6 Air Leakage and Water Vapor Control

In addition to thermal insulation and the thermal mass of the building envelope, discussed in Chapter 5, another factor that affects the heat loss or gain of a building is air leakage. The leakage of conditioned (heated or cooled) air through cracks and unsealed joints in the building envelope and its replacement by the outside air—referred to as exfiltration and infiltration respectively—is unwanted ventilation of the building.

This increases the energy consumption of a building since the infiltrating air must be heated or cooled to the required inside air temperature. In extremely hot or cold climates where the temperature difference between the inside and the outside air is large, air leakage can add significantly to energy consumption. In this chapter, we will study materials and construction practices employed to control air leakage in buildings.

Air always contains some water vapor. In fact, air is not only a mixture of nitrogen, oxygen and carbon dioxide but also of water vapor. The leakage of air through the building envelope is, therefore, always accompanied by water vapor.

Air leakage is not the only means by which water vapor moves in and out of the building envelope. Water vapor also moves through the envelope independent of air movement. This is due to the vapor pressure difference between the inside and the outside air. Therefore, we will examine the magnitude of the vapor pressure difference that commonly occurs in buildings.

The presence of water vapor in buildings or its passage through the envelope is of little or no significance in building construction. However, water vapor has the potential to convert into (liquid) water, a phenomenon known as *condensation*. Water causes a great deal of damage to construction assemblies. The causes of condensation and the strategies employed to control it are also discussed here.

6.1 AIR LEAKAGE FUNDAMENTALS

It is estimated that air leakage accounts for 20 to 40% of the heat loss in buildings in Canada and North America. Two factors that directly affect air leakage in a building are:

- Leakage area in the envelope
- Air pressure difference between the inside and outside air

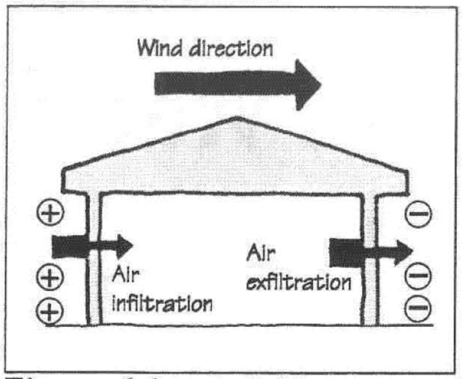


Figure 6.1 *Air infiltration and exfiltration through a building caused by the pressure differential created by wind.*

The greater the leakage area or the pressure difference, the greater the rate of air leakage. The leakage area is a measure of the relative tightness of the envelope. It is the area of cracks, tears, holes and openings in the envelope and is a function of the type of construction, design and workmanship. The leakage sites in the envelope usually occur at the joints of various components such as exterior doors, windows, skylights, fireplaces, electrical outlets, plumbing and duct penetrations.

The pressure difference between the inside and the outside air depends on wind speed and direction. Since wind speed increases with height above the ground, the pressure differences at the upper floors of a building are greater than those at the lower floors, causing greater air leakage at upper floors. We observed in Section 3.4 that the windward face of a building is under positive pressure and the other faces, under suction (negative pressure). Therefore, air infiltrates through the windward face and exfiltrates through the nonwindward faces of the building, Figure 6.1.

Another factor that affects the pressure difference is the temperature difference between inside and outside air. Since the density of air increases with decreasing temperature, cool (more dense) air exerts greater pressure than warm (less dense) air. During the cooling season, (cool) inside air has greater pressure than (warm) outside air. This leads to continuous exfiltration of cool air and infiltration of warm outside air through the envelope, Figure 6.2(a). This phenomenon is accentuated by the interior pressurization caused by the fans of the air conditioning system. During the heating season, cool outside air is at greater pressure than the warm inside air, and hence the air flow direction is reversed, Figure 6.2(b).

Since the inside-outside pressure difference is primarily a function of the outside climate (wind speed and air temperature), there is little that can be done to control it. Thus, the only means of reducing air leakage in a building is to reduce the leakage area in the building envelope.

This requires sealing all joints between fixed building components (e.g., door jamb and wall) and between fixed-operable components (e.g., door jamb and door) or operable components. Sealants between fixed components are typically nonhardening synthetic compounds, see Chapter 9. Resilient, compressible materials, called *weatherstripping* are used to seal gaps between fixed-operable or operable components.

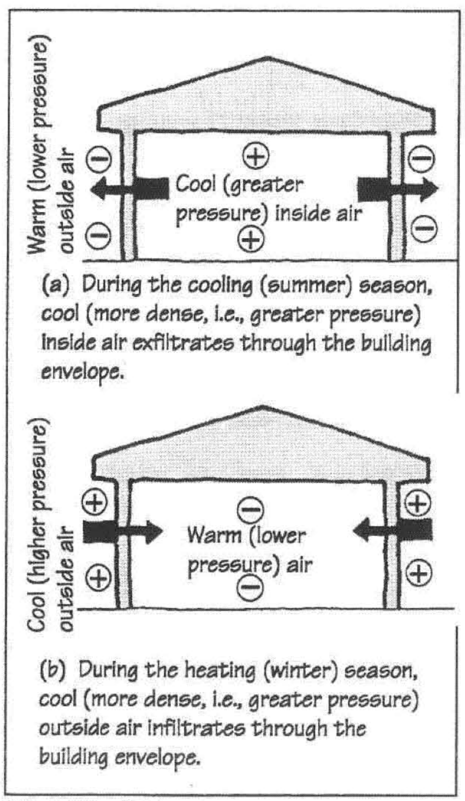


Figure 6.2 *Air infiltration and exfiltration through a building due temperature differences between inside and outside air.*

Air Leakage Rate

Since a great deal of air leakage in buildings occurs through doors, windows and glass curtain walls, limits are placed on their maximum permissible air leakage rates. The air leakage rate for windows (and curtain walls) is specified in terms of air leakage from a unit area of the window when the window is subjected to a standard air pressure difference (see Section 29.3 and 30.5).

6.2 AIR RETARDER

1 mil = one thousandth of an inch
= 0.001 inch

Air leakage is a particularly serious concern in wood or light-gauge steel (steel stud) frame buildings because their envelope is inherently more leaky than other types of construction such as concrete or masonry. Additionally, as stated in Section 5.11, nearly 60% of all energy consumed in buildings in the United States is in residential occupancies.

Most of these buildings are constructed of wood frame or light-gauge steel frame. Therefore, a small percentage decrease in energy consumption in residential buildings translates into large energy savings at the national level. The leakage sites in a typical wood frame or light-gauge steel frame building are shown in Figure 6.3.

A commonly-used technique of reducing air leakage in wood or light-gauge steel construction is to wrap the exterior walls with a continuous *air retarder*, Figure 6.4. Air retarders are available in rolls of up to one story high so that they can wrap the walls with very few joints.

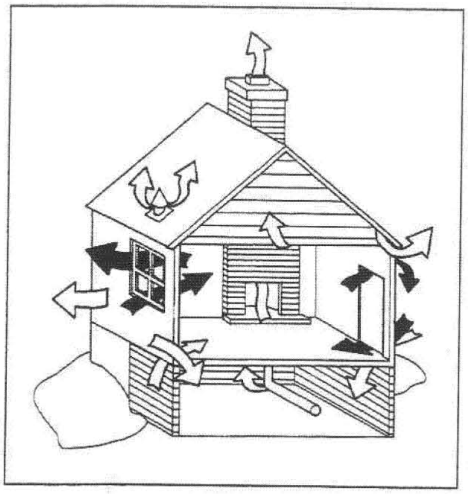


Figure 6.3 *Typical leakage sites in a wood frame or light-gauge steel frame building.*

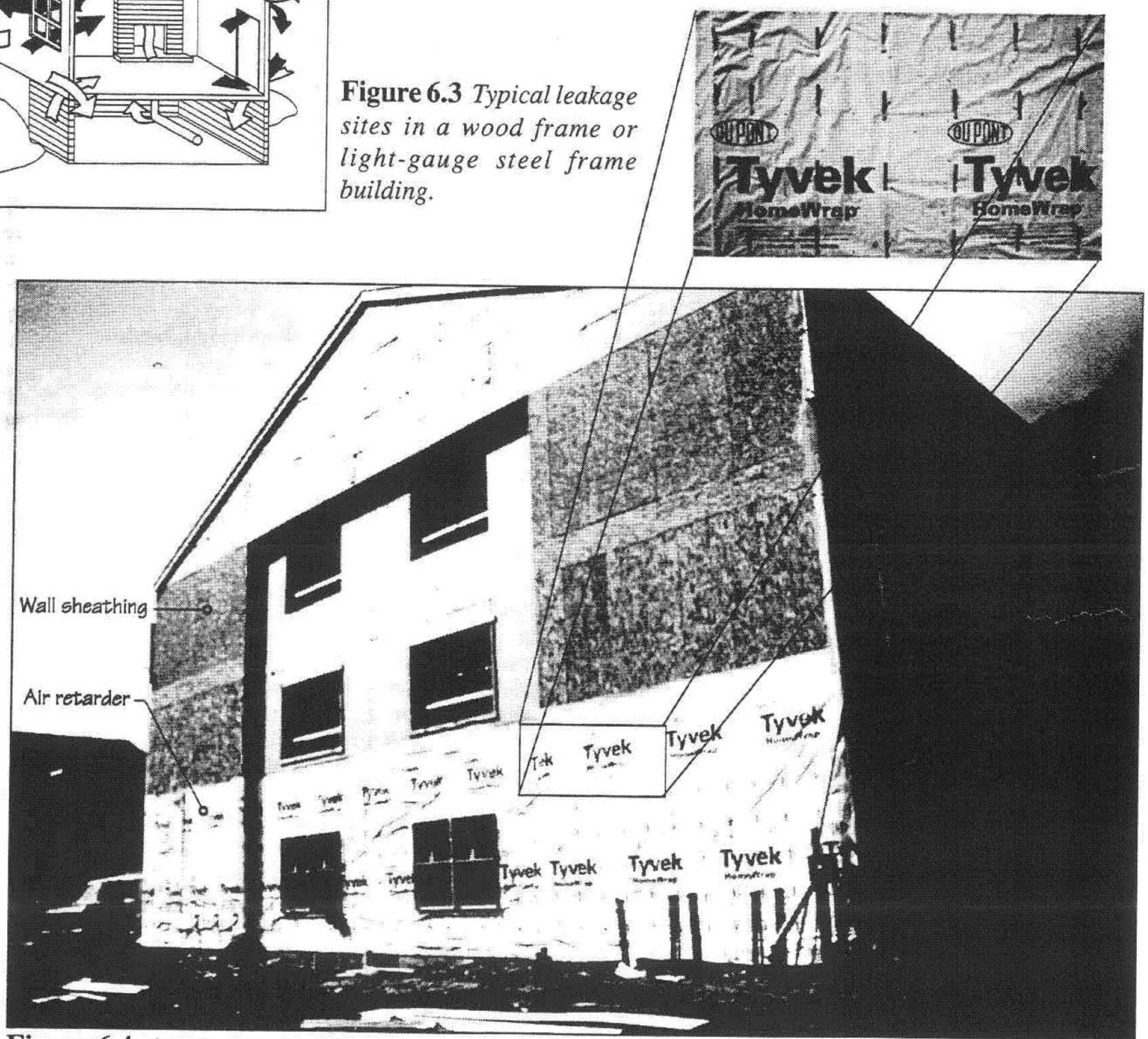


Figure 6.4 *An air retarder wrapped over the exterior wall sheathing of a 3-story wood frame apartment building.*

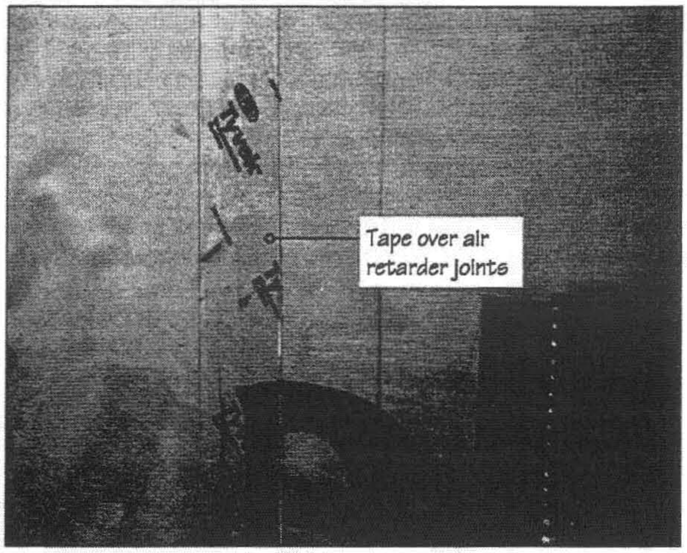


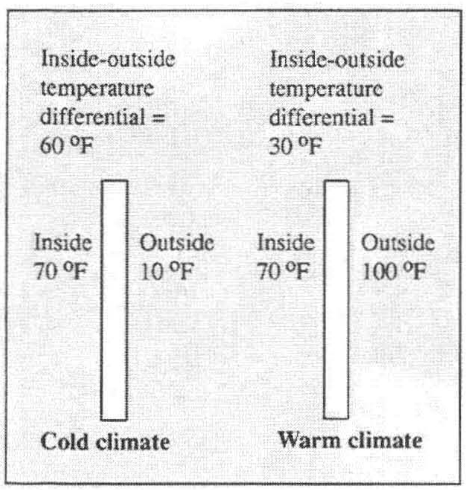
Figure 6.5 *Joints in air retarder are taped with a self-adhering tape supplied by the air retarder manufacturer.*

An air retarder is typically made of a 5 to 10 mil thick plastic sheet with micropores so that it allows very little air to pass through but has a high degree of permeability to water vapor. Depending on the manufacturer, it is made from plastic fibers which are either woven or spunbonded into a sheet. One manufacturer makes an air retarder out of a microperforated plastic sheet. (See Section 6.7 for the reasons why an air retarder must be perforated).

An air retarder is usually wrapped over the exterior wall sheathing and secured to the sheathing with staples. Joints in the air retarder are lapped and typically sealed with a self adhesive tape, Figure 6.5.

The air retarder not only reduces heat gain or loss by reducing air leakage but also reduces air movement in the wall cavity in the vicinity of the insulation, thereby increasing the effectiveness of the insulation. Low density, loose-fill and fibrous insulations, such as fiberglass or rock wool, are more susceptible to increased convective heat transfer from infiltration as compared to closed-cell foam insulations such as extruded polystyrene or polyisocyanurate foam insulations.

Note that the term "air barrie*r*" is sometimes used in the industry for air retarder, which is incorrect because most commercially available air barriers retard the flow of air through them, rather than completely stopping it.



Effectiveness of Air Retarders and Exterior Climate

The use of air retarders is standard practice in residential wood frame or light-gauge steel frame construction in climates where the winters are long and severe. This is due to the relatively large difference between the inside and the outside air temperatures in cold climates, and hence a greater loss of energy by leakage. For example, the difference between the inside and outside air temperatures may be 60 °F or more on a typical winter day in a cold climate (70 °F inside air temperature and 10 °F outside air temperature).

The corresponding difference in air temperatures in a warm climate is much smaller. For example, the difference in air temperatures during the summer in a hot climate seldom exceeds 30 °F (70 °F inside air temperature and 100 °F outside air temperature). Therefore, in warm or mild climates, the use of air retarders is relatively less critical. However, if the building is located on a windy site, e.g., close to sea front, lake or on a hill top, the use of an air retarder is advisable.

Air retarders also function to prevent the passage of exterior water through the wall. Therefore, they are also referred to as air-weather barriers. Their microperforations, while being permeable to water vapor, do not allow air or (bulk) water to pass through.

Sealing Exterior Window and Door Perimeter

Despite the use of the air retarder, the joints between the wall and the window (or door) perimeter can leak air (see dark arrows in Figure 6.3). Depending on the type of detail around the jamb, these joints can either be sealed by an elastomeric sealant (see Chapter 9) or a self adhering tape. The self adhering tape works particularly well where the window has a nailing flange so that the tape covers the flange and the wall, Figure 6.6.

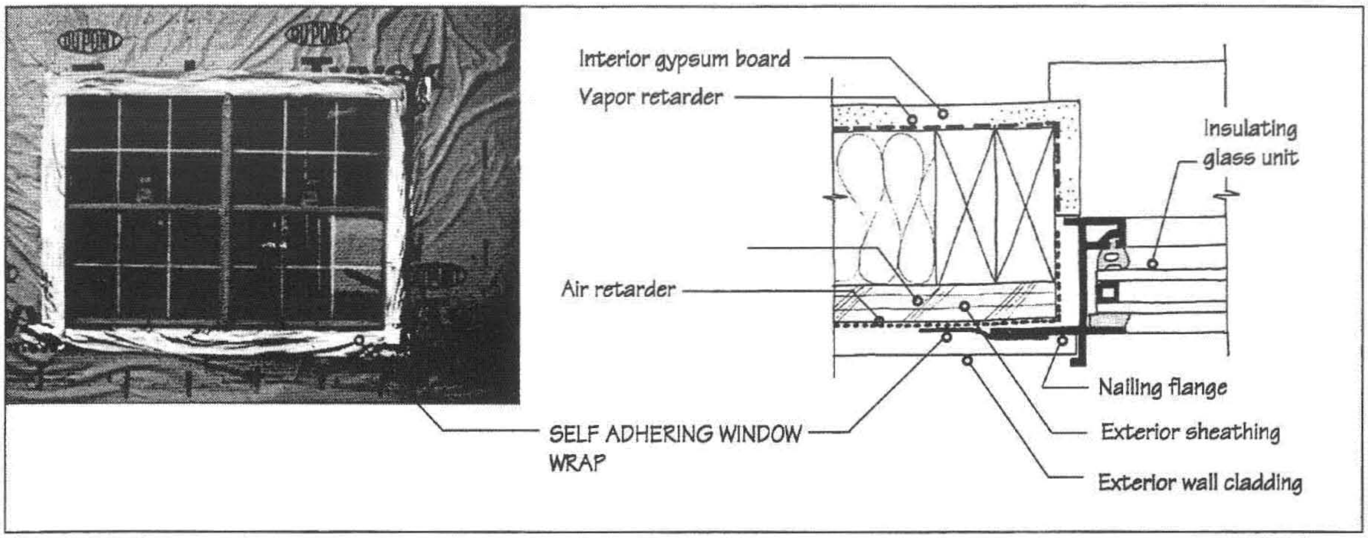


Figure 6.6 *A proprietary self-adhering tape on the outside of a window (referred to as window wrap) to reduce air leakage through the joint between the window and the wall. Photo taken before the application of exterior cladding.*

Air Leakage in Masonry and Concrete Walls

In a well-constructed masonry building, air leakage is relatively small. However, if the mortar joints in the walls are not completely filled, leakage of air through joints may result, particularly through vertical mortar joints. A coat of cold-applied asphalt emulsion is commonly used in a wall assembly with a masonry back-up wall. This coat provides weather (air and water) resistance to the back-up wall (see Figure 26.23, Chapter 26).

Air Leakage and Indoor Air Quality

The quality of indoor air in buildings has come under much scrutiny in the last few years due to complaints from the occupants—of headache, eye and nasal irritation, fatigue, and unacceptable odors. Studies conducted by the Environmental Protection Agency (EPA) in the United States have concluded that the indoor air may become excessively polluted, creating what has come to be known as "sick building syndrome".

In addition to dust, pollen and micro-organisms (fungi and mold), contaminants routinely added to indoor air are carbon dioxide, generated from combustion and human metabolism, and carbon monoxide from combustion and smoking. Several volatile organic compounds (VOC) are present due to the use of aerosols, cleaning chemicals and disinfectants (see also Chapter 10).

Formaldehyde, a colorless gas, is a major source of indoor air pollution. Although a VOC, formaldehyde is generally listed separately because of its widespread use in building products in the form of urea formaldehyde. Urea formaldehyde is an adhesive used in wood veneer and wood fiber products such as plywood, particleboard, fiberboard, etc. Other sources of formaldehyde are carpet pads and underlayments, ceiling tiles, upholstery and wall coverings.

Another dangerous source of indoor air pollution is radon, a colorless, odorless, radioactive gas present in some soils which may leak into the interior through cracks in the floors. Radon is produced by the decay of radium, a substance that occurs in most soils. However, it is dangerous only when its concentration is high. Radon gas particles affect human lungs in the same way as smoking, i.e., it increases the risk for lung cancer.

If buildings are adequately ventilated, the above pollutants are generally of little concern. However, due to the relative airtightness of the envelope (doors, windows, walls, etc., and the use of air retarders) in modern energy-efficient houses, concern about indoor air quality in buildings has grown. This is particularly significant as the population of western countries ages, with a greater number of older people spending less time in fresh outdoor air.

While an excessively tight envelope may save energy, it creates undesirable effects just mentioned. In order to provide the necessary amount of fresh air with a minimum impact on energy consumption, a system of controlled mechanical ventilation may be used. In this system, stale air is exhausted from one vent in the building and fresh air drawn through another vent. The heat from the stale air is used to warm the fresh air through a device called the *air-to-air heat exchanger*.

6.3 WATER VAPOR IN AIR

It is an observable fact that all air contains some water vapor. If water in a container is left exposed to air, the water disappears after a few days. This disappearance of water, referred to as *evaporation*, is in fact the conversion of water into water vapor. This property of converting water to water vapor and mixing with the surrounding air allows wet clothes and other materials to dry.

Water vapor is like steam existing at temperatures below the boiling point of water. It mixes readily with air and is invisible. In fact, air is not only a mixture of nitrogen, oxygen and carbon dioxide but also of water vapor. Absolutely dry air, i.e., air without water vapor is rare—only produced in laboratories for special purposes. Water vapor content in air is usually higher in coastal areas than inland locations.

Like air, water vapor is a gas. Consequently, it exerts pressure on the surfaces of the enclosure containing it. However, although air and water vapor are thoroughly mixed together, the pressure exerted by water vapor is independent[1] of that exerted by air. In other words, air pressure and vapor pressure do not add up but act separately.

Vapor pressure is directly related to the amount of water vapor present in air. The air cannot contain an unlimited amount of water vapor. When the air contains the maximum amount of water vapor it can possibly hold, it is referred to as *saturated air*, and the corresponding vapor pressure is referred to as the *saturation vapor pressure*.

The amount of water (in the form of water vapor) in saturated air increases with air temperature, Table 6.1. For instance, the amount of water in saturated air at 0 °F is nearly 5.5 grains per lb of dry air. At 20 °F, the amount of water is approximately 15.0 grains per lb of dry air; at 40 °F, the corresponding amount of water is 36.5 grains; at 60 °F, it is 77.5 grains, and so on.

Because the vapor pressure is directly related to the amount of water in air, the saturation vapor pressure also increases with air temperature, as shown in Table 6.1.

[1] Independence of pressures exerted by two gases, which are mixed together is as per *Dalton's Law of Partial Pressures*.

Table 6.1 Saturation Water Vapor Content and Saturation Vapor Pressure as Function of Air Temperature

1 lb of water = 7,000 grains of water

Temperature (oF)	Saturation vapor content (grains/lb of dry air)	Saturation vapor pressure (psf)
-20	2.0	1.0
-10	3.0	1.5
0	5.5	2.5
10	9.0	4.5
20	15.0	7.5
30	24.0	11.5
40	36.5	17.5
50	53.5	25.5
60	77.5	37.0
70	110.0	52.5
80	155.5	73.0
90	217.5	100.5
100	301.0	137.0
110	414.0	184.0

Relative Humidity of Air

The occurrence of saturated air is relatively uncommon. Outside air is saturated with water vapor only during or immediately after a rain shower. Inside air is seldom saturated. In other words, the inside air at a given temperature contains less water vapor than the saturated air (at that temperature).

The amount of water vapor in air is usually not given in terms of its "absolute" value, but as a "relative" amount of water vapor, referred to as the *relative humidity* (RH) of air. The relative humidity of air is expressed in percentage form by the following relationship.

$$RH = \frac{\text{Weight of water (as vapor) in air}}{\text{Weight of water (as vapor) in saturated air}} \times 100 \qquad (1)$$

Because the amount of water vapor in air and the vapor pressure of air are directly related, the relative humidity is also defined by the ratios of vapor pressures:

$$RH = \frac{\text{Vapor pressure of air}}{\text{Vapor pressure of saturated air}} \times 100 \qquad (2)$$

From Equation (1), we see that saturated air has a RH = 100%. Similarly, a 45% RH means that the air contains 45% of the amount of water present in saturated air. More specifically, 1 lb of air at 45% RH and at 70 ^{0}F contains (0.45)110 = 50 grains of water as water vapor. From Equation (2), this mass of air will exert (0.45)52.5 = 23.6 psf of vapor pressure.

Determining Vapor Pressure in Air

Example
Calculate the vapor pressure in air whose temperature is 70 ^{o}F and relative hunidity (RH) = 45%.

Solution
From Table 6.1, the vapor pressure of saturated air at 70 ^{o}F = 52.5 psf. Because RH = 45%, the vapor pressure of air from Equation (2) is:

$$\left(\frac{45}{100}\right) 52.5 = 23.6 \text{ psf}$$

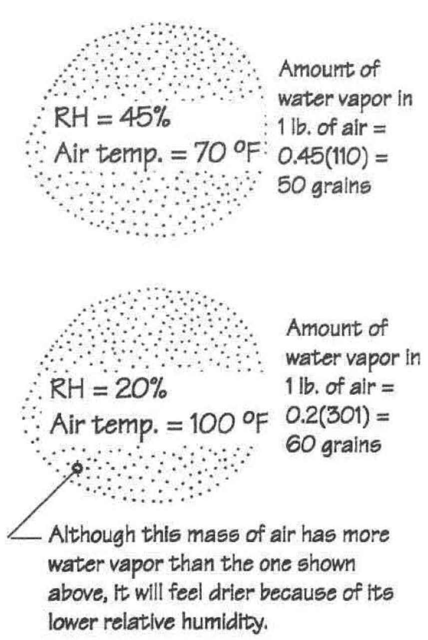


Figure 6.7 *Human sensation of dryness or dampness of air is a function of its relative humidity, not the absolute humidity value.*

> **Pressure Difference Between the Inside and the Outside Air Generated by Wind Speed of 90 mph**
>
> We observed in Section 3.5 (in box entitled: *Some Important Facts About Wind Loads*) that wind speed of V mph creates a pressure difference of nearly $[V/20]^2$ psf. Thus, if V = 90 mph, the pressure difference between the inside and outside air = $[90/20]^2 = 20.25$ psf.

The use of relative humidity of air (in place of absolute humidity) is based on the human sensation to water vapor content in air. Air feels drier or damper depending on its relative humidity, not on its absolute humidity. For example, air at 20% RH and 100 °F, which contains nearly 60 grains of water vapor, feels drier than air at 45% RH and 70 °F, which contains only 50 grains of water vapor, Figure 6.7.

Air with a low RH dries human skin, produces static electricity in carpeted interiors, causes respiratory health problems, and is generally uncomfortable. Air with a high RH feels moist, promotes fungal growth, and is also uncomfortable and unhealthy. The RH of mechanically conditioned air in offices is generally kept at about 45%.

Water Vapor Can Move Through Assemblies More Easily Than Air

Building assemblies are generally more vapor permeable than air permeable. This means that water vapor can pass through walls and roofs with greater ease than air. The reason is that the vapor pressure difference between the inside and the outside is generally much higher than the corresponding air pressure difference, as explained below.

In modern buildings, mechanical systems are designed to keep the inside air is kept at constant temperature and relative humidity throughout the year—nearly 70 °F air temperature and 45 % RH. As determined previously, the vapor pressure of this air is 23.6 psf. The outside vapor pressure changes continuously depending on the time of the day and the weather.

Let us now estimate the inside-outside vapor pressure differential on a typical winter day in North America, when the outside air temperature is 10 °F, and the relative humidity = 80%. The vapor pressure of this air = 0.8(4.5) = 3.6 psf. Therefore, the pressure differential between the inside and outside air = (23.6 - 3.6) = 20.0 psf, Figure 6.8(a).

This is a large pressure differential. For wind to create an inside-outside pressure differential of 20 psf, its speed must be nearly 90 mph—a hurricane wind speed. On a moderately windy day, with the wind blowing at 10 mph, the inside-outside air pressure differential is only about 0.25 psf, which is much smaller than the vapor pressure differential of 20 psf. It is because of the relatively greater inside-outside vapor pressure difference that vapor can move through building assemblies with much greater ease than air.

This fact also explains why air retarders are vapor permeable but not air permeable. Because of the high inside-outside vapor pressure differential in buildings, vapor can pass through the microperforations in an air retarder with ease. On the other hand, very little air passes through them because of the low air pressure differential. (In Section 6.7, we will see why it is necessary for air retarders to be perforated.)

Figure 6.8(b) shows the inside-outside vapor pressure difference that may occur during a typical summer day in North America. The corresponding vapor pressure difference (nearly 7 psf) is much smaller than that produced on a typical winter day (nearly 20 psf). This implies that vapor drive is much more forceful during the winters than the summers.

Figure 6.8 also shows the direction of vapor flow. During the winter, the vapor moves from the inside to the outside. The direction may reverse during the summer. Observe that, in general:

water vapor moves from the warm to the cold side of an assembly.

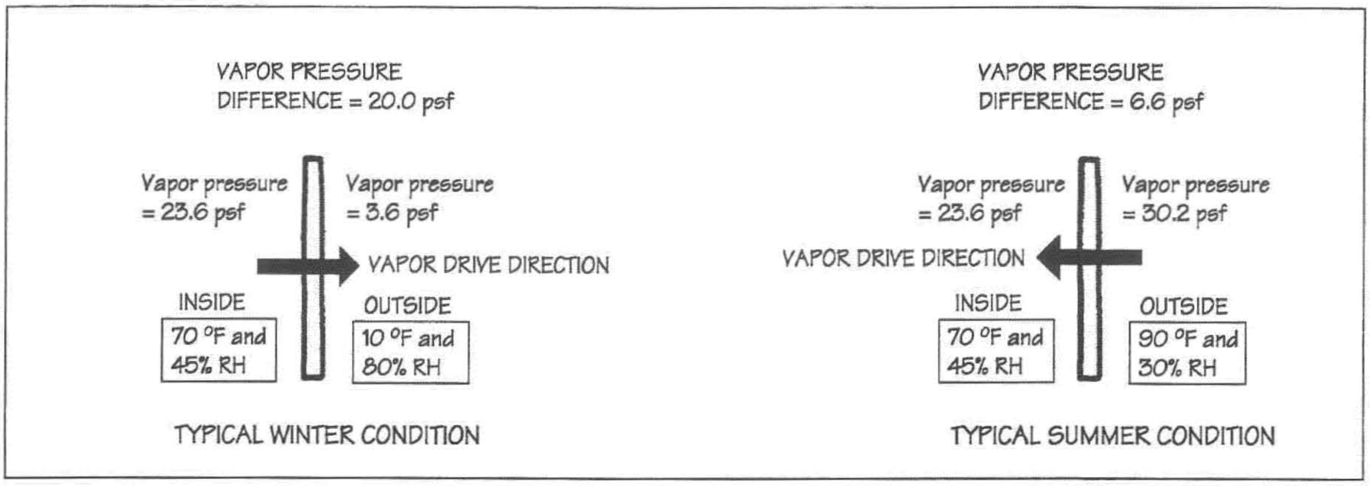


Figure 6.8 *Differences between indoor and outdoor vapor pressures during typical summer and winter conditions.*

6.4 CONDENSATION OF WATER VAPOR

Consider air at a certain temperature and relative humidity. If no moisture is added or subtracted from this air and its temperature is decreased, its relative humidity will increase. If the decrease in temperature is continued, a temperature will be reached when the RH of the air will become 100%. The temperature at which the air's RH becomes 100% (i.e., when the air becomes saturated) is called its *dew point temperature*, or simply the *dew point* of air. If the temperature of the air is decreased below the dew point, the water vapor in air will convert to (liquid) water—a phenomenon known as *condensation.*

Condensation occurs commonly in nature. The surface of a cup containing ice or cold water becomes wet because the temperature of the surface of the cup is below the dew point of warm and humid ambient air. As this air comes in contact with the surface of the cup, condensation of water vapor (present in air) occurs, which deposits on the surface of the cup. In heated building interiors, condensation is often observed during the winter on window glass. Such condensation is more pronounced in more humid interiors such as indoor swimming pools, aerobic centers, gymnasiums, gang showers, hotel kitchens, etc.

Both Dew Point and an Impermeable Surface Required for Condensation

Note that condensation occurs only surfaces through which water vapor cannot pass (permeate). In other words, because water vapor is mixed with air, it will continue to move freely until it encounters a surface that interrupts its movement. At that location, condenasation of vapor is possible if the temperature of the surface is less than or equal to the air's dew point. In the examples cited, the condensation occurs on the surface of the cup or window glass because they are impermeable to water vapor.

Interstitial and Surface Condensation

Apart from condensing on the surfaces of a window glass or any other cold surface, warm interior air can also condense inside a wall or roof assembly. If the water vapor can permeate into a wall or roof assembly, it will condense where the temperature of the assembly is at or below the dew point of the permeating vapor. The condensation of vapor inside an envelope assembly is referred to as *interstitial condensation*, as opposed to *surface condensation* that occurs on the envelope's surface, such as a window glass.

Although both surface and interstitial condensation are undesirable, the latter is more so. Interstitial condensation wets the assembly, which accelerates the corrosion of metals, the decay of wood, decreases the R-value of insulation, and generally reduces the strength of materials. Interstitial condensation may also contribute to the growth of fungi and mold—a major health hazard.

In other words, the control of condensation in buildings is important, particularly that of interstitial condensation. It is important to appreciate here that water vapor by itself is not damaging to a building assembly. It becomes damaging when it converts to water.

6.5 CONTROL OF CONDENSATION

Surface condensation can be prevented by simply increasing the R-value of the assembly. The reason why condensation occurs on a single glass sheet is because the R-value of glass is quite low (R = 1). If the single glass sheet is replaced by an insulating glass unit (say R = 3), condensation on the glass will not occur unless the interior air is very humid.

In general, if the R-value of the envelope is low, the dew point of air occurs at the surface of the envelope, leading to surface condensation. If the R-value of the envelope is raised, the dew point shifts to within the body of the envelope, Figure 6.9. This leads to interstitial condensation, which should be avoided. (See Appendix at the end of this chapter on how to locate the dew point in an envelope assembly).

Note that interstitial condensation became a concern only after the introduction of insulation in buildings. In older times, when the buildings were not insulated (low R-value), interstitial condensation did not occur because the dew point generally occurred on the interior surface, creating surface condensation.

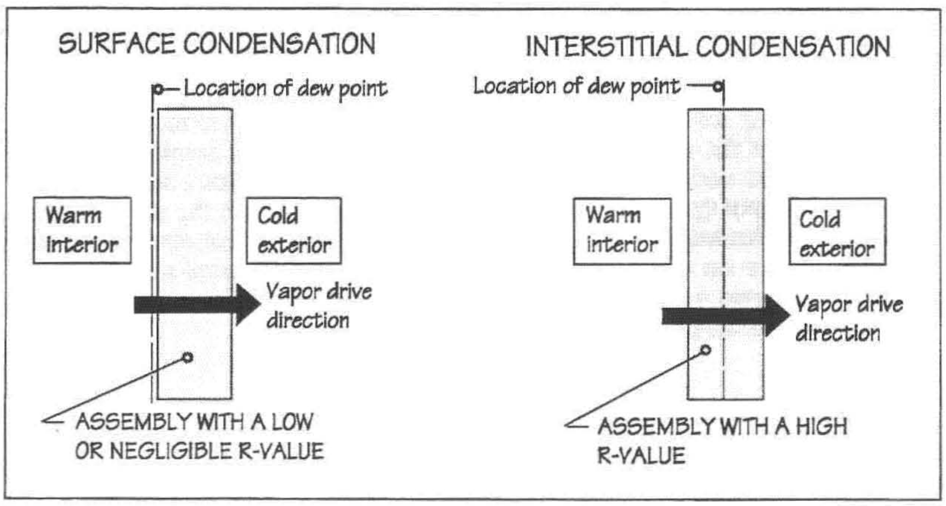


Figure 6.9 *Effect of R-value of the assembly on the location of dew point.*

Control of Interstitial Condensation—the Use of Vapor Retarder

As stated earlier, interstitial condensation occurs only if the water vapor is able to permeate into the assembly. Therefore, an obvious way to control interstitial condensation is to prevent the passage of water vapor from one side of the envelope to the other. The passage of water vapor through the envelope can take place by one or both of the following modes:

- Vapor movement due to leakage of air
- Water vapor diffusion

Because air and water vapor are thoroughly mixed, any leakage of air through the envelope is also accompanied by the leakage of water vapor. Since most leakage of air takes place at cracks, penetrations, and unsealed joints, sealing the envelope against air leakage prevents this mode of vapor flow.

The second mode of vapor flow takes place independently of the air flow. It occurs due to the vapor pressure differential between the inside and the outside air, and is referred to as *vapor diffusion*. Thus, vapor diffuses from a region of higher vapor pressure to that of a lower vapor pressure.

As shown in Figure 6.8, vapor flows from the inside to the outside during the winter. In summer, the direction of vapor flow may reverse (from outside to inside), particularly in warm coastal regions. However, for most of North America, the vapor drive from the inside to the outside is usually more critical. This is due to the generally higher inside-outside vapor pressure differential during the winters as compared with that during the summers (see Figure 6.8).

How can we prevent the diffusion of water vapor through the envelope and thereby prevent interstitial condensation? This is accomplished by the use of a vapor retarder. A vapor retarder is a material that is almost impermeable to water vapor. Although used, the term "vapor barrier" is not appropriate for the same reasons as the term "air barrier". Thus, a vapor retarder is a material whose vapor permeability is low.

6.6 MATERIALS USED AS VAPOR RETARDERS

The rate at which water vapor flows (diffuses) through a material is measured by its vapor permeability. The unit of vapor permeability is called the *permeance*, or simply the *perm*. A material with a higher perm value (or rating) is more vapor permeable. If the perm rating is zero, the material is vapor impermeable. Such a material is a perfect vapor retarder—a vapor barrier—provided it is free of holes, cracks, and unsealed joints.

Apart from being a property of the material, perm rating is also a function of the material's thickness. A larger thickness of the same material has a lower perm rating. That is why when the perm rating is given, the thickness of the component must be stated. The perm ratings of selected materials are given in Table 6.2. For instance, the perm rating of a 4-mil-thick polyethylene sheet is 0.08 (in the U.S. system of units); a 6-mil-thick polyethylene sheet's perm rating is 0.06.

For a material to qualify as a vapor retarder, its perm rating must be 1.0 perm (in the U.S. system of units) or less. However, for an effective vapor retarder, a much lower value—less than or equal to 0.1 perm—is recommended.

Glass and metals (even a thin metal foil, such as aluminum foil) have a zero perm rating. Roof membranes—built-up roof, modified bitumen, and single-ply membranes—are excellent vapor retarders. Plastics have low perm ratings, and are commonly used as vapor retarders. The most commonly used vapor retarder in lowrise residential structures is 4-mil thick polyethylene sheet.

Units of Permeance (Perm Rating)

U.S. System of Units
1 perm = One grain of water vapor passing through 1 ft^2 of a material in one hour under a vapor pressure difference of 1 in. of mercury.

SI System of Units
1 perm = One miligram of water vapor passing through 1 m^2 of a material in one second under a vapor pressure difference of 1 Pa.

1 (U.S) perm = 57.2 (SI) perm

Table 6.2 Approximate Perm Ratings of Selected Materials (in U.S. System of Units)

Component	Perm rating (perm)	Component	Perm rating (perm)
Aluminum foil (unpunctured)	0.0	Brick masonry, 4 in. thick	0.8
Aluminum foil on gypsum board	0.1	Concrete block masonry, 8 in. thick	2.4
Built-up roofing, 3- to 5-ply	0.0	Plaster on metal lath	15.0
15 lb asphalt felt	4.0	Building paper, grade A	0.25
PVC (plasticized), 4 mil thick	1.2	Building paper, grade B	0.38
Polyethylene sheet, 4 mil thick	0.08	Interior primer plus 1 coat flat oil paint on plaster	1.6 - 3.0
Polyethylene sheet, 6 mil thick	0.06	Exterior oil paint, 3 coats on wood	0.3 - 1.0
Polyethylene sheet, 8 mil thick	0.03		

Asphalt-treated paper, generally referred to as *building paper* or *kraft paper*, is also a good vapor retarder, see Table 6.2. Several fiberglass insulation manufacturers make fiberglass batts faced with a low-perm sheet material, such as building paper, see Section 5.7.

Another commonly used vapor retarder is aluminum foil. It has a zero perm rating provided it is without holes and (or) punctures. However, aluminum foil does not have the strength required to be stretched over framing members such as studs and joists and is readily damaged during handling. Lamination to another material provides the necessary strength.

Several manufacturers exploit the zero permeance of aluminum foil in producing vapor retarders. One manufacturer produces a vapor retarder consisting of 1 mil thick aluminum foil sandwiched between two 0.5 mil thick sheets of polyester, Figure 6.10. In this composite product, the aluminum foil provides zero permeance and the polyester sheet provides tensile strength and puncture resistance.

Since the polyester sheet also has a low permeability, any small holes in the aluminum foil are sealed by the polyester sheet so that the composite product has nearly a zero perm rating. The polyester sheet also helps to reduce the corrosion of the aluminum foil.

In addition to the products just described, there are several other products with low perm ratings, such as rubberized asphalt membranes, liquid-applied emulsions, reinforced plastic sheets.

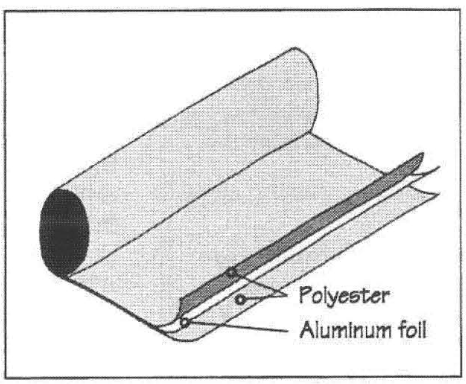


Figure 6.10 *Aluminum foil bonded to two sheets of polyester to provide a vapor retarder with nearly zero perm rating.*

6.7 LOCATION OF VAPOR RETARDER AND VENTILATION IN THE SPACE BEYOND THE VAPOR RETARDER

The building codes require that the vapor retarder should be installed on the "warm-in-winter side of the insulation". This generally implies the inside face of insulation because the inside face is warmer and is at a higher vapor pressure. In some warm and humid climates of North America, where the higher vapor pressure may occur on the outside face of the insulation, the codes do not require the use of a vapor retarder. A vapor retarder is also unnecessary in buildings which are not insulated.

Vapor Retarder Not Required in Warm Climates

The International Residential Code lists the counties in the United States where the the use of a vapor retarder is not needed in building assemblies.

Vapor Retarder in Conventional Residential Buildings

Because there are several vapor producing activities in a residential building, a 4-mil-thick polyethylene sheet is typically installed in the walls and the ceiling between the interior gypsum board and the insulation, Figure 6.11 (see also Figure 6.12).

In addition to using a vapor retarder, it is also important to ventilate the envelope assembly between the vapor retarder and the outside. The idea is that if any vapor escapes through the vapor retarder, it should be able to mix with the (infinite mass of) outside air to prevent its condensation within the assembly. That is why a typical attic must be ventilated. Without adequate attic ventilation, the vapor will be trapped in the attic where it can condense.

Because the dew point generally occurs within the insulation, the insulation must be vapor permeable. That is why the most commonly used insulation in residential buildings is fiberglass batt or blanket insulation. It is precisely for the reason of vapor permeability needed beyond the vapor retarder that the air retarder (which is always placed toward the outside of the wall assembly) must be perforated.

If the air retarder is not perforated, any vapor that travels through the vapor retarder will be trapped between the vapor and air retarders, and will condense there.

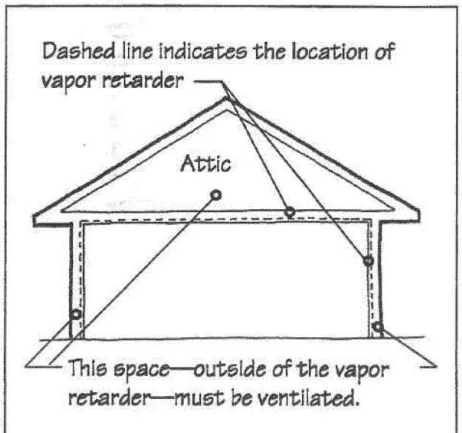


Figure 6.11 *Location of vapor retarder in a conventional residential construction in North America.*

Importance of Attic Ventilation

Ventilating the space beyond the vapor retarder is particularly important in attics. It is also required for reasons other than condensation control. In cold climates, ventilation prevents the formation of ice dams at projecting roof eaves. If the attic is not ventilated, it remains relatively warm because of the entry of heat into the attic from the warm interior, but the eave overhangs are cold. This melts the snow in the middle of the roof which freezes again at the eaves, forming ice dams. The problem is worse in an uninsulated roof-ceiling assembly, Figure 6.12(a).

Ice dams can substantially load the roof at eave overhang and gutter. They also prevent water from draining off the roof, which may cause roof leakage. Ceiling insulation, coupled with the ventilation of the attic, helps to eliminate ice dams in addition to preventing the build-up of water vapor, Figure 6.12(b).

The ventilation of the attic is also required in warm climates to reduce heat transmission from the ceiling into the interior of the building. The temperature of the air in an unventilated attic becomes much higher than the outside air because of the ability of air and the materials of the roof to store heat. This is particularly critical during the summer.

Temperature differences in excess of 40 ^{o}F between the outside air and the attic air have been reported in unventilated or inadequately vented attics. The higher attic temperature increases heat transfer to the interior of the building.

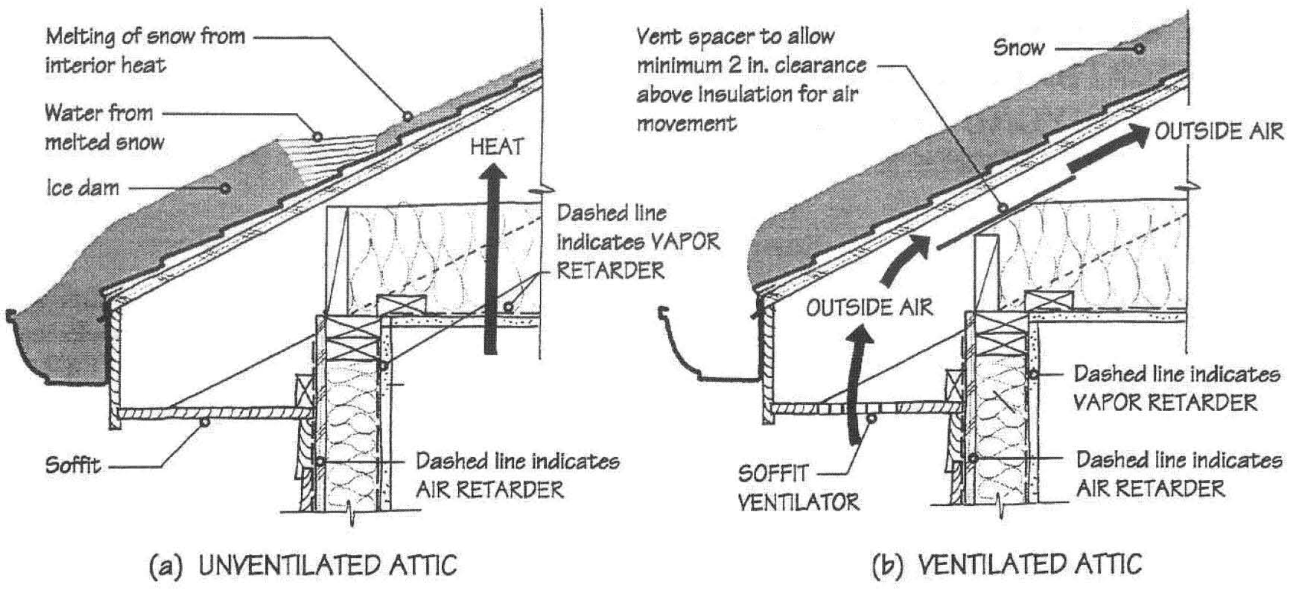


Figure 6.12 *The effect of attic ventilation on the formation of ice dams at overhanging eave of a sloping roof.*

As shown in Figure 6.12(b), attic ventilation can be provided through openings at the soffit. The openings must be covered with a mesh or screen to prevent the entry of insects. Building codes mandate a certain minimum area of soffit vents.

Soffit ventilation is considered as *intake ventilation*. Adequate ventilation of the attic requires cross ventilation, using intake as well as *exhaust ventilation*. Exhaust ventilation is required at a higher level in the attic. Four different alternatives are used for exhaust ventilation, Figure 6.13:

- Gable ventilators
- Ridge ventilators
- Turbine ventilators
- Gable fans

Vapor Tight Construction and Attic Ventilation

Although preventing condensation in an attic by providing attic ventilation is perhaps the safest approach and one that is currently mandated by building codes, it must be appreciated that it is not without disadvantages. In extremely cold climates with frequent blowing snow and rain, venting can cause serious problems by permitting snow and rain to infiltrate the vents. Experience in cold Canadian climates has demonstrated that if indoor humidity levels are controlled and the ceiling is provided with a well-installed vapor retarder with an extremely low vapor permeance (vaportight construction), it is possible to prevent attic condensation without providing attic ventilation.

A major advantage of eliminating attic ventilation lies in improving the effectiveness of attic insulation. However, if attic ventilation is not provided, the problem of ice dam formation should be investigated or prevented by not providing eave overhangs.

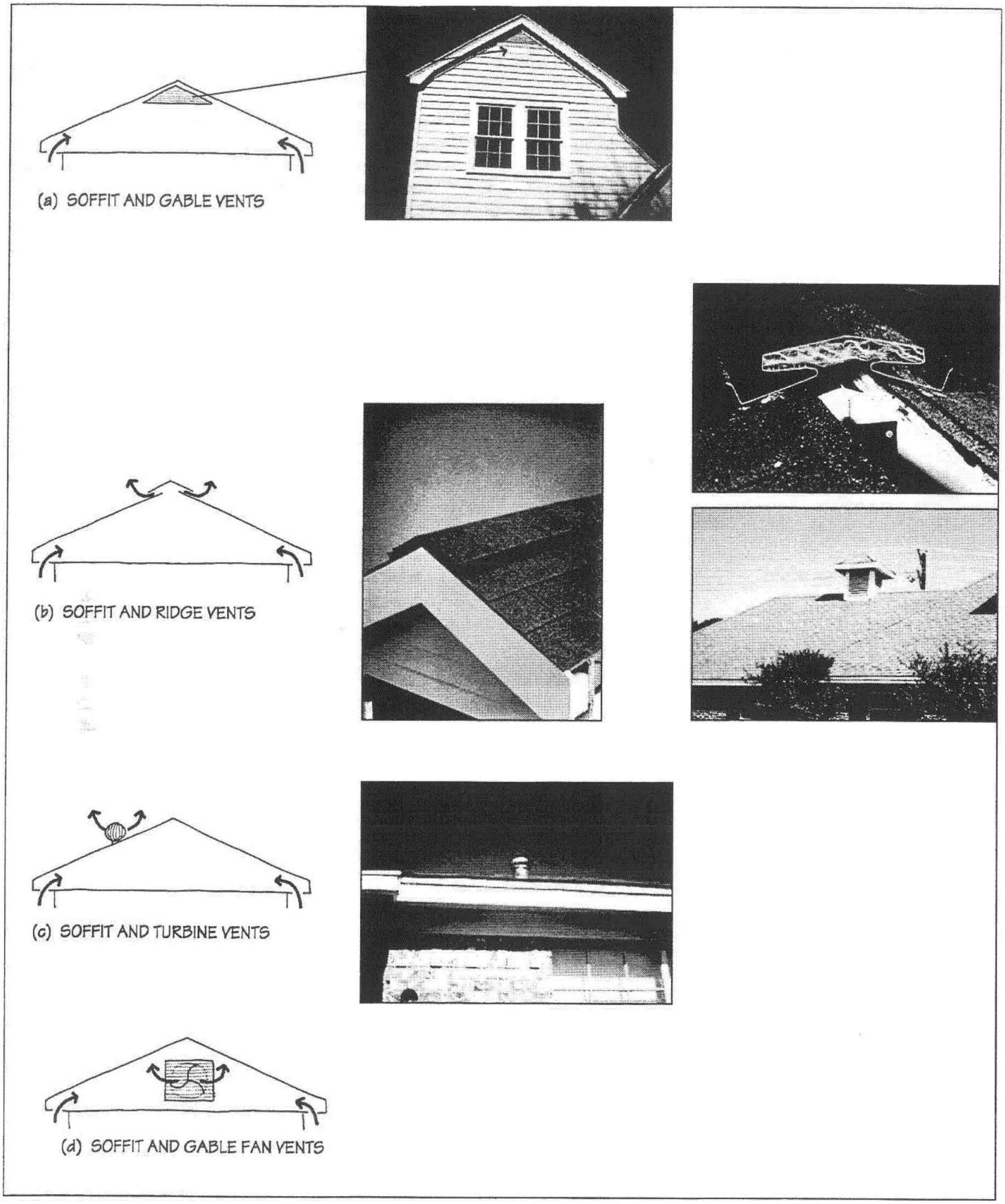


Figure 6.13 *Various alternatives of providing attic ventilation. Soffit vents function as intake ventilators, while gable vents, ridge vents, turbine vents or gable fan vents function as exhaust ventilators. Any one of the four exhaust ventilation options may be used along with soffit vents.*

6.8 VAPOR RETARDER UNDER A CONCRETE SLAB-ON-GRADE

A vapor retarder is also required under a concrete slab-on-grade in all climates to prevent subsoil moisture diffusing through the slab to the interior of the building, Figure 6.14 A 10 mil (0.25 mm) thick polyethylene sheet with joints overlapped is recommended as a vapor retarder under the slab. A layer of coarse sand below the vapor retarder drains water away from the vapor retarder by eliminating capillary action. Additionally, the sand functions as a protective cushion for the vapor retarder.

A vapor retarder is not required under a slab-on-grade if the migration of moisture is not detrimental to the occupancy of the building. Such buildings include garages, carports and other unheated spaces. A vapor retarder is also not required under driveways, walkways, patios, etc.

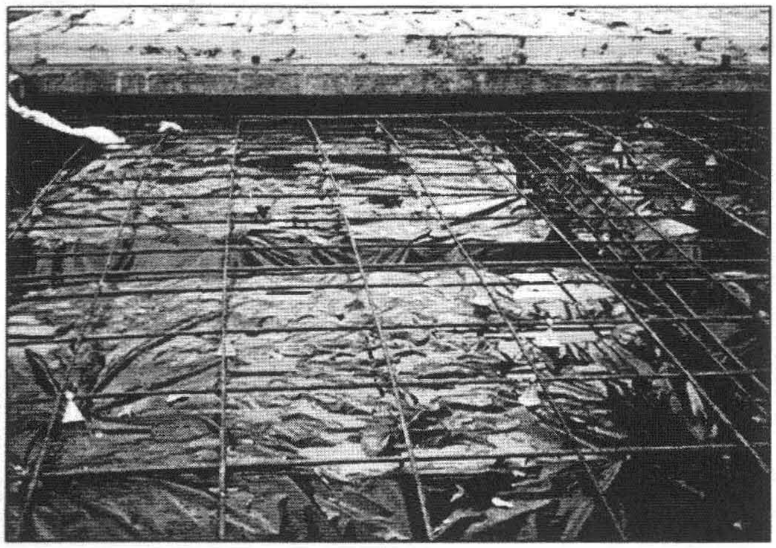


Figure 6.14 *A polyethylene sheet vapor retarder under a concrete slab-on-grade. The photograph shows steel reinforcing bars laid over the vapor retarder. The reinforcing bars will be embedded in the concrete.*

Suggestions for Further Reading

- International Code Council: *International Residential Code.*
- Beall, Christine: *Thermal and Moisture Protection Manual for Architects, Engineers and Contractors*, McGraw Hill, 1999.
- Graham, Charles: "Use of Air Barriers and Vapor Retarders in Buildings", Texas Architect Magazine, September/October 2004.
- Lstiburek, Joseph: "Understanding Vapor Barriers", ASHRAE Journal", August 2004

Important Web Sites

- Air Barrier Association of America (www.abaa.org)
- Building Science Corporation (www.buildingscience.com)
- National Research Council of Canada—Institute for Research in Construction (www.irc.nrc-cnrc.gc/irccontents)
- Whole Building design Guide (www.wbdg.org)
- US Army Corps of Engineers—Cold Region Research and engineering Laboratory (www.crrel.usace.army.mil)

Appendix

WHERE WILL DEW POINT OCCUR IN AN ASSEMBLY?

Temperature Gradient Across an Assembly

Consider a multilayer assembly. Let the R-values of various layers of the assembly be R_1, R_2, R_3 , ... etc., so that $R_t = R_1 + R_2 + R_3 + \ldots$, as shown in Figure 1. Let the difference between the interior and exterior surface temperatures of this assembly be Δt. From Equation (1), Chapter 5, the heat flowing through the assembly (q) is given by:

$$q = \frac{\Delta t}{R_t}$$

Since the heat flowing through each layer must be the same as that flowing through the entire assembly, it follows that:

$$q = \frac{\Delta t}{R_t} = \frac{\Delta t_1}{R_1} = \frac{\Delta t_2}{R_2} = \frac{\Delta t_3}{R_3}, \text{ etc.}$$

Thus, the temperature drop (Δt_1) across layer 1 is:

$$\Delta t_1 = \frac{R_1}{R_t} \Delta t$$

Similarly, the temperature drop (Δt_2) across layer 2 is:

$$\Delta t_2 = \frac{R_2}{R_t} \Delta t$$

The above analysis indicates that the temperature drop across a layer is proportional to the R-value of that layer. Let us now apply the above analysis to an assembly consisting of three layers whose R-values are R-2, R-12 and R-1 respectively, Figure 2. Let the interior surface temperature of layer 1 be 70 °F and the exterior surface temperature of layer 3 be 10 °F, so that Δt = 60 °F. Since R_t = 15, the temperature drop across layer 1 is:

$$\Delta t_1 = \frac{2}{15}(60) = 8\ ^{\circ}\text{F}$$

Similarly, Δt_2 = 48 °F, and Δt_3 = 4 °F. The change of temperature from one side of the assembly to the other is referred to as the *temperature gradient*. For the example just discussed, the temperature gradient of the assembly is shown in Figure 2.

Because the temperature drop across each layer is proportional to the R-value of the layer, it implies that if we draw a section through the assembly, using the R-values to represent the thickness of the respective layers, the temperature gradient across the assembly will be a single straight line, Figure 3. This procedure of drawing the temperature gradient is more convenient in some situations (see Example 2).

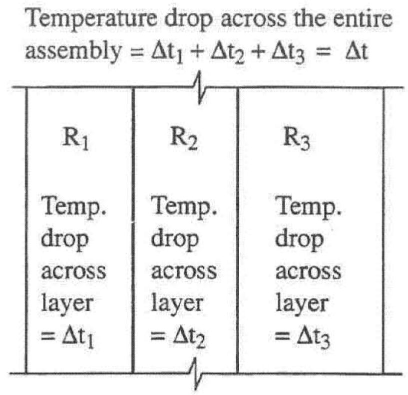


Figure 1 Temperature drops across various layers of a multi-layer assembly.

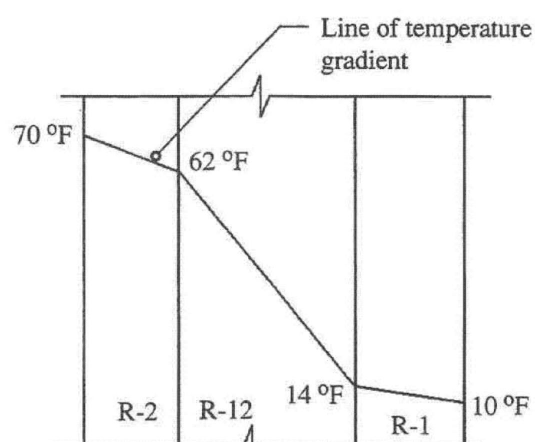


Figure 2 Temperature gradient superimposed over the section of a multi-layer assembly.

Location of Dew Point in the Assembly

In the example of Figure 2 (or Figure3), if the relative humidity of inside air is 50%, and that of outside air is 80%, the inside vapor pressure is much greater than the outside vapor pressure. Therefore, if the assembly is vapor permeable, the vapor will migrate from the inside to the outside.

Table 6.3 gives the dew point of air as a function of its temperature and relative humidity. From this table, the dew point of inside air (70 °F and 50% relative humidity) is 50 °F. As the vapor migrates toward the outside it reaches the temperature of 50 °F in the middle layer, shown by dashed line in Figure 2. It is at this location that the migrating vapor will condense.

In order to keep the analysis simple, we have so far ignored the presence of inside and outside surface resistance in assemblies (see Section 5.4). In practice, these should be taken into account, as illustrated in Examples 1 and 2.

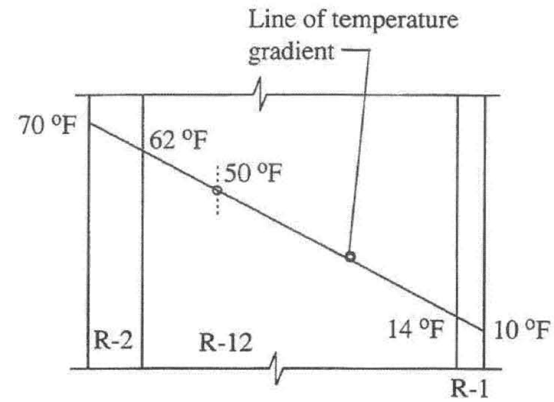


Figure 3 Temperature gradient superimposed over the section of the multi-layer assembly (of Figure 2). In this illustration, the thickness of a layer is proportional to its R-value.

In Figure 2, the thickness of a layer is its actual thickness.

Example 1

Determine the location of dew point in an insulating glass unit (IGU). Assume that the inside surface resistances = R_{si} = 0.7, R-value of IGU = 1.0, outside surface resistance, R_{so} = 0.2. Assume that the inside and outside temperatures are 70 °F and 10 °F respectively, and the inside relative humidity = 45%.

Solution

R_t = 0.7 + 1.0 + 0.2 = 1.9. The temperature drop across inside surface resistance = (0.7/1.9)60 = 22 °F. Therefore, the temperature of inside surface of glass = (70 - 22) = 48 °F. From Table 6.3, the dew point of inside air = 47.5 °F. Since dew point of inside air is below the temperature of inside surface of glass, condensation will not occur on glass—i.e., no surface condensation.

Also note that since the IGU is a sealed unit, the air (or water vapor) cannot flow through it. Therefore, there will be no condensation within the IGU—i.e., no interstitial condensation. Note, however, that if the IGU is replaced by a single sheet of glass, condensation on the interior surface of glass will occur under these conditions.

The temperature drop across the IGU = (1.0/1.9)60 = 32 °F. The temperature gradient across the IGU is shown in Figure 4.

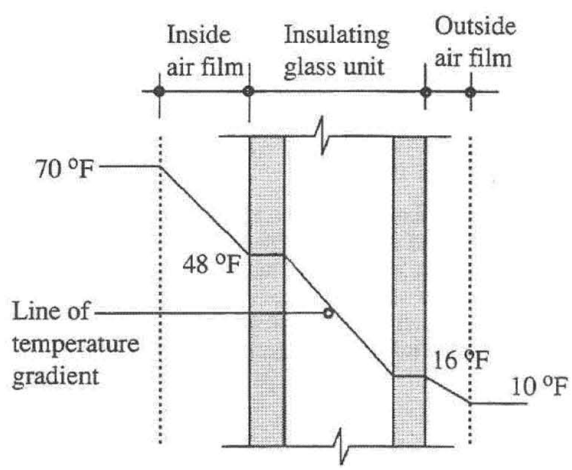


Figure 4 Temperature gradient through the insulating glass unit of Example 1. Note that the temperature gradient line is horizontal through both panes of glass because the R-value of a glass pane is nearly zero. Also note that the inside surface temperature of glass is 48 °F and the dew point of inside air is 47.5 °F. Therefore, condensation will not occur on the glass surface.

Example 2

Determine the R-value of the wall of Example 3 (in Chapter 5), consisting of 2 x 4 wood studs spaced 16 in. on center. The spaces between the studs are filled with 3-1/2 in. thick fiberglass insulation, as shown in Figure 5 (which is a copy of Figure 5.16 in Chapter 5).

Table 6.3 Dew Point of Air as a Function of its Temperature and Relative Humidity

RH (%)	Air temperature (°F)								
	30	40	50	60	70	80	90	100	110
100	30	40	50	60	70	80	90	100	110
90	28	37	47	57	67	77	87	97	107
80	25	34	44	54	64	73	83	93	103
70	22	31	40	50	60	69	79	88	98
60	19	28	36	46	55	65	74	83	93
50	15	24	33	41	50	60	69	78	88
40	11	18	27	35	45	53	62	71	81
30	5	14	21	29	37	46	54	62	72
20	3	8	13	20	28	35	43	52	62
10	1	5	6	9	13	20	27	34	43
0	This air will not condense.								

Solution

From Example 3 (in Chapter 5), the R-values of various layers of the assembly are:.

Inside surface resistance = 0.7
1/2 in. thick gypsum board = 0.3
3-1/2 in thick fiberglass insulation = 12.2
1/2 in. thick plywood = 0.5
2 in. wide air space = 1.0
3-5/8 in. thick brick veneer = 0.7
Outside surface resistance = 0.2

Hence, R_t = 0.7 + 0.3 + 12.2 + 0.5 + 1.0 + 0.7 + 0.2 = 15.6

The temperature gradient across the assembly, when the inside and outside air temperatures are 70 °F and 10 °F respectively, is shown in Figure 6. If the relative humidity of inside air is 45%, the dew point (47.5 °F) occurs within the insulation.

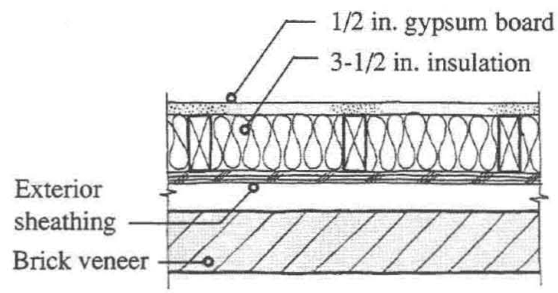


Figure 5 Plan of the wall of Example 2.

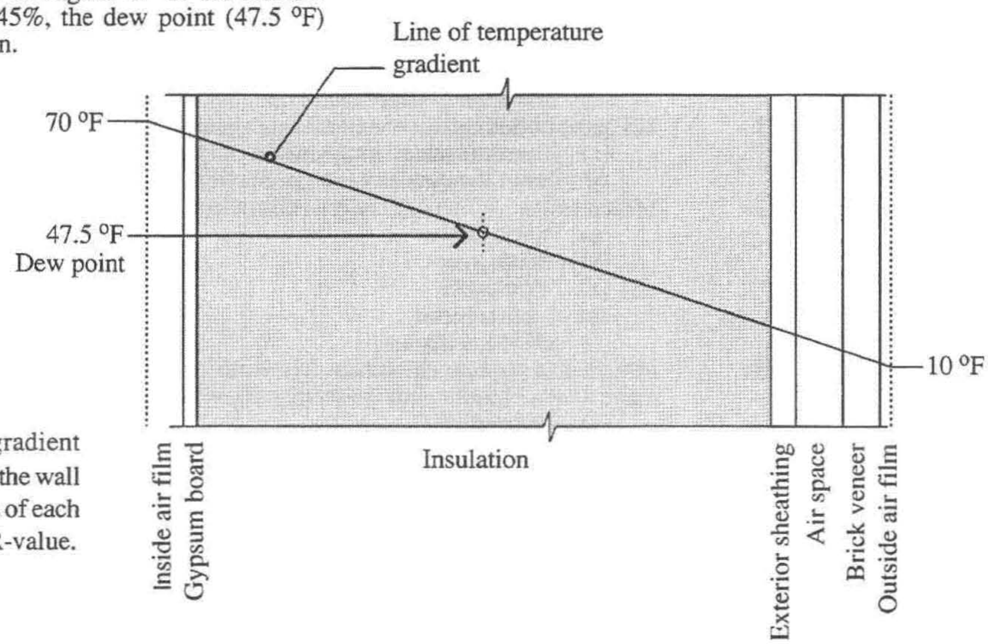


Figure 6 Temperature gradient across the vertical section of the wall of Example 2. The thickness of each layer is proportional to its R-value.

TEST YOUR KNOWLEDGE

Each question has only one correct answer. Select the choice that best answers the question.

1 Air leakage through a building envelope is a function of:
   (a) inside-outside pressure difference
   (b) inside-outside temperature difference
   (c) outside wind speed
   (d) all of the above
   (e) (a) and (c) only

2 Which of the following is a more appropriate term?
   (a) Air barrier
   (b) Air retarder

3 An air retarder is made from:
   (a) an unperforated plastic sheet
   (b) a perforated plastic sheet
   (c) an asphaltic felt
   (d) none of the above

4 An air retarder is placed on the warm side of the envelope assembly.
   (a) True
   (b) False

5 An air retarder is generally used to wrap:
   (a) the walls
   (b) the ceiling
   (c) the roof
   (d) all of the above

6 The use of an air retarder is more critical in:
   (a) cold climates
   (b) warm climates
   (c) hot-dry climates
   (d) hot humid

7 The use of air retarders in structures improves the quality of indoor air.
   (a) True
   (b) False

8 A vapor retarder is required to be placed on:
   (a) cold side of assembly
   (b) warm side of assembly
   (c) warm-in-winter side of insulation
   (d) cold-in-winter side of insulation

9 A vapor retarder is perforated so that:
   (a) water may pass through the pores
   (b) water vapor may pass through the pores
   (c) air may pass through the pores
   (d) a vapor retarder is not perforated

10 The dew point of air is always:
   (a) less than or equal to the air's temperature
   (b) greater than or equal to the air's temperature
   (c) dew point is unrelated to the air's temperature

11 In heated buildings, the vapor flow is generally:
   (a) from the inside to the outside of the envelope
   (b) from the outside to the inside of the envelope

12 Which of the following materials has the smallest perm rating?
   (a) Plastic sheet
   (b) Metal sheet
   (c) Brick wall
   (d) Concrete wall
   (e) All of the above

13 In which of the two assemblies, one with a negligible R-value (assembly A) and the other with a high R-value (assembly B), will interstitial condensation occur?
   (a) Assembly A
   (b) Assembly B

14 Perm rating is a property that measures the effectiveness of an air barrier.
   (a) True
   (b) False

15 In general, the greater the thickness of a material, the greater its perm rating.
   (a) True
   (b) False

16 For a material to be considered a vapor retarder, its perm rating in the U.S. System of units must be:
- (a) greater than 1.0
- (b) less than 1.0
- (c) greater than 2.0
- (d) less than 2.0
- (e) none of the above

17 Ventilation of an attic space is important in:
- (a) cold climates only
- (b) moderately cold climates only
- (c) hot climates only
- (d) all climates

18 Effective attic ventilation can be provided through the use of soffit vents only.
- (a) True
- (b) False

19 When gable vents are provided to ventilate an attic space:
- (a) ridge vents are also necessary
- (b) turbine vents are also necessary
- (c) soffit vents are also necessary

20 An ice dam occurs:
- (a) in the middle of a sloping roof
- (b) at the eave of a sloping roof
- (c) in the middle of a flat roof
- (d) at the edge of a flat roof

REVIEW QUESTIONS

1 Conduct a web search to identify at least two manufacturers of air retarders. How do these products differ from each other.

2 Draw a detailed plan through a typical residential wall and show the locations of the air retarder and vapor retarder.

3 Explain the concept of the relative humidity of air.

4 Explain why it is much easier for vapor to flow through building assemblies than air.