Fundamentals of Moisture in Houses

by Joseph Lstiburek and John Carmody

Moisture can be one of the most vexing areas of building science to diagnose. However, a basic understanding of the principles involved can help a novice sleuth develop a strategy for finding and combating moisture problems.

Note: This article was excerpted and adapted from Joseph Lstiburek and John Carmody, *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings* (New York: Van Nostrand Reinhold, 1993).

Moisture problems occur in buildings throughout North America, in almost every climate. The most common symptoms are mold, mildew, and condensation, and these can impair the health of the occupants, cause discomfort, and decrease the life of the structure.

Understanding Relative Humidity

Air contains varying amounts of moisture in the gaseous or vapor form. The actual amount of moisture contained in air is referred to as its *absolute humidity*. More precisely, the absolute humidity is the ratio of the mass of water vapor to the mass of dry air in a given sample of air.

Air is a mixture of several gases, including nitrogen, oxygen, and water vapor. The total air pressure exerted by a volume of air in a given container on that container is the sum of the individual (partial) pressures of these gases. The *vapor pressure* is the partial pressure of the water vapor.

The warmer air is, the more moisture it can hold. *Relative humidity* is the ratio of the amount of moisture in the air to the maximum amount of moisture the air can hold at a given temperature. Air is said to be saturated (at 100% relative humidity) when it contains the maximum amount of moisture possible at a specific temperature. Air holding half the maximum amount of moisture at a given temperature has a relative humidity of 50%. Relative humidity near surfaces is the single most important factor influencing moisture problems in buildings.

Mold and Mildew

Mold and mildew (two words for the same thing) are simple plants, of the group known as fungi, that grow on the surfaces of objects when the relative humidity is high. Mold discolors surfaces, causes odor problems, and causes deterioration of building materials. Mold can also produce allergic reactions, hypersensitivity, and infectious diseases. Certain fungi found in indoor air produce mycotoxins, which can be carcinogenic (induces cancer), teratogenic (induces birth defects), immunosuppressive (reduces immune system performance), or oxigenic (poisons tissues).

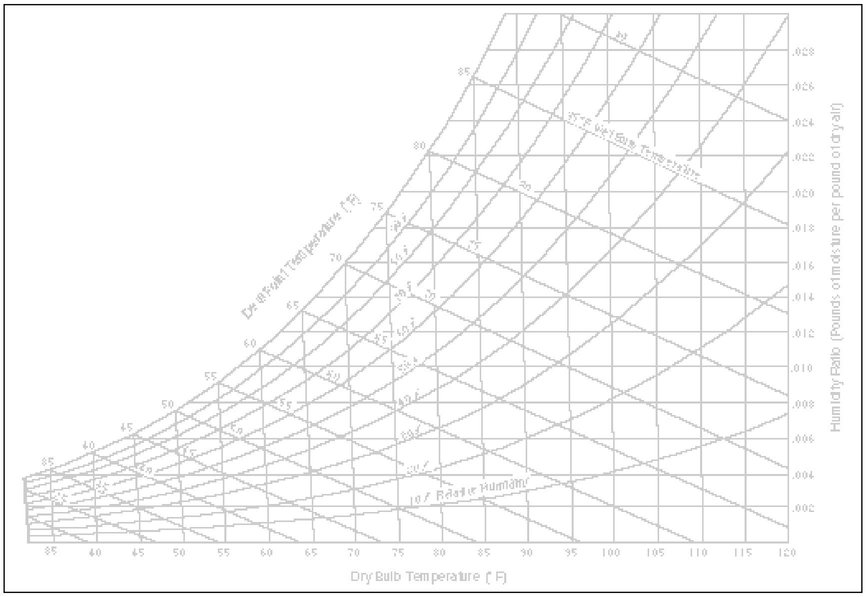

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Figure 1. Simplified psychrometric chart. (Based on the chart in the 1989 *ASHRAE Handbook of Fundamentals.*)

Most fungi have microscopic wind-borne spores. These spores are buoyant and can enter buildings as part of natural (wind- and temperature-driven) or controlled (fan-forced) air flow. Although their concentration varies seasonally, mold spores are almost always present in the outside air.

Fungi generally grow when the temperature is between 50°F and 100°F, with optimum growth occurring between 75°F and 95°F. However, some types of fungi can grow at temperatures as low as 35°F and as high as 120°F. Many building materials (wood products, cotton fabrics, wool fabrics, hemp fabrics, organic dust and lint, soaps, oils, paints, adhesives, certain plastics, and vinyls) provide nutrients for fungi.

Mold needs moisture to produce enzymes and to perform metabolic activities to digest carbohydrates, fats, and proteins. The optimum relative humidity for fungal growth is 70%. Since relative humidities are dependent on both temperature and vapor pressure, control strategies usually focus on either or both of these factors.

Mold Growth in Heating and Mixed Climates

In heating climates, mold grows on interior surfaces during the winter. Typically, the interior surfaces of exterior walls are cool (due to heat loss), while moisture levels within the conditioned space are high. Mold growth can be controlled in two ways: (1) by preventing the interior surfaces of exterior wall and other building assemblies from becoming too cold and (2) by limiting interior moisture levels. Adding insulation to a wall or ceiling raises the temperature of the interior surface. Controlled ventilation and control of moisture sources limit interior moisture levels.

In buildings with similar insulation levels, interior humidity levels must be kept lower in colder climates. For example, a 25% interior relative humidity at 70°F would probably be appropriate for Minneapolis; in a similar building in Cincinnati, interior relative humidities up to 35% at 70°F should be fine. During the heating season in milder climates, interior moisture levels should generally be kept at 35% to 45% relative humidity at 70°F.

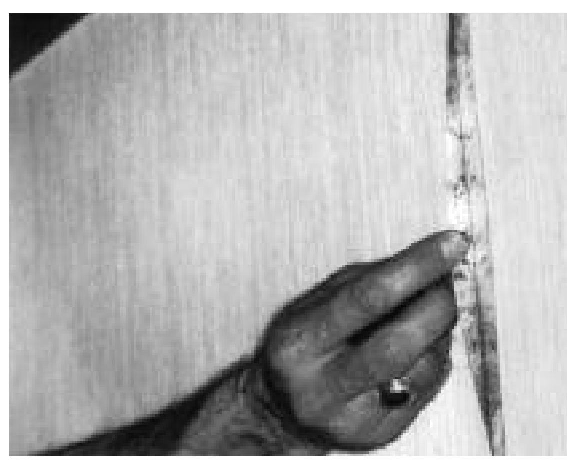
When there is excessive ventilation or excessive air change by infiltration and exfiltration during the heating season, uncomfortably low relative humidities can also occur. When relative humidities drop below 20%, membranes in the human respiratory system begin to dry, and defenses against infection begin to fail. At low relative humidities people wearing contact lenses become uncomfortable, and static electricity discharges can affect equipment and people. Relative humidities should be maintained above 25%. The higher the desired interior relative humidity, the higher the thermal resistance (R-value) necessary to control relative humidities adjacent to interior surfaces.

Mold Growth in Cooling Climates

Interior mold growth also occurs in cooling climates, because interior surfaces are typically cold from air conditioning, while interior moisture levels may be too high. When exterior hot air is cooled, its relative humidity increases. If the exterior hot air is also humid, cooling it can easily raise its relative humidity above the 70% optimal for mold growth.

Cold spots are often created when cold (air conditioned) air is blown against interior gypsum board surfaces due to poor design, location, or performance of supply air diffusers. Although this cold air is typically dehumidified by the air conditioner, there are often high levels of airborne moisture within the room, which contact the cooled surface.

If exterior humid air comes in contact with the cavity side of cooled inte-



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Mold and mildew aren't always obvious. This extensive mold growth is only apparent when the vinyl wall covering is peeled back. Impermeable wall coverings such as this can often worsen a mold problem by trapping moisture between the interior finish and the gypsum board.

rior gypsum board, its relative humidity can rise above 70% and mold growth can occur in the cavity. Impermeable wall coverings such as vinyl wallpaper can make the problem worse by trapping moisture between the interior finish and the gypsum board.

One of the most practical solutions in controlling mold and other biological growth in cooling climates is to prevent hot, humid exterior air from contacting the interior cold (air conditioned) gypsum board surfaces. This is most commonly done by maintaining the conditioned space at a positive air pressure relative to the exterior and installing an exterior vapor diffusion retarder. Airtight construction helps to pressurize building assemblies.

Interior moisture levels within conditioned spaces in cooling climates should be limited to 60% relative humidity at 75°F. This can be accomplished by dehumidification and source control, discussed later in this article.

Carpets located on cold surfaces such as concrete slabs are particularly sensitive to dust mite growth. Like mold, dust mites grow at about 70% relative humidity. Carpets on cold surfaces should be avoided, or these surface temperatures should be raised by installing insulation between the slab and the carpet. Slab edge insulation, though it is not cost-effective for energy savings in hot climates, should be installed in new construction for health reasons alone.

Diagnostic Tests and Tools

Every diagnostician should have a *thermometer* to measure temperature and some device that can measure relative humidity (a *sling hygrometer* or *digital moisture meter*). Beyond these simple tools, the following devices can also be useful.

Smoke Pencil

A smoke pencil is typically a handheld device that emits a chemical smoke when squeezed. Smoke pencils can be used to quickly and accurately determine the air pressure relationship between two spaces—for example, between the indoors and outdoors or between a bedroom and the space inside the wall separating the bedroom from the hallway. If smoke gets sucked into a crack or opening, the smoke pencil is located in a region of positive air pressure with respect to the crack.

Manometer

A digital manometer measures the air pressure relationship between two spaces, providing the magnitude of the pressure difference (if one exists) rather than just the direction.

Blower Door and Duct Tester

A blower door is a calibrated fan (or blower) in a portable expanding frame, typically installed in an exterior door opening. Blower doors are used to determine the leakiness of a building envelope. A blower door measures the total air flow rate through all of the openings in a house by extracting air from (or blowing it into) the house and measuring the air pressure drop across the house. From this information, the area of all the house cracks and openings can be calculated. A duct tester is a smaller fan and is used to measure the leakiness of ductwork.

A blower door can also be used to determine how much air must be added to change a building from operating under a negative air pressure to operating under a positive air pressure, or vice versa.

Spray Rack

A spray rack can be used in conjunction with a blower door to test the rain resistance of a particular building assembly. The blower door establishes an air pressure differential across a window or a wall to simulate the effect of wind acting on the outside of a building, while the spray rack uniformly deposits a fine mist of water across a large expanse of building surface to simulate the effect of rain. A garden hose with a mist attachment and a talented "hoser" can accomplish the same thing.

Wood Moisture Meter

A wood moisture meter can be used to determine the moisture content of wood. Wet or dry determinations can be made by visual observation and touch. Quantitative assessments are possible with a moisture meter.

Testing for Mold

If you can see it or smell it, you have mold. There is absolutely no point in trying to test for it. The human nose is far more accurate than all the testing money can buy, unless you want to identify the specific type of mold you are smelling or seeing.

Condensation

When relative humidity reaches 100%, moisture can condense. The temperature at which air reaches 100% relative humidity is called the *dew point* temperature (see Figure 1). Moisture will condense on a surface whose temperature is below the dew point temperature of the air next to it. For air at a given absolute humidity, the colder the surface, the higher the relative humidity next to that surface. So the coldest surface in a room is the place where condensation will probably occur first (called the *first condensing surface*).

Condensation can provide an environment for the growth of mold, mildew, and other biological pathogens. It can also cause deterioration in building materials. The same strategies used to control mold and mildew growth also control condensation on surfaces: increase surface temperatures and reduce moisture levels near surfaces.

Controlling Moisture Problems

Increasing Surface Temperatures

A classic example of a moisture problem in a heating climate can occur in an exposed closet on an exterior wall. The closet has a higher ratio of surface area to volume compared to other conditioned spaces, resulting in a greater heat loss. It is also more exposed to the wind. If it is poorly insulated and unheated, the closet is likely to be significantly colder than the adjacent bedroom.

Even when there is a small amount of moisture in the conditioned space, a significantly lower closet temperature can cause the relative humidity to rise enough to foster mold and mildew growth or even condensation.

The temperature of the closet can be raised by increasing the heat flow to the closet or decreasing the heat flow to the outside. Heat flow to the closet can be increased by leaving the closet door open; installing louvered closet doors; leaving a light on inside (even a few-watt night-light installed low on the wall makes a big difference; an overhead light is less effective); or installing a heat register (although this last is an inefficient use of heating energy and should be used only as a last resort).

Heat flow out of the closet can be reduced by insulating the exterior closet walls and installing a tight building paper or tight sheathing on the exterior of the wall to control windwashing through the insulation.

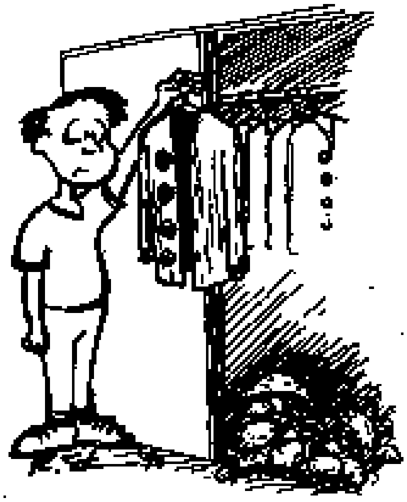
Reducing Air Moisture Levels

A similar closet with an only slightly lower temperature than the bedroom may also have problems if a relatively high amount of moisture is present in the conditioned space.

In this case the strategy should be to reduce the vapor pressure in the closet and house, which can be done by using one of three methods: source control, dilution, or dehumidification. Source control, the most energy-efficient of these methods, involves limiting the amount of interior airborne moisture that enters the space. Common strategies include directly venting bathrooms, clothes dryers, and kitchen stoves to the exterior; constructing dry basements and crawlspaces; venting space heaters directly to the exterior; removing unvented kerosene or gas space heaters; and storing firewood outdoors rather than indoors (storage of one cord of green firewood indoors can produce the same amount of moisture as that produced by a family of four through respiration).

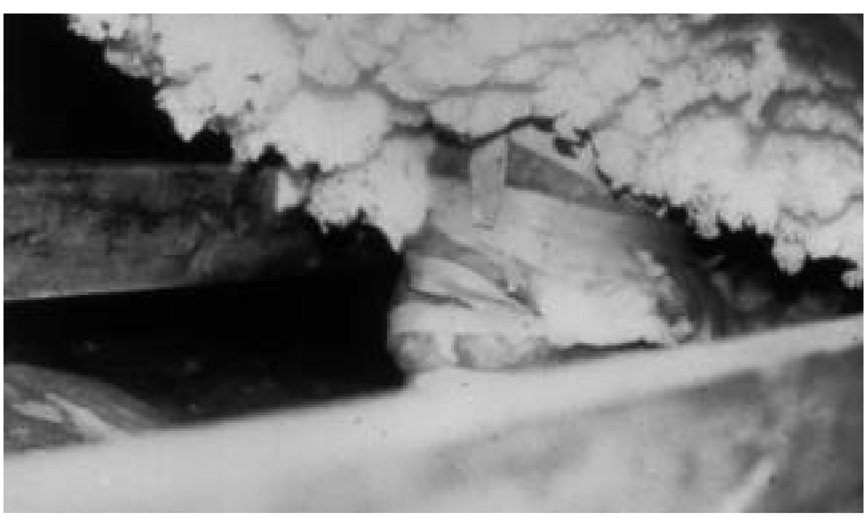
An exhaust fan that operates by timer or dehumidistat control can provide dilution—the exchange of interior moisture-laden air with exterior dry air. Dilution by air change is possible only where the exterior air is drier than the interior air. In cooling climates or during cooling periods, this is often not the case.

Dehumidification removes moisture from a space, usually by cooling warm, moisture-laden air to reduce its ability to hold moisture, thereby forcing the moisture to condense. Air conditioners provide dehumidification by condensing moisture on the cooling coils, although oversizing reduces their effectiveness at this task (see "Bigger Is Not Better—Sizing Air Conditioners Properly," *HE* May/June '95, p. 19). There are also stand-alone dehumidifiers, which heat the air, since their condensers reject heat into the living space.



RICK STOVER

Closets along exterior walls are especially vulnerable to condensation!



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A condensation and freezing nightmare, ice hangs from the underside of the roof deck in this attic.

Identifying Common Problems

Moisture problems related to low surface temperatures may not be eliminated by increasing ventilation, and those related to high vapor pressures may not be eliminated by increasing surface temperatures. Understanding which factor dominates—low surface temperature or high vapor pressure—will help in choosing the best strategy.

For example, consider an old, leaky, poorly insulated home in a heating climate, which is suffering from mold and mildew. Since the house is leaky, it has a very high natural air change that dilutes interior airborne moisture levels and therefore maintains a very low interior vapor pressure. Providing mechanical ventilation in this house by installing a fan probably will not control interior mold and mildew, since the interior moisture levels are already low. A better strategy would be to increase surface temperatures by insulating the exterior walls, thereby reducing surface relative humidities. Other common examples of surface moisture problems follow.

Setback Thermostats

Setback thermostats help reduce energy consumption in heating climates. House temperatures are dropped when occupants are sleeping and raised to normal comfort levels when occupants are awake. However, when temperatures are reduced at night, relative humidity also increases, which can cause mold and mildew to grow on cool surfaces.

Heating climate mold and mildew can often be controlled by increasing interior temperatures during heating periods. Unfortunately, this means increasing energy consumption. An appropriate balance must be achieved between reducing energy consumption and avoiding surface moisture problems. Insulating exterior surfaces lessens the need to maintain high indoor temperatures.

Closed-Off Rooms

Many people close off unused bedrooms or other rooms during heating periods to lower heating bills. Since air and room temperatures are reduced, these rooms can have high levels of relative humidity, leading to mold and mildew growth. Again, the benefits of energy conservation should be weighed against the possibilities of damage from mold and mildew. If rooms are closed off, control of interior moisture levels may be necessary.

Exterior Corners

In heating climates, exterior corners are common locations for mold growth or condensation, for several reasons.

Obstructions such as furniture can prevent heat from reaching corner surfaces. Sometimes rearranging furniture to remove air-flow obstructions from a corner is all that is needed. Homes with forced air heating systems or ceiling fans have less mold and mildew growth than homes with low levels of air movement.

Wind typically moves faster at corners, increasing heat loss at corner surfaces. When wind enters corner assemblies and blows through or short-circuits the thermal insulation (windwashing), the interior surface can be cooled significantly.

Corners have a greater exterior surface area per unit of interior surface area than other wall surfaces, and corner framing practices often result in more wood than insulation. Recent framing innovations such as two-stud corners reduce heat loss at corners as well as the amount of framing material required. Insulating sheathing also helps.

Exterior Wall-Roof Intersections

Cool interior surfaces in heating climates can also result where exterior walls intersect roofs. Ceiling thermal insulation is often reduced in thickness at building perimeters, causing cold spots, which in turn lead to higher surface relative humidities. The use of specialized roof framing details, such as raised trusses, can allow more insulation to be installed at building perimeters. However, the higher roof framing makes it easier for air entering at soffit vents to short-circuit the thermal insulation. Therefore, wherever soffit ventilation is used, wind baffles are also necessary to control windwashing.

Air Conditioned Spaces

In warmer climates, many problems are caused by wall air conditioners or supply registers that cool a particular spot on an exterior wall. If exterior humid air enters the wall cavity as a result of an air pressure difference and comes in contact with the cooled surface of the gypsum board or plaster, mold can grow in the wall cavity. Impermeable wall coverings, such as vinyl wallpaper, can exacerbate the problem by trapping moisture between the interior finish and the gypsum board.

Several solutions are possible: (1) preventing the hot, humid exterior air from contacting the cold gypsum board by controlling air pressure differences and air leakage openings; (2) eliminating the cold spots and elevating the temperature of the surface by relocating ducts and diffusers; (3) increasing indoor surface temperatures by preventing the overcooling of rooms; or (4) increasing the permeability (breathability) of interior finish materials in hot, humid climates.

Thermal Bridges

Thermal bridges are regions of relatively high conducted heat flow in a building envelope. An example of a thermal bridge is the wood stud of a typical exterior frame wall where insulation is installed between studs in the wall cavity. The wood stud has a greater conductivity to heat flow than the insulation and therefore provides an easy path for heat to bridge the wall. The result is a cold spot at the interior face of the gypsum board where it is in contact with the stud. Another example of a thermal bridge is a gap that occurs in insulation due to poor installation practices.

Concealed Condensation

Thermal insulation in wall cavities increases interior surface temperatures in heating climates, reducing the likelihood of interior surface mold, mildew, and condensation. However, it also reduces the temperature of the outer portions of the wall assembly, which may lead to concealed condensation within the wall cavities (see Figure 2). This can be controlled by reducing the entry of moisture into the wall cavities or by raising the temperature of the interior surface (back side) of the exterior sheathing. Installing insulation on the exterior side of this surface can raise its temperature.

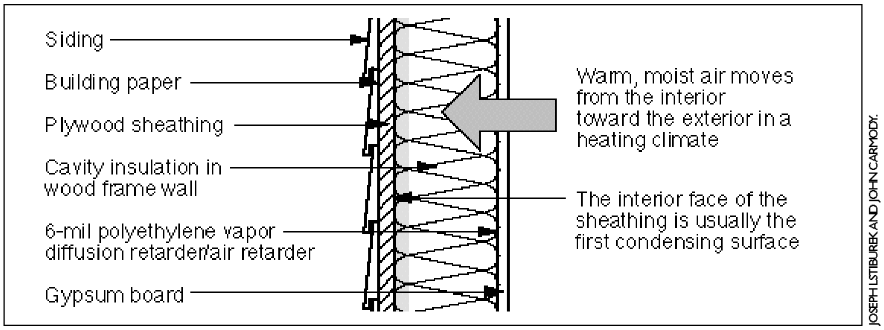

Figure 2: The inside face of the sheathing is usually the first condensing surface in a heating-climate wall assembly.

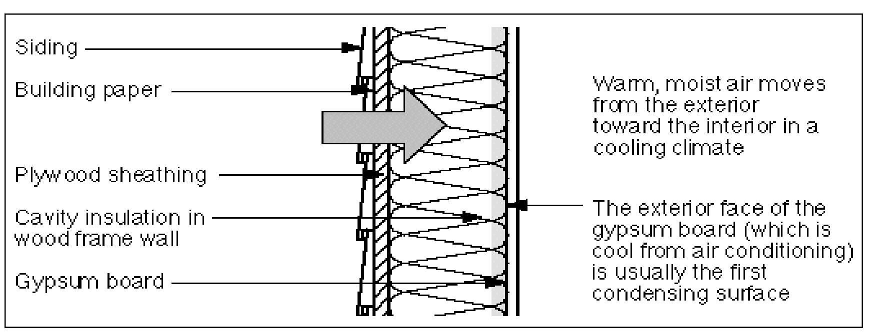

Figure 3: The exterior face of the gypsum board is usually the first condensing surface in a cooling-climate wall assembly.

A roof deck and rafters darkened by rot show that this attic has severe moisture problems.

In a cooling climate with air conditioning, condensation is most likely to occur on the back side of the interior gypsum board or other finish material (see Figure 3). Warm, moist exterior air condenses as it comes in contact with the cool interior finish material. The temperature of this surface can be raised by installing impermeable insulating sheathing to the interior of the wall framing, between the framing and the interior gypsum board.

Windows

Windows are typically the coldest surfaces in a room, and are therefore where moisture is most likely to condense. Condensation may occur either because the interior airborne moisture level is rising, or because the exterior air temperature (and the temperature of the interior surface of the glass) is dropping, so that the relative humidity adjacent to the window rises to 100%.

When condensation occurs, the window is acting as a dehumidifier for the room (unless the condensed moisture reevaporates). The more moisture generated in or entering a space, the more moisture will be deposited on the condensing surface. Vapor pressures will rise only when the rate of moisture generation or entry in a space exceeds the rate of moisture removal by the condensing surface. However, when moisture generation or entry stops or is reduced, equilibrium will occur at a vapor pressure limited by the temperature of the first condensing surface in the room. In effect, the temperature of this surface controls the behavior of moisture in the room.

Historically, to control condensation, window surface temperatures were raised by the use of storm windows; the replacement of single-glazed windows with double-glazed, and later triple-glazed, windows; and the use of selective-surface (low-e) and inert gas-filled windows. The colder the climate, the greater the required thermal resistance of window surfaces (see "Selecting Windows for Energy Efficiency," *HE* July/Aug '95, p. 11).

In a sense, the advent of higher-performance windows has led to greater incidence of moisture problems in heating climates because the houses can now be "operated" at higher interior vapor pressures without visible surface condensation on the windows. In older buildings, the thermally poor glazing systems limited interior moisture levels by condensing moisture. The visible condensation often alerted occupants to the need for ventilation to flush out interior moisture. In effect, the windows acted as an early warning system to identify excessive moisture and other indoor air pollutants.

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