# A STUDY OF SOME STRUCTURAL INTERRELATIONSHIPS BETWEEN POLYURETHANE FOAM AND PROTECTIVE COATINGS

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## ABSTRACT

The performance of a roofing system assembled from sprayed-in-place polyurethane foam and protective coatings depends on physical characteristics of both the foam insulation and the protective coating. This study looks at some of the interrelated characteristics using a technique of photomicroscopic examination with transmitted light through "thin sections" (cross sections approximately 0.025 millimeter thick). The study included 110 samples from roofs worldwide, ranging in age from 1 to 12 years with an average age of more than five years. In addition, 105 laboratory-prepared control samples were examined.

The performance of the two major materials used to construct polyurethane foam and protective coating roof systems is interdependent. Poor performance by one material is certain to be detrimental to the other and to the roofing system as a whole. Many roofing samples for this study were selected from specific problem areas. Of the 110 samples studied, 73 showed some degree of performance defects when examined microscopically. The percentage of defects was high since the study was designed to look at problem areas.

The observed foam defects consisted of inadequate structure in cell size, low closed cell content, and the lack of a surface skin. These defects could usually be attributed to the presence of moisture at the time of installation, and to a lesser degree, to misproportioned components, improper use of placement equipment, or defective materials such as low polyol-isocyanate reactivity, inappropriate levels of blowing agents and water contamination of the polyol components.

Coating defects included pinholes, cracking, poor weather durability, and poor adhesion. The most common cause for these defects was a coating application that was too thin. Unlike many other types of paint, the adhesion of an elastomeric coating is a function of physical thickness. This relationship is probably caused by lateral stress being more uniformly distributed by a thick coating than by a thin one. Other contributing factors include low coating elongation, inadequate tensile strength, defective materials and the entrapment of air or moisture during application.

Design errors also contributed to the observed defects and included the use of coatings with poor low temperature elongation in cold climates (as differentiated from elongation at room temperature), ice damage caused by poor drainage, and physical breakdown of both the insulation and coating because of the lack of a proper vapor barrier.

During the past 20 or more years, there has been an increased use of sprayed-in-place polyurethane foam insulation on exterior roof surfaces. To waterproof and protect the insulation from moisture absorption and degradation by the elements (particularly the ultra-violet portion of sunlight), protective coatings are applied over the foam.

During these years of foam use, engineers, contractors, inspectors and materials scientists have developed techniques for examining foam and coating structures. Typically a sample is cut with a sharp knife and viewed with a magnifying glass or pocket microscope. Large details such as voids in the foam or pinholes in the coating can be easily observed. Smaller details such as foam cell structure and coating thickness can be seen only with some difficulty, if at all.

Two problems limit the usefulness of the cut foam and coating technique. First, no matter how sharp and thin the knife or razor blade, some distortion of the foam and coating occurs during the cutting. Second, polyurethane foam is translucent and efforts to view or photograph the magnified structure are partially obscured by the internal scattering and reflection of light (Figure 1).

The method chosen for this study was to view and photograph very thin sections of both the foam and the coating under a microscope utilizing transmitted light. This method corrects the two problems mentioned above (Figure 2).

This study initially sought to determine if some coating flaws were related to or caused by the nature of the foam structure, most specifically pinhole development. After the first few samples were examined, the study was expanded to look at the relationships of physical damage, effects of solvents on foam, moisture transmission, and freeze/thaw cycling.

## PROCEDURE

### Sample Selection

Samples from various projects were supplied primarily by contractors in the foam and coating industry. A form was sent to these individuals requesting samples and certain specific information when available.

To date, 110 samples have been received from projects in nearly all parts of the world. In addition, 105 laboratory control samples were prepared to check specific properties and the relationships between foam and coatings.

### Thin Sections

A specimen was cut from each sample to a maximum size of

1-inch × 1-inch × 1.5-inch (25mm × 25mm × 38mm) and dried for seven days in a dessicator containing phosphorous pentoxide. When dried, the specimen was vacuum-impregnated and encapsulated with a low-viscosity epoxy optical resin containing a blue dye. Any open portion of the foam or porous coating structure was filled with the blue epoxy resin. The cured epoxy specimen was then sawed in half with a band saw, ground smooth and flat with 600 grit sandpaper adhered to a plate glass. The ground face was impregnated with epoxy resin dyed red for contrast. When the epoxy cured, the specimen was reground.

This process of filling with red epoxy and grinding was repeated from 4 to 12 times. After each grinding, the face was examined visually under a microscope to determine when a surface was obtained that was free of alteration from earlier cutting or grinding. When this point was reached, the flat face was filled with the same red epoxy which was then used as an adhesive to mount the specimen on a glass microscope slide. This slide was put in a holder and the specimen was band-sawed off, leaving a ¹⁄₁₆-inch (1.6-millimeter) thick slice on the glass slide.

The specimen was then "thinned" by more filling with red-dyed epoxy and grinding. When the specimen was about 0.005-inch (0.13-millimeter) thick, it was photographed with transmitted light at 1 X. This is the actual size image on a 35-millimeter film format. Some smaller specimens were enlarged up to 2 X. The specimens were finally "thinned" by grinding to 0.001-inch (0.025-millimeter), and a cover glass was adhered with red-dyed epoxy resin to permanently protect the sample.

This process leaves the specimen with slightly scratched surfaces from the 600-grit sandpaper. However, the epoxy mounting resin usually obscures these scratches for magnifications up to 200 X.

## FINDINGS

### Typical Foam Structure

Properly applied polyurethane roofing foams with specified densities of two and a half to three pounds per cubic foot (40 to 50 kilograms per cubic meter) were observed to have an average cell size of five mils (0.13 millimeters) perpendicular to the rise and a range of seven to 10 mils (0.18 to 0.25 millimeters) parallel to the rise. The heat-sink effect of the substrate causes a decrease in foam cell size adjacent to the substrate *(Figure 17)*.

In this study, nearly all foam samples were found to have a significant number of individual cells with ruptured walls. This does not seem to detract from the closed cell content when tested in accordance with ASTM D-1940 and it is believed that any small group of ruptured cells are still bound by a continuous enclosure which in effect maintains a closed system *(Figure 17)*.

### Typical Coating Structure

This study indicated that any coating with under 100 percent elongation when tested in accordance with ASTM D-412 in its specific service environment exhibited a risk of cracking. Rapidly dropping temperatures subject the coating to sufficient tensile stress to initiate a crack. Once a crack is started, continued stress concentrations promote crack growth *(Figure 14)*.

In addition, coatings with a film thickness of less than 20 mils (0.50 millimeters) were also subject to failure caused by delamination or surface cracking *(Figures 3 and 4)*.

### Pinholes In Coating Systems

Pinholes are a frequently observed defect in foam coating systems and little is known about the extent to which pinholes affect roofing performance. Pinholes were found to have three primary causes. The first and most prevalent was related to the structure of the foam substrate. Installing polyurethane foam under conditions that allow the over-expansion of gas during foam formation can lead to "blow holes." Over-expansion of gas causes a gas bubble to vertically rise through the foam, rupturing cells and leaving a void or capillary to the surface. When coatings are applied over these voids, expansion of gases (caused by solvent vapor pressure or a temperature increase) makes air within the void expand and rupture the coating. While the coating is still fluid it may heal and reseal; however, if the coating has "gelled" to the extent that it cannot heal, a pinhole is left in the coating. Once propagated, these can recur regardless of the number of coats applied *(Figures 5 and 6)*.

The second cause for pinholes is believed to be air trapped during the coating spray operation. The impingement of droplets of coating in a spray pattern tends to encapsulate and trap small particles of air. If the spray pattern is coarse, the air particles can be of significant size and some of these will rise and break at the surface. This type of pinhole does not completely penetrate the coating, so small air voids become trapped within the coating *(Figure 7)*.

The third type of pinhole appears to be caused by a direct reaction of isocyanate components in urethane coatings with water vapor or moisture droplets in the atmosphere. This reaction results in the generation of carbon dioxide gas which, if present in sufficient amounts, can cause porosity in the coating and pinholes at the coating surface. The major difference between this occurrence and trapped air is that carbon dioxide-generated voids are generally larger and can lead to delamination within the coating *(Figure 8)*.

### Effect of Coating Solvents on Fresh Foam

There has been concern that uncured foam will dissolve if exposed to some coating solvents. In an effort to evaluate this possibility, two different three-pound polyurethane foams were sprayed under laboratory conditions. These were exposed to the following solvents and blends at various times after the foam was sprayed.

### Solvents Tested

- Methyl-Ethyl—Ketone
- Coating Blend (Methyl-Ethyl-Ketone with Xylene and aliphatic solvent)
- Aliphatic Solvent
- Methylene Chloride
- Coating Thinner (Methyl-Ethyl Ketone with aliphatic solvent)
- Aromatic Solvent (Xylene)

*Foam Cure Time*

- 1 Minute
- 2 Minutes
- 5 Minutes
- 10 Minutes
- 30 Minutes
- 60 Minutes
- 120 Minutes
- 240 Minutes
- 24 Hours

The foam sprayed at an ambient temperature of 50F (10C) showed a sensitivity to methyl-ethyl-ketone and methylene chloride for up to 30 minutes *(Figures 9 and 10)*. It was resistant to all other solvents tested after a 10-minute cure time at 50F (10C).

The second foam was sprayed at an ambient temperature of 68F (20C), and the increased reactivity and resulting cure rate rendered the foam resistant to methyl-ethyl-ketone and methylene chloride in under five minutes.

The cure rate of individual foams and the temperature at which the foam cures determine how soon a surface can be coated without risk of dissolving the foam skin. If the skin is dissolved, released gas and open cell foam structure can proprogate pinholes in the protective coating. Without testing all types of foam and coatings available, the results of this limited study would indicate that a minimum of one hour should elapse for foam cure before solvent-based coatings are applied. Cold weather applications or foams that otherwise cure slowly could require a longer time before coating.

## Water Vapor Transmission Characteristics

Water vapor transmitted from the interior of a building can accumulate by condensation within roof insulation. The use of a vapor barrier on the warm side of the insulation restricts the flow of air carrying water vapor to the insulation and retards the formation of water within the insulation. Condensed water not only reduces the thermal effectiveness of the insulation, but also can lead to defects in the foam structure of polyurethane foam. The decrease in water vapor pressure with a lower temperature differential through the foam insulation causes migration of water vapor and subsequent condensation near the coldest portion of the roof system. In cool climates, the coldest part is the interface between the coating and the polyurethane foam insulation. On one project where samples were taken at two-year intervals over an eight-year period, the foam cell structure immediately under the coating was slowly being ruptured. This led to an increased ability to absorb water. Measurements showed that water absorption usually reached a maximum in March and then decreased during the dry summer months. With each interval of testing the weight of water within the sample would increase, indicating more water was absorbed with each wintertime exposure.

One theory holds that condensed water in the cells formed a shear layer under the coating that expanded with the formation of ice when temperatures dropped below freezing. This ice expansion appears sufficient to cause rupturing of the foam structure *(Figure 11 and 12)*.

To test this premise, an apparatus was constructed using an insulated chamber in which heated water produced an environment of 100 percent relative humidity at 78F (27C). Samples were attached to the lid of the chamber and the entire chamber was placed in a refrigerated compartment at 40F with near zero relative humidity. Tests were run to establish water vapor transmission rates through the coating into the insulation, as if the system were installed on a refrigerated tank *(Chart 1)*. In addition, several coating systems were tested to measure their relative rates of water vapor retention within the insulation, as if a roofing system were installed without a vapor barrier *(Chart 2)*. Samples from these tests were subjected to freeze/thaw cycle at one-week intervals. When water content by volume exceeded 10 percent, rupturing of the polyurethane foam cells developed, simulating those from field samples *(Figure 13)*.

This test supports the need for a vapor barrier in areas with warm and humid interior conditions and seasonal exterior temperatures averaging 20F (6C) or more below interior temperatures.

## Elongation Characteristics of Coatings

Coatings which have minimal ability to stretch can develop enough thermal stress to accelerate decomposition or cause cracking. The coating on the surface of a well-insulated substrate is subject to rapid temperature change and must compensate for the thermal expansion or contraction of the substrate by yielding. Without this ability, the coating will crack. Although specific elongations could not be measured from field-collected samples, it is estimated that those coatings with less than 100 percent elongation are likely to develop cracks during the part of each year when maximum temperature changes occur. This was observed in samples from both arctic and temperate climate areas *(Figure 14)*.

Field samples also showed that coatings with sufficient elongation can have that property compromised by the inclusion of a mineral granule surface. The granule is often used to increase fire and impact resistance, but also detracts from the ability of the coating to elongate under stress by increasing the surface area to which the coating is adhered. In addition, granulated coatings on flat roofs were observed to provide surface friction where ponds of water freeze. The resulting ice expansion cracks the coating and frequently the foam *(Figure 15)*.

## Foam and Coating Adhesion

Several causes of poor coating adhesion were observed during this study. Polyurethane foam that had been exposed to the weather long enough to cause deterioration of the surface skin showed poor coating adhesion caused by decreased cohesive strength of the surface foam. The presence of moisture can cause enough expansion of polyurethane-type coatings to cause delamination, and can prevent many other coatings from adhering to the surface.

Many of the precautions needed for coatings also apply to the adhesion of polyurethane foam to substrates. The substrates must have cohesive integrity and must be dry. The presence of moisture causes the generation of carbon dioxide during the foam application process. This gas can cause overexpansion of the cell structure to a point where there is delamination or decreased strength of the foam *(Figure 16)*. Primers used to inhibit water or water vapor transmission from a substrate were seen to be effective in preventing foam-water reactions and promoting good polyurethane foam cell structure. The primer, of course, must be compatible with the foam and substrate *(Figure 17)*.

## Other Considerations

The application techniques used to install polyurethane foam can lead to variations in the foam structure. Several samples observed in this study showed a high degree of open cell structure in areas of thin passes of polyurethane foam. These thin passes lose much of the heat generated by the exothermic reaction between polyol and isocyanate, so that insufficient energy is available to cause the blowing agent to develop a uniform foam structure *(Figure 18)*.

It was also observed that off-ratio foam resulted in decreased physical properties. Polyol-rich foam is frequently soft, with inadequate compressive strength. Isocyanate-rich

foam is often friable and brittle, without adequate structural strength. This study found that as the isocyanate content increased, there was also an increase in optical bifringence. Bifringence is an optical property of some crystalline materials to rotate polarized light. It is believed that either a high crosslink density of an isocyanate-rich foam produces such a crystalline property or that unreacted isocyanate forms urea crystals that in turn provide the bifringent property. The significance of bifringence is that a laboratory procedure could be established to determine the reacted ratio of polyurethane foam. The optical bifringence of foam should be retained regardless of age *(Figures 19, 20 and 21)*.

## SUMMARY

This study attempts to put into a visual context some of the known or assumed problems that can occur with a polyurethane foam and coating roof system. It verifies the need to apply proper proportions of plural component materials in a uniform manner for both the foam and the coating. Conditions when the foam and coating are applied affect the physical properties of these materials. A clean, dry surface is necessary to obtain adhesion.

Design considerations, including the use of vapor barriers, also affect the long-term performance of a foam and coating system. The benefits of using surface granules must be weighed against adverse climatic effects that can add to the stress on this coating system.

Some opinions are based on the author's observations from nearly two thousand photographs taken in the course of this study. Limited space has allowed only a selected sampling of those photographs.

The study was not meant to be comprehensive in scope, but was intended to provide basic information and to stimulate development of polyurethane and coating roof systems with optimum performance.
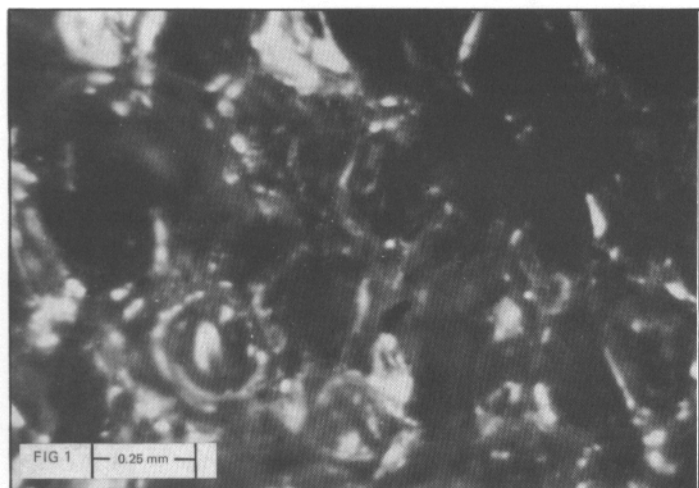


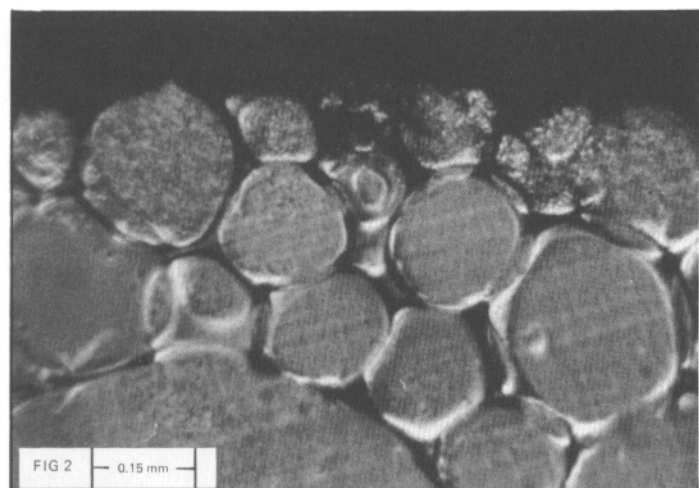*Figure 1   Three-pound foam cut with a razor blade and photographed in reflected light*



*Figure 2   Thin section of three-pound foam photographed in polarized light*
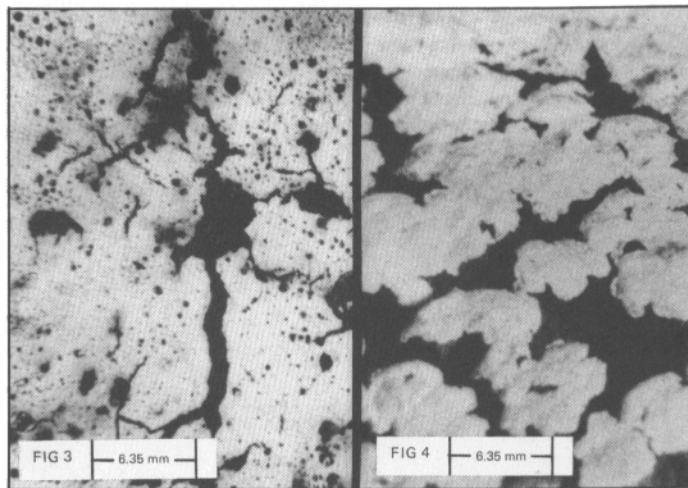


*Figure 3   Thin, rigid acrylic coating from central Idaho after three years roof exposure*

*Figure 4   Thin, chlorosulfonated polyethylene coating from Pacific Northwest after five years roof exposure*
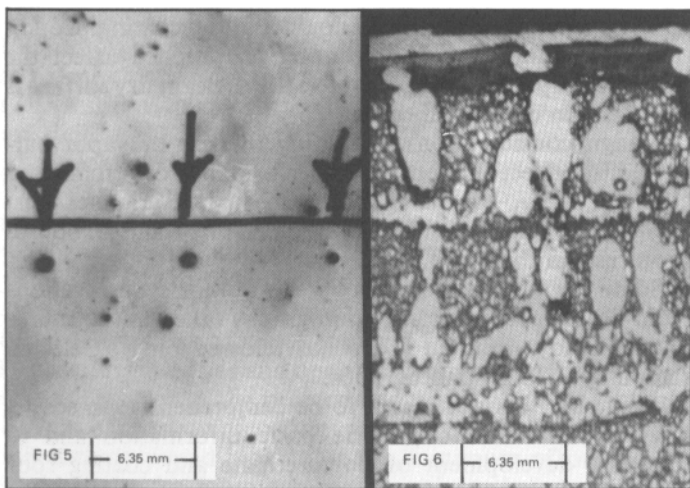
**Figure 5** Three "pinholes" in a urethane rubber coating from a roof in central Utah after two years exposure. Black line indicates where specimen was cut, then ground to center of the pinholes.

**Figure 6** Cross section of pinholes in Figure 5. Light colored voids in the foam are open to water entry through the coating.
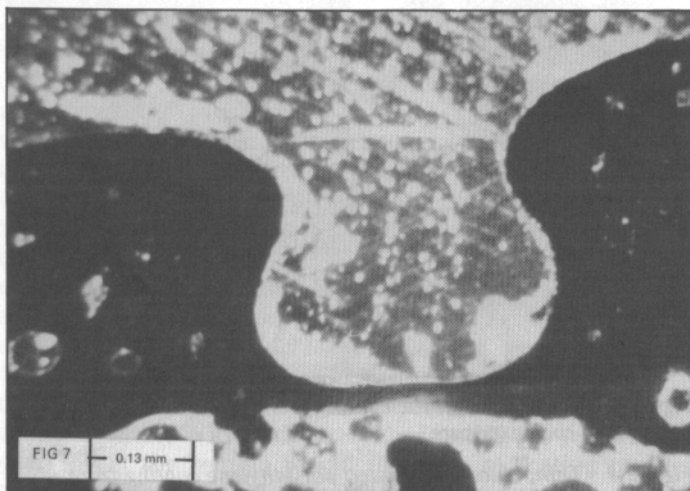


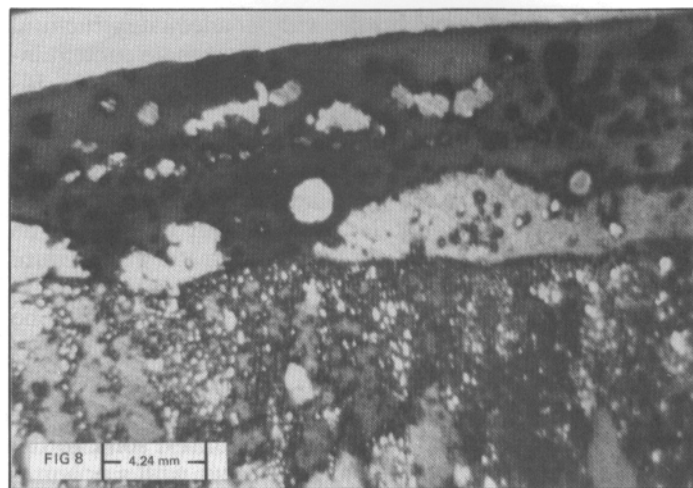**Figure 7** Pinhole in laboratory prepared urethane rubber coating. Air in spray application was entrained into the coating.



**Figure 8** Single component urethane rubber coating from Hawaii after two years exposure. Moisture reaction created considerable porosity in the rather thick coating.
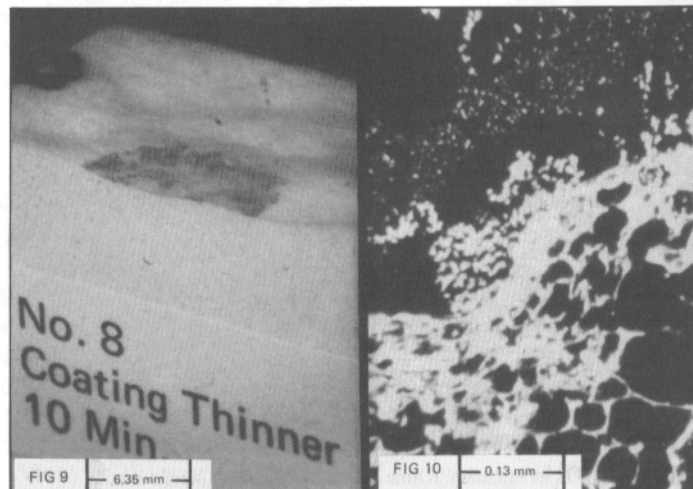


**Figure 9** Cross section showing drop of coating thinner containing a dye placed on three-pound foam 10 minutes after applying foam at 50F (10C)

**Figure 10** Cross section of specimen in Figure 9 photographed in dark field. Left side shows collapsed surface foam from solvent effect while right side is unaltered surface.
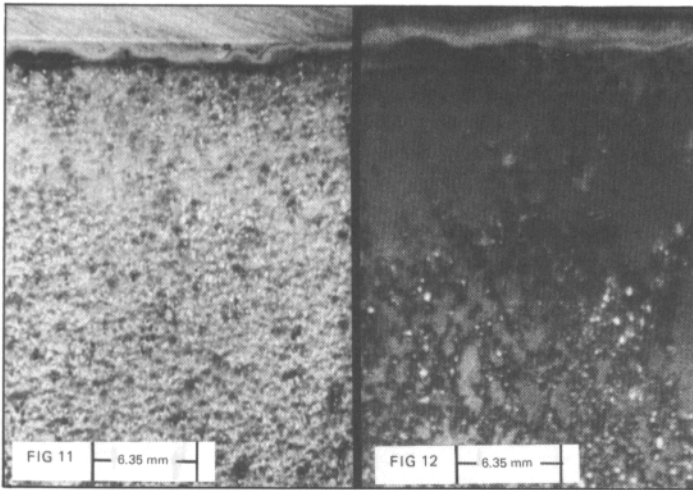
**Figure 11**  *Urethane rubber coating taken from a project in the Pacific Northwest at the time of installation in 1975*

**Figure 12**  *Specimen taken in 1983 from the same area of project shown in Figure 11. Note gray area under coating without foam detail. This volume filled with blue epoxy resin during section preparation indicating an open cell foam structure.*
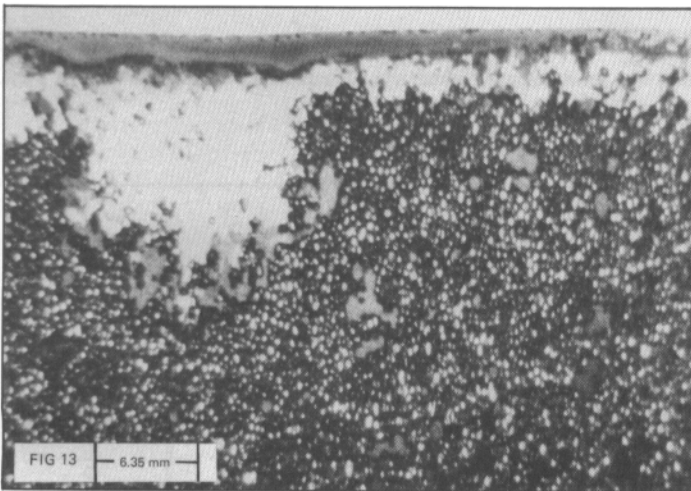


**Figure 13**  *Urethane rubber coating on three–pound foam after water transmission and freeze-thaw testing. Light area under coating filled with blue epoxy resin indicating open cell foam structure which developed after freeze cycles.*
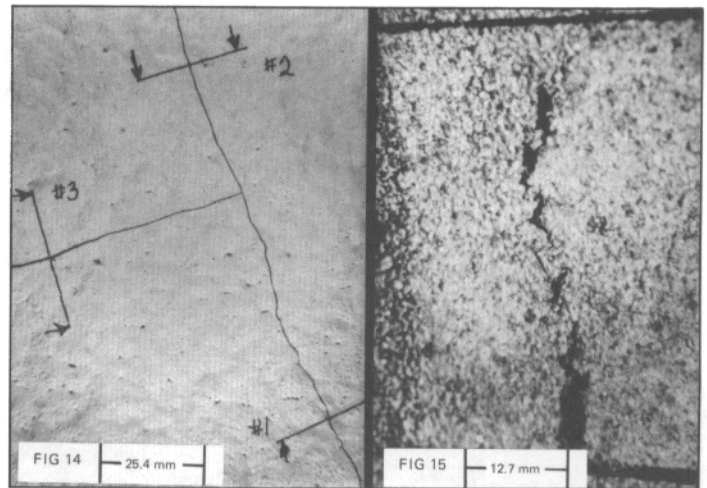


**Figure 14**  *Acrylic latex coating on foam after two years exposure in Alberta, Canada. Cracks occured after second winter and are believed to be the result of a rapid temperature drop. Black lines indicate where cross-sections were taken show a crack depth of $1/16$ to $1/8$" (1.5 to 3.0 mm) into the foam.*

**Figure 15**  *Polyurethane coating with granules on foam after two years exposure in Nova Scotia. Crack is believed to have developed as a result of ponded water freezing on a flat roof. Crack depth into the foam reached a maximum of $1/4$" (6.4 mm).*



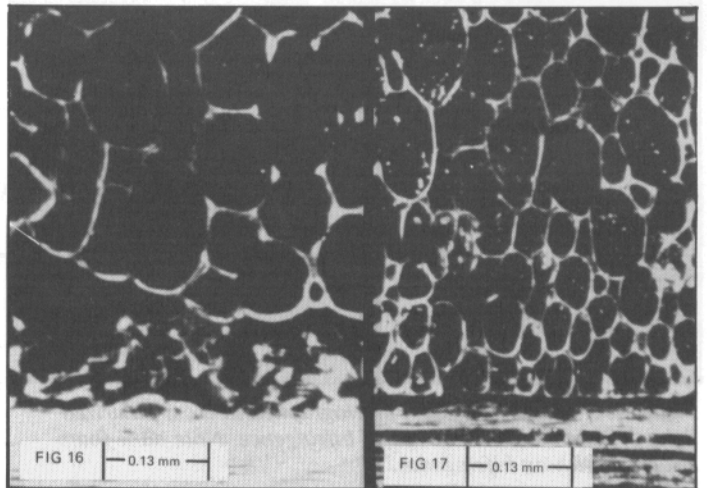**Figure 16**  *Cross section of three–pound foam that was applied to damp plywood. Note disrupted foam cell structure adjacent to plywood substrate.*

**Figure 17**  *Cross section of three–pound foam applied to primed plywood that had been dampened as substrate in Figure 16. Thin black line on plywood is the primer.*
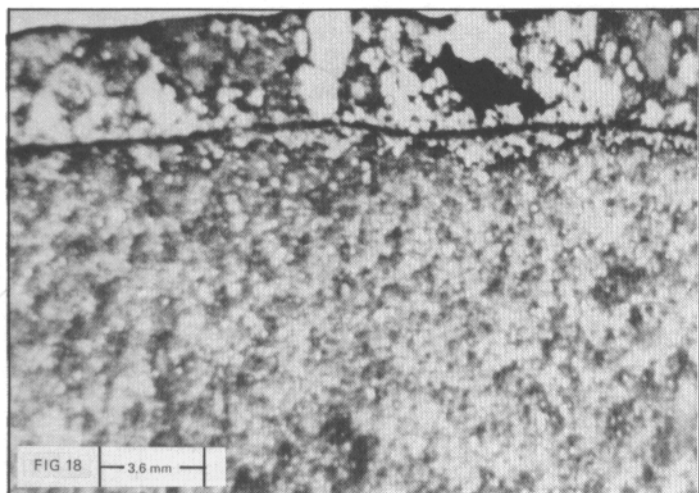
*Figure 18* Cross section of 2.7–pound foam after three years exposure in central California. Thin foam pass is porous as indicated by light colored area that filled with blue epoxy resin during section preparation. Dark spot is dirt that collected through a coating rupture. Coating is an acrylic latex.
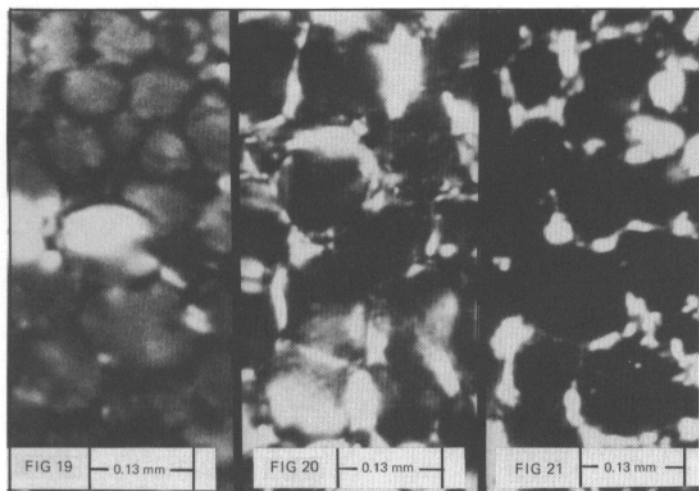


*Figure 19* Polyol rich foam photographed in cross polarized light. "Glare" indicates areas of bifringence. Note dark foam structure without bifringence.

*Figure 20* Isocyanate rich foam photographed as in Figure 19. Note the increased bifringence (glare).

*Figure 21* Normal ratio foam photographed as in Figures 19 and 20. This photo shows an intermediate degree of bifringence.

## INWARD WATER TRANSMISSION
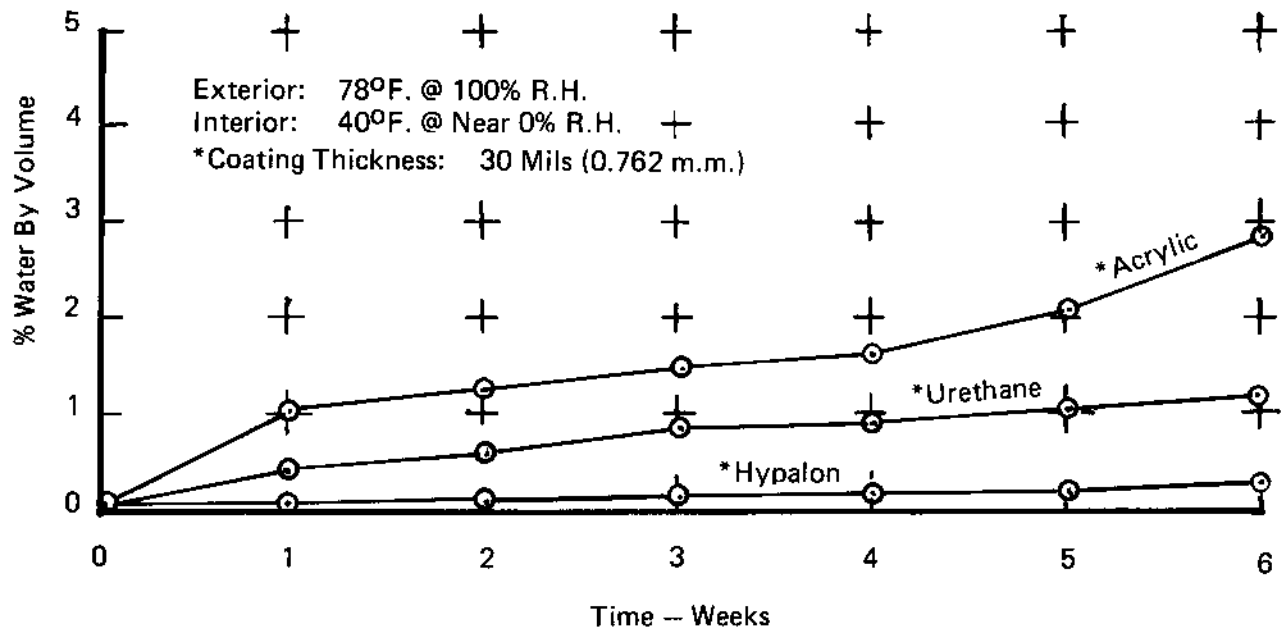## URETHANE FOAM-COATING COMPOSITE

Exterior: 78°F. @ 100% R.H.
Interior: 40°F. @ Near 0% R.H.
*Coating Thickness: 30 Mils (0.762 m.m.)

*Acrylic

*Urethane

*Hypalon

% Water By Volume

Time — Weeks

*Chart 1    Inward water transmission urethane foam-coating composite*

## OUTWARD WATER TRANSMISSION
## URETHANE FOAM-COATING COMPOSITE

Exterior: 40°F. @ Near 0% R.H.
Interior: 78°F. @ 100% R.H.
*Coating Thickness: 30 Mils (0.762 m.m.)

*Hypalon

*Urethane

*Acrylic

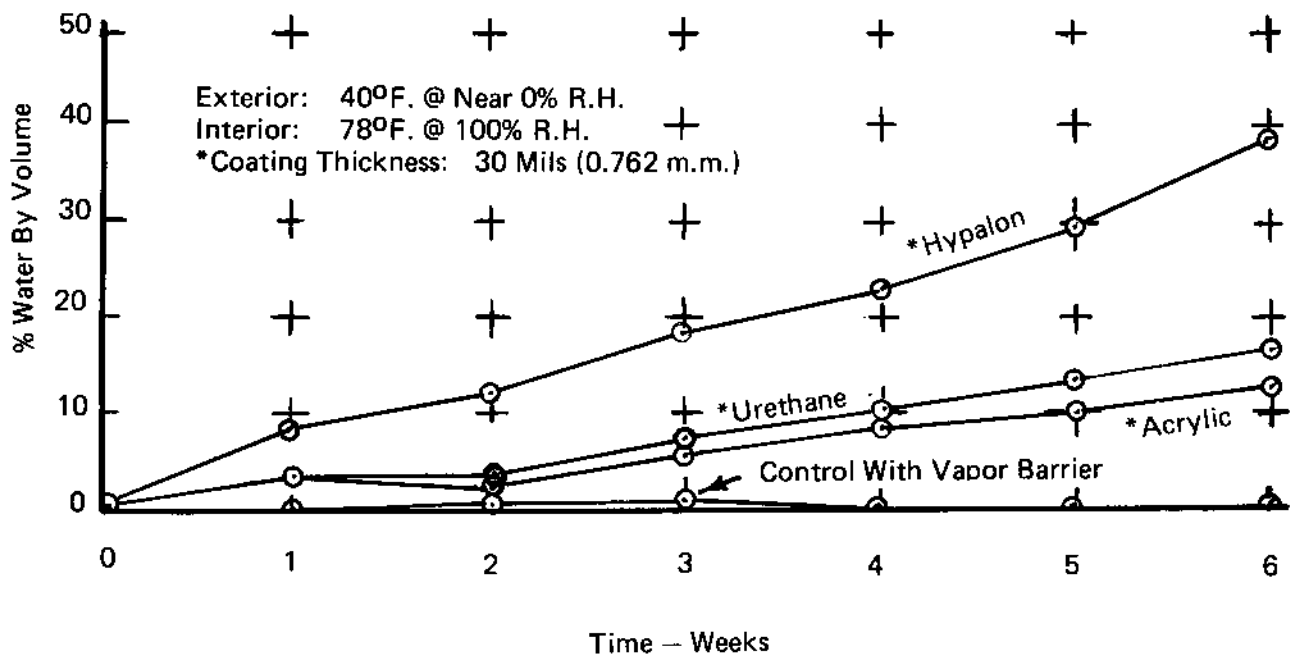Control With Vapor Barrier

% Water By Volume

Time — Weeks

*Chart 2    Outward water transmission urethane foam-coating composite*