Related Commercial Resources

CHAPTER 62

MOISTURE MANAGEMENT IN BUILDINGS

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, material, 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. 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 can prevent a problematic level of dampness, mold, or microbial growth by their actions alone.

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 climate.

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.

Note that the problems illustrated by Figure 1 required 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 (Zelinka 2013). 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.

The preparation of this chapter is assigned to TC 1.12, Moisture Management in Buildings.

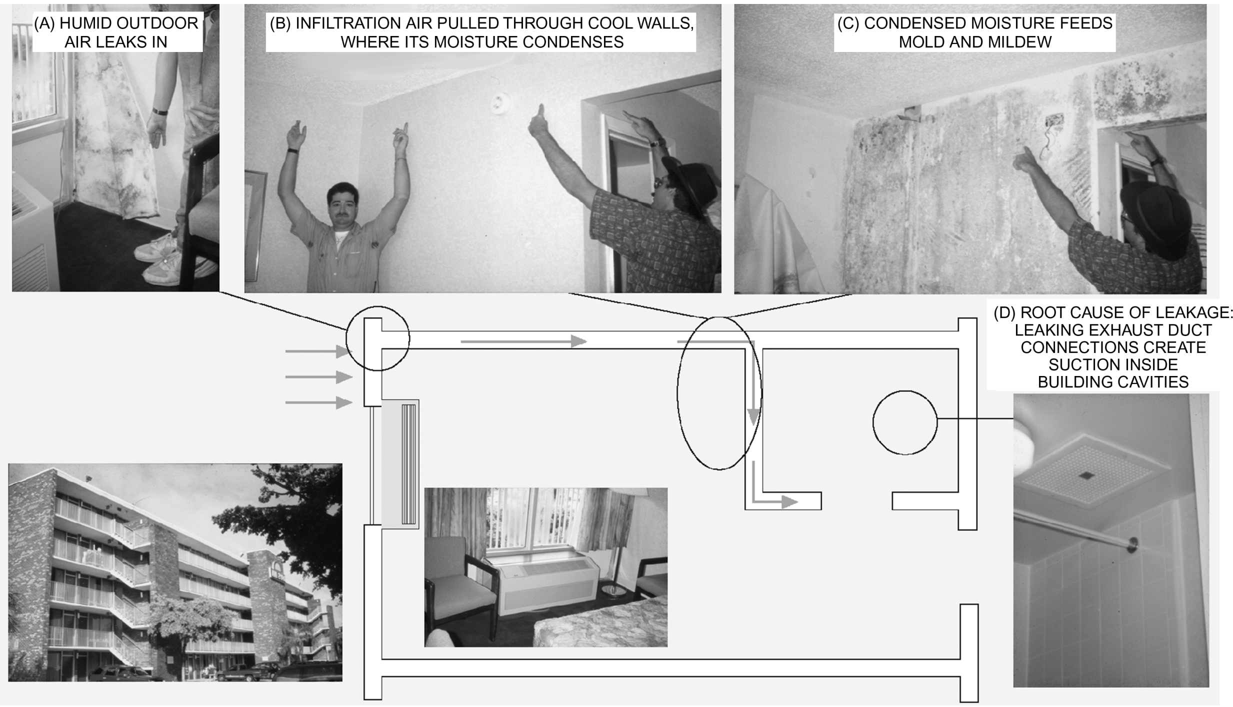

Fig. 1 Mold Caused by Complex Combination of Factors

All of these factors combine to support mold growth, given enough time.

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 take 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) (ASHRAE *Standard* 160).
- Being aware that, if adequate resources are not made available to keep the building, systems, and contents dry, then the risk of microbial growth including mold will increase.
- Addressing persistent dampness inside a building; constant, stagnant water in condensate drain pans; or constantly damp insulation, filters, or sound lining of HVAC systems.

2. 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 2 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 2010). In other locations, most of the wind-driven rain can come from quite different directions, varying by season of the year.

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,

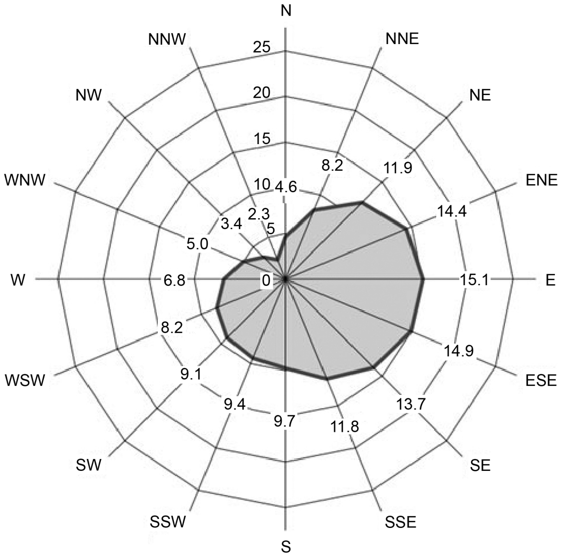

Fig. 2 Rain Loads Versus Wind Speed and Direction
(Straub 2010)

reducing the annual drying potential on the north wall to far less than 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 44 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.

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.

3. RISK FACTORS AND MITIGATION

Each area of professional and occupant activity involves decisions and actions that can 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.

Note also that these factors have seldom been responsible in isolation for moisture and microbial growth problems. More commonly, the risks have increased when more than one of these factors are present, or when an architectural risk factor is combined with risk factors associated with either HVAC systems or occupant activities.

3.1 HVAC SYSTEMS

Risk Factors

- 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).
- 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, but over time, 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 2000).
- 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).

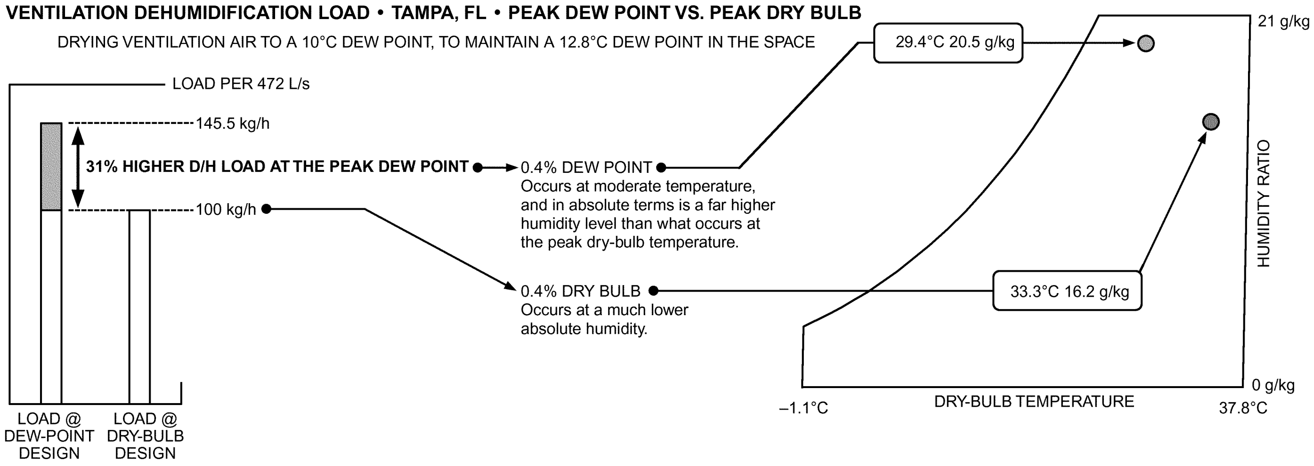

Fig. 3 Dehumidification Load Versus Peak Outdoor Dew Point Design and Peak Dry Bulb

- Failing to measure and limit the volume of ventilation and makeup air to the amount required for the current occupancy and that will in fact be dried by the system's dehumidification components. Ventilation without dehumidification during humid outdoor conditions has been responsible for major and widespread mold growth problems in hot and humid climates. Whenever any building in any climate is mechanically ventilated, the indoor dew point must remain low enough to keep the indoor surface relative humidity below 80%, even on hidden cool surfaces (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 accelerates when the indoor dew point stays high while surfaces are intermittently chilled by cooling systems. Moisture accumulation and mold has 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 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).

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 3 shows the large difference between these conditions in Tampa, FL; Figure 5 provides more detailed examples in other climates (Harriman and Lstiburek 2009; Harriman et al. 2001).
- 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, keeping the indoor 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 such cold pipes as they pass through high-dew-point spaces and building cavities (Harriman and Lstiburek 2009).

3.2 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 inward towards the foundation after freeze/thaw cycles in cold climates, or because of decorative edging around shrubbery that creates a pond near the foundation (ASTM 2010; 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 44) (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.
- Pan flashing under windows and doors to force any water leakage outward onto an effective water barrier and then out of the building wall (Harriman and Lstiburek 2009; ASTM *Standards* D7338, E2112; 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).

3.3 BUILDING OPERATIONAL DECISIONS

Risk Factors

- Failing to effectively exhaust humid air from showers, spas, decorative water fountains, indoor landscaping irrigation, and swimming pools. When the weather is hot and humid, a related problem is failure to dry outdoor air brought into the building to replace exhaust air.
- 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).

3.4 OCCUPANT DECISIONS

Risk Factors

- Failing to use either fans or window openings to effectively exhaust 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 effectively exhaust humid air from clothes driers or indoor drying racks. 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 otherwise removing the humidity they respire. Problems created by this oversight can be especially severe in cold climates.
- 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.
- 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) air 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).

4. SOLUTIONS

4.1 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).

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.

The architectural designer (as opposed to the craftsperson installing the flashing) is in the best position 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.

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 show in three dimensions 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.

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 or 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. Also, with sheets it is 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 especially doable when using spray-applied, vapor-permeable but waterproof membranes. However, 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 exterior vapor barriers 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 inwards into the sheathing. It is important to line the drainage gap for brick or stucco with a vapor barrier, and that layer may as well 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 above, 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 inside surface of the wall, not its outside surface.

The basic goal is to keep humid air out of any cold wall. In the cold-climate situation, the humid air is on the inside, so a combination vapor barrier/air barrier is useful in that location. In the hot climate, 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 Chapter 26 of the 2013 *ASHRAE Handbook—Fundamentals* and Chapter 44 of this volume.

Wrap-Around Air Barrier

Continuous exterior air barriers reduce the risk of indoor moisture problems. Continuous air barriers should not leak air around windows, or through gaps around wall penetrations. Also, the air barrier must continue up the walls and connect with airtight integrity to the roof assembly's air barrier. In short, the ideal air barrier is continuously sealed around all penetrations and fasteners, and it must wrap around the entire building. A continuous air barrier reduces the risk of moisture problems and also saves energy.

If warm, humid air outdoor leaks into a building, its water vapor may condense on indoor assemblies and materials cooled by the air conditioning system. These cool surfaces absorb moisture from infiltrating humid air, degrading materials and increasing the risk of corrosion and failure of structural fasteners. Also, leaking air imposes an additional load on the air-conditioning system, reducing its ability to keep the dew point low enough to prevent moisture-related problems.

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. From a moisture control perspective, pay special attention to air barrier continuity at the roof/wall joint, which is where major air leaks usually occur.

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 addition, it is useful to specify that any masonry or concrete covered by gypsum board must be dried to the required moisture content specified by the gypsum board manufacturer. The logic for this suggestion is easily apparent: 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.

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.

Finally, beyond construction moisture and potential rainwater leakage into exterior walls, there are the usual problems with plumbing leaks and indoor water spills. In bathrooms, shower rooms, and laundry rooms, high humidity and water spills are unavoidable. So, to limit risks from these everyday low-level moisture accumulations, it is useful to install moisture-tolerant and mold-resistant products in parts of the building that are likely to become wet.

Permeable Interior Finish for Exterior Walls

To reduce risks of trapping moisture inside walls, specify that any paint or other wall finish for the indoor surface of an exterior wall must have a net value above 860 ng/(Pa·s·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. The vinyl 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 usually happens when vinyl wall covering is adhered to exterior walls.

The same problem can occur with certain types of paint, notably the epoxies and high-durability latex paints. So it is useful to require that any paint or wall covering must have a rating above 860 ng/(Pa·s·m^2) if it is installed on the indoor surface of the exterior wall.

In recent years, manufacturers have developed permeable or semipermeable vinyl wall covering. The actual permeability of these products varies considerably. Risks of moisture accumulation can be reduced by specifying that the system as a whole (wall covering plus its adhesive) must have a wet-cup value (ASTM *Standard* E96-00) above 860 ng/(Pa·s·m^2).

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, or 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%. 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 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, moving most of the oncoming rain-laden wind up, over, and around. Consequently, most of the rainwater never reaches the surface of the building.

4.2 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. Additionally, if the DOAS units are equipped with return air connections, 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 4 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.)

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 both occupied and unoccupied periods.

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. The following logic behind this control level should help readers use their own judgment about the prudent maximum dew point for different types of buildings, occupancies, and climates.

Fig. 4 Mold Resulting from Humid Air Infiltration in Overcooled Health Clinic

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 4.

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.

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 5 shows the effect of this difference on the humidity loads of a medium-sized retail building that complies with the requirements of ASHRAE *Standard* 62.1-2010. 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 2013 *ASHRAE Handbook—Fundamentals* and on the CD accompanying that volume.

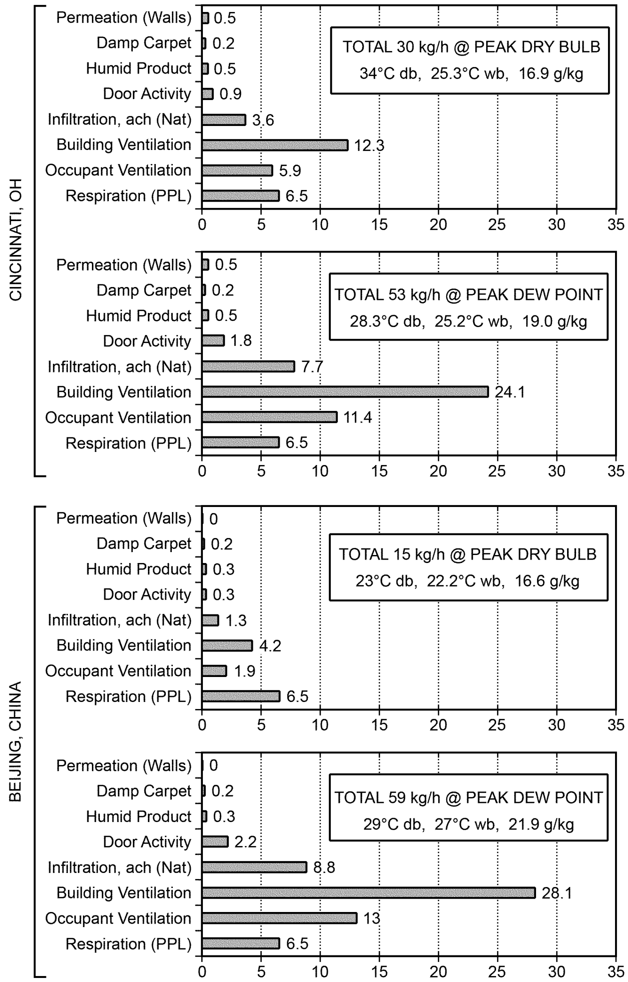

Fig. 5 Peak Dry-Bulb and Dew-Point Design: Retail Store Humidity Loads Based on ASHRAE *Standard* 62.1-2010

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 and seams must be both mechanically fastened and covered with durable mastic. Such an air sealing requirement also logically extends to 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.

Duct tape has been used to satisfy a duct sealing requirement, but this material has often proven inadequate over time. Field experience does not usually match the expectations set by the warranty of 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 as an air seal. Connections that are mechanically fastened and sealed with mastic 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 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 streams. 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 reason for 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. Less is better, in this case: 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 steams 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. During the heating season, the humid air is now on the inside of the building rather than the outside. It can be counterproductive to keep blowing warm, humid indoor air outward through the cold exterior enclosure, where it is likely to condense and create problems. During the heating season, airflows should target neutral pressure. In cold climates, big moisture and mold problems happen when humid indoor air is pushed into cold exterior walls. Also, a great deal of energy is wasted by heating excess outdoor air to keep buildings under an arbitrary positive pressure during cold weather. There is no energy or mold risk reduction benefit to positive pressure during cold weather.

5. MEASURING BUILDING DAMPNESS

The term *dampness* does not yet have an agreed-upon quantitative definition. This fact makes it difficult to assess the often discussed risks of damp buildings in a way that is comprehensive, repeatable and economically practical. The ASHRAE Board of Directors has called for research to develop a quantitative definition of building dampness that is relevant to health concerns, and to develop a companion assessment protocol that provides practical and repeatable results (ASHRAE 2013). Until such efforts are completed, the suggestions in this chapter will be confined to helping those who wish to understand the means of measuring the key factors that influence mold growth.

Contrary to popular impression, mold growth is not a direct function of humidity in the air, nor is it a function of the amount of air circulation in a space or sunlight on a surface. These factors influence mold growth only indirectly, based on the extent that they allow moisture accumulation in a material that serves as a nutrient source. When the amount of moisture in its food source reaches a critical range, mold enzymes can begin to dissolve the nutrient material, creating a solution that is pulled into the mold's cell walls to sustain and encourage further growth. As long as all carbon-based building materials, coatings, and dusty surfaces are kept dry, mold cannot access the nutrients it needs to grow and reproduce (Harriman et al. 2001).

5.1 WATER ACTIVITY

When moisture in a material is loosely bound, then its moisture is more easily accessed by 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 an 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}.

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.

5.2 MOISTURE CONTENT MEASUREMENT VARIATION

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.

Different Measurement Locations

Figure 6 shows the variation in moisture content readings in the same material, in the same environment separated by a distance of less than 144 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.

Different Moisture Meters

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 7 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.

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 8)
- 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

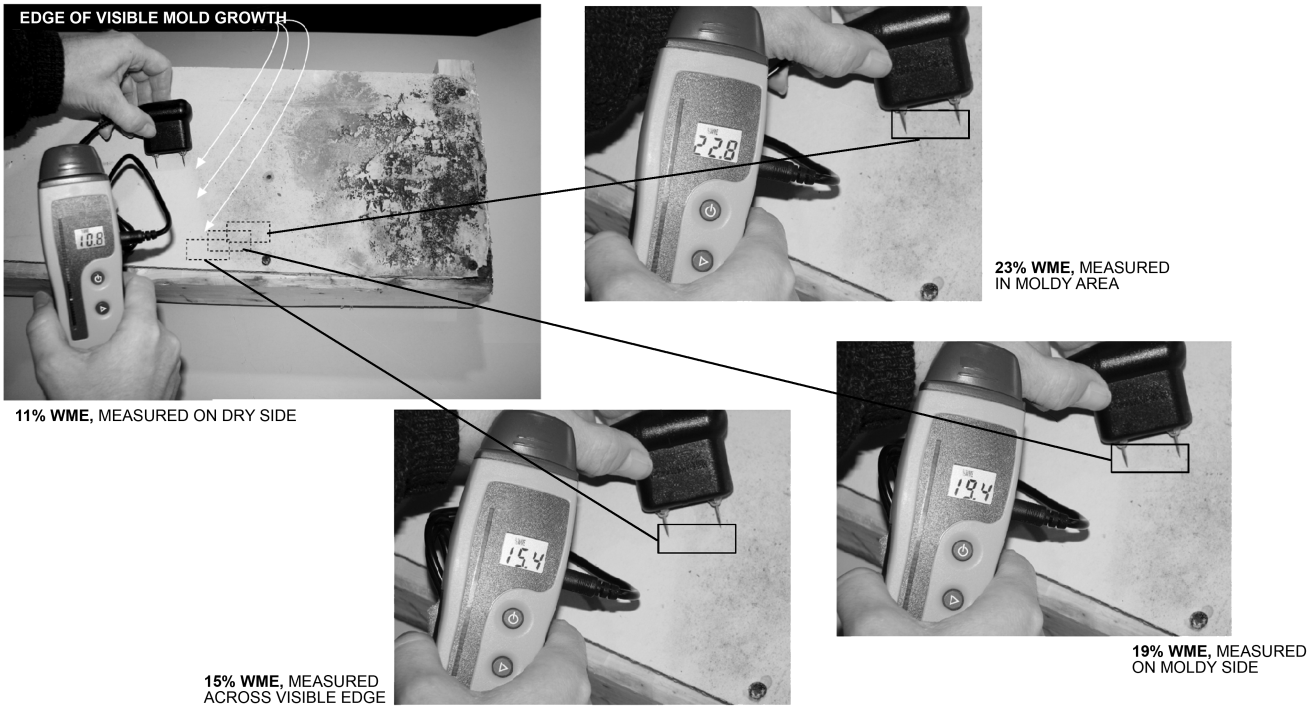

Fig. 6 Variation in Moisture Content and Mold Growth Across Short Distances

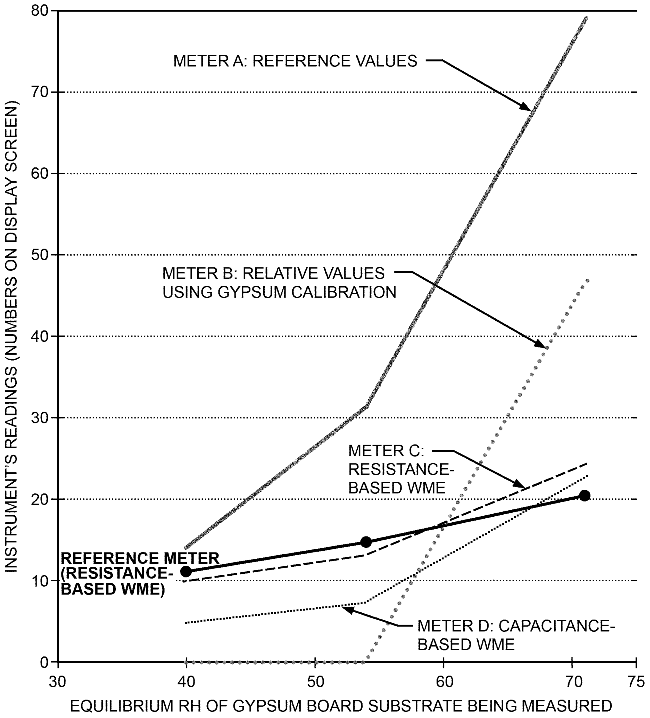

Fig. 7 Variation in Moisture Meter Readings on Same Material

Fig. 8 Example of Documenting Both Values and Pattern of Moisture

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.

REFERENCES

ACGIH. 1999. *Bioaerosols: Assessment and control*. American Conference of Governmental and Industrial Hygienists, Cincinnati, OH.

AIHA. 2008. *Recognition, evaluation and control of indoor mold*. B. Prezant, D.M. Weekes, and J.D. Miller, eds. American Industrial Hygiene Association. Fairfax, VA.

ASHRAE. 2013. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2013.

ASHRAE. 2013. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE *Standard* 90.1-2013.

ASHRAE. 2009. Criteria for moisture-control design analysis in buildings. ASHRAE/ANSI *Standard* 160-2009.

ASHRAE. 2013. Limiting indoor mold and dampness in buildings. *Position document*. Available at https://www.ashrae.org/File Library/docLib/About Us/PositionDocuments/Limiting-Indoor-Mold-and-Dampness-in-Buildings.pdf.

ASTM. 2014. Standard guide for assessment of fungal growth in buildings. *Standard* D7338-14. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2013. Standard test methods for water vapor transmission of materials. *Standard* E96-13. American Society for Testing and Materials, West Conshohocken, PA.

ASTM. 2007. Standard practice for installation of exterior windows, doors and skylights. *Standard* E2112-07. American Society for Testing and Materials, West Conshohocken, PA.

CMHC. 1998. Survey of building envelope failures in the coastal climate of British Columbia. *Technical Series* 98-102. Canadian Mortgage and Housing Corporation, Ottawa. Available at http://publications.gc.ca/collections/Collection/NH18-22-98-102E.pdf.

Derome, D., and S. Saneinejad. 2009. The nature, significance and control of solar-driven diffusion in wall systems. ASHRAE Research Project RP-1235, *Final Report*.

DOE. 2005. *Closed crawl spaces: An introduction to design, construction and performance*. Advanced Energy, Raleigh, NC. Report to the U.S. Department of Energy, Contract DE-FC26-00NT40995. Available at http://www.advancedenergy.org/portal/crawl_spaces/pdfs/Closed Crawl Spaces_An Introduction for the Southeast.pdf.

EPA. 2001. *Mold remediation in schools and commercial buildings*. U.S. Environmental Protection Agency, Washington, D.C.

EPA. 2013. *Moisture control guidance for building design, construction and maintenance*. U.S. Environmental Protection Agency, Washington, D.C. Available at http://www.epa.gov/iaq/pdfs/moisture-control.pdf.

GSA. 2008. Mechanical engineering. Chapter 5 in *Facilities standards (P100) for the public buildings service.* U.S. General Services Administration, Washington, D.C. Available from http://www.gsa.gov/portal/content/187611.

Harriman, L.G., and J. Lstiburek. 2009. *The ASHRAE guide for buildings in hot and humid climates*, 2nd ed. ASHRAE.

Harriman, L.G., G. Brundrett, and R. Kittler. 2001. *Humidity control design guide for commercial and institutional buildings*. ASHRAE.

IICRC. 2008. Standard and reference guide for professional mold remediation, 2nd ed. IICRC/ANSI *Standard* S520-2008. Institute of Inspection, Cleaning and Restoration, Vancouver.

JLC. 2007. *The JLC guide to moisture control: Practical details for durable buildings (residential)*. Journal of Light Construction and Hanley Wood.

Mudari, D., and W.J. Fisk. 2007. Public health and economic impact of dampness and mold. *Indoor Air* 17(3):226-235.

NAIC. 2008. *Property and casualty insurance industry 2007*. National Association of Insurance Commissioners, Washington, D.C.

NIM. 2004. *Damp indoor spaces and health*. National Institute of Medicine, Washington, D.C. Available at http://books.nap.edu/catalog.php?record_id=11011.

NIOSH. 2013. Preventing occupational respiratory disease from exposures caused by dampness in office buildings, schools and other nonindustrial buildings. DHHS NIOSH *Publication* 2013-102. National Institute for Occupational Safety and Health, Atlanta. Available at http://www.cdc.gov/niosh/docs/2013-102/pdfs/2013-102.pdf.

Rose, W.B. 2005. *Water in buildings: An architect's guide to moisture and mold*. John Wiley & Sons.

Straube, J. 2010. Simplified prediction of driving rain on buildings: ASHRAE 160P and WUFI 4.0. *Building Science Digest* BSD-148. Available at http://www.buildingscience.com/documents/digests/bsd-148-wufi-simplified-driving-rain-prediction.

Zelinka, S.L. 2013. Corrosion of embedded metals in wood: An overview of recent research with implications for building design. *ASHRAE Transactions* 119(2). *Paper* DE-13-039.

BIBLIOGRAPHY

ACCA. 2009. Residential duct systems. *Manual* D. Air Conditioning Contractors of America, Arlington, VA.

ASHRAE. 2013. Ventilation and acceptable indoor air quality in low-rise residential buildings. ANSI/ASHRAE *Standard* 62.2-2013.

ASHRAE. 2013. Standard for ventilation of health care facilities. ASHRAE/ANSI/ASHE *Standard* 170-2013.

ASHRAE. 2009. *Indoor air quality guide: The best practices for design, construction and commissioning*.

ASHRAE. 2010. Standard *62.1-2010 user's manual*.

Cox-Ganser, J.M., S.K. White, R. Jones, K. Hilsbos, E. Storey, P.L. Enright, C.Y. Rao, and K. Kreiss. 2005. Respiratory morbidity in office workers in a water-damaged building. *Environmental Health Perspectives* 113(4): 485-490. National Institute of Environmental Health Sciences. Available at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1278490/.

Criterium Engineers. 2003. *Construction quality survey, 2003*. Criterium Engineers, Portland, ME.

Cummings, J.B., C.R. Withers, N. Moyer, P. Fairey, and B. McKendry. 1996. Uncontrolled air flow in non-residential buildings. FSEC-CR-878-96, *Final Report*. Florida Solar Energy Center, Cocoa, FL. Available at http://www.fsec.ucf.edu/en/publications/html/FSEC-CR-878-96/.

Hardman, B.B., C.R. Wagus, and T.A. Weston. 2006. Performance and durability of the window-wall interface. *Paper* STP1484. American Society for Testing and Materials, West Conshohocken, PA.

Harriman, L.G., III, and S. Thurston. 1991. *Mold in hotels and motels—Survey results*. American Hotel and Lodging Association. Washington, D.C.

Hodgson, M.J., and B. Flannigan. 2011. Occupational respiratory disease: Hypersensitivity pneumonitis and other forms of interstitial lung disease. Chapter 3.2 in *Microorganisms in home and indoor work environment*, B. Flannigan, R.A. Samson, and J.D. Miller, eds. Taylor and Francis, New York.

Lstiburek, J. 2006. *Water management guide*. Building Science Corporation, Westford, MA.

Mendell, M.J., A.G. Mirer, K. Cheung, M. Tong, and J. Douwes. 2011. Respiratory and allergenic heath effects of dampness, mold and dampness-related agents: A review of the epidemiologic evidence. *Environmental Health Perspectives* 119(6):748-756. Available at http://dx.doi.org/10.1289/ehp.1002410.

Nielsen, K.F., G. Holm, L.P. Uttrup, and P.A. Nielsen. 2004. Mould growth on building materials under low water activities: Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration and Biodegradation* 54(4):325-336.

NY DOH. 2010. *New York state toxic mold task force: Final report to the governor and legislature*. New York State Department of Health. Available at http://www.health.ny.gov/environmental/indoors/air/mold/task_force/docs/final_toxic_mold_task_force_report.pdf.

Park, J.-H., J.M. Cox-Ganser, K. Kreiss, S.K. White, and C.Y. Rao. 2008. Hydrophilic fungi and ergosterol associated with respiratory illness in a water-damaged building. *Environmental Health Perspectives* 116(1):45-50. Available at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2199298/.

Pasanen, A.L., S. Rautiala, J.P. Kasanen, P. Raunio, J. Rantamäki, and P. Kalliokoski. 2000. The relationship between measured moisture conditions and fungal concentrations in water-damaged building materials. *Indoor Air 2000 Conference* 11:111-120.

Persily, A. 1999. Myths about building envelopes. *ASHRAE Journal* 41(3): 39-47.

Rowan, N.J., C.M. Johnstone, R.C. McLean, J.G. Anderson, and J.A. Clarke. 1999. Prediction of toxigenic fungal growth in buildings by using a novel modeling system. *Applied and Environmental Microbiology* 65(11):4814-4821. Available at http://aem.asm.org/content/65/11/4814.full.

Sedlbauer, K., M. Krus, W. Zillig, and H.M. Künzel. 2001. Mold growth prediction by computational simulation. Presented at IAQ 2001 Conference, San Francisco.

Shakun, W. 1990. A review of water migration at selected Florida hotel/motel sites. *Proceedings of the Biennial Symposium on Improving Building Practices in Hot & Humid Climates*, Texas A&M University, College Station.

Sorenson, W.G. 2001. Occupational respiratory disease: Organic dust syndrome. Chapter 3.3 in *Microorganisms in home and indoor work environment*, B. Flannigan, R.A. Samson, and J.D. Miller, eds. Taylor & Francis, New York.

Straube, J. 2012. *High performance enclosures*. Building Science Corporation, Westford, MA.

Treschel, H., and M. Bomberg. 2009. Moisture control in buildings: The key factor in mold prevention, 2nd ed. *Manual* MNL18-2ND. American Society for Testing and Materials, West Conshohocken, PA.

U.S. Gypsum Corporation. 2014. *The gypsum construction handbook*, 7th ed. Wiley, Hoboken, NJ.

Viitanen, H.A. 1997. Modelling the time factor in the development of brown rot decay in pine and spruce sapwood; The effect of critical humidity and temperature conditions. *Holzforschung—International Journal of the Biology, Chemistry, Physics and Technology of Wood* 51(2):99-106.

WHO. 2009. *Guidelines for indoor air quality: Dampness and mould*. World Health Organization, Geneva. Available at http://www.euro.who.int/__data/assets/pdf_file/0017/43325/E92645.pdf.

Wray, C. 2006. Energy impacts of leakage in thermal distribution systems. *Report* PIER II #500-98-026, California Energy Commission. Lawrence Berkeley National Laboratory, Berkeley, CA.