THE PROTECTED MEMBRANE ROOF (PMR)— A STUDY COMBINING FIELD AND LABORATORY TESTS

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INTRODUCTION

Over the past 10 years, the Protected Membrane Roof (PMR) concept has commanded steadily growing international interest as a solution to problems encountered with the conventional BUR roof system. Reversing the conventional positions of membrane and insulation, the PMR sandwiches the membrane between the deck below and the insulation above. For the membrane, the PMR concept offers two major life-prolonging benefits:

(1) Drastic reduction of the tremendous temperature ranges—up to 100°F (55°C) daily and 200°F (110°C) annually—experienced by the membrane in its exposed surface location.

(2) Protection from the chemical degradation of ultraviolet radiation and from the physical hazards of foot damage, hailstone impact, dropped tools, and miscellaneous missiles that occasionally find their destructive way onto a roof.

Still another advantage of a PMR is its construction speed, which is usually faster than a conventional roof's construction.

Its exposed position in a PMR creates several problems for the insulation—notably, physical degradation from chronic exposure to moisture and loss of thermal resistance from cyclical wetting and drying. These are the problems studied by a continuing research program at the Chalmers University of Technology, Gothenburg, Sweden, financed by the Swedish Council for Building Research. Test roofs constructed of different plastic foams already in service in thousands of PMRs located around the world are under investigation [1,2,3,4] along with a conventional BUR assembly used as a basis for comparison. These test roofs are periodically subjected to strong winds and driving rains, rigorous conditions whose effects are also reported. Laboratory tests were also conducted to complement the field findings and set them on a solid experimental foundation.

TEST RESULTS

Here are our principal findings:

- Thermal resistance of a polystyrene board insulated PMR is about 10% lower than the thermal resistance of a conventional roof under the same weather conditions.
- Extruded polystyrene is, by far, the best of the tested materials for resisting moisture penetration, with mean values of 0.05% water (by volume) compared with 5 to 6%, roughly 100 times as much, for expanded polystyrene.
- Two layers of insulation increased moisture absorption by about six times the moisture absorption of one layer.
- Thermal resistance decreases with increasing wind velocity.

BACKGROUND PREPARATION

This test program started with a survey of available literature and an inventory of Swedish PMR roofs and terraces. We interviewed owners, contractors and designers, questioning them about design, production and function [6]. Test roofs are under investigation at Chalmers research station at Fiskeback, on the west coast, near Gothenburg [7]. Simultaneously, the test roof insulations (different types of extruded and expanded polystyrene foam) are under investigation for heat-transfer and moisture transport. Heat losses are measured by heat-flow meters, temperatures by thermocouples. Moisture content of the plastic foams is measured by weighing test specimens taken from the roofs before and then after drying. Computers are recording and analyzing the tremendous volume of test values coming from the great number of testing points.

DESIGN OF THE TEST ROOFS

At the Fiskeback field station, the original wooden roof elements at north and south gables of the station building were replaced by 10-cm-thick reinforced concrete planks. At each gable an area of 26 m^2 (3.6 x 7.2 m) was reserved for different test roofs. Test samples were constructed with membrane, thermal insulation of polystyrene foam and on top a layer of aggregate. Six test roofs were built, plus a conventional BUR system reference roof, used as a standard of comparison.

At the north gable of the field station a rag board was first placed loose on the concrete deck as a slip sheet. Then a 0.8-mm thick plasticized, non-UV-stabilized PVC-sheet was laid and jointed in situ. Thermal insulation boards of extruded polystyrene foam, density 35 kg/m^3, were placed directly on the PVC-sheet in four roofs, including the reference roof according to different alternative designs (see Fig. 1). Roof B was laid with 8-cm-thick boards with straight edges, roof C with 8-cm-thick boards with ship-lap joints, roof D with 4-cm-thick boards in two layers with displaced joints and the reference roof with 8-cm-thick boards with straight edges. On the reference roof, a membrane of UV-stabilized, 0.8-mm-thick PVC foil, went on top of the insulation. It was welded to the underlying PVC foil. A 5-cm-thick layer of washed aggregate, 16/32 mm, was placed on the polystyrene foam boards of the PMR and on the membrane of the reference roof as a surface cover.

At the south gable a 1.5-mm-thick prefabricated butyl rubber membrane was laid directly on the concrete elements. Three test sample roofs were constructed, with boards of expanded polystyrene foam of different densities placed loose on the membrane according to the following alternative designs. Roof E was laid with 8 cm thick boards, density 30 kg/m^3 with straight edges, roof F with 8 cm thick boards, density 30 kg/m^3 with ship lap joints, and roof H with 8 cm thick boards, density 40 kg/m^3 with straight edges (see Fig. 1) On the foam boards a 5-cm-thick layer of washed aggregate 16/32 mm was placed here too as a surface protection.

To simulate field conditions, the insulation foam boards were placed with 2mm (1/16 in. plus) joint gaps with small aluminum spacers.

Since effective drainage is vital for a PMR, the test roofs were sloped about 3/16 in. per ft. (about 1:70). At each gable there are two gutters large enough to discharge heavy rains. The gutters are placed 2-4 cm above the membrane at the roof edges. By ponding water at the lower part of the test roof, we could study the different behavior of a ponded PMR vs. a well-drained roof (the upper portions of the test roof).

PROPERTIES OF MOISTURE ABSORPTION AND THERMAL CONDUCTIVITY OF DIFFERENT POLYSTYRENE AND POLYURETHANE FOAMS

Laboratory tests were made to investigate the properties of moisture absorption and thermal conductivity of different types of extruded and expanded polystyrene foam and polyurethane foam [5].

Moisture absorption of the different materials in per cent by volume are shown in Fig. 2. Test specimens of the dimensions 5 x 5 x 10 cm were waterproofed on four sides so that only two opposite sides 5 x 10 cm were open to water absorption. They were immersed in water at 20°C with the top side about 1 cm below the water surface.

The tests were continued for about five months. Through periodic weighing of the test specimens, we plotted moisture absorption as a function of time. Moisture absorption of all polystyrene foams tends to decrease with time. The tests indicate much greater moisture absorption for expanded than for extruded polystyrene foam. Extruded polystyrene and polyurethane foams concentrated absorbed moisture at the surface. Comparison of the tests in Fig. 2 with capillary suction tests (samples floating on the water surface) indicated that moisture absorption by capillary suction is about 3-25% of the values given in Fig. 2. Moisture absorbed for 120 days according to Fig. 2 dried in 30 days in a room at 21°C and 50% R.H. A somewhat longer time is needed for drying Roofmate extended polystyrene and polyurethane.

Increased thermal conductivity as a function of increased moisture content was studied on foam boards 45 x 45 x 8 cm. Moisture was forced to penetrate by a special apparatus with constant climate conditions with 60°C and 100% relative humidity on the warm side and 21°C and 50% relative humidity on the cold side. The moistening took place by vapor diffusion. The thermal conductivity was determined in a plate apparatus according to the Lang method at a mean temperature of 10°C. The thermal conductivity as a function of the moisture content in per cent by volume as well as its spread is shown in Fig. 3.

The increase of the thermal conductivity is about 10-15% for expanded polystyrene foam at a moisture content of 7% by volume, the maximum value of the moisture absorption in the field tests after one year. For the extruded foams, Roofmate, the moisture absorption was much less.

EVALUATION OF THE TEST RESULTS FROM THE FIELD STATION

All field-station measurements are carried out by a computer-controlled data acquisition system. Measuring data are stored on magnetic tape. All the measuring points of the PMR are scanned continuously at intervals of ten minutes. They include temperature and heat flow as well as general meteorological data. Further analysis of the measuring data to determine the thermal resistance of the various test roof sections is made with especially composed data programs [7].

Since the roofs are studied under actual climate conditions heat transfer does not take place at ideal steady-state conditions. Outside temperature varies and the roof is occasionally cooled by wind and rainfall. Moreover the roof and the concrete elements constitute a heavy construction with a high thermal capacity.

These factors complicate the determination of the various test roofs' thermal resistance. To determine these thermal resistances, it is necessary to know the size and variation of heat flow during a certain time, plus inside and outside temperatures for the same period. By measuring and calculating surface temperatures, it is possible to avoid the uncertainty caused by the variation of the coefficients of heat transfer for the surfaces. Since temperatures and heat flows vary with time, the definite integrals over the time interval $t_1 - t_2$ of the temperature difference T (t) and of the heat flow Q (t) through the roof are introduced. The following expression is obtained:

$$\frac{\int_{t_1}^{t_2} \Delta T(t)\,dt}{\int_{t_1}^{t_2} Q(t)\,dt} \left(\frac{m^2\,^\circ C}{w}\right)$$

where m = the thermal resistance of the roof excluding the transistion resitances.

This equation is valid if the roof temperatures are equal at the beginning and at the end of the measurements, and if the measuring period is so long that the effect of heat capacity is nullified.

To study the thermal resistance of the PMR at the field station, inside and outside air temperatures are measured. Temperatures are also measured at three levels of the construction with copper/constantan thermocouples and the heat flow through the roof with heat-flow meters.Measurements are made for each test roof in two cross sections—one through foam-board joints, and the other through the middle of foam boards. The position of the gauges at the different test roofs is shown in Fig. 1.

Started in the autumn of 1975, these measurements are still going on. Thermal resistances of the different test roofs have been studied for different periods. Note that the insulation foams of the different roofs have inherently different thermal conductivities and that their moisture-absorptive properties also vary, thus influencing the thermal conductivity of the different test materials.

In Fig. 4 the measured thermal resistances of the different test roofs for the period 75/10/24—75/11/28 are shown in relation to the temperatures on top and bottom sides of the roof. The design of the test roofs is shown in Fig. 1. The result shown in Fig. 4 corresponds to measurements on the section at the middle of a foam board.

By comparing the thermal resistances of the test roofs with that of the reference roof for the same type of plastic foam, you can study the special properties of the PMR. Fig. 5 shows the thermal resistances of the test roofs B, C and D, compared with the reference roofs. It also shows the influence of rainfall and wind. Thermal resistance of the PMR is about 10% lower than that of a conventional roof under the conditions indicated.

Moisture absorption of polystyrene foam after about one year as roof insulation varies with foam quality. There may also be some influence if the foam boards are laid in one or two layers. The moisture content of extruded foam in one layer was about 0.05 per cent by volume, while the same material in two layers of the same total thickness contained about 0.3 per cent by volume. The moisture content of expanded polystyrene foam in one layer was about 5-6 per cent by volume.

Judged by the test results under different weather conditions, thermal resistance appears to vary with rainfall and wind, PMR thermal resistance appears to decrease somewhat with increasing wind velocity. These conditions will be further studied for more accurate determination of PMR thermal resistance.

As a general interim conclusion of this test program, extruded polystyrene appears to be the best commercially available solution to the problem of rain-exposed insulation in the PMR. It shows, by far, the best moisture absorptive characteristics of tested plastic foam insulations and a correspondingly low loss in thermal conductivity.

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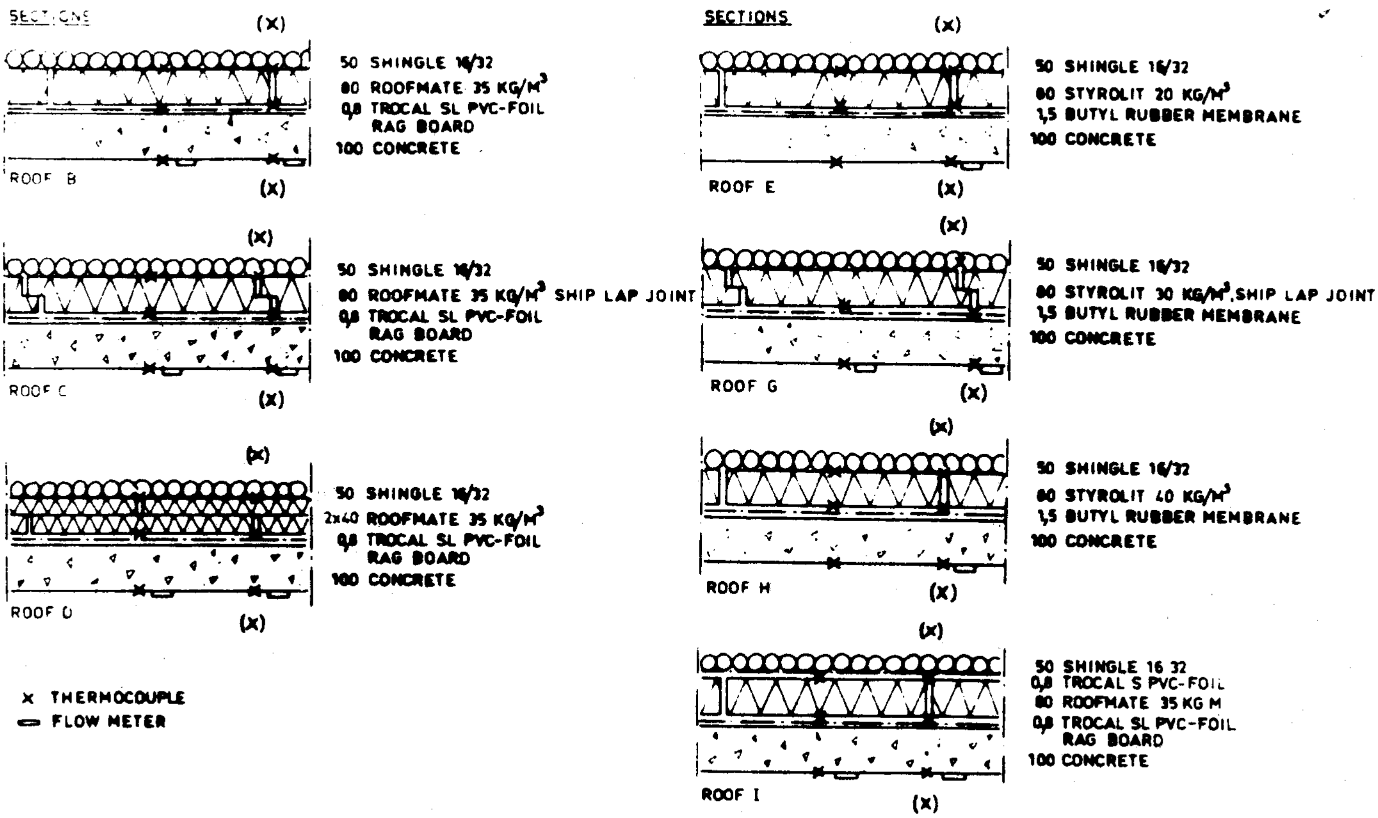

FIGURE 1 - DESIGN OF TEST ROOFS (B, C, D, E, G, H), REFERENCE ROOF (I) AND POSITIONS OF THERMOCOUPLES AND FLOW METERS.

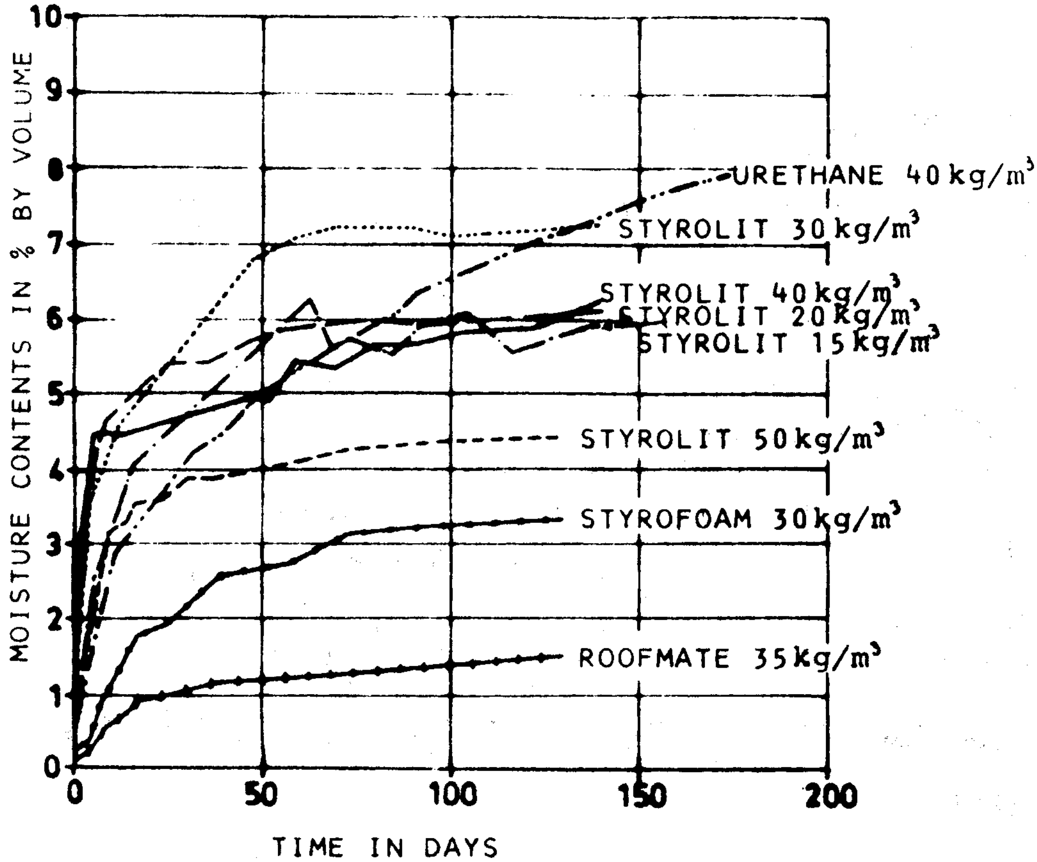

FIGURE 2 - MOISTURE ABSORPTION OF DIFFERENT PLASTIC FOAMS. TEST SPECIMENS 5x5x10 CM IMMERSED WITH FOUR SIDES WATERPROOFED AND TWO OPPOSITE SIDES 5x10 CM EXPOSED TO WATER PENETRATION.

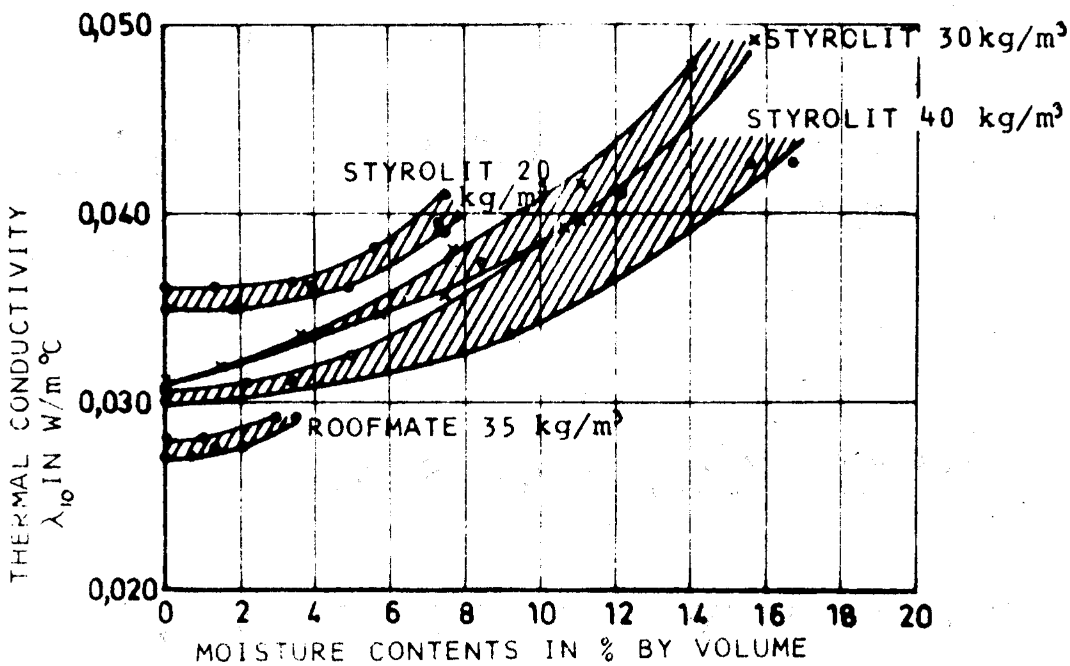

FIGURE 3 - THERMAL CONDUCTIVITY AS A FUNCTION OF THE MOISTURE CONTENT FOR DIFFERENT EXTRUDED (ROOFMATE) AND EXPANDED (STYROLIT) POLYSTYRENE FOAMS.

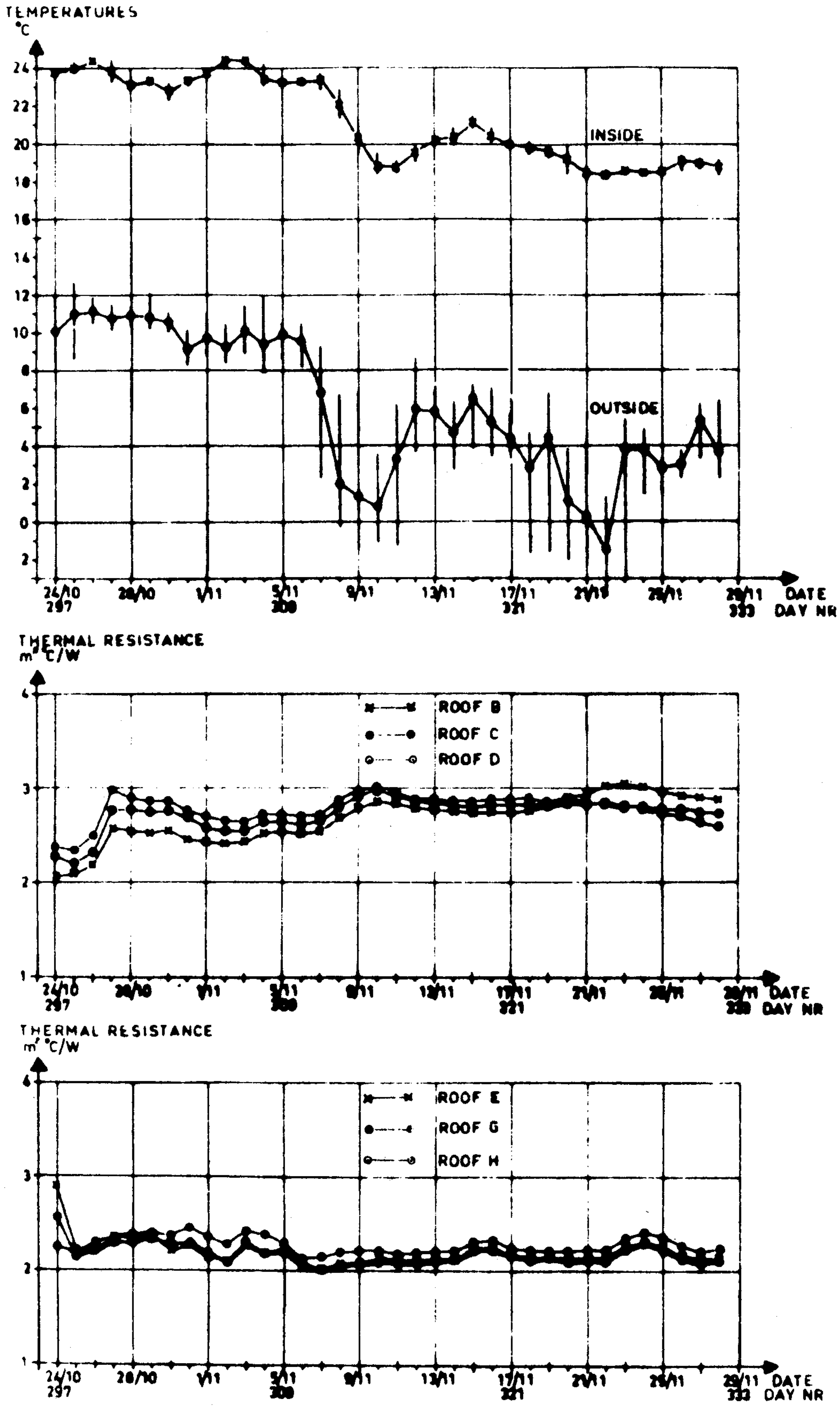

FIGURE 4 – THERMAL RESISTANCE OF THE TEST ROOFS B, C, D, E, F AND H RELATED TO THE TEMPERATURES OF THE UPPER AND UNDER SURFACES OF THE ROOFS.

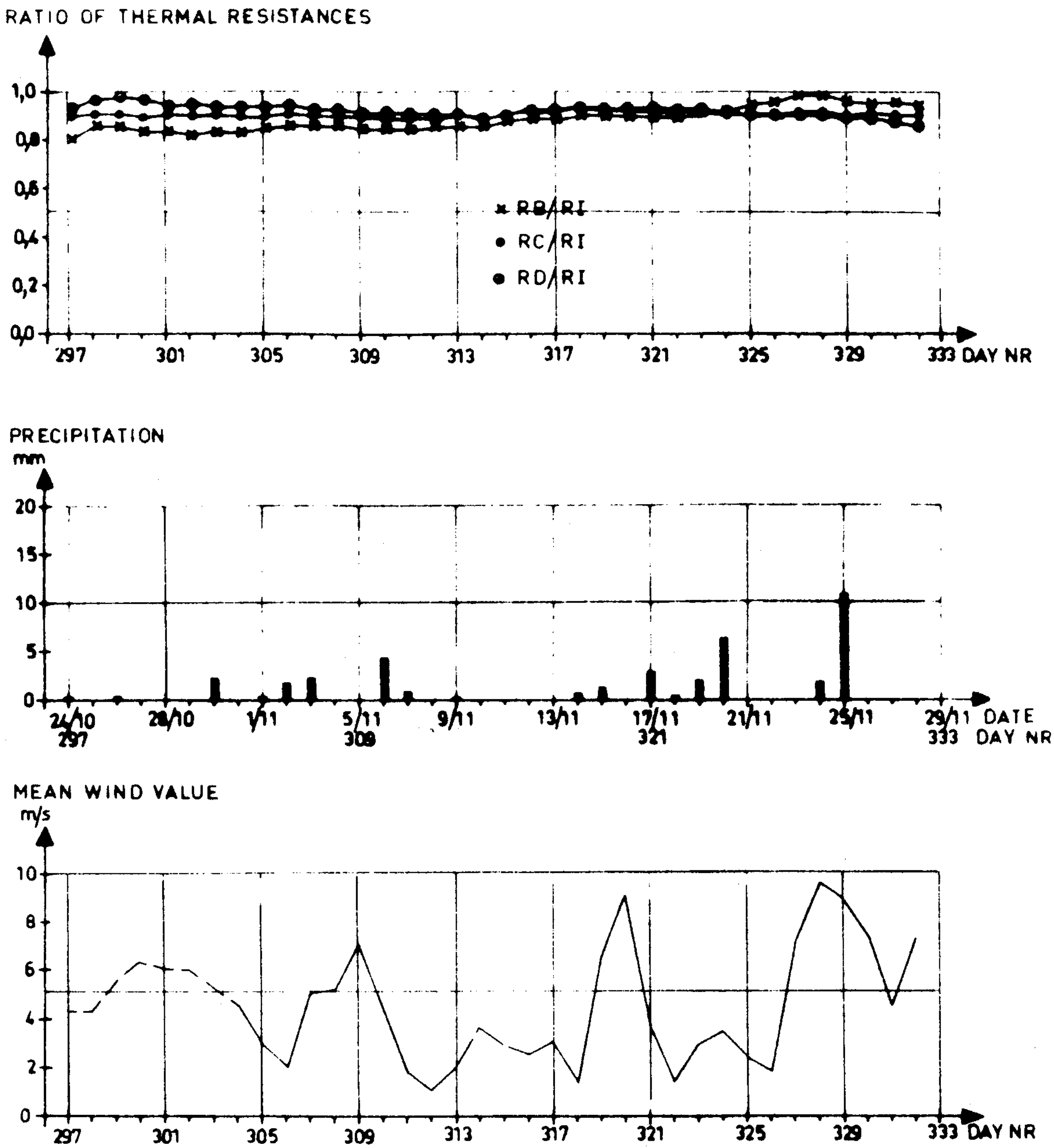

FIGURE 5 – THE RATIO OF THERMAL RESISTANCE OF THE TEST ROOFS B, C AND D TO THAT OF THE REFERENCE ROOF I. CORRESPONDING PRECIPITATION AND WIND CONDITIONS ARE INDICATED.