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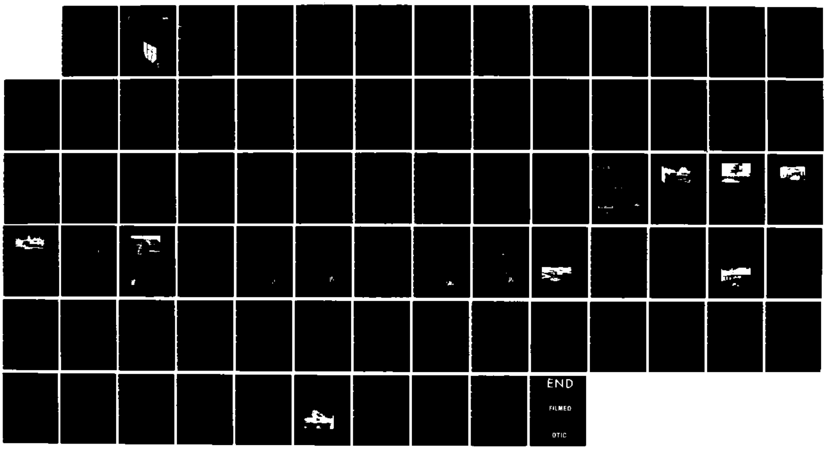

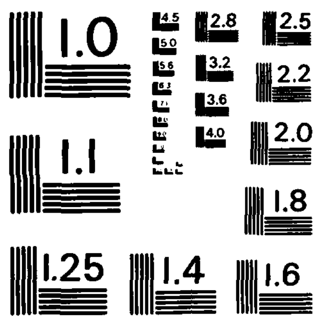

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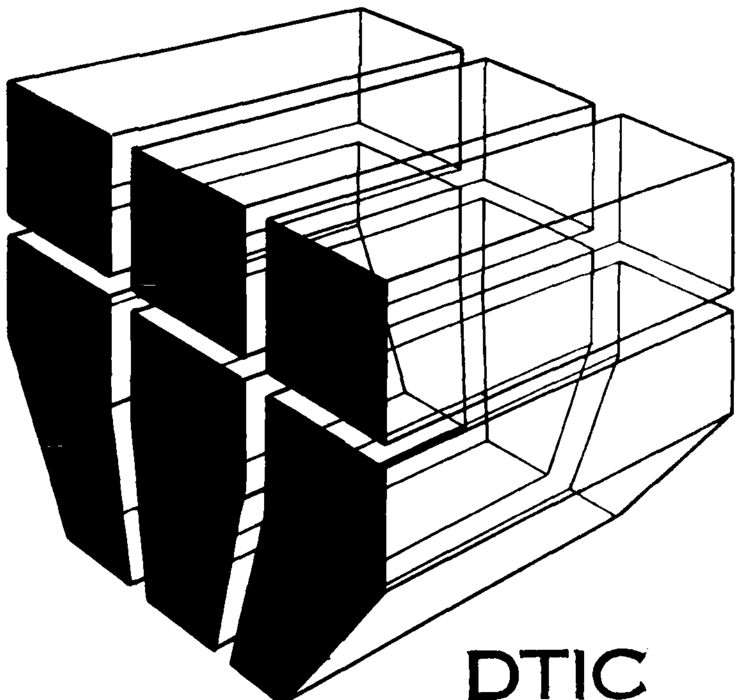
Technical Report M-357
September 1984

Improved and New Roofing
for Military Construction

FIELD TEST RESULTS OF EXPERIMENTAL EPDM AND PUF ROOFING

by
Myer J. Rosenfield



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This report presents the results of 2 years of study of ethylene propylene diene monomer (EPDM) and sprayed-in-place polyurethane foam (PUF) roofs following their installation. Initial samples taken from the materials as delivered were tested to establish initial characteristics. Further samples were cut from the roofs every 6 months for 2 years to determine what changes were occurring from natural aging. Thermocouples and strain gages were also used to study response of the roof systems to changes in ambient conditions.

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The EPDM showed an increase in mechanical properties during the first 6 to 12 months, probably due to completion of the curing process, followed by no significant change in properties for the rest of the test period. There was little consistency to the results for PUF during the same time of exposure. This could happen for several reasons: differences among PUF products used, application techniques, and inconsistent atmospheric conditions during application.

Test results indicated that both EPDM and PUF, when properly installed, will perform satisfactorily.

FOREWORD

This work was performed by the Engineering and Materials (EM) Division of the U.S. Army Construction Engineering Research Laboratory (USA-CERL) for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Military Facilities Engineering Technology"; Task A, "Facilities Planning and Design"; Work Unit 044, "Improved and New Roofing for Military Construction." The OCE Technical Monitor was Mr. Joel Seifer, DAEN-ZCF-B.

Appreciation is expressed to the personnel at Forts Benning, Knox, and Lewis for taking samples from the test roofs and tape recordings of the weather and instrument data; to Mr. Bernard V. Jones and Mr. Vernon L. Kuehn of the U.S. Bureau of Reclamation for performing the mechanical and physical tests on the material samples; and to Prof. Donald E. Brotherson of the University of Illinois for reducing and analyzing the recorded data.

Dr. Robert Quattrone is Chief of USA-CERL-EM. COL Paul J. Theuer is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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FIELD TEST RESULTS OF EXPERIMENTAL EPDM AND PUF ROOFING

1 INTRODUCTION

Background

Most Army facilities use conventional roofing systems, such as built-up roofing (BUR), that are sometimes expensive and complicated to construct. These conventional roofing systems are often comparatively short-lived, resulting in high life-cycle roofing costs which are difficult for already overburdened Army operation and maintenance budgets to absorb. Therefore, the Office of the Chief of Engineers has asked the U.S. Army Construction Engineering Research Laboratory (USA-CERL) to attempt to identify alternative, easy-to-install roofing systems that can improve the performance of Army roofing while reducing life-cycle costs. This involves (1) evaluating innovative roofing systems and materials to determine alternatives to BUR systems, (2) providing a means to improve Army roof performance and reduce life-cycle costs, (3) improving contractor quality control (CQC) of BUR construction, and (4) developing or improving guide specifications for selected alternative systems.

Previous work identified and evaluated alternative roofing systems that would be less susceptible to installation error or misapplication and would not be as sensitive to storage, handling, and weather considerations.[1] Three of these systems were selected for field evaluation by means of full-scale roof construction. These were the single-ply membranes of the ethylene-propylene-diene monomer (EPDM) and polyvinyl chloride (PVC) types, and the sprayed-in-place polyurethane foam (PUF) with a suitable elastomeric coating. EPDM and PUF roofs were constructed in 1980,[2] and the PVC roofs were completed during summer 1983.[3]

Objective

The objective of this report is to document the results of a field test program to evaluate the EPDM and PUF systems.

Approach

The following procedures were used to carry out the objective of this study:

1. Roof systems for a 2-year field evaluation were selected based on earlier USA-CERL studies.[4]

2. A test plan was developed using standard test methods published by the American Society for Testing and Materials (ASTM) where available, and other tests developed by Government agencies where needed.

3. Test sites were selected.

4. Test guide specifications were developed.

5. Instrumentation systems were designed.

6. Construction of the test roofing systems was monitored.

7. Test data were collected for 2 years after completion of construction.

8. Each roof was inspected visually once a year.

Mode of Technology Transfer

Information generated by this study will impact on Corps of Engineers Guide Specification (CEGS) 07530, *Elastomeric Roofing (EPDM)*, and CEGS 07540, *Elastomeric Roofing, Fluid Applied.*

2 DESCRIPTION OF TEST PROGRAM

Construction of Test Roofs

Two EPDM roofs were constructed: one at Fort Benning, GA, and one at Fort Lewis, WA. Both are fully adhered, unballasted systems, with the membrane

[1] E. Marvin, et al., *Evaluation of Alternative Reroofing Systems*, Interim Report M-263/ADA071578 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], 1979); Myer J. Rosenfield, *An Evaluation of Polyvinyl Chloride (PVC) Single-Ply Membrane Roofing Systems*, Technical Report M-284/ADA097931 (USA-CERL, 1981); Myer J. Rosenfield, *Evaluation of Sprayed Polyurethane Foam Roofing and Protective Coatings*, Technical Report M-297/ADA109696 (USA-CERL, 1981).

[2] M. J. Rosenfield and D. E. Brotherson, *Construction of Experimental Roofing*, Technical Report M-298/ADA109595 (USA-CERL, 1981).

[3] Myer J. Rosenfield, *Construction of Experimental Polyvinyl Chloride (PVC) Roofing*, Technical Report M-343 (USA-CERL, 1984).

[4] E. Marvin, et al., 1979.

attached to the surface; insulation is sufficient to give the roofing system an overall R-value of 20.

The system at Fort Benning consists of a fluted steel deck, 3 in. (76 mm) of composite board insulation mechanically fastened to the deck, and 60-mil (1.5-mm)-thick single-ply EPDM membrane. The system at Fort Lewis consists of a poured-in-place concrete roof deck, a one-ply vapor retarder of No. 43 asphalt-saturated and coated glass fiber base sheet in hot asphalt, 2½ in. (64 mm) of rigid inorganic board stock with asphalt-saturated organic felt facer sheets installed in hot asphalt, and a 60-mil (1.5-mm)-thick single-ply EPDM membrane. Figure 1 shows cross sections of those EPDM roofs.

Three PUF roofs were constructed: one each at Fort Benning, GA, Fort Knox, KY, and Fort Lewis, WA (Figure 2). The system at Fort Benning consists of a poured-in-place concrete roof deck, a two-ply vapor retarder of No. 15 asphalt-saturated organic felt, a minimum of 3½ in. (90 mm) of sprayed PUF, and a minimum of 20 mils (0.5 mm) of a single-component, moisture-cured silicone coating, applied in two coats with granules in the second coat.

The system at Fort Knox consists of a gypsum plant deck, one ply of asphalt-saturated base sheet nailed to this deck, a minimum 4 in. (102 mm) of sprayed PUF, and two coats of a single-component, moisture-cured silicone coating, with granules in the second coat. Although the minimum thickness was specified as 20 mils (0.5 mm), it was actually determined to be 12 mils (0.3 mm).

The system at Fort Lewis consists of a poured-in-place concrete roof deck, one ply of No. 43 asphalt-saturated and coated glass fiber base sheet in hot asphalt, a minimum 3 in. (76 mm) of sprayed PUF, and a coating consisting of a base coat of a two-component polyurethane elastomer and a top coat of chlorosulfonated polyethylene with granules in the top coat. The minimum thickness was specified as 20 mils (0.5 mm) but was actually determined to be 10 mils (0.25 mm).

In addition to the EPDM and PUF roofing systems, a conventional BUR was installed as a control at Forts Benning and Lewis (Figure 3). The system at Fort Benning consists of the same type of deck and insulation as the EPDM system, with a four-ply organic felt and asphalt BUR coated with aggregate specified as conforming to ASTM D 1863-77. The system at Fort Lewis consists of the same type of deck and vapor retarder as the EPDM and PUF systems, but uses tapered insulation of polystyrene covered with a ½-in. (13-mm) layer of rigid fiberboard, with a four-ply BUR consisting of three plies of glass fiber felt in asphalt and a top ply of mineral-surfaced glass fiber cap sheet.

Figures 4 through 7 show the buildings selected, respectively, for EPDM and BUR roofing at Fort Benning; PUF roofing at Fort Benning; PUF roofing at Fort Knox; and EPDM, PUF, and BUR roofing at Fort Lewis. USA-CERL Technical Report M-298 describes construction of these systems.

Test Program

The test program was designed to determine how weathering would change the mechanical and physical characteristics of the three systems. Properties selected for study were those deemed essential to successful performance of the materials in a roof assembly. American Society for Testing and Materials (ASTM) standards were used as much as possible to determine these properties. Where no ASTM test method could be found, tests developed by the U.S. Bureau of Reclamation (USBR) or the U.S. Navy Civil Engineering Laboratory (NCEL) were used.

To establish a relationship between property changes and exposure to the weather, the test and control systems were instrumented to monitor and record the following:

1. Thermal conditions within the roof systems.

2. Weather conditions at the test site, including temperature, humidity, solar radiation, and wind speed and direction.

3. Strains that occurred within the EPDM roof system.

The initial set of tests was designed to establish the mechanical and physical characteristics of the materials at the time of application. Subsequent tests were scheduled at 6-month intervals over a 2-year period and once a year for 8 more years to establish a pattern of performance or to note changes in properties. A final test of field-exposed materials is proposed for 10 years after construction is completed. In addition to the laboratory tests, visual inspections are being made once a year to check for changes in appearance, loss of adhesion of EPDM or PUF coating, blistering, cracking, pinholing, loss of granules, or any evidence of mechanical damage from foot or equipment traffic.

unauthorized attachments or penetrations, or natural phenomena such as hail.

Tables 1 through 3 list the PUF, EPDM, and BUR characteristics, respectively, of interest to this study. As shown in Table 3, original plans were to measure strains in the BUR assembly. However, preliminary laboratory attempts at calibration indicated that such strains could not be measured due to softening of the asphalt resulting in plastic flow.

3 PHYSICAL AND MECHANICAL PROPERTY CHANGES

Manufacture of EPDM Membrane Materials

Understanding the test results, especially the original properties of the materials, is not possible without first reviewing the manufacturing process, particularly of the EPDM membrane. It is often assumed that EPDM is the same material, regardless of its source; however, this is not the case.

Figure 8 shows an abbreviated flow sheet for EPDM membrane manufacture. Ethylene and propylene occur in petroleum refinery off gases, or can be produced by cracking propane.[5] The polymer chain produced from these two gases does not contain sufficient unsaturation for conventional vulcanization, so another ingredient must be added. Dienes such as butadiene, hexadiene, cyclopentadiene, dicyclopentadiene, etc., make this valuable property possible. The resin produced from reacting these materials is mixed with additives, chiefly carbon black. The resulting material is rolled into slabs which are then converted into the familiar rolls of roofing membrane on a calender. Many of the necessary operations, such as laminating, vulcanization, talc application, and trimming, have been omitted from Figure 8.

It is now apparent that the term "EPDM" does not necessarily describe a single product, but more properly applies to a family of products. Proportions of ethylene and propylene and the diene used may vary, depending on availability, price, and formula. Exact proportions are proprietary information, which is not released by the various manufacturers. Specific additives may vary by time and by producer. Thus, even the products of one company may differ from one time to the next.

EPDM Property Changes

Initial EPDM Properties

Considering the above discussion, the differences between the initial values, shown in Table 4, can now be understood. The EPDM materials delivered to the two sites are the products of the same manufacturer. The test values shown are averaged from several tests on the materials delivered to each location: the range of values is also stated.

The mechanical properties of the delivered materials (tensile strength, elongation, and hardness) exceed the values that were specified, which are the minimums stated in the manufacturer's literature. These values indicate good-quality rubber sheet. The field seam strength appears to be very low, however. A minimum peel strength value of 5 lb/in. (0.876 N/mm) of width would be more appropriate. The shear strength of the seams at Fort Benning is 18 lb/in. (3.5 N/mm) of width, or only 20 percent of the sheet strength, while that of the seams at Fort Lewis is 28.7 lb/in. (5.02 N/mm) of width, or 29 percent of the sheet strength. According to the manufacturer, the shear strength of the seam should be at least 30 percent of the sheet strength. Observations of the seam area after separation indicated that the sheet was not completely cleaned of its talc coating before the seam cement was applied.

Of the physical properties, only the brittleness, ozone resistance, and water vapor permeability were specified. Water absorption and abrasion loss were determined so that the effect of aging on these properties could also be measured. The brittleness value was exceeded and the ozone resistance was met, but a difference was noted for the water vapor permeability, which was specified as 2.0 perm-mils (2918 $ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-1}$). According to the manufacturer, this is neither a maximum nor a minimum, but is the actual value as determined in the laboratory. The measured value at Fort Benning of .06 perm (3.4 $ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-2}$) calculates to 3.6 perm-mils (5371 $ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-2}$) while the Fort Lewis value of 0.04 perm (2.3 $ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-2}$) calculates to 2.4 perm-mils (3581 $ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-1}$). Any value less than 1 perm (57.4 ng) is considered to be a vapor retarder, and the manufacturer describes this product as impermeable. The manufacturer's determination was conducted by Procedure BW of ASTM E 96, while the results of the USA-CERL study were obtained from Procedure B of

[5] R. Norris Shreve and J. A. Brink, Jr., *Chemical Process Industries*, 4th ed. (McGraw Hill Book Company, 1977), p 645.

the same test method, since the testing laboratory did not have the proper equipment for Procedure BW. Test method E 96 states that "agreement should not be expected between results obtained by different methods,"[6] so even though the measured values are not the same, they are of the same order of magnitude and are close. What is significant is the change that occurs in the value with the lapse of time.

Changes in EPDM Properties With Time

Tables 5 and 6 outline the aged physical and mechanical properties of the EPDM membrane at Fort Benning and Fort Lewis, respectively. The changes in property values indicate a slight deterioration in many of the desirable characteristics of the material. Since the dimensional stability test indicates negligible shrinkage (Table 4), changes in tensile strength do not appear significant. However, the decrease in elongation could be serious, depending on the amount of relative movement between various components of the roofing system. Visual inspections to date have indicated no cracking or tearing of the membrane, but this will be one of the aging effects to be looked for during inspections over the next 8 years.

Tests by others[7] indicate that the EPDM roof materials display reduced elongation properties, increased tensile strength, and increased hardness after accelerated aging. Results of the field test shown in Tables 5 and 6 indicate similar effects of natural aging. There was an initial increase in tensile properties after exposure of 6 months at Fort Benning, but the tests after 12, 18, and 24 months indicate a gradual return to lower properties. At Fort Lewis, a small increase was evident after exposure of 12 months, with a much larger increase after 18 months.

Decreases in elongation and abrasion loss indicate long-term hardening of the material. It has also been observed that repair of the cutouts for sample removal becomes more difficult over time. For the newly installed material, washing the seam area with heptane or white gasoline to remove the talc (according to the manufacturer's instructions) was sufficient for the contact adhesive to produce a good bond. It later became necessary to abrade the contacting surfaces of the roof membrane and the patch, in addition to the washing, in order for the adhesive to bond to them both. This could result from the apparent hardening of the membrane, from oxidation of the membrane surface, or both. In any case, it indicates that special attention to technique is necessary if aged EPDM membranes must be repaired.

Water vapor transmission, slight as it was initially, has decreased with time. Since EPDM is not considered a "breathable" membrane, the change in this property is not in itself important. Its significance is only apparent when viewed in the context of changes to the other properties.

Equally significant is the slight rise in the glass transition temperature, which is the temperature range where heat is absorbed as the material undergoes a phase change. In the case of EPDM, the value is far below the temperatures normally expected in the continental United States.

The only property which behaved differently at Forts Benning and Lewis is the Shore A hardness. This showed an increase at Benning and a decrease at Lewis.

None of these property changes is expected to affect the long-term serviceability of the EPDM membranes, since the changes seem to level off in time. This is probably due to a short-term continuation of the curing process as a result of exposure to the elements.

Figure 9 shows a typical group of patches where samples were taken.

Manufacture of Polyurethane

Like EPDM rubber, manufacture of polyurethanes is not consistent. Polyurethanes are the reaction products of certain organic diisocyanates and polyglycols.[8] The resulting compounds are either specialty rubbers of outstanding properties, possessing high abrasion resistance, which are useful at high temperatures and with high concentrations of solvents and oxygen or ozone, or they may be hard, glossy polymers. A major use for the rubber type is for producing flexible foam; the major use for the hard polymer type is for producing rigid foam.

The reaction of the two components may be extremely rapid. Evolving gas expands the mass, yielding foams which are either hard or soft, depending on the

[6] *Standard Test Methods for Water Vapor Transmission of Materials*, ASTM E 96-80 (American Society for Testing and Materials, October 31, 1980).

[7] Rene Dupuis, et al., *Temperature Induced Behavior of New and Aged Roof Membranes*, Proceedings, Second International Symposium on Roofs and Roofing, Brighton, England (September 1981).

[8] Shreve and Brink, p 643.

reactants and the conditions. Additional gas may be supplied to regulate the density of the resultant foam.

Rigid foams use aromatic di- or poly-isocyanates.[9] Such compounds are toxic and are generally eye and respiratory irritants. The poly-isocyanates typically have lower vapor pressures and are less likely to cause vapor-induced irritation. These isocyanates, called "resins," are reacted with hydroxyl-terminated polyethers, known as "polyols." The number and types of these reactants are many and varied; the specific ones used depend on the manufacturer, the end product desired, availability, and price. Gases used for foam formation, called "blowing agents," are chlorinated fluorocarbons (CFC), the most common being trichlorofluoromethane (CCl_3F), commonly known as the refrigerant R-11. Experience in the industry has shown that foams with densities between 2.5 and 3.5 pcf, having minimum compressive strength of 40 psi, are necessary to withstand the abuse of foot traffic without crushing.

In addition to the reactants and blowing agent, small amounts of catalysts are used to control the rate of reaction. Surfactants are used to regulate cell size and cell wall rigidity, and fillers are used to extend the foam to lower its cost or alter a physical property. Additives, such as flame retardants, antioxidants, and pigments are used to impart other desired characteristics.

Description of Coatings for PUF

Corps of Engineers Guide Specification CEGS 07540, *Elastomeric Roofing, Fluid Applied*, presently limits the elastomeric coating for sprayed PUF roofing to silicone materials.* Silicones are available in two forms: a two-component, catalyzed liquid which is mixed in the gun as it is sprayed, and a single-component, moisture-cured liquid which requires no mixing. These materials have demonstrated excellent retention of all necessary properties.

The urethane base coat/Hypalon** top coat system was selected to obtain a basis for evaluating a different coating. Each system included an application of ceramic granules applied to the top coat while it was still fluid.

PUF Roofing Property Changes

Initial Foam and Coating Properties

The initial values of the PUF properties (Table 7) reflect the differences between the products of three manufacturers. Densities of the foams were within the specified range. Closed-cell content exceeded the 90 percent value normally expected for sprayed PUF within the specified density range.[10] Compressive strengths of the foams at Forts Benning and Knox exceeded the specified value of 40 psi (27.6 N/cm^2), but the foam at Fort Lewis, with a minimum compressive strength of 35 psi (25.2 N/cm^2), cannot be considered as having met specifications. No foam met the specified tensile properties, but the high tensile strength at Fort Benning indicates better interlayer adhesion than at either Fort Knox or Fort Lewis. In general, the polyurethane foam at Fort Lewis was found to be slightly different in cell structure and material composition from the foams at Forts Benning and Knox. This difference is indicated by lower strength and closed-cell content as well as higher water vapor transmission and dimension change.

Dimensional stability values are reported by the manufacturers as the percent change in linear dimension in the direction of foam rise. The samples from the field were allowed to expand unrestrained. Linear dimensional stability values in the direction of rise were comparable to those claimed by the manufacturers. Overall, the initial properties exhibited by the three PUF materials fell within the normal ranges expected.

For the coatings, the only values specified were minimum thickness and maximum perm rating. The variation in thicknesses cannot be attributed only to foam surface texture, since the foam at Fort Lewis had a smoother surface than at either Fort Benning or Fort Knox, and the coating at Fort Benning met the specified minimum thickness. Application technique undoubtedly had much influence on the results. All coatings met the specified water vapor transmission (WVT) requirements.

Measured and advertised properties for the coatings could not be compared. Since coating thicknesses were

[9] W. C. Cullen and W. J. Rossiter, *Guidelines for Selection of and Use of Foam Polyurethane Roofing Systems*, Technical Note 778 (National Bureau of Standards, May 1973).

*At the time this report was prepared, CEGS 07540 was being revised to permit the use of other coating materials.

**Hypalon is the registered trade name for chlorosulfonated polyethylene of the E. I. DuPont de Nemours and Co.

[10] *Properties of Rigid Urethane Foams*, Elastomer Chemicals Department (E. I. DuPont de Nemours and Company).

so varied for any given sample, determination of tensile properties would be meaningless. The manufacturers do not publish the brittle temperatures of their products, so the determination of this property was for initial characterization only, as was the glass transition temperature. It should be repeated that the glass transition temperature is not the same as the brittle temperature, but is a temperature range in which heat is absorbed as the material undergoes a phase change. This difference is readily apparent from an inspection of data in the various tables. In keeping with the purposes and financial constraints of the test program, it was felt that only physical properties of the coatings would be significant, so the tensile properties were not determined.

Changes in PUF Roofing Properties Over Time

Except for one time each, samples of PUF roofing from Forts Benning and Lewis were taken on schedule. No intermediate samples were received from Fort Knox, so no valid conclusions can be drawn from changes in property values at this location. Therefore, discussion of property changes is limited to Forts Benning and Lewis. It must be emphasized that PUF, as used in liquid-applied roofing, is manufactured at the location of use, under ambient atmospheric conditions, and not within the enclosed space of a factory under controlled conditions. Trends therefore become more important than singularities which may result from a change in any one of many localized conditions.

Thus, it can be deduced that density, compressive strength, and water absorption do not show any significant change at either Benning or Lewis. Tensile strength values, however, need to be interpreted in the light of actual application methods. At first, it appears that the tensile strength of the Fort Lewis foam is much less than the value advertised by the manufacturer. However, this is not necessarily the case. The manufacturer performed the test on a monolithic block of the foam, whereas the sample from the field was composed of several layers. Failure occurred at an interface between layers and actually indicated interlaminar adhesion qualities rather than strength of the foam itself. The foam at Fort Knox apparently showed excellent interlaminar adhesion, with higher tensile test values than those reported by the manufacturer. The manufacturer of the Fort Benning foam does not report tensile strength in its published literature. Table 8 shows that the interlaminar bond strength of the foam at Fort Benning is declining. This will be kept in mind during the annual visual inspection of the roof, in case any blistering is observed. Interlaminar blisters have already been observed at Fort Knox (Figure 10), possibly because moisture was present on the surface of one of the lifts of foam as the next lift was being sprayed. The origin of the moisture could have been a drop of perspiration from the worker using the spraygun. When combined with the linear dimension change perpendicular to rise, the moisture can form the type of blister shown in Figure 10.

Tables 8 through 10 show the changes in coating properties with time. Glass transition temperatures have remained essentially constant, as have water vapor transmission (WVT) properties. During the annual visual inspections, it was observed that the granules are becoming dislodged, with many bare areas of coating appearing.

Tables 8 through 10 also outline changes in foam and coating assembly properties. Impact and indentation values at Fort Benning have markedly improved over the 2-year time, but the value of coating adhesion to the foam has shown a serious decrease. The manufacturer has recognized that this coating material exhibits a decrease in adhesion over time. The formulation of the base coat has been changed to provide increased adhesion and longer time retention of this property. On the other hand, impact properties at Fort Lewis show a deterioration, while coating adhesion has remained essentially constant.

Continuing visual inspections each year will pay particular attention to possible infiltration of water under the coating, which would tend to saturate the foam and destroy the bond between foam and coating.

Built-Up Roofing

Initial properties of the built-up roofing (BUR) installed at Forts Benning and Lewis were determined for material characterization only. Table 11 gives the results of these tests; as shown, the specified properties were not completely met by the materials used.

The aggregate at Fort Benning was larger in particle size than the ASTM D 1863-77 size range allows. More material was retained on both the 1/2-in. (13-mm) sieve and the 3/8-in. (10-mm) sieve than the specification allows. However, this is not considered a serious problem.

The glass roofing felt used at Fort Lewis met all the applicable criteria of ASTM D 2178-76, exceeding them by about 100 percent. However, the organic felt used at Fort Benning, which was certified as meeting ASTM D 226-77, did not comply, except for the perforations. Breaking strengths and unit weight were less than specified values, while volatile loss was 50 percent higher. These results are not reflected in the service life of the two roofs. The roof at Fort Lewis is heavily blistered, but does not leak. The roof at Fort Benning is still in excellent condition and does not yet require maintenance.

Gas chromatographic/mass spectral analyses were conducted on samples cut periodically from the roofs to determine what changes occurred in the asphalt as it aged. In addition to the initial controls, tests were conducted on 18- and 24-month samples from Fort Benning and 12- and 18-month samples from Fort Lewis. By comparing the aged samples with the controls, it is possible to detect differences. Computer-generated traces of the various analyses exhibit differences which indicate that chemical changes have occurred in the asphalt as it aged on the roofs. The asphalts that were analyzed came from or near the top of the samples, where the effect of sun and water was more intense. All samples except the initial controls exhibit traces of chemicals identified as dialkyl esters of phthalic acid, indicating that these products are formed in the asphalt as it ages. They are volatile compounds, and as they are produced and lost, the asphalt will become brittle.

For Fort Benning, traces of the initial control samples are shown in Figures 11 and 12, the 18-month samples in Figures 13 and 14, and the 24-month samples in Figures 15 and 16. For Fort Lewis, traces of the initial control samples are shown in Figures 17 and 18, the 12-month samples in Figures 19 and 20, and the 18-month samples in Figures 21 and 22. The designations "Fraction I" and "Fraction II" on the figures refer to test runs which separated aliphatic from aromatic compounds in each sample. Fraction I refers to aliphatic compounds and Fraction II to aromatic compounds.

Attempts were made to measure changes in mechanical and physical properties as the asphalt aged. Results were inconclusive, since the tests are not sensitive enough to determine minute changes. In all cases, the spread of results was less than the anticipated experimental error, so these attempts are not reported.

4 STRAIN AND TEMPERATURE RESPONSES

Instrumentation

A part of the overall test plan was to monitor thermal conditions within the roof system and the weather conditions at the test site, including air temperature, wind direction and speed, and solar radiation. An attempt was also made to monitor strains occurring in the EPDM membrane. The instrumentation system provides a thermal profile through the roof systems by the use of thermocouples installed at the insulation-deck interface and on the membrane surface. Mercury strain gages were attached to the surface of the EPDM membrane.

Fort Benning

Instrumentation was installed only on Building 2823. Thermocouples were installed on the structural deck below the insulation on the roof areas covered by the EPDM system and the conventional BUR. Additional thermocouples were installed on top of both membranes, and strain gages were installed on the EPDM membrane only. The weather station was placed on the BUR portion as shown in Figure 23. All wiring was brought into a room located below the BUR part of the building. Figures 24 and 25 show the locations of thermocouples and strain gages, and Figure 26 shows the equipment layout in the data recording room.

Fort Lewis

Instrumentation was installed on all three sections of Building 1450. Thermocouples were installed on the structural decks and on the surfaces of the three membranes. Strain gages were installed on the EPDM membrane surface only. The weather station was placed on the PUF system as shown in Figure 27. All wiring was brought into a room located under the PUF part of the building, where equipment similar to that at Fort Benning was located. Figures 28 and 29 show the locations of thermocouples and strain gages at Fort Lewis.

In both locations, data for 2 weeks were recorded on a cassette tape. This tape was mailed to USA-CERL, where the recordings wer transferred to a master file. The cassettes were then r rned for recording of more data.

Roof Surface Temperatures

Roof surface temperatures affect the performance of the roof system and the thermal load on the building. The data collected at Forts Benning and Lewis were subjected to statistical analysis using the Statistical Package for the Social Sciences (SPSS). Data were selected from April 1981, August 1981, October 1981, and January 1982 to represent four different periods during an exposure year.

The data indicate a strong relationship between the roof surface temperature and solar incidence, and a less significant relationship between roof surface temperatures and air temperatures. The black surface of the EPDM membrane experiences much higher temperatures than either the gravel-surfaced BUR or the white-coated PUF. The difference is statistically significant at solar incidence levels above 0.375 Langley. There appears to be almost no difference between the surface temperatures of the gravelled BUR and the PUF roofs. When roof surface temperatures were compared to air temperatures, it was observed that at air temperatures below 50°F (10°C), the EPDM was cooler than the other two roofs; at temperatures above 75°F (24°C), the EPDM was significantly warmer than the other two roofs.

The data for the instrumented roof systems for the four collection periods were divided into three levels of air temperature: low, medium, and high. They were then analyzed using scattergram and regression line techniques. Figures 30 through 34 show the relationships between roof surface temperatures and solar exposure for the three levels of air temperature and the five instrumented roofs at Forts Lewis and Benning. The roof temperatures represent an average of all the temperature points on the roof surface. When the diagrams were created, the options available were to use each thermocouple point plotted against the other parameters, or to combine all the points into one plot. Because of the variations of construction and activities within the buildings, it was not possible to select one thermocouple point as representative or typical of the whole roof. An examination of the data indicated that certain roof points were consistently warmer or cooler than other points on the same roof. Since there was no evidence that any one point was incorrect, all points were included. A 90 percent confidence interval constructed from the data for each of the roofs confirmed the decision to take the average of all the thermocouple points.

Table 12 lists minimum, maximum, and mean roof temperatures for selected days at Forts Benning and Lewis. The confidence interval depends on the average, the deviation, and the number of thermocouples involved. It is possible to have a large spread between minimum and maximum temperatures with a relatively small spread in the confidence interval because of the distribution around the mean and the total number of data points. For Figures 30 through 34, an equation for each of the regression lines is shown, as well as the standard error of estimate and the "R^2", a measure of the strength of the linear relationship between the two variables.

Figures 35 through 39 are similar data plots, except that they relate the solar radiation to temperatures at the interface between the insulating material and the structural deck. There is an indication of some effect from solar radiation and air temperature, but the interface temperatures are probably more affected by inside than by outside temperatures. Data from the PUF roof at Fort Lewis substantiate this conclusion. Temperatures at the deck rose only 10°F (5.5°C) for a 40°F (22°C) rise in air temperature at one instance; temperatures never went below 60°F (16°C), even when outdoor temperature dropped to as low as 20°F (- 7°C).

Strain Gage Readings

The successful application of strain gages to an elastomeric material such as EPDM or to a visco-elastic material such as BUR has not been reported for long-term studies. Unpublished investigations show some success for short-term tests on EPDM roofs and on elastomeric-coated fabrics. The strains in elastomeric materials can be expected to be much larger than those measured by conventional strain gages.

A number of different types of electrical strain gages were investigated during the initial stages of this study. Most were eliminated for reasons such as long-term stability, sensitivity to temperature changes, weatherability, problems of attachment, and other mechanical reasons. One series of tests was made on foil strain gages attached to omega-shaped strips of brass shim stock fastened to the membrane. This was not successful during field tests.

The final installation used mercury capillary gages attached directly to the membrane. The locations are shown in Figures 13 and 17. The gages indicate the change in strain as a change in electrical resistance. They were developed by the Southwest Research Institute (San Antonio, TX) to measure strain on the bow seals of surface effects ships (SES) and adapted for use on this project.

A plot of percent strain versus time for four of the gages at Fort Lewis shows twice daily peaks in the percent strain. Peaking began at about 0800 hours on two days and at about 1000 hours on the other five. The drop in percent strain occurred at about the same time each day. A second peak occurred again about 1900 hours, with completion of the cycle at about

2300 hours to midnight. This phenomenon was not evident at Fort Benning.

Figures 40 through 47 are each a composite of roof temperature, air temperature, solar incidence, and percent strain plotted against a three-day interval. The three-day periods, which were selected by using United States climatological data for the area, represent periods of high solar gain with high and low air temperatures, and low solar gain with high and low air temperatures. Since all four strain gages responded almost identically, only one gage is shown on the plots.

The plots clearly show the strong relationship between solar incidence and strain gage response. The plots with low solar incidence show virtually no change in percent strain, while those with high solar incidence show an almost immediate response to solar incidence. The double peak condition at Fort Lewis is very obvious in Figures 40 and 42.

Figures 40 through 47 show the time lag between rising-air and roof-surface temperatures. On days with little or no solar incidence and overcast skies, roof-surface temperatures followed air temperatures. In contrast, on clear nights the roof-surface temperatures were lower than the air temperatures. This is not unexpected and repeats data previously published by the National Bureau of Standards.[11]

5 SIGNIFICANCE OF DATA

When evaluating any building material exposed to the natural environment for a long time, it is important to keep records of exposure period conditions. Lack of such a record greatly reduces the evaluation's significance. The instrumentation described in this report was designed to provide this record.

Just as important as the data is that the method of recording the data require only a minimum of attention and manpower. The analysis presented in this report indicates that the temperature-recording system has been successful and that relationships between ambient air, solar incidence, and roof temperatures have been established. The analysis shows extremes of temperature and daily cyclic changes.

The significance of the strain gage data is not clear. The EPDM material exhibited strains of about 4 to 4.5 percent, which is well below the maximum allowable strain for this type of material. The data are useful for seeing the movement that occurs during daily cycling. However, the installations have not been reliable over long time spans and may only be useful during early stages of the test. It has also not been possible to explain the "double peak" that occurs in the data for gages installed at Fort Lewis. Discussions with various technical personnel have not produced an acceptable explanation. A laboratory test is needed to simulate the temperature and solar incidence on the roof so that a mercury gage attached to EPDM can be monitored. Such a test may indicate why this response of the field gages occurred.

The collection and analysis of roof temperatures and weather conditions is part of an overall study to evaluate alternative roofing systems. How these roof systems will age (i.e., what changes will occur in their physical characteristics over time) is of great concern to this program. Tests performed by others[12] indicate that the EPDM roof materials display reduced elongation properties, increased tensile strength, and increased hardness after accelerated aging. Preliminary test results of the physical characteristics of the test EPDM roofs at Forts Lewis and Benning agree with the elongation and hardness changes, but may disagree with tensile strength changes. There was an initial increase in tensile strength properties after a 6-month exposure at Fort Benning, but the last three tests after 12, 18, and 24 months of exposure indicate a gradual return to lower tensile strengths. At Fort Lewis, a small increase was evident after a 12-month exposure. Current plans are to continue removing samples for testing at 1-year intervals to monitor physical changes in the material.

From the weather data collected at Forts Benning and Lewis, it is evident that the solar intensity at Fort Lewis rarely exceeds 0.625 Langley, while at Fort Benning, it is often 1.0 Langley or higher. It is possible that the intensity of the solar radiation, as well as the total solar incidence, may have a very marked effect on the aging process.

Accelerated weathering techniques must intensify the exposure conditions to affect the aging process. As with other building materials, such as paints, sealants, and traditional roofing materials, the acceleration

[11] William Cullen, *Solar Heating, Radiative Cooling, and Thermal Movement*, NBS Technical Note 231 (National Bureau of Standards, December 1963).

[12] Rene Dupuis, et al., 1981.

process may not provide a true picture of the aging process on the EPDM roof materials.

Continued monitoring of the EPDM roof systems will provide an excellent means of comparing accelerated and long-term testing. It will also help determine the usefulness of accelerated tests as a means of evaluating roof systems.

The physical properties of PUF have also been tested on samples removed from roofs at Forts Lewis, Benning, and Knox. Tests of density, compressive strength, interlaminar bond strength, and water absorption show both negative and positive changes. The only possibly significant change appears to be at Fort Benning, where interlaminar bond strength has declined from an average of 78 lb/sq in. (538 kN/m^2) (60 to 89 range) (414 to 614 range) to an average 36 lb/sq in. (248 kN/m^2) (0 to 75 range) (0 to 517 range). Coating vapor transmission rates have increased, mainly due to granule loss resulting in pinholes in the coating. Coating glass transition appears to be stable, but coating adhesion appears to be declining. Average values of 160 to 198 lb/sq in. (1103 to 1365 kN/m^2) have declined to average values of 115 to 156 lb/sq in. (793 to 1076 kN/m^2) over the 24-month test period.

The most severe declines in coating adhesion and interlaminar bond strength have occurred at Fort Benning. Degradation of the PUF roof is probably not related to temperature or exposure, but most likely is a direct result of the application problems encountered by the contractor.[13]

The foam assembly is also being tested for indentation strength and impact strength. Indentation strength has shown increased values at all three sites. Impact strength has increased at Fort Benning, while declining at Forts Knox and Lewis.

Continued monitoring of the PUF systems will provide data to help determine if further degradation is related to exposure factors or to application problems.

6 RESULTS OF VISUAL OBSERVATIONS

Each roof has been inspected annually as part of the evaluation process. At each inspection, the roof is carefully checked for visible signs of deterioration. Special attention is paid to the patches where samples for testing have been removed, as well as to flashings and indications of maintenance or repair.

First Annual Inspections

The first annual inspections (July 1981) indicated only minor problems. Granules were not firmly adhered to the coatings on the PUF roofs and were washing down the drains and collecting in depressions in the foam. At Fort Knox, the vent from a heating boiler was causing a large rust stain to form on the roof surface, but this was not causing any apparent deterioration.

Minor problems were already becoming evident on the EPDM roofs. At Fort Benning, there were a few minor blisters, evidently caused by wrinkles in the sheet at the time of installation. At Fort Lewis, some blistering was occurring above the nail heads where the membrane had been fastened to the wood nailers. At both locations, it was observed that patches over the sample cuts were not adhering properly to the membrane. Satisfactory repairs were achieved by abrading the contacting surfaces with wire brushes and coarse sandpaper, followed by renewed application of fresh contact cement.

The BUR at Fort Benning looked as if it had just been installed. Some slight blistering was evident in the BUR at Fort Lewis. Field personnel stated that blistering of BURs with mineral-coated cap sheets was very common at Fort Lewis, probably because of the combination of high humidity and mild temperatures which always exists there. The only 6-month samples taken were of the BUR and EPDM roofs at Fort Benning.

Second Annual Inspections

The second annual inspections (June 1982) indicated some need for maintenance. The PUF roof at Fort Benning was in excellent condition, but some blisters were beginning to form in the PUF roof at Fort Knox. Figure 10 is typical of this blistering. At both Forts Benning and Knox the foam samples were smaller than had been requested, so ideal data were not available. Sampling technique was discussed so that further samples would be the proper size. At Fort Knox, the second set of sample cuts had been patched with roofing felt and asphalt cement, as if the roof were a BUR. Proper repair techniques were discussed. Even though more than 2 years had elapsed since completion of construction, only the 24-month samples had ever been sent to the laboratory for analysis. The

[13] M. J. Rosenfield and D. E. Brotherson, 1981.

6- and 12-month samples had never been taken, and the 18-month samples had been lost.

The PUF roof at Fort Lewis was in excellent condition, except for flashing at a vent from a heating boiler. Design of this flashing had not allowed for expansion and contraction of the pipe, so the foam had broken. Proper flashing techniques were discussed. The coating over one of the patched areas where a sample had been removed was partially detached from the foamed repair. This could be repaired easily by abrading the foam surface and recoating the area.

The EPDM roofs at both Forts Benning and Lewis were generally in very good condition. One patch at Benning was no longer adhered to the membrane and needed repair. Two problems were evident at Fort Lewis. One was the presence of considerable ash from one of the Mount Saint Helens eruptions, which had occurred a year before the inspection. The other was the continued existence of small blisters above the nail heads. Figure 48 shows a typical blister. The membrane manufacturer was contacted about this problem. It had apparently occurred elsewhere, and repair methods were recommended.

The BUR at Fort Benning was still in excellent condition. However, the one at Fort Lewis was severely blistered and would soon need extensive repair or replacement.

It was noted that drains at Fort Lewis were constantly being plugged by debris blowing onto the roofs from the surrounding pine trees, causing water to remain ponded on the roofs for an excessive time after the rain had stopped. It was pointed out that these drains should be kept clear to remove the water.

Third Annual Inspections

The third annual inspections (June 1983) demonstrated the value of prompt and proper maintenance procedures. The PUF roof at Fort Benning was still in excellent condition, except for some scratches through the coating of one patch. All previously discovered deficiencies in the PUF roof at Fort Knox had been repaired recently, and the roof was in excellent condition. The vent from the boiler had been piped to discharge directly into a nearby gutter; all previous stains had been scrubbed off and the area given a fresh application of coating and granules.

However, at Fort Lewis, a serious problem had developed in the PUF roof since the previous inspection. Twenty samples had by now been taken from the roof for inspection, and all had cracks through the coating around part or all of each perimeter. Eight had become so wet that water spurted out when they were stepped on. This is not to be construed as a defect in the PUF roofing system. On the contrary, the roof itself was still in sound condition. The defect occurred because of improper procedures for repairing the holes where samples were removed. Once these areas are removed and properly repaired, the roof will be in excellent condition. The only other deficiency noted was that wind had scoured the surface so that many bare streaks were now visible in the coating, showing where granules had been removed.

The EPDM roof at Fort Benning was still in generally very good condition. One patch had been sealed with the wrong type of sealant, which had deteriorated rapidly and was peeling away. A thorough cleaning and use of proper sealant will provide adequate repair. However, at Fort Lewis, a serious problem was now evident. The membrane had become detached from the underlying insulation around one of the drains. The watertight integrity of the membrane did not seem to be affected, however, and the insulation did not feel as if it were wet. The small blisters above the nail heads, noted during the previous year, had been repaired, but new ones had formed at the same locations. No surface cracks or crazing had appeared in either of the EPDM roofs.

The BUR at Fort Benning was still in excellent condition. Recent rains had caused some shallow ponding, but there was neither evidence nor history of roof leaks. Because of the high solar incidence and ambient temperatures, as well as the shallow depth of the ponds, the water tended to evaporate rapidly, usually lasting no longer than 2 to 3 days. Blistering in the BUR at Fort Lewis was even more pronounced than in the previous year, but only one leak had developed, and this had been repaired. Some blisters had opened, and these had been patched by spreading roofing cement over the surface. Discussion with Fort Lewis personnel indicated that the asphalt surface inside the blisters was shiny, indicating poor adhesion of the cap sheet to the BUR surface. However, it must be noted that the cap sheet was applied to the BUR surface after the three plies had been completely shingled in and allowed to cool; this undoubtedly led to a poor bond between the BUR and the cap sheet. Blistering of BURs with mineral-coated cap sheets is very common at Fort Lewis.

7 CONCLUSIONS AND RECOMMENDATIONS

EPDM single-ply membrane roofing, when properly applied and maintained, is a good material for use on Army and other Government buildings, having demonstrated the capability to retain its properties for a long period of time. Seaming techniques require close attention to ensure that the sheet is completely cleaned of talc or other coating before seam cement is applied. Repairs and corrections are relatively easy to perform when compared to the standard BUR.

When provided with adequate coating, PUF provides a lightweight roof which can be easily maintained to yield a long service life. Care must be taken during design to allow for situations where expansion and contraction of items penetrating the roof may tend to fracture the foam. Repairs to surface defects are simple to accomplish, but care must be taken when foam is removed and replaced so that leaks do not develop.

Conventional BUR can provide a serviceable roof, but the surfacing used can affect the durability of the final product; this may be due partly to the application of the cap sheet as a separate layer after the shingled felt has been applied.

Both EPDM and PUF can provide good-quality roofs with long life expectancy, and should be given widespread acceptance and use in military construction. Both systems are already approved for Army use.

Monitoring of the changes to physical and mechanical properties of the materials should continue to obtain complete data on the effect of aging under service conditions.

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METRIC CONVERSION FACTORS

1 lb/sq in. = 703.070 Kg/m^2 (mass)

= 6.895 KN/m^2 (force)

$$°C = (°F - 32)\frac{5}{9}$$

1 perm-mil = $1.459 \times 10^{-3}\ ng \cdot PA^{-1} \cdot S^{-1} \cdot m^{-1}$

1 lb/cu ft = 16.0185 Kg/m^3

Table 1
PUF Test Characteristics

Property	Test Method	Remarks
Tests at Beginning of Exposure Program		"Property" refers to physical properties of interest.
Foam		
Water Vapor Transmission	ASTM C 355	The amount of movement or dimensional change must not exceed the coating capacity.
Dimensional Stability	ASTM D 2126	
Closed Cell Content	ASTM D 2856	
Coating		
Thickness	USBR Test	These tests will establish "baseline" for coating for comparison with later tests taken from field-exposed samples.
Brittle Temperature	ASTM D 2137	
Tests at Beginning and Intermittently During Program		
Foam		
Foam Density	ASTM D 1622	The material must not deteriorate or lose density.
Water Absorption	ASTM D 2842	Urethane foams are sensitive to moisture.
Tensile Strength	USBR Test	Moisture may enter from below (condensation) or above (leakage).
Compressive Strength	ASTM D 1621	
Coating		
Water Vapor Transmission	ASTM E 96	
Glass Transition	ASTM D 3418	
Foam With Applied Coating		
Indentation Hardness	USBR Test	The foam and coating must be capable of resisting foot traffic and other mechanical abuses, including continued resistance to hail and falling objects.
Adhesion	NCEL Test	
Impact Resistance (with applied coating)	USBR Test	
Field Monitoring		
Visual Inspection		Check for adhesion loss, blistering, cracking, flaking, peeling, pinholing, hail damage, and severe cracking or erosion.
Weather Data		
Temperature		
Humidity		
Solar Radiation		
Wind Speed and Direction		
Temperature Measurements		
Thermocouples at interface of foam and supporting deck; on surface of coating.		

Table 2
EPDM Test Characteristics

Property	Test Method	Remarks
Tests at Beginning of Exposure Program		
Heat Aging	ASTM D 573	"Property" refers to physical properties of interest. This group of tests is used to provide a means of predicting weather performance. They will be used for comparison at the end of the 2-year period to see how well they predicted the actual condition of the membrane materials.
Accelerated Aging	ASTM D 2565	
Brittleness	ASTM D 2137	
Dimensional Stability	ASTM D 1204	
Tests at Beginning and Intermittently During Program		
Abrasion Loss	ASTM D 3389	These are tests to establish the basic physical characteristics typical of roof membranes. Any changes in these characteristics during service could signal aging, deterioration, and reduction of lifetime expectancy. Abrasion resistance is necessary if the roof will experience regular foot traffic; seam strength is essential in one-ply systems; changes in hardness indicate a loss of plasticizer and resistance to mechanical damage; absorption and permeability are necessary characteristics if the membrane is used over existing roofing systems with possible moisture entrapment; D 1876 and D 412 tests should be run at 70°F.
Seam Strength	ASTM D 1876 and D 882, Method A	
Tensile Strength	ASTM D 412	
Ultimate Elongation	ASTM D 412	
Hardness	ASTM D 2240	
Water Resistance		
Absorption	ASTM D 570	
Permeability	ASTM E 96, Proc. B	
Ozone Resistance	ASTM D 1149	
Glass Transition	ASTM D 3418	
Field Tests and Monitoring		
Weather Data		These measurements are needed to correlate with strain and temperature measurements.
Temperature		
Humidity		
Solar Radiation		
Wind Speed and Direction		
Strain Measurements Some points on center line of test area with strain gages at 90 degrees to measure longitudinal and transverse strains. At some corners, penetrations, and at center of perimeter.		Previous studies indicate that these locations will give good data on movement within the membrane.
Temperature Measurements Thermocouples at interface of insulation and structural deck and at surface of membrane at strain gage locations.		The thermocouple stack is a standard method of measuring temperatures in a building component. Thermocouples at strain gage locations are needed to correct strain gage output.
Periodic Field Observations		
Visual Inspection		This type of inspection with photographs will provide a record of physical changes and/or appearance.
Nondestructive Moisture Measurement		Moisture survey techniques (infra-red, nuclear, capacitance, and cores as needed) will be used to determine any changes in moisture content of the insulation.

Table 3
BUR Test Characteristics

Tests at Beginning of Exposure Program

Property	Test Method	Remarks
Asphalt	ASTM D 312	These tests will establish that the materials used to construct the membrane meet minimum ASTM standards.
Surfacing	ASTM D 1863	
Felts	ASTM D 226, D 2178	
BUR Assembly	ASTM D 3617	This test taken during the assembly operation will establish the quality and quantity of the membrane materials.

Tests at Beginning and Intermittently During Program

Property	Test Method	Remarks
Glass Transition	ASTM D 3418	Glass transition tests will be run as required.
Mass Spectrograph	ASTM E 137, E 304	This test will detect chemical changes with time as the asphalt weathers and ages.

Field Tests and Monitoring

Item	Remarks
Weather Data	
Temperature	
Humidity	
Solar Radiation	
Wind Speed	
Strain Measurements	
Selected points at expected maximum and minimum strain.	This will reveal membrane movements.
Temperature Measurement	
Thermocouple "stacks" at one or two locations and single thermocouples at strain gage locations.	These are needed to correct strain gage outputs and to conduct research on the thermal performance of the roof.

Table 4
Initial Properties of EPDM Roofing Materials

Property[9]*	Specified Value		Test Method		Fort Benning	Fort Lewis
Tensile strength, lb/sq in.	1400	Longitudinal	ASTM D 412	Average	1585	1705
				Range	1445 to 1705	1640 to 1845
		Transverse		Average	1525	1645
				Range	1405 to 1650	1135 to 1820
Elongation, percent	300**	Longitudinal	ASTM D 412	Average	540	505
				Range	475 to 640	480 to 540
		Transverse		Average	580	515
				Range	530 to 640	480 to 580
Hardness,Shore "A"	50 to 70**		ASTM D 2240	Average	58	57
				Range	56 to 60	56 to 58
Ozone resistance	No cracks		ASTM D 1149		No cracks	No cracks
Water absorption, weight %			ASTM D 570	Average	+0.5	+0.4
				Range	0.26 to 0.72	0.34 to 0.48
Vapor transmission,perm-mils	2.0***		ASTM E 96 Procedure B	Average	3.6	1.98
				Range	2.4 to 5.3	1.86 to 2.04
Glass temperature, °F	−50 max		ASTM D 3418	Average	−60	−65
				Range	−62 to −58	−66 to −65
Abrasion loss, grams/1000 rev.			ASTM D 3389	Average	0.19	0.19
				Range	0.15 to 0.22	0.17 to 0.21

*Numbers refer to Remarks and Observations, p 35.
**Manufacturer's published value.
***Manufacturer's published value by Procedure BW.

Table 4 (Cont'd)

Property[9]*	Specified Value		Test Method		Fort Benning	Fort Lewis
Seam strength, lb/in. width		Peel	ASTM D 1876	Average	0.8	2.5
				Range	0.4 to 2.0	1.6 to 4.3
		Shear	ASTM D 882 (A)	Average	18.0	28.7
				Range	14.9 to 19.7	22.8 to 34.0
Low temperature brittleness (°F)	−75**		ASTM D 2137	Average	−80	−66
				Range	−79.1 to −80.5	−65.0 to −66.4
Dimensional stability 24 hours at 100°F % change		Longitudinal	ASTM D 1204	Average	0.0	0.0
				Range	0.0 to 0.0	−0.1 to 0.0
		Transverse		Average	−0.1	−0.3
				Range	−0.1 to −0.1	−0.5 to −0.1
Heat aging, longitudinal direction		Tensile strength		Average	102	100
				Range	100 to 107	97 to 103
		Elongation	ASTM D 573	Average	61	70
				Range	57 to 66	65 to 80
Percent of original physical properties		100% modulus		Average	193	136
				Range	178 to 205	128 to 143
Xenon arc exposure[2]*		Period exposed	ASTM D 2566		3-13-81/4-28-82 Operating hours 4024	
Outdoor exposure[2]*		Period exposed		USBR	8-80 to 4-83	
		Surface change			Surface graying—no significant change	
		Months			32	32

*Numbers refer to Remarks and Observations, p 35.
**Manufacturer's published value.

Table 5
Aged Properties of EPDM Membrane at Fort Benning

Property[9]*		Test Method		Age-Months 0	6	12	18	24	30
Tensile strength, lb/sq in.	Longitudinal	ASTM D 412	Average	1585	1660	1650	1650	1630	1627
			Range	1445 to 1705	1610 to 1790	1580 to 1680	1607 to 1698	1590 to 1655	1516 to 1654
	Transverse		Average	1525	1620	1610	1620	1555	1585
			Range	1405 to 1650	1565 to 1655	1505 to 1725	1561 to 1702	1524 to 1575	1491 to 1648
Elongation, percent	Longitudinal	ASTM D 412	Average	540	470	494	421	430	381
			Range	475 to 640	440 to 505	470 to 510	410 to 431	395 to 465	335 to 420
	Transverse		Average	580	500	425	435	425	402
			Range	530 to 640	455 to 530	350 to 480	388 to 465	405 to 475	380 to 425
Hardness, Shore "A"		ASTM D 2240	Average	58	61	61	62	63	62
			Range	56 to 60	60 to 62	60 to 62	61 to 62	62 to 64	61 to 62
Ozone resistance		ASTM D 1149		No cracks	No cracks	No cracks	No cracks	No cracks	No cracks
Water absorption, weight %		ASTM D 570	Average	+0.5	+0.6	+0.7	+0.9	+0.9	+0.9
			Range	0.26 to 0.72	0.38 to 0.77	0.58 to 0.76	0.80 to 0.98	0.81 to 0.97	0.76 to 0.92
Vapor transmission, perm-mils		ASTM E 96 Procedure B	Average	3.6	1.8	1.2	1.6	2.3	1.8
			Range	2.4 to 5.3	1.7 to 1.8	1.2 to 1.2	1.4 to 1.8	2.1 to 2.4	1.7 to 1.9
Glass temperature, °F		ASTM D 3418	Average	−60	−60	−60	−58	−58	−54
			Range	−62 to −58	−62 to −58	−62 to −58	−62 to −56	−62 to −54	−54 to −53
Abrasion loss, grams/1000 rev.		ASTM D 3389	Average	0.19	0.16	0.13	0.08	0.10	0.09
			Range	0.15 to 0.22	0.13 to 0.18	0.11 to 0.15	0.07 to 0.09	0.07 to 0.16	0.08 to 0.11
Seam strength, lb/in. width	Peel	ASTM D 1876	Average	0.8	No sample	No sample	No sample	1.6	No sample
			Range	0.4 to 2.0				1.3 to 2.1	
	Shear	ASTM D 882 (A)	Average	18.0	No sample	No sample	No sample	27.0	No sample
			Range	14.9 to 19.7				22.5 to 37.0	

*Numbers refer to Remarks and Observations, p 35.

Table 6
Aged Properties of EPDM Membrane at Fort Lewis

Property[9]*		Test Method		Age-Months 0	12	18	24
Tensile strength, lb/sq in.	Longitudinal	ASTM D 412	Average	1705	1710	1810	1761
			Range	1640 to 1845	1518 to 1879	1793 to 1858	1713 to 1810
	Transverse		Average	1645	1681	1650	1721
			Range	1135 to 1820	1563 to 1765	1569 to 1722	1693 to 1773
Elongation, percent	Longitudinal	ASTM D 412	Average	505	495	400	449
			Range	480 to 540	424 to 569	385 to 425	425 to 473
	Transverse		Average	515	508	493	459
			Range	480 to 580	449 to 580	395 to 580	430 to 485
Hardness, Shore "A"		ASTM D 2240	Average	57	57	54	59
			Range	56 to 58	55 to 60	52 to 56	57 to 61
Ozone resistance		ASTM D 1149		No cracks	No cracks	No cracks	No cracks
Water absorption, weight %		ASTM D 570	Average	+0.4	+0.3	+0.4	+0.7
			Range	0.34 to 0.48	0.29 to 0.35	0.35 to 0.42	0.67 to 0.81
Vapor transmission, perm-mils		ASTM E 96 Procedure B	Average	2.0	2.4	2.2	2.0
			Range	1.9 to 2.0	1.8 to 2.6	1.9 to 2.5	1.6 to 2.4
Glass temperature, °F		ASTM D 3418	Average	−65	−58	−58	−59
			Range	−66 to −65	−59 to −57	−62 to −56	−60 to −58
Abrasion loss, grams/1000 rev.		ASTM D 3389	Average	0.19	0.14	0.13	0.11
			Range	0.17 to 0.21	0.13 to 0.17	0.11 to 0.14	0.10 to 0.13
Seam strength, lb/in. width	Peel	ASTM D 1876	Average	2.5	2.7	2.8	1.9
			Range	1.6 to 4.3	1.8 to 3.8	1.9 to 3.4	1.5 to 2.6
	Shear	ASTM D 882 (A)	Average	28.7	26.0	25.0	24.2
			Range	22.8 to 34.0	23.2 to 29.0	21.7 to 28 2	21.8 to 28.0

*Numbers refer to Remarks and Observations, p 35.

Table 7
Initial Properties of PUF Roofing Materials

Property			Specified Value	Test Method		Location: Fort Benning	Fort Knox	Fort Lewis
Density, lb/cu ft			2.7–3.5	ASTM D 1622	Average	2.87	3.11	3.07
					Range	2.77 to 3.04	2.92 to 3.40	2.89 to 3.31
Compressive strength, lb/sq in.			40 min	ASTM D 1621	Average	53	62	39
					Range	44 to 58	51 to 76	35 to 41
Tensile interlaminar[4]* strength, lb/sq in.				USBR	Average	78	64	55
					Range	69 to 89	50 to 93	42 to 64
Water absorption,[5]* g/m^2 surface area				ASTM D 2842	Average	48	30	49
					Range	43 to 53	27 to 33	46 to 54
Foam water vapor transmission (perms)				ASTM C 355	Average	1.05	0.86	1.28
					Range	1.04 to 1.06	0.83 to 0.89	0.85 to 1.65
Closed cell content of foam (percent)		Corrected for for cell size		ASTM D 2856	Average	97.0	98.0	96.0
					Range	96.3 to 97.5	97.1 to 99.3	95.4 to 98.4
		Uncorrected			Average	92.1	94.7	91.4
					Range	91.8 to 92.4	94.3 to 95.7	90.3 to 91.9
Dimensional stability[1]* of foam, percent change in linear dimension	Perpendicular to rise 30 percent RH	1 day		ASTM D 2126	Average	0.0	0.15	+0.56
					Range	−0.42 to +0.48	−0.59 to +0.15	0.10 to 1.23
		7 days			Average	+0.39	−0.03	+1.19
					Range	−0.06 to +1.13	−0.24 to +0.30	0.59 to 1.74
		14 days			Average	+0.40	−0.04	+1.13
					Range	−0.12 to +0.96	−0.59 to +0.49	0.38 to 1.45
	Parallel to rise 30 percent RH	1 day			Average	+0.11	−0.41	−0.24
					Range	−0.18 to +0.36	−0.74 to +0.05	−0.28 to −0.20
		7 days			Average	0.0	−0.39	−0.25
					Range	−0.30 to +0.12	−0.64 to +0.10	−0.39 to −0.10
		14 days			Average	−0.16	−0.39	−0.03
					Range	−0.50 to +0.06	−0.59 to 0.15	−0.39 to +0.34

*Numbers refer to Remarks and Observations, p 35.

Table 7 (Cont'd)

Property			Specified Value: Benning	Specified Value: Knox	Specified Value: Lewis	Test Method		Location: Fort Benning	Location: Fort Knox	Location: Fort Lewis
	Perpendicular to rise 100 percent RH	1 day					Average	6.74	4.36	19.52
							Range	4.76 to 7.79	2.25 to 6.28	19.26 to 19.65
		7 days					Average	7.89	4.60	21 40
							Range	5.78 to 9.32	2.84 to 6.97	20.12 to 22.38
		14 days					Average	8.27	5.61	16.48
							Range	6.13 to 9.61	3.47 to 7.17	14.77 to 17.83
	Parallel to rise 100 percent RH	1 day					Average	0.89	+0.04	12.14
							Range	0.53 to 1.25	−0.05 to +0.15	11.61 to 12.67
		7 days					Average	0.88	+0.39	13.50
							Range	0.77 to 1.07	−0.0 to +0.44	11.86 to 15.13
		14 days	8**	5**	7**		Average	0.97	+0.65	7.50
							Range	0.71 to 1.24	−0.49 to +0.84	6.22 to 8.77
Coating thickness, (mils)				20 min.		USBR	Average	30	37	20
							Range	20 to 40	12 to 60	10 to 25
Coating brittle temperature, °F		Coldest available temperature shown				ASTM D 2137 Typical		Below −104	Below −98	Below −95
Indentation strength, lb/sq in.		Yield				USBR	Average	68	78	65
							Range	46 to 82	62 to 89	54 to 75
		Coating break					Average	79	84	No break at
							Range	72 to 85	81 to 105	½-in. deflection
Impact strength, grams		Top				USBR	Average	210	370	140
							Range	194 to 225	328 to 418	120 to 192
		Base								650
										623 to 675
Coating vapor[6]* transmission, perms				3.5 max.		ASTM E 96 Procedure B	Average	2.2	2.4	1.6
							Range	2.0 to 2.4	2.4 to 2.4	0.8 to 2.4
Coating adhesion,[7]* lb/sq in.						NCEL	Average	160	198	174
							Range	123 to 192	169 to 232	157 to 192
Coating glass[8]* transition, °F		Top				ASTM D 3418	Average	−189	−189	+51
							Range	−190 to −188	−190 to −188	50 to 52
		Base								−67
										−69 to −65

*Numbers refer to Remarks and Observations, p 35.
**Manufacturer's published specification.

Table 8
PUF Roofing—Physical Properties for Initial and Aged Characteristics

Fort Benning

Property[3]*		Test Method		Age-Months 0	12	18	24	30
Density, lb/cu ft		ASTM D 1622	Average	2.87	3.45	3.50	3.38	3.46
			Range	2.77 to 3.04	3.16 to 3.81	3.33 to 3.37	3.36 to 3.45	3.11 to 3.71
Compressive strength, lb/sq in.		ASTM D 1621	Average	53	71	59	54	59
			Range	44 to 58	68 to 76	53 to 65	34 to 63	48 to 64
Indentation strength, lb/sq in.	Yield	USBR	Average	68	91	100	90	89
			Range	46 to 82	72 to 111	97 to 104	80 to 98	71 to 102
	Coating break		Average	79	126	144	117	114
			Range	72 to 85	114 to 138	132 to 155	107 to 125	99 to 123
Impact strength, grams		USBR	Average	210	535	394	453	420
			Range	194 to 225	430 to 730	260 to 500	330 to 560	400 to 440
Tensile interlaminar[4]* strength, lb/sq in.		USBR	Average	78	42	67	60	54
			Range	69 to 89	18 to 68	24 to 100	44 to 89	36 to 75
Water absorption,[5]* g/m^2 surface area		ASTM D 2842	Average	48	57	47	48	47
			Range	43 to 53	51 to 63	42 to 51	43 to 53	45 to 49
Coating vapor[6]* transmission, perms		ASTM E 96 Procedure B	Average	2.2	2.0	2.1	[6]*	1.3
			Range	2.0 to 2.4	1.3 to 2.9	1.9 to 2.3		1.1 to 1.6
Coating adhesion,[7]* lb/sq in.		NCEL	Average	160	130	111	115	118
			Range	123 to 192	83 to 184	74 to 158	105 to 124	115 to 120
Coating glass[8]* transition, °F		ASTM D 3418	Average	−189	−186	−185	−186	−183
			Range	−190 to −188	−187 to −185	−186 to −184	−187 to −185	−184 to −182

*Numbers refer to Remarks and Observations, p 35.

Table 9
PUF Roofing–Physical Properties for Initial and Aged Characteristics

Fort Knox

Property[3]*		Test Method		Age-Months 0	24
Density, lb/cu ft		ASTM D 1622	Average	3.11	3.65
			Range	2.92 to 3.40	3.42 to 3.97
Compressive strength, lb/sq in.		ASTM D 1621	Average	62	96
			Range	51 to 76	89 to 106
Indentation strength, lb/sq in.	Yield	USBR	Average	78	136
			Range	62 to 89	134 to 138
	Coating break		Average	84	144
			Range	81 to 105	132 to 155
Impact strength, grams		USBR	Average	370	280
			Range	328 to 418	230 to 330
Tensile interlaminar[4]* strength, lb/sq in.		USBR	Average	64	90
			Range	50 to 93	67 to 114
Water absorption,[5]* g/m^2 surface area		ASTM D 2842	Average	30	36
			Range	27 to 33	32 to 40
Coating vapor[6]* transmission, perms		ASTM E 96 Procedure B	Average	2.4	1.8
			Range	2.4 to 2.4	1.6 to 2.0
Coating adhesion,[7]* lb/sq in.		NCEL	Average	198	156
			Range	169 to 232	130 to 181
Coating glass[8]* transition, °F		ASTM D 3418	Average	−189	−184
			Range	−190 to −188	−185 to −183

*Numbers refer to Remarks and Observations, p 35.

Table 10
PUF Roofing–Physical Properties for Initial and Aged Characteristics

Fort Lewis

Property[3]*		Test Method		Age-Months 0	12	18	24
Density, lb/cu ft		ASTM D 1622	Average	3.07	3.05	3.05	2.94
			Range	2.89 to 3.31	2.89 to 3.30	2.93 to 3.31	2.73 to 3.23
Compressive strength, lb/sq in.		ASTM D 1621	Average	39	40	50	38
			Range	35 to 41	38 to 43	45 to 54	36 to 48
Indentation strength, lb/sq in.	Yield	USBR	Average	65	60	80	65
			Range	54 to 75	56 to 65	72 to 83	58 to 73
	Coating break		Average	No break at	103	130	100
			Range	½-in. deflection	90 to 117	116 to 142	98 to 120
Impact strength, grams	Top	USBR	Average	140	No separate break visible		
			Range	120 to 192			
	Base		Average	650	323	320	335
			Range	623 to 675	140 to 460	235 to 435	270 to 400
Tensile interlaminar[4]* strength, lb/sq in.		USBR	Average	55	72	81	81
			Range	42 to 64	48 to 87	76 to 87	78 to 83
Water absorption,[5]* g/m² surface area		ASTM D 2842	Average	49	36	47	44
			Range	45 to 54	30 to 43	41 to 52	41 to 46
Coating vapor[6]* transmission, perms		ASTM E 96 Procedure B	Average	1.6	6*	6*	1.3
			Range	0.8 to 2.4			1.1 to 1.5
Coating adhesion,[7]* lb/sq in.		NCEL	Average	174	190	150	168
			Range	157 to 192	170 to 209	132 to 166	150 to 186
Coating glass[8]* transition, °F	Top coat	ASTM D 3418	Average	+51	+55	+57	+61
			Range	50 to 52	53 to 57	55 to 59	58 to 63
	Base coat		Average	−67	−64	−68	Unable to
			Range	−69 to −65	−65 to −63	−69 to −66	obtain specimen

*Numbers refer to Remarks and Observations, p 35.

Table 11
Initial Properties of BUR Materials

Property	Test Method	ASTM Spec. Requirements		Location: Fort Benning	Location: Fort Lewis
Assembly characteristics	ASTM D 3617-77				
Average number of plies				4.2	3.2
Membrane mass, lb/100 sq ft				173.	251.
Asphalt mass, lb/100 sq ft				123.	211.
Lap spacing, average				7.5	11.0
Roof surfacing characteristics	ASTM D 1863-77				
Hardness, percent loss after tumbling		Max 20		9.	N/A
Unit weight, lb/cu ft		Min 60		97.8	N/A
Gradation, percent passing 3/4 in.		100		100.0	N/A
1/2 in.		90 to 100		82.8	N/A
3/8 in.		40 to 70		25.2	N/A
No. 4		0 to 15		0.6	N/A
No. 8		0 to 5		0.3	N/A
Roofing felt characteristics	ASTM D 226-77 at Benning, ASTM D 2178-76 at Lewis	Benning	Lewis		
Breaking strength, lb/in. width with fiber		Min 30	Min 15	8.4	35.6
across fiber		Min 15	Min 15	8.0	29.0
Pliability at 77°F, (1/2-in. radius)				Pass	Pass
Openness of perforations, percent		Min 30		100	N/A
Loss on heating at 105°C, 5 hours, percent		Max 4		6.0	N/A
Weight, lb/100 sq ft		Min 13	Min 6.7	11.9	12.2
Holes/sq ft		Min 115		144.	N/A
Asphalt characteristics	ASTM D 312-78				
Flash point (COC), °F		Min 437		585.	580.
Softening point, °F		185 to 205		195.	194.
Penetration at 77°F		15 to 35		17.	13.
Penetration at 115°F		Max 90		32.	31.
Solubility in TCE, %		Min 99		99.8	99.8
Ductility at 77°F, cm		Min 2.5		4.	4.

Note: See Remark No. 10, p 35.

Table 12
Roof Surface Temperatures

Date	Time	Min.	Max.	Avg.	Dev.	90% Confidence Interval
Fort Lewis						
8-11-81	0000					
	PUF	55.0	65.0	59.0	2.6	(57.4, 60.6)
	BUR	59.0	65.0	62.1	2.5	(60.5, 63.7)
	EPDM	56.0	62.0	59.3	1.8	(58.2, 60.4)
	1200					
	PUF	139.0	160.0	151.1	7.2	(146.7, 155.5)
	BUR	128 0	167.0	146.0	11.8	(138.4, 153.6)
	EPDM	141.0	160.0	154.2	6.7	(150.1, 158.3)
9-11-81	0000					
	PUF	40.0	49.0	44.0	2.4	(42.6, 45.4)
	BUR	40.0	48.0	43.9	2.8	(42.1, 45.7)
	EPDM	39.0	45.0	43.2	1.9	(42.1, 44.3)
	1200					
	PUF	112.0	133.0	125.1	7.2	(120.8, 129.4)
	BUR	99.0	145.0	121.6	13.3	(113.0, 130.2)
	EPDM	110.0	136.0	128.5	6.7	(124.5, 132.5)
11-29-81	0000					
	PUF	30.0	42.0	37.9	5.0	(34.9, 40.9)
	BUR	41.0	43.0	42.0	.5	(41.7, 42.3)
	EPDM	41.0	41.0	41.0	.0	(41.0, 41.0)
	1200					
	PUF	49.0	62.0	57.8	4.2	(55.3, 60.3)
	BUR	48.0	60.0	53.2	3.5	(51.0, 55.3)
	EPDM	56.0	60.0	58.2	1.7	(57.2, 59.2)
4-25-82	0000					
	PUF	28.0	35.0	31.0	2.2	(29.8, 32.4)
	BUR	28.0	34.0	31.4	2.3	(30.0, 32.9)
	EPDM	25.0	34.0	30.1	2.3	(28.7, 31.5)
	1200					
	PUF	78.0	94.0	88.0	4.8	(85.1, 90.9)
	BUR	73.0	99.0	85.7	7.4	(80.9, 90.4)
	EPDM	78.0	95.0	89.7	4.5	(87.0, 92.4)
Fort Benning						
9-03-81	0000					
	BUR	70.0	79.0	73.9	3.0	(71.7, 76.0)
	EPDM	70.0	74.0	71.9	1.2	(71.2, 72.5)
	1200					
	BUR	88.0	108.0	100.9	6.3	(96.4, 105.4)
	EPDM	108.0	194.0	173.5	21.1	(163.2, 183.8)
10-23-81	0000					
	BUR	59.0	64.0	60.9	2.2	(59.3, 62.5)
	EPDM	56.0	60.0	57.6	1.0	(57.1, 58.2)
	1200					
	BUR	66.0	69.0	67.8	1.0	(67.1, 68.4)
	EPDM	71.0	84 0	78.3	3.7	(76.5, 80.1)

Table 12 (Cont'd)

Date	Time	Min.	Max.	Avg.	Dev.	90% Confidence Interval
1-10-82	0000					
	BUR	40.0	47.0	44.1	2.6	(42.2, 46.0)
	EPDM	34.0	46.0	39.3	3.7	(37.5, 41.1)
	1200					
	BUR	25 0	41.0	34.0	5.7	(29.9, 38.1)
	EPDM	30.0	89.0	66.9	17.1	(58.5, 75.2)

REMARKS AND OBSERVATIONS FOR TABLES 4 THROUGH 10*

1. The 14-day 100 percent relative humidity dimensional stability results at Fort Lewis are generally lower than might be expected. While some consolidation could have occurred during the process of stabilizing after such large expansion, the magnitude of difference suggests some relative humidity drop during the 7- to 14-day interval.
2. No significant change (visual) in EPDM rubber or polyurethane foam specimens has occurred during outdoor exposure at Denver or xenon arc accelerated aging. Outdoor exposure was started in August 1980 and now has an age of 32 months. Xenon arc exposure was started March 1981 and now has an age of 4024 hours.
3. Fort Benning and Fort Knox aged foam samples differ from the original, but Fort Lewis samples do not. If the original samples had been cut out of the roof instead of being sprayed into boxes, one possible reason for this difference could be eliminated.
4. The interlaminar bond strength of the Fort Benning foam is declining. These data may be of value in determining the cause of blisters if they are observed during future inspections.
5. The foam water absorption tests were conducted according to ASTM D 2842. However, under a separate program, it is intended to rerun this test using a modified procedure. Investigators hope to eliminate some of the difficulties encountered and obtain less change in dimension of specimens during water immersion by testing at less than atmospheric pressure and reducing the exposure time.
6. High water vapor transmission test results (perms) were obtained for these samples: Fort Benning–24 months, 5.7; Fort Lewis–12 months, 5.5; 18 months, 6.4. This may have resulted from holes caused by mineral granules puncturing the coating or voids left when granules were dislodged. It could also have happened either during normal roof service or during removal and shipping of samples. Observations of the samples tend to confirm this possibility. However, to be sure that no error was introduced during testing, these tests were rerun and indicated high values, although with a few lower individual results in the 3 to 5 perm range.
7. The U.S. Navy Civil Engineering Laboratory test method was used for coating adhesion, since no other standard was available and no other such data are known to be published. Values in the table reflect the adhesion strength fairly well for purposes of categorization. However, the test is operator-sensitive in terms of sample preparation and test execution.
8. The glass transition temperature appears stable for all materials, except for the Hypalon topcoat at Fort Lewis. The gradual upward shift compares with observations of early deterioration in Hypalon performance on USBR roofs.
9. No significant change, or even trend toward change, in the EPDM rubber can be established except for the shift between the original and the first 6 months of age.
10. For asphalt, the composition complexity produces an equally complex pattern of softening over a broad temperature range. This includes the beginning of thermal motion at −45°F and continues through the highest observed melting point of 135°F. Two distinct glass transition temperatures have been identified: one at −27°F and the other at 41°F. An endothermic peak (melt) regularly occurred at 57°F, and two additional peaks were found, one in the 81°F to 110°F region, and the other in the 102°F to 135°F region. Results of a large number of tests using different techniques on the differential scanning calorimeter indicate that the two resins involved at the higher temperatures are highly sensitive to their thermal history and may be more prone to interact with other elements of their compound environment. Nevertheless, no distinguishable shift has occurred during the 24-month aging.

*Remarks and observations were provided by the U.S. Bureau of Reclamation.

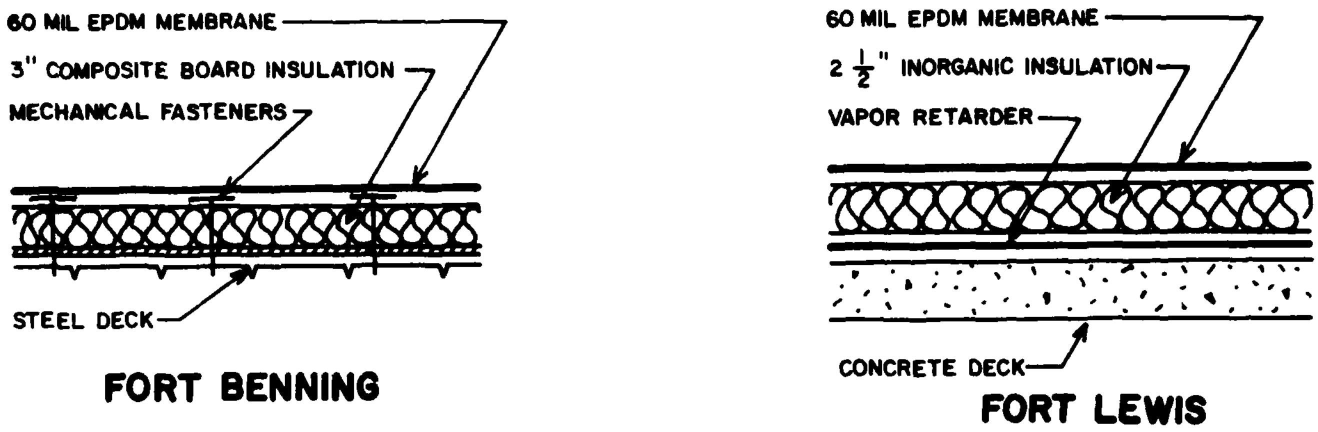


Figure 1. EPDM roofs, cross sections.

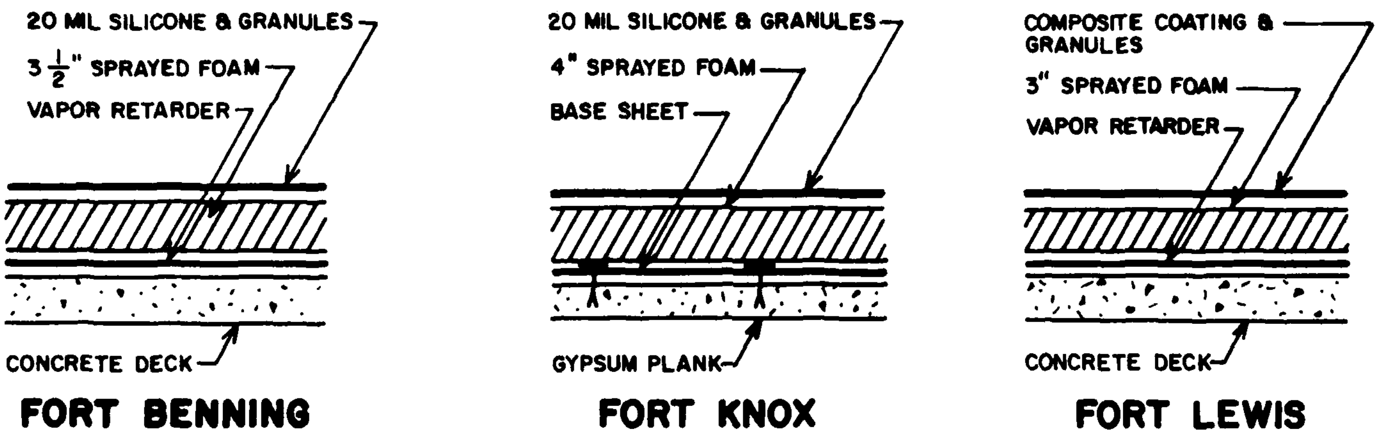


Figure 2. PUF roofs, cross sections.

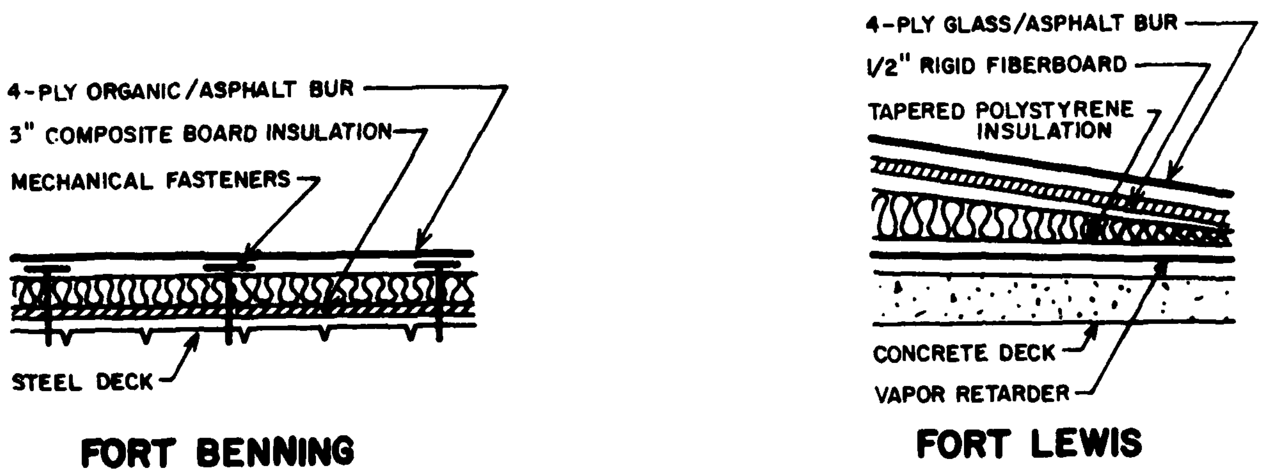


Figure 3. BUR roofs, cross sections.

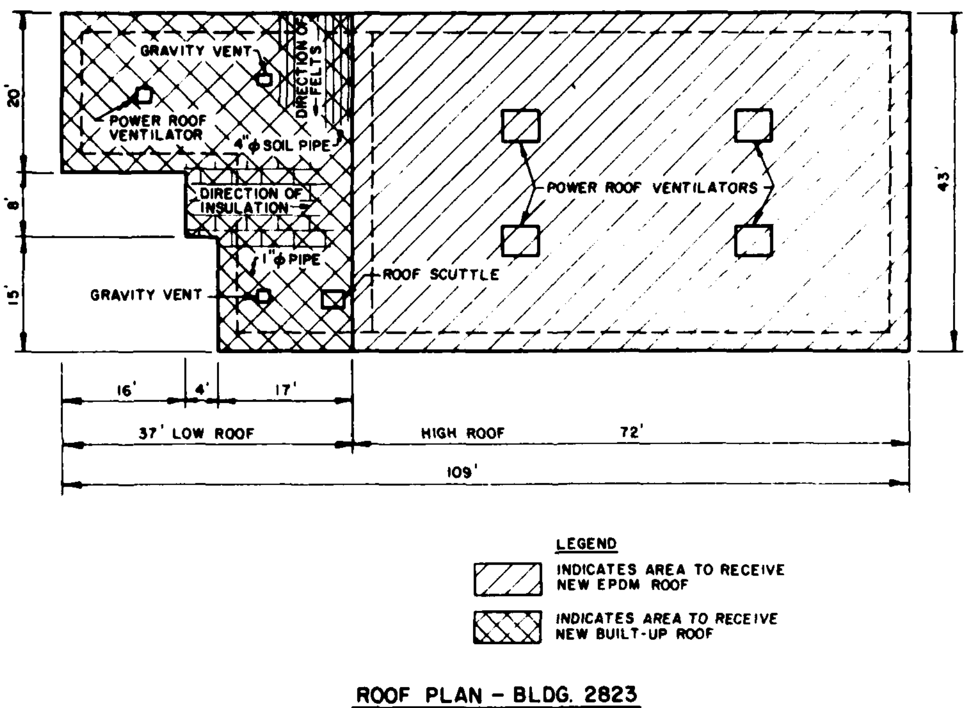


Figure 4. Building selected for EPDM and BUR at Fort Benning.

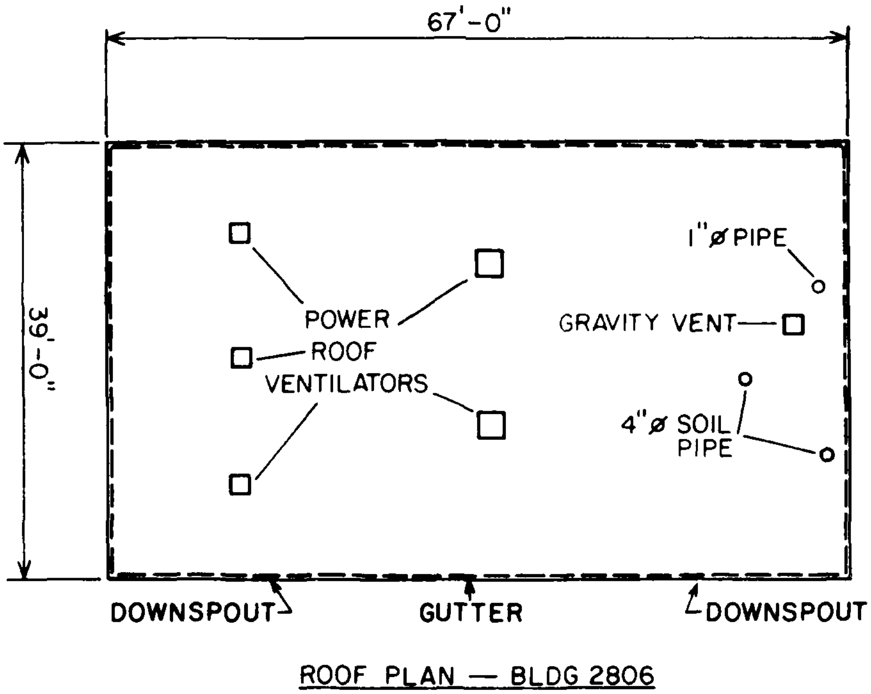
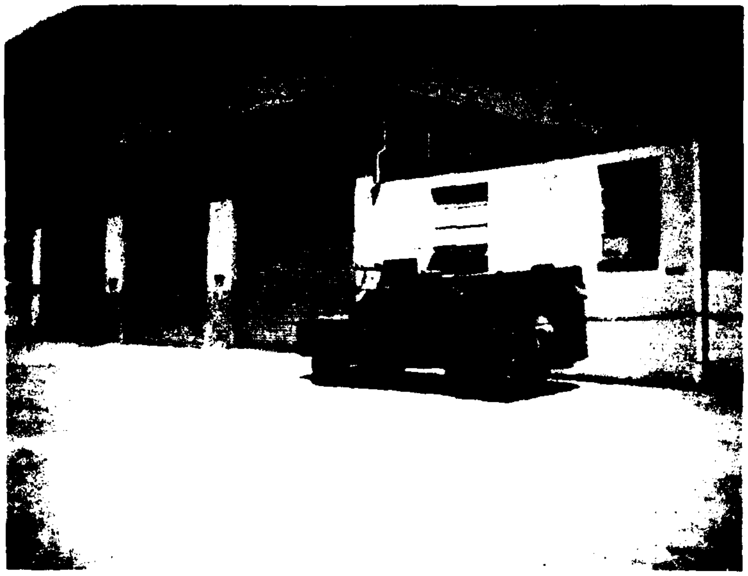


Figure 5. Building selected for PUF roofing at Fort Benning.



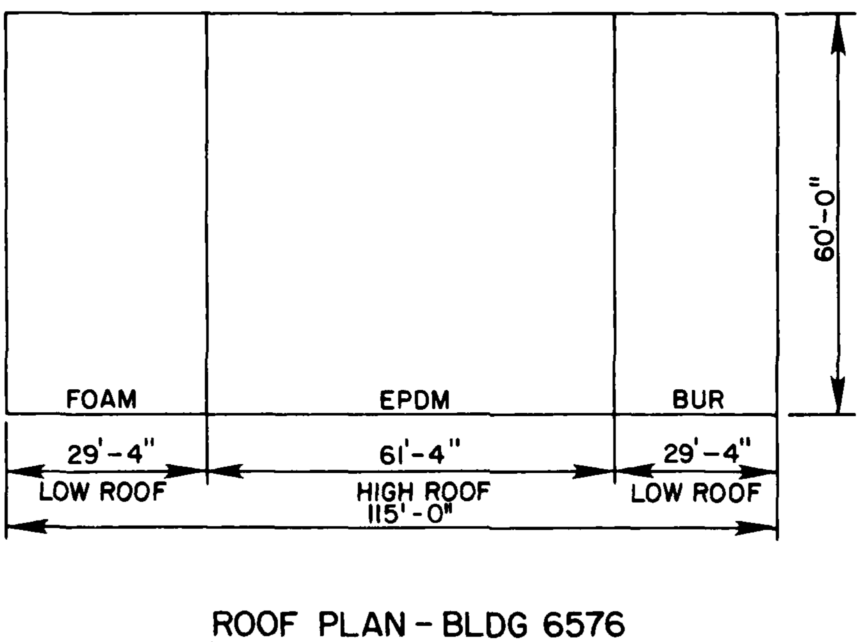


Figure 6. Building selected for PUF roofing at Fort Knox.

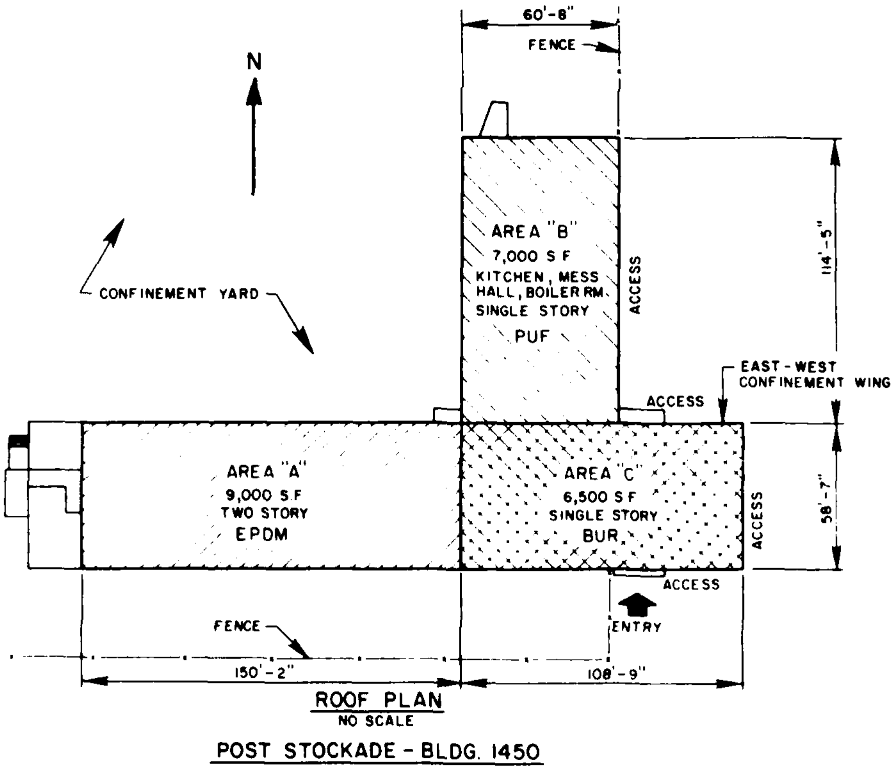


Figure 7. Building selected for EPDM, BUR, and PUF at Fort Lewis.

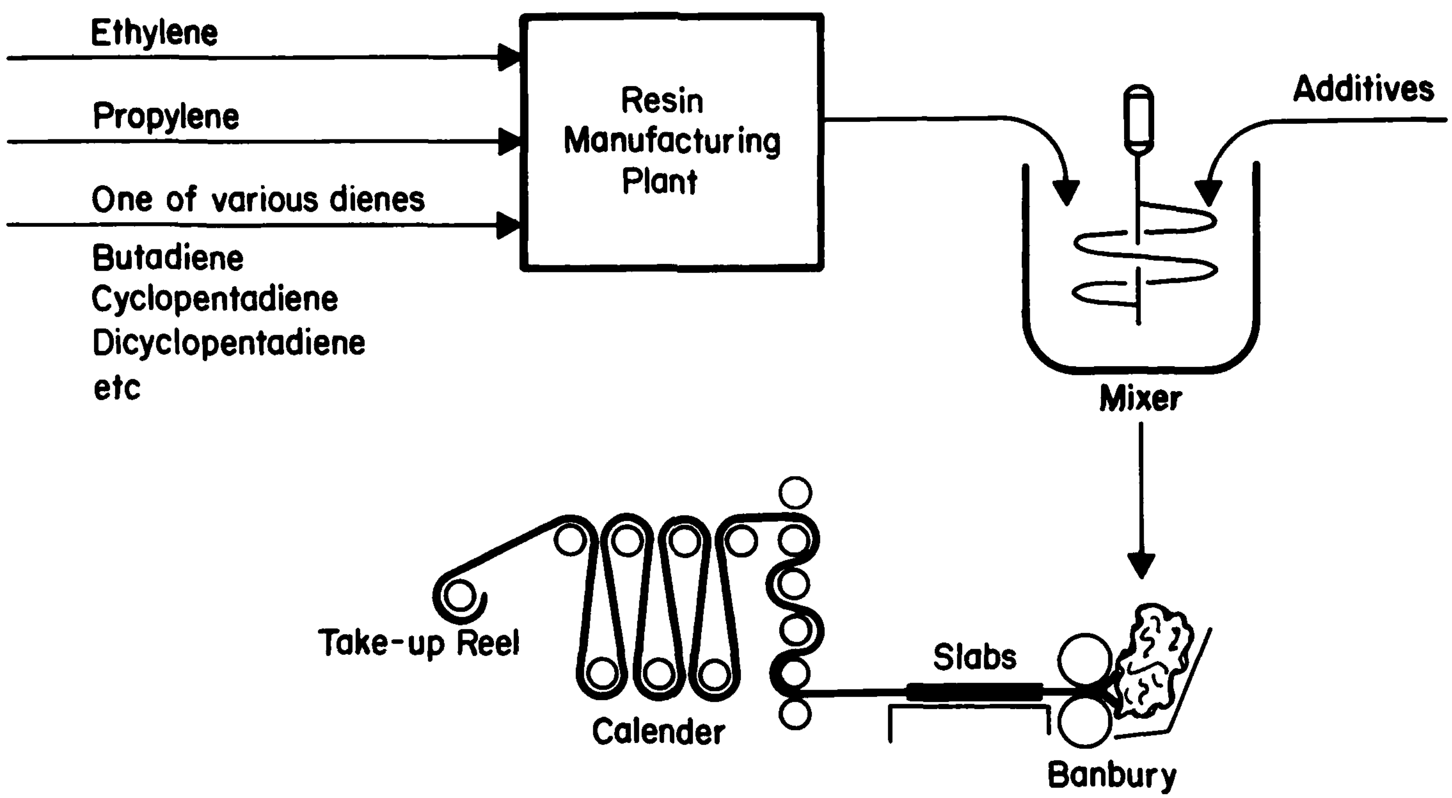


Figure 8. EPDM manufacture.

Figure 9. Typical group of EPDM sample patches.

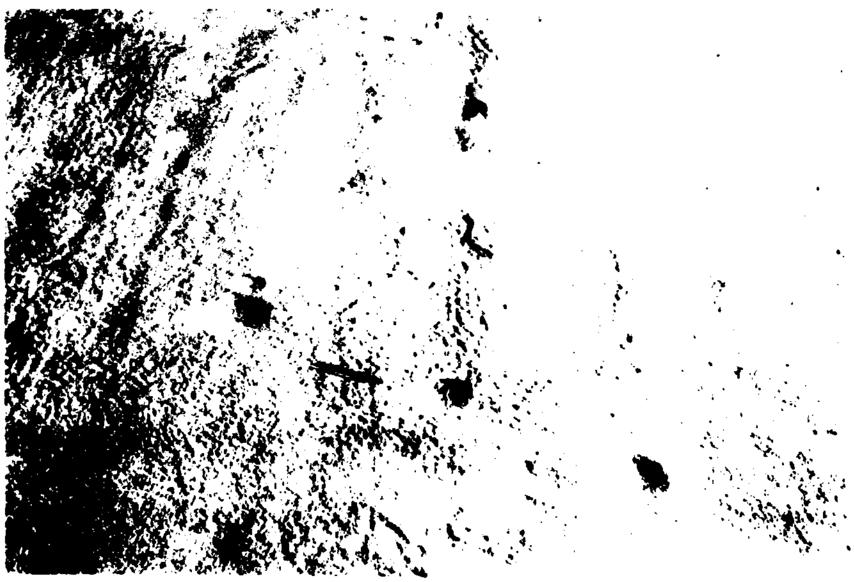


Figure 10. Interlaminar blisters in foam at Fort Knox.

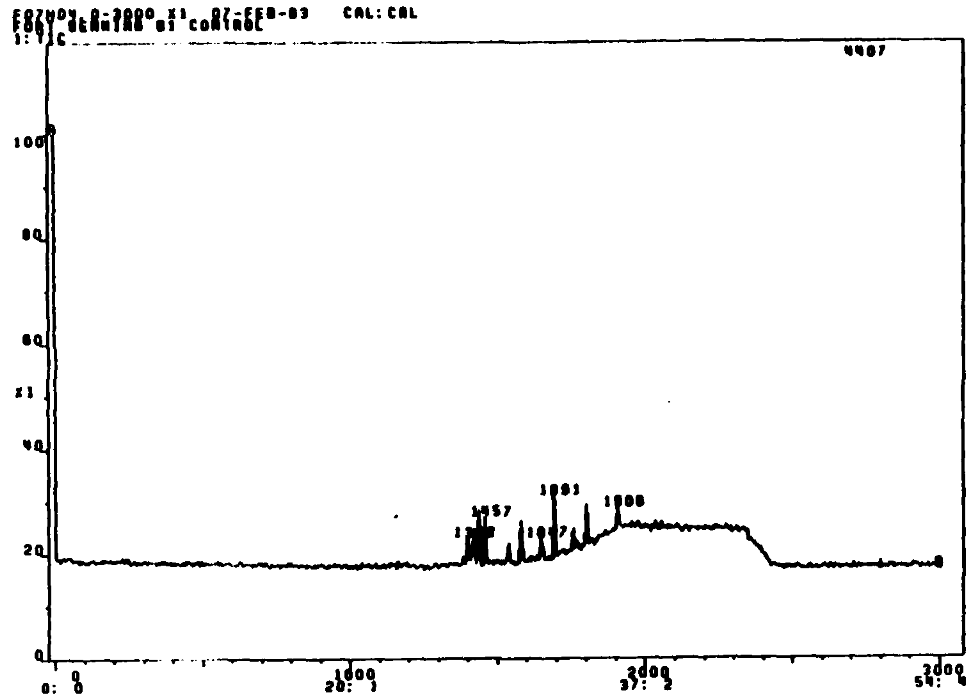


Figure 11. Fort Benning control fraction I.

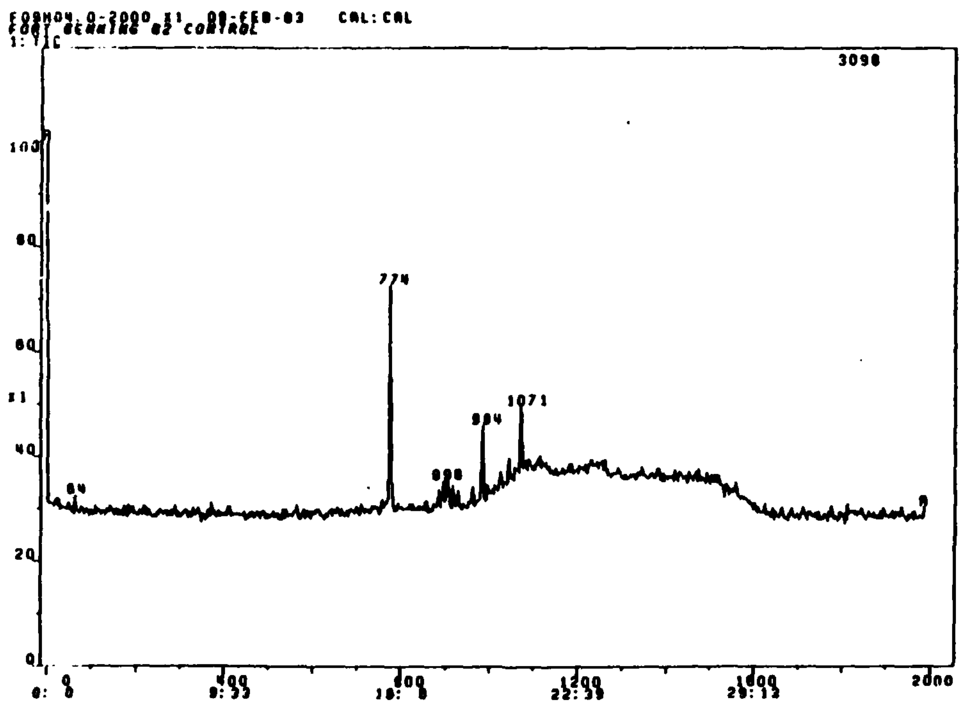


Figure 12. Fort Benning control fraction II.

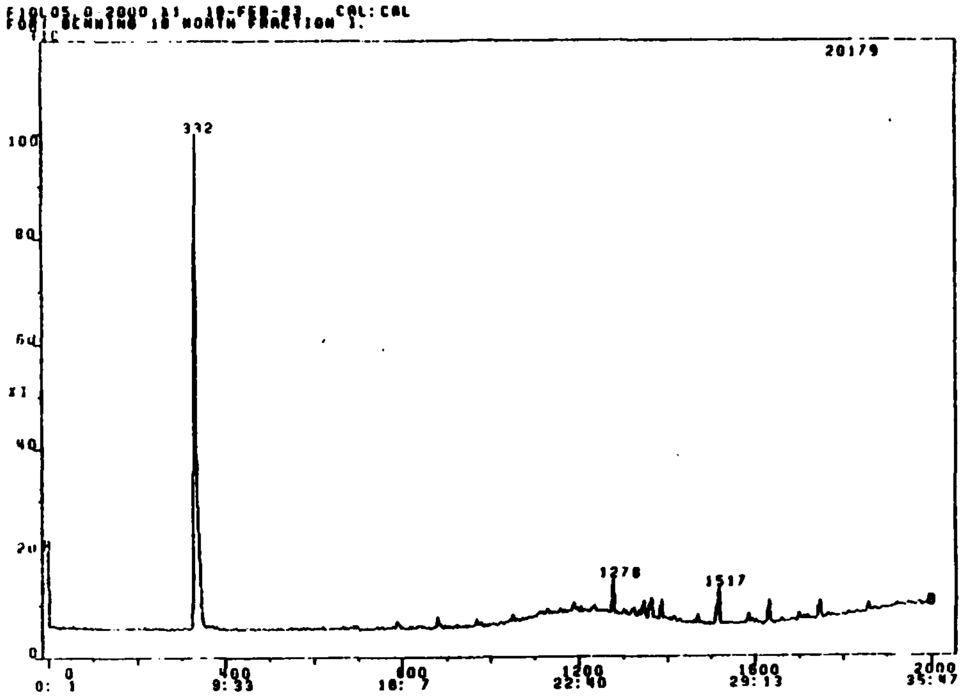


Figure 13. Fort Benning 18-month fraction I.

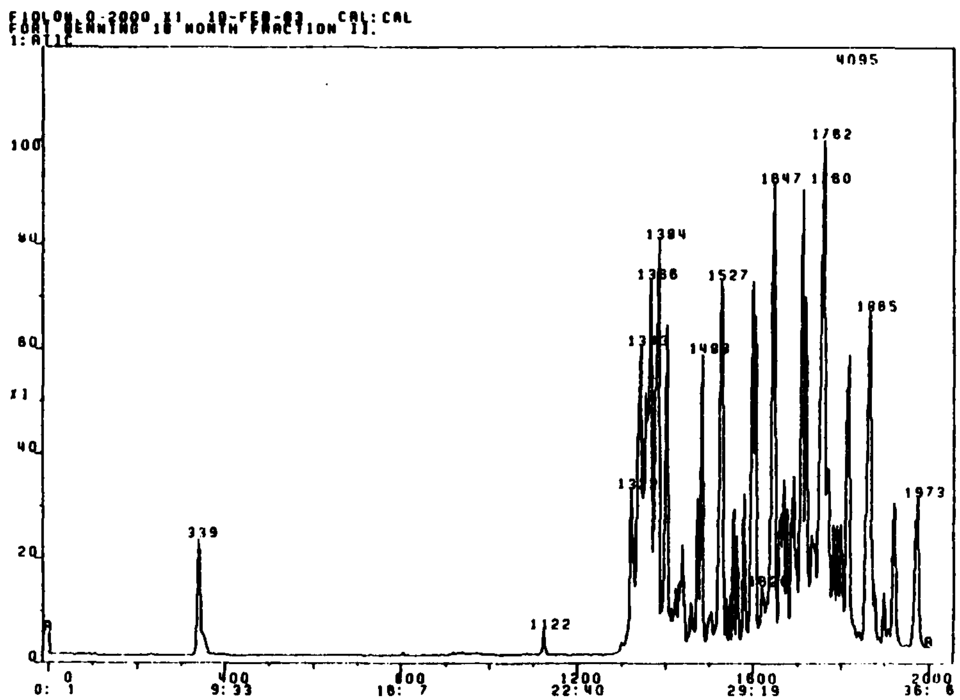


Figure 14. Fort Benning 18-month fraction II.

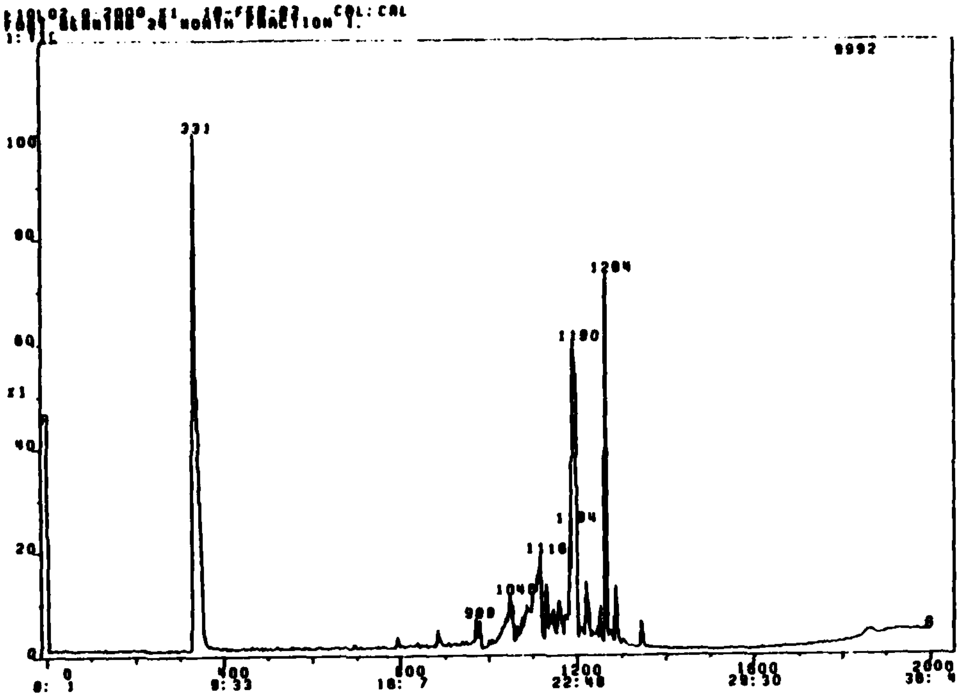


Figure 15. Fort Benning 24-month fraction I.

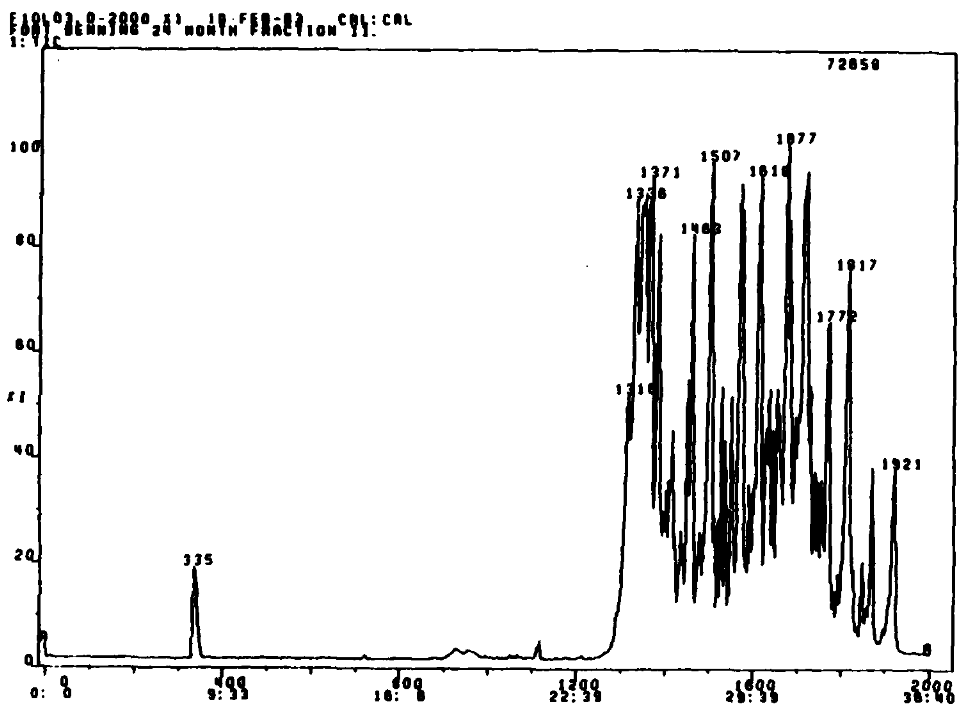


Figure 16. Fort Benning 24-month fraction II.

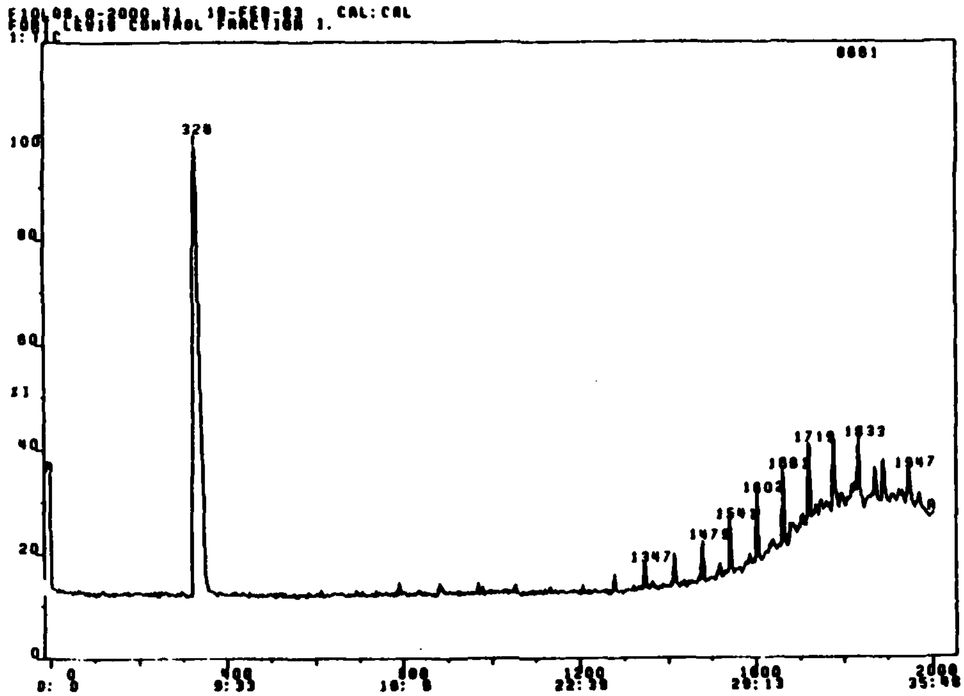


Figure 17. Fort Lewis control fraction I.

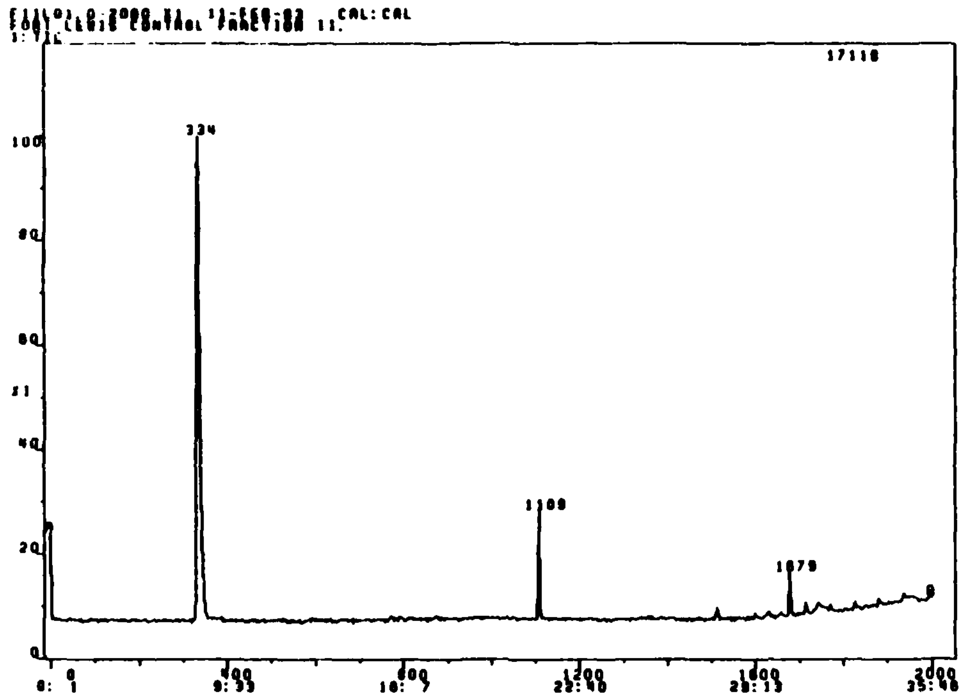


Figure 18. Fort Lewis control fraction II.

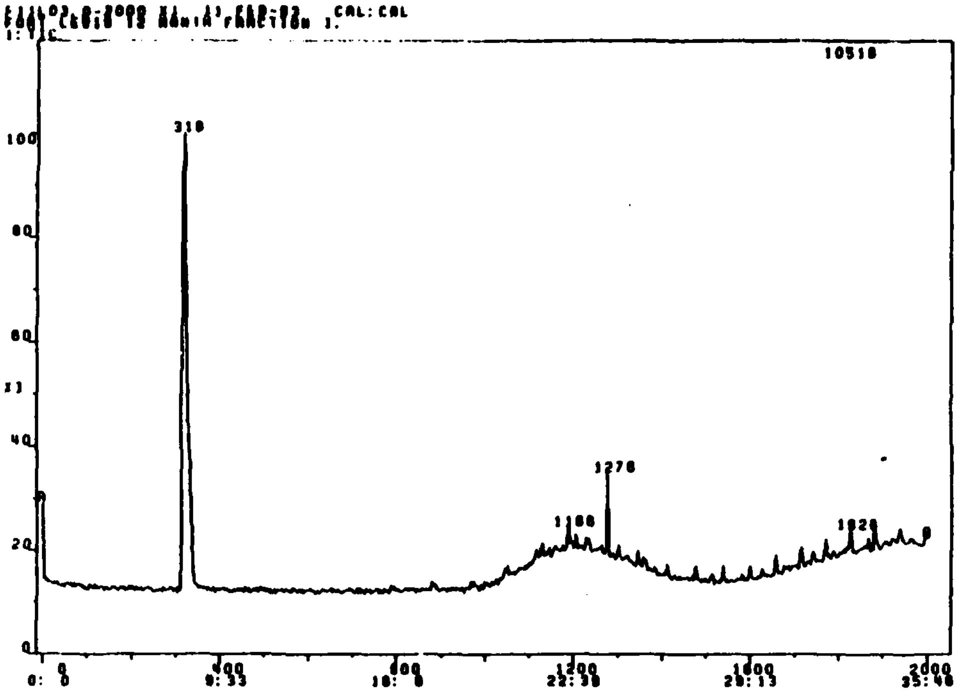


Figure 19. Fort Lewis 12-month fraction I.

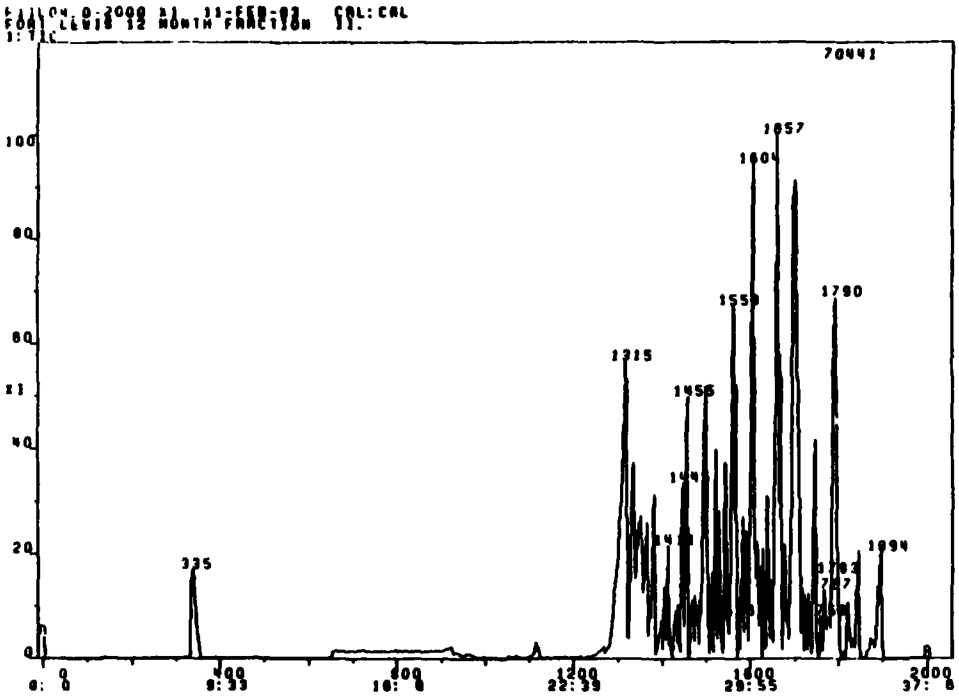


Figure 20. Fort Lewis 12-month fraction II.

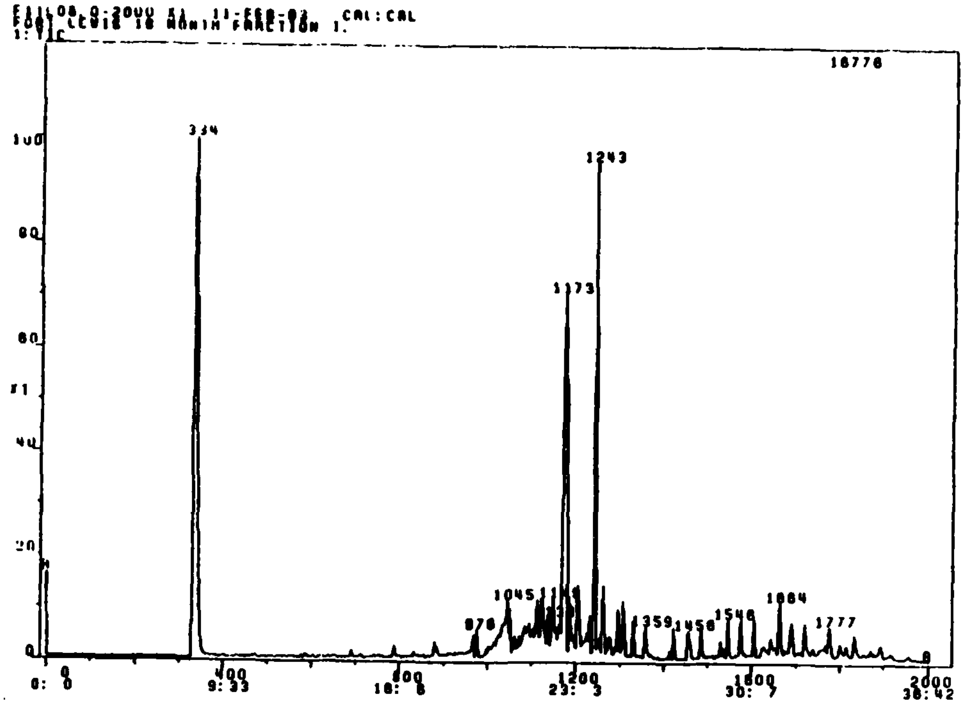


Figure 21. Fort Lewis 18-month fraction I.

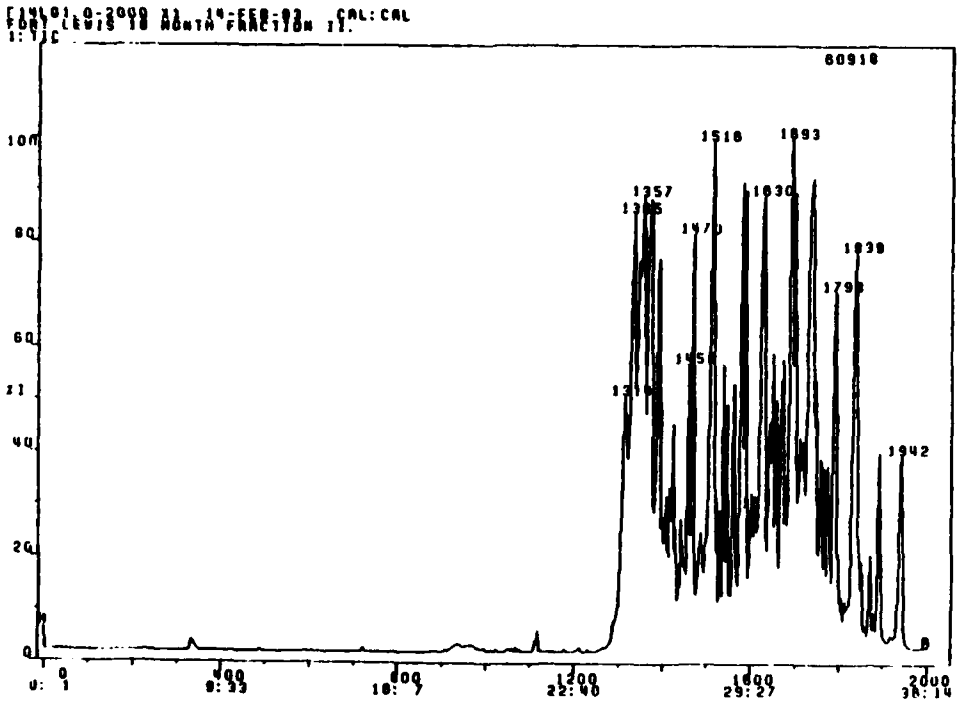


Figure 22. Fort Lewis 18-month fraction II.

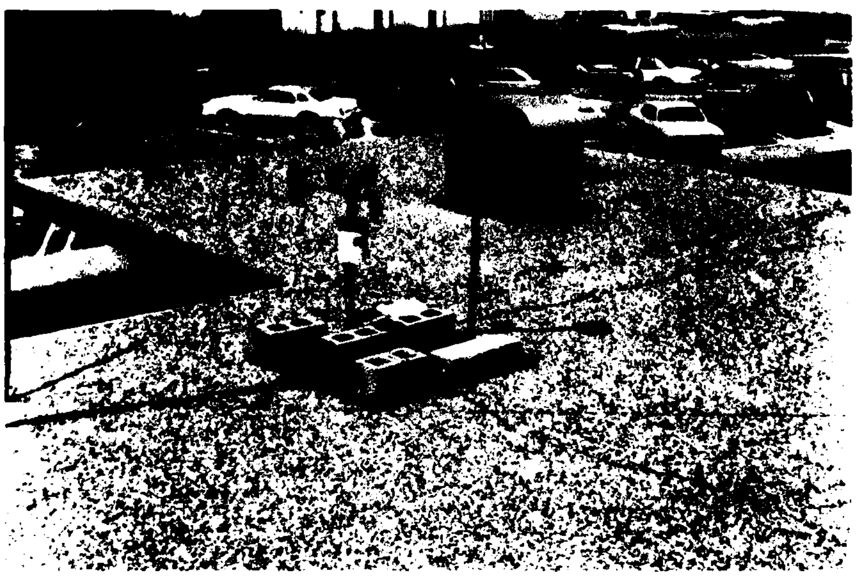


Figure 23. Weather station at Fort Benning.

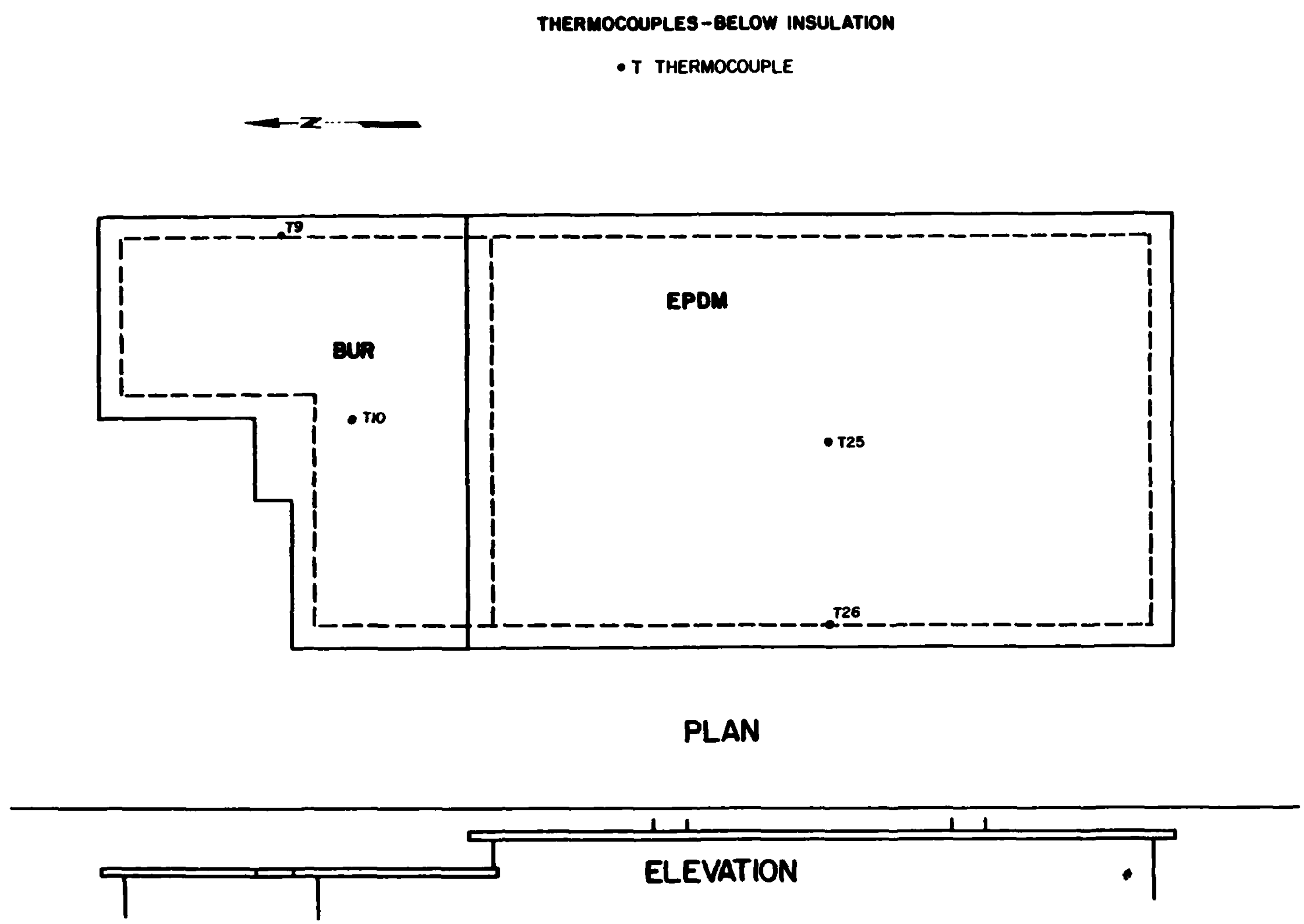


Figure 24. Thermocouples below insulation–building 2823, Fort Benning.

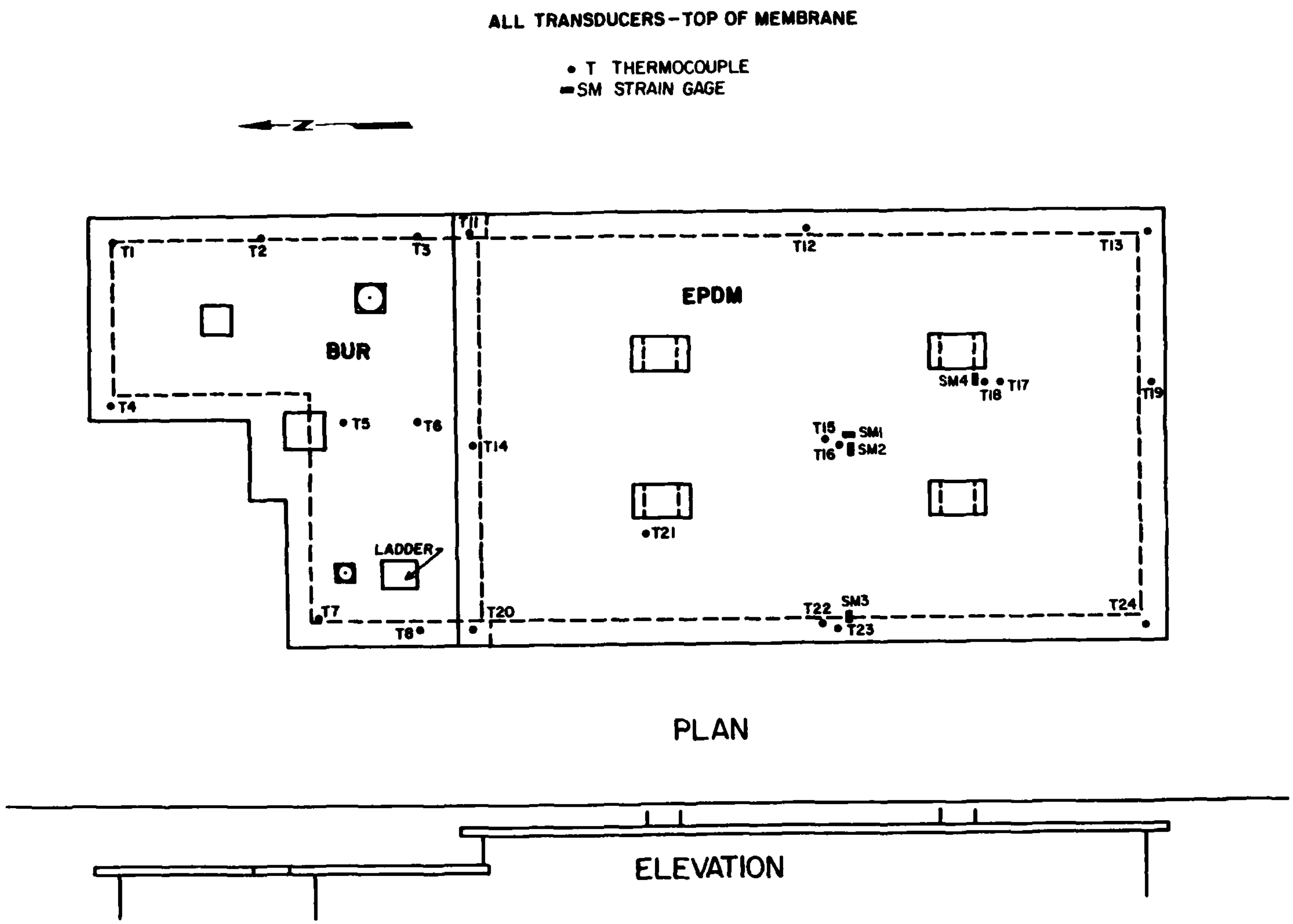


Figure 25. Thermocouples and strain gages on top of membranes–building 2823, Fort Benning.

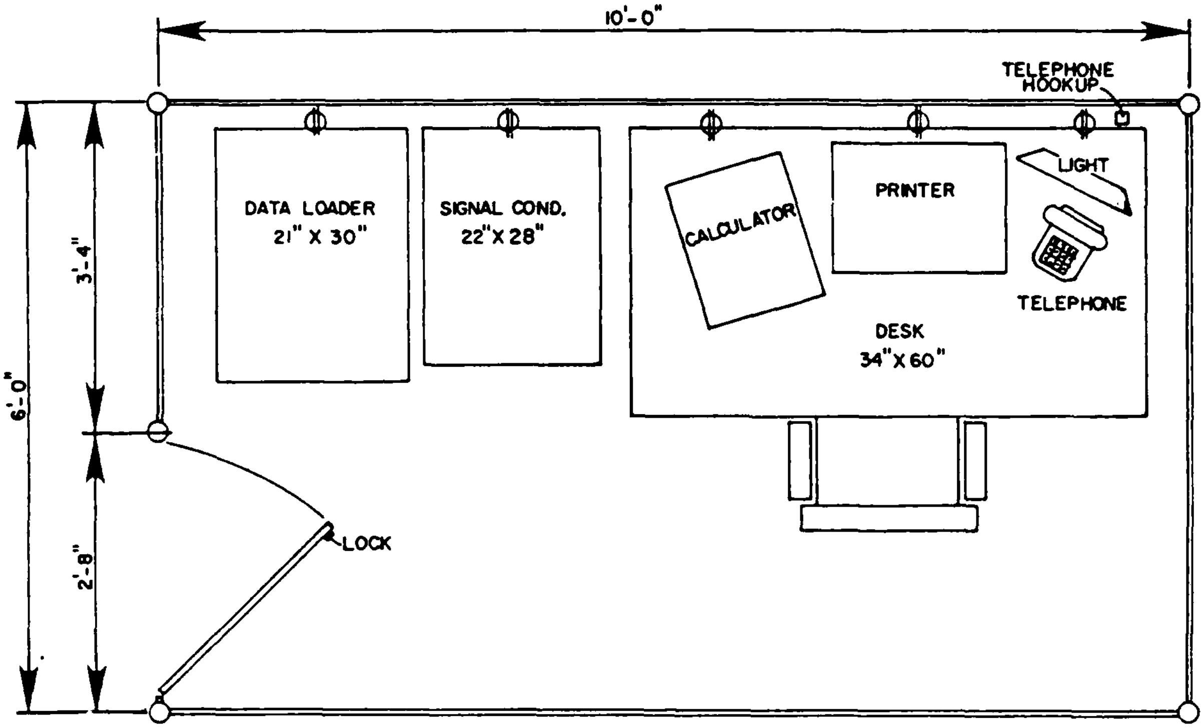


Figure 26. Data recording equipment room layout–Fort Benning.

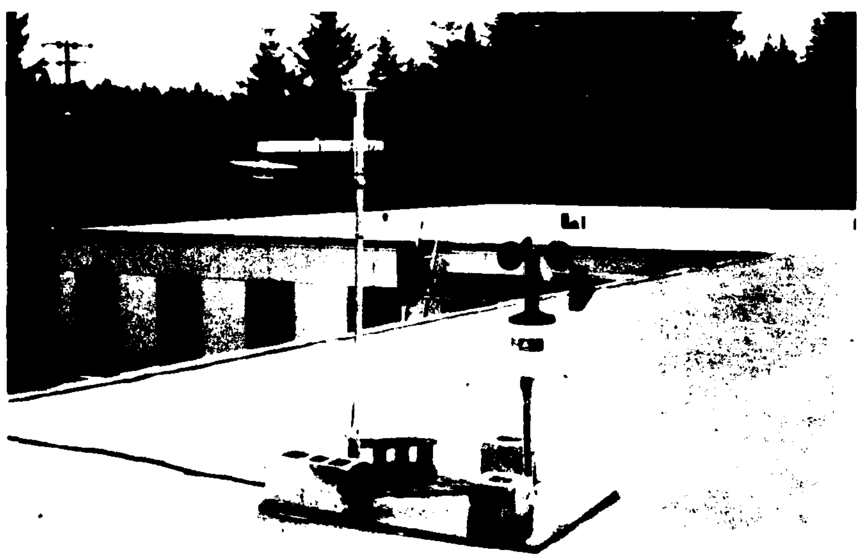


Figure 27. Weather station at Fort Lewis.

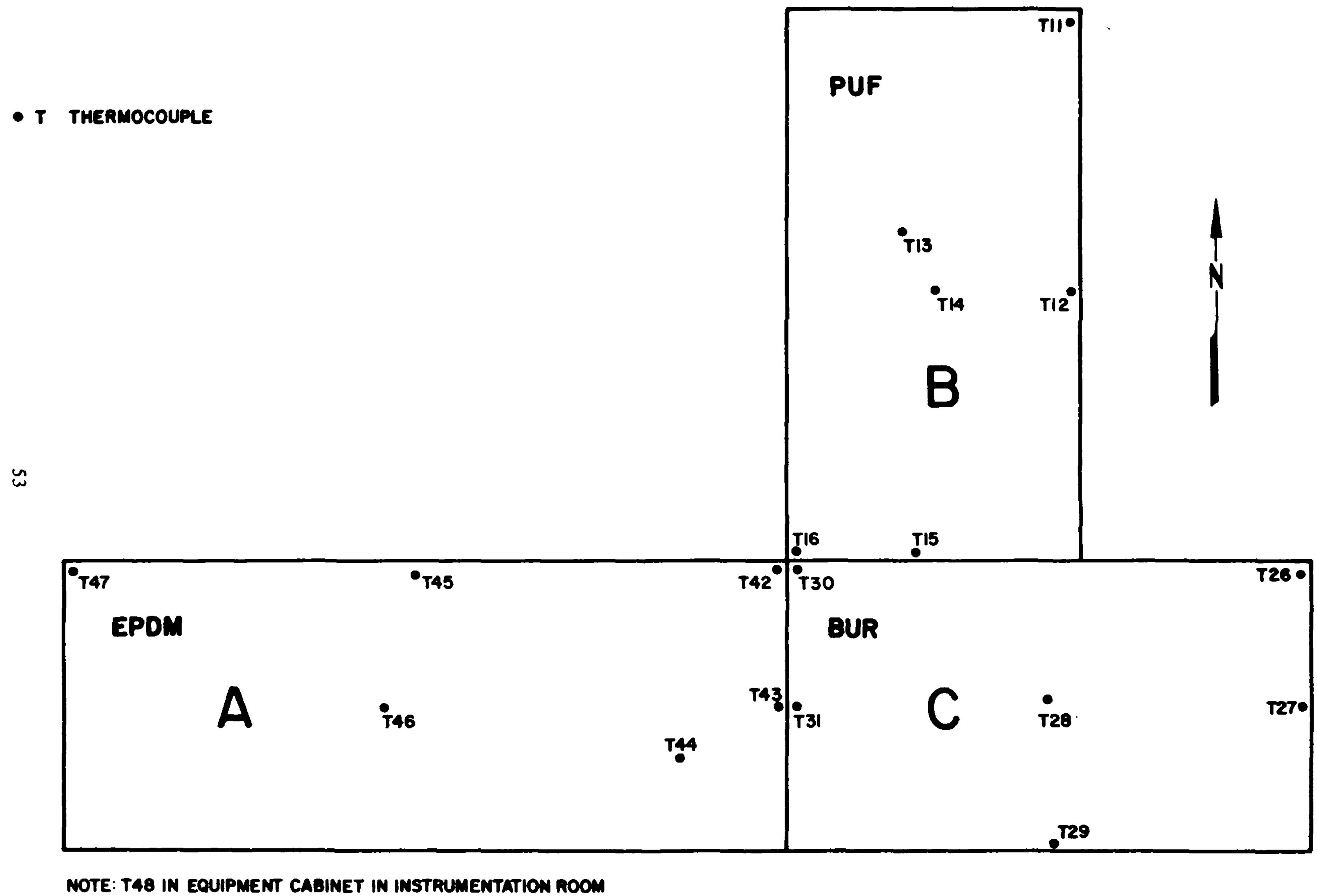


Figure 28. Thermocouples below insulation–building 1450, Fort Lewis.

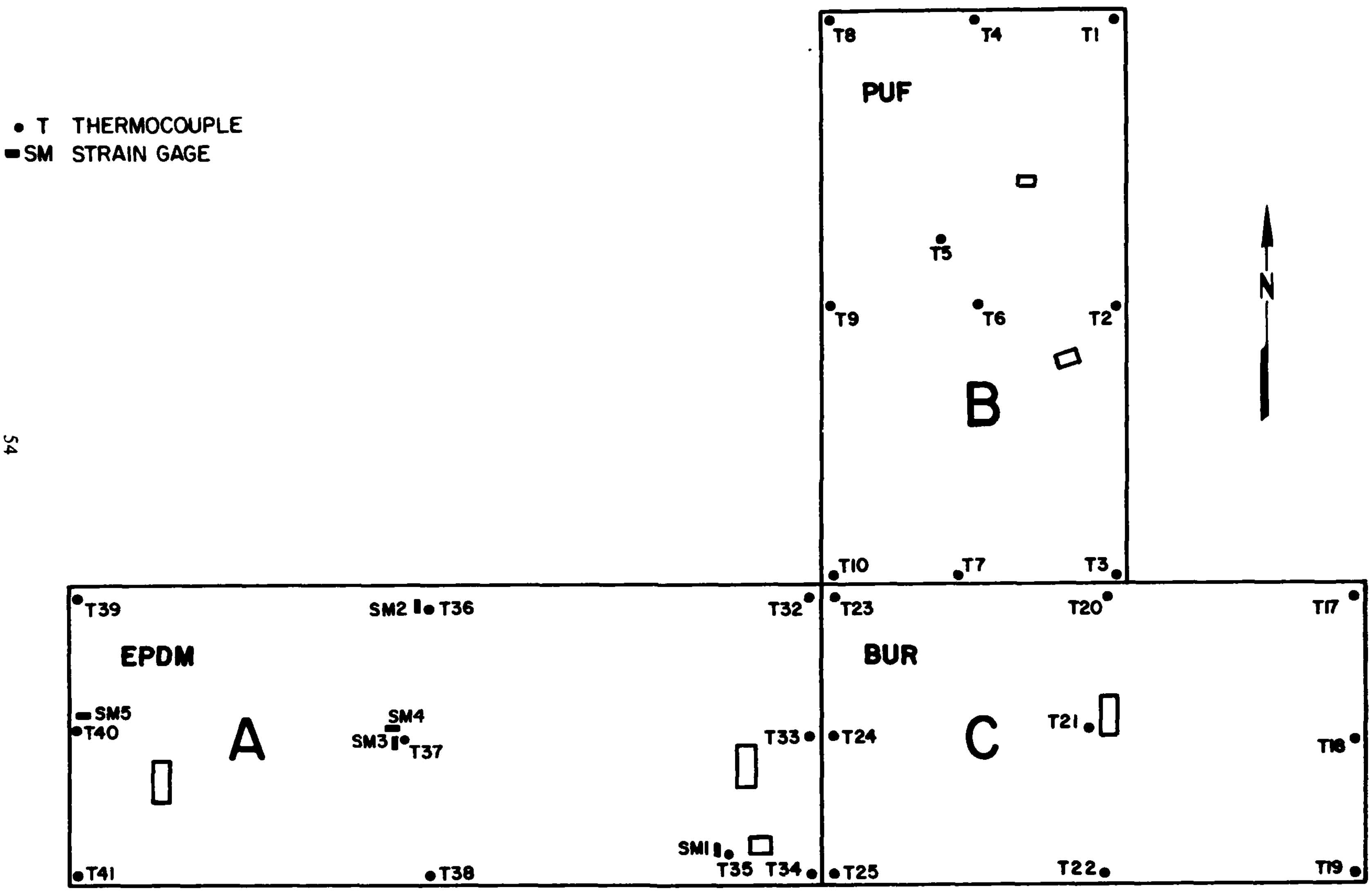


Figure 29. Thermocouples and strain gages on top of membranes–building 1450, Fort Lewis.

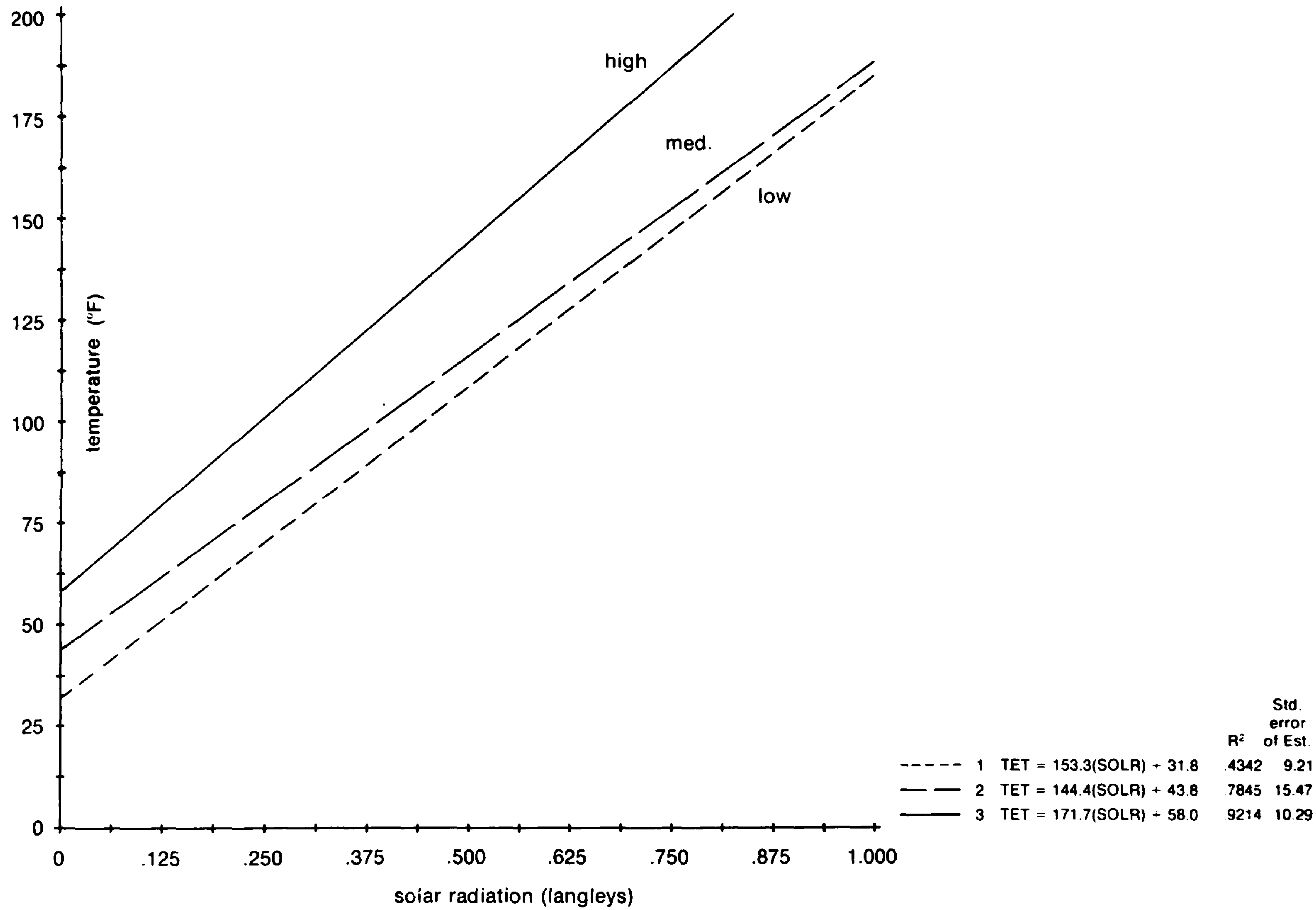


Figure 30. EPDM temperature vs. solar radiation—Fort Lewis.

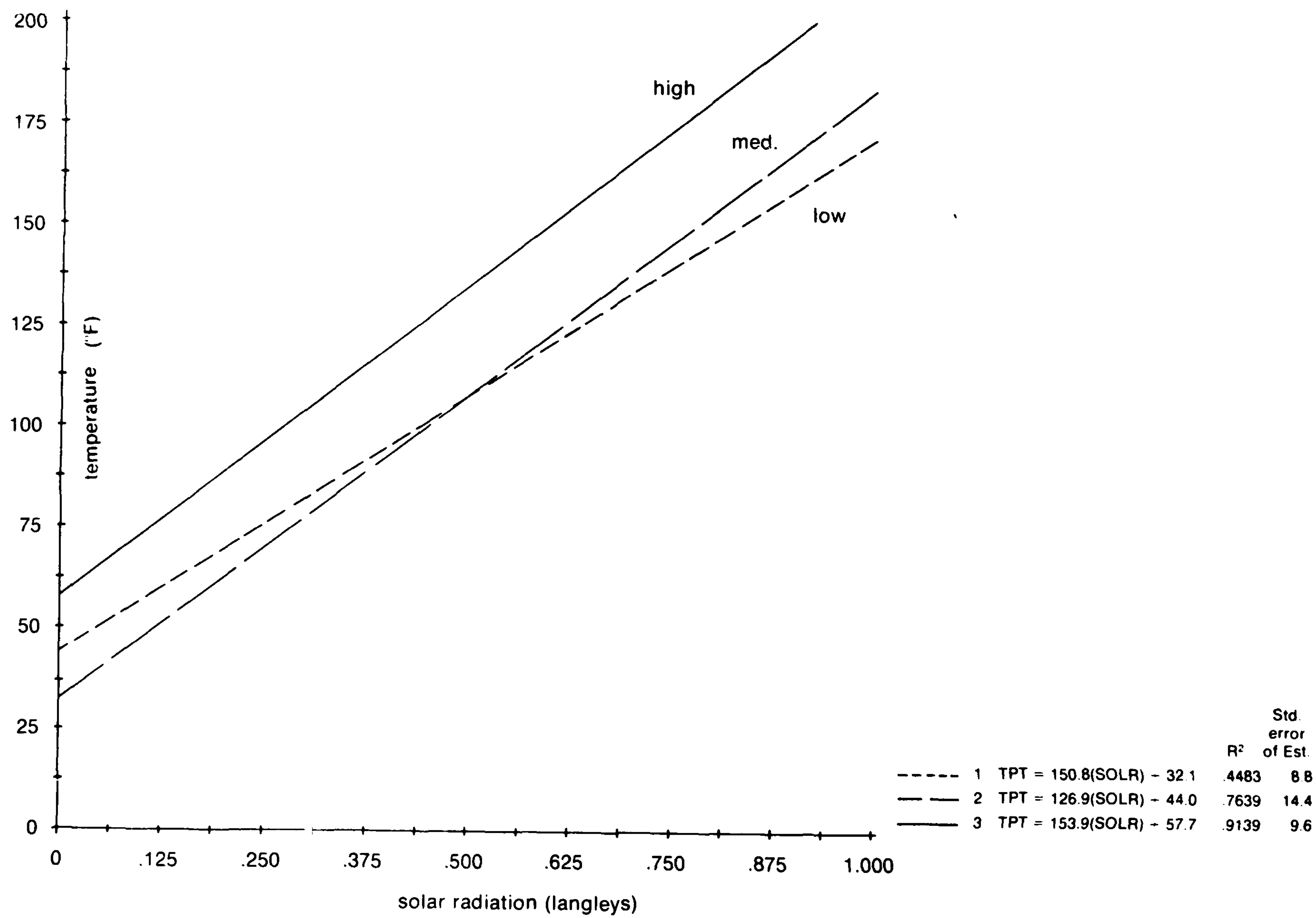


Figure 31. PUF temperature vs. solar radiation—Fort Lewis.

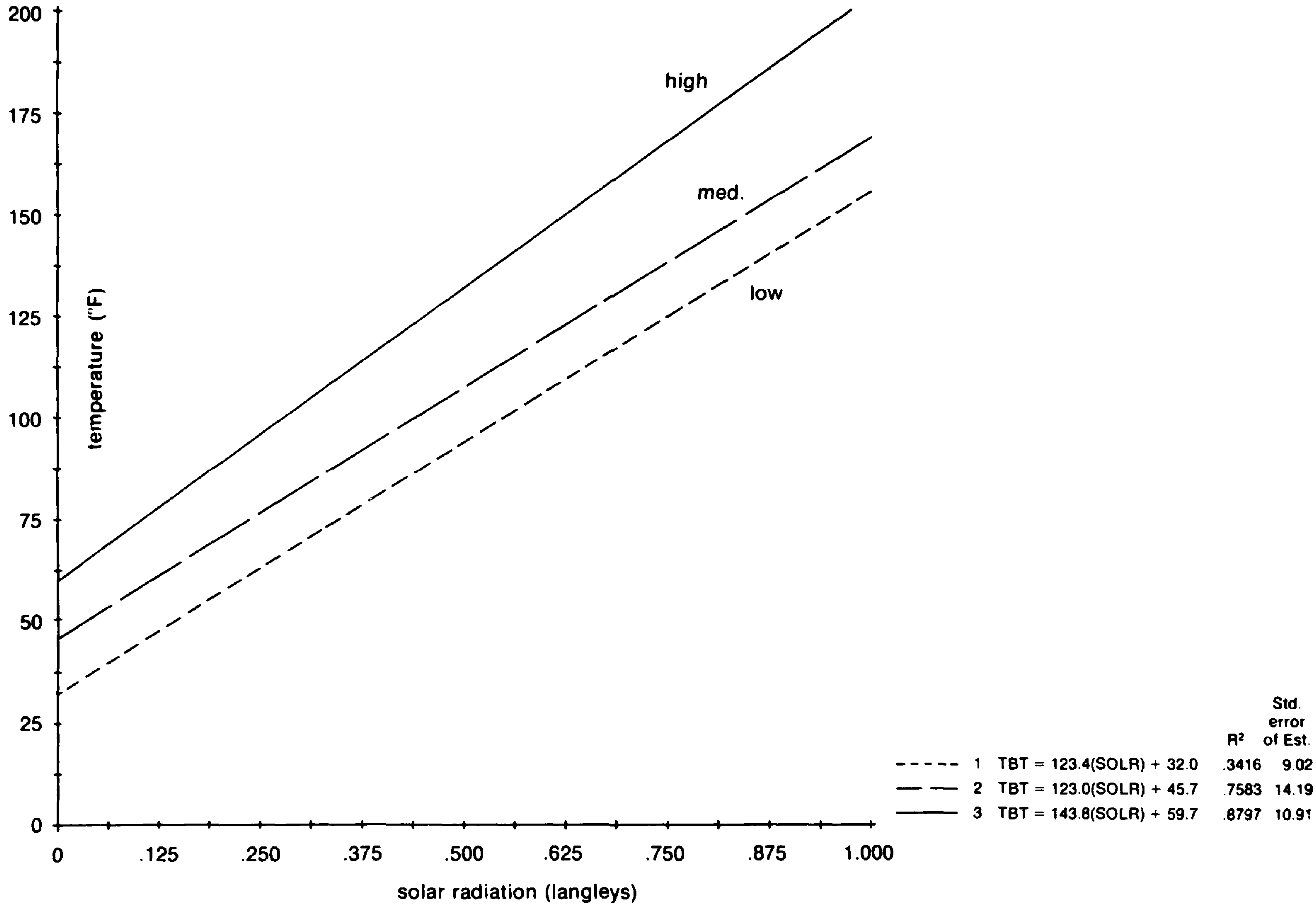


Figure 32. BUR temperature vs. solar radiation–Fort Lewis.

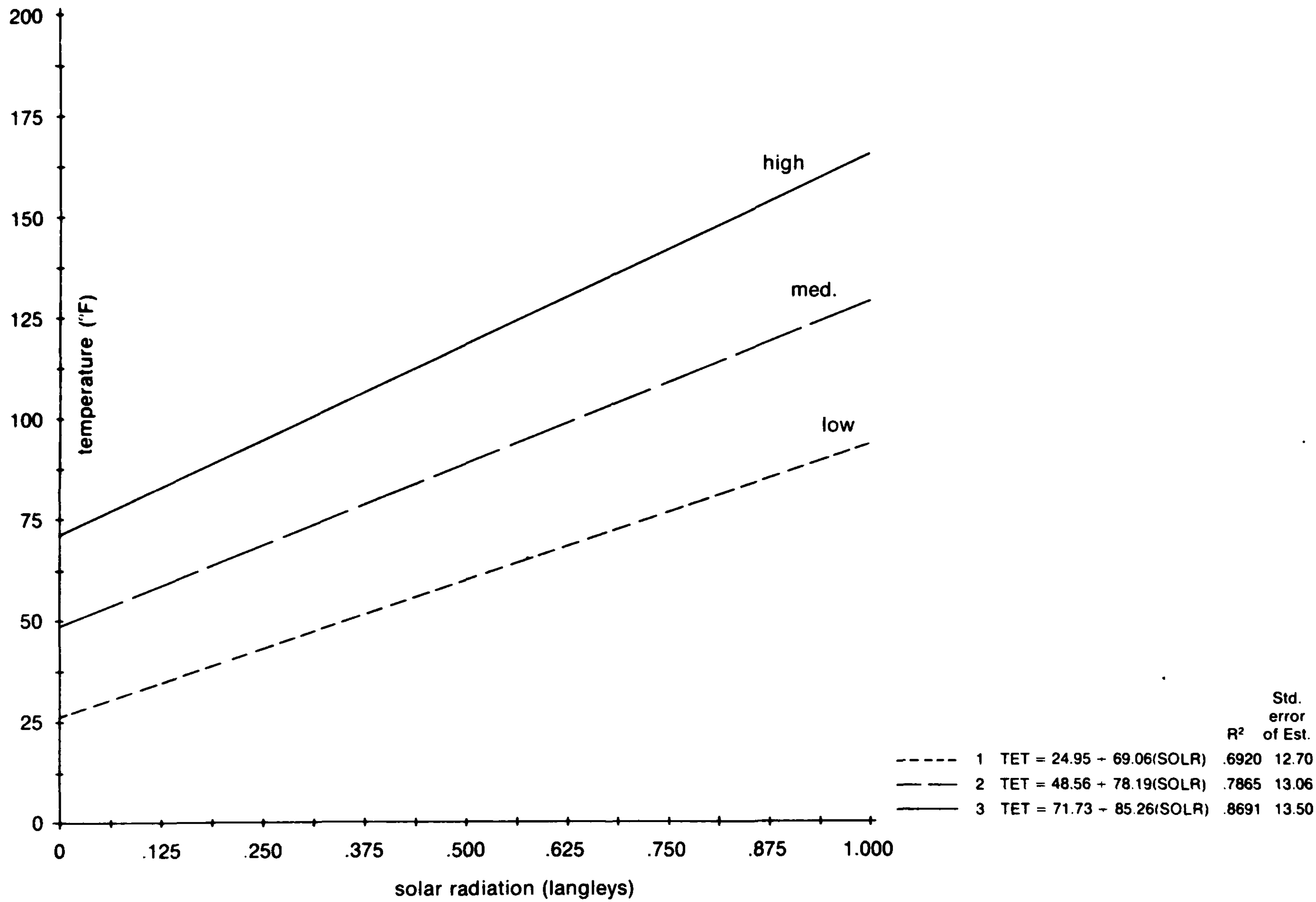


Figure 33. EPDM temperature vs. solar radiation—Fort Benning.

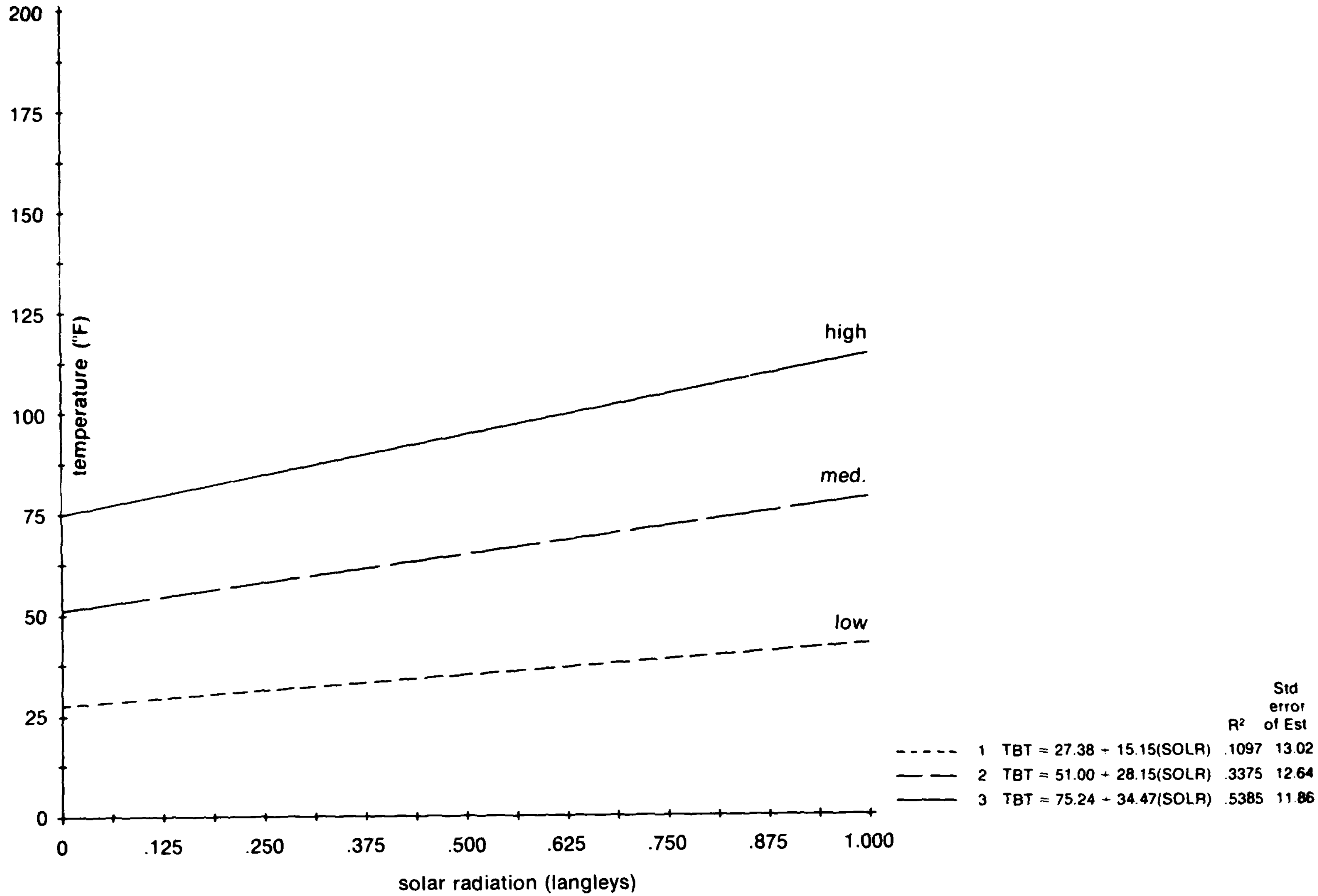


Figure 34. BUR temperature vs. solar radiation Fort Benning.

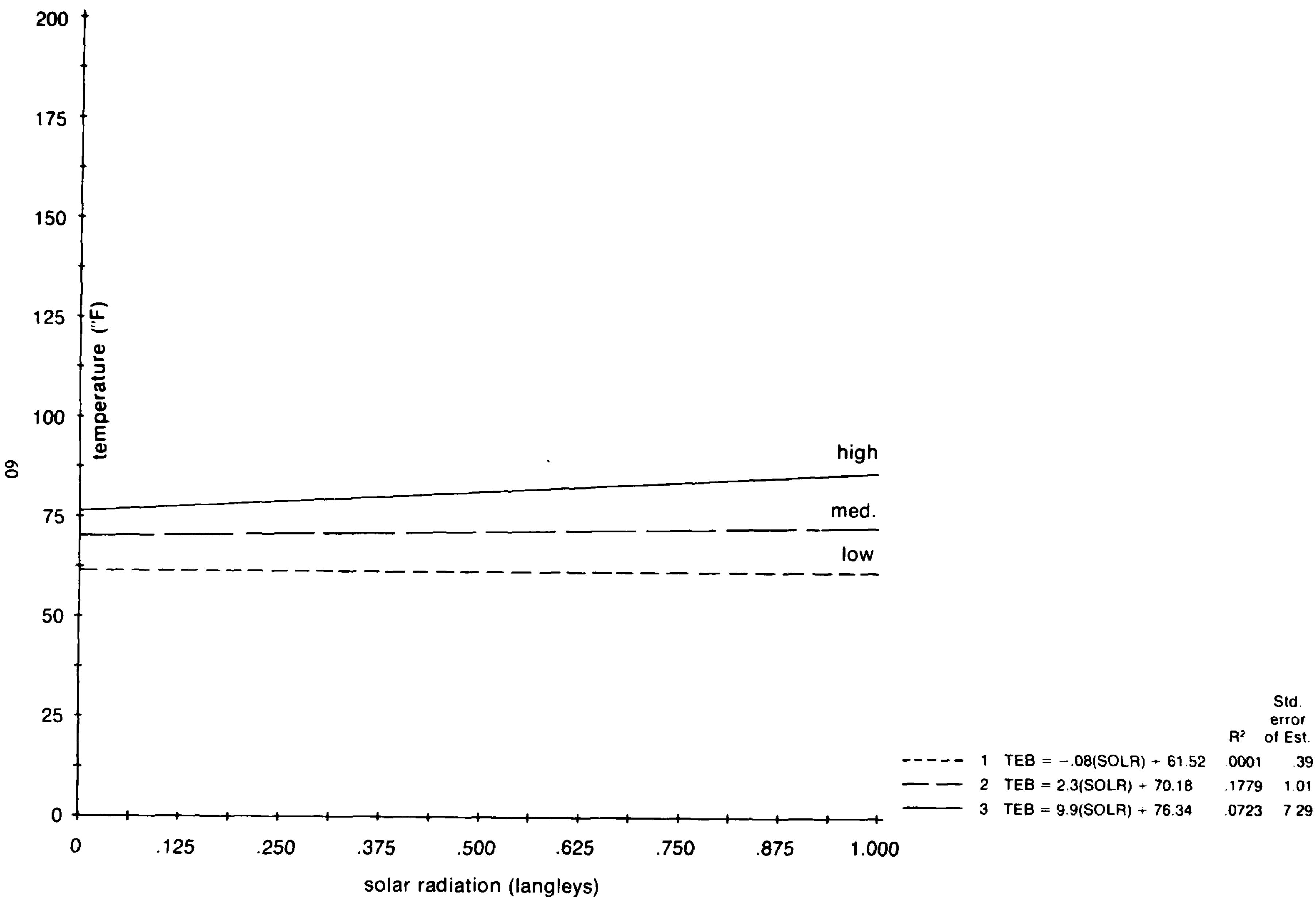


Figure 35. Deck temperature under EPDM vs. solar radiation—Fort Lewis.

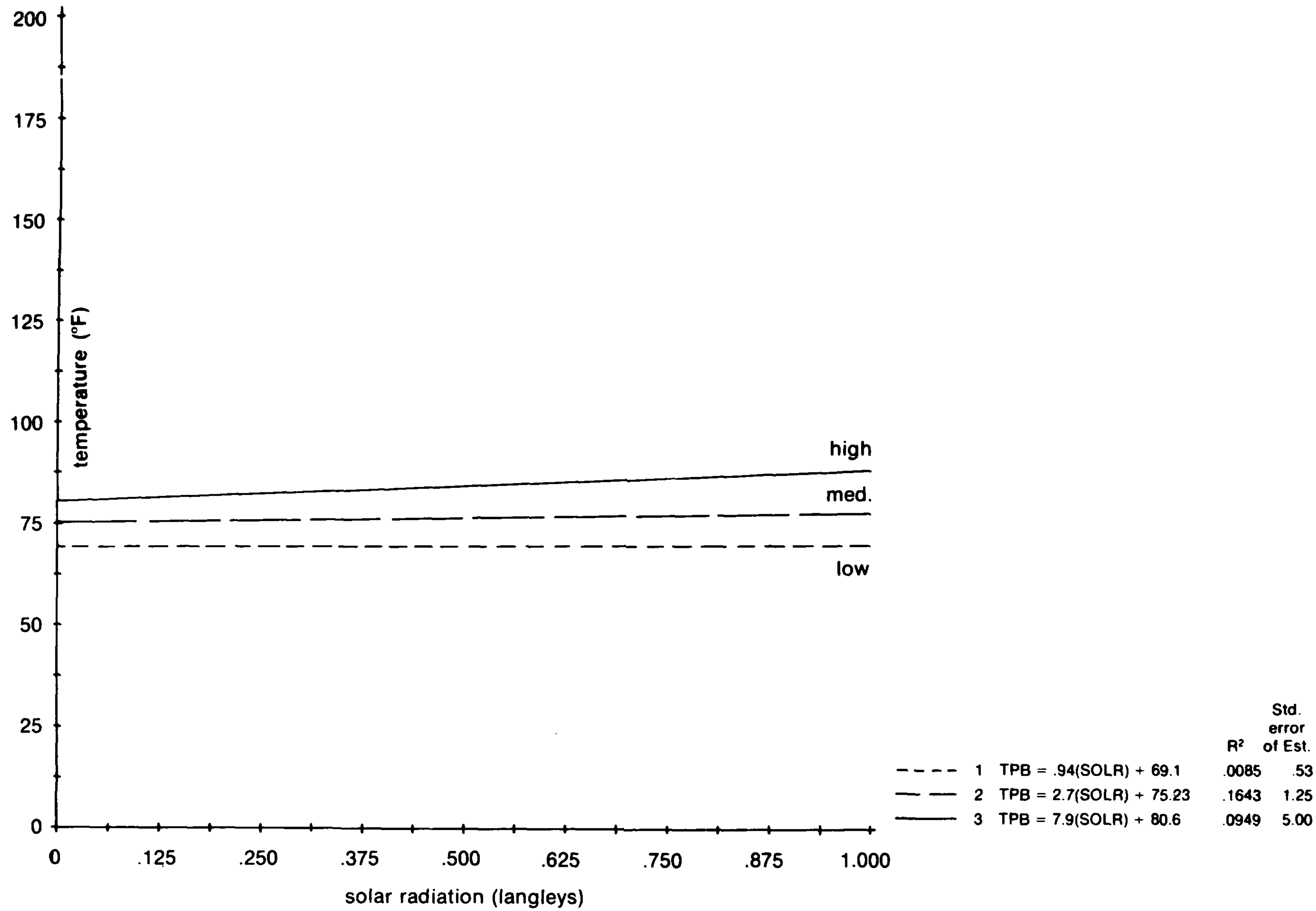


Figure 36. Deck temperature under PUF vs. solar radiation—Fort Lewis.

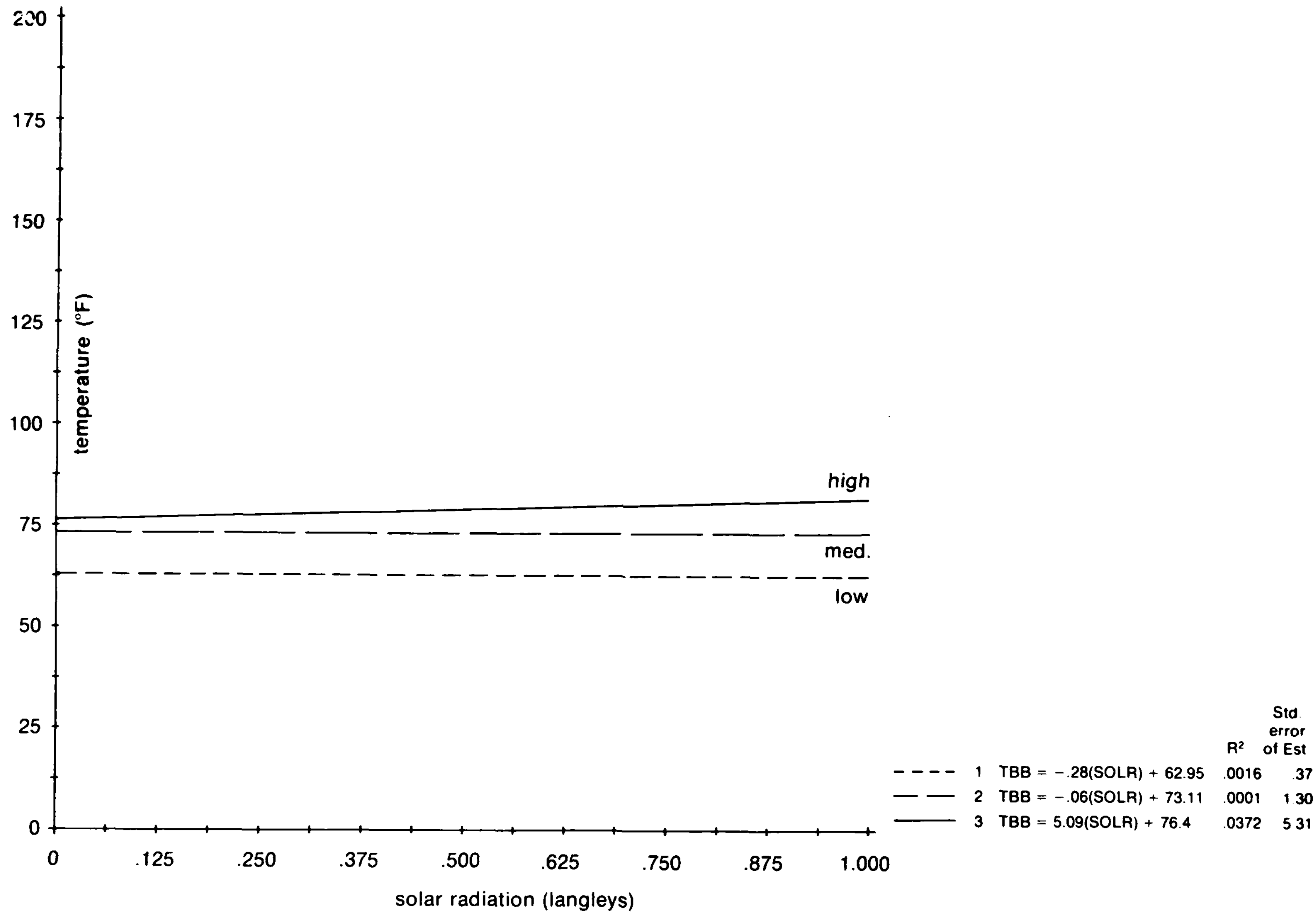


Figure 37. Deck temperature under BUR vs. solar radiation—Fort Lewis.

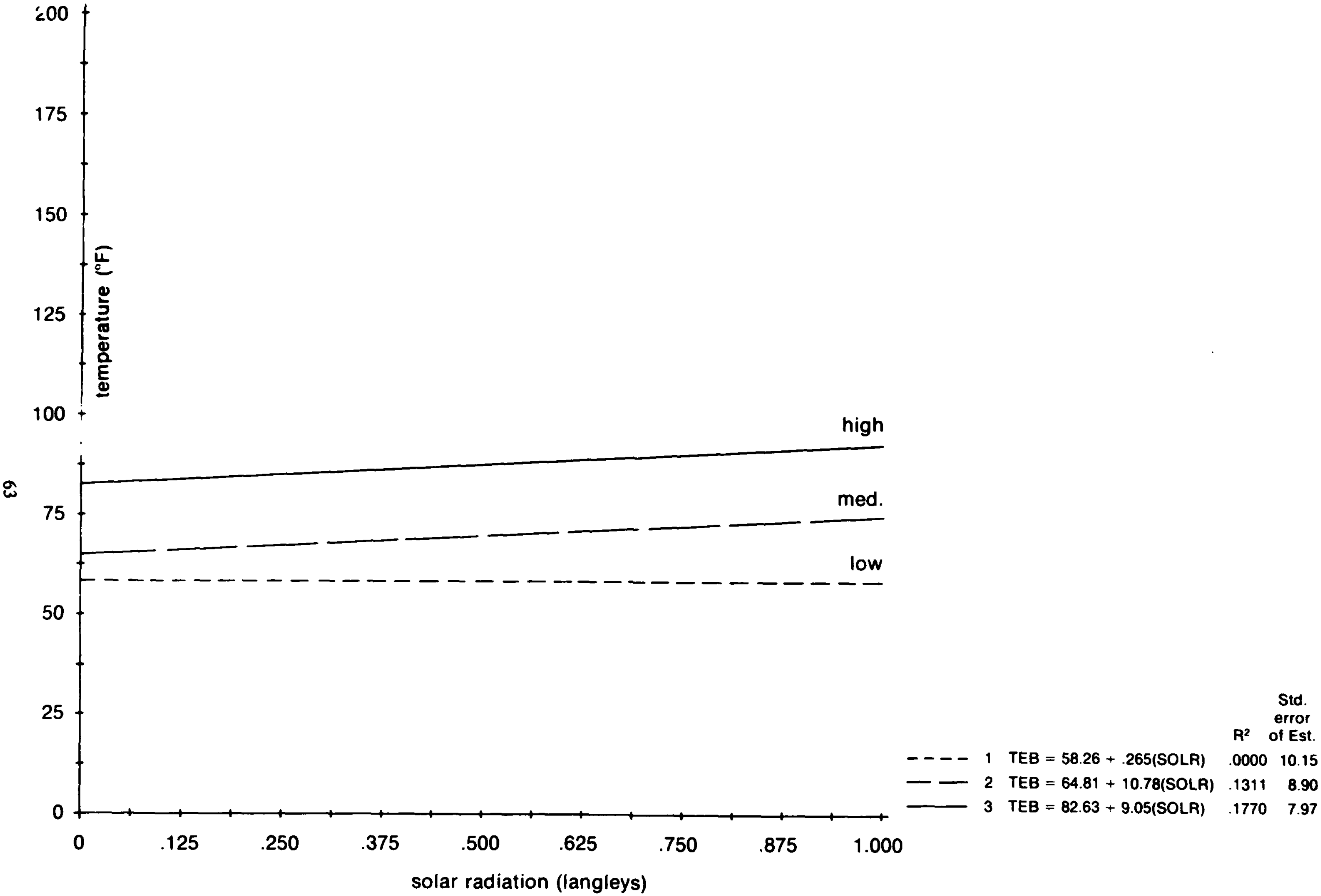


Figure 38. Deck temperature under EPDM vs. solar radiation—Fort Benning.

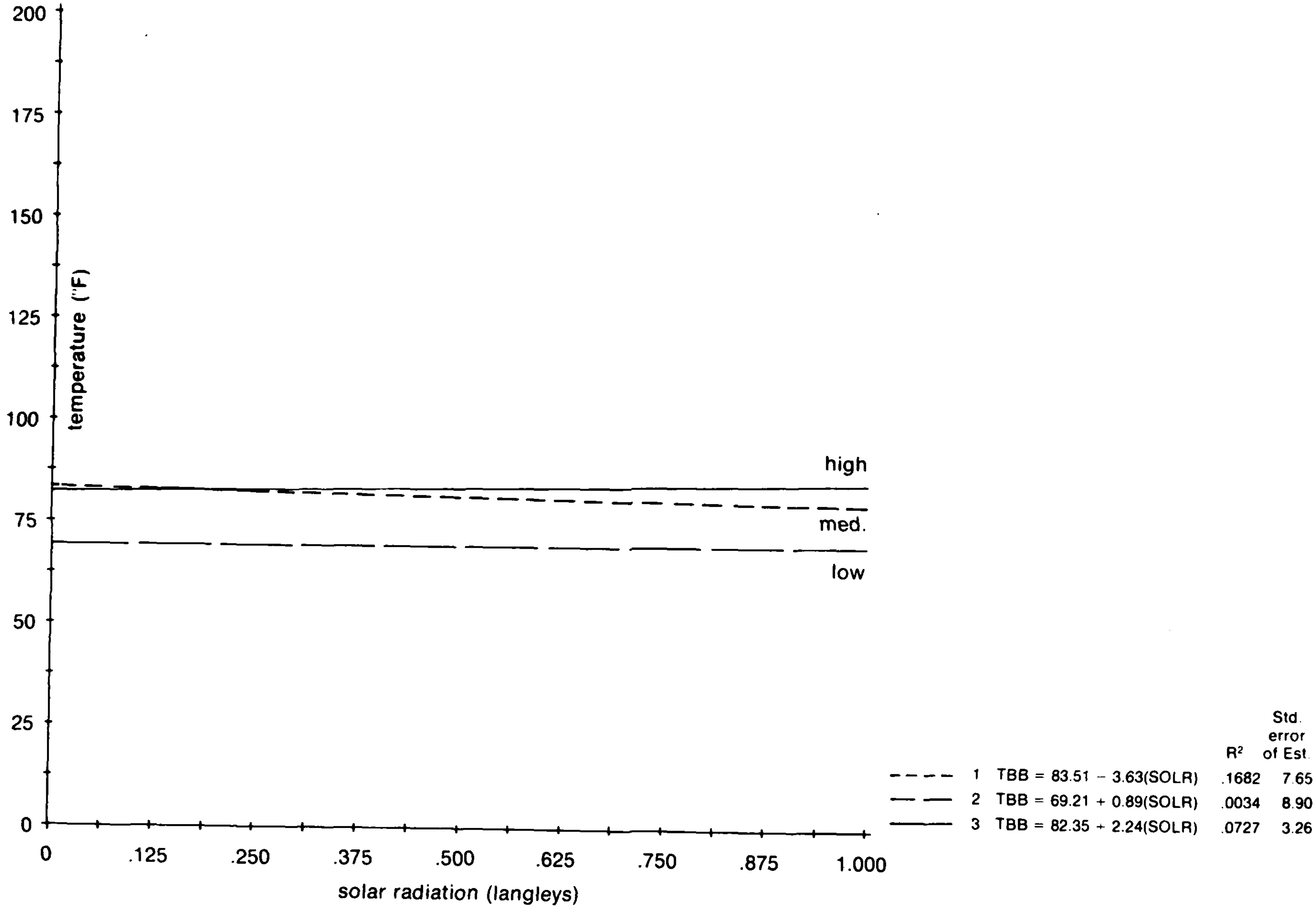


Figure 39. Deck temperature under BUR vs. solar radiation–Fort Benning.

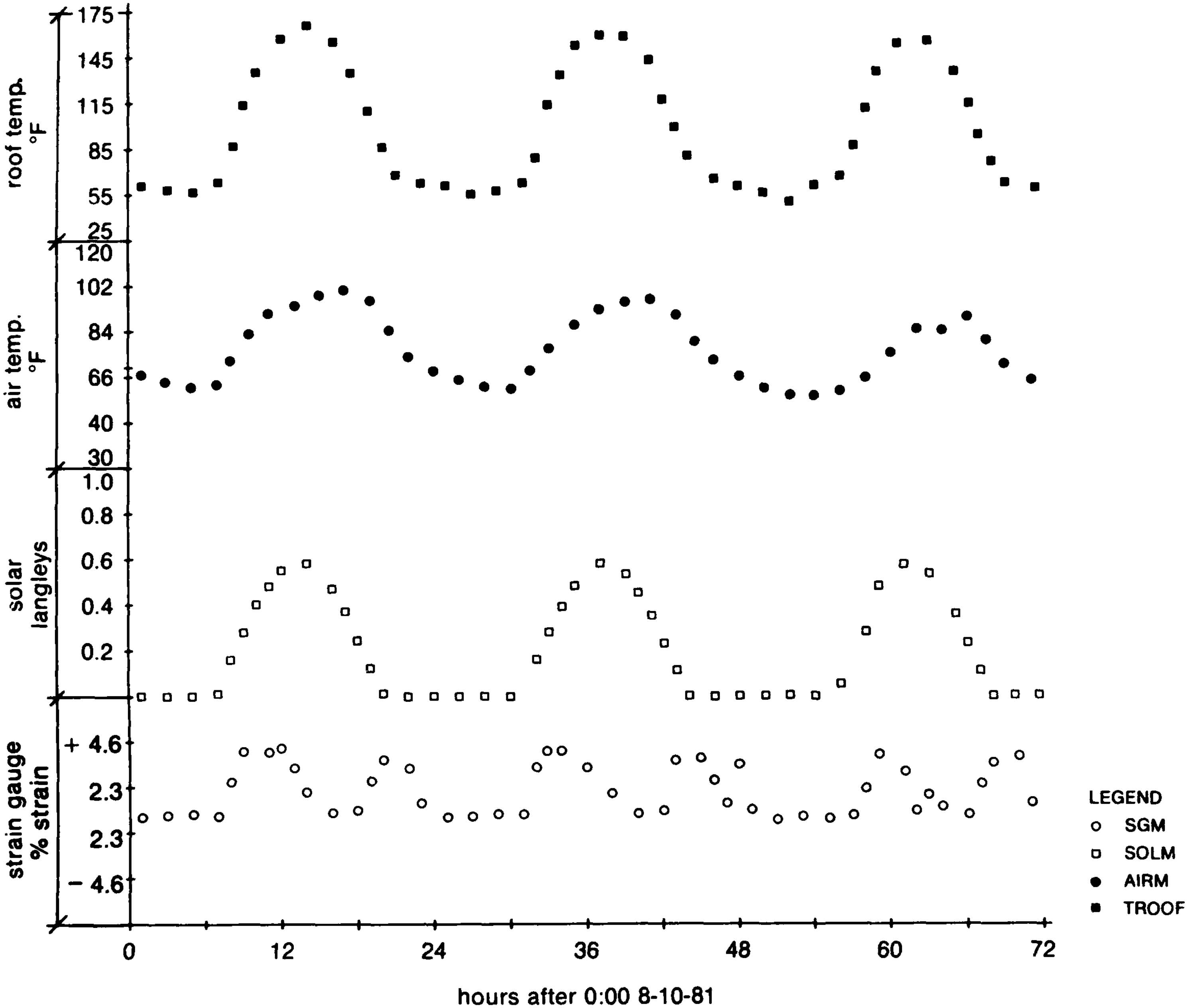


Figure 40. Parameters vs. time, high temperature and high sun—Fort Lewis, August 10–12, 1981.

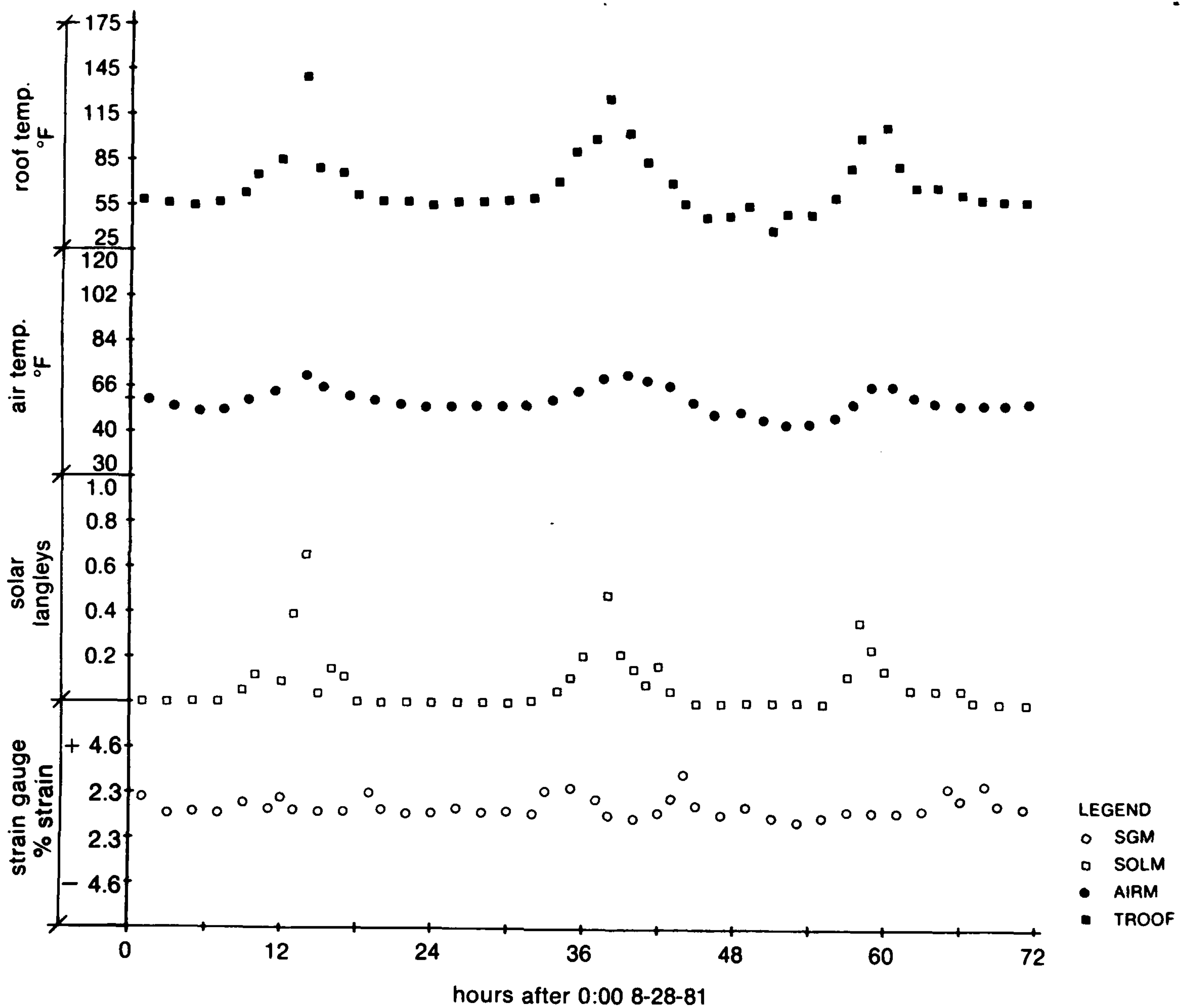


Figure 41. Parameters vs. time, high temperature and low sun—Fort Lewis, August 28–30, 1981.

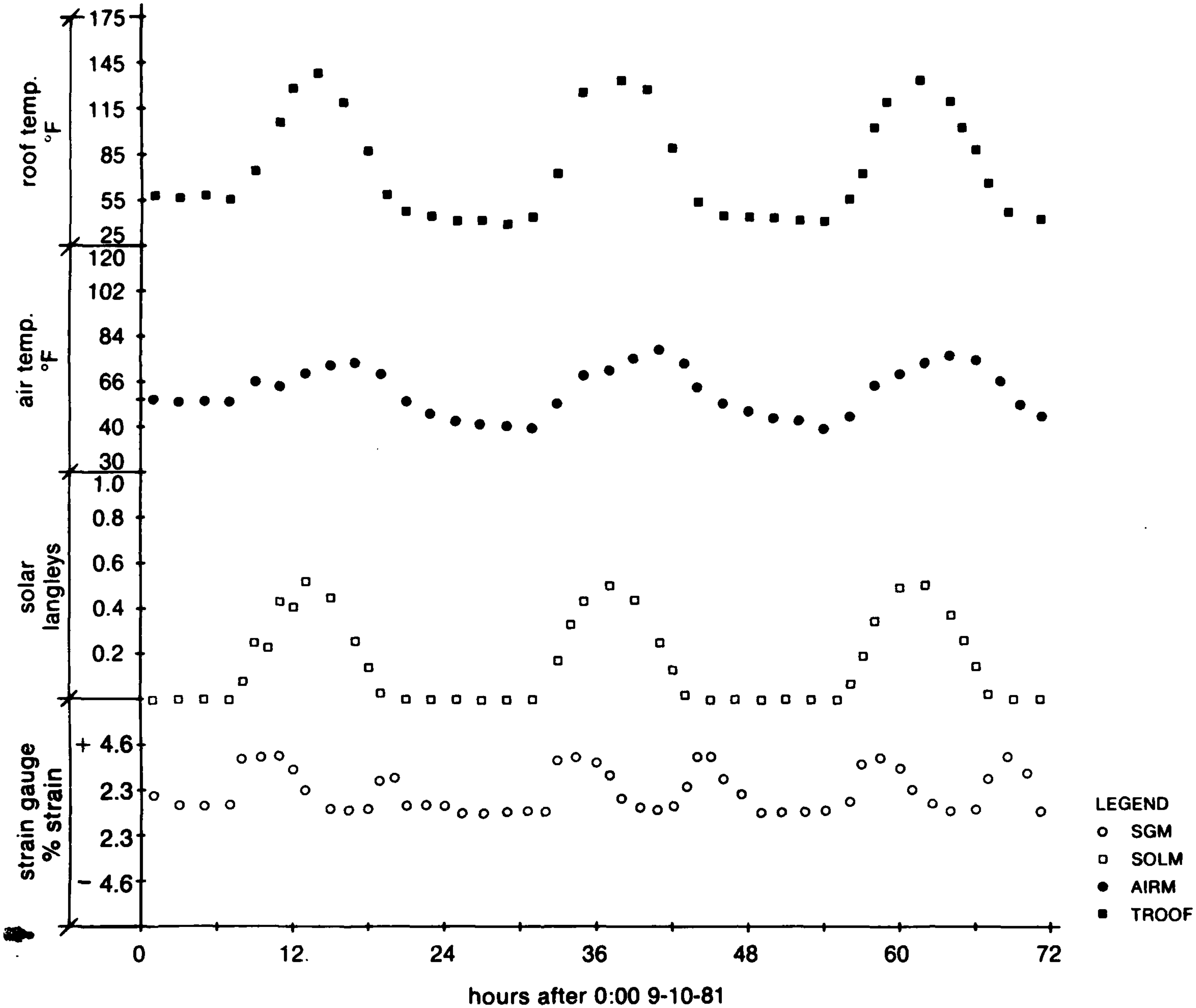


Figure 42. Parameters vs. time, low temperature and high sun—Fort Lewis, September 10–12, 1981.

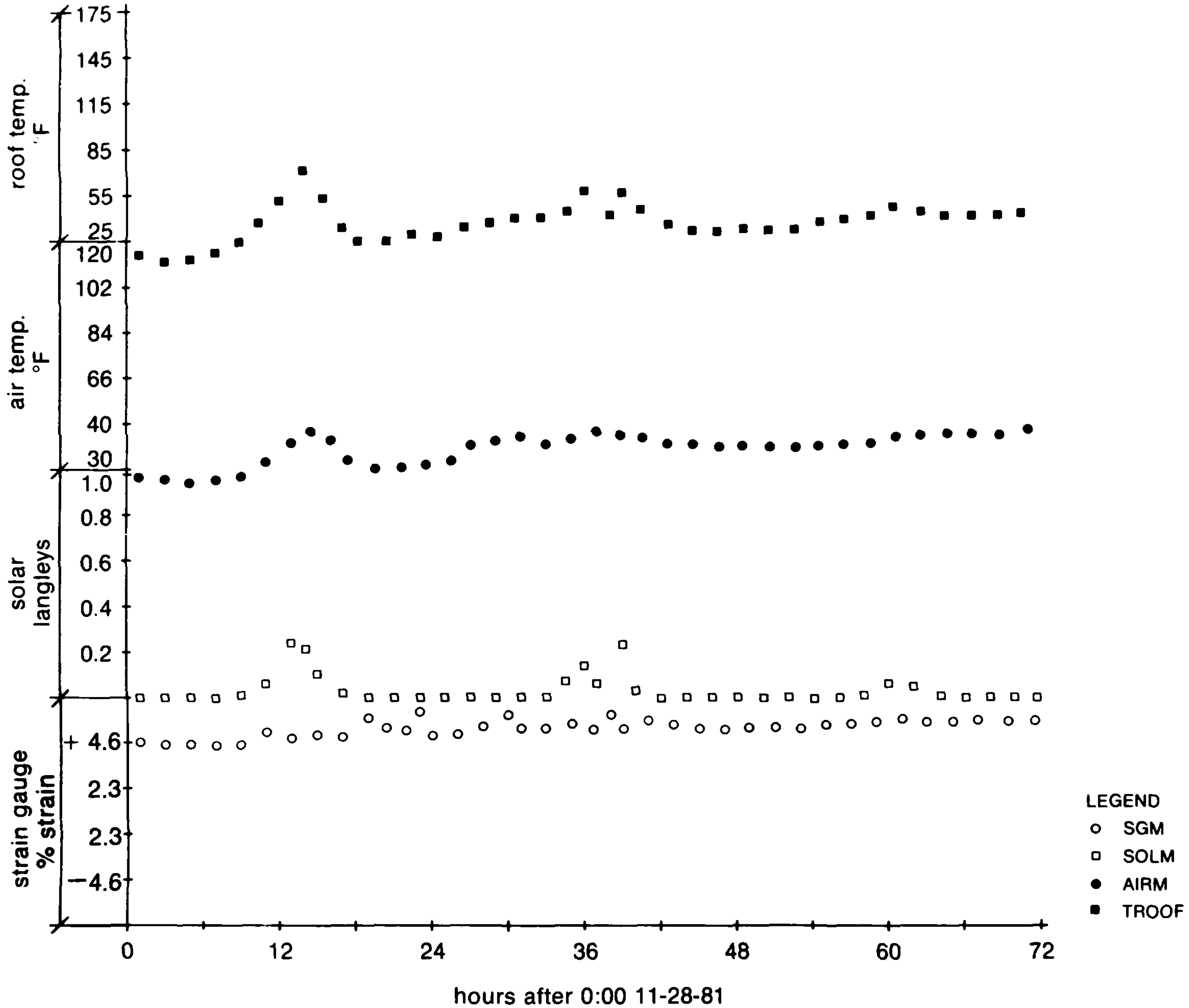


Figure 43. Parameters vs. time, low temperature and low sun—Fort Lewis, November 28–30, 1981.

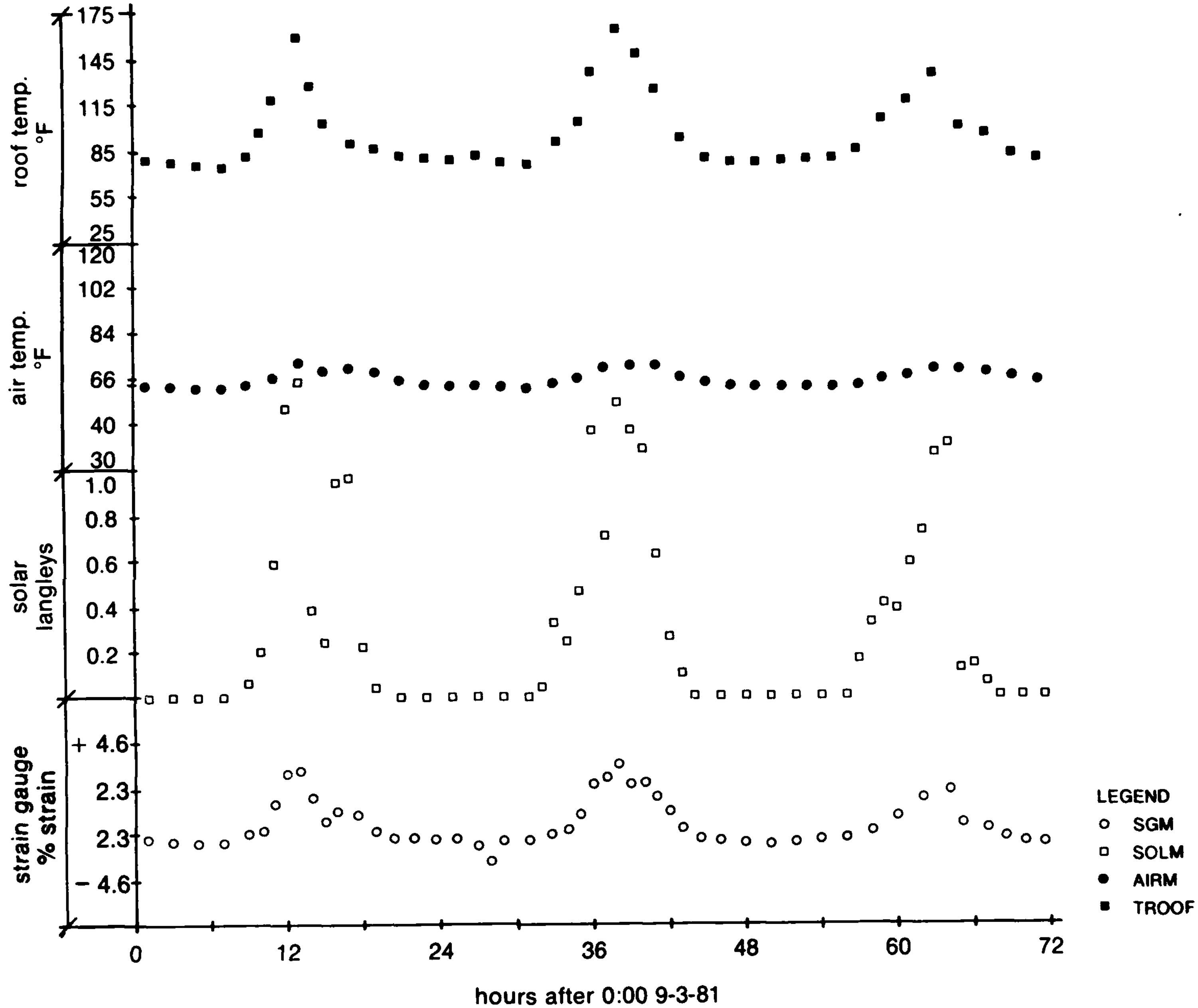


Figure 44. Parameters vs. time, high temperature and low sun—Fort Benning, September 3–5, 1981.

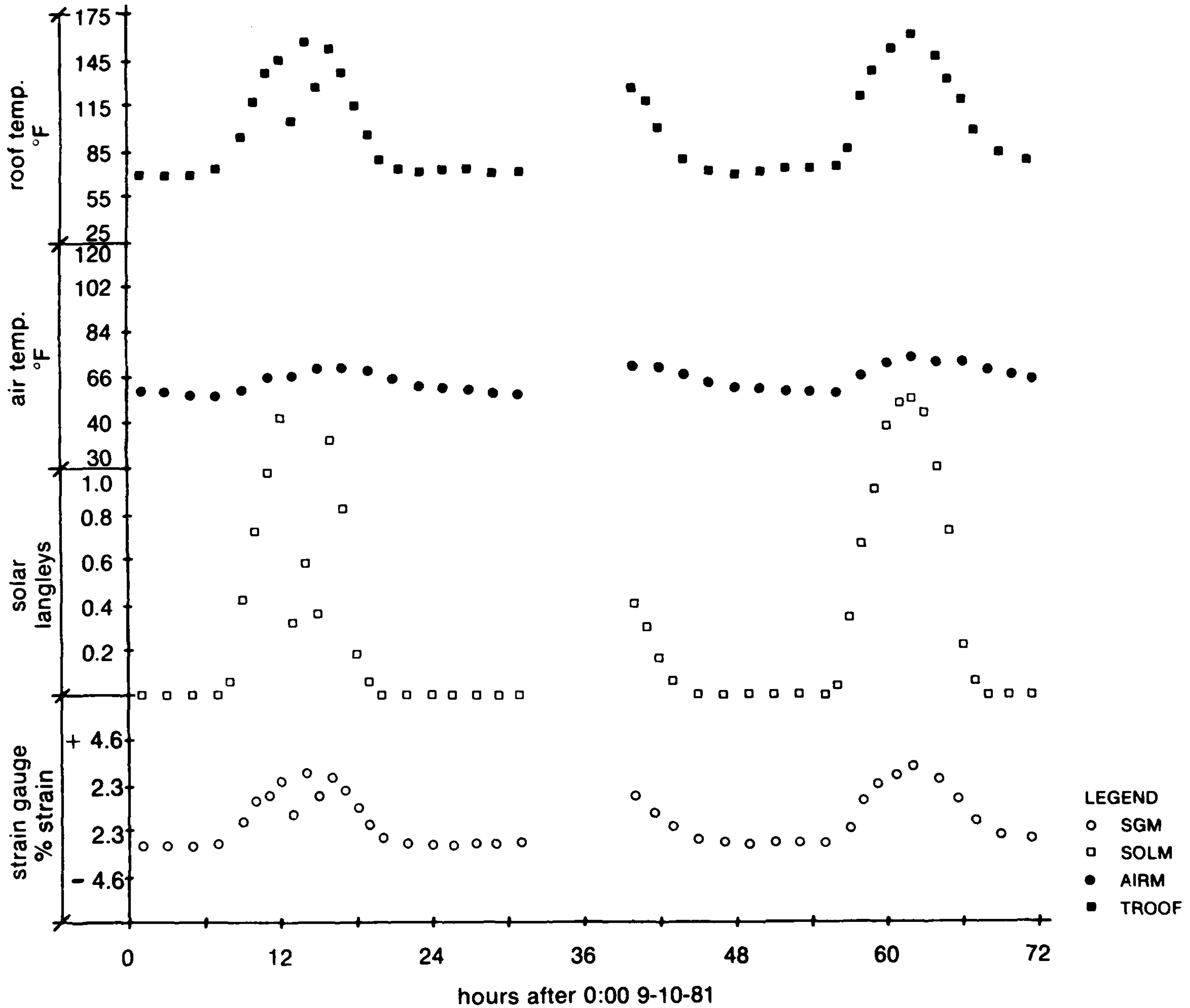


Figure 45. Parameters vs. time, high temperature and high sun–Fort Benning, September 10–12, 1981.

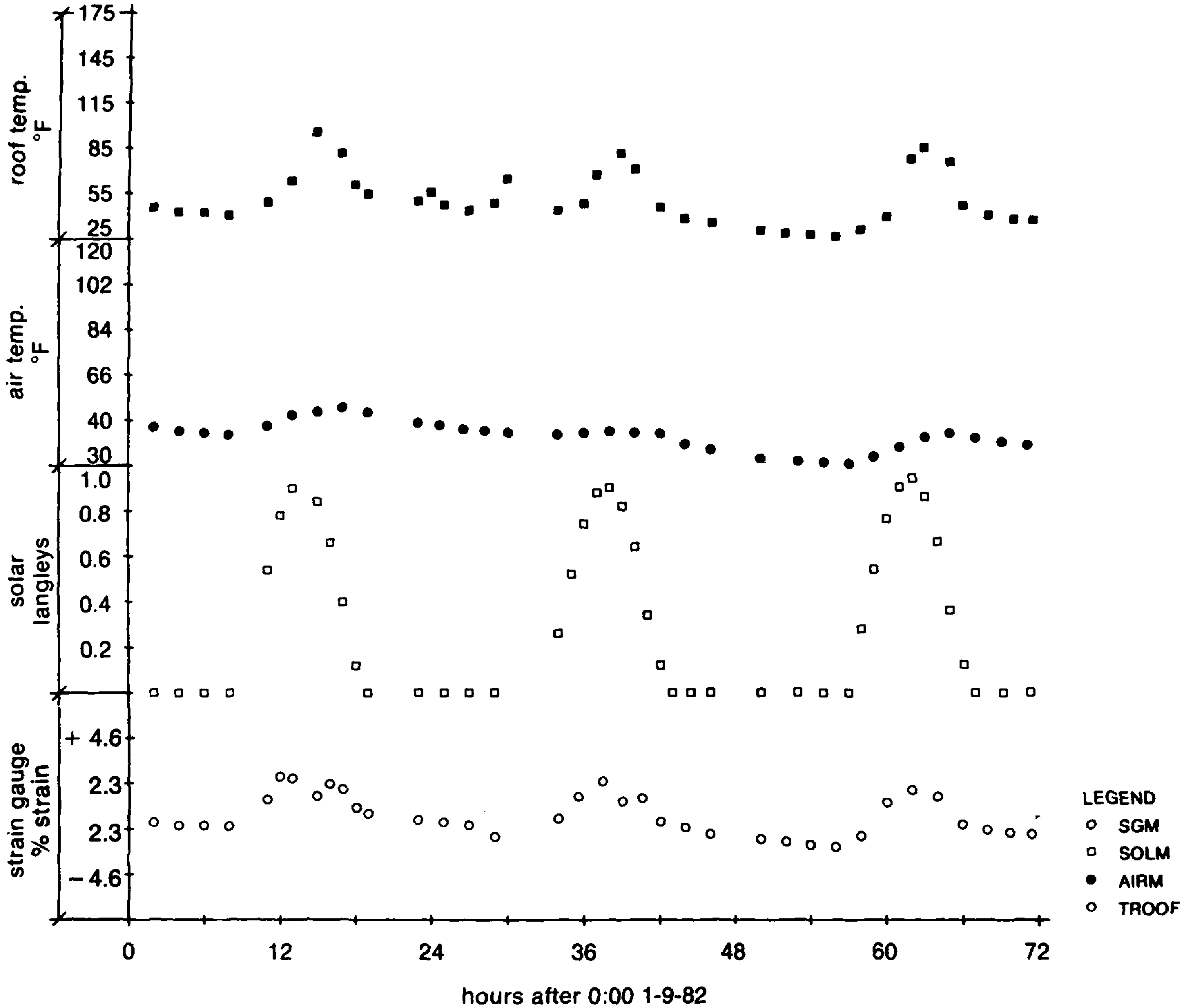


Figure 46. Parameters vs. time, low temperature and high sun—Fort Benning, January 9–11, 1982.

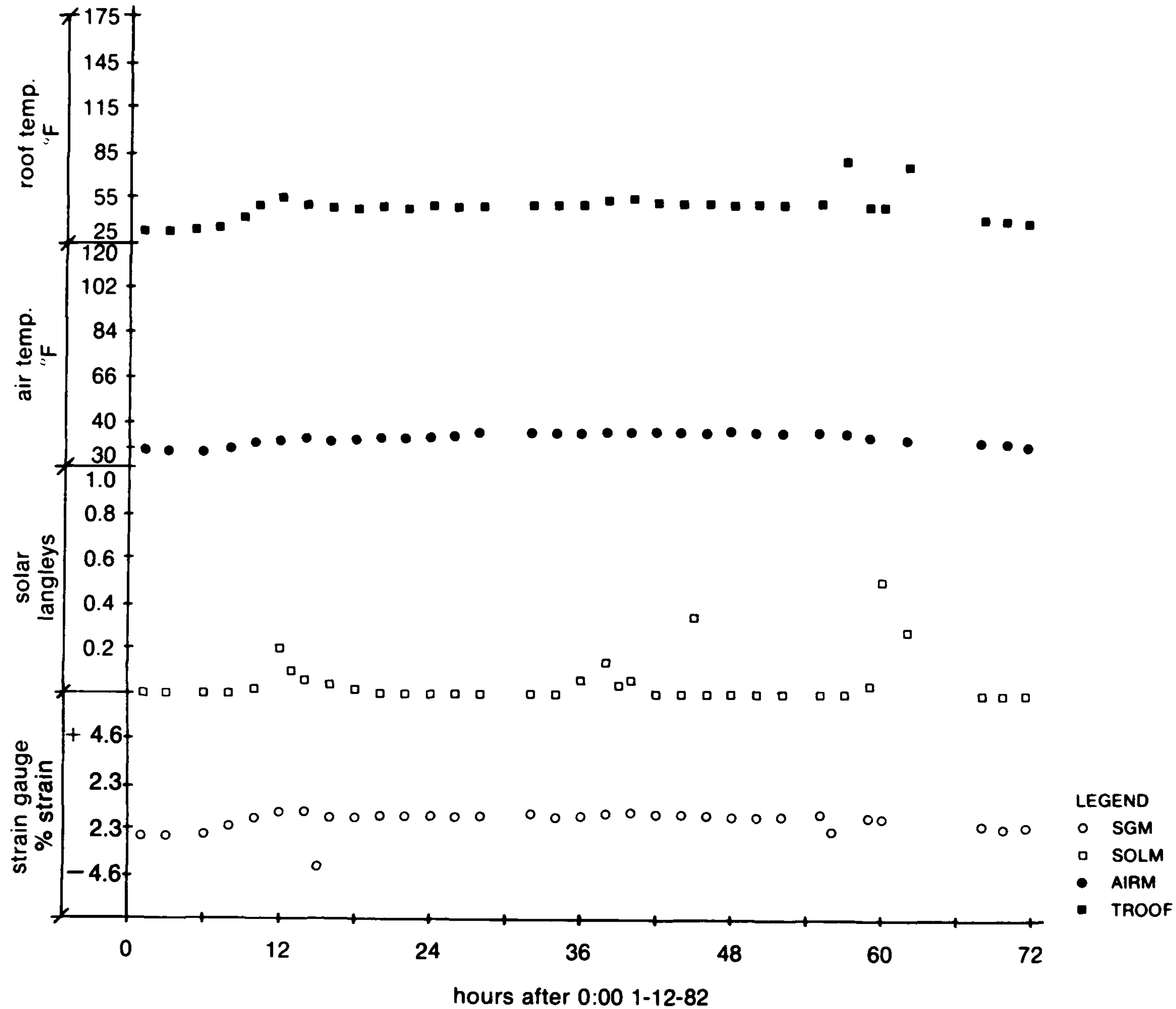


Figure 47. Parameters vs. time, low temperature and low sun—Fort Benning, January 12–14, 1982.

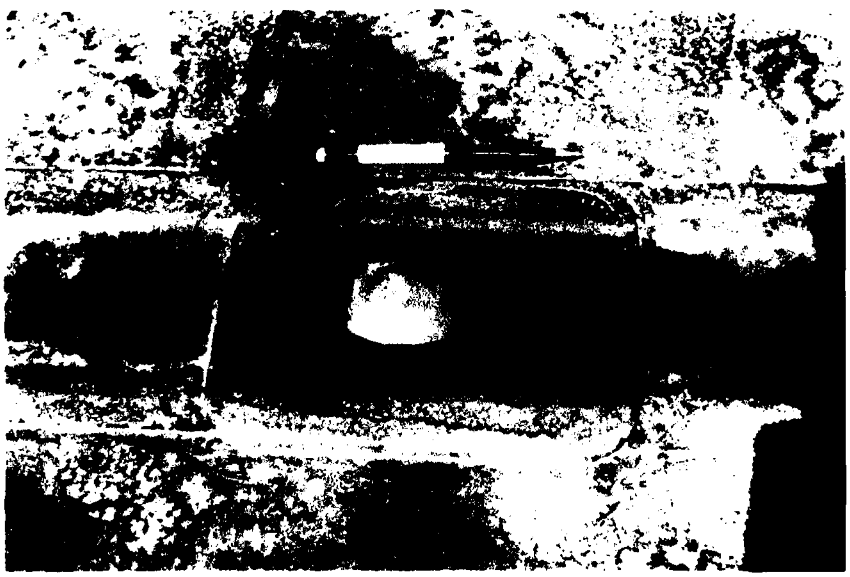


Figure 48. Blister over nail head at Fort Lewis.

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