Moisture Conditions of Non-Ventilated, Wood-Based, Membrane-Roof Components

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ABSTRACT

During recent years, prefabricated, lightweight, wood-based membrane-roof components have been increasingly used in Denmark. It has become common practice to build these roofs without ventilation of the cavity between the insulation and the deck. Six types of roof cassettes have been tested in the field for their moisture performance. The roofs have different designs and insulation thicknesses, and several of them use a water-permeable vapor retarder (WPVR). Each of the roof types is placed over a room with typical dwelling conditions and over a more humid room. Some of the roof sections contained construction moisture, while others were installed factory dry. The experiments were also simulated with a numerical model for combined heat and moisture transfer. This paper presents the results for the first two years of the experiment.

INTRODUCTION

Wood-based, cold-deck roofs (i.e., roofs in which the deck is located on the external side of the insulation) are a cheap and flexible kind of roofing commonly used in Denmark in the 1960s and 1970s for many kinds of buildings. The roofs were typically built on site, and the cavity above the insulation and below the wooden deck was vented to the outside to ensure escape of excess moisture. It was prescribed in the building code that roofs could be vented from eave to eave, but no guidance was given for roofs with areas so large that this was not practically possible.

However, many of these roofs suffered from too much moisture in the wooden components with subsequent degradation of the materials and a need for repair or replacement of the damaged roof. Investigations (Korsgaard et al. 1985; Nicolajsen 1982) showed that the cause of the unexpected damage was that very often more moisture accumulated in the roof than was vented away to the outside. Wind conditions around buildings typically cause the air pressure above the roof and at the leeward eave to be less than inside the building. When roof vents were provided, good pressure release existed between the roof cavity and the outside air surrounding the roof. However, together with the stack effect during winter, this resulted in lower air pressures in the roof cavity than in the building interior. Thus, moisture was transported by convection into the roof from the rooms below through cracks and unintended penetrations of the interior lining of the roof. Even the best of workmanship did not prove effective in avoiding these imperfections. High-quality vapor retarders did not help much either, since the convective transport mechanism was much more influential than the diffusion process. In a horizontal roof there is only a small potential for driving the air laterally in the cavity, and, thus, the moisture that entered could not always be vented away readily. It should be noted, however, that for roofs with small distances between the eaves (less than 30 ft [10 m]) ventilation from eave to eave is still regarded as a functional precaution as long as the roof surface has no vents. In this case, the air pressure in the cavity is about the same as inside the building, and the pressure drop and the relatively short flow path between the eaves give these small roofs a sufficient lateral movement of the air.

Other investigations have shown (Lohse 1978) that unvented stressed-skin roofing elements without vapor retarders would remain dry if they were installed dry, exposed to sunshine, and not located over humid rooms. This conclusion was based on laboratory tests and in-situ experiments carried out during three years of exposure to the Danish outdoor climate and the indoor climate of a hardware store. The problem with the unvented roof in climates where a vapor retarder is necessary is that construction moisture or moisture from leaks has no way to escape, and such a roof can only be used in climates where the annual potential for diffusive intrusion of moisture into the roof (winter) is less than the potential for diffusion out of the roof (summer). Convection of moist room air into the cavity of these roofs is prevented by having airtight conditions on the external side of the roof provided by the roof membrane. In this way, the pressure difference between inside and outside air is concentrated across the rooftop, and, since the roof cavity has the same air pressure as the indoor air, there is no potential for driving the moist room air across the inner construction layers into the cavity.

Today, cold-deck roofs are typically factory manufactured as closed roofing cassettes produced under controlled conditions using dried lumber. The bituminous base sheet is often applied in the factory, and proper logistic handling of the elements makes it possible to minimize outdoor

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storage and to seal the gaps between individual cassettes with bitumen strips immediately after they have been mounted on the roof. This production technique makes it unlikely that moisture would be built in during construction and has helped the cold-deck roof to a recent revival, particularly when used on industrial buildings.

A relatively new type of product, the water-permeable vapor retarder (WPVR), allows excess moisture to escape during summer conditions when it migrates out of the deck and condenses on the vapor retarder, which then slowly drains the moisture to the building interior. These membranes have adequate vapor resistance when they are dry to keep a roof's moisture uptake at a sufficiently low rate during winter.

The critical limit for moisture-induced decay of wood is between 24% and 31% moisture content by weight (ASHRAE 1989). Fungal growth is negligible when the temperature is below 41°F (5°C). In most situations, the wood is drier during summer and, therefore, the spring and fall seasons are potentially the worst. The critical moisture content may be somewhat lower for previously attacked wood and for problems with surface mold and mildew. It is common practice in Denmark to regard 20% moisture by weight as the critical limit.

This project focuses on premanufactured, nonvented timber roofs with a cold deck utilizing the new kinds of vapor retarders. Participants in the project were the Danish Non-Life Insurance Association, five manufacturers of roofing components and materials, a consulting engineering firm, a building research institute, and a technical university. Experimental roofing cassettes have been studied in a controlled field experiment over a test building since the summer of 1990. A simultaneous activity seeks to gather information from similar roofs that were built within the latter part of the eighties. The goal for these two investigations is to provide future guidelines for the design and use of low-slope roofing cassettes. This paper concentrates on the controlled field experiment.

EXPERIMENTS

The measurements at the research institute are carried out on roofing cassettes with a polyethylene vapor retarder or with one of two different WPVRs (see Figure 1). WPVR 1 was introduced by Korsgaard (1985). It consists of a synthetic felt with polyethylene strips staggered on both sides such that the polyethylene on one side overlaps the polyethylene on the other and thus ensures a good vapor-retarding effect. WPVR 2 consists of a sheet of polyethylene wrapped around the edges and at the top side with synthetic felt. The roofing cassettes cover a test house in which the indoor climate is controlled separately in the two halves of the building. The total roof area is 970 ft^2 (90 m^2).

Six different variations of the roofing cassettes have been used (see Figure 2). The first four are cold-deck constructions consisting of (from outside in) modified

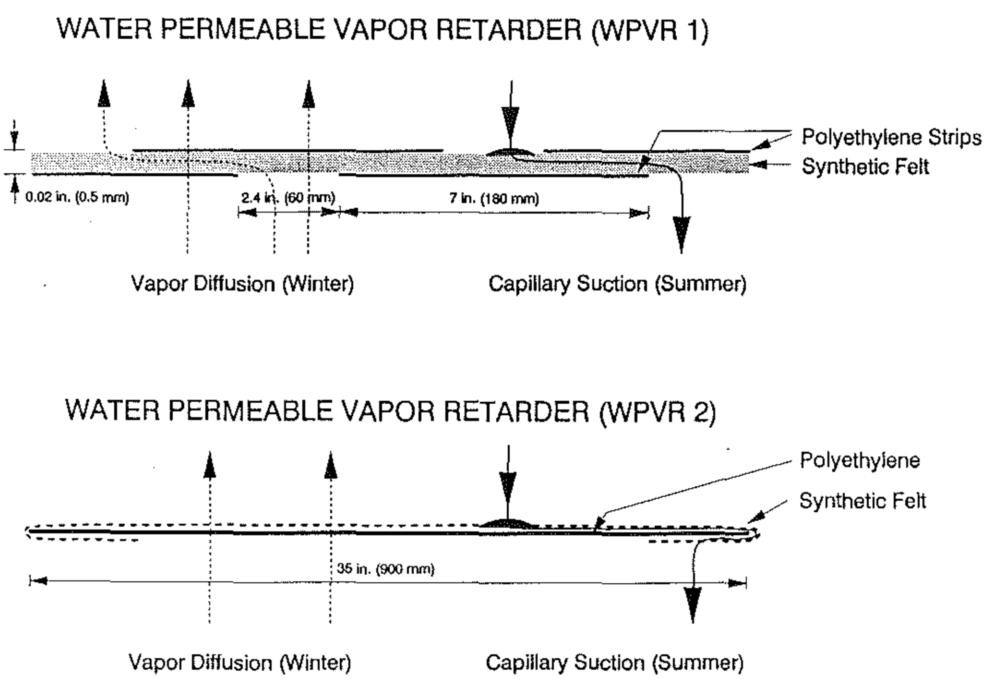

Figure 1 *Conception of the two water-permeable vapor retarders used in the experiments. Only a section of WPVR 1 is shown (drawn thicker for display), while WPVR 2 is shown in full roll width.*

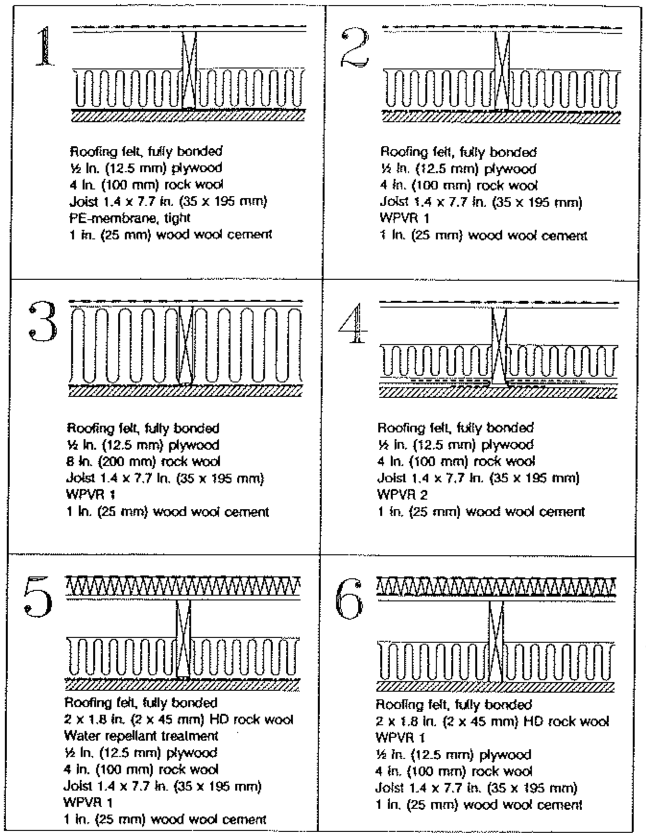

Figure 2 *Cross sections of the six types of roofing cassettes used in the field experiment.*

bitumen, 0.5 in. (12.5 mm) plywood, usually a 4-in. (100-mm) nonvented air gap, rock wool (usually 4 in., 100 mm), the vapor retarder, and 1 in. (25 mm) wood wool cement ceiling. The vapor retarders, of cassette types 1, 2, and 4 are polyethylene, WPVR 1, and WPVR 2, respectively). Cassette type 3 is the same as type 2 except that the cavity is filled with insulation (8 in., 200 mm).

Roof types 5 and 6 are similar to type 2 with the variation that 3½ in. (90 mm) of high-density (HD) rock wool has been added between the plywood deck and the roof membrane. In type 6 the WPVR has been moved to the interface between the plywood and the top insulation. The top of the plywood deck in type 5 has been coated with a water-repellent paint. The type of roof with insulation on both sides of the wood deck may be commonly seen in refurbishing of old cold-deck roofs but may also be constructed in this way as new roofs. In particular, the type is commonly used above humid indoor climates because the warmer location of the wood deck makes it less susceptible to condensation or hygroscopic uptake of moisture.

Each of the six types has been installed under four different conditions, which brings the total number of test areas up to 24. The four different conditions of installation are:

A. Room climate: 72°F (22°C), 40% RH, dew-point temperature 46°F (7.8°C). No construction moisture.
B. Room climate: 72°F (22°C), 60% RH, dew-point temperature 57°F (13.9°C). No construction moisture.
C. Same room climate as A, 0.61 lb/ft^2 (3.0 kg/m^2) construction moisture.
D. Same room climate as B, 0.61 lb/ft^2 (3.0 kg/m^2) construction moisture.

Construction moisture was added to a layer of cardboard on top of the insulation in cassette types 1-4 and in the middle of the external insulation in types 5 and 6. The indoor climate was maintained during the heating season with electric heaters and humidifiers that were controlled with thermostats and hygrostats. The climatic conditions were similar in the two room halves during summer.

The plan (Figure 3) shows the structure of each element. Moisture contents are measured in each element with sensors located as shown in Figure 4. Moisture content is monitored at the top and bottom of the joists, in the plywood deck, and in the top insulation (cassette types 5 and 6) with wooden probes in which the electrical resistance between two pins is measured. The probes consist of a cylindrical piece of beech wood with a diameter of 0.39 in. (10 mm) (see Figure 5). In one end are mounted two brass nails with a diameter of 0.06 in. (1.4 mm) and a distance of 0.2 in. (5.5 mm). The nails protrude 0.2 in. (5 mm) from the end of the cylinder and the top is embedded in an

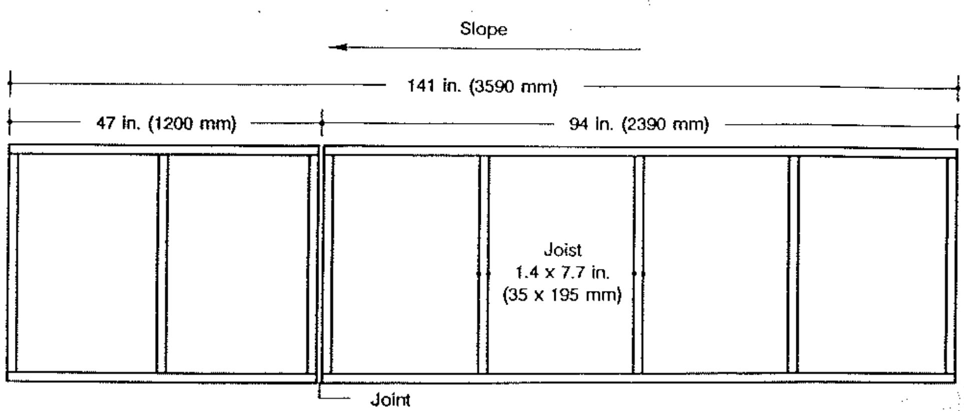

Figure 3 *Plan of one set of roofing cassettes with the supporting joists. The moisture sensors are located in the joists.*

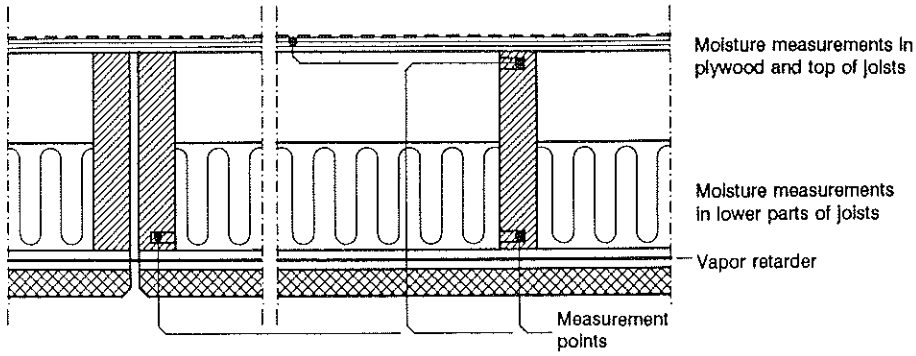

Figure 4 Location of moisture sensors in the cassettes of types 1-4.

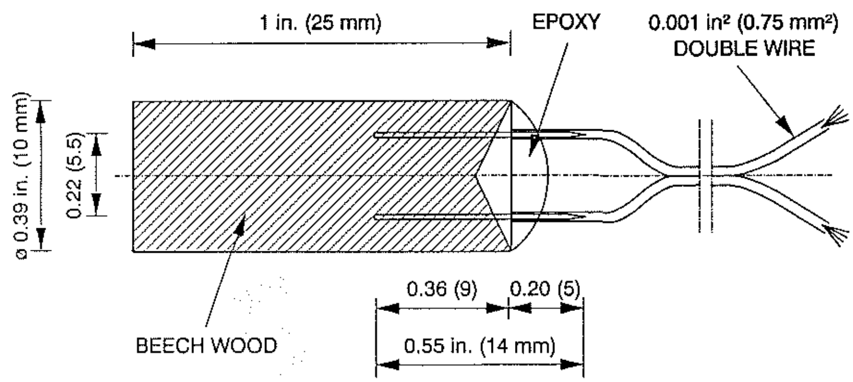

Figure 5 Design of the moisture probes used.

epoxy glue. Wires go to the ohmmeter where the resistance is measured. The relation between resistance and moisture content is established during a calibration procedure. Since calibration is made at 68°F (20°C), a correction is made for temperatures deviating from this. Several years of experience have shown that the calibration curve remains constant over time. Each probe has been calibrated to give the moisture content in the wood to an accuracy of about 2% by weight. The probes are not able to distinguish between moisture contents above fiber saturation (approximately 30% by weight). Moisture probe readings are taken every three to four weeks.

Temperatures were measured in the roofing cassettes and at the roof membrane and stored hourly together with registrations of the indoor climate (temperature and RH) and outdoor climate (temperature, RH, sunshine minutes, wind speed and direction, and precipitation). Denmark has a moderate Nordic climate with approximately 5400 degree-days, base 62.6°F (3000 K·days, base 17.0°C) and an average outdoor temperature in the heating season of 39°F (4°C). The last winters have been a little milder than normal.

CALCULATIONS

Although many models for transient calculation of combined heat and moisture transfer have been developed for use in the research community (Hens 1992), such tools have not been available for building designers and consultants to compute and design constructions that are safe with respect to the undesired impacts of moisture. Only a few countries have regulations for the calculation of moisture transfer, and therefore rules of thumb gained over years of practical knowledge have been used instead. This knowledge has been supplemented by calculations of water vapor diffusion according to steady-state schemes, e.g., the one by Glaser (1957).

A number of improvements of the Glaser methodology have been implemented in a PC program for combined heat and moisture transfer (Korsgaard and Pedersen 1989; Pedersen 1990). The most important of these is that the program calculates both the thermal and the moisture problem transiently in one-hour time steps and that the boundary conditions may be varied with the same detail in time. The program is able to consider both liquid and vapor moisture transport in one dimension but not the issues of convection.

The model is able to adjust the moisture permeabilities of the materials according to their level of moisture content. WPVR 1 has been simulated this way by using a small vapor permeance (0.174 perm, SI resistance 100 GPa·m^2·s/kg) when dry and a large permeance (3.48 perm, SI resistance 5 GPa·m^2·s/kg) when wet, i.e., RH>98%. These values have been determined in the laboratory. Similar properties are not known for WPVR 2 used in cassette type 4. Therefore, calculations have not been carried out for this type of cassette.

The permeability used in the calculations for plywood is 1.7/6.8 perm-in. at 60/98% relative humidity (2.5/10 ng/(m·s·Pa)). The program makes a linear interpolation between these values when the relative humidity is between 60% and 98% and uses the dry and wet values as they are for relative humidities below 60% and above 98%, respectively. The permeability for the rock wool located below the deck is 108 perm-in. (157 ng/(m·s·Pa)), both dry and wet, while the HD rock wool above the deck has a permeability of 77 perm-in. The wood wool cement has dry/wet permeabilities of 27/34 perm-in. (40/50 ng/(m·s·Pa)). Finally, the roof membrane is simulated by a permeance of 0.018 perm (SI-resistance 1050 GPa·m^2·s/kg). These and other properties of the materials in the constructions are taken from the program's data base of material data. Most of these data originate from the literature.

The measured values of indoor temperature and humidity and roof surface temperature have been used as input to calculations with the program to simulate the same moisture conditions as were measured with the wood probes.

The program is user friendly. If the positive experience gained with it so far is supported by the comparison with the experimental results of this test, the program may be considered an appropriate tool to aid the analysis of moisture conditions of similar constructions.

RESULTS

Results of the measurements and calculations of moisture content in the plywood are shown in Figures 6-11. Measurements are shown with symbols, and the calculation results are shown with lines. Note that while the probes are unable to distinguish between different moisture contents above fiber saturation, this is not a limitation for the calculation results, and this may be the cause for some apparent discrepancy between predicted and measured moisture contents in the high region.

For simplicity, probe readings from the joists will not be shown graphically. As expected, the probes located in the tops and bottoms of the joists signaled the seasonal shifting of the moisture between the tops and bottoms of the roofs. Generally, the tops of the joists were a little drier than the plywood decks, a result attributed to the thermal bridge effect of the joists themselves.

Since the moisture may be located in other layers than the plywood during part of the season, it makes sense to compare the total amount of moisture between moisture membranes (i.e., the roof membrane and the vapor retarder) per unit roof area. This can only be surveyed experimentally by weighing representative sections of the tested roofs. However, this technique, which has some drawbacks as well, has not been used in this project. Instead, as Figure 12 shows, the total amount of moisture between the roof

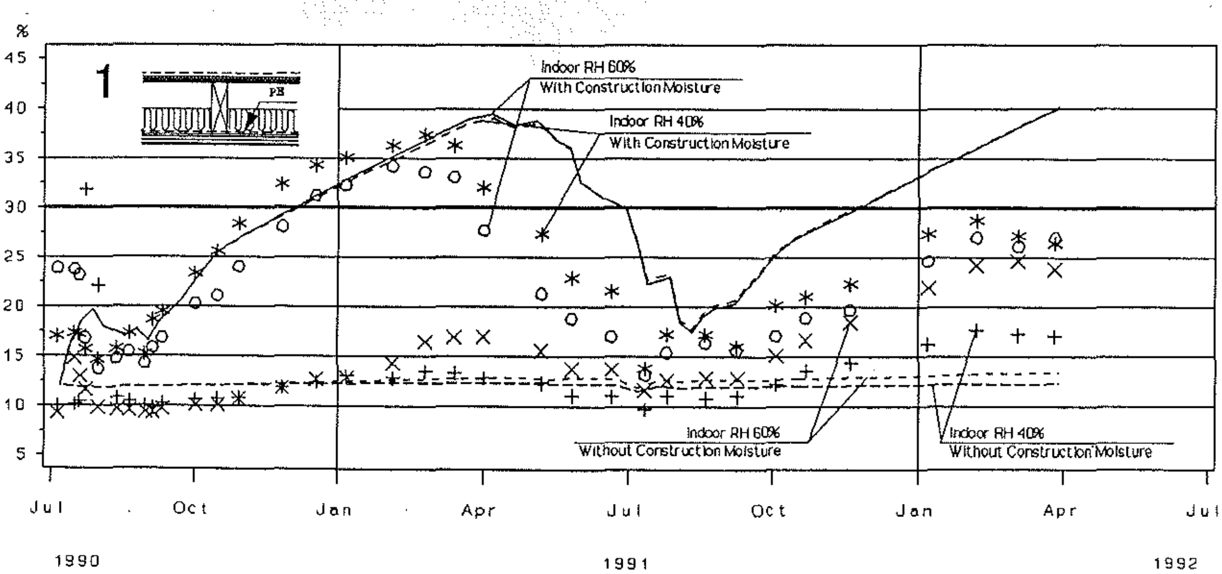

Figure 6 *Measured (symbols) and calculated (lines) moisture contents in the plywood deck for roof type 1 with four different installations using a polyethylene vapor retarder.*

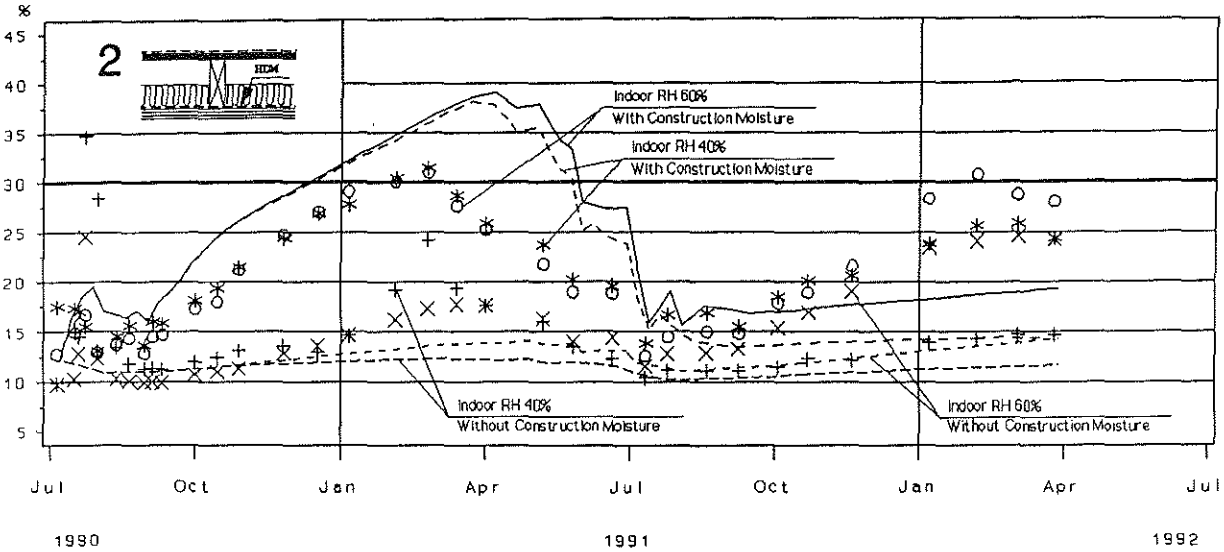

Figure 7 *Measured and calculated moisture contents in the plywood deck for roof type 2 with four different installations using a water-permeable vapor retarder (WPVR 1).*

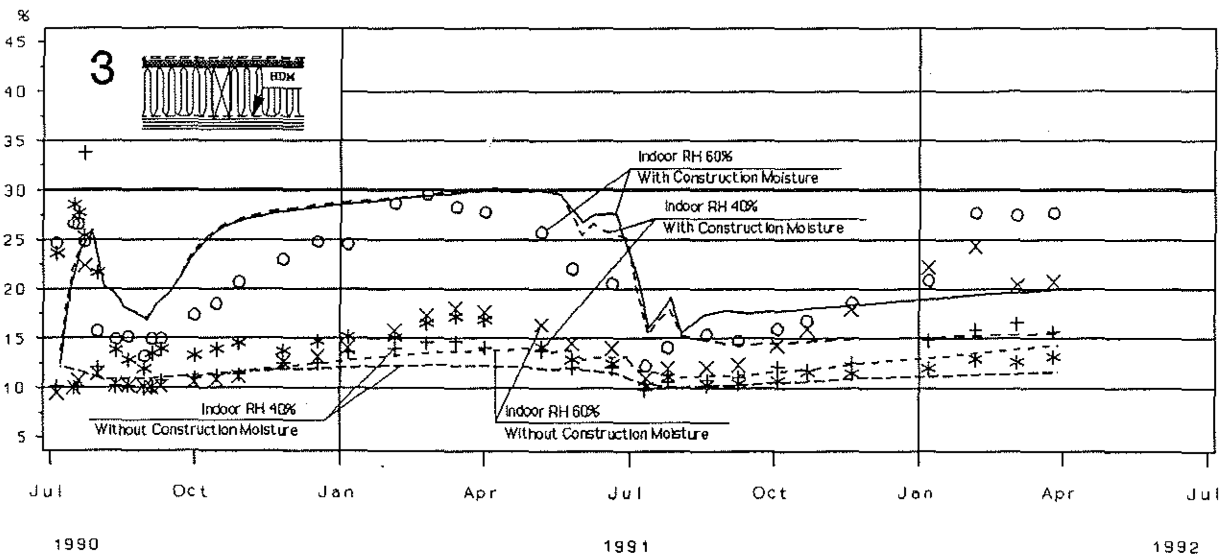

Figure 8 *Measured and calculated moisture contents in the plywood deck for roof type 3 with four different installations using a water-permeable vapor retarder (WPVR 1) and twice as much insulation as in roof type 2.*

membranes has been calculated with the model. Results are shown for the roofs with construction moisture located over the room with 40% RH.

DISCUSSION

Measurements

The results through the two winters, 1990/91 and 1991/92, are as follows:

Type 1 The cold-deck roof type with polyethylene vapor retarder (type 1) has performed acceptably well over both indoor climates when the roofs are installed dry. However, the initially dry roof over the humid indoor climate has accumulated more moisture than the similar roof over the drier room, and the moisture content was close to the critical value during the second winter. The construction moisture in two of the roofs appears to have caused a critical accumulation of moisture in the wooden parts. This moisture dried out of the wood in the summer, but because of the tight vapor retarder, it was difficult for it to dry out of the roof as such, and much of the moisture returned to the wood in the subsequent winter.

It appears that the plywood was drier in the second winter than in the first, but this conclusion may be colored

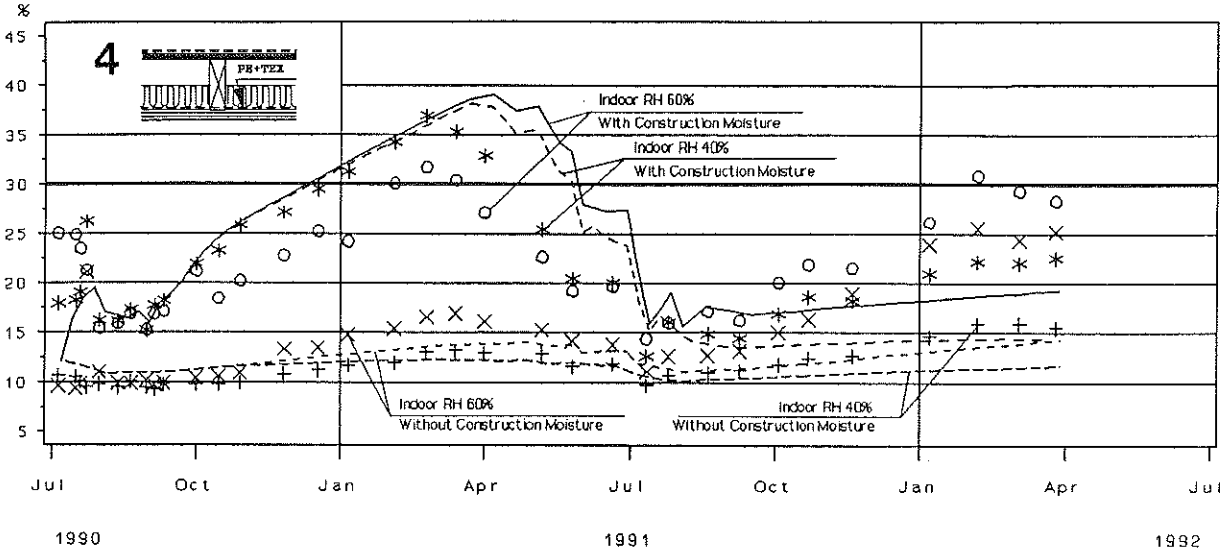

Figure 9 *Measured moisture contents in the plywood deck for roof type 4 with four different installations using a water-permeable vapor retarder (WPVR 2). The calculation results have been copied from roof type 2.*

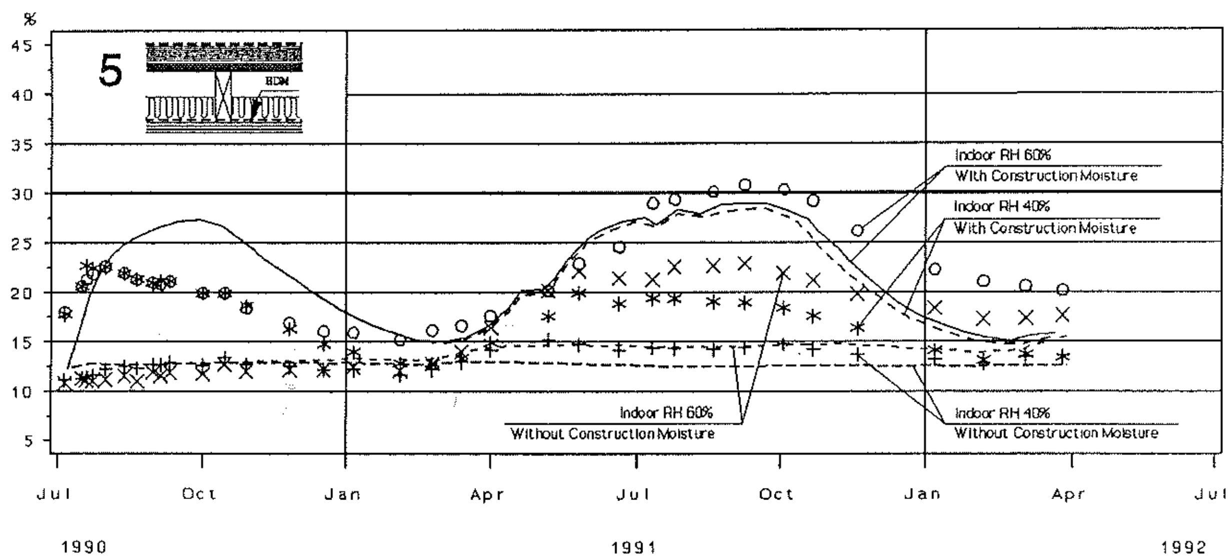

Figure 10 *Measured and calculated moisture contents in the plywood deck for roof type 5 with four different installations using insulation on both sides of the deck and a water-permeable vapor retarder (WPVR 1) between the ceiling and the inner insulation layer.*

by the fact that the measurements were taken at moisture contents close to fiber saturation of the wood where the accuracy of the moisture probe is poor.

Types 2, 3, and 4 There were only small differences between the moisture contents of cassette types 2, 3, and 4, i.e., the cold-deck types with water-permeable vapor retarders. The development of the moisture contents even looks much as it did in roof type 1 with polyethylene.

In the second winter period, the moisture contents were somewhat higher than in the first winter period in the initially dry cassettes, types 1, 2, 3, and 4 — especially in those over the 60% RH climate. This seems to indicate that the vapor retarders are not as tight as anticipated.

The roofs with construction moisture were too wet during the first winter and almost as wet during the second. Neither the short bit of summer that was left when the test was started nor the whole of the second summer were sufficient to dry out all the construction moisture that was added (cassette type 3 over the dry indoor climate may be an exception—it is suspected that the probes are not operating properly, and this will be checked later on).

A comparison of the moisture contents in roof type 3, with 8 in. (200 mm) of insulation, and types 2 and 4, with

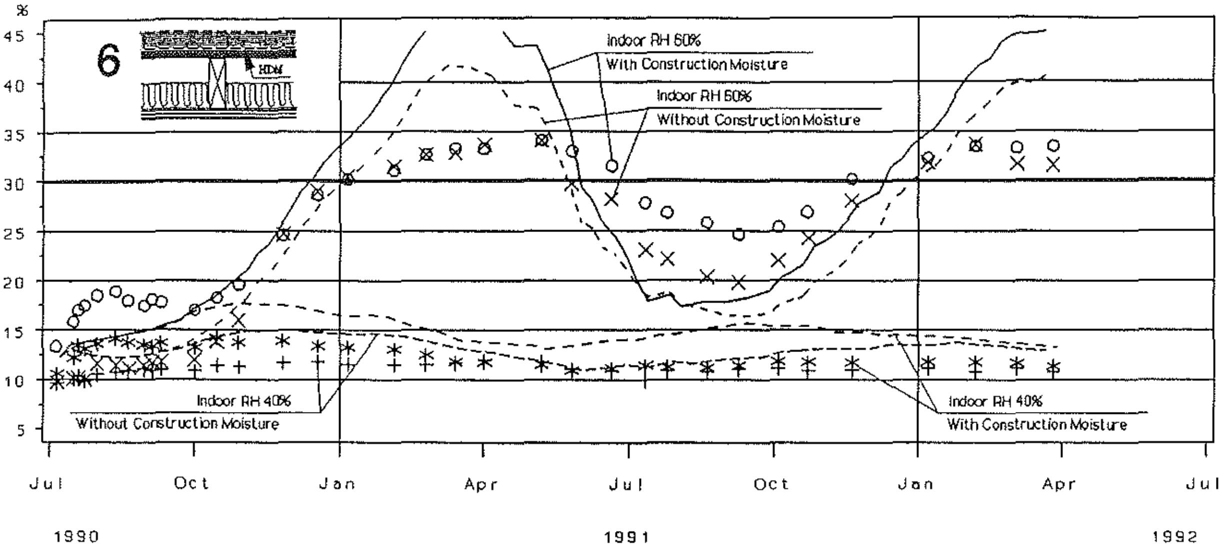

Figure 11 *Measured and calculated moisture contents in the plywood deck for roof type 6 with four different installations using insulation on both sides of the deck and a water-permeable vapor retarder (WPVR 1) between the plywood deck and the top insulation.*

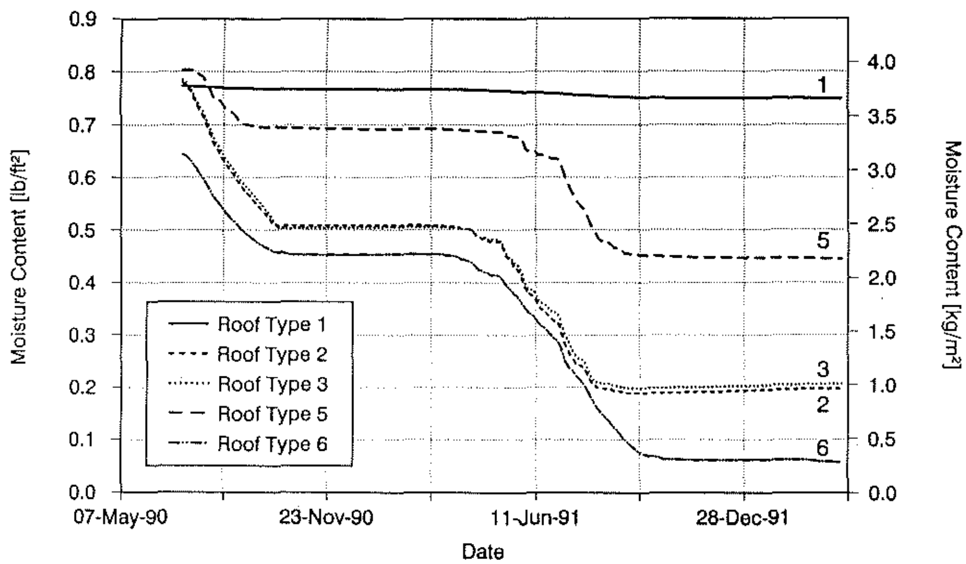

Figure 12 *Calculated total amount of moisture between the vapor retarder and the roof membrane in roof types 1, 2, 3, 5, and 6 with construction moisture located above the room and 40% RH in the heating season. Type 6 does not include the plywood deck since it is located below the vapor retarder.*

4 in. (100 mm), does not seem to indicate that the doubling of the insulation thickness makes the moisture conditions of the plywood deck worse.

Types 5 and 6 The moisture conditions in the roofs with "warmer" decks were significantly different from the conditions in the pure cold-deck roofs.

The deck of roof type 5 (WPVR 1 beneath), with construction moisture and situated over the humid indoor climate, reached a high moisture content in summer and a low moisture content in winter. The reason is that the wood acted as a buffer for the moisture coming down from the insulation above during summer and delivered its moisture to the insulation in the winter. Also, the initially dry roof, type 5, over the humid climate got moist in the second summer and showed an increase in moisture content from year to year. The variation in moisture content was stable at a safe level for type 5 over the drier indoor climate.

Roof type 6 (WPVR 1 above the deck) had variations in moisture content that depended more on the indoor climate than on whether or not the roof contained construction moisture. Because the vapor retarder was located on the external side of the deck, moisture accumulated in the plywood at a very high rate over the humid indoor climate. The reason is that the deck was colder than the dew point of the indoor air throughout the heating season. This was not the case over the drier indoor climate, and the deck stayed dry under these conditions.

Calculations

The general impression of the comparison between calculations and measurements is that the numerical model is able to describe the qualitative behavior of the evolution of the moisture contents. The major deviations are the following:

- There appear to be larger annual variations in the moisture content of the roof assemblies without initial moisture than predicted by the model. The vapor retarders may not be as tight as assumed in the calculations.
- Initially wet roofs with WPVRs appear to be slightly drier during the first year than estimated by the model. The drying during the half summer of 1990 may be underestimated, or there may be some moisture stored in the cardboard next to the plywood that must be considered. Also, measurements in these cases are close to the point were the accuracy of the wood probes becomes poor (moisture content > 30% by weight).
- The opposite (i.e., experimental moisture contents are the highest) appears to be the case for roof types 2 and 3 during the second year. Apparently the drying rates have been overestimated by the calculation model, which could be the result if the wet permeance of the WPVR was assigned too high a value.
- The difference in moisture content measured in roof type 5 between the two indoor climates does not appear in the calculations. This could be an indication that the dry vapor resistance of the WPVR is less favorable than anticipated by the model.
- The calculated variations in moisture content of the plywood in roof type 6 appear to be larger than measured. This suggests that less moisture is retained by the wood during the process of upward migration in winter than predicted by the calculations and that, instead, some moisture may have migrated further into the top insulation. This could have happened if moisture condensed on the underside of the WPVR and made it wet and, therefore, permeable.

Total Moisture Content Between Membranes

With the above-mentioned reservations, the calculations predict the following changes in total moisture content between membranes for the various roof types:

Types 1, 2, and 3 From Figure 12 it is seen that the cold-deck roof cassettes with WPVR 1 (types 2 and 3) should dry out the construction moisture within a few seasons, while the total moisture content should remain almost constant in the roof with polyethylene (type 1).

Types 5 and 6 When comparing results for these two types in Figure 12, note that the level of moisture content is lower for type 6 since the moisture contained by the plywood is not included (because it is not between membranes). Only the rate of drying should be extracted from the figure. Comparison of the results for roof types 5 and 6 shows that excess moisture should dry out faster when there is no plywood contained in the part of the roof to be dried out (the part between membranes).

CONCLUSION

Unventilated cold-deck roof cassettes with polyethylene vapor retarders may remain dry when installed dry and when there is no possibility that moisture may enter in any way (e.g., through leaks or perhaps even by diffusion from a humid indoor climate). However, as demonstrated in the tests with construction moisture, this type of roof appears to release excess moisture at a slow rate that may not be sufficient to provide any safety against moisture degradation.

The measurements of three different cold-deck test roofs with water-permeable vapor retarders (WPVR) did not show the drying effect expected. The tests seem to indicate that at least a couple of seasons are required to dry out the 0.61 lb/ft^2 (3.0 kg/m^2) that was added, while the simulations projected the drying to be completed after one and a half summers. Unfortunately, with the measuring technique used, it has not been possible to see any differences between the four roof types in their moisture content above fiber saturation, though different fractions of the 0.61 lb/ft^2 (3.0 kg/m^2) of moisture that was added may be present in the different roof types after the second summer. Thus, with the amount of moisture added, it may be necessary to wait for at least one more season to see if the permeable vapor retarders really distinguish themselves from the polyethylene by having a higher effective permeance when wet. It should be noted, however, that the effect of permeable vapor retarders has been clearly demonstrated in other Danish field experiments, and it is strongly believed that the drying effect will be observed, only somewhat delayed when compared with the results from theoretical calculations.

All of the cold-deck roof types had rather high moisture uptakes when installed dry over the humid room. This may question whether the laboratory value for the dry permeance of the vapor retarders should be used to describe conditions during service conditions, even when the roofs are assembled under well-controlled conditions.

The insulation thickness has not appeared to be of importance for the moisture conditions.

Constructions with insulation both on top of and below the deck may dry out excess moisture when there is a WPVR on the interior of the construction. However, the lower temperature of the deck on hot summer days is likely to result in a slower drying rate than in the "cold-deck roof." If, instead, the WPVR is located between the deck and the top insulation, the moisture conditions of the wood deck depend almost entirely on the indoor climate. In this situation it is necessary that the indoor dew point stay safely below the temperature of the wood deck year-round. The constructions with the deck in the middle of the insulation have demonstrated that the deck acts as a buffer for moisture flow to and from the top insulation. Particularly when the WPVR is located at the bottom of the roof, this means that the top insulation may get wet during the winter season.

The simulation of the moisture content in the plywood deck with a transient model may provide results that qualitatively describe the transport phenomena taking place in a roof. The deviations seen may be explained by the inaccuracies in the material data needed for the model, the inaccuracy of the measurements with the moisture probes (especially with moisture contents close to fiber saturation), and typical variations in a field experiment. With some adjustment of the membrane permeances used by the model to the values under service conditions, the model should give correct results that separate constructions that work well from those that do not, and, thus, it should be an appropriate tool for the design of similar building elements.

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