while not impeding the lateral diffusion of heat and moisture within the material that occurs in any normal building environment.

8.2 MOISTURE CONTENT

Although moisture content and water activity are not the same thing, it is often true that when a material has a high moisture content, it may also have a high water activity. When water activity measurements are not available, moisture content measurements can provide a potentially useful quantitative indicator of relative dampness. It is important to remember, however, that there is usually a wide variation between moisture content readings taken in nearly the same location. There are two principal causes of this variation: different exact measurement location and different scales and measurement technologies of moisture meters.

Measuring moisture content in wood-based materials is usually done to determine water activity in the context of safety associated with fungal activity. Kiln-dried wood is generally considered to be free from fungal contamination, but can be re-infected if the moisture content exceeds 28 to 30% (depending on the wood species). Such high moisture contents indicate that the wood fiber is saturated, and free water is available for a fungal species to colonize the wood. Once the fungal colony is established, it will remain active as long as the moisture content stays above 20%. If the moisture content drops below 19%, the colony becomes dormant until the moisture content again exceeds 19 to 20% (depending on the wood species), and then the decay process resumes (FPL 2010).

Measuring the moisture content of gypsum-based construction materials poses two challenges. First, users should understand that moisture content is expressed as a percentage of the dry weight of the specimen, and gypsum is much denser than many building materials. Thus, the expected range of values is on the order of 0 to 2%, and anything beyond that would indicate that the wrong instrument is being used for measurement. Second, many moisture meters are calibrated for paper-faced gypsum, and the more recent development of gypsum boards faced with fiberglass mats will result in moisture-content readings that are approximately three percentage points higher than the actual (gravimetric) value. This is possibly because moisture meters do not measure moisture content; rather, they measure

electrical resistivity, which is then converted to an equivalent reading on the gauge. Specimens faced with glass mats may provide a shorter path for electrical conduction than paper-faced specimens, resulting in a higher apparent electrical conductivity, and consequently a higher moisture-content reading. [Figure 9](#) shows a comparison between measured moisture content according to a calibrated moisture meter vs. the actual (gravimetric) measurement, determined in accordance with ASTM *Standard C1789* (CMHC, 2007). In the graph, specimens labeled "GWB" are standard paper-faced gypsum wallboard for interior use; "XGG" represents exterior-grade gypsum sheathing (paper facers treated to improve water-resistant properties); and "FFG" represents gypsum sheathing with random-woven glass-fiber facers.

Importance of Documenting Measurement Location

[Figure 10](#) shows the variation in moisture content readings in the same material, in the same environment separated by a distance of less than 150 mm. Mold growth is apparent where the moisture content reading is above 20% wood moisture equivalent (WME). Just a few millimetres away, the same meter shows the moisture content to be less than 15% WME, and in that location, no mold growth is visible. This figure illustrates two key points about moisture content measurements: they can and do vary widely within a few millimeters, and small differences in measured moisture content can lead to big differences in mold growth rates.

Moisture Meter Distinctions

Different types of moisture meters use different measurement principles, and each manufacturer generally chooses to scale the measured values differently. Therefore a moisture content reading of 26% has no useful meaning until both the meter model and the meter's scale are defined. [Figure 11](#) shows why this issue is important in assigning any level of concern based on readings from undefined moisture meters. It shows that readings from different meters provide very different values when connected to the exact same electrodes planted in the same material at the exact same moment. This is not a matter of meter accuracy, but rather because each moisture meter manufacturer designed both the measurement principle and the scale for different purposes, and each different material has different electrical characteristics that affect the meter reading.

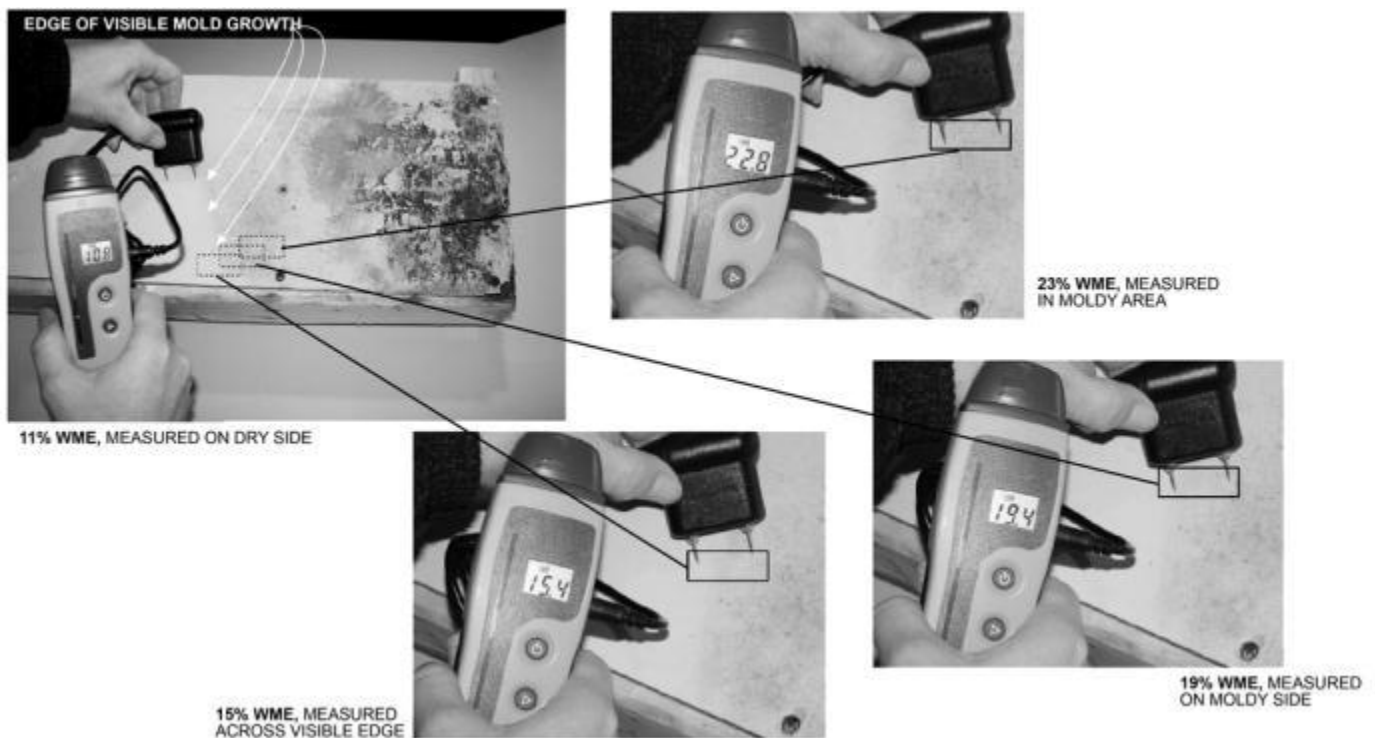


Figure 10. Variation in Moisture Content and Mold Growth Across Short Distances

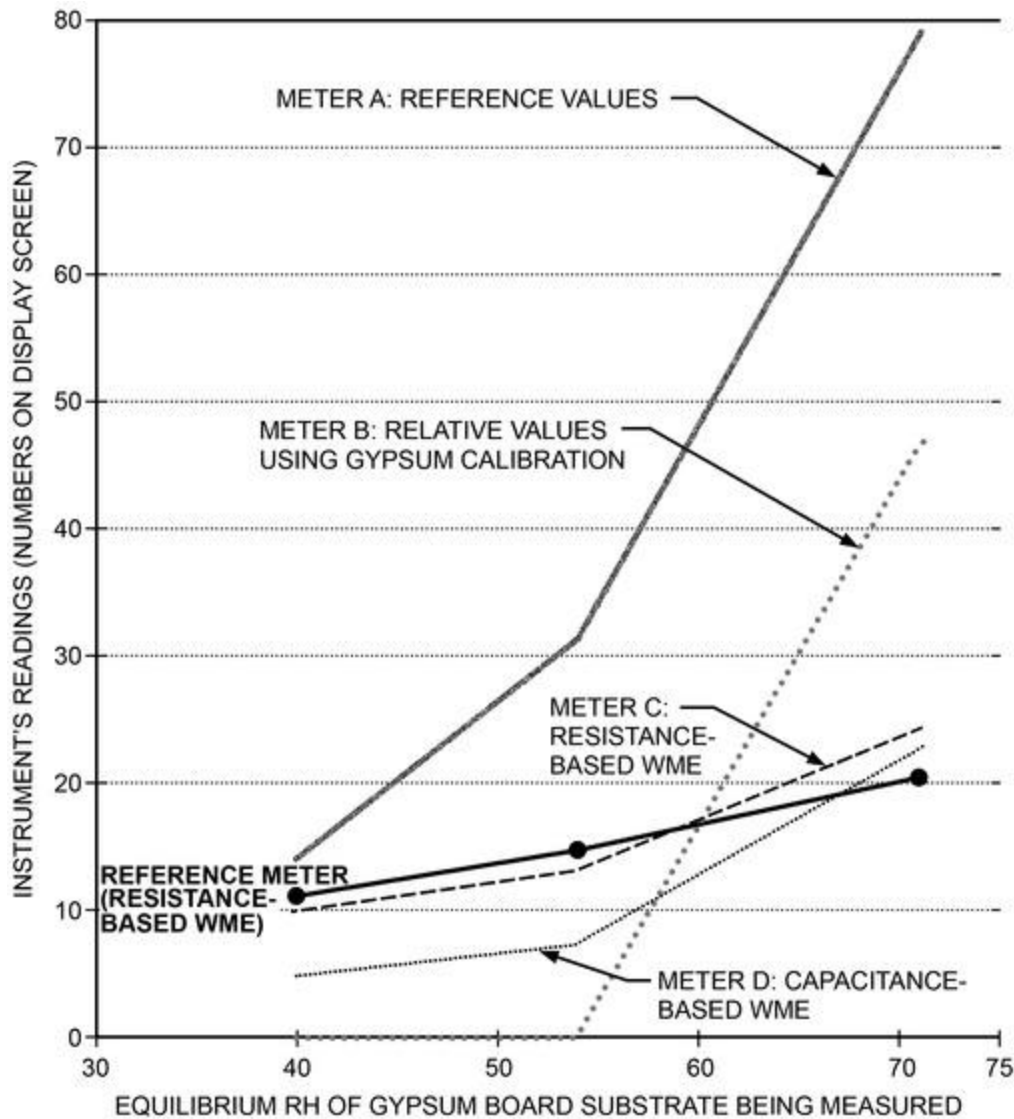


Figure 11. Variation in Moisture Meter Readings on Same Material

Similar variability is also typical of water activity measurements in buildings, because of different means of attaching sensors to building assemblies. Consequently, the investigator concerned with assessing the extent of moisture and dampness in a building is well advised to

- Note the date and time, and document the exact location of readings using a camera ([Figure 12](#))
- Record the manufacturer, model number, and measurement scale of the instrument used to make the measurements

Building owners, investigators, and those who read their reports should consider that observations and measurements made at a single moment, at a single location in a building are rarely representative of that entire building's behavior over the extended time frame and variability of normal building operations. Also, different types of building materials, building construction, and environmental exposures present quite different risks with respect to dampness. Consequently it is usually helpful to make repeated visual observations, interview building occupants, and take measurements in all suspect locations over a representative time frame of days or weeks to obtain the information to support robust conclusions about the causes and risks of dampness in a given building.



Figure 12. Example of Documenting Both Values and Pattern of Moisture

8.3 DAMPNESS CLASSIFICATION

Although building dampness is recognized as a major factor in occupant health and structural deterioration, there is no generally accepted definition for what constitutes a “damp building.” Epidemiological studies and building investigation have used widely divergent criteria for classifying dampness and none have addressed the full spectrum of building moisture sources. A standardized, inclusive method for classifying building dampness would be very useful to facilities personnel identifying and prioritizing moisture issues, to health professionals evaluated occupant symptoms and estimating potential health risks, and researchers presenting results in a standardized format which can be readily compared with other studies.

Lacking an accepted protocol for defining and classifying building dampness, a site-specific assessment can consider the following general principles:

1. (a) Assessment should initially look for all sources of moisture and their impacts. These commonly include:
 - Contact with liquid water:
 - Wet surface with active suspect growth, physical water damage, or standing water
 - Dry surfaces with suspect growth or physical water damage.
 - Excessive moisture in air causing condensation, suspect growth, physical water damage, or discomfort.
 - Unhygienic conditions in HVAC equipment.
2. Classification of dampness should not just represent a single point in time, but also differentiate past issues which have been resolved from ongoing and intermittent (i.e., seasonal) conditions.
3. Because dampness often impacts only a portion of the building, dampness ratings can be localized (i.e., differentiate affected and unaffected areas) (Light 2022).

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