ASSESSING RISK OF CONDENSATION IN LOW-SLOPED ROOFS BASED ON BASIC SCIENTIFIC AND PROBABILISTIC PRINCIPLES

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Moisture and Roofing

Roofing performance is dictated to a large extent by how well it can prevent water leakage. Water can affect the performance of a roofing system in different ways. Visible water leakage through the roof into the interior is the most noticeable form of a dysfunctional roofing system. However, even when water does not show up as a leak, moisture that enters the roofing system and damages components will be considered a failure of the roof to function adequately.

The need for vapor barriers or retarders, (whatever the nomenclature, this author prefers the term "barrier"), and that of air barriers, is widely discussed. Confusion between air barriers and vapor barriers abounds. Debate about their function and need rages on, and dichotomies exist amongst design methods promulgated by various professionals (see *Figure 1*). Unfortunately, the roofs are in no position to understand these human vacillations and continue to either have no problems or big problems, depending on who you wish to believe.

So what is the down-to-earth roof consultant to do about making tough decision such as:

- Is a vapor retarder needed or not?
- Is an air barrier needed or not?
- If they are needed, where should they be located?
- Is venting effective?

No matter what the answers, there probably is some justification for each. But ultimately you, as a consultant, are responsible for your decision. Minimizing the risk in your decision requires an understanding and assessment of the risks before making decisions. Fortunately, the science related to the movement of moisture can help in qualitatively assessing the risks involved. This article provides the scientific basis that, used in its simple form, can provide the decision maker with reasonable assessment of risks involved.

MOISTURE FROM WATER LEAKAGE

It helps to distinguish between the sources of moisture entering the roof. Water leakage—so often characterized by waste baskets deployed for water collection and brown-stained ceilings—is what frequently causes the owners to summon consultants. Roofing systems in their primary form are designed to prevent water from such exterior sources as rain or melting snow/ice from entering into the roofing system. The major forces moving the exterior water to the interior are gravity and capillarity. The mechanisms and paths of water entry may vary, but the forces stay the same. This article assumes that the consultant is well versed in making sure that the forces of gravity and capillarity do not make the better of his or her design. A functionally waterproof roof is assumed.

AIRBORNE MOISTURE

Moisture that accumulates in the roofing system as a result of condensation is the issue at hand. Think of this type of moisture as a trail left by warm air which found the roofing components too cold for its comfort. For effective design, it is necessary to understand: Where did the warm air come from? And how did it get into the roofing system? Unlike water from the exterior, airborne moisture travels along with the air. Wherever the air goes, the moisture goes with it. The forces that drive the movement of airborne moisture result from the difference in air pressure and/or the difference in vapor pressure.

MEASURES TO ADDRESS AIRBORNE MOISTURE

There are various measures in dealing with airborne moisture that enters and condenses into the roofing system. The most common measures are the following:

Project Location	January Temperature	Maximum Permissible Indoor Relative Humidity Before a Vapor Retarder is Required		
		NRCA Guideline	CRREL Guideline	
			Ti = 68°F	Ti = 75°F
Miami, FL	47°F	100%	80%	64%
Atlanta, GA	22°F	45%	60%	48%
St. Louis, MO	6°F	45%	50%	40%
Chicago, IL	-4°F	45%	40%	32%

Figure 1: Different Methods Lead to Different Requirements for Vapor Barrier—NRCA and CRREL Guideline.

- Provision of an air barrier
- Provision of a vapor barrier
- Provision of materials that are unaffected by expected condensation
- Provision of venting within the roofing assembly
- Control of the interior environment

The level of effectiveness of each of these measures is at the heart of the debate among various roofing professionals. Understanding and using basic scientific principles as shown in this article can help assess the risks associated with condensation and thereby aid in selecting the most appropriate moisture control measures.

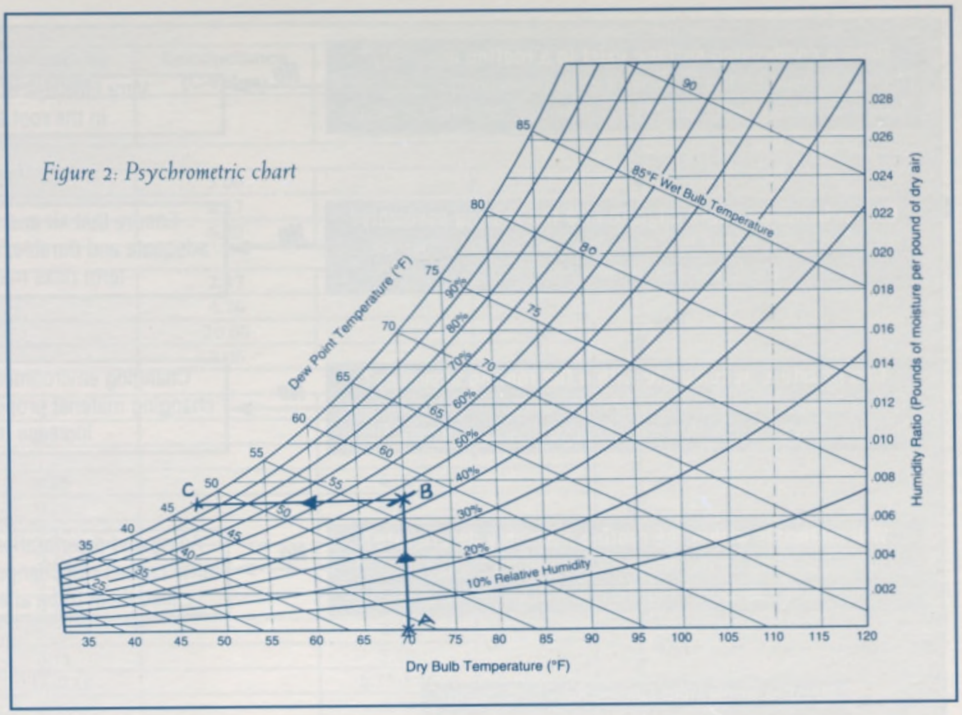

Figure 2: Psychrometric chart

Science of Moisture Movement and Accumulation

The science that deals with moisture in air and its relationship to the air temperature is know as psychrometry. Most of us are familiar with the concept of relative humidity, which is one of the properties that defines the condition of air. A psychrometric chart (*Figure* 2) shows the relationship between the relative humidity of air, the temperature of air, and the corresponding moisture content of air. The moisture content is expressed as a humidity ratio in pounds of moisture per pound of dry air. The humidity ratio gives a measure of the vapor pressure. Generally, the higher the humidity ratio, the higher the vapor pressure. It can be seen from *Figure* 2 and *Figure* 3, that air at different temperatures but with the same relative humidity has different humidity ratios (and therefore different vapor pressures). Warmer air has a higher humidity ratio than colder air at the same relative humidity. And remember, vapor moves from high moisture content (vapor pressure) to low moisture content (vapor pressure).

In order to assess what measures, if any, are required to deal with airborne moisture, the following questions need to be answered:

- Does a condensing surface exist in a roofing assembly?
- Can airborne moisture migrate into the roofing assembly?
- Can moisture accumulate within the roofing assembly?
- Will materials within the roofing assembly deteriorate from accumulated moisture?

The degree to which answers to the above questions are affirmative provides the degree of the risk of condensation. *Figure* 4 shows a flow chart of the above questions. In the rest of the article, we will see how fundamental scientific principles can be used to answer the above questions.

DOES A CONDENSING SURFACE EXIST IN A ROOFING ASSEMBLY?

Moisture will condense when the surface temperature at any point in the roofing assembly is below the dew point of the moisture-laden air (interior for heated buildings in cold climate). Dew point of air at a given temperature and relative humidity can be found from the Psychrometric Chart (see *Figure* 2). Locate the temperature of air on the horizontal axis—Point A (dry bulb temperature) and draw a vertical line until it meets with the curve of relative humidity—Point B. This point is called the" state point" of air with a given temperature and relative humidity. Draw a horizontal line from the state point to meet the line of 100% relative humidity—Point C. The temperature that can be read along the 100% relative humidity curve gives the dew point temperature. If the surface temperature at any point in the roof assembly is below the dew point of the air, then condensation will take place.

The temperature at any interface "x" in a roofing assembly can be calculated using the following formula:

Relative Humidity %	Temperature (^{0}F)	Humidity Ratio lbs/lbs of dry air	Dew Point of Air (^{0}F)
25	60	.003	<30
	70	004	34
	80	.005	43
50	60	.005	44
	70	008	51
	80	.011	59
75	60	.008	52
	70	.011	62
	80	.017	72

Figure 3: Relationship of Humidity Ratio Temperature and Relative Humidity.

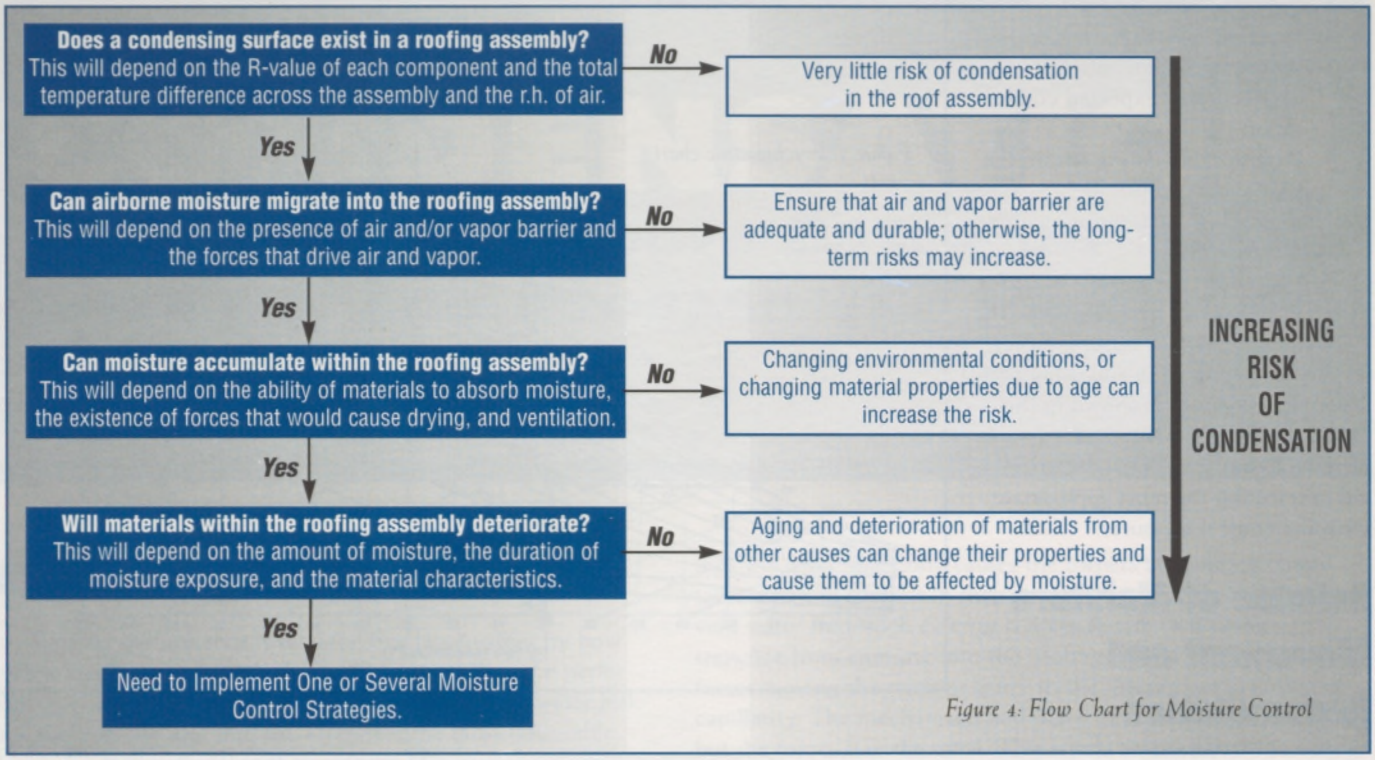

Figure 4: Flow Chart for Moisture Control

$$\frac{\Delta T_x}{R_x} = \frac{(T_i - T_o)}{R_T}$$

or

$$\Delta T_x = \frac{R_x (T_i - T_o)}{R_T}$$

where:

- R_x is the thermal resistance of all components from the inside to the surface x
- ΔT_x is the temperature difference between the inside and temperature at surface x that is $\Delta T_x = T_i - T_x$
- R_T is the total thermal resistance of the whole assembly, and
- T_i and T_o are the inside and outside temperatures respectively.

The thermal resistance can be calculated from values of thermal conductivity and thermal conductance or procured from the manufacturers. Thermal resistance is calculated as 1/C or as thickness/k. *Figure 5* provides the values of k and C for various common roofing components. Further details can be found in Reference 1.

Example: Determining surface temperature within a roofing assembly

The following example illustrates the calculation of surface temperature at a point within the roofing assembly. Consider the following assembly as shown below:

- Steel roof deck
- Expanded Polystyrene Insulation—two layers, 2″ thick each, having a density of 1.25 lb./ft.^{3}
- Single ply membrane.

It is required to calculate the temperature at the interface of the two layers of insulation. We will assume that the steel roof deck and single ply membrane have a high conductance and therefore negligible thermal resistance, and they will be ignored in this example.

From *Figure 5*, the conductance C of inside and outside air film are taken for winter conditions

$C_i = 1.63$

$C_o = 6.00$

From *Figure 5*, the conductivity k of insulation is

$0.25\ \text{Btu}/{}^{o}\text{F} \times \text{ft}^2 \times \text{h} \times \text{in}$

Thickness of insulation is $t = 4''$

$$R_T = \frac{1}{1.63} + \frac{4}{0.15} + \frac{1}{6.0} = 0.61 + 16 + 0.17 = 16.78$$

$$R_{\text{interface of two layers of insulation}} = \frac{1}{1.63} + \frac{2}{0.25} = 0.61 + 8 = 8.61$$

$T_i = 70^oF$, $T_o = 0^oF$,

$$\Delta T_{\text{interface of two layers of insulation}} = \frac{8.61\ (70-0)}{16.78} = 35.91\ {}^oF$$

Therefore the temperature at interface of two layers of insulation is equal to $(70 - 35.91) = 34.1^oF$. If the interior humidity was 45% at 70^oF, then the dew point from the Psychrometric chart would be approximately 48^oF. Since the surface temperature is lower than the dew point, there is a potential for moisture to condense if it comes in contact with the surface.

In summary:

- Condensation will occur at a surface when its temperature is below dew point of air.
- Dew point depends on relative humidity and temperature

Material	Conductivity (k-value)	Conductance (C-value)	Resistance (R-value) Per Inch thickness	Listed thickness
Roof Membranes				
Built-up membrane (aggregate surfacing)		3.00		0.33
Built-up membrane (smooth surfaced)		4.17		0.24
Roll roofing		6.50		0.15
Steep Slope Roofing				
Asphalt shingles		2.27		0.44
Fiber-cement shingles		4.76		0.21
Slate		20.00		0.05
Wood shingles/shakes		1.06		0.94
Roof Insulation Boards				
Mineral Fiber (basalt top faced)	0.24		4.20	
Cellular glass (faced)	0.33		3.03	
Expanded Polystyrene (EPS)				
1.25 lb/ft^3	0.25		4.00	
1.5 lb/ft^3	0.24		4.17	
2.0 lb/ft^3	0.23		4.35	
Extruded polystyrene	0.20		5.00	
Glass Fiber	0.26		3.82	
Gypsum Faced	0.89		1.12	
Perlite	0.36		2.78	
Polyisocyanurate faced	0.18		5.60	
Polyurethane	0.16-0.18		6.25-5.56	
Wood fiberboard	0.36		2.78	
Fill type roof insulation products				
Asphaltic/perlite insulating fill 22 lb/ft^3	0.40		2.50	
Foam Concrete				
120 lb/ft^3	5.4		0.19	
100 lb/ft^3	4.1		0.24	
70 lb/ft^3	2.5		0.40	
Cellular Concrete				
60 lb/ft^3	2.1		0.48	
20 lb/ft^3	0.8		1.25	
Vapor Retarder Materials				
Permeable felt		16.70		0.06
2-ply felt and asphalt membrane		8.35		0.12
Structural Deck Materials				
Cement-wood fiber panels	0.57		1.75	
Concrete normal weight (150 lb/ft^3)	20.0		0.05	
Concrete Lightweight (120 lb/ft^3)	9.1		0.11	
Precast Panels	12.5		0.08	
Gypsum 2" poured + 1/2" board		0.61		1.65
2" precast panel		1.41		0.71
Wood plank softwood	1.12		0.89	
Wood plank hardwood	1.25		0.80	
Plywood	0.80		1.25	
Ceiling Insulation and Finish Material				
Glass fiber batt	0.32		3.17	
Loose Fill Cellulose	0.32		3.13	
Gypsum Board	1.11		0.90	
Mineral Fiber board	0.35		2.86	
Air Film				
Exterior in winter		6.00		
Exterior in summer		4.00		
Interior heat flow up		1.63		
Interior heat flow down		1.08		

Figure 5: Thermal Properties of Common Roofing Materials

of air in question.

- Surface temperature depends on inside air temperature, outside temperature, and the ratio of the R-value to the condensation surface compared to the total R-value of the assembly.

Since the exterior and interior conditions vary, it is helpful to do the above for ranges of different temperature and relative humidity conditions. This will provide a better assessment of the risks.

Can airborne moisture migrate into the roofing assembly?

As explained earlier, there are two mechanisms that can move the airborne moisture to the condensation plane: air pressure difference and vapor pressure difference.

AIR PRESSURE DIFFERENCE

There are two factors to consider regarding the impact of air pressure difference to move the air to the plane of condensation:

- Magnitude of difference
- Resistance to air flow

Some form of air pressure difference always exists across roof assemblies. Air pressure differences used for wind load calculations should give a reasonable idea of the air pressure difference existing across the roofing system. More important, though, is to understand the nature of resistance offered by the various components in the roofing assemblies. In general, the more air-tight the assembly, the more resistance to air flow will be offered. By its very nature, the waterproofing component of the roofing assembly can provide resistance to air flow. However, flexible systems such as single-ply membranes that are mechanically attached can billow and cause enough suction to draw air into the roofing system. In such systems, the air tightness of the other parts of the roofing system can play an important role to reduce air leakage.

Also note that if holes exist on the high and low pressure sides of the roof, then air can flow through the roofing system. Such a situation can exist, for example, when there is a hole in the deck and there is a hole at a junction in the roof at the top of the flashing. This can cause air to travel between the two holes. If it meets a surface below its dew point during its travel, then there will be a potential to condense. The longer the path for air to travel, the more chances for it to condense.

In summary:

- The greater the chance of air to flow into the roofing system due to air pressure differences, the greater is the likelihood of condensation.
- The more openings around the roof on the high and low pressure sides, the more widely distributed and problematic the condensation.

Note that air resistance may also be required from the point of view of adequacy of roofing system attachment. This is not discussed in this article.

DIFFERENCE IN MOISTURE CONTENT OR VAPOR PRESSURE

There are two factors to consider in understanding the impact of vapor pressure difference in moving the air to the plane of condensation:

- Magnitude of difference between the humidity ratio on two sides of the roofing assembly
- Resistance to vapor pressure (typically given as the inverse of vapor permeability)

The magnitude of the moisture content for any given temperature and humidity conditions can be found by reading across on to the y axis of the psychrometric chart. The greater the difference, the greater is the propensity of vapor to flow into the roofing system and therefore to condense.

Resistance to vapor flow is offered by materials in the roofing assembly. A breathable or vapor permeable material provides less resistance than a non-breathable or vapor-impermeable material. Typically, the most resistance should be located on the side that is warmer than the dew point of the air. Otherwise, the vapor can reach the surface and condense before it even meets with resistance. Any vapor-resistive material that can allow air to move around it, (such as a steel deck), cannot be expected to provide vapor resistance, since the air will bypass the vapor barrier. There are some in the industry that feel that the vapor barrier need not be continuous. This should be carefully considered, especially in the following situations:

- Where the vapor barrier is part of an air barrier system that needs to be continuous.
- When holes or discontinuities in the vapor barrier allow convective air flows to develop (such as the case with steel deck).

It is possible to carry out detailed calculations to determine vapor flow. The details can be found in Reference 1.

In summary:

- The higher the vapor pressure difference, the higher the propensity for moisture to migrate
- The lower the resistance, the more propensity for moisture to migrate.

Can moisture accumulate within the roofing assembly?

The factors that will cause the moisture to accumulate are as follows:

ABSORPTION BY MATERIALS

Once moisture condenses, it goes from a vapor phase to a liquid phase (water) and maybe even a solid phase (ice). In a liquid phase, unlike the vapor phase, the water can be absorbed by materials. The absorption capacity of the materials is dictated by its porosity, density, and cell structure. Typically closed-cell products (even though of low density) will not absorb water unless the cell structure is damaged. Fibrous products, on the other hand, will absorb water. Organic facers on insulations are likely to absorb more water than inorganic facers. Higher porosity, lower density, and more open cells all make the materials more prone to water absorption. Even in situations where roofing materials may not absorb moisture—large gaps between insulation boards, for example—a condition may be created for water to accumulate at joints in the frozen state. This can be particularly detrimental to certain types of membranes, particularly BURs with organic felts.

DRYING

The vapor pressure drive and the air pressure drive can change directions. This may permit some drying. One way to determine the impact of drying is by conducting the vapor pressure analysis for the whole year as shown in *Figure 6* (see also Reference 2). A plot is made of the vapor pressure of interior air and the vapor pressure in the roof assembly at the condensation plane. During the summer months, the roofing system will have a tendency to gain solar radiation and, therefore, have a poten-

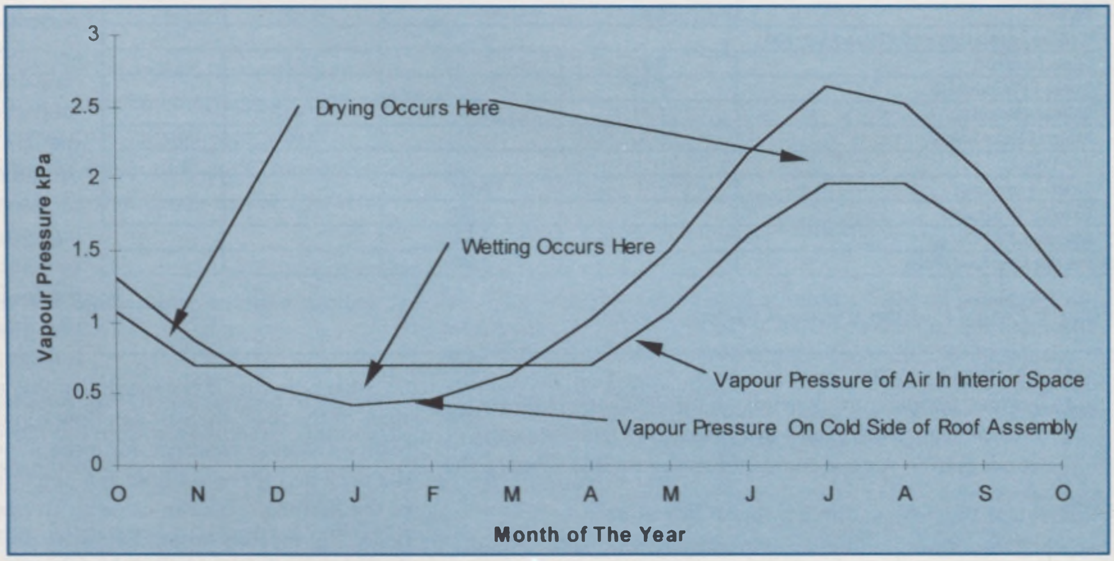

Figure 6 - Wetting and drying potential

tial for higher vapor pressure within the assembly. Area under the curve represents the wetting potential and drying potential. If wetting potential over the annual cycle is small compared to the drying potential, then some drying can be expected. A similar approach using the dew-point is provided in Reference 3.

Drying will be reduced due to the change of phase of vapor to water. This should be taken into account when assessing the risk. In areas with prolonged winter, the drying potential shown by the above method may not truly reflect the drying ability.

VENTING

Venting can be effective in preventing moisture accumulation. Venting essentially occurs when there is an air pressure difference between the plane of condensation and the space to which the roof assembly is vented (typically the exterior). For venting to be effective, there has to be an air pressure difference and an unimpeded path for air to move between the spaces that are vented. The air pressure difference can be provided by mechanical means or can occur due to stack effect. Pressures due to stack effect in a low-sloped roofing system are very small. This, combined with the high resistance to air flow offered by a compact assembly, makes venting difficult. Compact roof assemblies can benefit by providing an air cavity such as is done in a roofing assembly of a cathedral ceiling.

After substantial moisture accumulation has occurred, venting in compact, low-sloped roofing systems is unlikely to be effective. Change of phase from vapor to liquid or solid makes it difficult for venting to be effective. For venting to be effective in drying the moisture, a change of phase from liquid to vapor (evaporation) is required which can be difficult in a low-sloped compact roofing system.

In summary:

- Accumulation of moisture will occur if the moisture condenses and is absorbed by the materials.
- Vapor pressure reversals and air pressure reversals can induce drying. Over an annual cycle, the reversals may cause a net drying.
- Venting is difficult to achieve in a low-sloped roofing system where there is no air space in the system.

Will materials within the roofing assembly deteriorate from moisture?

The impact of moisture prompting materials to deteriorate or become dysfunctional varies. Typically, organic materials are more prone to deterioration then inorganic materials. The length of exposure to moisture and the extent of moisture in the roofing system will determine the amount of deterioration. The following are possible:

- Loss of R-value of insulation
- Rotting of organic materials
- Dimensional changes in materials causing stresses
- Loss of strength of roofing components
- Loss of strength of structural deck
- Freeze/thaw damage

Each of the materials in the roofing assembly should be assessed in terms of its properties to resist the above deterioration. An assembly such as a loose-laid rubber system with a closed cell type insulation is less likely to have an impact from moisture accumulation than a BUR with an organic felt and using glass fiber insulation with an organic facer.

Potential for damage from moisture accumulation should be assessed assuming both long-term sustained moisture accumulation (very little drying) and short-term but heavy moisture accumulation (high amount of moisture which can eventually dry out).

Summary

Impact of moisture condensation within a roofing assembly requires an understanding of the underlying physical principles. Appropriate moisture control measures can be selected by dealing with the following four issues:

- Existence of condensing surface within a roofing assembly.
- Potential of moisture to move toward the condensing surface, either by vapor diffusion or by air leakage.
- Amount and duration of accumulation which will be affected by absorptance of materials, drying potential created by environmental conditions, and venting of the roof assembly.
- Potential for deterioration and damage to materials from moisture accumulation.

Based on the above, one may decide to handle the risks of condensation by addressing one or all of the above issues as seen in *Figure 4*. As can be seen in the figure, moisture control may be achieved with a high level of certainty simply by completely addressing just one of the above issues. Dealing with several of the issues allows the user to handle uncertainties and allows redundancies to be built into the moisture control design of roofing assemblies.

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