Laboratory and Practical Experience with a Novel Water-Permeable Vapor Retarder

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ABSTRACT

This paper describes a novel water-permeable vapor retarder (WPVR) that can help solve some of the moisture problems that frequently occur in certain roof and wall constructions.

Preliminary results are given from investigations on moisture movements in exterior wood-frame walls carried out in a climate simulator. Three different walls have been investigated: one with a polyethylene (PE) vapor retarder on the inside, one with a WPVR on one side of the insulation layer, and one with a WPVR on both sides of the insulation layer.

Results are given from measurements in a small test hut of the seasonal variation of moisture content of a number of roof segments with different vapor retarders, with or without a plywood deck between the insulation and the roof membrane.

The WPVR has been installed in a large number of roofs in Denmark. Results from a few case studies are given.

INTRODUCTION

To prevent interstitial moisture problems in a building envelope due to condensation, it has been common practice in most countries in cold or temperate climatic zones to install a vapor barrier or vapor retarder with a low water vapor permeance on the warm side of the thermal insulation layer. The purpose of the vapor retarder is to reduce the amount of water vapor migrating into the envelope by diffusion to an amount small enough to migrate through the envelope to the outside without causing condensation.

In cold climates, flat roofs constitute a special problem owing to the highly impermeable roofing membrane (ASHRAE 1989).

In zones with a warm, humid climate and, therefore, a long air-conditioning season but also with a short but rather cold heating season, there exists the controversial problem of where to place a vapor retarder in the exterior building envelope—on the inside or the outside of the insulation layer (TenWolde 1985).

THE WATER-PERMEABLE VAPOR RETARDER

The water-permeable vapor retarder (WPVR), shown in Figure 1, consists of a synthetic fabric with good capillary suction properties sandwiched between strips of diffusion-tight plastic film (Korsgaard 1985). The strips are staggered with an overlap. The size of the overlap and the thickness of the fabric, together with the permeance of the plastic film strips, determine the diffusion resistance of the WPVR. With a fabric thickness of 0.012 in. (0.3 mm), an overlap of 2.4 in. (60 mm), a film width of 7.1 in. (180 mm), and a film permeance of 0.17 perm (9 $ng/m^2 \cdot s \cdot Pa$), the permeance of the WPVR membrane is 0.17 perm (9 $ng/m^2 \cdot s \cdot Pa$) corresponding to a 2-mil (0.05 mm) PE film. This means that less than 0.35 oz/ft^2 (100 g/m^2) of moisture will diffuse through the membrane during a typical northern European winter. The drying capacity of the WPVR is illustrated in Figure 2.

The WPVR membrane can be considered as a hygrodiode, since it stops moisture in the form of water vapor (usually coming from below) but allows moisture in the form of water (from above) to wick through.

EXTERIOR WALLS IN A HOT-HUMID CLIMATE

As a contribution to solving the controversy about the placement of the vapor retarder in buildings exposed to a hot, humid climate, preliminary laboratory tests have been carried out on a typical insulated stud wall.

Test Walls

Three test sections of a typical insulated wooden stud wall were built. The three sections were identical except for the type of vapor retarder and its location in the test wall. A cross section of the test walls is shown in Figure 3.

The sidings most commonly used in Denmark are open to air infiltration, which means that the condition of the air between the siding and the air infiltration barrier is close to the condition of the outside air. The siding, therefore, has been left out.

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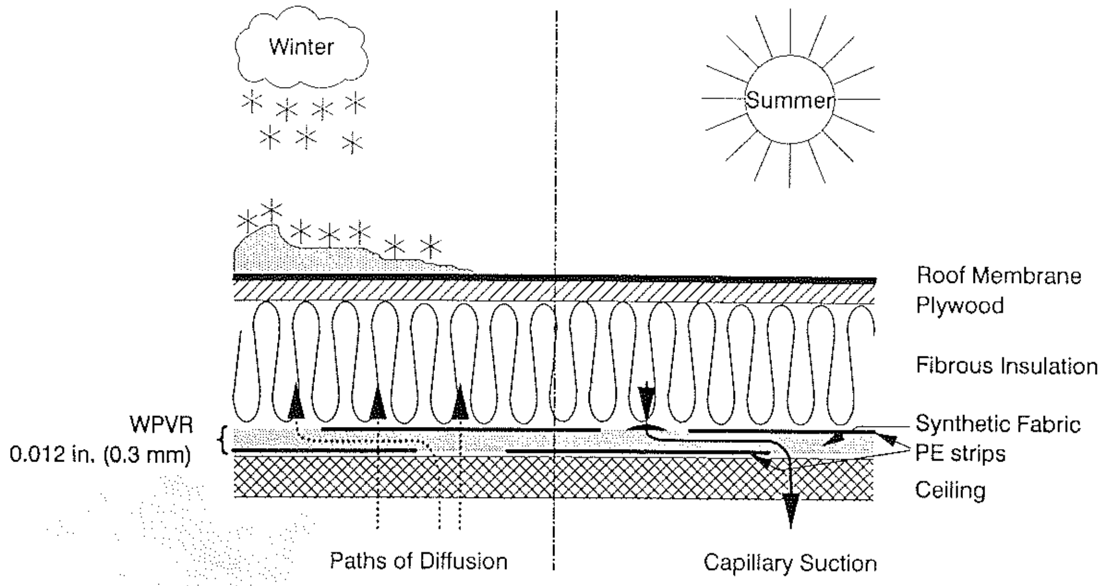

Figure 1 ***Embodiment of the water-permeable vapor retarder installed in a low-slope roof. The drawn membrane thickness is exaggerated.***

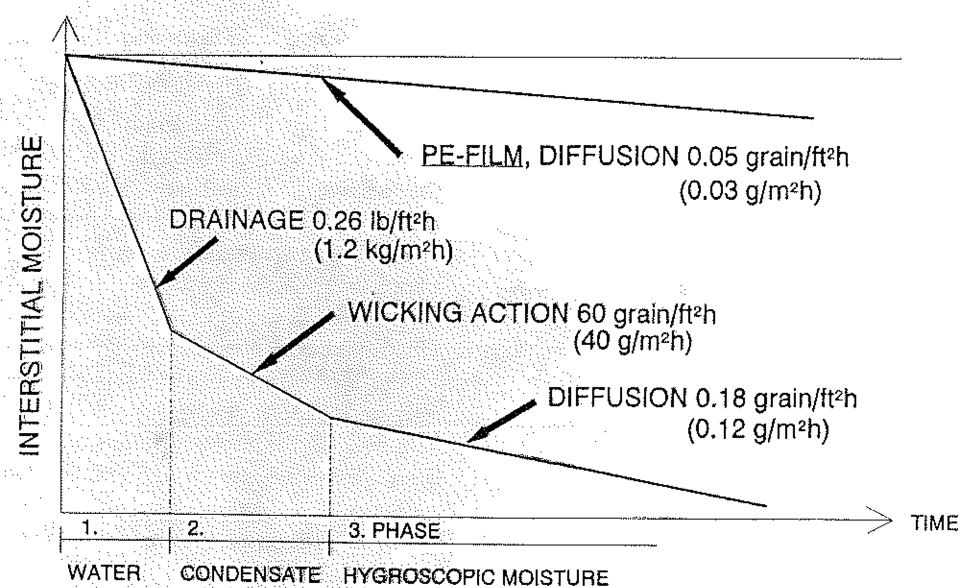

Figure 2 ***Drying capacity of the water-permeable vapor retarder.***

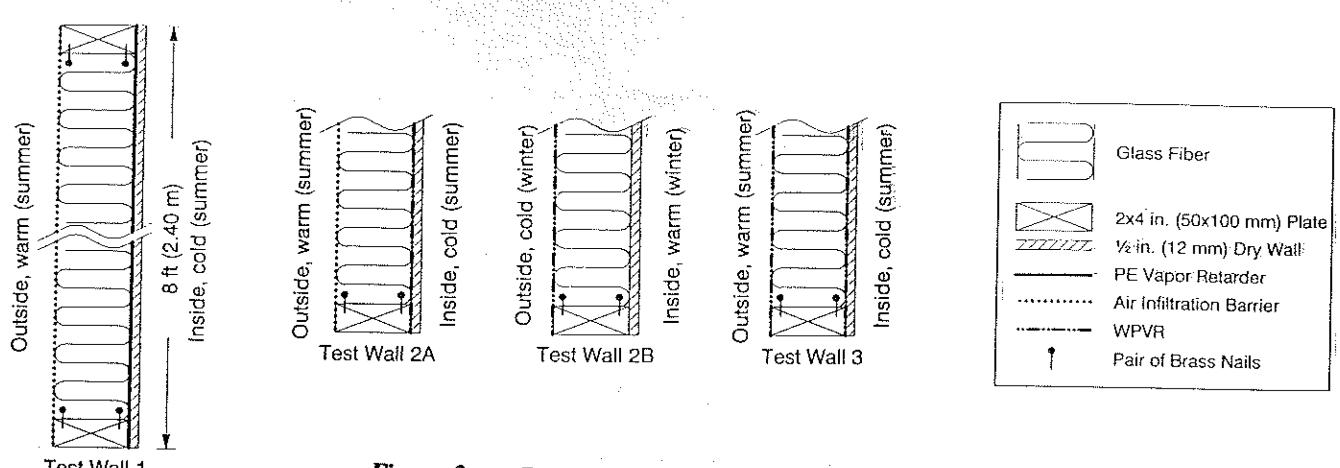

Figure 3 ***Cross section of the three test walls.***

The most critical part for developing a high moisture content and hence for mold or fungal growth is the sill (bottom plate). The less critical part is the top plate. The risk for the studs is in between. To determine the moisture content in the wooden plates, a pair of brass nails at a distance of ¾ in. (20 mm) was beaten into the bottom and the top plates. The electrical resistance between each pair of nails was measured and transformed into a moisture content using a calibration curve for similar types of wood. One pair was located ½ in. (12.5 mm) from the dry wall and one pair was located behind the vapor retarder or wind barrier on the outside (Figure 4).

Test Facility

The three test sections were installed in a partition 10 × 15 ft (3.1 × 4.5 m) of construction similar to the test walls, separating two climate chambers where the temperature and the relative humidity can be controlled separately (Figure 5).

Test Results

The development of the moisture content at the bottom and top plates of the three test walls is shown in Figures 6, 7, and 8.

The tests were run during three periods simulating a short summer period, an intermediate period, and a short winter period. Conditions for each of these periods were steady state and did not coincide with the real outdoor weather conditions during the tests.

Discussion of Test Results

Summer Period The summer period was 17 days in length, with outside air conditions of 84°F (29°C), 80% RH, and dew point 79°F (26°C) and inside air at 72°F (22°C), with 40% RH.

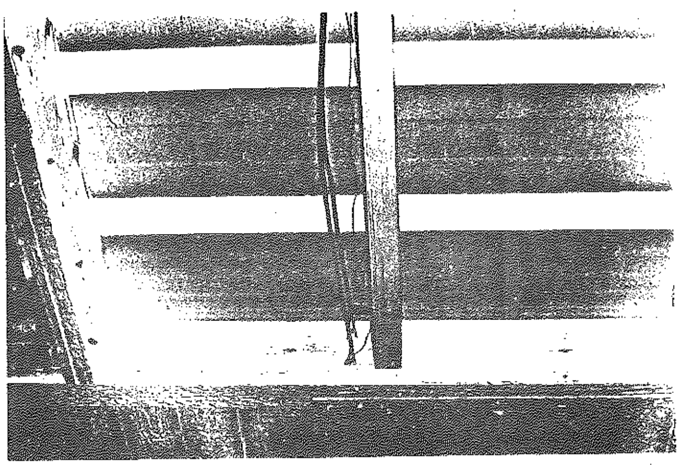

Figure 4 *Photo of the lower part of a test wall before installation of the insulation.*

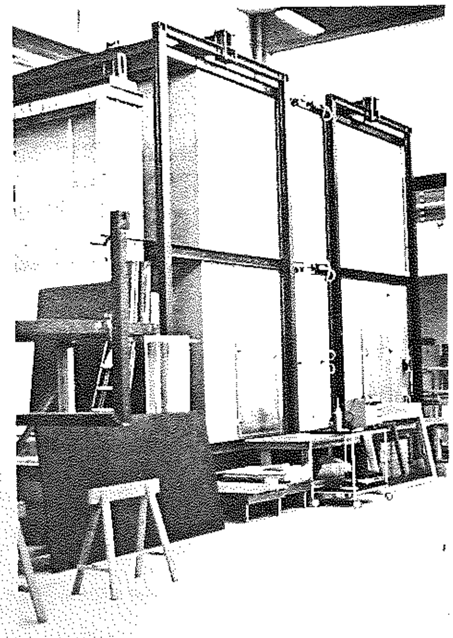

Figure 5 *Photo of double climate chamber.*

Test Wall 1 From Figure 6 it is seen that the moisture content of the sill close to the dry wall (inside) and close to the air infiltration barrier (outside) increases to fiber saturation within a few days. This is to be expected, since condensation will take place on the PE vapor retarder as its temperature is several degrees below the dew point of the outside air. Some of the condensed water will run down the PE film and be absorbed by the sill. The moisture content of the top plate increases more slowly to 13% at the cold side and 10% at the warm side. After an earlier, similar test period, the air infiltration barrier and the glass fiber insulation were removed. The sill was very black, and growth of mildew had started. The PE foil was completely covered with droplets from top to bottom, and the moisture

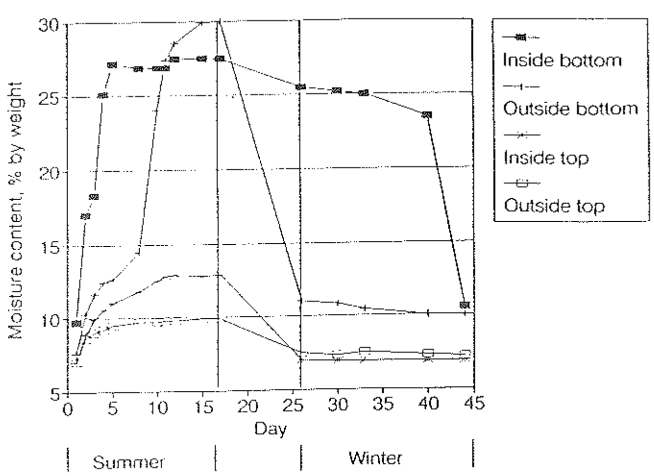

Figure 6 *Development of the moisture content of test wall 1.*

content of the glass fiber was gravimetrically determined to be 13% by weight at the top and 28% at the bottom. The top plate was not discolored.

Test Wall 2A The WPVR was located at the cold side (inside) during this part of the test. From Figure 7 it is seen that the moisture content of the sill close to the dry wall (inside bottom) increases to fiber saturation within a week. At the inside top, the moisture content increases to 14%.

The moisture content at the outside increases slowly to 10% at both the top and the bottom. After an earlier, similar test period, a slight discoloration of the sill near the cold side was observed. Droplets on the PE strips of the WPVR were also observed, and the visible strips of the wicking fabric were wet.

The moisture content of the glass fiber insulation was determined to be 7% by weight at the top and 10% at the bottom. By comparing the test results from Wall 1 with the results from Wall 2, one may assume that the WPVR on the cold inside has been able to wick through a significant part of the moisture condensing on the retarder and to reduce the amount of condensed water running down to the sill.

Test Wall 3 From Figure 8 it is seen that the plates at the top and the bottom stay completely dry. After a similar, earlier test period, the moisture content of the glass fiber was determined to be 1.0% by weight.

From this it may be concluded that the difference between the amount of water vapor diffusing through the WPVR on the warm side of the insulation and the amount diffusing through the WPVR on the cold side is too small to cause interstitial condensation during the test period. This would also have been the case with PE vapor retarders. If, however, wet insulation were installed between two impermeable membranes, it would dry out very slowly, whereas a WPVR would allow a much faster drying out, as shown in the section of this paper dealing with membrane roof systems.

Winter Period The winter period was 29 days in length with outside air at 40°F (4.4°C), 80% RH, and inside air at 72°F (22°C), 46% RH, and dew point 50°F (10°C).

Before the winter period was started, there was an intermediate period of one week where the climate chamber doors to the laboratory hall were open, and the condition of the air equalized at approximately 70°F (21°C) and 40% RH.

Test Wall 1 From Figure 6 is seen that the top plate dried up during the intermediate period. The outside of the sill almost dried up during the intermediate period, which was to be expected as there is no vapor retarder on this side to prevent or slow down the drying out. The inside part of the sill dried out during the winter period.

Test Wall 2B After the summer period, this test wall was separated and the WPVR on the inside was removed

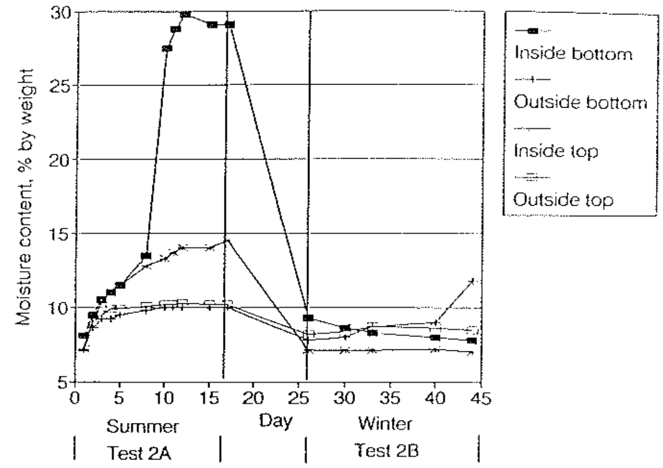

Figure 7 *Development of the moisture content of test walls 2A and 2B.*

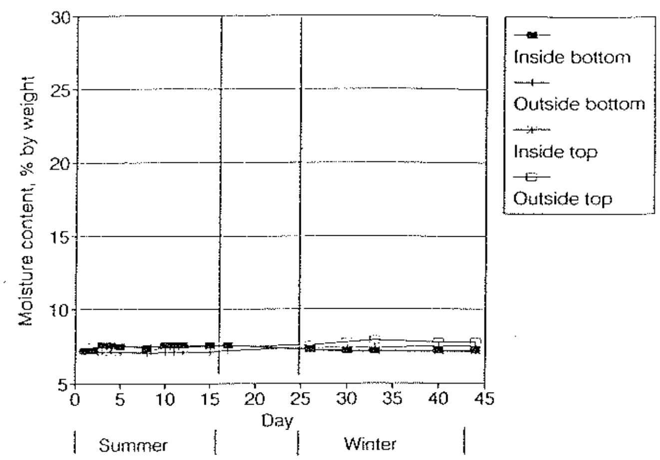

Figure 8 *Development of the moisture content of test wall 3.*

and placed on the outside just before the winter period was started. It is seen from the figure that both the top and the bottom plates completely dried out during the intermediate period.

The reason for changing the wall construction was to see if one WPVR placed on the outside of the insulation and no vapor retarder on the inside of the insulation would result in moisture accumulation in the plates and the glass fiber. From Figure 7 is seen that only a little moistening of the plates took place during the 19-day winter period.

As there is no siding, the WPVR can be observed directly from the outside. It was noted that after a few days condensed water on the inside of the WPVR was sucked through the retarder by wicking action.

Test Wall 3 As could be expected, no change in the moisture content of the dry plates took place during the winter period (Figure 8).

MEMBRANE ROOF SYSTEMS

To prevent water vapor from migrating into the roof systems by convection through flaws in the vapor retarder, both warm and cold deck roof systems should be unventilated, making use of the airtightness of the roofing.

Water vapor migrating into the roof system by diffusion during the cold season should be reduced to an amount that will not increase the moisture content to a critical value for fungal attack in wood-based roof systems, cause corrosion on metal parts, or decrease the insulation value significantly. This means that a vapor retarder with a sufficiently low permeance should be installed below the insulation.

The idea behind the WPVR is as follows: To allow moisture trapped in the roof during construction or later through leaks in the roofing to migrate out of the roof system, the vapor retarder membrane should be permeable to water. Such a membrane, similar to the one tested in the stud walls, was developed a few years ago and has been installed in approximately $5 \cdot 10^6$ ft^2 ($0.5 \cdot 10^6$ m^2) of roof systems in Denmark and Austria.

Moisture trapped in or migrating into the roof system will accumulate directly under the roof membrane during winter. When the sun heats the roof membrane, the vapor pressure will increase drastically in the top of the roof, and by diffusion the moisture will be driven through the insulation layer where it will condense on the relatively cold WPVR membrane. By wicking action, the condensate will pass through the membrane to the supporting deck and diffuse through the deck to the underlying room. A somewhat similar technique was described by Hedlin (1982) when he showed that a polyester fabric used as underlay for the insulation was able to drain moisture from slightly sloped roof panels.

Field Test of Flat Roof Elements

Experimental Setup Several different small sections of flat roofs were tested in an outdoor test facility. The small test hut consisted of two rooms, each 16 × 6 ft (5.00 × 1.75 m). One of the rooms was humidified at 60% RH throughout the year, while the other room was humidified to follow typical conditions for a Danish dwelling, i.e., 40% RH in February varying up to 65% RH in September. Electric heaters in each room maintained the temperature at 68°F (20°C). However, since no cooling was provided, the temperature was allowed to drift higher in the summer, especially in the southern room.

The Danish climate is a moderate Nordic one, with temperatures around the freezing point in winter and approximately 5,400 heating degree-days (3,000 K days). The winters when the experiment took place were a little milder than usual. An earlier experiment in the same test house was described by Korsgaard and Pedersen (1989).

Above the test hut were roof cassettes with holes for location of 15.7 × 13.8 in. (0.40 × 0.35 m) test elements. This way, eight different roof sections were tested over each room. A cross section of a roof cassette with a test element inserted is shown in Figure 9. Each test element consisted of a polymethyl methacrylate acrylic (PMMA) plastic box with the above-mentioned lateral dimensions and approximately 6 in. (150 mm) high. The roof cassette containing the elements is made of similar materials and approximately the same insulation thicknesses as in the test elements. Thus, the heat flow pattern should be fairly one-dimensional.

Different compositions of materials were used in the test elements. Half of the elements contained a ½-in. (12.5 mm) plywood deck located on the exterior side of the insulation, while the other half contained only insulation material between the top of the PMMA box and the vapor retarder. Most of the elements contained fibrous insulation —either rock or glass. However, a few elements were insulated with combinations of polystyrene and a thin layer (about 1 in. [25 mm]) of high-density fibrous insulation. The total thickness of the insulation ranged between 4.8 in. (122 mm) and 5.7 in. (145 mm) for all the elements.

Most of the elements had a water-permeable vapor retarder between the insulation and the ceiling/warm deck. However, for reference, one element had a plain PE vapor retarder, another had a PE vapor retarder with a single 0.4-in. (10-mm) hole, and three elements contained different types of membranes with higher permeances than typical vapor retarders. The purpose of the hole in one of the PE

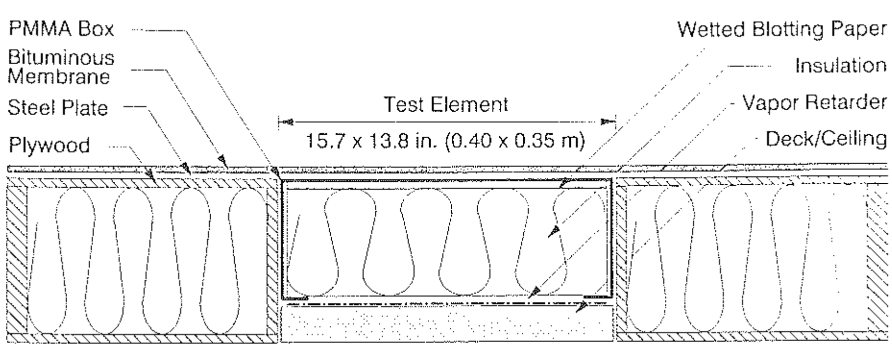

Figure 9 Cross section of test hut roof cassette with a test element inserted.

membranes was to simulate an imperfect vapor retarder and to compare moisture absorption in a roof element that had this membrane with the results from the other elements. The vapor-permeable membranes were used to investigate moisture uptake in the roof elements when only a small vapor resistance is provided. Ideally, the vapor resistance of the vapor retarder should not be larger than absolutely necessary to control moisture uptake during winter, since this will also prevent drying in the summer.

The roof cassettes have a continuous sheet of metal to support the load from traffic over the elements, and it is finished with a dark bitumen membrane strewn with mineral granules. The roof has a small northern inclination (1:40) to provide water runoff.

Materials used for the ceiling/warm deck were: 0.35 in. (9 mm) gypsum boards, ½ in. (12.5 mm) plywood boards, 1 in. (25 mm) wood wool cement plates, 1.8 in. (45 mm) concrete or perforated, corrugated sheets of metal. These materials are located outside the boxes themselves such that the materials inside the boxes are indicative of the conditions between membranes. The composition of all the elements and how they are located over the two rooms are shown in Figure 10.

The small size of the elements was chosen so they could be weighed on an accurate balance, which was done regularly throughout the period since the experiments began in November 1989. Before the experiment began, all materials were oven dried at 221°F (105°C), weighed, and put in a climate chamber to reestablish normal levels of hygroscopic moisture content. This way it was possible to determine the total moisture content of the elements by simply weighing the boxes and subtracting their dry weight.

At the end of the first winter, on April 25, approximately 0.308 lb (0.140 kg) of water, corresponding to 0.204 lb/ft^2 (1.00 kg/m^2), was added to a sheet of blotting paper that was inserted in the top of each of the boxes.

Danish practice is to consider 20% moisture by weight the critical limit for fungal attack of wood. When the roof has a plywood deck, most of the moisture in the roof will migrate to this layer during cold periods because it is the most hygroscopic layer and it is located at the exterior side of the insulation. Thus, the aforementioned critical limit may be transformed into a demand that the moisture content stay below 0.28 lb/ft^2 (1.40 kg/m^2) or 0.42 lb (0.190 kg) for the actual size of the plywood sheet.

Experimental Results The total moisture contents of the boxes are shown in Figures 11-14.

Three of the boxes show very large variations. They are the ones that have membranes that are more permeable than typical vapor retarders. Two of them (#14 and #16) were not installed until January 16, 1991, while the third (#5) had no vapor-retarding membrane before that date.

The rest of the elements showed more moderate variations and, as will be noted in the following, most of them showed a decline in moisture content after the water was induced.

Discussion of the Results The vapor-retarding membrane in roof element #5 is an asphalt-coated wind barrier with a moderate permeance (0.7 perm, SI vapor resistance 25 GPa·m^2·s/kg). It is seen from Figure 11 that the moisture content of the roof element with this membrane increased less steeply after this membrane was installed in winter 1990-91, although the subsequent summer drying

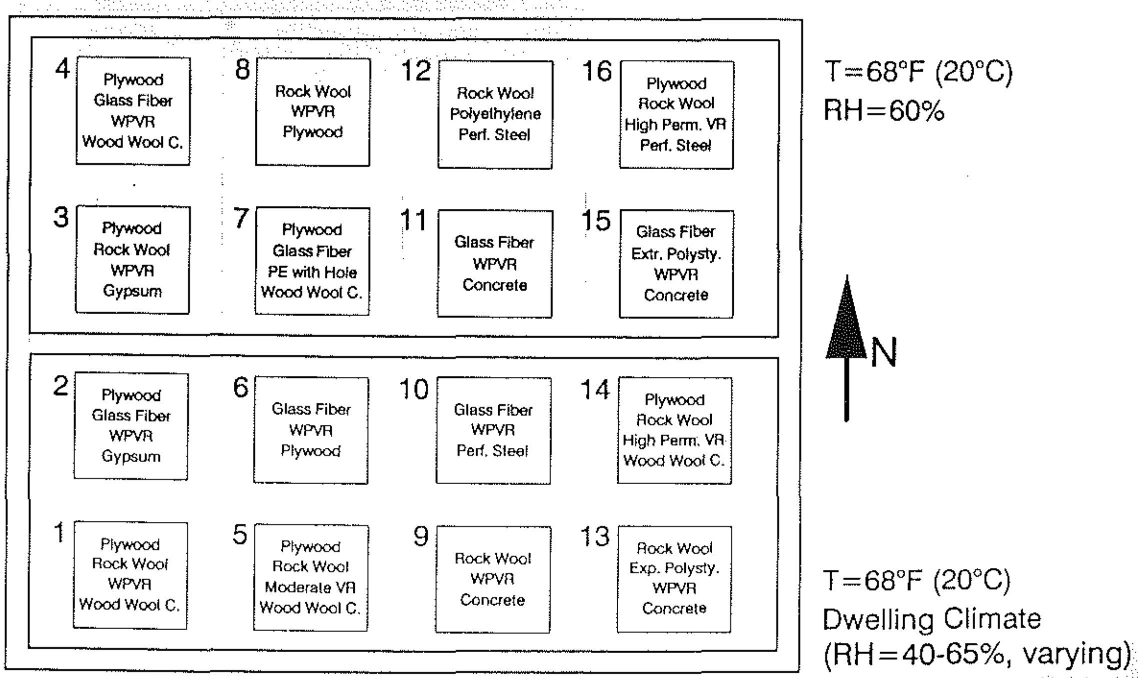

Figure 10 *Composition of test elements and location in the test hut roof.*

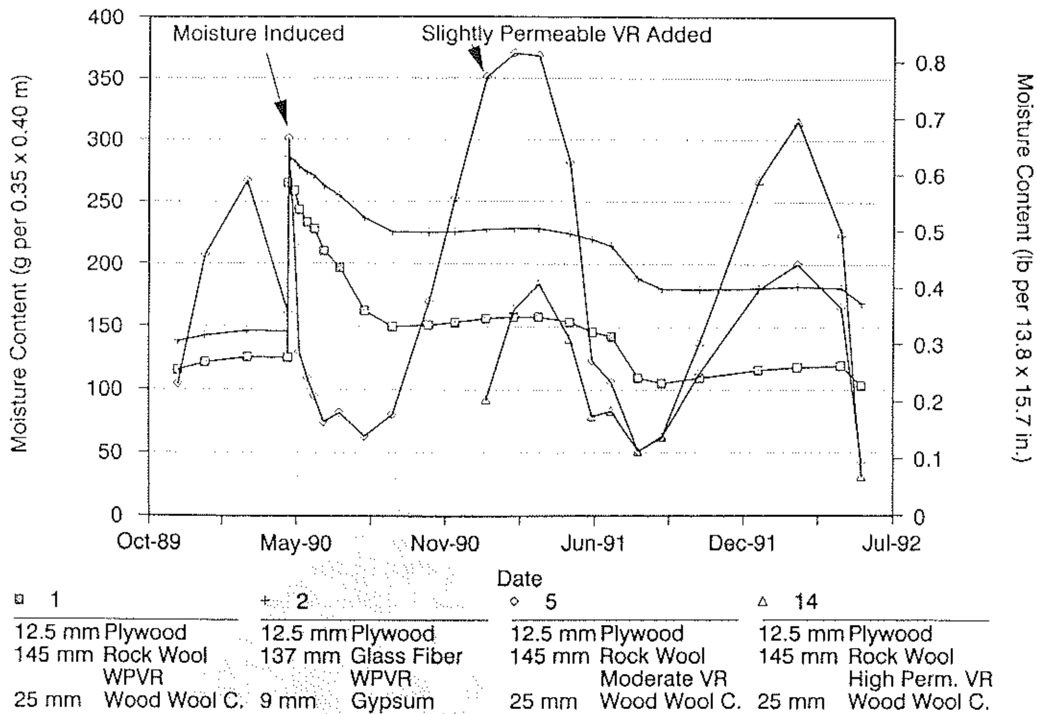

Figure 11 Moisture content in roof elements with plywood, dwelling climate.

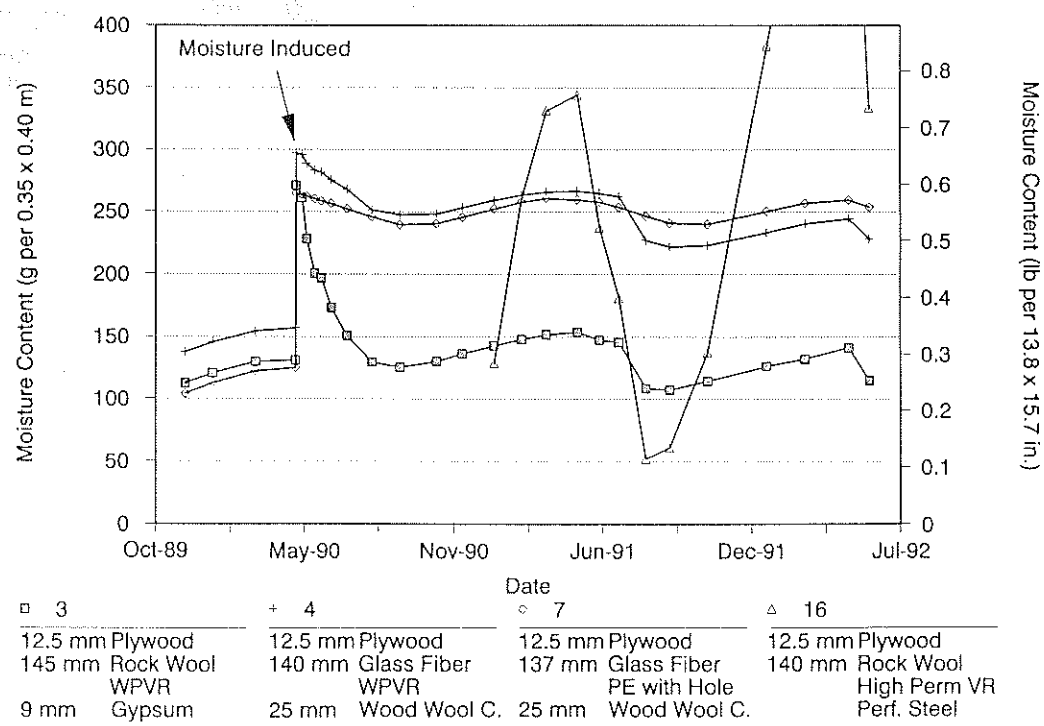

Figure 12 Moisture content in roof elements with plywood, 60% RH climate.

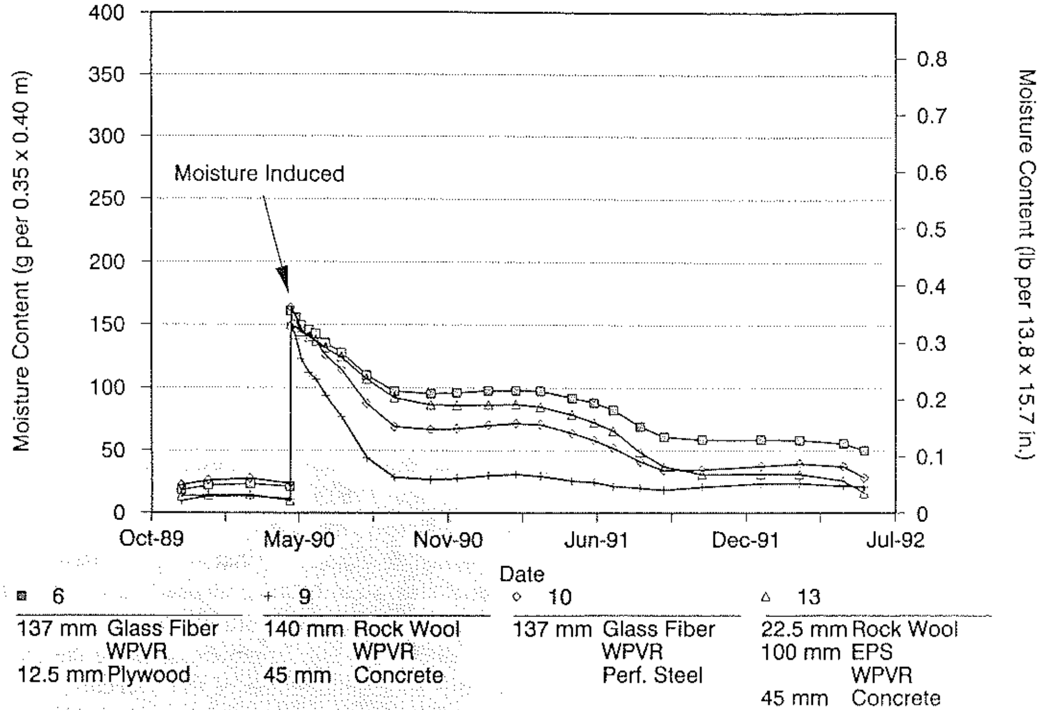

Figure 13 *Moisture content in roof elements without plywood, dwelling climate.*

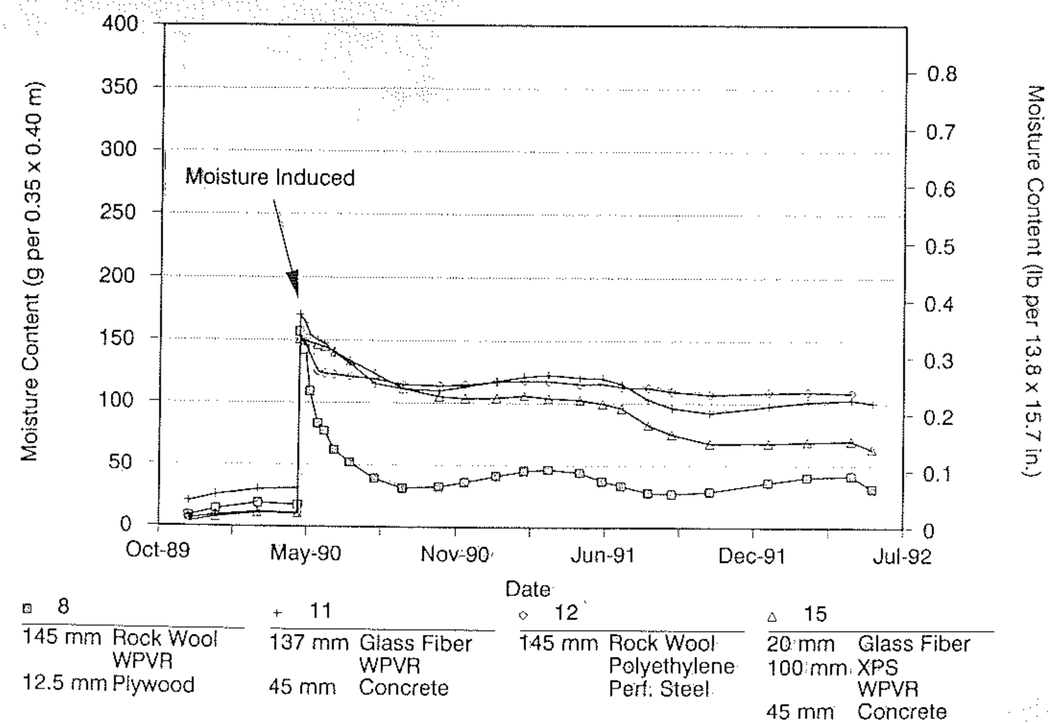

Figure 14 *Moisture content in roof elements without plywood, 60% RH climate.*

was fully satisfactory. The moisture content in this roof ends close to the critical limit for fungal attack during winter 1991-92, which means that this membrane is almost sufficient to prevent moisture damages in roofs over a dwelling.

The membrane in roof element #14 (Figure 11) is a spun-bonded polypropylene product that is very permeable (100 perm, SI vapor resistance 0.17 GPa·m^2·s/kg). The membrane in roof element #16 (Figure 12) is a perforated plastic foil (5 perm, SI vapor resistance 3.5 GPa·m^2·s/kg). The moisture content in the roof elements with these two membranes increases unacceptably fast during the winter period, such that there is a great risk that fungi will develop in the plywood of these elements. Element #16 over the humid climate contained 1.22 lb (0.553 kg) of moisture by the end of winter 1992. The plywood boards in these two elements were visually affected by the moisture (dimensional expansion, dark color, excess moisture visible as condensate between the top of the boards and the PMMA box), but severe fungal attacks were not obvious.

Roof element #12 (Figure 14) with the PE vapor retarder dried out somewhat shortly after the moisture was added. The tightening of the bottom of the PMMA box where the vapor retarder was fixed was improved, and since then migration in and out of the element has been very little—as expected. Roof element #7 (Figure 12), which has a hole in the PE, also shows a moderate, though larger, migration in and out of the roof. This shows that even though a hole covers only a small fraction of the vapor-retarding area, the amount of vapor transported through the hole is dominant over the diffusion through the rest of the membrane. Despite the variations, there is no annual drying or wetting of this element.

All the elements with a WPVR dried out some of the moisture that was added by the end of the first winter. However, there are differences in the rate at which the drying takes place depending on the indoor environment, the insulation material used, the presence of plywood within the insulated cavity, and the material used for the deck/ceiling. The absolute level of moisture content is largest for the roof elements with a plywood deck inside the box, since the wood will always contain some hygroscopic moisture. This, of course, is acceptable as long as the moisture content is not above the critical limit for fungal attack.

The greatest drying rates among the elements with a WPVR were seen in elements #1, #3, #8, and #9. These were all insulated with rock wool. The moisture that was added dried out of all these elements within the first summer. The drying rate was the same over both rooms (because the relative humidity was about the same during summer), while the elements over the humid room (#3 and #8) absorbed a small amount of moisture during winter. The vapor permeability of the WPVR is a little larger than for regular PE vapor retarders, but, as can be seen, the moisture absorption during winter is not critical.

The drying rates of similar roof elements with glass fiber insulation (#2, #4, #6, #10, and #11) were noticeably less. Since the glass fiber and rock wool should be equally permeable materials, the same amount of moisture was expected to have condensed on the WPVR and drained out of the assembly. To investigate this, one of the elements (#2) was opened on August 6, 1990, to determine how the moisture was distributed among the materials inside the box. Of the 0.31 lb (0.140 kg) that was added, 0.19 lb (0.087 kg) remained to be dried out. Of this, the plywood contained 0.06 lb (0.028 kg) and the glass fiber 0.13 lb (0.058 kg), while there was almost no condensate on the WPVR (notice that the moisture deposited in the glass fiber may be potentially harmful for the plywood if not dried out of the roof before the subsequent fall). A separate analysis (Pedersen 1991) revealed that the glass fiber used was considerably more hygroscopic than the rock wool and retained the moisture that would otherwise (as when rock wool was used) have condensed on the WPVR and drained away. The elements with glass fiber insulation do dry out, but even after two summers, some of the moisture that was added remains in some of the elements.

Elements #13 and #15 have hybrid insulation systems of which expanded or extruded polystyrene has the dominating thickness. Both of these dry out at a slower rate than was seen with rock wool insulation, which was expected since these insulations are less permeable and therefore impede downward moisture migration during summer. However, after two years, most of the moisture added to these elements had dried out.

Case Studies

Roof Over Auditorium Building The roof over one of the auditorium buildings at a Danish university had a leaky membrane and a very tight vapor retarder, such that the insulation had become soaking wet. In the restoration, the old insulation was replaced with new high-density rock wool batts (5.7 in., 144 mm). The old aluminum-laminated bitumen vapor retarder was nailed to the wooden deck, so in a test area it was easy to tear off and replace with a WPVR. On top of the insulation was a layer of synthetic fabric that was watered with a garden hose before finishing the roof with a black EPDM-membrane (see Figure 15). Weighing, drying, and re-weighing arbitrary sections of the fabric used as a sponge indicated that about 0.2 lb/ft^2 (1 kg/m^2) of moisture was added to the roof.

In the top and bottom of the insulation were built-in moisture probes of wood whose electrical resistance was measured and transformed into moisture content of the wood using a calibration curve for these probes. Since the wood probes get into equilibrium with their environment, these signals are used as a relative measure of the moisture conditions at these two places. It is preferred that the moisture content remain below 20% by weight (this

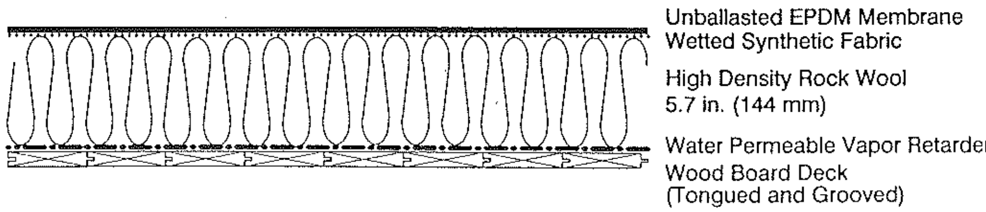

Figure 15 *Cross section of roof over auditorium building after reroofing.*

corresponds to approximately 85% RH around the probe). The probes become inaccurate above fiber saturation (about 30% by weight), so this limit may be taken as an indication of a too-wet condition around the probe (i.e., close to 100% RH).

The experiment started in the fall of 1987 and measurements have been taken regularly since then. Results are plotted in Figure 16. The moisture content remained high in the top of the roof throughout the first year and into the second summer when it suddenly dropped. The summer condensate formed on the topside of the WPVR and caused an increase in the probe readings at this location the first two summers. During this period, the WPVR was wetted by the summer condensation, and moisture would drain through to the wood deck. The subsequent seasons showed only small variations in moisture content—all in the region from 6% to 14% by weight. The situation corresponds to having only hygroscopic moisture left and this moisture being subjected to the natural seasonal redistributions.

Specimens were removed from the roof twice during the test period. The first time, in September 1988, the rock wool contained 10.4% moisture by weight while the synthetic fabric was essentially dry (less than 1% by weight) and the WPVR had a little moisture condensed on its surface (30% of the dry membrane weight). At this time a ½ in.-diameter hole was discovered in the roof membrane that could have brought in as much rainwater as was dried out through the WPVR during the first summer. The second time, in July 1990, all materials appeared hygroscopically dry (rock wool 1.7% by weight, synthetic fabric 0.4% by weight).

Roof Over a Sports Center The roof over a sports center, oriented west with a slope of 5°, is built of 8 × 8 ft (2.4 × 2.4 m) prefabricated stressed-skin elements with a WPVR below the fibrous insulation.

One of the elements was opened from above and the moisture content of the insulation and the plywood deck at the top was determined. The fibrous insulation was dry, and the moisture content of the plywood was 19% by weight. After that, four layers of cellulose cardboard were placed on top of the insulation and evenly wetted with 0.13 gal/ft^2 (5 L/m^2).

The test section, 6½ × 6½ ft (2.0 × 2.0 m), was sealed off from the rest of the roof and reestablished, the

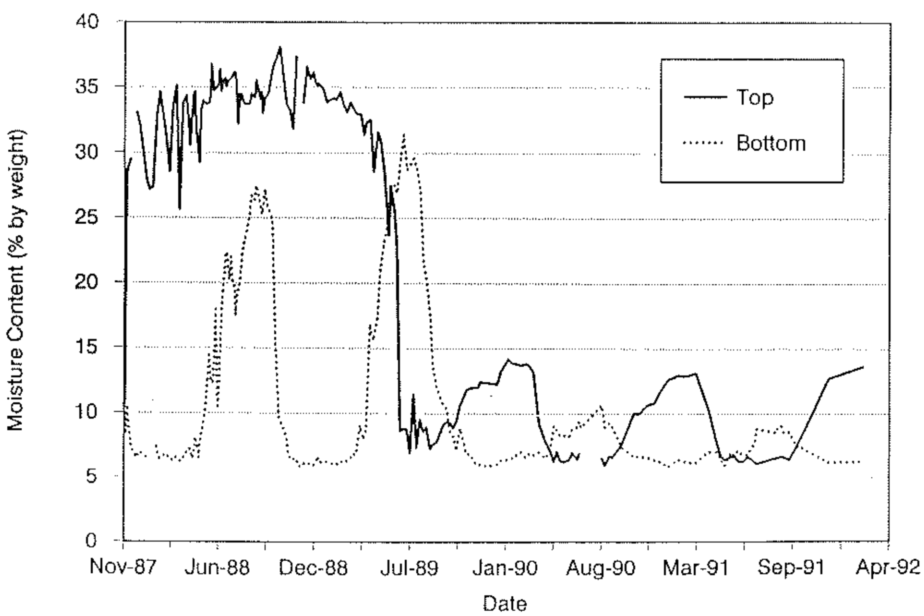

Figure 16 *Moisture content in auditorium roof after reroofing.*

plywood was soaked with 0.07 gal/ft^2 (2.6 L/m^2), and electrodes were built in the plywood deck to determine its moisture content by measuring the electrical resistance. Plywood probes with electrodes were installed between the WPVR membrane and the insulation.

The test period was from April to September 1989, when the test area was opened up again, and the moisture content was determined gravimetrically to be dry for the insulation and around 10% by weight for the plywood deck and the electrical probes.

CONCLUSION

Preliminary climate chamber test results for three traditional, insulated, 2 × 4 in. stud walls without siding in a hot, humid climate with a large air-conditioning load and a small heating load, suggest:

1. A traditional waterproof PE vapor retarder placed between the insulation and the dry wall may cause moistening of the insulation and the top and bottom plates with risk of mold, mildew, or fungal growth.
2. By omitting the PE vapor retarder on the inside and installing a water-permeable vapor retarder (WPVR) on the outside of the insulation, moistening and, hence, risk of fungal growth can be reduced
3. In climates with a shorter air-conditioning season and a longer heating season, a safer way to prevent moisture problems may be to install the water-permeable vapor retarder on both sides of the insulation.

Results from test hut measurements and from two case studies seem to show that the WPVR is able to dry out, during a few summer months, a significant amount of water (between 0.06 and 0.20 lb/ft^2 [0.30-1.0 kg/m^2], depending on the type of construction and insulation material used) that may be trapped between the roofing and the WPVR during construction or through leaks.

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