Transient Moisture Distribution in Flat Roofs with Hygro Diode Vapor Retarder

V. Korsgaard
Fellow **ASHRAE**

C.R. Pedersen

ABSTRACT

In the paper, a computer program developed to calculate the transient seasonal moisture distribution in unventilated flat roofs is briefly described. The input data are hourly weather data for a given location and indoor temperature and humidity. The program has been validated using values from laboratory measurements on typical warm–deck and cold–deck roofs. Graphs are shown for the calculated moisture content for a number of different flat roof assemblies with built–in moisture. Only moisture migration by diffusion is taken into consideration, as migration by convection through air leaks in the vapor retarder can be reduced to an insignificant amount by omitting roof vents. Two different types of vapor retarders are used: a common type of plastic film, and a recently developed composite membrane which functions as a moisture check valve or moisture diode. Its high resistance to water vapor diffusion permits the transfer of condensed water by capillary suction. It is shown that if this new type of vapor retarder is used, moisture will not accumulate over the years, and built–in moisture will dry out during the first warm season.

INTRODUCTION

Thermal insulation can only contribute as an effective energy–conserving measure if the insulation material is kept dry. Experience over the years has shown that the insulation in a large percentage of flat roofs with vapor–impermeable roofing membranes will get wet during their service life and lose a substantial part of the insulation value and deteriorate the whole roofing system (ASHRAE 1985, Tobiasson 1985, Baxter 1986, Hedlin 1988). The reason why this happens is obvious. Sooner or later water will enter the roof system and moisten the insulation material. In most flat roof systems a vapor retarder has been installed under the insulation to minimize moisture migration into the roof system from below. As the vapor retarder is not only vaporproof, but also waterproof, moisture or water can accumulate in the roof system. One way and perhaps the safest way to prevent this would be to install a vaporproof but water–permeable membrane instead of a traditional vapor retarder.

In the paper, such a membrane, the Hygro Diode (HDM) (Korsgaard 1985), is described, and graphs are shown to compare the seasonal moisture development in flat roof systems with a polyethylene (PE) film and the HDM as vapor retarder.

Flat Roof Designs

Flat roof designs are usually divided into three groups: the cold deck roof, the warm deck sandwich roof, and the warm deck inverted roof. Only the first two designs will be dealt with in this paper.
A typical cold deck assembly is shown in Figure 1 and a typical warm deck assembly is shown in Figure 2. The cold deck roof is usually ventilated. Both roof designs usually have an insulation layer installed between an air vapor retarder and an impermeable roofing membrane.

V. Korsgaard is professor, and *C. Rode Pedersen* is post graduate student at the Thermal Insulation Laboratory, the Technical University of Denmark, DK–2800 Lyngby.

Moisture Sources

It is well known that moisture can enter into a roof assembly in different ways, free water in the form of rainfall during construction or later through leaks or in the form of water vapor. Water vapor induced by a difference in vapor pressure is called diffusion. Water vapor induced with moist air by a difference in air pressure is called convection.

One should recognize that not only fibrous insulation, even when treated to be waterrepellent, but also plastic foams can become waterlogged by condensation of water vapor diffusing into the closed cells.

Water vapor entering a roof assembly will condense and hence be transformed to free water if the partial pressure is higher than the saturation pressure corresponding to the lowest temperature inside the roof assembly. This means that during the winter months condensation will take place below the roofing. In the summer months condensation will take place on top of the vapor retarder.

To calculate or even predict how much rainwater will enter the roof assembly during construction or later through leaks is impossible. One can only state that sooner or later some rainwater will be trapped in the roof.

Discussions in the literature have mainly treated vapor diffusion through material layers and membranes and to some extent also diffusion through holes, slots, and joints. Although it is difficult to estimate the number and size of flaws or leaks in a vapor retarder, the amount of water vapor diffusing into the roof assembly will, for normal workmanship, only be of the same magnitude as diffusion through the intact membrane.

In contrast to this, the amount of water vapor that can enter a roof assembly by convection through even a minor leak can be 10 to 100 times as much, depending on the pressure difference across the membrane.

Next to rain during construction or later through leaks in the roofing, experience has shown that convection is the main source for moisture accumulation in a roof assembly. A roof assembly should therefore be airtight. By omitting ventilation openings, roof vents, and pressure relief valves, convection can be eliminated or reduced to an insignificant amount since the roofing is airtight.

The Computer Program

As part of a current Ph.D. study, a computer program, MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) has been developed. The computer program calculates the hygrothermal conditions in multilayer constructions exposed to natural outdoor climate and typical indoor conditions.

The outdoor climate is taken from the Danish test reference year (TRY) comprising typical values of the outdoor temperatures, dewpoint temperatures, global radiation, and wind velocities on an hourly basis.

The calculations proceed as follows (when calculating from one time step to the next): after reading the current TRY data, a transient calculation of the temperatures in all the layers of the construction is carried out. This calculation also accounts for the latent heat involved in phase changes such as ice formation and evaporation/condensation in the layers.

The temperature distribution calculated in this manner gives the new distribution of the saturation vapor pressures that are needed in the transient calculation of new vapor pressures. Also needed are the hygroscopic capacities of the materials in the construction. These capacities are given by the slopes of the sorption curves for each material for which an analytical expression is being used. The saturation pressures and the hygroscopic capacities (depending on the level of moisture content) are now used together with Fick's law to find the new vapor pressures. Also, the new moisture contents in the layers are calculated from Fick's law and the vapor pressures.

The numerical technique involved in calculating the temperature as well as the moisture distribution is an implicit formulation of a control volume difference technique. It is programmed on a PC with the advantages it gives for easy access and for presentation using a graphic display. On the screen one can follow the variation of the temperatures, the vapor pressures, the relative humidity, and finally the moisture contents as the calculation proceeds. The approximate time of calculation for one year would be close to one minute per layer involved. Though one year would be a normal period to simulate, other periods can be chosen ranging from a few days to several successive TRY.

Validation of the Computer Program

The computer program has been validated by comparing the calculated moisture development with measured values for a number of different test roof systems installed in a small test hut. In Figure 6 is shown an example for a roof system with plywood as structural deck. The negative values are due to initial hygroscopic moisture in the insulation and plywood. As can be seen, the agreement is good.

Development of Moisture Content

The accumulation of moisture between the impermeable roofing membrane and the vapor retarder is calculated for a number of flat roof designs with two different types of vapor retarder. The roof is assumed to be unshaded and black with values for the emissivity as well as for the absorptance of global radiation equal to 0.9. The indoor temperature is kept constantly at 20^0C, and the indoor moisture production is sufficient to maintain the moisture content of the indoor air at 0.3 g/m^3 above that of the outdoor air. Time steps are one hour, which is equal to the interval length in the test reference year. For most of the calculations there are three nodal points in the insulation layer, while there will be only one for each of the other thinner layers. This provides an accuracy that exceeds the accuracy of the various assumptions and material parameters.

Results are presented as graphs showing the development of the total moisture content between the vapor retarder and the roofing membrane.

Vapor Retarder

The two different types of vapor retarder used in the calculations are an ordinary 0.1 mm polyethylene film with and without minor leaks and a recently developed composite vapor retarder which functions as a moisture check valve or moisture diode, called the Hygro Diode Membrane (HDM).

The Hygro Diode Membrane

The HDM (Figure 3) consists of synthetic fabric with good capillary suction properties sandwiched between stripes of diffusion–tight plastic film. Gaps are present in the top and bottom films. The gaps are staggered without overlap.

The diffusion resistance of the HDM can, with good accuracy, be calculated as three diffusion resistances in parallel, as shown in Figure 4. In Figure 4, the diffusion resistance is calculated for an HDM now marketed in Denmark. The calculated value agrees well with the measured dry–cup value. Due to the structure of the HDM, a large cup (1 by 0.5 m^2) has been used.

The wicking action of the fabric core makes it possible for moisture trapped in the roof, when it condenses on the HDM during sunny periods, to migrate down through the HDM by capillary suction to the underside, where it can evaporate into the underlying room.

Due to the wicking action the HDM will also signal larger leaks in the roofing so that precautions can be taken. A conventional vapor retarder allows areas of wet insulation to grow undetected in roofs.

The drying of water from the roof space with HDM and PE vapor retarders is illustrated in Figure 5.

In the computer program the ability of the HDM to transmit condensed water is taken into consideration by letting the diffusion resistance alternate between the measured dry–cup value (100 PAM), when no condensation occurs on the HDM and a low–value (1 PAM) (wicking action) when condensation occurs. 1 PAM (mmHg$\cdot$m$^2\cdot$h/g) $\simeq$ 0.48 (GPa$\cdot$m$^2\cdot$s/kg) $\simeq$ 0.0275 (in Hg$\cdot$ft$^2\cdot$h/grain) $\simeq 0.48\cdot10^{-3}$ Rep(TPa$\cdot$m$^2\cdot$s/kg) corresponding to a Perm value of approximately 2000 ng/Pa$\cdot$s$\cdot$m^2.

For the PE film without leaks, the dry–cup value (500 PAM $\simeq$ 4 Perm) is used both when it is dry and wet. For the PE film with minor leaks the diffusion resistance alternates between 100 PAM (20 Perm) when dry and 200 PAM (10 Perm) when wet. These values are based on a two–dimensional diffusion model, but should be verified by measurements.

Test Hut

A small test hut has been built with a flat roof containing 2 by 8 different roof systems, with the HDM and a

PE film as vapor retarders. The roofing is bitumen felt strewn with granulated slate. The test hut is divided into two separate rooms. Each room has eight roof systems. One room has an indoor climate corresponding to dwelling conditions. The other is kept at 20°C and 60% relative humidity (RH).

The test specimen's (Figure 7) 40 by 35 cm measuring area was built into the heavily insulated prefabricated roof elements in such a way that it is possible to pull the specimen out and weigh each layer to accurately determine its moisture content.

Calculation of Moisture Development

The PC computer program (MATCH) described above has been used to calculate the moisture development for a number of flat roof systems.

In Figure 8, the moisture content variation is shown for five different roof systems for three consecutive Danish test reference years. It is assumed that the moisture content of the roof system is 1 kg/m^2 (0.2 lb/ft^2) of roof area when the calculations start the first of January. It is further assumed that this amount of moisture is deposited in a thin layer at the top of the insulation just below the roofing.

The supporting steel deck of roof system No. 1 in Figure 8 is assumed to be of perforated panels or with open end and side laps to ensure some ventilation so that the moisture absorbed in the HDM vapor retarder can evaporate into the room air.

It is seen that for roof system No. 1 with a PE vapor retarder, hardly any drying takes place over the three–year period. With single–ply roofing (No. 5) instead of built–up roofing there is a slight drying. However, in a climate with warmer, moister summer months the opposite could be the case.

For roof systems 2, 3, and 4 with an HDM vapor retarder, the built–in moisture will dry up almost completely the first summer. The larger oscillation of No. 3 is due to the large moisture capacity of the concrete deck compared to the steel deck.

It should be noted that for No. 2 the drying–up resistance of the HDM is 10 PAM corresponding to 200 Perm, as the drying only takes place by evaporation. For Nos. 3 and 4 drying will also take place by capillary suction to the concrete and plywood deck, for which reason a value of 1 PAM is used corresponding to 2000 Perm.

In Figures 9 and 10, the seasonal development of moisture in the top, middle, and bottom layers of the mineral fiber insulation is shown. During the first winter, the built–in moisture for both roof systems will be deposited in the top layer. The middle and bottom layer will be almost dry. In a sunny period around June 1, the moisture is diffusing to the bottom layer, where it condenses on the vapor retarder.

γ–ray measurements have shown that the condensed water is concentrated in a thin layer of the insulation in contact with the roofing in the winter, and the vapor retarder in the summer. This also shows that the water–repellent insulation material has no capillary suction properties.

In the roof system with a PE vapor retarder (Figure 9), the moisture will be trapped as water on top of the PE film. Around September 1, when the roofing starts to get colder, the condensed water will start to evaporate and diffuse back and condense in the top layer just below the roofing. This cycling back on force will continue for years, as only a small amount, if any, will migrate out of the roof system. It should be stressed that during the winter months the bottom layer of the insulation will be dry, and the top layer will be dry during the summer months.

In the roof system with an HDM vapor retarder (Figure 10), the moisture development is quite different except for the first winter, where it is similar. During the first summer most of the built–in moisture will migrate out of the system through the HDM, and the insulation will stay dry in the years to follow. In a similar way water which later might enter through leaks will migrate out of the roof. Larger leaks will cause dripping from the ceiling, so that precautions can be taken.

In Figures 11 and 12, the moisture development for a short sunny period the first week in June of the Danish test reference year is shown. Figure 11 clearly shows the drying of the top layer and the simultaneous moistening of the bottom layer in the case of the PE vapor retarder. Hardly any drying–up of the roof system takes place, as $\underline{A} + \underline{B} + \underline{C} \simeq 1\ kg/m^2$. In the case with the HDM vapor retarder, $\underline{A} + \underline{B} + \underline{C} = 0.4\ kg/m^2$, which means that 60% of the initial moisture content has dried up.

In Figure 13, the course of the roofing temperature corresponding to Figures 11 and 12 is shown. By comparing these figures, it can be seen that there is a small diurnal cycling of vapor diffusion between the top and bottom layers of the insulation, corresponding to the diurnal cycling of the temperature of the roofing.

CONCLUSION

For unventilated flat roofs it is possible by means of an advanced PC program to compute the development of the moisture content between the impermeable roofing membrane and the vapor retarder membrane for a number of consecutive years. It is shown that a traditional low permeance vapor retarder does not allow the drying of interstitial moisture. A new vapor retarder, the Hygro Diode Membrane (HDM), is described, which will allow moisture to dry up during the warm season but will still have a sufficiently high diffusion resistance to prevent a significant amount of water vapor to migrate into the roof system during the cold season. When the HDM is used as vapor retarder, both cold–deck and warm–deck roofs should be left unventilated to prevent moisture transport into the roof system by convection through air leakage in the vapor retarder.

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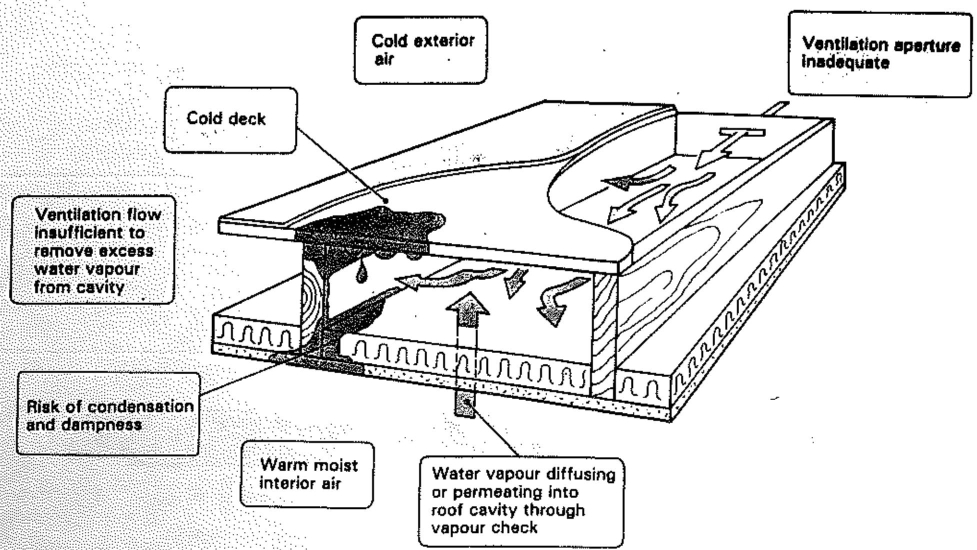


Figure 1. Cold deck roof, insulation below the deck

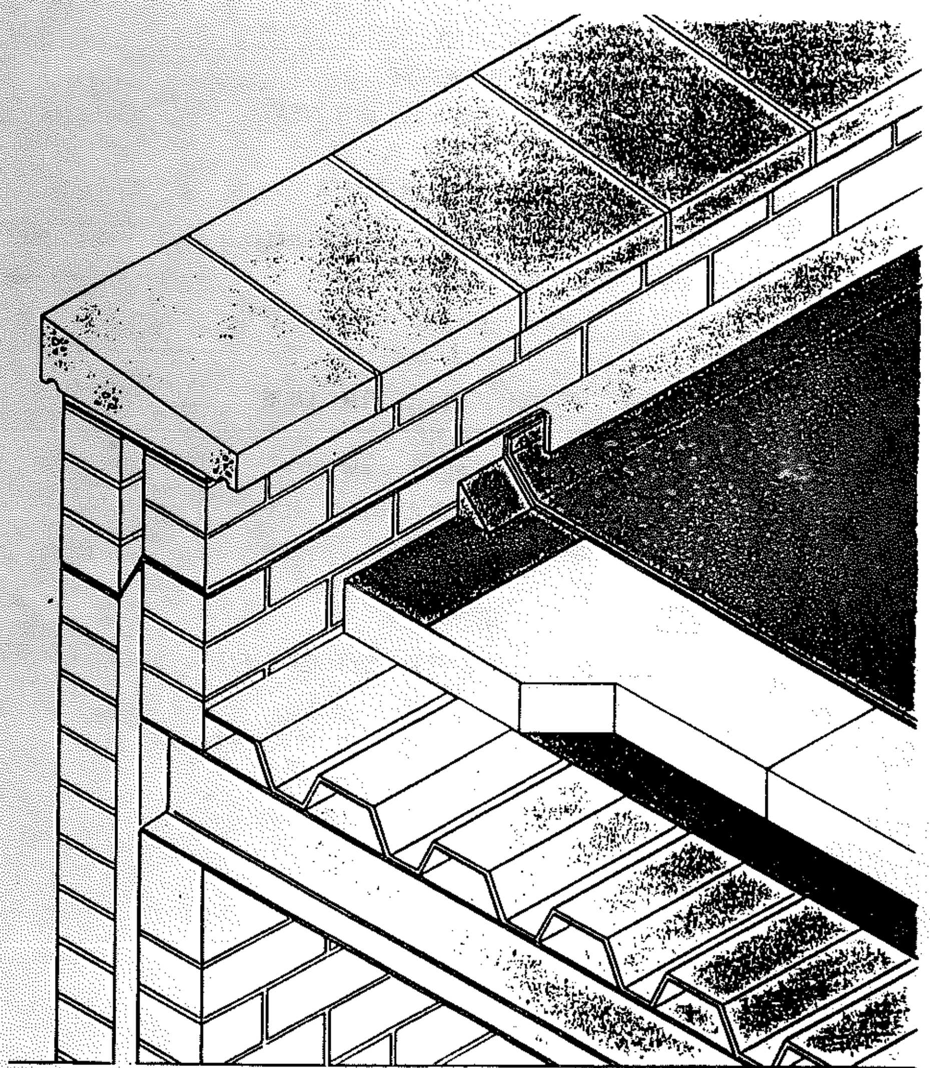


Figure 2. Warm deck roof, insulation above the deck

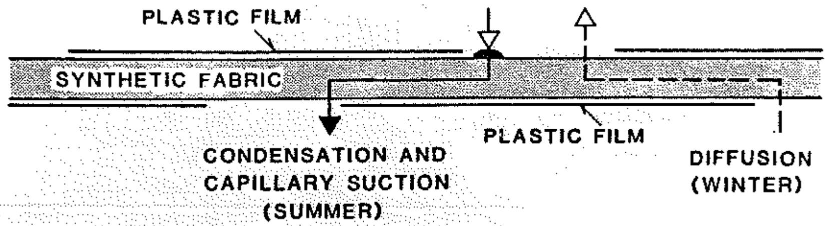
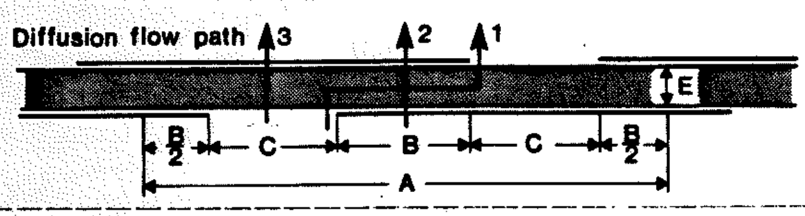


Figure 3. The Hygro Diode Membrane vapor retarder, its structure and function



DIFFUSION

$G_A = (\Delta P / Z_{HD}) \cdot A$ (FICK'S LAW)

$Z_{HD} = R_A \cdot A$

WHERE G_A = MASS OF VAPOR TRANSMITTED
ΔP = DIFFERENCE OF VAPOR PRESSURE
Z_{HD} = OVERALL VAPOR RESISTANCE PER UNIT AREA
A = AREA CONSIDERED
R_A = OVERALL VAPOR RESISTANCE OF AREA A

$R_A^{-1} = 2(R_1^{-1} + R_2^{-1} + R_3^{-1})$ RESISTORS IN PARALLEL
$R_1 = B/\delta \cdot E$ RESISTANCE OF FLOW PATH 1
$R_2 = 2Z/B$ - - - - 2
$R_3 = Z/C$ - - - - 3

WHERE δ = PERMEABILITY COEFFICIENT OF FIBER FABRIC
E = THICKNESS OF FIBER FABRIC
Z = VAPOR RESISTANCE OF POLYETHYLENE FILM
B = WIDTH OF OVERLAPPING POLYETHYLENE FILM
C = WIDTH OF UNCOVERED STRIPES

EXAMPLE

δ = 70 PERM M (NG/S·M·PA) SYNTHETIC FIBER FABRIC
E = 0.0005 M
Z = 0.2 REP (TPA·M^2·S/KG) 0.1 MM POLYETHYLENE FILM
A = 0.20 M, B = 0.05 M, C = 0.05 M
$R_1 = 0.05/70 \cdot 0.0005 = 1.43$ REP/M^2
$R_2 = 2 \cdot 0.20/0.05 = 8.0$ REP/M^2
$R_3 = 0.20/0.05 = 4.0$ REP/M^2
$R_A^{-1} = 2(1.43^{-1} + 8.0^{-1} + 4.0^{-1}) = 2.15$
$Z_{HD} = 2.15^{-1} \cdot 0.20 = 0.093$ REP

Figure 4. Calculation of diffusion resistance of Hygro Diode Membrane

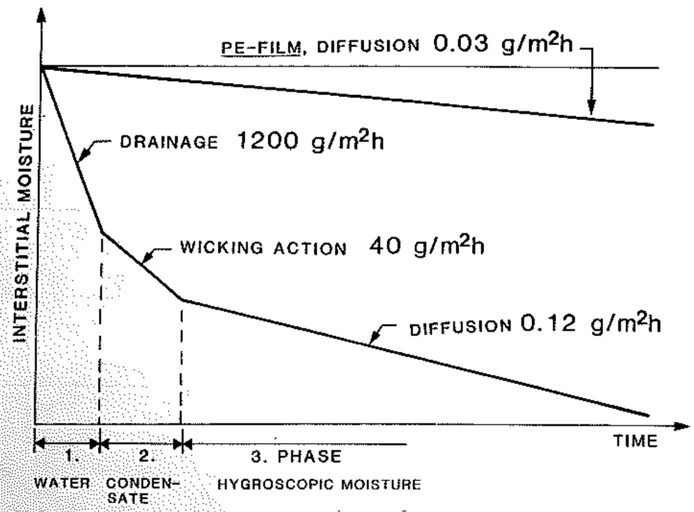


Figure 5. *Drying-up of interstitial moisture in unventilated flat roof systems with PE film and Hygro Diode vapor retarder*

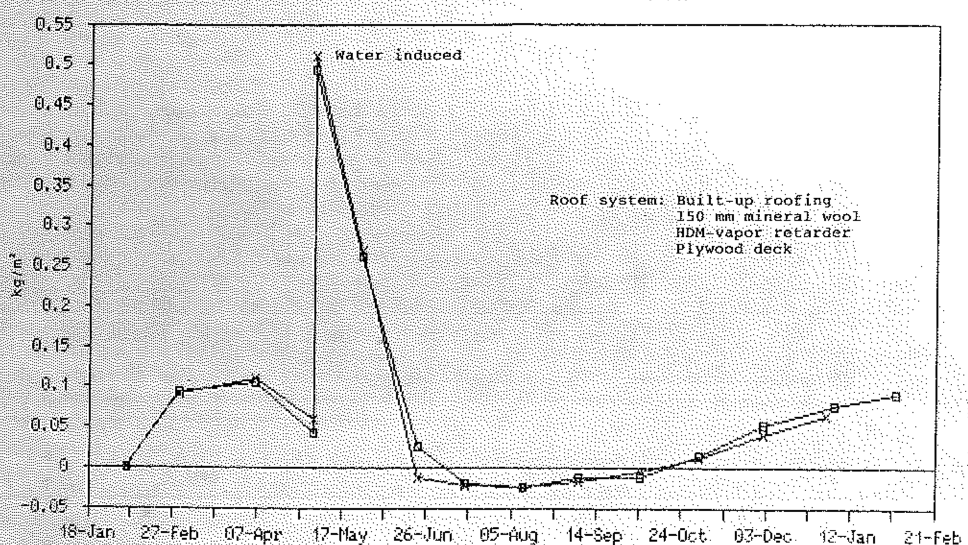


Figure 6. *The development of the moisture content in a flat roof, measured and calculated. The negative values are due to initial hygroscopic moisture in the materials.*

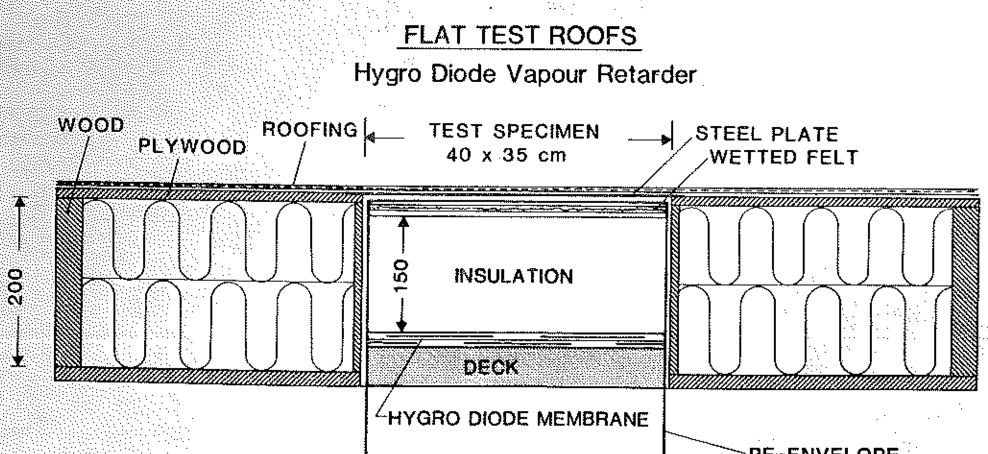


Figure 7. *Cross section of specimen integrated into a flat test roof*

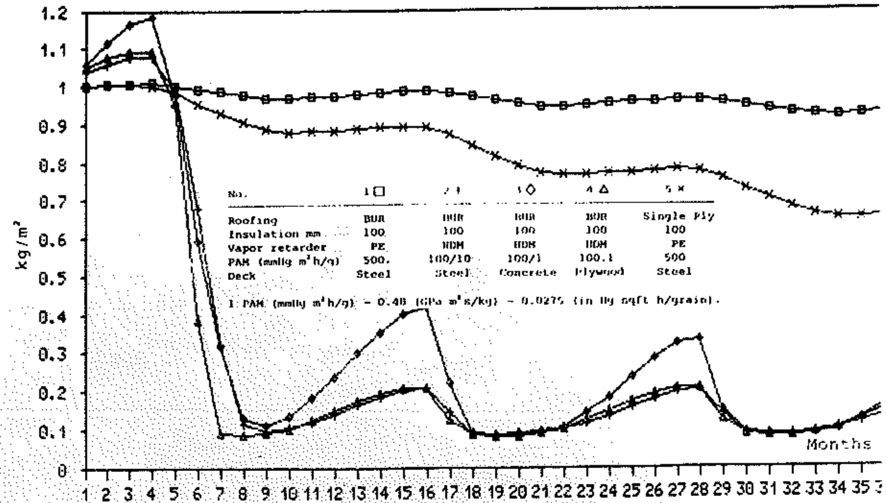


Figure 8. *Development of the moisture content in five different unventilated flat roof systems for a three-year period*

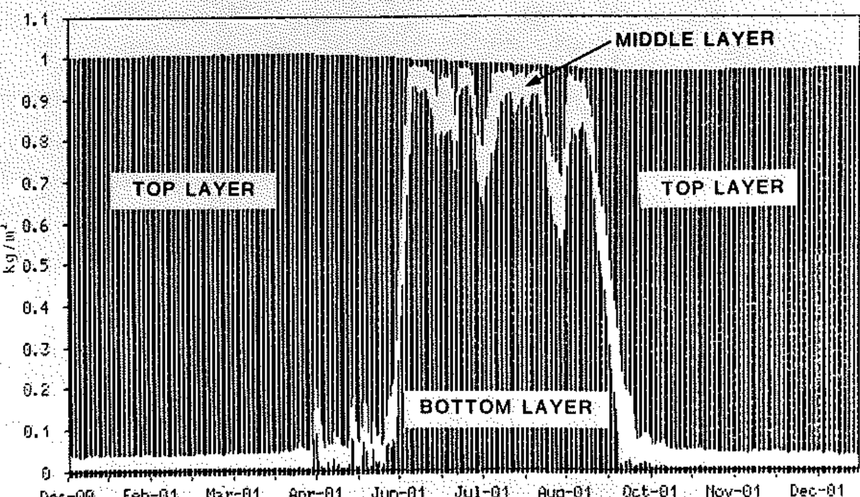


Figure 9. *Development of the moisture content in top, middle, and bottom layer of 100-mm mineral fiber insulation of an unventilated flat roof with vapor retarder*

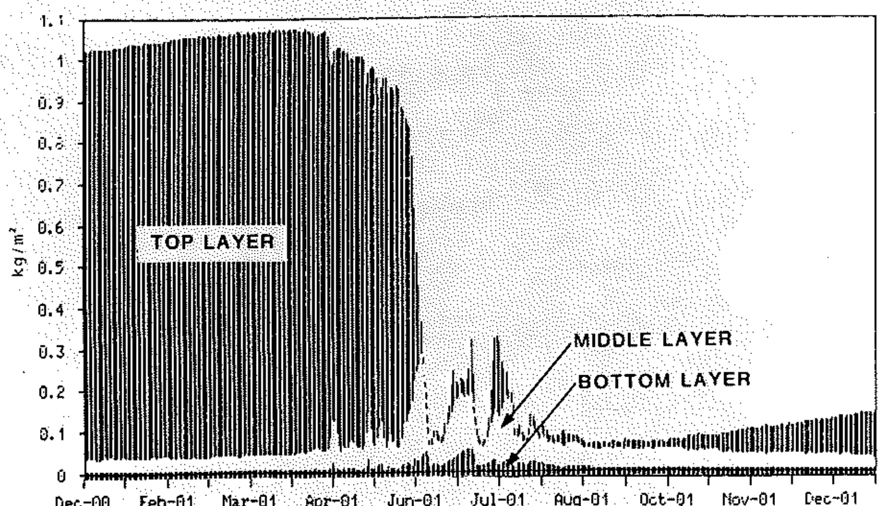


Figure 10. *Development of the moisture content in top, middle, and bottom layer of 100-mm mineral fiber insulation of an unventilated flat roof with a HDM vapor retarder*

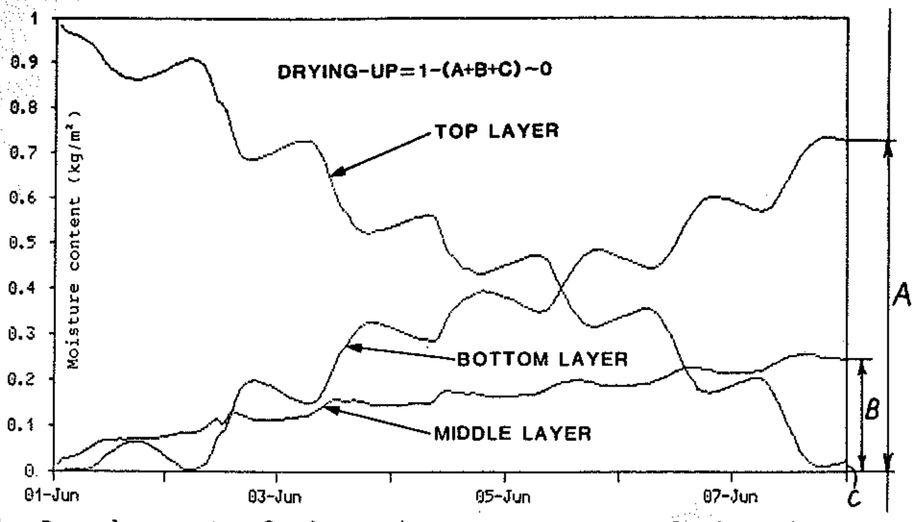


Figure 11. *Development of the moisture content of the mineral fiber insulation of an unventilated flat roof in the sunny first week of June of the Danish test reference year. PE film vapor retarder. No drying up takes place as* $\underline{A} + \underline{B} + \underline{C} \simeq 1$ *kg/m*^{2}.

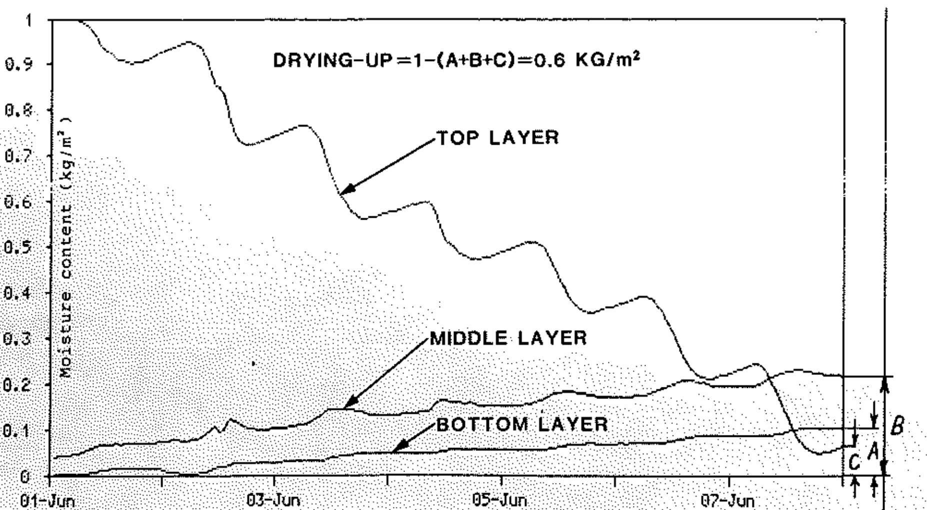


Figure 12. *Development of the moisture content of the mineral fiber insulation of an unventilated flat roof in the sunny first week of June of the Danish test reference year. HDM vapor retarder. 60% of the initial moisture content has dried up as* $\underline{A} + \underline{B} + \underline{C} \simeq 0.4$ *kg/m*^{2}.

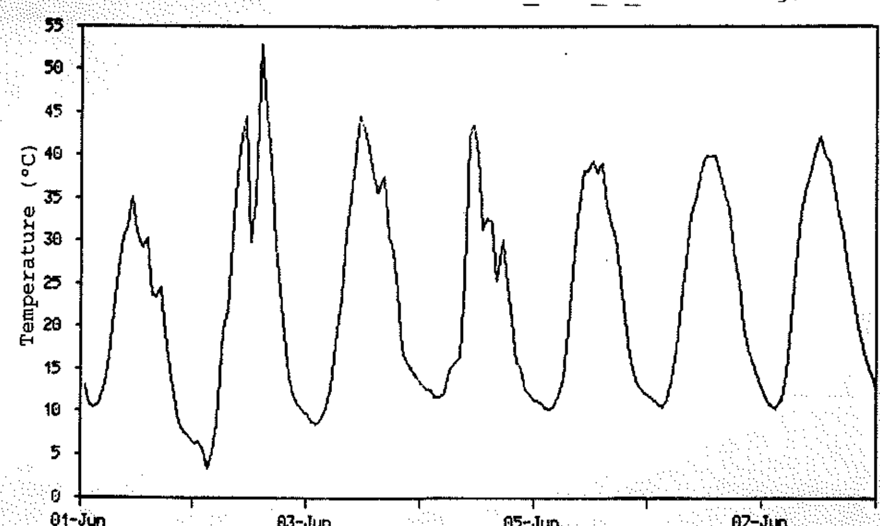


Figure 13. *Temperature swing of the roofing corresponding to the graphs shown in Figures 11 and 12*