AIR INFILTRATION:

THE ENEMY OF WIND RESISTANCE AND CONDENSATION CONTROL

By Philip Dregger, PE, RRC

ABSTRACT

Roof professionals spend considerable effort specifying and constructing roof systems to 1) survive windstorms and 2) to avoid damage from accumulation of condensation moisture. Yet, each year what appear to be appropriately designed and constructed roofs experience wind damage and condensation-induced deterioration. In part, this is due to overlooking a major cause of roof wind and condensation damage – excess air infiltration.

Figure 1 **shows a roof damaged by wind speeds well below code levels.** *Figure 2* **shows a roof with condensation-induced deterioration. In both cases, air infiltration played a major role in creating the problem conditions.**

This paper will review current design aids for wind resistance and condensation control and present several case histories illustrating how air infiltration contributed to roof wind and condensation damage. Finally, suggestions will be offered regarding how to identify and seal common air infiltration pathways.

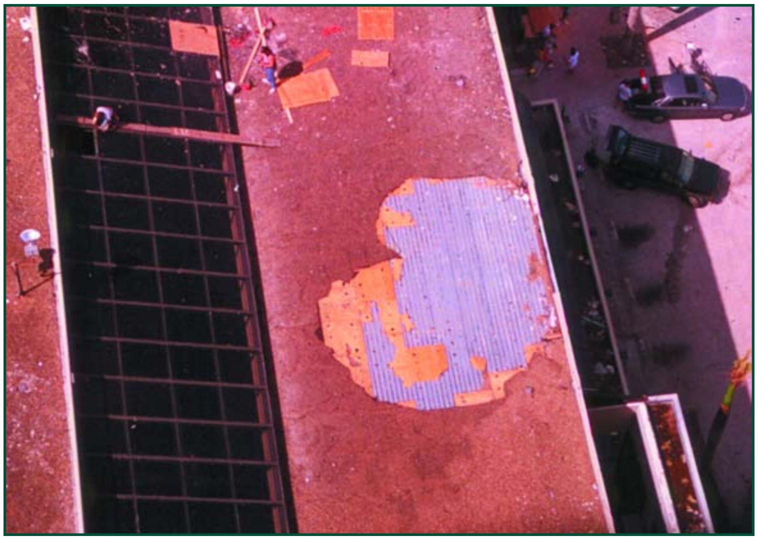

Figure 1: Roof damaged by wind speeds well below code levels.

Figure 2: A roof with condensation-induced deterioration.

Air Infiltration

Air infiltration, as discussed in this paper, refers to the physical transport of air into and within a roof assembly. For most applications, the concern is over the movement of air from inside the building into the roof assembly. However, for some applications, movement of exterior air into the roof assembly is of concern. Air infiltration is not the same as attic ventilation.

Aerodynamics and Load Transfer (Membrane Roofing)

Winds accelerating up and over a building create zones of air pressures on top of the roof that are much less than those of the still air inside. These differences in air pressures create uplift forces on the roof deck assembly. If the roof assembly incorporates air layers, the pressure difference, for a moment, acts just across or on the roof membrane (all air layers beneath the roof membrane are assumed to be at the same air pressure as the air inside.) However, if the roof membrane and/or insulation can move upward in response to the pressure difference (e.g., if the assembly is not fully adhered), much of the pressure difference very quickly shifts down to the deck.

For example, when strong winds blow over a low-sloped roof covered with a mechanically-attached roof membrane, the membrane moves upward and quickly reduces the pressure of the relatively small amount of air trapped between the membrane and the deck, to match that of the outside air (less the weight of the roof and tension forces in the membrane). This transfers much of the pressure difference (e.g., uplift force) down to the roof deck. Since most roof decks have large quantities of air available immediately below them, a corresponding upward deflection of the deck has virtually no effect in reducing the air pressure on the underside of the deck.

If the deck, either by design or by its nature, is sealed against air infiltration, the pressure difference (uplift force) remains primarily resisted by the roof deck.

However, if interior air can leak upward through the roof deck into the space below the membrane, the pressure difference above and below the deck gradually "equalizes," transferring the uplift load back up to the roof membrane (and attachment devices). The more permeable the roof deck, the faster uplift loads are transferred and the greater likelihood that the roof system itself will experience uplift forces associated with shorter and shorter durations of high wind conditions. *Figure 3* illustrates how rates of load transfer can differ between highly air permeable decks and decks that resist air infiltration.

In summary, although differences between outside and inside air pressures may start out primarily between the roof membrane and the outside air, relatively small movements of the roof membrane in compact, non-fully adhered roof assemblies rapidly transfer uplift forces down to the roof deck. Then, if air inside the structure can rapidly flow into the space between the roof membrane and the deck, portions of the uplift force transfer back again to act on the roof membrane and its attachment devices.

This shifting back and forth is of no consequence if the roof covering is able to resist the full uplift force and if the force is applied in a manner similar to how the system was tested. However, in some cases where air can rapidly infiltrate into the space between the roof deck and roof membranes, uplift forces can delaminate adhered roof membranes in "peel" and can balloon loose-laid and ballasted roof membranes upward during wind conditions far less than would otherwise be anticipated or required by code.

Wind Uplift Loads

Building codes stipulate the wind uplift forces that roof decks and roof coverings need to resist. Section 1504.1 of the 2000 International Building Code states that "Roof decks and roof coverings shall be designed for wind loads in accordance with Chapter 16 and Sections 1504.2, 1504.3, and 1504.4."

Codes provide various equations and charts to determine roof wind uplift forces. Some building codes require that the design wind loads for buildings over 60' in height to be determined in accordance with ASCE 7, "Minimum Design Loads for Buildings and Other Structures."

The concept of apportioning the design wind uplift force between roof assembly components is not addressed by building codes. For design purposes, it is typically assumed each component layer receives the full design uplift pressure applicable to that component. Note: Some building codes allow for reduced wind uplift pressures for design of air-permeable roof coverings (e.g., rigid tile).

Building codes and ASCE 7 define the uplift loads that a roof covering system needs to resist but not necessarily how to resist them. Some building codes reference Factory Mutual Global and Underwriters Laboratory test procedures for roof assembly wind resistance.

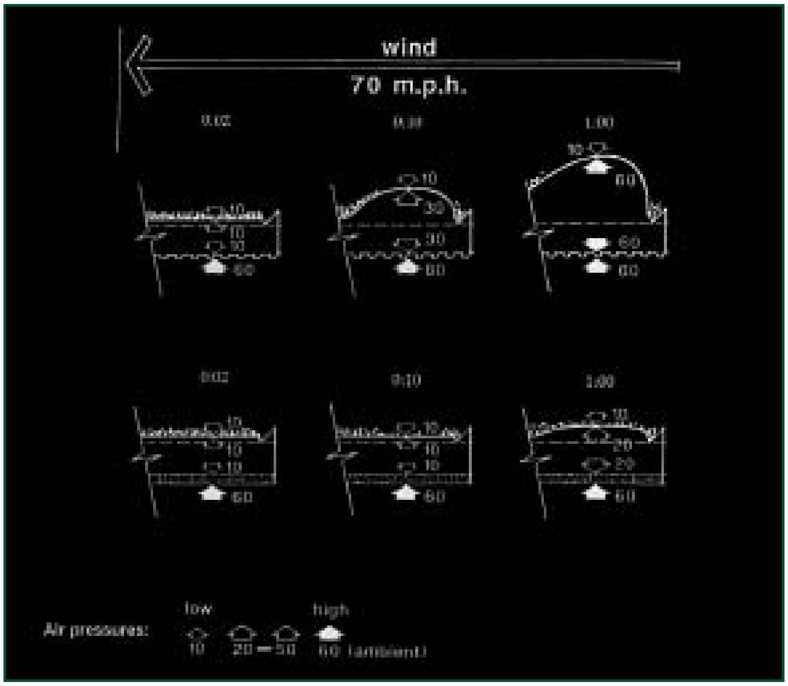

Figure 3: Rates of load transfer can differ between highly air permeable decks and decks that resist air infiltration.

Roof System Uplift Tests

FM Global and Underwriters Laboratory have developed test procedures intended to provide information about a roof system's ability to resist uplift forces. FM Global's Approval Standard 4470, "Class I Roof Covers," includes three test procedures for determining wind uplift resistance of roof coverings: "FMRC 5x9 Uplift Pressure Test Procedure," "FMRC 12x24 Uplift Pressure Test Procedure," "FMRC Uplift Pull Test Procedure," Underwriters Laboratory's Standard for Safety UL 580 "Tests for Uplift Resistance of Roof Assemblies," and UL1897 "Standard for Uplift tests on Roof Coverings."

Although quite different in specifics, each of these procedures (except the FMRC "pull test") involves securing a panel of the roof assembly in a test frame and applying differential air pressures below and/or above the test panel and monitoring performance. The panels include the roof membrane, insulation (if specified), and the deck.

It is important to realize that these tests all tightly secure the roof membrane along the edges of the test panel and there are no interruptions in the assembly (e.g., penetration opening) within the panels. Accordingly, information about the effective wind resistance of coverings where edges are not tightly secured or in areas near penetrations is not necessarily provided by these tests.

Design Aids

Since building codes do not provide "allowable" uplift pressures for specific roof assemblies, some sort of "rational method" is needed to select a specific roof assembly to resist specific code stipulated uplift forces.

FM Global Data Sheets, coupled with the *FM Approval Guide,* constitute one such rational method. For example, FM Global Data Sheet (DS) 1-28 indicates a 30-foot high roof in Galveston, TX, requires a Class 90 rated roof assembly if it is positioned in an Exposure C area and that a Class 105 rated assembly is required if the building is located in an Exposure D area. *FM Approval Guide* lists, by manufacturer, numerous roof assemblies rated I-90, I-105 or higher.

ANSI/RMA/SPRI RP-4, "Wind Design Standard for Ballasted Single-ply Roofing Systems," (RP-4) and FM Global DS 1-29 provide rational methods for selecting ballasted single ply roof systems to meet code stipulated wind speeds. Although these methods are based on wind tunnel studies and successful field experience, they pose a perplexing question – How can a loose-laid and ballasted roof system resist wind uplift forces well in excess of its own weight?

Although the complete answer is anything but simple, one reason loose-laid and ballasted roof coverings have a history of successful performance is that they are not usually subject to the full design uplift force; most of the load is resisted by the deck as explained above. Conversely, when a loose-laid and ballasted installation, for whatever reason, does allow large amounts of air to rapidly infiltrate into the space between the roof deck and the membrane, these types of roof coverings sometimes do not perform as predicted.

Examples of Wind Damage Associated With Air Infiltration

A three-story hotel structure with an aggregate-surfaced built up roof (BUR) over mechanically fastened insulation and a steel deck had wind damage along one side. *Figure 4* shows that the damage started near two roof drains with adjacent through-wall overflow scuppers midway along the windward side of the building. No damage was observed near corners. Observations indicated openings for air infiltration around through-wall overflow scuppers and around drains. Base flashings near overflow scuppers are believed to have lifted and initiated progressive peel fueled by rapid air infiltration around the drains.

Figure 5 shows a twelve-story office building with a smooth-surfaced BUR that experienced wind damage at wind speeds well below design levels. The BUR included a fiberglass base sheet fastened into lightweight insulating concrete (LWIC) over a structural concrete deck – an assembly typically viewed as "impermeable" to air infiltration. Investigation indicated a pathway for rapid air infiltration around the impermeable deck and into the space between the base sheet and LWIC. Relatively high-pressure interior air could flow up through stud spaces within EIFS-clad parapet walls, behind the wood fiber cant strips, and below the base sheet. Upward and outward movements of base flashings initiated progressive peel of the membrane. Base sheet deterioration contributed to the damage conditions.

A high school gymnasium was covered with a ballasted EPDM roof installed over LWIC and a steel deck – an assembly also typically viewed as "impermeable" to air infiltration. The

Figure 4: Damage initiated near two roof drains with adjacent through-wall overflow scuppers midway along the windward side of the building.

roof experienced damage at wind speeds well below design levels. Membrane ballooning initiated near one windward corner and progressed inward due to wind speeds below design levels. Openings for air infiltration were noted between the exterior masonry wall and the edges of the independently supported steel/LWIC deck.

Figure 6 shows a fourteen-story building with 4' parapet walls and a concrete roof deck. The fully-adhered, felt-back PVC membrane experienced wind damage shortly after installation. The system carried an FM 1-90 rating. Openings for air infiltration around the edges of the concrete deck were present in the stud spaces of stucco-clad parapet walls. Membrane base flashings did not include a termination bar at roof level – only along the top of base flashings. Air infiltration from below is believed to have billowed membrane base flashings outward and initiated progressive peel of membrane – a scenario consistent with eyewitness observations. Other non-air infiltration related conditions contributed to this example of damages at wind speeds well below design levels.

The common thread in the above examples is some sort of opening in the roof deck or perimeter walls that allows large amounts of air into the space between the membrane and the deck. The key, therefore, is to eliminate passages for air infiltration along perimeters and penetrations. Not only will this help maximize wind resistance, it will also help avoid another common problem – condensation.

Figure 5: A twelve-story office building that experienced wind damage at wind speeds well below design levels

Condensation Control in Non-Vented Roofs - Definitions

- Dew Point – The temperature at which a vapor begins to condense.
- Relative Humidity – The ratio of the amount of water vapor actually present in the air to the greatest amount possible at the same temperature.
- Water Vapor Drive – The difference of water vapor pressure between two points.
- Saturation Vapor Pressure – The vapor pressure associated with a specific temperature at which vapor begins to condense.
- Vapor Retarder – Any material with a perm rating of less than one.
- Air Retarder – Any material that retards airflow and is continuously installed.

Condensation Mechanics (winter condition)

In most climates and for most occupied buildings, the air inside in the winter is warmer and contains more water vapor than the air outside. Just as heat flows out through the walls and roof, water vapor diffuses out through the walls and roof. And, just as the temperature of roof and wall constructions gradually decreases in temperature from inside to outside, the "pressure" of the water vapor inside the building gradually decreases from inside to outside.

When properly designed, walls and roofs keep the inside surface warmer than the dew point. However, this means that the

Figure 6: A fourteen-story building with a concrete deck and a fully-adhered, felt-back PVC membrane surrounded by 4' parapet walls that experienced wind damage shortly after installation.

"dew point" temperature will occur somewhere within the roof or wall assembly. Again, when properly designed, condensation within the roof or wall assembly is avoided or controlled at low levels by installing vapor retarders and/or controlling the relative permeability of the different layers. This assures that the water vapor pressure drops fast enough as it migrates through the roof/wall assembly and cools off to stay below its saturation vapor pressure (dew point). If not properly designed, large amounts of water vapor can condense on surfaces within roofs and walls – sometimes with disastrous results.

Some model codes stipulate when a vapor retarder is required. The 2001 California Building Energy Standards, Section 150, states that for low-rise residential buildings in certain cold and temperate climate zones, a "vapor barrier shall be installed on the conditioned space side of all insulation in all exterior walls, unvented attics, and unvented crawl spaces to protect insulation from condensation." The 1997 Uniform Building Code (UBC), Table 15-E, Built-Up Roof Covering Application, states in regard to vapor retarders over insulated decks, "A vapor retarder shall be installed where the average January temperature is below 45°F (7°C), or where excessive moisture conditions are anticipated within the building…". The 1997 UBC does not define "excessive moisture conditions" and is silent in regard to vapor retarder requirements for other types of low-sloped roof coverings. The 2000 IBC does not have similar provisions.

Guidelines for Vapor Retarder Installation

Several industry organizations have published guidelines for when a vapor retarder should be installed in a roof system.

The National Roofing Contractors Association (NRCA) *Roofing and Waterproofing Manual*, Fifth Edition, 2001, suggests installing vapor retarders when two conditions are present – the average January temperature is below 40°F (7°C) and the interior relative humidity is greater than 45%. By these criteria, low-slope roofs in Galveston, TX, would not need a vapor retarder.

Cold Regions Research and Engineering Laboratory (CRREL) researchers Wayne Tobiasson and M. Harrington published a paper in 1986 that suggests vapor retarders be installed when interior relative humidity exceeds certain levels based on geographic location. The CRREL map of interior relative humidity levels (*Figure 7*) factors in general climate conditions. CRREL guidelines are intended to limit maximum winter wetting vapor drive conditions to 2.03 kPa•month (0.6 in Hg•month). This allowable wetting value was selected based on a survey of roofing professionals. Low-sloped roofs in Galveston, TX, would need vapor retarders only if interior relative humidity well over 80% were anticipated. However, summer condition condensation may well need to be considered.

Oak Ridge National Laboratory (ORNL) researchers André Desjarlais and N.A. Byars published a paper, "A New Look at Moisture Control in Low-Slope Roofing," in 1997 and developed a moisture "calculator" that suggests when a vapor retarder is needed, based on the types of insulation, membrane color, and building location. The ORNL guidelines consider climate conditions and the ability of insulation components to absorb moisture. ORNL criteria are intended to avoid any increase in the total moisture content of a roof system with time, avoid formation of condensation under the membrane during winter uptake, and avoid condensation on the upper surface of the roof deck after a small leak. See ORNL's website at http://www.ornl.gov/roofs+walls.

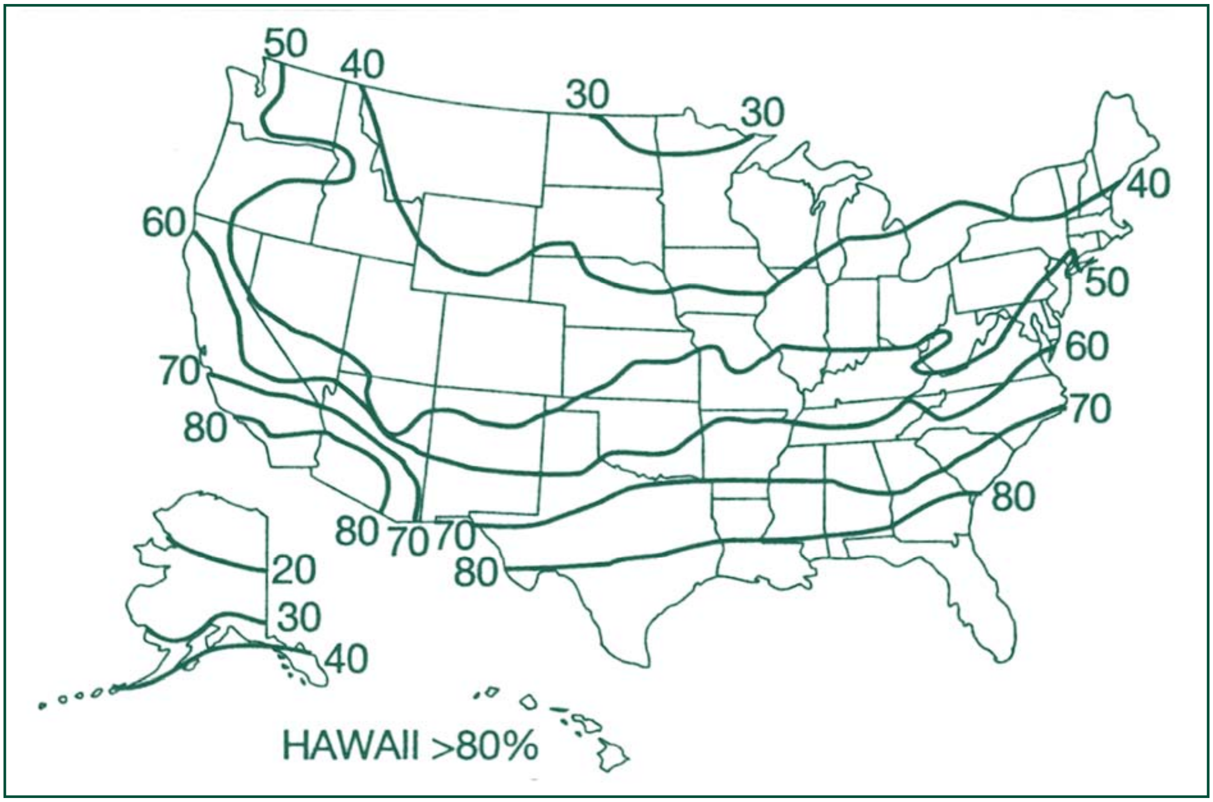

Figure 7: The CRREL map of interior relative humidity levels factors in general climate conditions.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) *Fundamentals* book recommends vapor retarders be installed as needed to keep actual vapor pressures within the building section below saturation levels (i.e., avoid condensation).

Please note that all of these guidelines assume no airflow within the roof assembly (e.g., ORNL instructions include a specific warning against air infiltration). And, except for the ASHRAE guidelines, they assume insulation is installed above, not below the roof deck. Therefore, if insulation is positioned below the deck or if significant air infiltration anticipated, these guidelines may not be appropriate and, if used, may be less than conservative.

EXAMPLES OF CONDENSATION CONDITIONS ASSOCIATED WITH AIR INFILTRATION

Health Club

A San Francisco Bay Area Health Club had a swimming pool and a workout/office area separated by a common wall. The swimming pool area walls included a vapor retarder and insulation installed above a sloped plywood deck with a shed-shaped, standing seam metal roof. The adjacent workout/office area had a low-sloped BUR installed over a plywood deck over insulated joist spaces and a suspended ceiling. Advanced deterioration was discovered in the roof deck and framing members over the office/workout areas – primarily adjacent to the common wall. Relative humidity in the office/workout areas ranged from 45% to 60%. Although immediately adjacent to a high humidity area; UBC, NRCA, CRREL, and ORNL guidelines did not indicate the need for a vapor retarder over the office/workout area. ASHRAE type analysis indicated the potential for condensation during winter conditions. Observations indicated openings along the ridge of the metal shed roof allowed large quantities of moisture-laden air to bypass the vapor retarder and flow into the stud spaces of the common wall and then into the plenum area below the low-sloped roof area.

The familiar guidelines did not adequately predict the need for a vapor retarder because the guidelines assume "compact" assemblies with little or no opportunity for the physical transport of water vapor.

Figure 8: Saturated plywood conditions uncovered near tops of barrels.

Barrel Roofs

Several barrel-shaped roofs were constructed in a California coastal location during the winter season. The barrel roof assemblies, from top to bottom, consisted of standing seam copper, felt underlayment, an "ice and water" type self-adhering modified bitumen membrane, plywood, polyisocyanurate insulation, plywood, and a decorative wood ceiling. Steel support arches were encapsulated (hidden) within the roof assembly. The first few hot summer days near the end of construction produced multiple "leaks." *Figure 8* shows saturated plywood conditions uncovered near tops of the barrels. Since "construction"-related moisture was suspected as the cause, additional investigation was delayed for one year.

Test cuts performed one year later revealed increased moisture accumulation. Monitoring of temperature and humidity conditions, however, indicated very little vapor drive. UBC, NRCA, CRREL, and ORNL guidelines did not indicate a need for a vapor retarder. ASHRAE type analysis predicted condensation conditions during only the coldest few weeks of winter. Moisture accumulation occurred mostly near tops of ridges, but further observation showed that the locations were not uniformly distributed; very wet areas were positioned next to virtually dry areas. Although the roof assembly appeared on paper to be

OSHA TO PUBLISH ERGONOMICS "GUIDELINES"

The Occupational Safety and Health Administration has announced it will issue voluntary guidelines sometime this year to help reduce musculoskeletal disorders in the workplace. This announcement of this decision comes more than a year after President Bush revoked a Clinton Administration ergonomics rule that would have gone into place in 2002. The AFL-CIO dismissed the announcement as a "meaningless measure."

"compact" as constructed, there were many openings and small voids in which water vapor could easily flow. A correlation was noticed between areas of moisture accumulation and these openings for air infiltration into and within the roof assembly. Moisture tended to accumulate near and up-slope of the openings. Remedial work included installing a warm-side vapor retarder and venting above sprayed-in-place foam insulation.

Note: The installation of an "ice and water" type membrane below the entire copper roof as part of the original construction, created a very effective but counterproductive "cold-side" vapor retarder and air barrier. It contributed significantly to the condensation conditions. Ice and water type membranes, although quite effective against leaks from ice dams and against leaks from openings in transition areas, should not be installed over *entire* roof areas (in non-vented assemblies), unless review by qualified persons indicates condensation will remain within acceptable limits. For more information, see the article, "Steep Roofing Underlayments – Upgrades That Sometimes Aren't" by this author in the January/February 2002 issue of *Western Roofing* magazine.

Warehouse

A large Southern California distribution center with a BUR over a panelized plywood deck with a radiant barrier below also experienced condensation-induced deterioration. Occupants were alerted to condensation conditions when corroded joist hangers allowed a purlin to fall to the floor. UBC, NRCA, CRREL, ORNL, and ASHRAE (*Figure 9*) guidelines indicated no need for a vapor retarder. Observations indicated a correlation between deterioration conditions and high points in the deck and near joist spaces with various penetrations. Among other things, the condensation conditions were attributed to convective air movements transporting large amounts of moisture-laden air into areas with surfaces below the dew point of the water vapor. Remedial action by others included replacement of much of the roof deck and cutting back the radiant barrier about 1/2" at each end of each joist space. (See American Institute of Timber Construction Technical Note No. 20, "Guidelines to Minimize Moisture Entrapment in Panelized Wood Roof Systems.")

Cautions Regarding Air Infiltration Are Not New

- The 1986 Dow Technical Note No. 20, "A Guide to Achieve the Secured Single Ply," states that "prevention of air infiltration into the area beneath a loose-laid single-ply membrane is a key ingredient to its wind stability."
- The 1989 *NRCA Energy Manual* states that the "key to condensation control in roofing systems is control of air leakage." The 1996 *NRCA Energy Manual* adds that "air leakage can be responsible for conveying several times as much water vapor into the roof system as diffusion."
- The 1989 ASHRAE Fundamentals Chapter 22 states that "under one set of conditions, six or seven times as much water can be deposited as a result of air leakage as by vapor diffusion… under different circumstances, the rates could be 100:1 or higher."

How Much Air Infiltration Is Too Much?

Little information is available regarding how sensitive roof coverings are to air infiltration. Many roofs with imperfect air/vapor retarders perform quite adequately. Some do not. Further research is recommended into quantifying the effect of different amounts of air infiltration on roof wind uplift resistance and condensation control.

In terms of condensation control, the question is quite complicated. Field observations suggest that although some air infiltration can be harmful, in some circumstances, relatively large amounts of air infiltration may facilitate summer drying conditions.

Suggestions For Enhanced Roof Wind Resistance and Condensation Control

- Comply with codes and recognized design aids.
- Install vapor retarders where required or needed.
- To enhance wind resistance, seal pathways that allow rapid air movement into the space between the roof deck and the roof membrane. Please note that some roof assemblies, if air sealed at edges, have FM Global uplift ratings more than 45 psf greater than the identical roof assembly without perimeter air sealing.
- To enhance condensation control, avoid cold side vapor retarders when practical and seal openings that may allow rapid air infiltration into insulated spaces. Make sure vapor retarders also serve as air retarders.

Note: This document does not address mechanical systems – a critical component.

Conclusion

Several design aids exist to help roof professionals select roof systems to survive high winds and to avoid harmful accumulations of condensation moisture.

Field experience indicates that air infiltration can reduce roof wind resistance by exposing roof coverings to wind forces and uplift conditions that vary from conditions tested. And air infiltration can greatly increase condensation moisture accumulation by physically transporting water vapor into zones where surfaces are at temperatures below the dewpoint. Relatively simple measures to seal pathways for air infiltration can help avoid harmful effects associated with excess air infiltration.

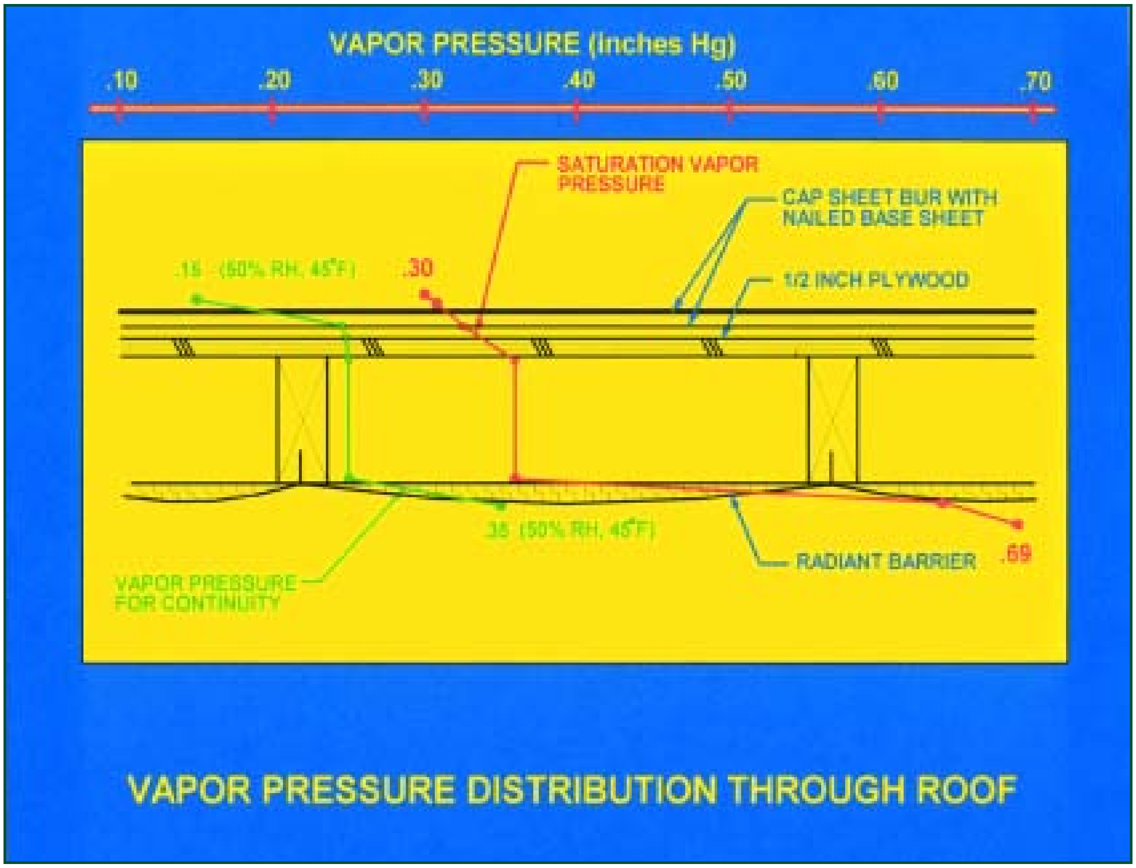

Figure 9: UBC, NRCA, CRREL, ORNL, and ASHRAE guidelines indicated no need for a vapor retarder.

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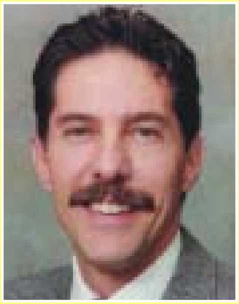

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