ASHRAE Journal

Moisture in Buildings

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HVAC designers must consider and deal with moisture in almost all of their work. The moisture most building designers consider is in vapor form inside ducts, conditioned spaces, or outdoors. Although this may be the form of moisture that most interests a design engineer, understanding the *source* of this vapor is important, as this understanding allows for more robust and economical designs, better risk management, more accurate diagnostics and improved forensics.

This article briefly describes the most common sources of moisture in buildings and introduces the processes by which this moisture moves in and through buildings.

Moisture Problems

Moisture has long been important to building designers since it is the single most important agent of building deterioration. For example, moisture, from whatever source, is involved in

- Electrochemical corrosion of metal components such as HVAC equipment, ducts, structural framing, reinforcing bars, masonry anchors, etc.;
- The chemical deterioration and dissolution of materials such as gypsum sheathing, ceiling tiles, wood products, and damaging chemical processes such as carbonation and alkali-aggregate reaction;
- Freeze-thaw deterioration of concrete, stone, and masonry;
- Discoloration (staining, "dusting," irregular wetting, etc.) of building finishes;
- Volume changes (swelling, warping, shrinkage) that can cause degradation of appearance, structural failure, cracking, etc.; and
- The growth of biological forms, including mold, plants, dust mites, etc.

Moisture-related biological growth (mostly fungal) has taken on new significance recently because such growth can have a major effect on occupant health (IAQ), structural capacity, and appearance.

For a moisture-related problem to occur, it is necessary for at least four conditions to be satisfied:

1. A *moisture* source must be available,
2. There must be a *route* or means for this moisture to travel,
3. There must be some *driving force* to cause moisture movement, and
4. The material(s) involved must be *susceptible* to moisture damage.

To avoid a moisture problem, one could in theory choose to eliminate any one of the four conditions. In reality, it is practically impossible to remove all moisture sources, to create buildings with no imperfections, or to remove all forces driving moisture movement. It is also uneconomical to use only materials that are not susceptible to moisture damage. Hence, in practice it is often advantageous to address two or more of these prerequisites so as to reduce the probability of having a problem.

Therefore, controlling or managing moisture and reducing the risk of moisture-related problems by judicious design, assembly and material choices is the most practical approach for designing buildings and conditioning systems.

The Moisture Balance

If a balance between wetting and drying is maintained, moisture will not accumulate over time, and moisture-related problems are unlikely (*Figure 1*). Therefore, the extent and duration of wetting, storage and drying must always be considered when assessing the risk of moisture damage.

Most moisture control strategies tend to reduce the amount of wetting by, for example, increasing the airtightness and vapor resistance of the enclosure, reducing the volume of rain water penetration and absorption, etc. However, it has become generally accepted that most building construction will not be perfect, thus wetting will occur. Chilled water piping may not be perfectly insulated at all joints; windows have a propensity to leak; etc. Therefore, the provision of greater drying potential and storage capacity have begun to receive more at-

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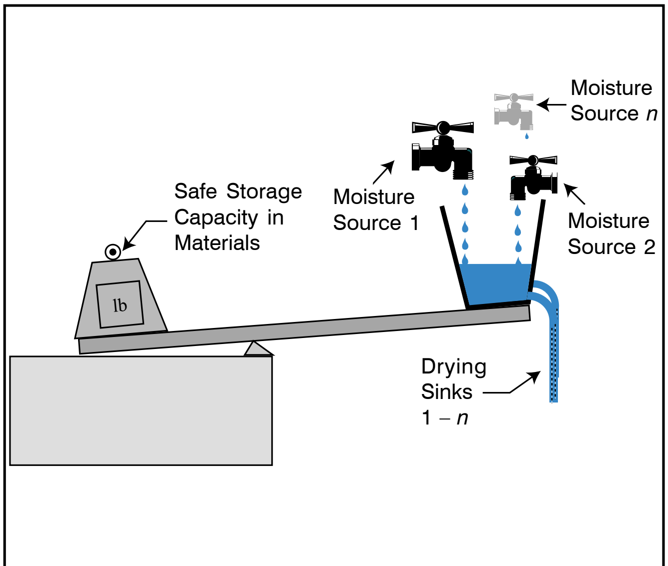

Figure 1: The moisture balance for* n *sources and sinks.

Source	Moisture Production Liters per Day
People (Evaporation per Person)	0.75 (Sedate), 1.2 (Avg.) to 5 (Heavy Work)
Humidifier	2–20+
Hot Tub, Whirlpool	2–20+
Firewood, per Cord	1–3
Washing Floors etc.	0.2
Dishwashing	0.5
Cooking for Four	0.9 to 2 (3 with Gas Range)
Frost-Free Fridge	0.5
Typical Bathing/Washing per Person	0.2 to 0.4
Shower (ea.)	0.5
Bath (ea.)	0.1+
Unvented Gas Appliance	0.15 kg/kWh for Natural Gas, 0.10 kg/kWh for Kerosene
Seasonal Desorption (or New Materials)	3 – 8 Depends on the House Construction
Plants/Pets	0.2-0.5 (Five Plants or One Dog)

Table 1: Sources of interior moisture. [2,3,4,5]

tention. These are powerful, and often overlooked moisture control design strategies that are often present in buildings that have survived for centuries. Finally, increasing moisture tolerance through intelligent design of building location, orientation, geometry, HVAC design, etc. is often the least expensive and best approach (although it must be considered very early in the concept stage).

The major wetting and drying processes and the moisture transport mechanisms involved in the movement of moisture into and out of the enclosure are summarized in *Figure 2*.

Moisture Sources

There are four *primary* sources of moisture in buildings. It is useful to categorize them as:

1. Liquid water, from precipitation (rain and melting snow) or plumbing leaks;
2. Water vapor, from the exterior and from activities and processes within the building;
3. Liquid and vapor from the soil adjoining the building; and
4. Moisture built-in with the materials of construction or brought in with goods and people.

Piping leaks and rain penetration are obvious sources of water that must be avoided. Rain deposition on roofs is usually of the order of several hundred to one thousand kg/m^2 (200 lb/ft^2) in most climates. Walls typically receive about 25% to 50% of this load.[1] If only a very small fraction of this precipitation leaks into a building or its enclosure, serious damage is possible given time.

It is not often appreciated how little leakage is required to cause serious problems. For example, a leaky valve or window that leaks one drop of water per hour onto a drywall ceiling below is likely to cause rapid and potentially serious mold growth. Further, liquid water from these sources can quickly reach catastrophic proportions. Rain leaks or plumbing pipe failures can result in hundreds of gallons of water being discharged into a building.

Water vapor can be almost as problematic as direct liquid water sources, although the magnitude of the moisture involved is typically much less. Water vapor condensation on uninsulated chilled water or domestic cold water pipe is a relatively common problem, as is condensation hidden within walls and roofs or running down windows. The water vapor from the exterior enters the building both through intentional supply air ventilation and unintentional air leaks through the building enclosure and ducts.

In many types of buildings, a significant amount of moisture can be released or generated by occupants, their activities, and processes. *Table 1* lists different internal moisture sources and their significance. This source of vapor is highly variable. The amount of water provided by a well used heated indoor pool or papermaking process is obviously very significant whereas the moisture given off by a two people in a large home is not. Design engineers should investigate specific processes in some detail to allow the prediction of average and peak vapor production.

Soil can be a significant source of moisture near the basement, foundation, and the first floor of buildings. Soil is a large source of moisture in both liquid and vapor forms. Liquid water, draining directly from the surface or from the water table tends to penetrate through cracks, holes and other unintentional openings. The liquid water stored within the soil matrix will wick through the soil and porous building materials (concrete, stone, wood, etc.).

Stored liquid water deep below the surface and bound to the soil also provides a practically inexhaustible supply of water vapor. Since diffusion is a less powerful mechanism, soil water vapor is less significant than liquid water, but it is still a large

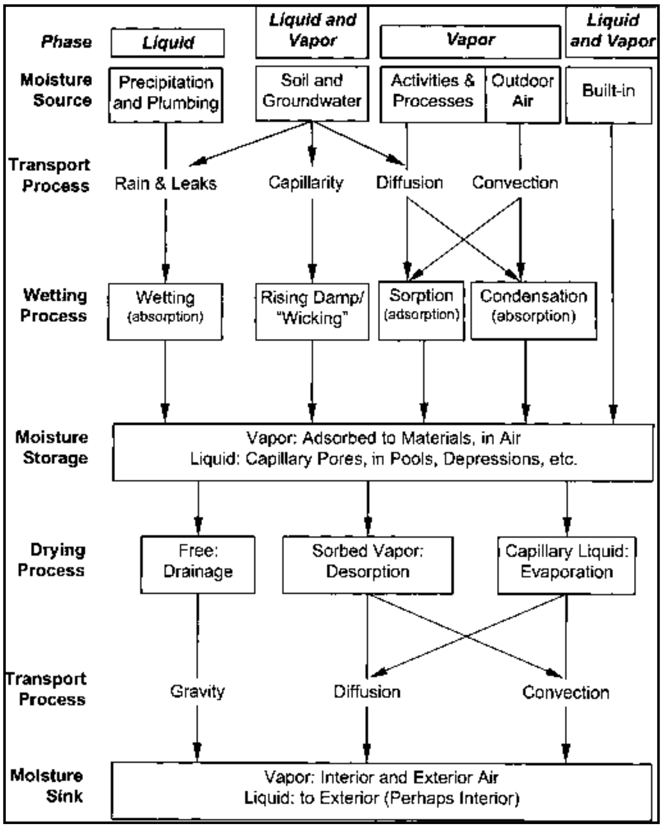

Figure 2: Moisture sources, transport, and storage in buildings.

Rainwater drained from the roof onto the wall was absorbed into the brickwork, allowing freeze-thaw damage to occur.

moisture source. Water vapor from soil enters buildings primarily by diffusion, although convection (air leakage) may occur through soil in some cases. Soil in a wet basement or an uncovered crawlspace has been found to evaporate at a rate of 100 to 500 g/m^2 per day (e.g., Trethowen, in a survey of 60 crawlspaces, found an average evaporation rate of 400 g/m^2 per day.) Crushed stone acts as a capillary break between moist soil and the building enclosure, but allows vapor diffusion to act relatively unhindered. Hence, sheet or paint-applied vapor barriers are often required near the exterior of below grade assemblies.

Built-in moisture can be important, but this source is specific to the type of building construction and only plays a role for the first few years of a building's life. Wood framing typically loses close to 10% of its weight in moisture. A normal concrete mix contains about 200 kg (440 lb) of water per cubic meter, of which about half is later released as vapor. Hence, a typical house basement system containing 20 to 30 m^3 (700 to 1050 ft^3) of concrete will release several thousand liters of water over the first year or two. Similarly, a 200 mm (8 in.) thick reinforced concrete floor slab in an office building can be expected to release 20 liters per m^2 during the first two years. Concrete block (and water trapped in the cores during construction), drywall compounds, paints, flooring adhesives, etc., all contribute to built-in moisture.

Transport Processes

Moisture moves under different mechanisms in each of its phases.* The primary transport processes, beginning with the least powerful to the most, are:

1. Vapor diffusion (and surface diffusion within some porous materials);
2. Vapor convection (i.e., air movement);
3. Liquid water capillarity (i.e., wicking) through porous materials; and
4. Liquid gravity flow (including hydrostatic pressure) through cracks, openings, and macropores.

Vapor diffusion moves water vapor from regions of high vapor concentration to low concentration. Diffusion acts to move vapor through the air, or through the air within porous materials. Hence, water vapor does not diffuse through non-porous materials like steel, glass, some plastics, etc.

Water vapor diffusion through the insulation covering a chilled water line, for example, will causing wetting and corrosion if it acts for long enough. Water vapor diffusion also plays a role in transporting water vapor into the building en-

*"Bound" water is a term used differently by various sources. Adsorbed moisture moves by surface diffusion, and this can be a significant mechanism for some materials at high relative humidities. Chemically bound water does not participate in normal transport mechanisms, whereas water held in material pores by capillary forces is still in the liquid phase. Solid moisture (ice) practically does not move.


Water vapor has bypassed the vapor impermeable interior glazing unit (by convection through small flaws in the caulking) and condensing on the exterior pane of this window in winter. The same phenomena occur within walls and roofs as in the wall at right.

closure where it can sometimes condense. To control this flow, vapor barriers are often specified (on the inside in cold climates and on the outside in hot-humid climates), although vapor diffusion is not usually the cause of moisture damage in walls. That vapor diffusion was not a powerful transport mechanism in practice was first recognized as early as the 1950s,[6] and taken into practice by the mid-1980s in Canada by publications for practitioners.[7]

Vapor diffusion can be important in roofs and walls with absorptive claddings, however. Rainwater is absorbed into the cladding and subsequently heated by the sun. Even in cold climates, very high vapor pressure gradients can form in this situation and move damaging quantities of moisture inward.[8] This damage is exacerbated by the use of interior low permeance vapor barriers.

Vapor convection is the primary transport mode used to move water vapor along ducts and to distribute it within a space. Very small flows of air usually move much greater quantities of water vapor than diffusion can. Convection through openings in the building enclosure is a major cause of interstitial condensation (tens to hundreds of times more significant than diffusion), and is the largest source of moisture inside building enclosures after rain penetration. Continuous, durable, stiff, and strong air barrier systems must be provided in all building enclosures to control or eliminate convective moisture transport. Control of vapor convection (essentially synonymous with airflow control) also demands sealing of all air ducts that penetrate the air barrier system, control of pressure zones within buildings (so that air and vapor does not flow through unintentional paths) and the proper operation of supply and exhaust fans.

Capillary Suction moves liquid moisture slowly and steadily through porous materials from regions of high liquid concentration to regions of low concentration. The smaller the pores, the more powerful the capillary suction but the slower the flow. Although the rate of moisture transport by this mechanism is relatively slow, it can act for years. Capillarity is important in constructions contacting soil (since in almost all areas the soil is usually wet), and rain-wetted surfaces. Capillary flow can be controlled or eliminated by installing a barrier to capillary flow. A small air gap or a capillary inactive material (e.g., non-porous or hydrophobic) is often sufficient. Both approaches are used in practice, either in the form of an air space behind brick cladding, as crushed stone below a concrete slab, or as a piece of building paper below wood framing on a concrete floor.

Gravity flow can be the most powerful means of moisture transport. Very large quantities of liquid water, often measured in liters per second, can flow downward through openings, cracks, pipes, or air spaces when driven by gravity. Gravity flow requires relatively large openings (of the order of a millimeter [0.04 in.] or larger) since capillary suction forces tend to overwhelm gravity forces in small pores. Hence, water will not flow out of a saturated brick (despite some myths that one hears), but can flow through a screw hole in a plastic windowsill.

Gravity can drive rainwater that penetrates through a leaky window into a wall, or water in the soil through a crack in the foundation walls. The size of the flows and the sources are often sufficient to cause catastrophic failures. Flashing is one example of how gravity flow can be used to advantage by intercepting water flows and redirecting them outward. Similarly, condensation pans and disaster pans under appliances are commonly used to manage liquid water that is driven by gravity.

Combined Processes. Transport processes rarely act alone to move moisture within and through buildings. In reality, a number of transport processes act in parallel and series. For example, liquid water from the groundwater may wick upward to below the surface of a crawlspace floor, where it evaporates and moves by diffusion through the soil into the crawlspace. Small air pressures then act to transport the water vapor into the main space of the building, raising the interior humidity and resulting in condensation on a cold water pipe within a suspended ceiling. The condensate accumulates at this point until it begins dripping onto the drywall ceiling below. Here mold accumulates and the ceiling is damaged. The moisture


Water vapor diffusing inward during summer conditions in a cold climate (Waterloo, Canada) condensing on a low-permeance vapor barrier. The resulting damage is shown at right.

source may be the soil in this case, although understanding the whole moisture transport process can provide the designer with a number of interventions: a ground soil cover, a powerful dehumidification system (or ventilation in some climates), insulated piping, etc.

Every mode of moisture transport that can cause moisture problems also can help dry building materials and surfaces. Hence, attempting to block transport mechanisms is not always the best approach for managing moisture. A sensible combination of reducing the source strength, controlling and directing transport mechanisms, and encouraging drying should be used.

Summary and Conclusions

The control of moisture in buildings is key to their durability, functionality, health, and efficiency. Understanding the sources of moisture and the mechanisms by which they move within the building and the building enclosure allows professionals to design better buildings and conditioning systems. All moisture management and control strategies and techniques must be solidly based on this understanding.

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