SOME DESIGN CHARACTERISTICS OF INSULATION IN FLAT ROOFS RELATED TO TEMPERATURE AND MOISTURE

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INTRODUCTION

The performance of thermal insulation in a flat roof system depends on many complex variables – notably, thermal conductivity; moisture transmission properties; dimensional stability (creep); thermal coefficient of expansion/contraction; shear, compressive, and tensile strength; impact resistance; resistance to solar radiation; susceptibility to freeze-thaw cycling; chemical attack and aging; combustibility and flame spread properties. Its behavior is further complicated by its environment in the roof system and its interaction with the other mutually interdependent components that collectively constitute the roof system.

This report discusses some aspects of moisture and thermal effects and the effects of environment or special treatment on insulation performance. Its conclusions emerge partly from research work at Saskatoon and partly from the published results of others.

Here, in summary, are the key conclusions:

- Roof components other than the thermal insulation can contribute significantly to heat-transmission control. As a notable example, membrane surface color can substantially reduce heat transmission and alter the insulation environment.
- In protected membrane roofs dependent on an adhesive agent to anchor the insulation, it is important to minimize bonding stresses from the insulation's expansion/contraction.
- Heavily insulated roof systems may perform better with part of the insulation placed above the membrane (as in protected membrane roof assembly) and part below the membrane (as in conventional deck-insulation-membrane sandwich assembly).
- Substantial reductions in moisture gain in insulation can be achieved via (a) surface sealing, or (b) avoidance of water entrapment against the insulation surface. Further, drying of wet insulation in flat roofs by gravity, wicking and vapor pressure forces is likely to be slow.

Roofing studies related to the foregoing conclusions were conducted over the past several years at the Prairie Regional Station, Division of Building Research, National Research Council of Canada, Saskatoon. They involved work in the laboratory, in the field, and at an outdoor test facility designed to simulate actual roof service conditions. At the outdoor test facility, moisture contents of insulations are measured by periodic weighing. Heat flow through experimental roof systems is measured with heat-flow meters held against the roof deck (Figure 1). Thermocouples measure temperatures. Results are recorded on magnetic tape and processed by a computer [Ref. 1].

INSULATING EFFECT OF OTHER COMPONENTS

Most of the insulating effect is likely to reside in the thermal insulation, but other components also contribute via their conductive, convective, and radiative properties, or by attenuating and delaying heat flow because of thermal mass [Ref. 2, 3, 4, 5]. These effects are treated in detail in the *ASHRAE Handbook of Fundamentals*.

Surface color can have a significant effect on heat flow. The effect varies with solar radiation intensity and wind speed. The solar effect is illustrated by temperature and heat-flow plots for selected one-day periods in July (Figure 2), on black, white, and concrete surfaces over foamed-in-place urethane insulation approximately 75 mm (3 in.) thick, on a 9.5 mm (3/8 in.) thick marine plywood deck. (The 25 mm (1 in.) thick concrete-surfaced section was not graphed.)

On a sunny day (when it is usually desirable to minimize daytime heat flow into buildings) total heat inflows were 270 kJ/m^2 (25 Btu/ft^2), 74 kJ/m^2 (6.5 Btu/ft^2) and 113 kJ/m^2 (10 Btu/ft^2) for the black, white and concrete-covered areas, respectively (Figure 2a). Differences on a cloudy day, two weeks later, were very small (Figure 2b).

In cold weather a dark surface can be beneficial in reducing heat loss through the roof if it is not snow covered [Ref. 6].

MUTUAL STRESSES IN ROOFING COMPONENTS

Associated with its influence on heat flow, roof color exerts an effect on the insulation environment and its interaction with neighboring components [Ref. 7, 8].

As shown in Figure 2a, temperatures of the insulation's top surfaces under the black, white and concrete surfaces ranged from 6 to 63, 3 to 40 and 7 to 52°C, respectively, whereas the lower surface temperatures (not shown) ranged from about 22 to 28°C.

These temperature changes produce dimensional changes in the insulation, depending on its coefficient of thermal expansion and degree of restraint. Coefficients of expansion are small for some fibrous insulations, e.g., 5 x 10^{-6}/°C for wood fiberboard, but considerably higher for some foam plastics [Ref. 9]. Observed mean temperature change under the black surface was 31°C. With an assumed modulus of elasticity of 6.9MN/m^2 (1000 psi) and thermal coefficient of expansion of 6.3 x 10^{-6}/°C, i.e., for extruded polystyrene having a density of 40 kg/m^3 (2.5 pcf), [Ref. 10], the force required to totally restrain the insulation during this temperature change would have been 69 kg/m (47 lb/ft) of edge length for 51 mm (2 in.) thick material. For white surface material, the corresponding force would have been 42 kg/m (29 lb/ft). In practice, the restraint would not be total and some movement would have to be accomodated by the system [Ref. 11].

Since the temperature does not change uniformly through the insulation, it produces not only elongation but also a bowing, with consequent stresses on components bonded to the insulation [Ref. 12]. To prevent deformation, the insulation would have to be restrained longitudinally in two directions and normal to its surface.

Illustrating the effect of dimensional changes, interaction at the butt joint produced membrane deformation within a year of placement in the experimental protected membrane roof shown in Figure 30. The insulation was covered by paving-stone ballast.

TWO LAYERS FOR HEAVILY INSULATED ROOFS

Recent demand for thermal resistances up to 6 m^2 • °C/W (35 hr • ft^2 • °F/Btu) would require anywhere from 150 mm (6 in.) to 250 mm (10 in.) of insulation, depending on type. In some experts' opinion, application of such insulation may be more easily managed in two layers: one below the membrane and the other above, with the top insulation layer secured either by ballast or by bonding to the membrane.

This design would reduce the extremes of temperature experienced by the roof membrane. A membrane in a conventional system might reach 70°C (158°F) in summer, and −40°C (−40°F) in winter. With half the thermal resistance above it, these extremes would be cut to approximately 45°C (113°F) and −10°C (14°F).

In addition to lowering the thermal stress on the membrane, this arrangement would reduce the likelihood of moisture condensation in the insulation below the membrane. The benefit of the warming of topside insulation was experienced in a metal working shop in Winnipeg, Manitoba. When the building was constructed, cork insulation was adhered to the underside of the folded plate concrete roof deck. In time, this insulation absorbed moisture produced in the building and began to fall off. The upper surface of the deck was then insulated with foamed-in-place urethane. Subsequently, the cork dried out and resumed its insulating function.

One obstacle to placement of board insulation about the membrane is the problem of holding it in place. For each 25 mm (1 in.) insulation thickness, it takes about 30 kg/m^3 (6 psf) of ballast, additional dead load on the roof deck and structural framing. In existing buildings not designed for this additional load, above-membrane insulation could be anchored by hot-mopped asphalt or other adhesive. In Canada, this method is still at an early stage of development. The bonding agent must resist flotation and wind uplift, plus forces resulting from elongation and bowing of the insulation. Good membrane-insulation adhesion requires use of dimensionally stable insulation, good bond at the outset, and use of an adhesive that can resist the stresses applied to it. Slashing the insulation across the long dimension allows it to follow roof contours more easily and to be set with firmer contact with the adhesive.

MOISTURE IN INSULATION

Moisture intrusion into thermal insulation has two deleterious effects:

- possibly drastic reductions in thermal resistance [Ref. 13, 14]
- potential destruction of the insulating material

There is a continuing need to understand the behavior of moisture in insulation, and to develop methods through design or special protective measures to prevent its entry.

Moisture may enter by vapor diffusion, free water flow, and by hygroscopic forces, depending on the nature of the insulation. In any given case, the flow is likely to result from a complex mix of these three modes. In closed cell insulations, and probably some of the porous ones as well, free-water flow and wicking may be insignificant, and the rate of movement in a given insulation depends mainly on vapor-pressure gradient.

Figure 5a shows the rates of moisture gain when temperature gradients were applied to closed cell insulation 25 mm (1 in.) thick. The warm surface was kept wet. The edges and cold surface were waxed to prevent moisture escape. The rate of moisture uptake increased with increased temperature difference. The results for the temperature differences of 22, 11 and 2.8 C deg can be represented more coherently by the equation

$$\frac{W}{A} = \mu \frac{dp}{d\theta} \frac{\Delta\theta}{\Delta X} \tau \qquad \text{[Ref. 1].}$$

where W is the amount of moisture transmitted into the insulation through the surface of area A,

$\frac{dp}{d\theta}$ is the slope of water vapor saturation curve Pa/k (in.Hg/°F),

$\frac{\Delta\theta}{\Delta X}$ is the average temperature gradient across the insulation, °C/m (°F/in.),

τ is the time elapsed from the beginning of the test, seconds,

μ is the constant of proprotionality and corresponds to permeability at the surface of entry, kg/TPa•m•s (perm in.)*.

In Figure 5b, the accumulated moisture gain per unit of surface area is plotted against the product of vapor pressure gradient at the warm surface and elapsed time. The slope of the line has the units of permeability and gives a measure of the insulation susceptibility to moisture gain [Ref. 15].

The rate of moisture gain is strongly dependent on vapor-pressure gradient. In winter, moisture beneath roofing insulation tends to be driven into it due to the temperature gradient which parrallels the vapor-pressure gradient. In summer, if moisture is trapped against the membrane surface, or if water ponds on the membrane, high vapor pressures, induced by temperature peaks illustrated in Figure 2, result in rapid penetration of moisture.

Various protective measures can substantially reduce the rate of moisture gain in some insulation. In one test, two sets of bead polystyrane specimens with densities of 15.3 kg/m³ (0.95 lb/ft³) and 26.5 kg/m³ (1.7 lb/ft³) with bottom surface sealing (S) (coated base sheet adhered by asphalt) and topside ventilation (SU), were compared with unscaled (US) specimens also lacking top surface ventilation (SD) (paving stones resting on the top surface). The results shown in Figure 6 demonstrate the effect of these two measures in controlling moisture gain. However, if either measure is neglected, large moisture gains occur [Ref. 16]. Even some fibrous insulations remained at moisture contents of less than 4% by volume when protected in this way [Ref. 16, 17]. Note, however, that these test demonstrations of principles do not necessarily show the practicality of using fibrous insulations in protected membrane systems.

Roof design often assumes complete protection of the insulation from moisture intrusion. In practice, however, some moisture is likely to penetrate the roof. In some cases, it may be more practical to try to ensure that the balance between gain and loss maintains moisture content at or below acceptable levels. This principle has been enunciated for sprayed-on insulations in certain environments. It is fairly well established in protected membrane roofing, where the prescence of some moisture in insulation is generally accepted. What constitutes an acceptable level depends on (a) the resulting physical degradation of the insulation and (b) reduction in thermal resistance.

Roof drying or moisture balance design can exploit natural forces acting to move moisture. In flat roofs, both thermal and gravity forces act normal to the insulation surface, and do not promote lateral movement. Lateral movement depends on free water flow under hydraulic head or, in some cases, wicking action. Lack of lateral movement was illustrated in a test with water introduced into an experimental roof system from the underside to wet the insulation. When the membrane was removed five years later, only a small area around the entry points was wetted (Figure 7).

Confirmation of this phenomenon comes from measurements on wet roofs. Surveys with neutron moisture meters and cut tests often reveal sharply defined wet areas. From Figure 8, it appears that water, on entering the roof, has wetted a region but that the transition to dry insulation occurred within a few feet [Ref. 18].

Further confirmation of the slow lateral movement of moisture in flat roof insulation comes from observations of the drying of wetted insulations enclosed in panels. The 0.61-m (2 ft) x 1.22-m (4 ft) x 51-mm (2 in.) – thick

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*kg/TPa•m•s simplifies to ps (T – tera = 10^{12}, p – pico = 10^{-12}),
kg = kilogram, PA = Pascal, m = metre, K = kelvin.

insulation was sealed in 0.15 (0.006 in.) polyethylene, except for an opening to a roof vent secured to the centre of the top surface of the panel. Gradual drying occurred through the nearly six-year-long test. Some moisture loss doubtless occurred through the polyethylene, and lateral movement to the vent was even smaller than the graph in Figure 9 suggests. There was only one vent per panel, consequently no through-flow of air would occur [Ref. 19].

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REFERENCES

1. Hedlin, C. P., Orr, H. W. and Tao, S. S. *"Thermal Resistances of Experimental Flat Roof Systems Measured with Heat Flow Meters."* ASTM Thermal Insulation Conference, Tampa, Florida, Oct. 1978.
2. *"ASHRAE Handbook of Fundamentals,"* 1977.
3. Rossiter, W. J. and Mathey, R. G. *"Effect of Insulation On Surface Temperature of Roof Membranes."* U.S. National Bureau of Standards, NBS TR 66-987, Feb. 1976.
4. Aamot, H. W. C. *"Thermal Efficiency Measurements on a Protected Membrane Roof."* International Syposium on Roofs and Roofing, Brighton, England, Sept. 1974.
5. Larssen, L-E., Ondrus, J. and Petersson, B-A. *"The Protected Membrane Roof – A Study Combining Field and Laboratory Tests."* Proceedings of the Symposium on Roofing Technology, NBS/NRCA, Washington, Sept. 1977.
6. Mitalas, G. P. *"Net Annual Heat Loss Factor Method for Estimating Heat Requirements in Buildings."* National Research Council of Canada, Division of Building Research, Building Research Note No. 117, Nov. 1976.
7. Givoni, B. and Hoffman, M. E. *"Effect of Roof Design on Indoor Climate in Hot Arid Zones."* Build International, Vo. 6, No. 5, Sept.-Oct. 1973, pp. 525-540.
8. Cullen, W. C. *"Solar Heating, Radiative Cooling and Thermal Movement – Their Effects on Built-up Roofing,"* U.S. National Bureau of Standards, Technical Note 231, Dec. 1963.
9. Griffin, C. W. *"Manual of Built-up Roofing Systems."* New York, McGraw-Hill, 1970.
10. Product data, Dow Chemical of Canada, Ltd.
11. Chaise, A. *"Behavior of Thermal Insulations Used as Substrates for Roofing Membranes."* Proceedings of the Symposium on Roofing Technology, NBS/NRCA, Washington, Sept. 1977.
12. Cash, C. G. *"Thermal Warp – A Hypothesis for Built-up Roofing Splitting Failures."* Roofing Systems, ASTM STP 603, June 1975.
13. Powell, F. J. and Robinson, H. E. *"The Effect of Moisture on the Heat Transfer Performance of Insulated Flat Roof Constructions."* Building Science Series 37, 1971.
14. Epstein, K. A. and Putnam, L. E. *"Performance Criteria for the Protected Membrane Roof System."* Proceedings of the Symposium on Roofing Technology, NBS/NRCA, Washington, Sept. 1977.
15. Hedlin, C. P. *"Moisture Gains by Foam Plastic Roof Insulations Under Controlled Temperature Gradients."* Journal of Cellular Plastics, Vol. 13, No. 5, Sept.-Oct. 1977, pp. 313-319, 26. Available as Reprint No. NRCC 16317.
16. Hedlin, C. P. *"Moisture Content in Protected Membrane Roof Insulations – Effect of Design Features."* Roofing Systems, ASTM STP 603, June 1975. Available as Reprint No. NRCC 15382.
17. Hedlin, C. P. *"Moisture Attack on Insulations in Protected Membrane Roofing."* Second International CIB/RILEM Symposium on Moisture Problems in Buildings, Rotterdam, Sept. 1974. Available as Reprint No. NRCC 14590.
18. Hedlin, C. P. *"The Use of Nuclear Moisture Density Meters to Measure Moisture in Flat Roofing Insulations."* Second International CIB/RILEM Symposium on Moisture Problems in Buildings, Rotterdam, Sept. 1974. Available as Reprint No. NRCC 14593.
19. Baker, M. C. and Hedlin, C. P. *"Venting of Flat Roofs."* National Research Council of Canada, Division of Building Research, Canadian Building Digest 176, May 1976.

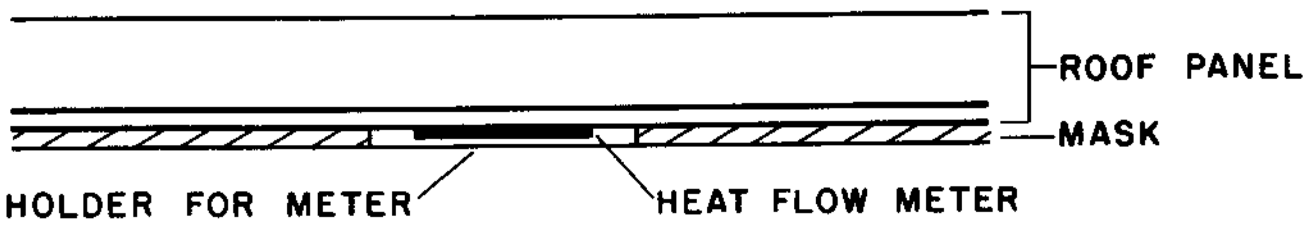

FIGURE 1 – FOR MEASUREMENT OF HEAT FLOW, THE METER IS SECURED TO THE LOWER SIDE OF THE EXPERIMENTAL ROOF PANEL.

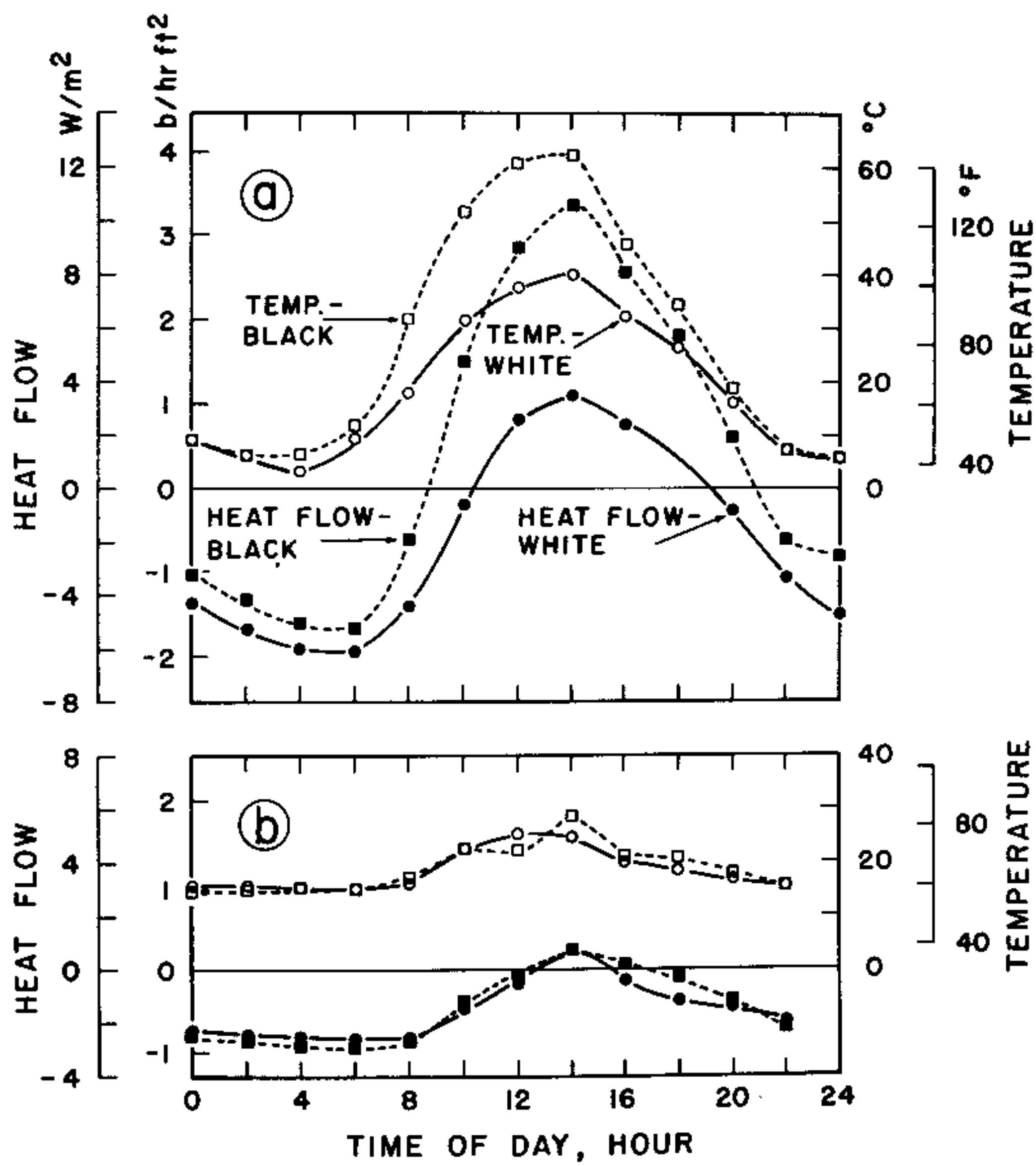

FIGURE 2 – HEAT FLOW RATES AND TOP SURFACE TEMPERATURES FOR 75 MM THICK FOAMED-IN-PLACE URETHANE. THE UPPER SURFACE OF ONE SECTION WAS PAINTED BLACK AND THE OTHER WHITE. POSITIVE HEAT FLOW IS INTO THE BUILDING, NEGATIVE IS OUTWARD.

(A) BRIGHT DAY (B) CLOUDY DAY

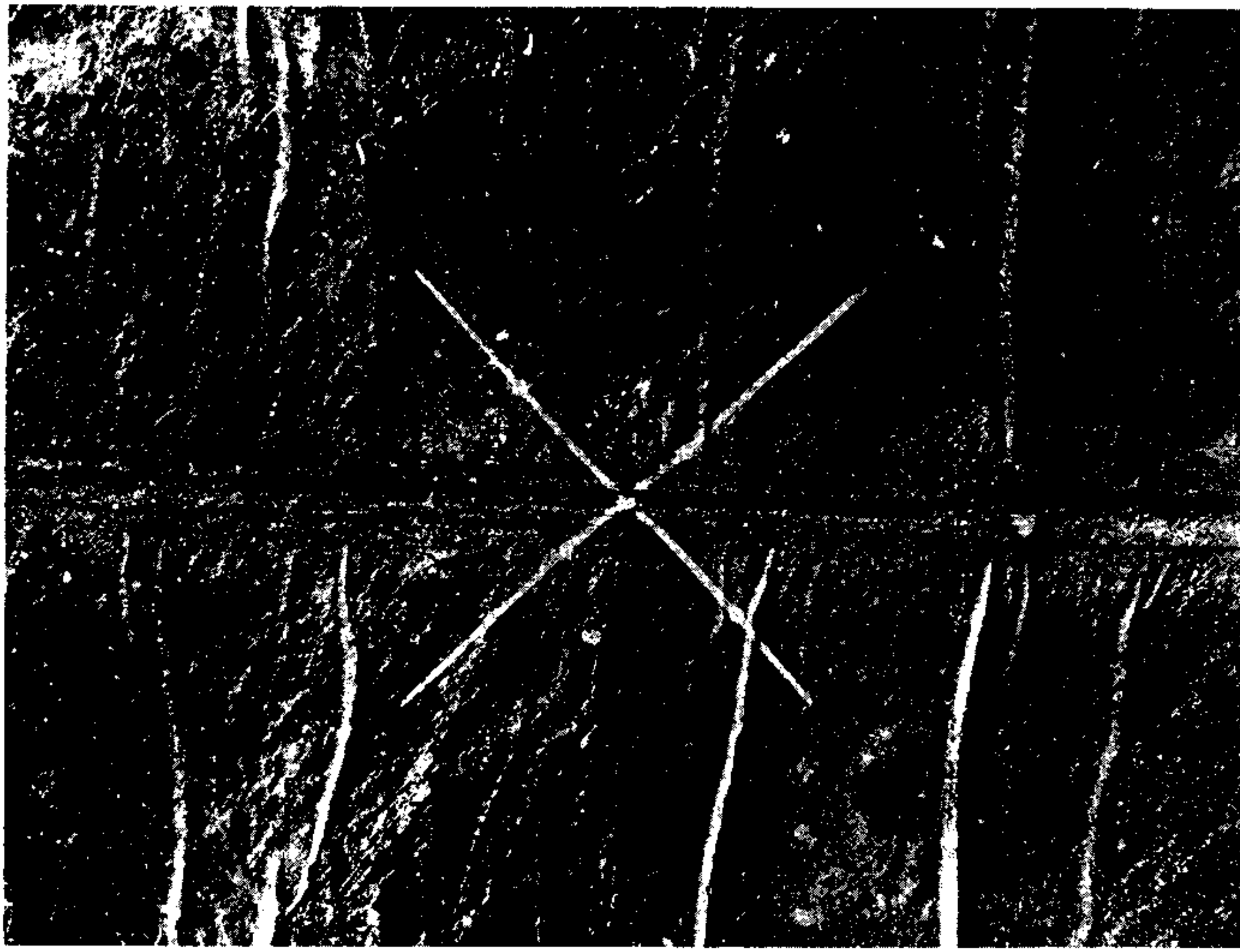

FIGURE 3 - RIDGE IN MEMBRANE AT INSULATION BUTT JOINT (RUNNING ACROSS THE FIGURE) - PROTECTED MEMBRANE ROOF. THE "X" IS SIMPLY A REFERENCE MARK ON THE MEMBRANE.

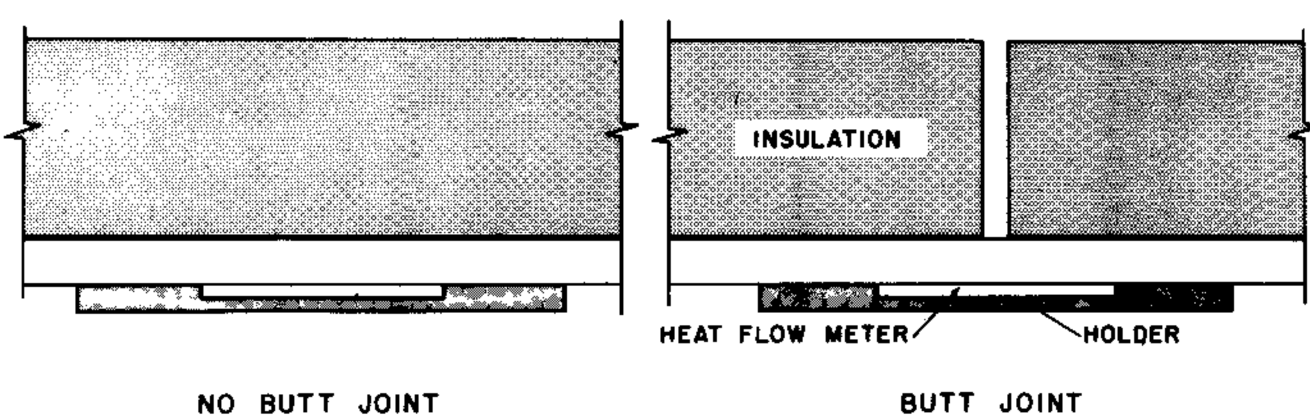

FIGURE 4 - HEAT FLOW METERS USED TO COMPARE HEAT LOSSES WITH AND WITHOUT A BUTT JOINT (PROTECTED MEMBRANE ROOF SYSTEM).

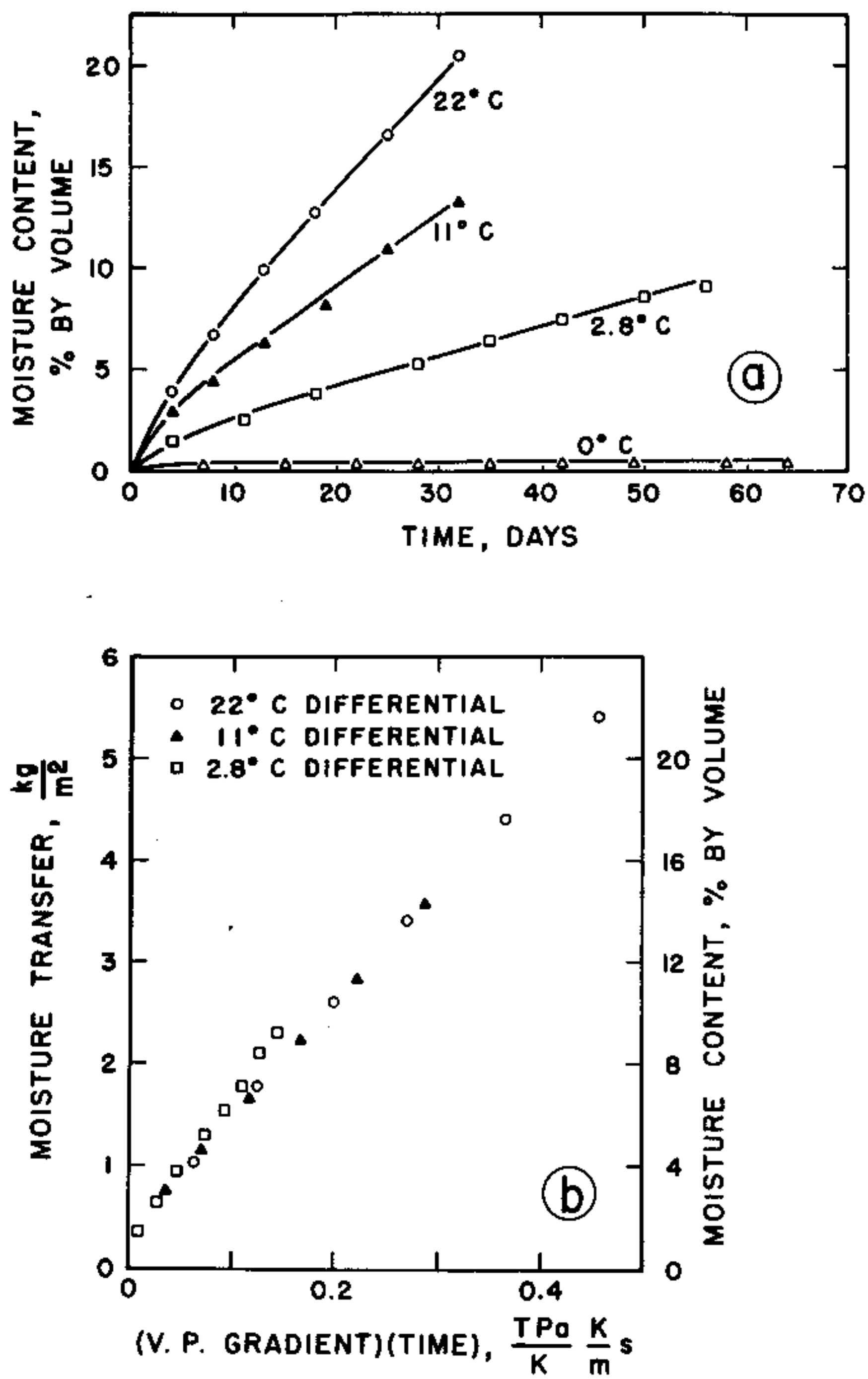

FIGURE 5 - MOISTURE ABSORPTION BY A POLYURETHANE INSULATION. EDGES AND ONE SURFACE OF THE SPECIMENS WERE COATED WITH WAX. THE REMAINING SURFACE WAS KEPT WET AND 2.8, 11 OR 22 C DEG WARMER THAN THE WAXED SURFACE. "B" SHOWS THE SAME DATA (EXCEPT 0°C DIFFERENTIAL) PLOTTED IN A DIFFERENT WAY.

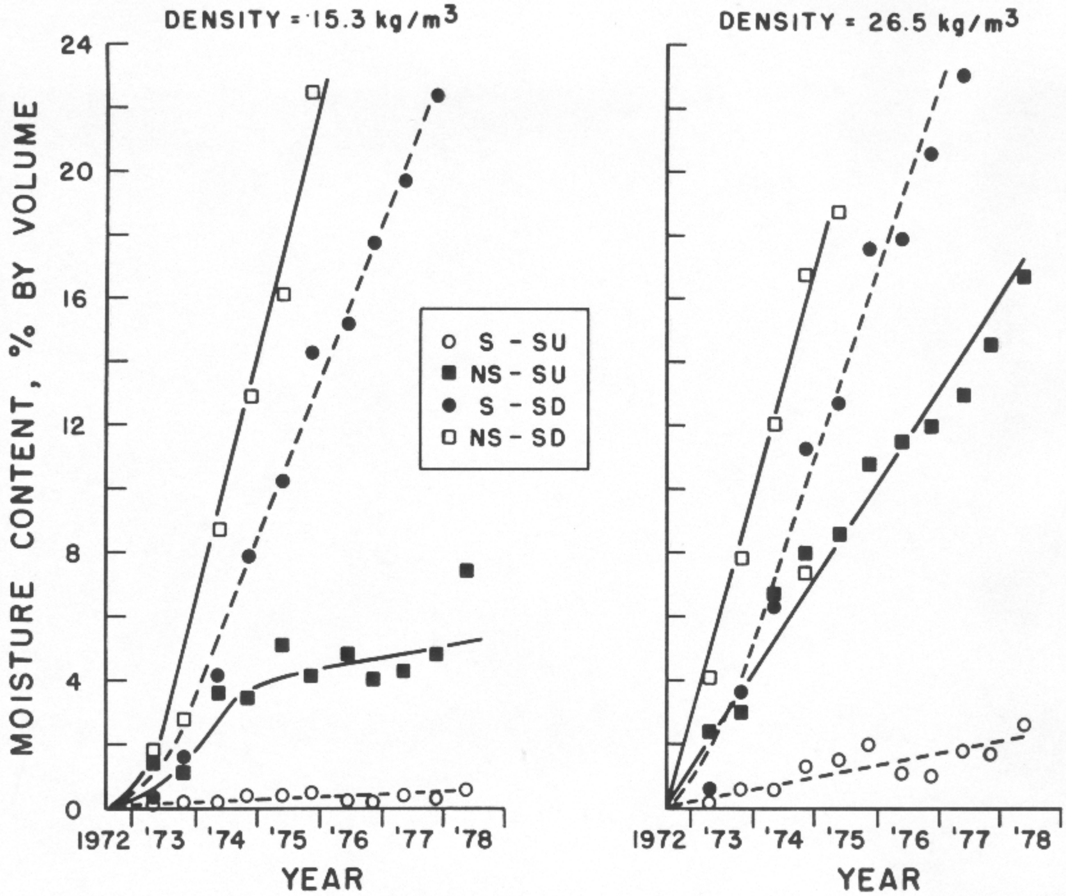

FIGURE 6 – MOISTURE ABSORPTION BY BEAD POLYSTYRENE SPECIMENS 0.61 M SQUARE and 51 MM THICK WITH AND WITHOUT BOTTOM SURFACE SEALING (S, NS) AND WITH AND WITHOUT TOP SURFACE VENTILATION (SU, SD).

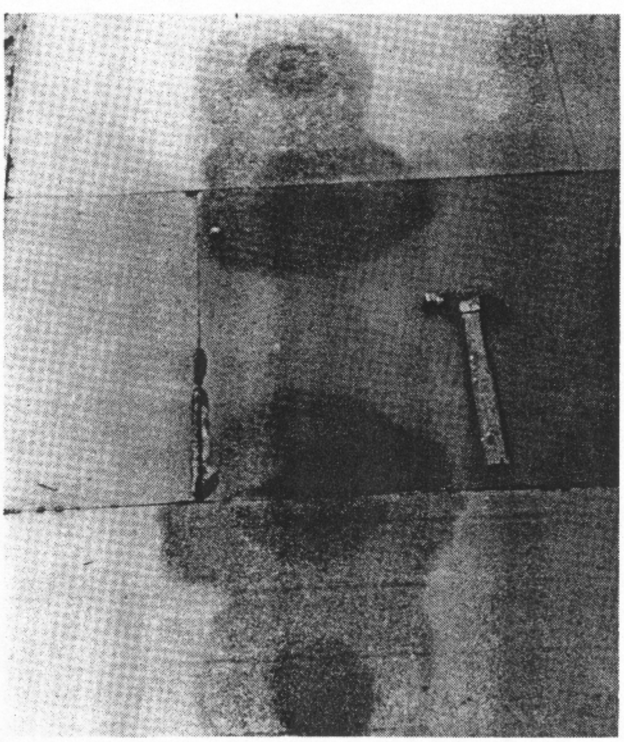

FIGURE 7 – WATER INJECTED INTO ROOF SYSTEM PRODUCED ONLY LOCAL WETTING OF THE INSULATION.

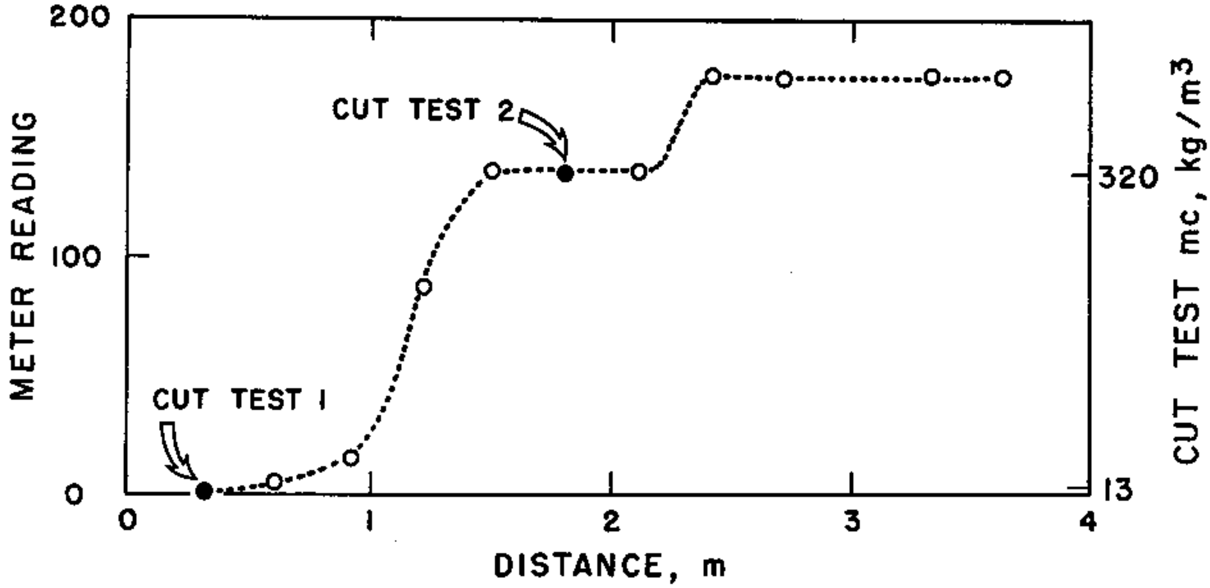

FIGURE 8 - INSTRUMENT READINGS AND INSULATION MOISTURE CONTENTS ACROSS THE BOUNDARY OF A WET AREA.

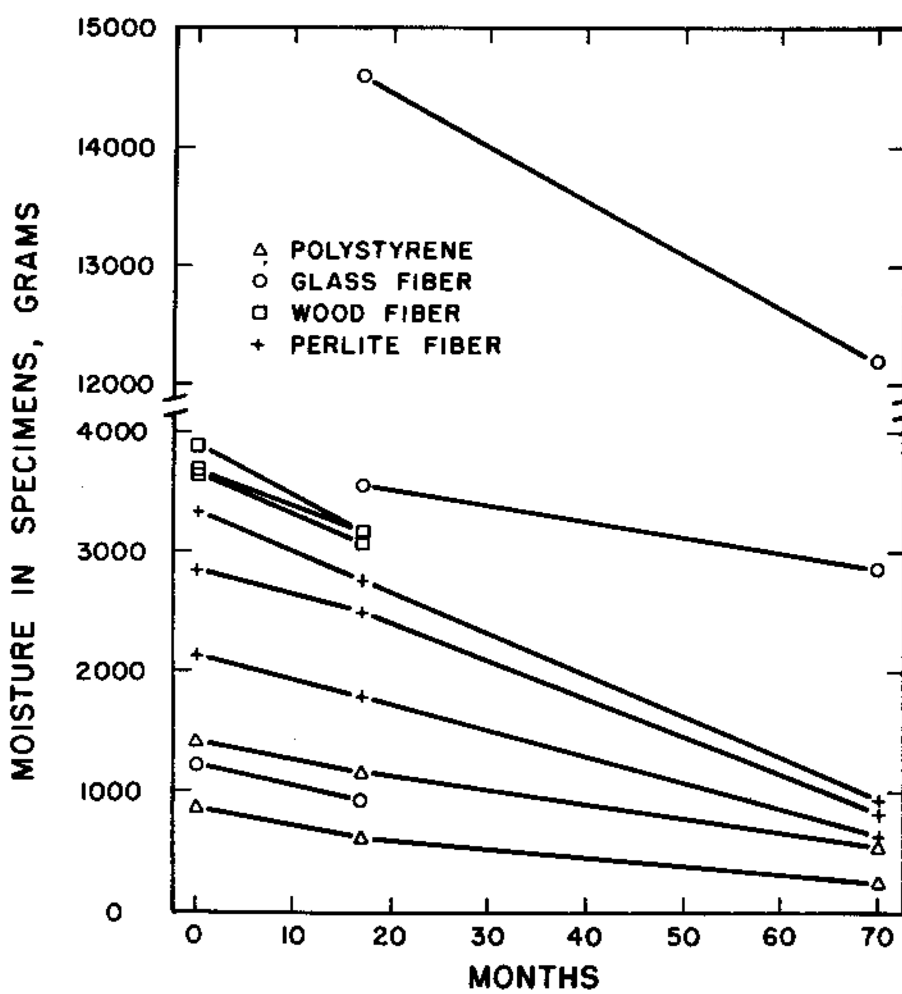

FIGURE 9 - MOISTURE REMOVAL FROM 0.61M x 1.22M x 51 MM THICK INSULATIONS ENCLOSED IN POLYETHYLENE AND WITH A ROOF VENT IN THE UPPER SURFACE OF THE PANEL.