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Insulations, Sheathings and Vapor Retarders

Research Report - 0412

November-2004

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Abstract:

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Insulations, Sheathings and Vapor Retarders

Two seemingly innocuous requirements for building enclosure assemblies bedevil builders and designers almost endlessly:

- keep water vapor out
- let the water vapor out if it gets in

It gets complicated because, sometimes, the best strategies to keep water vapor out also trap water vapor in. This can be a real problem if the assemblies start out wet because of rain or the use of wet materials (wet framing, concrete, masonry or damp spray cellulose, fiberglass or rock wool cavity insulation).

It gets even more complicated because of climate. In general, water vapor moves from the warm side of building assemblies to the cold side of building assemblies. This means we need different strategies for different climates. We also have to take into account differences between summer and winter.

The good news is that water vapor moves only two ways - vapor diffusion and air transport. If we understand the two ways, and know where we are (climate zone) we can solve the problem.

The bad news is that techniques that are effective at controlling vapor diffusion can be ineffective at controlling air transported moisture, and vice versa.

Building assemblies, regardless of climate zone, need to control the migration of moisture as a result of both vapor diffusion and air transport. Techniques that are effective in controlling vapor diffusion can be very different from those that control air transported moisture.

Vapor Diffusion and Air Transport of Vapor

Vapor diffusion is the movement of moisture in the vapor state through a material as a result of a vapor pressure difference (concentration gradient) or a temperature difference (thermal gradient). It is often confused with the movement of moisture in the vapor state into building assemblies as a result of air movement. Vapor diffusion moves moisture from an area of higher vapor pressure to an area of lower vapor pressure as well as from the warm side of an assembly to the cold side. Air transport of moisture will move moisture from an area of higher air pressure to an area of lower air pressure if moisture is contained in the moving air (Figure 1).

Vapor pressure is directly related to the concentration of moisture at a specific location. It also refers to the density of water molecules in air. For example, a cubic foot of air containing 2 trillion molecules of water in the vapor state has a higher vapor pressure (or higher water vapor density) than a cubic foot of air containing 1 trillion molecules of water in the vapor state. Moisture will migrate by diffusion from where there is more moisture to where there is less. Hence, moisture in the vapor state migrates by diffusion from areas of higher vapor pressure to areas of lower vapor pressure.

Moisture in the vapor state also moves from the warm side of an assembly to the cold side of an assembly. This type of moisture transport is called thermally driven diffusion.

The second law of thermodynamics governs the exchange of energy and can be used to explain the concept of both vapor pressure driven diffusion and thermally driven diffusion. The movement of moisture from an area of higher vapor pressure to an area of lower vapor pressure as well as from the warm side of an assembly to the cold side of an assembly is a minimization of available “system” energy (or an increase in entropy).

When temperature differences become large, water vapor can condense on cold surfaces. When condensation occurs, water vapor is removed from the air and converted to liquid moisture on the surface resulting in a reduction in water vapor density in the air near the cold surface (i.e. a lower vapor pressure). These cold surfaces now act as “dehumidifiers” pulling more moisture towards them.

Vapor diffusion and air transport of water vapor act independently of one another. Vapor diffusion will transport moisture through materials and assemblies in the absence of an air pressure difference if a vapor pressure or temperature difference exists. Furthermore, vapor diffusion will transport moisture in the opposite direction of small air pressure differences, if an opposing vapor pressure or temperature difference exists. For example, in a hot-humid climate, the exterior is typically at a high vapor pressure and high temperature during the summer. In addition, it is common for an interior air conditioned space to be maintained at a cool temperature and at a low vapor pressure through the dehumidification characteristics of the air conditioning system. This causes vapor diffusion to move water vapor from the exterior towards the interior. This will occur even if the interior conditioned space is maintained at a higher air pressure (a pressurized enclosure) relative to the exterior (Figure 2).

Vapor Retarders

The function of a vapor retarder is to control the entry of water vapor into building assemblies by the mechanism of vapor diffusion. The vapor retarder may be required to control the diffusion entry of water vapor into building assemblies from the interior of a building, from the exterior of a building or from both the interior and exterior.

Vapor retarders should not be confused with air barriers whose function is to control the movement of air through building assemblies. In some instances, air barrier systems may also have specific material properties which also allow them to perform as vapor retarders. For example, a rubber membrane on the exterior of a masonry wall installed in a continuous manner is a very effective air barrier. The physical properties of rubber also give it the characteristics of a vapor retarder; in fact, it can be considered a vapor "barrier." Similarly, a continuous, sealed polyethylene ground cover installed in an unvented, conditioned crawlspace acts as both an air barrier and a vapor retarder; and, in this case, it is also a vapor "barrier." The opposite situation is also common. For example, a building paper or a housewrap installed in a continuous manner can be a very effective air barrier. However, the physical properties of most building papers and housewraps (they are vapor permeable - they “breathe”) do not allow them to act as effective vapor retarders.

Water Vapor Permeability

The key physical property which distinguishes vapor retarders from other materials, is permeability to water vapor. Materials which retard water vapor flow are said to be impermeable. Materials which allow water vapor to pass through them are said to be permeable. However, there are degrees of impermeability and permeability and the classification of materials typically is quite arbitrary. Furthermore, under changing conditions, some materials that initially are “impermeable,” can become “permeable.” Hygroscopic materials change their permeability characteristics as relative humidity increases. For example, plywood sheathing under typical conditions is relatively impermeable. However, once plywood becomes wet, it can become relatively permeable. As a result we tend to refer to plywood as a vapor semi-permeable material.

Non-hygroscopic materials such as polyethylene or plastic housewraps do not change their permeability as a function of relative humidity.

The unit of measurement typically used in characterizing permeability is a “perm.” Many building codes define a vapor retarder as a material that has a permeability of one perm or less as tested under dry cup test method.

Materials are typically tested in two ways to determine permeability: dry cup testing and wet cup testing. Some confusion occurs when considering the difference between wet cup perm ratings and dry cup perm ratings. A wet cup test is conducted with 50 percent relative humidity maintained on one side of the test sample and 100 percent relative humidity maintained on the other side of the test sample. A dry cup test is conducted with 0 percent relative humidity maintained on one side of the test sample and 50 percent relative humidity maintained on the other side of the test sample.

Different values are typical between the two tests for materials that absorb and adsorb water — materials that are hygroscopic. As the quantity of adsorbed water on the surface of hygroscopic materials increases, the vapor permeability of the materials also increases. In other words, for hygroscopic materials, the vapor permeability goes up as the relative humidity goes up.

In general, for hygroscopic materials, the wet cup test provides perm ratings many times the dry cup test values. For non-hygroscopic materials, materials that are hydrophobic, there is typically no difference between wet cup and dry cup test results. For plywood, a hygroscopic material, a dry cup permeability of 0.5 perms is common. However, as the plywood gets wet, it "breathes" and wet cup permeabilities of 3 perms or higher are common.

Materials can be separated into four general classes based on their permeance:

• vapor impermeable	0.1 perm or less
• vapor semi-impermeable	1.0 perms or less and greater than 0.1 perm
• vapor semi-permeable	10 perms or less and greater than 1.0 perm
• vapor permeable	greater than 10 perms

Materials that are generally classed as impermeable to water vapor are:

- rubber membranes,
- polyethylene film,
- glass,
- aluminum foil,
- sheet metal,
- foil-faced insulating sheathings, and
- foil-faced non-insulating sheathings.

Materials that are generally classed as vapor semi-impermeable to water vapor are:

- oil-based paints,
- most vinyl wall coverings,
- unfaced extruded polystyrene greater than 1-inch thick, and
- traditional hard-coat stucco applied over building paper and OSB sheathing.

Materials that are generally classed as vapor semi-permeable to water vapor are:

- plywood,
- bitumen impregnated kraft paper,
- OSB,
- unfaced expanded polystyrene (EPS),
- unfaced extruded polystyrene (XPS)— 1-inch thick or less,
- fiber-faced isocyanurate,
- heavy asphalt impregnated building papers (#30 building paper), and
- most latex-based paints.

Depending on the specific assembly design, construction and climate, all of these materials may or may not be considered to act as vapor retarders. Typically, these materials are considered to be more vapor permeable than vapor impermeable. Again, however, the classifications tend to be quite arbitrary.

Materials that are generally classed as permeable to water vapor are:

- unpainted gypsum board and plaster,
- unfaced fiberglass insulation,
- cellulose insulation,
- synthetic stucco,
- some latex-based paints,
- lightweight asphalt impregnated building papers (#15 building paper),
- asphalt impregnated fiberboard sheathings, and
- "housewraps."

Part of the problem is that we struggle with names and terms. We use the terms vapor retarder and vapor barrier interchangeably. This can get us into serious trouble. Defining these terms is important.

A vapor retarder is the element that is designed and installed in an assembly to retard the movement of water by vapor diffusion. There are several classes of vapor retarders:

Class I vapor retarder	0.1 perm or less
Class II vapor retarder	1.0 perm or less and greater than 0.1 perm
Class III vapor retarder	10 perms or less and greater than 1.0 perm

(Test procedure for vapor retarders: ASTM E-96 Test Method A — the desiccant or dry cup method.)

Finally, a vapor barrier is defined as:

Vapor barrier	A Class I vapor retarder

The current International Building Code (and its derivative codes) defines a vapor retarder as 1.0 perms or less using the same test procedure. In other words, the current code definition of a vapor retarder is equivalent to the definition of a Class II vapor retarder used here.

Air Barriers

The key physical properties which distinguish air barriers from other materials are continuity and the ability to resist air pressure differences. Continuity refers to holes, openings and penetrations. Large quantities of moisture can be transported through relatively small openings by air transport if the moving air contains moisture and if an air pressure difference also exists. For this reason, air barriers must be installed in such a manner that even small holes, openings and penetrations are eliminated.

Air barriers must also resist the air pressure differences that act across them. These air pressure differences occur as a combination of wind, stack and mechanical system effects. Rigid materials such as interior gypsum board, exterior sheathing and rigid draftstopping materials are effective air barriers due to their ability to resist air pressure differences.

Magnitude of Vapor Diffusion and Air Transport of Vapor

The differences in the significance and magnitude vapor diffusion and air transported moisture are typically misunderstood. Air movement as a moisture transport mechanism is typically far more important than vapor diffusion in many (but not all) conditions. The movement of water vapor through a 1-inch square hole as a result of a 10 Pascal air pressure differential is 100 times greater than the movement of water vapor as a result of vapor diffusion through a 32-square-foot sheet of gypsum board under normal heating or cooling conditions (see Figure 4).

In most climates, if the movement of moisture-laden air into a wall or building assembly is eliminated, movement of moisture by vapor diffusion is not likely to be significant. The notable exceptions are hot-humid climates or rain wetted walls experiencing solar heating.

Furthermore, the amount of vapor which diffuses through a building component is a direct function of area. That is, if 90 percent of the building enclosure surface area is covered with a vapor retarder, then that vapor retarder is 90 percent effective. In other words, continuity of the vapor retarder is not as significant as the continuity of the air barrier. For instance, polyethylene film which may have tears and numerous punctures present will act as an effective vapor barrier, whereas at the same time it is a poor air barrier. Similarly, the kraft-facing on fiberglass batts installed in exterior walls acts as an effective vapor retarder, in spite of the numerous gaps and joints in the kraft-facing.

It is possible and often practical to use one material as the air barrier and a different material as the vapor retarder. However, the air barrier must be continuous and free from holes, whereas the vapor retarder need not be.

In practice, it is not possible to eliminate all holes and install a "perfect" air barrier. Most strategies to control air transported moisture depend on the combination of an air barrier, air pressure differential control and interior/exterior moisture condition control in order to be effective. Air barriers are often utilized to eliminate the major openings in building enclosures in order to allow the practical control of air pressure differentials. It is easier to pressurize or depressurize a building enclosure made tight through the installation of an air barrier than a leaky building enclosure. The interior moisture levels in a tight building enclosure are also much easier to control by ventilation and dehumidification than those in a leaky building enclosure.

Combining Approaches

In most building assemblies, various combinations of materials and approaches are often incorporated to provide for both vapor diffusion control and air transported moisture control. For example, controlling air transported moisture can be accomplished by controlling the air pressure acting across a building assembly. The air pressure control is facilitated by installing an air barrier such as glued (or gasketed) interior gypsum board in conjunction with draftstopping. For example, in cold climates during heating periods, maintaining a slight negative air pressure within the conditioned space will control the exfiltration of interior moisture-laden air. However, this control of air transported moisture will not control the migration of water vapor as a result of vapor diffusion. Accordingly, installing a vapor retarder towards the interior of the building assembly, such as the kraft paper backing on fiberglass batts is also typically necessary. Alternatives to the kraft paper backing are low permeability paint on the interior gypsum board surfaces.

In the above example, control of both vapor diffusion and air transported moisture in cold climates during heating periods can be enhanced by maintaining the interior conditioned space at relatively low moisture levels through the use of controlled ventilation and source control. Also, in the above example, control of air transported moisture during cooling periods (when moisture flow is typically from the exterior towards the interior) can be facilitated by maintaining a slight positive air pressure across the building enclosure thereby preventing the infiltration of exterior, hot, humid air.

Overall Strategy

Building assemblies need to be protected from wetting by air transport and vapor diffusion. The typical strategies used involve vapor retarders, air barriers, air pressure control, and control of interior moisture levels through ventilation and dehumidification via air conditioning. The location of air barriers and vapor retarders, pressurization versus depressurization, and ventilation versus dehumidification depend on climate location and season.

The overall strategy is to keep building assemblies from getting wet from the interior, from getting wet from the exterior, and allowing them to dry to either the interior, exterior or both should they get wet or start out wet as a result of the construction process or through the use of wet materials.

In general moisture moves from warm to cold. In cold climates, moisture from the interior conditioned spaces attempts to get to the exterior by passing through the building enclosure. In hot climates, moisture from the exterior attempts to get to the cooled interior by passing through the building enclosure.

Cold Climates

In cold climates and during heating periods, building assemblies need to be protected from getting wet from the interior. As such, vapor retarders and air barriers are installed towards the interior warm surfaces. Furthermore, conditioned spaces should be maintained at relatively low moisture levels through the use of controlled ventilation (dilution) and source control.

In cold climates the goal is to make it as difficult as possible for the building assemblies to get wet from the interior. The first line of defense is the control of moisture entry from the interior by installing interior vapor retarders, interior air barriers along with ventilation (dilution with exterior air) and source control to limit interior moisture levels. Since it is likely that building assemblies will get wet, a degree of forgiveness should also be designed into building assemblies allowing them to dry should they get wet. In cold climates and during heating periods, building assemblies dry towards the exterior. Therefore, permeable ("breathable") materials are often specified as exterior sheathings.

In general, in cold climates, air barriers and vapor retarders are installed on the interior of building assemblies, and building assemblies are allowed to dry to the exterior by installing permeable sheathings and building papers/housewraps towards the exterior. A "classic" cold climate wall assembly is presented in Figure 5.

Hot Climates

In hot climates and during cooling periods the opposite is true. Building assemblies need to be protected from getting wet from the exterior, and allowed to dry towards the interior. Accordingly, air barriers and vapor retarders are installed on the exterior of building assemblies, and building assemblies are allowed to dry towards the interior by using permeable interior wall finishes, installing cavity insulations without vapor retarders (unfaced fiberglass batts) and avoiding interior "non-breathable" wall coverings such as vinyl wallpaper. Furthermore, conditioned spaces are maintained at a slight positive air pressure with conditioned (dehumidified) air in order to limit the infiltration of exterior, warm, potentially humid air (in hot, humid climates rather than hot, dry climates). A "classic" hot climate wall assembly is presented in Figure 6.

Mixed Climates

In mixed climates, the situation becomes more complicated. Building assemblies need to be protected from getting wet from both the interior and exterior, and be allowed to dry to either the exterior, interior or both. Three general strategies are typically employed:

- Selecting either a classic cold climate assembly or classic hot climate assembly, using air pressure control (typically only pressurization during cooling), using interior moisture control (ventilation/air change during heating, dehumidification/air conditioning during cooling) and relying on the forgiveness of the classic approaches to dry the accumulated moisture (from opposite season exposure) to either the interior or exterior. In other words the moisture accumulated in a cold climate wall assembly exposed to hot climate conditions is anticipated to dry towards the exterior when the cold climate assembly finally sees heating conditions, and vice versa for hot climate building assemblies;
- Adopting a "flow-through" approach by using permeable building materials on both the interior and exterior surfaces of building assemblies to allow water vapor by diffusion to "flow-through" the building assembly without accumulating. Flow would be from the interior to exterior during heating periods, and from the exterior towards the interior during cooling periods. In this approach air pressure control and using interior moisture control would also occur. The location of the air barrier can be towards the interior (sealed interior gypsum board), or towards the exterior (sealed exterior sheathing). A "classic" flow-through wall assembly is presented in Figure 7; or
- Installing the vapor retarder roughly in the middle of the assembly from a thermal perspective. This is typically accomplished by installing impermeable or semi-impermeable insulating sheathing on the exterior of a frame cavity wall (see Figure 8). For example, installing 1.5 inches of foil-faced insulating sheathing (approximately R-10) on the exterior of a 2x6 frame cavity wall insulated with unfaced fiberglass batt insulation (approximately R-19). The vapor retarder is the interior face of the exterior impermeable insulating sheathing (Figure 8). If the wall assembly total thermal resistance is R-29 (R-19 plus R-10), the location of the vapor retarder is 66 percent of the way (thermally) towards the exterior (19/29 = .66). In this approach air pressure control and utilizing interior moisture control would also occur. The location of the air barrier can be towards the interior or exterior.

The advantage of the wall assembly described in Figure 8 is that an interior vapor retarder is not necessary. In fact, locating an interior vapor retarder at this location would be detrimental, as it would not allow the wall assembly to dry towards the interior during cooling periods. The wall assembly is more forgiving without the interior vapor retarder than if one were installed. If an interior vapor retarder were installed, this would result in a vapor retarder on both sides of the assembly significantly impairing durability.

Note that this discussion relates to a wall located in a mixed climate with an exterior impermeable or semi-impermeable insulating sheathing. Could a similar argument be made for a heating climate wall assembly? Could we construct a wall in a heating climate without an interior vapor retarder? How about a wall in a heating climate with an exterior vapor retarder and no interior vapor retarder? The answer is yes to both questions, but with caveats.

Control of Condensing Surface Temperatures

The performance of a wall assembly in a cold climate without an interior vapor retarder (such as the wall described in Figure 8) can be more easily understood in terms of condensation potentials and the control of condensing surface temperatures.

Figure 9 illustrates the performance of a 2x6 wall with semi-permeable OSB sheathing (perm rating of about 1.0 perms, dry cup; 2.0 perms, wet cup) covered with building paper and vinyl siding located in Chicago, IL. The interior conditioned space is maintained at a relative humidity of 35 percent at 70 degrees Fahrenheit. For the purposes of this example, it is assumed that no interior vapor retarder is installed (unpainted drywall as an interior finish over unfaced fiberglass, yech!). This illustrates a case we would never want to construct in a cold climate, a wall with a vapor retarder on the exterior (semi-permeable OSB sheathing and no vapor retarder on the interior.

The mean daily ambient temperature over a one-year period is plotted (Figure 9). The temperature of the insulation/OSB sheathing interface (back side of the OSB sheathing) is approximately equivalent to the mean daily ambient temperature, since the thermal resistance values of the siding, building paper and the OSB sheathing are small compared to the thermal resistance of the insulation in the wall cavity. The dew point temperature of the interior air/water vapor mix is approximately 40 degrees Fahrenheit (this can be found from examining a psychrometric chart). In other words, whenever the back side of the OSB sheathing drops below 40 degrees Fahrenheit, the potential for condensation exists at that interface should moisture migrate from the interior conditioned space via vapor diffusion or air movement.

From the plot it is clear that the mean daily temperature of the back side of the OSB sheathing drops below the dew point temperature of the interior air at the beginning of November and does not go above the dew point temperature until early March. The shaded area under the dew point line is the potential for condensation, or wetting potential for this assembly should moisture from the interior reach the back side of the OSB sheathing. With no interior vapor retarder, moisture from the interior will reach the back side of the plywood sheathing.

Figure 10 illustrates the performance of the wall assembly described in Figure 8, a 2x6 wall insulated on the exterior with 1.5 inches of rigid foil-faced impermeable insulating sheathing (approximately R-10, perm rating of about 0.1 perms, wet cup and dry cup), located in Chicago, IL. The wall cavity is insulated with unfaced fiberglass batt insulation (approximately R-19). Unpainted drywall is again the interior finish (no interior vapor retarder). Now this wall assembly also has a vapor retarder — in fact, it has a vapor barrier — on the exterior, but with a huge difference. This exterior vapor retarder (vapor barrier) has a significant insulating value since it is a rigid insulation. The temperature of the first condensing surface within the wall assembly, namely the cavity insulation/rigid insulation interface (the back side of the rigid insulation), is raised above the interior dew point temperature because of the insulating value of the rigid insulation. This illustrates a case we could construct in a cold climate, a wall with a “warm” vapor retarder (vapor barrier) on the exterior and no vapor retarder on the interior.

The temperature of the condensing surface (back side of the rigid insulation) is calculated in the following manner. Divide the thermal resistance to the exterior of the condensing surface by the total thermal resistance of the wall. Then multiply this ratio by the temperature difference between the interior and exterior. Finally, add this to the outside base temperature.

$$T_{(interface)} = R_{(exterior)} / R_{(total)} \times (T_{in} - T_{out}) + T_{out}$$

where: $T_{(interface)}$ = the temperature at the sheathing/insulation interface or the temperature of the first condensing surface

$R_{(exterior)}$ = the R-value of the exterior sheathing

$R_{(total)}$ = the total R-value of the entire wall assembly

T_{in} = the interior temperature

T_{out} = the exterior temperature

The R-10 insulating sheathing raises the dew point temperature at the first condensing surface so that no condensation will occur with interior conditions of 35 percent relative humidity at 70 degrees Fahrenheit. In other words, no interior vapor retarder of any kind is necessary with this wall assembly if the interior relative humidity is kept below 35 percent. This is a “caveat” for this wall assembly. Now remember, this wall is located in Chicago, IL. This is another “caveat” for this wall assembly.

What happens if we move this wall to Minneapolis? Big change. Minneapolis is a miserable place in the winter. The interior relative humidity would have to be kept below 25 percent to prevent condensation at the first condensing surface. What happens if we move the wall back to Chicago and install a modest interior vapor retarder, such as one coat of a standard interior latex paint (perm rating of about 5 perms) over the previously unpainted drywall (perm rating of 20)? If we control air leakage, interior relative humidities can be raised above 50 percent before condensation occurs.

What happens if we move this wall to Tupelo, MS, and reduce the thickness of the rigid insulation? Another big change. Tupelo has a moderate winter. Figure 11 illustrates the performance of a 2x6 wall insulated on the exterior with 1 inch of rigid extruded polystyrene insulating sheathing (approximately R-5, perm rating of about 1.0 perms, wet cup and dry cup), located in Tupelo.

In Tupelo, with no interior vapor retarder of any kind, condensation will not occur in this wall assembly until interior moisture levels are raised above 45 percent, 70 degrees Fahrenheit during the coldest part of the heating season. Since these interior conditions are not likely (or desirable), the potential for condensation in this wall assembly is small.

What happens if we move the wall assembly described in Figure 9 that experienced condensation in Chicago to Las Vegas, NV? No condensation results (see Figure 12) until interior moisture levels exceed 40 percent relative humidity at 70 degrees F. In Las Vegas, an interior vapor

About this Report

This report was first published in the Builder's Guide for Cold Climates, 2004 edition.

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