The Influence of Low-Permeance Vapor Barriers on Roof and Wall Performance

J.F. Straube, Ph.D.

ABSTRACT

Low-permeance vapor barriers are widely used on the interior of wall and roof systems in large parts of North America. Many codes and standards imply or even state that low-permeance vapor barriers should be used in all cold regions as well as many moderate climate zones.

The influence of vapor barriers on the hygrothermal performance of wall and roof systems is a function of exterior climate, interior climate, solar absorptance, rainwater absorption, and the vapor and thermal resistance of all of the layers in the system. In many practical situations, a low-permeance vapor barrier will not improve hygrothermal performance and may in fact increase the likelihood of damaging condensation or trap moisture in the system.

This paper will examine the role of vapor barriers on hygrothermal performance with the aid of simple and transparent diffusion calculations supported by measurements from full-scale natural exposure monitoring. The phenomenon of summertime condensation, the drying of roofs and walls, and multiple vapor barrier layers will be explored. The importance of properly assessing both the interior and exterior climate will be discussed. Vapor diffusion control strategies will be presented.

INTRODUCTION

Low-permeance vapor barriers are widely used on the interior of wall and roof systems in large parts of North America. ASHRAE and many codes and standards imply or even state that low-permeance vapor barriers should be used in all cold regions as well as many moderate climate zones. The use of low-permeance finishes on the interior in hot-humid climates is almost as common.

The modern scientific literature is rich with detailed accounts of vapor-diffusion physics. Unfortunately, many articles and documents still confuse the functions and requirements of air and vapor barriers, and the scientific understanding available has not been applied to codes, standards, manufacturers' guidelines, etc.

The goal of this paper is to show that the definition of vapor barriers/retarders used in codes and standards is arbitrary and not based on our current physical understanding of moisture movement in enclosure wall systems. It will also be demonstrated that the influence of vapor barriers on the hygrothermal performance of wall and roof systems is in fact a function of exterior climate, interior climate, solar absorptance, rainwater absorption, and the vapor and thermal resistance of all of the layers in the system. In many practical situations, a low-permeance vapor barrier will not improve hygrothermal performance and may in fact increase the likelihood of damaging condensation or trapping moisture in the system.

This paper will examine the role of vapor barriers on the moisture conditions within building enclosures through the use of simplified building physics. The phenomenon of summertime condensation, the drying of roofs and walls, and multiple vapor barrier layers will be explored. The importance of properly assessing both the interior and exterior climate will be discussed. Vapor diffusion control strategies will be presented.

J.F. Straube is an assistant professor in the Civil Engineering Department and School of Architecture, University of Waterloo, Waterloo, Ontario, Canada.

BACKGROUND

To ensure durability, health, and in-service performance, the control of moisture is widely recognized as a critical part of the design and operation of building enclosures. The actual moisture conditions within an enclosure, and its materials at any given time, is a balance of its previous wetting and drying history.

Wetting primarily occurs by liquid absorption from rain and groundwater and condensation of water vapor transported into the enclosure by air movement (convection) and diffusion.

Field experience has shown that wetting inevitably occurs, especially from rain leaks through enclosure penetrations, built-in moisture, and intermittent air leakage. This reality has heightened the awareness that encouraging drying can be as important as resisting wetting.

Drying can occur by (1) drainage of liquid water, (2) evaporation and drying by air movement through the enclosure, and (3) by vapor diffusion. The direction of this drying depends on the gradient of the driving potential, while the magnitude depends on the combination of the magnitude of the driving potential and the resistance to flow of the assembly in question.

Moisture storage within an enclosure is also critical to its moisture performance. Wetting can occur without problems provided that the moisture is subsequently removed and the safe storage capacity of the materials in the assembly is not exceeded. If an assembly allows a significant amount of safe storage, wetting and drying can occur at quite different times (e.g., different seasons). Many modern enclosures have little safe storage and, hence, must either limit wetting or have good drying potential at all times of the year. A traditional solid masonry wall with plaster on the interior can avoid exceeding its safe storage capacity even if it becomes wet in one season (e.g., winter) since it can dry in another (e.g., summer).

Modern enclosures attempt to completely control airflow and its related wetting (i.e., air barrier systems are provided). This means that airflow is eliminated as a means of both wetting and drying. Drainage aids drying by removing bulk liquid water—especially from parts of saturated or non-absorptive materials—and can be a powerful mechanism. However, most damage mechanisms (e.g., corrosion, rot and mold, freeze-thaw) require much less moisture than the maximum that can be removed by drainage (Straube 1998). Hence, if moisture damage is to be avoided, additional drying is not only necessary—it is critical to good moisture performance. Since air leakage drying is eliminated, and drainage is insufficient, diffusion is the only other mechanism available for drying. For this reason, understanding diffusion is becoming increasingly important to the understanding of the performance of modern building enclosures.

Diffusion Physics and Definitions

Water vapor is always striving to move from high concentrations to lower concentrations, or from more to less. Vapor transport by this mechanism is called vapor diffusion. All materials exhibit some resistance to water vapor diffusion. The vapor permeability of a material is a measure of this characteristic. The permeability of steel is zero, while that of air is very high. In a building assembly that separates the interior from the exterior, there will usually be a difference in vapor content and, hence, a drive to force vapor through or within the enclosure. If the materials that make up the enclosure have low vapor permeability, the flow of vapor will be retarded. This means that the water vapor content will change as it moves through the system. If the permeability of the materials is high enough, or the difference in pressure large enough, vapor may reach saturation (100% RH) somewhere within the system and then condense on the next cold downstream surface. If the permeability or the driving force is low enough, the relative humidity may increase within the enclosure but condensation may not occur.

The most common North American definition of a vapor barrier is a material layer with a permeance of less than 1 U.S. perm or about 60 ng/Pa s m^2. Although this definition appears in many codes, it has not been chosen based on the results of any thorough scientific study.

Despite the popular belief otherwise, neither the *National Building Code of Canada* (NBCC), the *International Residential Code* (IRC), nor the *ASHRAE Handbook—Fundamentals* requires the use of a vapor barrier in all enclosures. These codes also do not require the use of a polyethylene sheet as an air barrier or a vapor barrier. The IRC (1998) states in Clause 321.1:

> In all frame walls and floors and ceilings, not ventilated to allow moisture to escape, an approved vapour retarder having a maximum perm rating of 1.0 when tested in accordance with ASTM E96 shall be used on the warm-in-winter side of the thermal insulation.

Hence, any enclosure wall or ceiling that is not of framed construction, or any framed construction that is ventilated, does not require a vapor barrier.

Canadian codes (i.e., Part 5 of the NBCC) wisely require that vapor diffusion be controlled only when an assembly “would be adversely affected by condensation.” The need for a specific vapor barrier layer can be assessed by simple calculations, and rarely is a layer with very low permeance required (although it may be acceptable for many enclosure systems in some climates). However, in this author’s experience both in the U.S. and Canada, the local code official and many engineers will still require vapor barriers even when the specific code wording does not apply.

History

The early history of the science of moisture control is primarily one of controlling vapor diffusion wetting. One of the reasons for this is the relative ease with which vapor diffusion can be calculated and explicitly controlled by the designer.

Rowley, who can be considered the father of vapor barrier requirements (Rose 1997), built a full-scale house and placed it inside a refrigerated climate chamber. With outdoor conditions of –29ºC (–20ºF), his data showed that a framed wall without a vapor retarder would experience a condensation rate of about 21.5 g/m^2 day (0.07 $ounce/ft^2$ day) or 1 g/m^2 h. This would increase the moisture content of a 12.7 mm (0.5 in.) wood sheathing by 2.4%/month. This small source of moisture was his evidence that vapor barriers were required. The common misunderstanding of the relative magnitude of vapor diffusion wetting is one reason for the common belief that vapor barriers play a significant role in preventing wetting in most enclosures.

The concept of drained and screened wall systems as a superior means of controlling rain penetration by enhancing drainage drying was widely used but only analyzed and promoted from the 1950s and 1960s. The control of air leakage and the energy and moisture it carries into an enclosure was the emphasis of much research and education throughout the 1970s and 1980s in Canada (e.g., Latta 1976; IRC/NRCC 1986) but still receives little attention in many modern codes.

Air Barriers Versus Vapor Barriers

The fact that many vapor barriers also retard or eliminate airflow sometimes causes confusion. In fact, much of the older literature (and a remarkable proportion of current documents) confuse or combine the function of the air barrier system and vapor barriers, and the difference between the two is still one of the most common building science questions. Therefore, the distinction will be presented here once again.

The function of a vapor barrier is simply the control of water vapor *diffusion* to reduce the occurrence or intensity of condensation. As such, it has one performance requirement: it must have the specified level of vapor permeance and be installed to cover most of the area of an enclosure. If a small crack or perforation occurs in a vapor barrier, its performance is not substantially reduced and such imperfections can be accepted.

Air barrier systems control airflow and thereby control *convective* vapor transport. The control of air flow provides other benefits such as increased comfort, reduced energy consumption, control of odor, and sound transmission and has at least five performance requirements to meet: it must be continuous, durable, stiff (or restrained), strong, and air impermeable (Straube 2001).

Some building codes require an air barrier system in all enclosures, or (in the case of Canadian codes) in those that would be adversely affected by condensation. In practice, this means air barriers are required for almost all conceivable types of building enclosures, especially since air barriers do more than just control condensation.

The vapor permeance of an air barrier system (ABS) must be considered in the same way as the vapor permeance of all other materials in an assembly should be. The vapor permeance of the ABS is no more important than the vapor permeance of any other materials in an assembly, such as the cladding, sheathing, insulation, interior finish, etc. For example, in cold climates, a vapor barrier on the exterior is usually not desirable but can be designed for, as it is in an exposed membrane, a low-slope roof, or a wall with metal cladding. By contrast, in hot, humid climates, locating the vapor barrier on the exterior would be desirable, but it is also not necessary if the remainder of the enclosure is designed properly.

EXAMPLE CALCULATIONS

This section provides simple steady-state vapor-diffusion calculations using the method shown in the *1997 ASHRAE Handbook—Fundamentals* and initially promoted by Rowely. It is important to note that all of the following calculations assume good air barrier systems. While these calculations are not very accurate, they are transparent, generally very conservative, and have been used since the mid-1930s (since their development by Miller) to assess vapor diffusion in building enclosures. The same calculations can be conducted using a more sophisticated hourly analysis program, but these types of programs require detailed input data (material properties and weather conditions) and specialist knowledge.

Avoiding Condensation

It is often believed that including a vapor barrier on the warm side of a wall in a cold climate will eliminate condensation. As will be shown with the aid of a few simple examples, this belief cannot be supported by the physics of vapor diffusion, yet it is the underpinnings of the reasoning used for the widespread use of low-permeance vapor retarders.

Consider a framed wall with a 60 metric perms (1 U.S. perm) vapor retarder inside, 90 mm of batt insulation, and 40 metric perm (0.7 U.S. perm) sheathing (e.g., such as dry plywood). For a cold climate such as Omaha, Nebraska, the 97.5% winter design temperature is –19ºC (–2ºF)and heating degree-days (HDD) are 3500ºC (6300ºF) (ASHRAE 1997). Table 1 shows the predicted vapor conditions calculated, which indicate condensation will occur (at the back of the plywood). Although –19ºC is very cold weather, further calculation shows that condensation will also occur under outdoor temperatures as warm as 5ºC (41ºF). To avoid condensation at –19ºC, a vapor barrier with a vapor permeance of lower than 1.5 metric perms (e.g., more than two sheets of 6 mil, 0.15 mm thick polyethylene) would be required.

If the code-approved vapor retarder were replaced with a layer of primer and two coats of latex paint over gypsum drywall (which has a permeance of about 3 U.S. perms, or 180 metric perms), condensation would of course still occur and would only stop at temperatures above 6ºC (43ºF).

Controlling the Amount of Condensation

Comparing the performance of the wall above with and without a vapor barrier, it can be seen that the *occurrence* of condensation is not a very useful measure of the need for a vapor barrier. The primary benefit

TABLE 1
First Pass Calculation for Omaha, Nebraska

Element	R	ΔT	t °C	M	R_v	ΔP_v	P_v	P_{sat}	RH
			21.0				990	2474	40%
Inside film	0.120	1.8		10000	0.000	2			
			19.2				988	2212	45%
Vapor retarder	0.000	0.0		60	0.017	344			
			19.2				643	2212	29%
Batt insulation	2.500	37.6		2000	0.001	10			
			–18.4				633	143	442%
Plywood	0.012	0.2		40	0.025	517			
			–18.6				117	141	83%
Outside film	0.029	0.4		20000	0.000	1			
			–19.0				115	136	85%

of a vapor-retardant layer is that it reduces the amount of condensation, not its occurrence. The amount of moisture that would condense on the backside of the sheathing in the previous example can easily be calculated. For the case with a code-approved vapor barrier, the amount of accumulation would be 0.17 g/m^2/h (0.00057 oz/ft^2 h). This amount of moisture accumulation would only increase the moisture content of the sheathing slightly, since a 12.7 mm (0.5 in.) thick layer of 500 kg/m^3 (31 pcf) density plywood can absorb about 63.5 g/m^2 for each 1% MC increase. Hence, an entire month-long exposure at –19ºC (–2ºF) would cause the plywood moisture content to rise by only 2% MC in this example. (Note that the maximum safe moisture content is over 20%, and that dry plywood will contain between 6% and 12% MC).

The 97.5% winter temperature of –19ºC occurs for only 54 hours per winter in Omaha, and the average temperature over the three winter months in Omaha is –4ºC (25ºF). Average conditions provide a more accurate picture of performance. For average conditions, the rate of condensation is of course smaller than for extreme conditions. In the case of the wall with a code-approved vapor retarder (permeance of 60 ng/Pa s m^2), the condensation rate for these average interior and exterior conditions would be 0.10 g/m^2/h versus 0.30 g/m^2/h for the standard painted drywall (Table 2). Over a three-month winter period, the MC of the plywood would increase by 3.4% and 10.2% MC, respectively. Hence, it could be concluded that in locations like Omaha, a vapor retarder with a permeance of 1 U.S. perm would keep the moisture increase (condensation rate) to a safe level while just painting the drywall could be considered be risky (i.e., a 10% MC rise may be too much, although it is clearly not a serious problem). The addition of a very low-permeance vapor barrier, such as polyethylene, would provide little additional benefit.

Karagiozis and Kumaran (1993) conducted one-dimensional computer modeling of a wall similar to that described above for three Canadian locations. They found that while unpainted gypsum provided too little wintertime diffusion control in the extreme Winnipeg climate (design temp of about –33ºC/ –27ºF), adding a layer with only 400 metric perm (7 U.S. perm) was sufficient to avoid diffusion moisture problems with interior conditions of 38% RH.

Influence of Interior Humidity

The conclusion that a 60 metric perm vapor retarder is needed in Omaha would be wrong, however, if the interior humidity were reduced to 30% RH (which is a more realistic residential value given the cold climate). If these conditions were maintained, the total moisture accumulated over the winter months for the two walls with interior conditions of 30% RH would be 1.6% and 5.2% MC, respectively—both well within the safe capacity of the plywood. Note that an indoor humidity of 30% RH with an outdoor temperature of –19ºC would cause severe condensation on most commonly available residential windows. More detailed hourly computer models have also shown the effect of interior conditions on moisture performance. For example, modelling by Tsongas et al. (1995) showed that linking interior RH levels to exterior weather conditions (which is more realistic) strongly affects results. In almost every case, the use of a fixed RH is not conservative, and walls are predicted to be much drier with the more realistic variable RH levels.

Some buildings maintain the interior humidity at dangerously high levels (over about 40% RH in cold climates), such as swimming pools, hospitals, etc. If the interior humidity inside a swimming pool were 70% over the winter, the accumulation within the plywood of the wall with the code-approved vapor retarder would be limited to 8.7% MC. For a building with this type of interior conditions, a low-permeance

TABLE 2
Calculation of Moisture Accumulation

Element	R	ΔT	t °C	M	R_v	ΔP	P	P_{sat}	RH
			21.0				990	2474	40%
Inside film	0.120	1.1		10000	0.000	3			
			19.9				987	2307	43%
Vapor retarder	0.000	0.0		60	0.017	506			
			19.9				481	2307	21%
Batt	2.500	23.5		2000	0.001	15			
			–3.6				465	465	100%

Flow to back of sheathing

Permeance: 57.9 Pressure: 524

Flow to: 3243 ng/m^2 s = 0.11 g/m^2h

Element	R	ΔT	t °C	M	R_v	ΔP	P	P_{sat}	RH
Plywood	0.012	0.1		40	0.025	81			
			–3.7				385	462	83%
Outside film	0.029	0.3		20000	0.000	1			
			–4.0				384	452	85%
Total resistance	2.66	23.9			0	603			

Flow away from back of sheathing

Permeance: 40 Pressure: 81

Flow away: 3243 ng/m^2 s = 0.01 g/m^2/h

Net Accumulation 0.10 g/m^2/h

vapor retarder will often be required on the interior of insulated framed walls in cold climates. However, air leakage control is even more important, and good design would likely not employ an insulated framed wall for these types of interior conditions. An externally insulated wall, for example, would provide protection against both air leakage condensation and vapor diffusion.

Although relative humidity has been discussed above, it is the combination of temperature and relative humidity that influences the vapor diffusion drive and the potential for condensation. In most cases, the interior temperature is maintained within a few degrees of 20°C to 24°C (68°F to 75°F), so temperature does not play much of a role. Some buildings have much higher or lower temperatures, depending on the preferences of the occupants, the cost of energy, etc. These temperatures can be especially important in air-conditioned interiors that are kept well below this range. In cases with significantly warmer or colder interior conditions, common rules of thumb can be rendered inaccurate, and calculations must be undertaken.

Influence of Exterior Sheathing Permeance

The use of a sheathing material such as fiberboard, which is highly vapor permeable and insulating, in conjunction with painted drywall on the interior has a significant impact on wall performance. Table 3 presents these calculations for the extreme –19°C (–2°F) condition of Omaha and 30% RH interior conditions. It can be seen that condensation does not occur for this wall under these extreme conditions, unlike the case in which a vapor barrier was provided but plywood sheathing was used. For interior humidity of 40% RH, some condensation does occur, but the moisture content rise for 280 kg/m^3 density fiberboard over the winter is less than 6% MC.

Despite this, most codes, many code officials, and many designers rarely consider the influence of the vapor permeance of other layers in the wall, although they are just as important as the permeance of the inner layers. This fact has long been known, as evident by a quote from a 1939 Canadian paper (Babbit 1939):

> It is essential to point out that in the calculation of the possibility of condensation in a wall, the permeability of the exterior portions of the wall plays a role only a little less important than that of the interior portions.

It must also be pointed out that the vapor permeance of many organic materials varies, sometimes dramatically, with the relative humidity surrounding the material. The previous calculations have been conducted using the dry-cup vapor permeance values. This can have a significant effect on the results and actual wall performance. For example, the vapor permeance of 0.5 in. plywood may be as low as 40 metric perms in the dry cup test, but at humidities of 90% RH, the permeance is in the order of 1150 metric perms (20 U.S.

TABLE 3
Calculation of Vapor Diffusion with Fiberboard Sheathing

Element	R	ΔT	t ºC	M	R_v	ΔP	P	P_{sat}	RH
			21.0				742	2474	30%
Inside film	0.120	1.7		10000	0.000	9			
			19.3				733	2231	33%
Painted drywall	0.000	0.0		180	0.006	512			
			19.3				221	2231	10%
Batt insulation	2.500	34.7		2000	0.001	46			
			–15.4				175	184	95%
Fiberboard	0.231	3.2		1666	0.001	55			
			–18.6				120	141	85%
Outside film	0.029	0.4		20000	0.000	5			
			–19.0				115	136	85%

TABLE 4
Calculation of Vapor Diffusion with EPS Insulating Sheathing

Element	R	ΔT	t ºC	M	R_v	ΔP_v	P_v	P_{sat}	RH
			21.0				990	2474	40%
Inside film	0.120	0.8		10000	0.000	5			
			20.2				985	2532	42%
Vapor retarder	0.000	0.0		180	0.006	261			
			20.2				724	2352	31%
Batt insulation	2.500	17.1		2000	0.001	24			
			3.1				700	757	93%
EPS sheathing	1.000	6.8		150	0.007	314			
			–3.8				387	459	84%
Outside film	0.029	0.2		20000	0.000	2			
			–4.0				384	452	85%

perms)—for 95% RH the vapor permeance will be approximately the same as the fiberboard used in the example above. Remarkably, the IRC does not specify which of the many test procedures in ASTM E96 should be used in its definition of a vapor barrier, so a wide range of products can have a wide range of results.

Influence of Insulating Material Permeance

The use of insulating materials with some vapor resistance is also possible. In roofing, the use of closed-cell foam is very common, and this foam can provide the vapor resistance required to control diffusion even in very cold climates (as always, an air barrier system is still required).

If unfaced closed-cell polyisocyanurate foam were used in lieu of batt insulation in the example wall, condensation would be eliminated. More realistically, many closed-cell spray-applied polyurethane foams are sufficiently vapor-resistant to obviate the need for a special vapor control layer. Structural insulated panel systems (SIPS) are another example of an enclosure system that almost never requires a separate vapor barrier because of the combination of thickness and moderate permeability of the insulating material. For expanded polystyrene (EPS) with a permeability of 5.8 ng/Pa s m (4 U.S. perms / in.), a 140-mm-thick panel (5.5 in.) would have a permeance of 41 metric perms—less than mandated by most codes. The OSB skins have been ignored in this assessment, although they can decrease the vapor permeance significantly.

Influence of Exterior Insulating Sheathing

The application of insulating sheathing over framing not only reduces heat flow and thermal bridging, it reduces the need for a low-permeance vapor barrier. Table 4 presents a calculation for average Omaha winter exterior conditions for

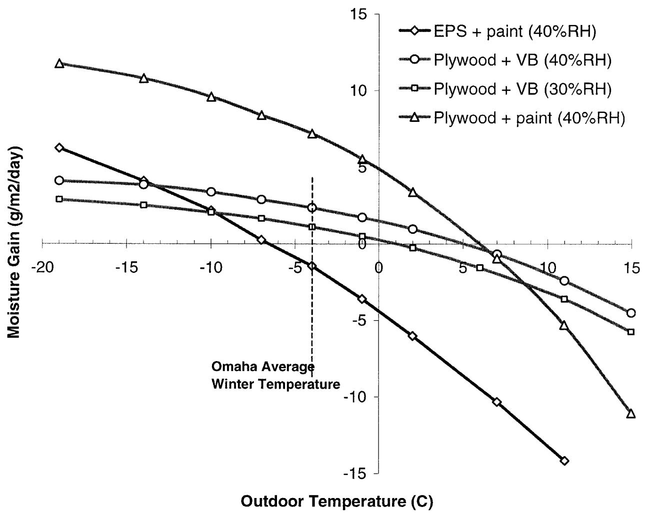

Figure 1 *Impact of exterior temperature on condensation rate.*

the wall with 38 mm (1.5 in.) of expanded polystyrene (M = 150 metric perms) in lieu of the plywood. Under average conditions, a paint layer would be sufficient to control condensation within the stud space, even with 40% RH interior conditions.

It should be noted that the addition of insulated sheathing dramatically increases the temperature of the first cold-weather condensation plane, namely, that of the back of the sheathing. This will reduce the frequency and severity of condensation due to air leakage, a significant benefit. A potential drawback of using foam sheathing is the reduced safe moisture storage capacity it provides relative to a wood-based sheathing.

Influence of Exterior Climate

It should be clear from the above that the temperature, especially the average winter temperature, is a critical variable necessary for the assessment of the level of vapor permeance required in an enclosure. It is unclear how prescriptive codes can implicitly deal with this obvious and important issue.

The daily moisture accumulation (or drying) rate for the example wall described above with EPS and plywood sheathing has been plotted against temperature in Figure 1. Both walls were analyzed for the case with a 180 metric perm paint layer on the gypsum wallboard. It can be seen that the rate of condensation is a nonlinear function of outdoor temperature. Condensation begins to occur at quite different temperatures for the two different wall assemblies. Finally, the effect of interior RH and paint has also been plotted for the wall with plywood sheathing.

Clearly, the wall with EPS sheathing will have a very different behavior than the wall with plywood sheathing when condensation begins (–6.5ºC vs. 5ºC)—the rate of wetting at very cold temperatures (6.2 vs. 4.1 g/m^2 day at –19ºC) and the rate of drying when the temperature is slightly above average (6 g/m^2/day drying vs. 1 g/m^2/day wetting at 2ºC).

Summary

Figure 1 also provides a summary of several variables that impact the hygrothermal performance of walls. The impact of insulated sheathing, outdoor temperature, indoor RH, and the vapor permeance of the inner layer is clear. One important variable missing from the plot is moisture storage—the 0.5 in. plywood sheathing can store over 600 g/m^2 for a 10% MC rise, whereas the EPS itself can store less.

It should be clear from these examples that one cannot make a simple rule or statement about the need for vapor barriers and their permeance without explicitly dealing with

1. the interior temperature and relative humidity,
2. the outdoor temperature, and
3. the properties (the vapour permeance, insulating value, and moisture storage capacity) of other materials in the wall.

REASONS NOT TO INCLUDE VAPOR BARRIERS

A common misconception regarding low-permeance vapor barriers is that their inclusion where one is not technically needed provides an extra level of performance and resistance to moisture problems. Quite the opposite is true.

If one is used, the assumption must be made that the vapor barrier is located on the correct side of the enclosure. The “warm side in winter” rule provided by many sources, and widely held to be true in the building community, is often incorrect. If an enclosure is exposed to a moderate winter, with an average outdoor temperature of 10ºC, then condensation is unlikely to occur at all in winter. If the climate in summer is warm (e.g., an average of 25ºC), then the drive is likely to be inward more often than outward.

Another reason for avoiding low-permeance inside layers (whether labeled vapor barriers or not) is to promote the interaction of hygroscopic enclosure materials with the interior environment as an aid to moderating interior humidity conditions. This rather uncommon approach is described more fully in Straube and deGraauw (2001).

Encouraging Inward Drying

The most commonly understood reason to avoid low-permeance vapor barriers is to encourage vapor-diffusion drying. As stated in the introduction, vapor diffusion is the only mechanism available for drying once air leakage has been eliminated and drainage has eliminated extreme amounts of liquid water.

The common assumption is that drying occurs predominately to the outside in cool and cold climates, and, hence, vapor barriers on the interior do not unduly restrict drying since vapor does not diffuse to the interior. This assumption becomes less true as the climate becomes warmer and as the enclosure is exposed to more solar heating.

Wet materials have, almost by definition, a relative humidity of essentially 100%. These materials will dry to any region with a lower absolute moisture content, which is to say air with a dew point temperature lower than the temperature of the wet material. Thus, if interior conditions are maintained at cold weather conditions of 21ºC and 30% (with a dew point temperature of about 3ºC (37ºF), then any wet material within the enclosure warmer than 3ºC (37ºF) can dry to the interior. In practical damage terms, materials at a temperature below this will not rot, corrode, or support mold since these mechanisms almost stop at temperatures near freezing.

Spring season interior conditions are more likely to be closer to 50% RH, and hence only wet materials over about 10ºC (50ºF) will be able to dry inward. It is at these temperatures that deterioration can begin to occur at damaging rates. Hence, inward drying can occur from wet materials that are at dangerous moisture contents (high relative humidities) when the temperatures are also high enough for deterioration to proceed. In warm climates, the temperature of most enclosure layers will tend to be higher than about 10ºC (50ºF) for a large part of the year and so drying can occur inward. In colder climates, the temperature within a wall in the spring is also likely to often be 10ºC (50ºF) or higher.

Low-Slope Roofs and Inward Drying

The fact that all diffusion condensation is not damaging and that diffusion wetting can be safely balanced by inward drying, provided sufficient safe storage capacity is provided, has been promoted in the roof literature for at least 20 years. The literature indicates that the desirability of a roof that provided drying was identified as early as 1971. Powell and Robinson (1971) stated, “The most practical and economical solution to the problem of moisture in insulated flat-roof constructions is to provide a design that would have in-service self-drying characteristics.”

Many in the roofing industry have promoted inward drying for the following three primary reasons:

1. The exposed membrane of most low-slope roofs has very low-vapor permeance and, hence, low outward drying capacity.
2. Drainage of condensate is not useful in most practical low-slope roofs, and air leakage is well controlled in the field of the roof; hence, other drying mechanisms are unavailable.
3. Solar heating of low-slope roofs is understood as a powerful force driving water vapor inward.

Another reason supporting the concept of inward drying might be that millions of square meters of roofing have been successfully installed for many years without vapor barriers and have performed as well or better than roofs with vapor barriers.

It has also long been recognized that vapor barriers in the form of a separate layer or a specific vapor permeance are not always needed in roofs. Max Baker of the Division of Building Research published what is still one of the most significant books on roofing design (Baker 1980). In this book (pp. 224-227), he describes a simple technique for assessing the need for a vapor barrier. This method is based on a simple assessment of the monthly average moisture content of the interior and exterior air. His approach conservatively did not take into account either solar heating of the roof membrane or the resistance of the roof insulation to vapor flow. (The same method has been used in the previous section except that the relative vapor and thermal properties of different roofs were not accounted for by Baker). He provided an example of a building in Toronto (HDD = 4060ºC / 7300ºF) with interior conditions of 20ºC (68ºF) and 40% RH. The calculations show that the wetting potential is only 60% of the drying potential and so a vapor barrier would not be required. The assumption is that sufficient safe moisture storage capacity is provided to retain the winter wetting for drying in the summer.

Condren published a paper two years later that followed a similar approach as Baker but also estimated the effect of vapor permeance of the deck and insulation and solar heating (Condren 1982). This provided a more realistic and less conservative estimate. He also specifically listed a number of reasons why one would choose to avoid the use of a vapor barrier—the primary reason being:

> A vapour retarder will trap any roof leakage, and may create a large reservoir of water in the insulation, before the leak is detected. This reservoir lowers the thermal resistance of the insulation and wastes energy and it provides a source of water which will degrade most elements of the roofing system.

In 1985, Wayne Tobiasson published a series of maps of the U.S. and southern Canada that indicated the maximum interior RH that could be tolerated in roofs without a vapor barrier (but, of course, with an air barrier) (Tobiasson and Harrington 1985). These maps were developed (using Baker’s conservative method) in response to the lack of confidence in existing rules of thumb. For a balance of wetting and drying, his maps showed that an interior RH of almost 50% could be tolerated in climates such as Chicago. Tobiasson was as clear as Baker and Condren that installing a vapor barrier on the inside when one was not needed decreased the performance of a low-slope exposed membrane roof by trapping incidental water leaks inside the assembly.

Desjarlais (1995) revisited the concept of self-drying roofs by applying more sophisticated analysis techniques that included the effects of sun and vapor resistance of the building materials. His paper is of interest since it spells out the same problems of vapor barriers and requirements for roof performance as authors as far back as Baker have. In a more detailed and sophisticated manner, he presents results for a range of different climates, roof assemblies, and interior conditions. This paper also quantified the benefits of a moisture storage medium such as fiberboard. For a Chicago climate he found that an interior humidity of 50% could be tolerated.

In summary, simple design tools have long been available to a designer who wished to calculate whether a vapor barrier

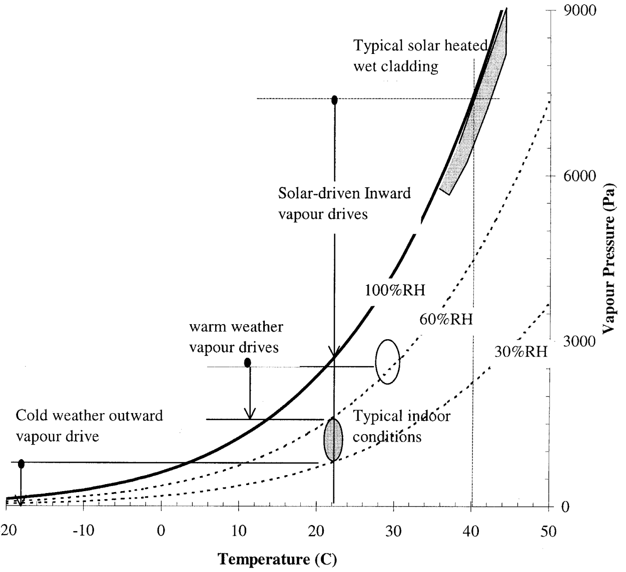

Figure 2 *Vapor pressures in and around enclosure walls.*

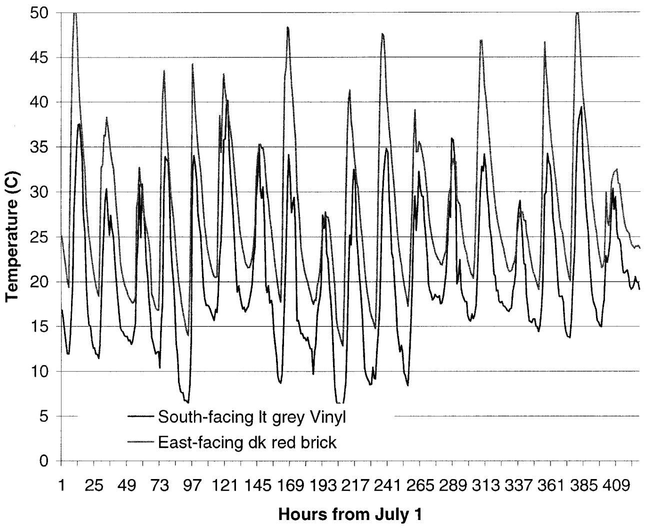

Figure 3 *July temperature of two claddings in the climate of Waterloo, Canada.*

was required (e.g., Baker and Condren's calculation methods and Tobiasson's maps). It has also been understood that including a vapor barrier on the inside has the drawback of trapping moisture within a roof. Research in the last decade has only served to emphasize these points. Despite this, roofing manufacturers, codes, and national associations still often recommend vapor barriers based on simple rules.

Solar-Driven Summer Condensation

One of the most compelling reasons for not providing a low-permeance vapor retarder on the interior of some enclosures even in cold climates is the phenomenon of solar-driven summer condensation. Figure 2 is a plot of vapor pressure versus temperature, which includes typical interior conditions, exterior weather conditions, and the effect of solar heating on wet materials. It is clear that any wet material (which will have an RH of 95% to 100%) that is heated by the sun will generate large inward vapour drives.

Cladding and sheathing directly behind the cladding can be heated to at least 20°C (36°F) above the interior temperature for several hours of many days of the spring and summer. In fact, the brick temperature of an east-facing red brick veneer wall monitored during the entire summer was above 40°C (104°F) for 187 hours (12% of the hours). South-facing claddings receive much less solar radiation in summer than east-facing claddings, and light-colored claddings absorb much less. A light-grey vinyl clad wall was measured over the same period and found to be above 40°C for only 79 hours (3.1% of the time). Typical hourly plots of temperature are shown in Figure 3.

The fact that summer condensation could occur in cold climates has long been known in the research community (Wilson 1965; Sandin 1991; Hensand Fatin 1995). In fact, a Canadian paper by Hutcheon (1953) described it as one of the fundamental design considerations almost half a century ago:

> When a vapour barrier is used, the wall can lose moisture only to the outside. In summer, hot sun following a rain drives moisture as vapour to the inside of the wall, and condensation behind the vapour barrier can occur.

Field measurements of walls by many researchers (Sandin 1993; Straube and Burnett 1998; Wilson 1965) have shown that damaging inward vapor drives do occur in the summer even in "cold" climates. As expected, others have confirmed that they occur in warm climates (Tenwolde and Mei 1985; Tobiasson and Harrington 1989).

Enclosures with high, outboard vapor permeance, wet materials (rain-wetted absorptive claddings or wet materials from leaks, built-in moisture, etc.), and low-permeance inner vapor barriers are the most at risk. For example, consider the wall assembly described in Table 3. If the fiberboard were "wet" (at a high humidity) or the wall clad with rain-wetted wood siding or brick, very high inward drives can be developed. This can be modeled by setting the fiberboard to 95% to 100% RH and calculating condensation as for the winter case. Table 5 presents these calculations. As can be seen, the rate of condensation on the inner vapor retarder would be about 13.6 g/m^2 h, or 325 g/m^2 day—about 100 to 200 times higher wetting than for the walls shown in Figure 1. These conditions will typically only occur for three to four hours per day. The impact of even the 79 hours above 40°C measured for the vinyl-clad wall can be seen to be dramatic—much more moisture can be moved inward in a warm July from a wet cladding or sheathing than would be moved outward in even a bitterly cold January.

Summer condensation should be more of a concern than it presently is in design practice for the following two reasons:

TABLE 5
Calculation of Summer Condensation

Flow into building

Permeance: 59.6 Pressure: 1175

Flow away: 70109 ng/m^2 s = 0.25 $g/m^2/h$

Net accumulation 13.64 $g/m^2/h$

RH% = 60%

Element	t (mm)	k	C	R	ΔT	t ºC	M	R_v	ΔP	P	P_{sat}	RH
						22.0				1578	2631	60%
Inside film	2	NA	8.30	0.120	–0.8		10000	0.000	5			
						22.8				1574	2754	57%
Vapor retarder	0	NA	0.00	0.000	0.0		60	0.017	784			
						22.8				2754	2754	100%
								0.017	1175			

Flow from back of sheathing

Permeance: 869 Pressure: 4438

Flow away: 3858595 ng/m^2 s = 13.89 $g/m^2/h$

Batt	90	0.036	0.40	2.500	–15.6		2000	0.001	1929			
						38.4				4683	6727	70%
Fiberboard	12.7	0.06	4.33	0.231	–1.4		1666	0.001	2316			
						39.8				6999	7267	96%
Outside film	2	NA	34.00	0.029	–0.2		20000	0.000	193			
						40.0				7192	7339	98%

1. the temperature of the condensation plane is usually much warmer in the summer so fungal growth and corrosion occur at much higher rates than at cold wintertime condensation planes;
2. the warm weather condensation plane is often close to the interior, a location within an enclosure that is rarely built with moisture-tolerant materials (drywall interior finishes are unlike cladding and sheathing products, which are often assumed to receive some wetting).

Nevertheless, most design professionals rarely consider the control of inward vapor transport through enclosures in cold and temperate climates, and some codes, such as the IRC, still require a low-permeance vapor barrier on the interior in warm climates.

The advantage of a moderate permeance interior layer (e.g., 180 metric perms) versus a very low permeance (e.g., 5 metric perms) sheet barrier is that much of the water vapor driven inward can be dried to the inside. The vapor pressures due to this mechanism are so high that summer condensation itself can only be avoided by placing lower-permeance materials on the exterior in conjunction with moderate permeance materials on the inside. The wall example in Table 4, for example, would eliminate summer condensation under many (not all) hours, while dramatically reducing (by an order of magnitude) the quantity of condensation when it occurs and allowing easy subsequent inward drying of this small amount of condensate.

Inward vapor drives can be controlled by avoiding rainwater absorption of cladding (on both the front and back side, since rainwater that penetrates most cladding can drain down the back and be absorbed) or the wetting of outer layers of the enclosure. A moderate vapor permeance on the exterior (e.g., a vapor permeance in the order of 100 to 200 metric perms) combined with a moderate vapor retarder on the interior (in the order of 150 to 300 perms) will reduce the severity and occurrence of summer condensation in many cool and temperate climates. In hot climates, the ratio of inner permeance to outer permeance must be increased beyond these ranges.

VAPOR CONTROL STRATEGIES

There is no doubt that vapor diffusion needs to be controlled in building enclosures. As suggested by the examples above, there are several ways to achieve this control. However, as shown above, the vapor pressure differences are often highest and most significant in warm weather (as distinct from warm climates) during drying of wet materials, not during cold weather.

Given these basic facts, several strategies for vapor control can be formulated. All of the strategies should be implemented only after calculations have been conducted to assess their impact. In general, simple calculations using the tabular format shown above are useful for understanding, but the use of detailed models is usually more accurate and more reliable. The accuracy of such computer models is limited by the input used. For example, the material data and weather files are detailed and may be difficult to obtain. A certain level of expertise is also required to use and interpret the results. However, anyone incapable of using a model such as WUFI-ORNL certainly does not have the analytical ability to decide on the need for, and the permeance of, a vapor control layer in an enclosure.

Low-Permeance Vapor Barriers

Typically located on either the interior or the exterior, depending on climate, the use of a low-vapor-permeance barrier assumes that diffusion wetting occurs primarily in one direction only. If the vapor flow direction reverses, vapor is trapped in the system and condensation can occur. Low-permeance vapor barriers can cause these types of systems to fail if the cladding is absorbent and exposed to rain and sun or if water enters the system through a flaw. A classic example of the limitations of the performance of this system is provided by exposed membrane roofs with leaky membranes—even a small amount of water penetration will be trapped in the roof and cause premature failure. EIFS are reasonably vapor-impermeable (the combined permeance of the finish coat, base coat, and 50 mm of EPS insulation can be less than 60 metric perms). If water penetrates into an EIFS wall through a window, for example, drying to the interior will not be possible if a low-permeance barrier is used on the interior, and damage can result. This scenario has been described as a vapor trap.

Storage System

Systems made of hygroscopic materials such as masonry and concrete can store significant quantities of moisture. The sheathing in wall systems used in the previous sample calculation can store condensation and high humidity during the colder times of the year and release it during the warmer. Similarly, the gypsum board and wood studs can safely store some small amount of summer condensation. In roofing, placing the membrane on fiberboard provides the advantage of an excellent moisture storage layer. This is the principle behind Desjarlais' self-drying roof (Desjarlais 1995).

Highly Permeable Walls

As shown in the examples above, increasing the permeance of the exterior layers of a wall can, in cold weather, eliminate the occurrence or severity of condensation. This can be achieved using highly permeable outer layers of sheathing (e.g., gypsum, fiberboard) and building paper. The cladding must also have a very high permeance or, if of low or moderate permeance, be able to absorb (a storage system) or drain the condensate that will likely form.

Alternatively, outward vapor flow through exterior cladding or roofing can be encouraged by venting. Ventilation also increases the equivalent vapor permeance of the outer layers of an enclosure, thereby reducing the need for low-permeance barriers on the interior during cold weather. A standard ventilated sloped residential roof assembly can perform in this way.

Insulated Sheathing

By modifying the temperature regime within the enclosure, the use of insulating semi-permeable foam sheathings can reduce or eliminate condensation (see Table 4). This strategy has the advantage of reducing the severity and occurrence of air-leakage condensation as well in cold weather while reducing inward vapor wetting in warm weather.

Integral Heat and Vapor Resistance

Some building systems use materials that have integral vapor and heat flow resistance. Materials such as closed-cell foams, logs, solid masonry, and aerated concrete provide sufficient vapor resistance, and the vapor pressure changes as quickly as the temperature through the wall. These systems can be used to resist inward and outward vapor flow but may also be vapor resistant enough to slow drying.

Summary

Provided the designer considers the interior and exterior conditions and the properties of the materials, any of the strategies described above can, and has been, used successfully for enclosure walls and roofs.

CONCLUSIONS

Applying, or requiring, low-permeance vapor barriers (e.g., those with a permeance of less than 60 metric perms or 1 U.S. perms) will not always eliminate diffusion-related condensation, nor are such vapor barriers required to ensure good performance in all or even most walls and roofs in most or all climates.

The preoccupation of codes and manufacturer's literature with vapor barriers is not supported by the small amount of diffusion wetting that can generally occur.

The influence of vapor barriers on the moisture performance of wall and roof systems is, in fact, a function of exterior climate, interior climate, solar absorptance, rainwater absorption, and the vapor and thermal resistance of all of the layers in the system. Any prescriptive code clauses or rules that do not account for these fundamental variables will fail to predict when and what kind of vapor barrier to use. In many practical situations, a low-permeance vapor barrier will not improve hygrothermal performance, and it may in fact increase the likelihood of damaging condensation or of trapping moisture in the system.

Some degree of vapor diffusion control is required in almost all enclosure systems. The relative location, vapor permeance, and insulating value of the materials that make up the enclosure should be used to control vapor diffusion-related wetting while enhancing the potential for drying. In some cases, a low-permeance vapor barrier may be called for, but in many practical high-performance enclosures, none is needed, and eliminating them will actually improve performance by encouraging drying and avoiding solar-driven diffusion wetting.

The preconceptions of many building codes, standards, and designers need to be modified to acknowledge the facts of low-permeance vapor barriers.

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