MOISTURE, MATERIALS, & BUILDINGS

Water is the most common cause of mold, rot, and corrosion within buildings, yet is commonly misunderstood by engineers and property owners

By **J.F. Straube**
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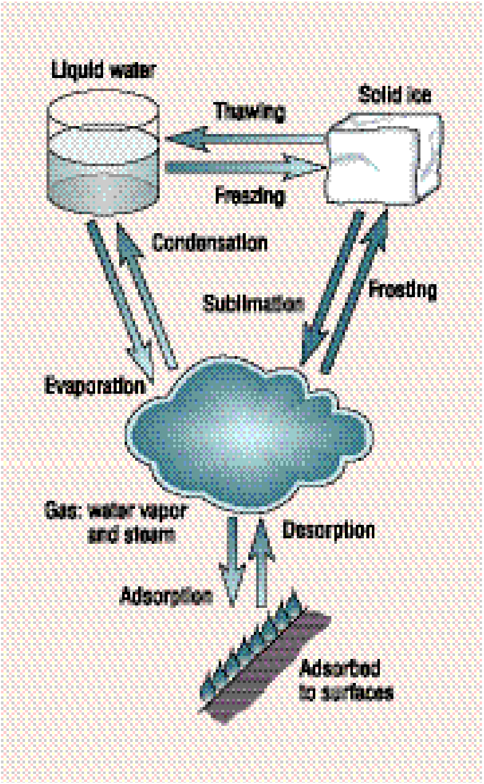
Moisture is involved in many building-related problems, such as corrosion, rot, staining, mold growth and its health effects. To avoid many of these problems, an understanding of moisture and how it moves through a structure and equipment is useful.

Recent *HPAC Engineering* articles (Acker, June 1998; Lotz, Jan. 1998; Lstiburek, Dec. 2001, January 2002) have described moisture problems and some strategies to avoid them. This article aims to explain some of the more fundamental aspects of moisture and its interaction with materials while classifying sources and the ways in which it moves.

FIGURE1. Moisture states and phase-change processes.



A UNIQUE SUBSTANCE

One unique and significant characteristic of moisture is that we experience it everyday in all of its states. Conversely, the full range of states for substances like steel or alcohol exist only at industrial process temperatures or on laboratory benchtops. Figure 1. details the states of water and phase changes. The adsorbed state is the least understood, and will be described in more detail later in this article. A significant change in energy content, called latent energy, must occur before moisture changes state. The additional energy required to change liquid water to vapor is very large (approximately 1,075 Btu per lb at boiling—the energy released when vapor condenses into liquid is identical but opposite in direction.

Moisture in all its states, is a molecule with two positively charged hydrogen atoms, and one negatively charged oxygen atom (H_2O). The molecule is only about 0.3 nanometers in diameter: one billion laid end to end would be about 1 ft long.

It can be seen from Figure 2 that the centroid of the two positive charges is not coincident with the centroid of the two negative charges. This spatially-unbalanced distribution of charges means that H_20 is a polar molecule and behaves like a tiny magnet. The hydrogen end is permanently positive and the oxygen end is permanently negative. This polar nature plays a significant role in how water interacts with other materials.

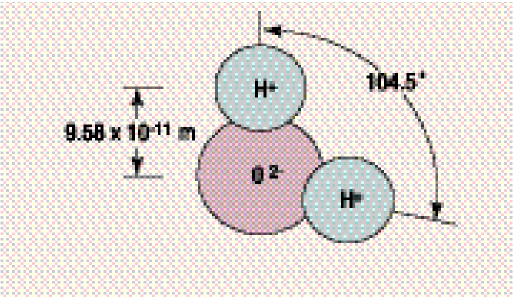


FIGURE2. H_2O, the water molecule.

J.F. Straube specializes in the areas of building enclosure design, moisture physics, and whole building performance as a consultant, researcher, and educator. He is a faculty member in both the Department of Civil Engineering and the School of Architecture at the University of Waterloo, where he teaches building science and structural engineering.

INTERACTION WITH MATERIALS

The polar water molecule "magnet" is attracted to many materials in both the vapor and liquid state. For example, water drops will cling to your skin and to the mirror after a shower. Liquid water is actually sucked into the very small tubes or capillaries present in porous materials: the smaller the pore the greater this capillary suction. The suction, or wicking, of interconnected capillaries explains why water is drawn up into celery, bricks, and the top of tall trees. A few materials, like silicone and oils, repulse water and this repulsion causes water to bead (e.g., rain on the hood of a freshly-waxed car, or water on new, oily, ductwork). Detergents are used in cleaning because they are double-ended molecules that can attach one of their ends to water and the other end to oil.

The manner in which water molecules interact with other water molecules is also due to their polar nature. The hydrogen of one molecule attracts the oxygen of another and causes the water to group together by a process called hydrogen bonding. Hence, liquid water tends to exist in large clusters. As the temperature increases, the clusters gain more energy and break up into smaller clusters. When liquid water is evaporated, the molecules gain so much energy that they act individually as lone vapor molecules. The difference in size between the liquid water molecule clumps and the lone vapor molecule explains how materials such as Gore-Tex and Tyvek can simultaneously be watertight and highly vapor permeable.

MOISTURE STORAGE

Many surfaces in contact with water vapor molecules have the tendency to capture and hold water molecules because of the polar nature of the water molecule. This process is called adsorption. These materials are called hydrophilic, whereas materials that repel water are called hydrophobic. Most building materials are hydrophilic, porous and have very large internal surface areas. For example, the interior surface area is about 50 sq ft per ounce of gypsum board, 5,000 sq ft per ounce of cement paste and even more for wood or cellulose. As water vapor molecules in the air adsorb to the internal surfaces (the pore walls) of these materials, the water content increases significantly. Such materials are described as hygroscopic. (Desiccants are a special type of hygroscopic material. They can absorb (or adsorb as a vapor?) a very large amount of moisture, typically several times their dry weight at high relative humidities). Materials such as glass, plastic, and steel do not have internal pores and are therefore not hygroscopic—they do not pick up moisture from water vapor in the air.

When a material has adsorbed all the moisture it can, further moisture will be stored in the pores and cracks within the material by capillary suction, or by absorption. For example, wood will adsorb vapor from the air up to approximately 25 or 30 percent moisture content at 98 percent RH, but fully capillary saturated wood wetted by liquid water may hold 2-2-4 times this amount of moisture. Once a material is capillary saturated, it will generally not be able to store any more moisture. When this moisture content is exceeded, a material is called over-saturated, and no more water can be wicked into the material. At this point, drainage, if possible, will begin to remove the excess moisture.

In summary, liquid water is absorbed into capillary pores and significant amounts of water vapor can be adsorbed to the surface of pore walls.

MOISTURE STORAGE REGIMES

Figure 3 shows the three different regimes of moisture storage: the sorption or hygroscopic regime (regions A-C), the capillary regime (D) and the over-saturated regime (E). It is very important to recognize that the moisture content varies primarily with relative humidity, not with absolute humidity.

In the hygroscopic regime, water vapor adsorbs to the pore walls. As relative humidity increases, more layers adhere, although the first few layers are strongly attached (regions A and B). In region C, the layers grow to such a size that they begin to interact and interconnect. At this point, the surface tension of water causes meniscuses to form within the smallest pores. At the highest relative humidities, all but the largest pores are filled with water. The capillary regime (region D) is somewhat arbitrarily designated as that part of the moisture storage function above the critical moisture content. Physically, it is presumed that a continuous liquid phase forms. Finally, in the supersaturated state, the relative humidity

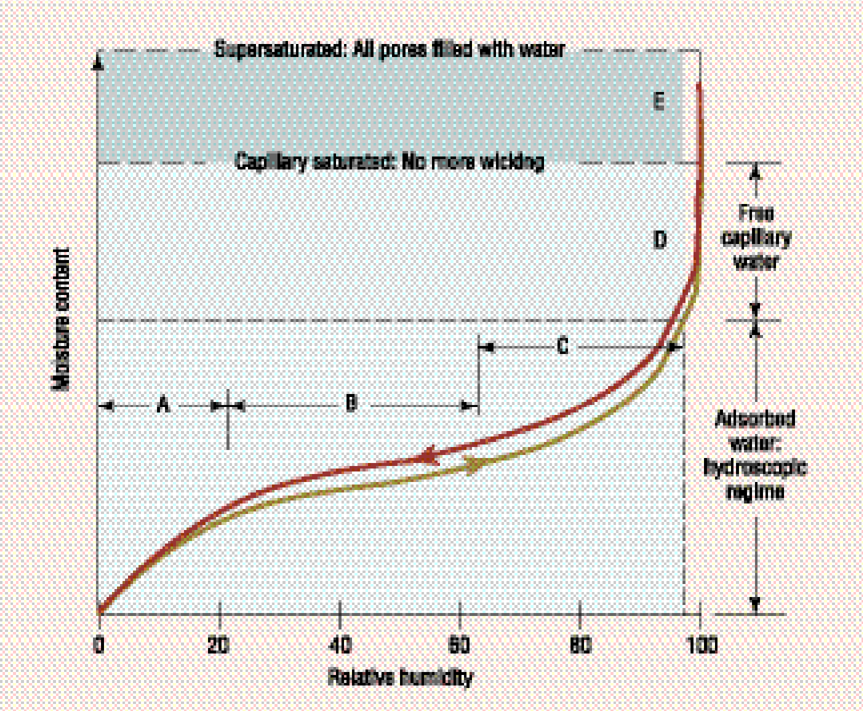


FIGURE 3. The three regimes of moisture storage: the sorption or hygroscopic regime (A-C), the capillary regime (D) and the over-saturated regime (E).

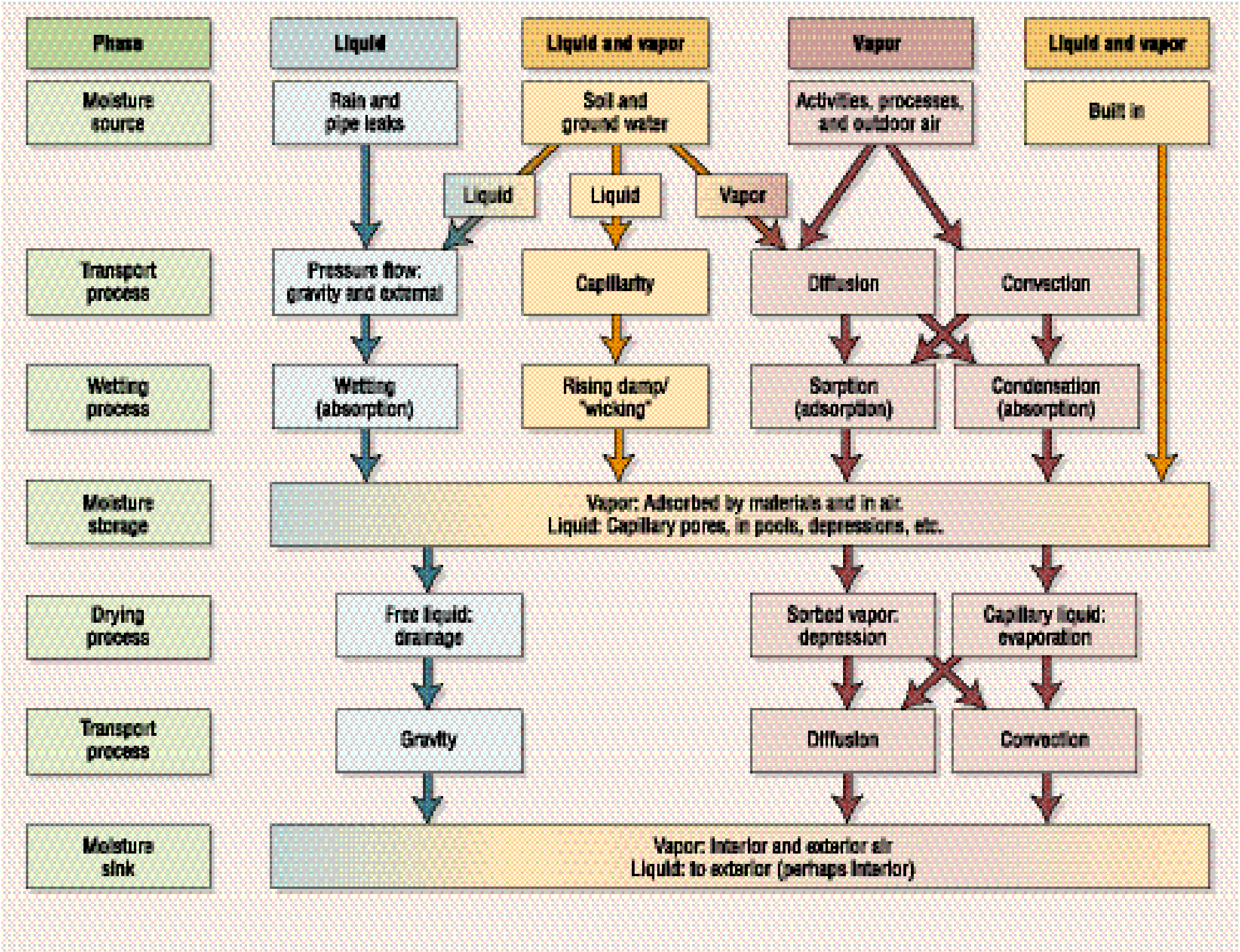


FIGURE4. The wetting, drying, and storage of moisture within buildings in each of the three H_2O phases.

is always 100 percent and no more water will wick into a material—external forces must force it in (such as air pressure, gravity, etc.).

PRACTICAL IMPLICATIONS

Materials such a wood, mortar, gypsum, and concrete begin life with all of their pores filled with water. As the material dries, the water content in the pores drops and adsorbed water will be tempted to leave the surface of the pores. However, the strength of the bonding between water molecules that make up the adsorbed layers results in tension forces as drying progresses. It is these internal tension forces that cause drying shrinkage stresses and the consequent cracking in wood, clay, concrete,etc.

Conversely, brick begins life in a high temperature oven—completely dry. When water vapor subsequently enters the pores, compressive forces are developed as water molecules force themselves close to the brick material and other adsorbed water molecules. This internal compressive force causes the initial expansion of brick, and the wetting expansion of other porous materials like clay and wood.

Hence, wetting and drying due to adsorption will cause expansion and contraction in many materials and explains why wooden doors tend to be tight in the humid summer and loose-fitting in dry winter interior spaces. As shown in Figure 3, the desorption or adsorption occurs because of changes in the relative humidity adjacent to the material. Shrinking and swelling materials can destroy paintings, furniture, and other artifacts. To avoid this, museums and some archives must be operated with stable relative humidities. Hence, it is not the absolute mass of water vapor in the air (humidity ratio, dew-point temperature or vapor pressure) that must be maintained in such facilities, but the relative humidity. Typical temperature variations cause much less stress to materials so temperature can be allowed to float and relative humidity held within a narrow range. The relative humidity level specified for museums is often 50 percent, although this is mostly for arithmetic convenience, not scientific reasoning. The key for materials is non-cycling relative humidities over many weeks, whereas for health and building durability, low relative humidity is preferred. Therefore, an interior RH OF 40 percent is obviously preferable to 50 percent in a cold climate museum. In a hot humid climate, an RH of 55-60 percent could be chosen to minimize the latent ventilation loads.

In the upper portion of the hygroscopic regime (typically once the RH exceeds about 80 percent), the adsorbed water vapor is attached loosely enough that it may be available for fungal growth and corrosion (the temperature must also exceed about 37 F). It is for these reasons that humidity control of interior air and air within ducts and air spaces is so important for design (Gatley 2000, Harriman and Brennan, 2000). When the RH exceeds 90 percent, and the temperature tops 60 F, very fast deterioration of all organic building products can be expected, along with the rapid growth of molds, some of which are potentially allergenic or toxigenic.

To dry out a building exposed to a flood, one must reduce the relative humidity within the materials to below 80 percent as quickly as possible (two or three days maximum according to most public health publications). It should be clear from Figure 3 that drainage (which leaves a material capillary saturated) is not sufficient since it can leave a large amount of saturated material. Capillary and adsorbed moisture can only be dried by evaporation (Straube 1998) because it takes more energy to break the attractive forces than gravity can supply.

THE MOISTURE BALANCE

Given the fundamentals of moisture described above, one can begin to understand moisture movement and sources. The prevention of moisture-related damage requires the moisture content of surfaces and porous materials to be controlled to within the limits suggested above. If a building material or surface gains moisture from any source (wetting), it must also be able to eventually lose moisture (drying) without crossing the performance thresholds described above. The difference in time between wetting and drying events can be safely bridged by storage if the material or surface allows safe storage.

Hygroscopic materials are often able to safely store a significant amount of moisture. For example, contrast the response of your mirror and towel as you step from a hot shower. The mirror (as well as all the glazed tile and other nonporous surfaces) are coated with a thin film of condensate, whereas the towel, which has adsorbed the water vapor without condensation, is still dry to the touch.

The magic of understanding the moisture behavior of building materials and surfaces is often about grasping the importance of the dynamic balance of wetting, drying and storage.

Figure 4 summarizes the wetting, drying, and storage of moisture within buildings and their enclosures in each of the three H_2O phases. The source of moisture is listed first followed by the transport process that moves the moisture. The wetting process is the manner in which the moisture actually increases the moisture content of the material. Note the distinction between adsorption (increasing material moisture content from H_2O vapor) and absorption (increasing material moisture content in liquid form).

MOISTURE SOURCES

There are four primary sources of the moisture that interact with building materials. It is useful to categorize these as:

- Liquid water, from precipitation (rain and melting snow) or piping leaks.
- Liquid and vapor from the soil adjoining the building.
- Water vapor, from the exterior air (supply air and infiltration) and from activities and processes within the building.
- Moisture built-in with the materials of construction or brought in with goods and people.

MOISTURE SINKS

The primary moisture sinks for moisture in buildings are:

- Storage of water vapor by increasing the humidity ratio of the interior air
- Storage of water vapor by increasing the humidity ratio of the exterior air.

Moisture in the interior air can then be considered as a vapor source that can subsequently be removed from the building by dilution with drier ventilation air, by dehumidification (condensation), or adsorption into drier materials (which essentially describes desiccant dehumidification or increasing the moisture content of buffer materials).

TRANSPORT PROCESSES

The processes that transport moisture can be listed in order of maximum movement capacity:

- Flow of liquid water due to pressure differences (including gravity, hydrostatic and air or wind pressure differences) through cracks, openings, and macropores.
- Capillarity (wicking) of liquid through porous materials.
- Convection of air (air movement) and its associated water vapor due to mechanical or stack-effect pressure differences.
- Diffusion of vapor (and of the adsorbed layers within some porous materials).

APPLICATIONS AND IMPLICATIONS

The framework presented above can be applied to some important practical situations.

Condensation on chilled water lines is a common problem. The moisture content of the interior air is often higher than that of saturated air at the surface of the pipe during warm humid weather. Hence, vapor diffusion drives water vapor molecules from the surrounding air (an area of high concentration) to the surface of the pipe (an area of low concentration). Fibrous pipe insulation has little resistance to vapor flow, since it has a very open pore structure. Although a vapor barrier (a material with closed pores that greatly restricts vapor diffusion) should always be installed, some vapor always penetrates through the material because of punctures in the vapor barrier or through imperfections of the installation. Over time, vapor flows to the cold pipe, changes to liquid form (condenses) and moisture inevitably accumulates since drying does not occur. The result is soaking wet insulation with poor thermal performance and corroding chilled water piping (figure 5).

Lowering the interior dewpoint temperature, increasing the chilled water temperature. Improving the quality of the vapor barrier will also reduce wetting. However, the solution to this common problem is not to attempt to completely avoid wetting (since this is often practically impossible) but to increase drying so that there is a balance.

There are two ways to provide drying. The system can be designed so that there is warm or hot water in the pipe for enough of the year that the condensation that happens during warm and humid weather is removed during cold and dry weather by the same diffusion transport mechanism that caused the wetting.

One commercially available pipe insulation uses a second and more much more clever approach. As seen in figure 6, different transport mechanisms are used to affect drying at the same time as wetting. The pipe is wrapped in an absorbent material that wicks condensation. By carrying this fabric to the exterior of the vapor barrier, liquid water is transported by gravity assisted-capillary flow from the surface of the chilled water pipe to the exterior where it can evaporate (figure 6). Liquid water will always be able to evaporate to interior air at less than 100 percent relative humidity. In this case, wetting is balanced by drying, and loss of insulation R value can be avoided.

Coupled series serial and parallel storage and transport processes also occur in building enclosures.For example, consider the wall system analyzed in the January 2002 issue of *HPAC Engineering* (Lstiburek 2002), which has been duplicated in this article for convenience (figure 7). When it rains, the water repellent (hydrophobic) roofing membrane causes the water to bead up until gravity drives the water down the slope of the roof towards a roof drain and out to the storm sewer. Initially dry and hydrophilic brickwork, (region C of figure 3), capillary suction will absorb the rain into the small pores (much less than one thousandths of an inch) and cause the moisture content to rise well into region D. If the brick becomes capillary saturated (typically at 5 to 15 percent water by weight) it will cease to absorb water. Brickwork leaks due to suction of water into the larger cracks between the mortar and brick (typically 5 to 10 thousandths of an inch) and then gravity then drives it out of the crack, down the drainage space, and out the weepholes (Straube 1997). The capillary break provided by the air gap and the hydrophobic insulation resist capillary transport inward and work together with the flashing that use gravity to drive water harmlessly outward.

When the rain stops, the brick, or at least the front face of it, will be saturated. As the sun returns, it will heat the brickwork and evaporate the water from both the front and back face. This reduces the water content (although the relative humidity at the face of the brick remains at 100 percent). As the faces dry, capillary forces wick water from the interior of the brick to the face, re-supplying the face with water for evaporation. The water that evaporates from the front face enters the atmosphere, but that evaporated from the back face will significantly increase the moisture content of the air in the cavity. Because the sun heats the brickwork at least 50 F above ambient air temperatures, very high vapor pressures are generated (look up 100 percent RH and 120 F on the psychrometric chart). This water vapor can be transported inward by vapor diffusion or removed from the cavity by ventilation (Straube 1998). If the rigid insulation were to be highly vapor permeable (e.g. semi-rigid glass fiber), this type of inward vapor drive could easily cause condensation on a low-permeance interior vapor barrier and damage to the light-gauge steel framing. The wall system considered avoids this problem by using exterior rigid foam insulation with some moderate vapor resistance and by not installing a low permeance interior vapor barrier.

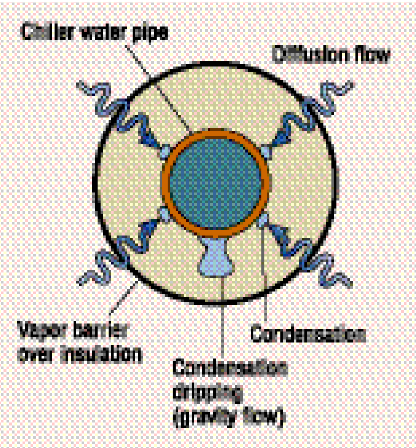


FIGURE5. Fibrous pipe insulation with breached vapor barrier. Vapor flows to the cold pipe and changes to liquid form (condenses). The result is soaking wet insulation with poor thermal performance and corroding chilled water piping.

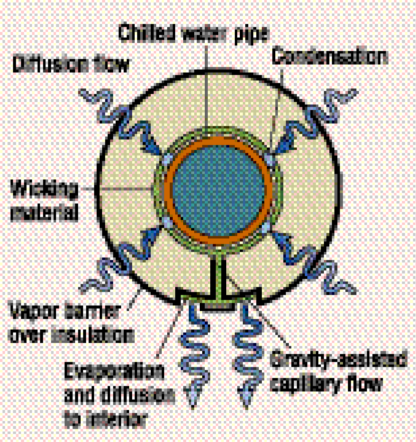


FIGURE6. One solution: wrap the pipe with an absorbent material that wicks condensation. By carrying this fabric to the exterior of the vapor barrier, liquid water is transported by gravity assisted-capillary flow from the surface of the chilled water pipe to the exterior where it can evaporate .

In cold weather, water vapor inside the building can condense on any surface below its dewpoint. In the wall detail in question, the thermal bridge of the concrete roof slab might become cold enough for vapor to condense to liquid. Condensate would likely wick into the concrete and slowly raise its moisture content. However, the application of the R5 insulated sheathing to the slab practically eliminates this possibility for all but the coldest climates provided the interior relative humidity is controlled.

Water vapor in winter may also be transported by convection (e.g., outward air leakage) into the insulation-filled studspace and condense on the back of the rigid insulation. For the same reasons given for the slab above, the insulation layer will likely avoid this condensation problem. Of course, the installation of the air barrier system described in the wall design should also practically eliminate air leakage.

Very little water vapor will diffuse outward through the wall system because the vapor resistance of paint will restrict diffusion. The air within the studspace will have a lower moisture content because of this interior vapor resistance (Acker 1998) and condensation is extremely unlikely. Note that a vapor barrier in the classic definition was not necessary to control diffusion in this case—two coats of latex paint would be both sufficient and superior.

SUMMARY AND CONCLUSIONS

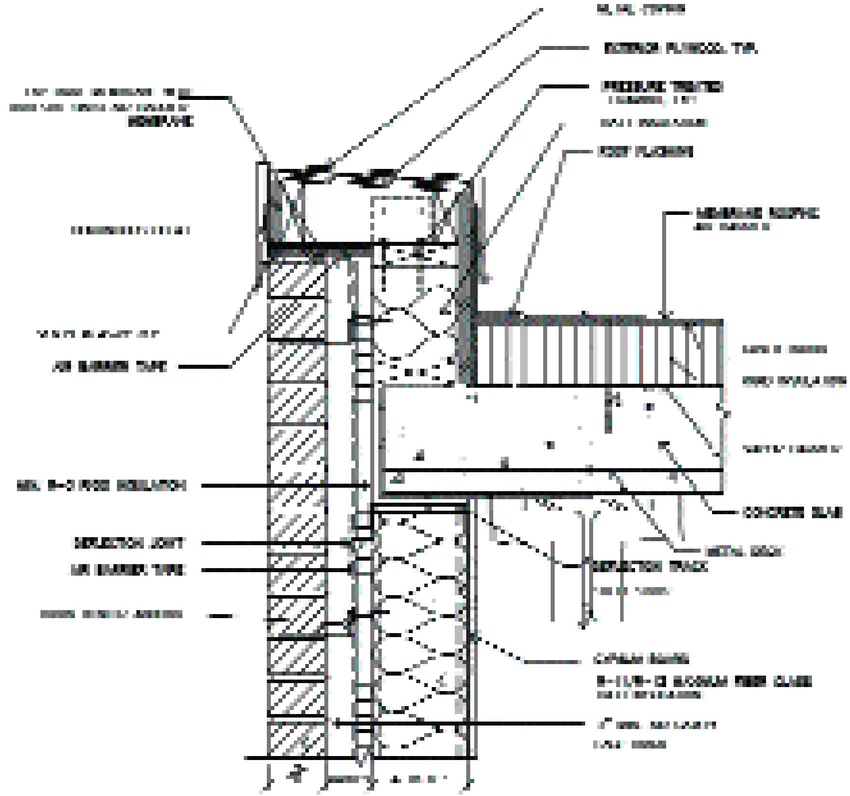


FIGURE7. Detail of roof parapet. Figure courtesy of the Massachusetts Board of Building Regulations and Standards (BBRS).

Understanding moisture , its source, and the mechanisms by which it moves within the building and the building enclosure allows professionals to design better buildings and environmental control systems while avoiding many of the health and performance problems that have become so common. This article has introduced some fundamental moisture concepts required for understanding, but each specific problem and situation requires a unique analysis based on scientific principles not just tradition and common practice.

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