US Army Corps of Engineers
Construction Engineering
Research Laboratories

USACERL Technical Report 98/09
January 1998

Laboratory Investigation of Selected Sensors for Use With Passive Roof Leak Detection Systems

by
David M. Bailey, Allen Prell, and Christopher Coad

The U.S. Army has a large inventory of buildings with low-slope membrane roofs. Between the time that leaks to these roofs occur and are detected, located, and repaired, water damage to roofing systems, structures, and building contents can be quite costly. Providing Army managers with a system to detect roof leaks could reduce the Army's roofing maintenance budget.

An initial investigation identified the four components of a passive roof leak detection system (PRLDS): sensors, signal, transmission medium, and a signal processing unit. The sensors are devices that respond to a stimulus, such as water, and transmit a resulting impulse signal. The signal passes through a transmission medium, such as conductive wires, to a signal processing unit, where it is deciphered and processed.

Laboratory investigations of six promising sensor technologies were conducted to evaluate their effectiveness for application with PRLDS. For Phase I, the sensors were placed in roof samples and exposed to four temperature/humidity environments for 30 weeks to assess the effect of long-term exposure to harsh environments on the durability and reliability of the sensors. In Phase II, a roof leak simulation test program was conducted to evaluate different combinations of sensor, roof system design, and sensor placement, to assess their affects on overall performance, and to establish system design requirements. Results showed that all of the evaluated sensors can be expected to exhibit adequate durability performance when placed in typical roofing system environments. Except for one sensor, they performed reasonably well in detecting leaking water within the simulated roofing system.

An effective placement of the sensor for leak detection appears to be at the bottom surface of the insulation board, which is placed on an impermeable substrate such as a vapor retarder or a layer of polyisocyanurate boards with taped joints. Sensors that are embedded in the insulation should be placed at the edge face of the board. Those sensors that are not embedded should be placed at board joints of an overlying insulation layer. Typical roof system designs for loose-laid and ballasted membranes and mechanically fastened membranes are excellent candidates for PRLDS. The inability to visually inspect ballasted systems without the removal of stones or pavers make the use of PRLDS even more attractive.

It is recommended that a Corps of Engineers Construction Specification for a PRLDS for membrane roofs be developed. A preliminary draft construction specification is presented in Appendix A.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
January 1998

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Laboratory Investigations of Selected Sensors for Use With Passive Roof Leak Detection Systems

5. FUNDING NUMBERS
4A162784
AT41
C53

6. AUTHOR(S)
David M. Bailey, Allen Prell, and Christopher Coad

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 98/09

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
ATTN: CEMP-EA
20 Massachusetts Ave. NW
Washington, DC 20314-1000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The U.S. Army has a large inventory of buildings with low-slope membrane roofs. Between the time that leaks to these roofs occur and are detected, located, and repaired, water damage to roofing systems, structures, and building contents can be quite costly. Providing Army managers with a system to detect roof leaks could reduce the Army's roofing mainte-nance budget.

An initial investigation identified the four components of a passive roof leak detection system (PRLDS): sensors, signal, transmission medium, and a signal processing unit. Laboratory investigations of six promising sensor technologies were conducted to evaluate their effectiveness for application with PRLDS. For Phase I, sensors in roof samples were exposed to four temperature/humidity environments for 30 weeks. In Phase II, different combinations were assessed to establish system design requirements. Results showed that all of the evaluated sensors can be expected to exhibit adequate durability performance when placed in typical roofing system environments. Except for one sensor, they performed reasonably well in detecting leaking water within the roofing system. Typical roof system designs for loose-laid and ballasted membranes and mechanically fastened membranes are excellent candidates for PRLDS, especially because of the inability to visually inspect ballasted systems without the removal of stones or pavers.

14. SUBJECT TERMS
passive roof leak detection system (PRLDS)
leak detection
maintenance and repair
roofing

15. NUMBER OF PAGES
66

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

Foreword

This study was conducted for Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit C57, "Smart Roofing Systems." The Technical Monitor was Frank Norcross, CEMP-EA.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL Principal Investigator was David M. Bailey.

Dr. Ilker R. Adiguzel is Acting Chief, CECER-FL-M, and L. Michael Golish is Acting Operations Chief, CECER-FL. The USACERL technical editor was Linda L. Wheatley.

COL James A. Walter is Commander of USACERL and Dr. Michael J. O'Connor is Director.

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1 Introduction

Background

The U.S. Army has a large inventory of buildings with low-slope membrane roofs. Over time, most of these roofs will develop water leaks. Between the time a leak begins and is detected, located, and repaired, water damage to the roofing system, structure, and building contents can be quite costly. Providing Army managers with a system to detect roof leaks could reduce the Army's roofing maintenance budget.

Conventional moisture detection techniques that use infrared thermography, nuclear meters, or capacitance meters, require frequent, regular surveys to provide early roof leak detection. A passive roof leak detection system (PRLDS) (Bailey et al. 1994) uses sensors placed in the roof to detect water intrusion caused by flaws in the roof covering. Sensors are embedded into the roofing system during or after construction and provide continuous monitoring for leak water.

An initial investigation (Bailey et al. 1994) identified four components which comprise a PRLDS: sensors, signal, transmission medium, and a signal processing unit. The sensors respond to a stimulus, such as water, and transmit a resulting impulse signal. The signal passes through a transmission medium (i.e., conductive wires) to a signal processing unit where it is deciphered and processed. Placement and spacing of the sensors on a roof, which determine the system's resolution, are based on system cost and the level of protection desired. The study also presented several feasible moisture sensing technologies and discussed the performance characteristics required of a PRLDS.

Objective

The objective of this study was to conduct laboratory investigations of six sensor technologies that exhibit promise for application with a PRLDS. The investigation of these technologies would evaluate their reliability, durability, compatibility, and effectiveness with roofing systems and materials.

Approach

The study was conducted in two phases. For Phase I, the sensors were placed in roof samples and exposed to four different temperature/humidity environments to assess the effect of long-term exposure to harsh environments on their reliability and durability. In Phase II, a roof leak simulation test program was conducted to evaluate different combinations of sensor, roof system design, and sensor placement to assess their effect on overall performance and to establish system design requirements.

Mode of Technology Transfer

This research provides the testing and evaluation phase for developing system requirements for a PRLDS for the Army. It is recommended that the final product of this research be the development of a Corps of Engineers Construction Specification for PRLDS for membrane roofs. Appendix A presents a preliminary draft construction specification.

Metric Conversion Factors

This report uses U.S. standard units of measure throughout. When not provided in text, the table below provides the most frequently used metric conversion factors.

1 in.	=	25.4 mm
1 oz	=	28.35 g
°F	=	(°C x 1.8) + 32

2 Description of Sensors

Six different sensors (Bailey et al. 1994) were included in the test program. Three of the sensors (resistance probe, wooden probe, plywood disc) can be classified as resistance sensors, and three sensors (moisture-detection tape, water activated battery, water-sensing cable) are classified as circuit-activating sensors. The water-sensing cable was identified as a sensor after the Phase I investigation, so it was only included in the Phase II investigation.

Resistance Sensors

Resistance sensors measure the moisture content of a material by monitoring its electrical resistance and relating it to a reference value or calibration curve. The electrical resistance of most materials will decrease as they become wet. The relative moisture content of a test material can be determined either by directly measuring the resistance of the material between two probes or by measuring the resistance of another system in hydrostatic equilibrium with the test material.

A basic circuit diagram for a resistance sensor is shown in Figure 1. A constant current is introduced into the circuit and passes through the material under test.

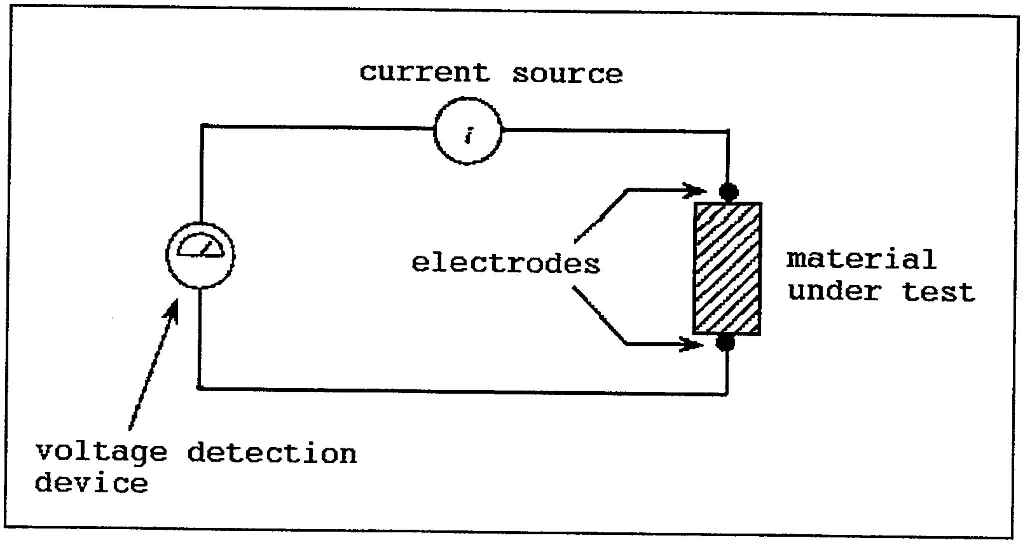


Figure 1. Basic circuit diagram for a resistance sensor.

The voltage across the electrodes is monitored and related to the electrical resistance of the material through Ohm's Law, R=V/I, where I is the current flowing in the circuit and V is the voltage across the electrodes. A pair of conductive wires serves as the transmission medium for this type of sensor.

Resistance Probe

The resistance probe is 3/4-in. high and 3/4-in. wide and consists of two prongs in parallel with a nominal resistor. For a PRLDS application, the prongs are inserted into the roof insulation. A cross section of an installed probe is shown in Figure 2. The effective resistance of the probe can be expressed as:

$$R_{eff} = \left(\frac{1}{R_{nom}} + \frac{1}{R_{ins}} \right)^{-1} \qquad \textbf{[Eq 1]}$$

where R_{nom} is the value of the nominal resistor and R_{ins} is the resistance of the insulation between the prongs. The effective resistance of the probe will decrease as the insulation becomes wet. This decrease in resistance will cause a drop in the voltage being monitored by the signal processing unit. A decrease in the voltage from the nominal (dry) level to some established "threshold" level signals the occurrence of a roof leak. A voltage signal higher than the nominal level indicates damage in the circuit.

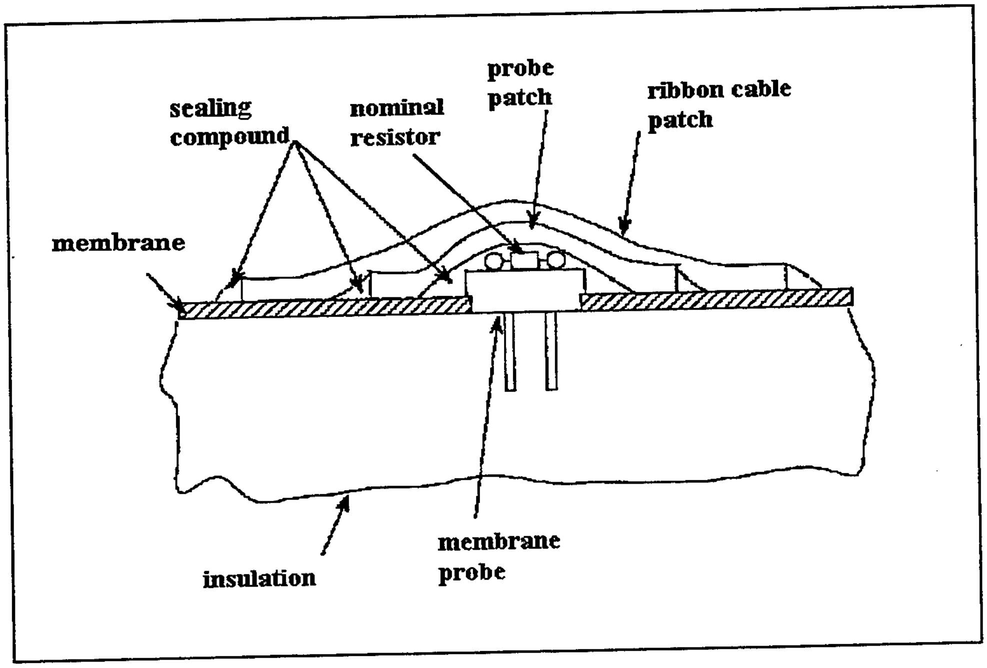
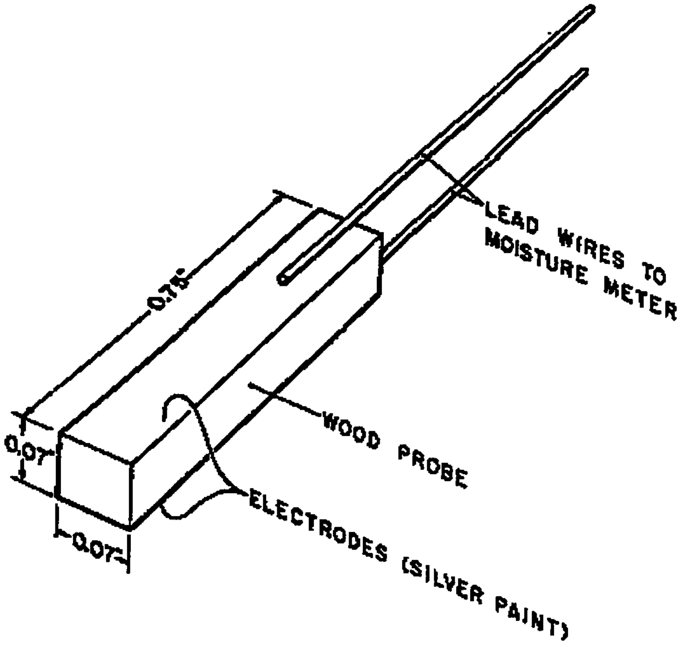


Figure 2. Cross-sectional view of an installed resistance probe.

The resistance probe is currently marketed by Industrial Options, Inc. (1992) as part of a roof leak detection system. As recommended by the system designer, the sensor is installed after the roof membrane is put in place. At each sensor location, a small incision is made in the membrane to allow for insertion of a probe. Once the probes are set, a sealant is applied to ensure watertightness, and a circular protective patch is placed over the top. The pairs of conductive wires connecting each sensor to a signal processing unit are grouped along trunk lines using ribbon cable. The cables are placed on top of the roof membrane and covered by membrane patch materials. The system designer also noted that, for adequate performance, the resistance probes must be installed in open-cell insulation.

Wooden Probe

The U.S. Department of Agriculture (USDA) Forest Products Laboratory (FPL) in Madison, WI, has been using a wooden probe design since 1966 to sense moisture in wood (Duff 1966). Their design includes a piece of soft wood ¾-in. long and 0.07-in. square (Figure 3). The top and bottom surfaces of the probe are painted with conductive silver paint to which electrodes are then glued. The University of Illinois Small Homes Council has since modified the design by making the probe shorter and putting a protective plastic sleeve around it.



(Source: Duff 1966.)

Figure 3. Diagram of wooden probe.

The selected wood is naturally hygroscopic in that it absorbs moisture from its surroundings. As the wood absorbs moisture, its resistance is reduced.

Plywood Disc

The plywood disc was used as a moisture sensor by Oak Ridge National Laboratory (ORNL) in previous research studies. The sensor is made and sold by a Danish company and consists of a 2-in. disc of 1/2-in. plywood with two electrodes nailed into it (Courville et al. 1988). Electrical resistance between the two electrodes can be calibrated to give the moisture content of the plywood disc sensor. The operating moisture range of the plywood disc sensor is 6 to 30 percent moisture by weight. Below 6 percent, readings lack sufficient accuracy, and at the 30 percent level the plywood reaches saturation. The disc can be inserted into insulation or placed on top of a watertight vapor retarder.

Circuit-activating Sensors

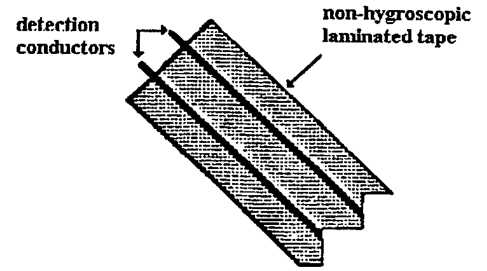
The water battery is activated when a certain amount of water fills a trough containing the battery, starting a chemical reaction. For the detection tape and sensing cable, liquid bridges the gap between two wires and completes a circuit. All three sensors require some pooled water to be activated. Once water activates the circuit, its presence can be indicated by the transmission of a signal.

Moisture-detection Tape

Moisture-detection tape (Figure 4) has two wire electrodes embedded in a fabric tape (Ross and Sontag 1987). The tape is nonhygroscopic and unaffected by high humidity levels, but it allows water to pass between its fibers. A nominal current passed through the wire electrodes is continually monitored. When a pool of water bridges the parallel wires, the circuit resistance drops substantially, signifying the presence of a leak. Unlike the resistance sensors previously described, the tape can serve as both the sensor and transmission medium.

Water-activated Battery/Transmitter

A water-activated battery/transmitter is the sensor in a PRLDS system currently being marketed and sold in the United States. The system (Bryan 1986; MID 1992) was patented in 1986, and consists of an array of sensors that emit pulse coded radio signals to a remote receiver functioning as the signal processing unit. A cross-sectional view of an installed sensor is shown in Figure 5. The sensor is 5-1/2 in. in diameter, 1-in. high, and powered by a water-activated



(Source : Ross and Sontag 1987. Used with permission.)

Figure 4. Diagram of moisture-detection tape.

battery. When 1 oz of water accumulates in the surrounding trough, a reaction is initiated that produces the current needed to activate the battery and transmit a radio signal. Because the signal is transmitted by radio wave, no hardware is required for the transmission medium.

The joints in the bottom layer of roof insulation boards either are taped or have a layer of polyethylene installed on top of them. After the top layer of insulation is in place, holes are cut in the top boards, and the sensors are inserted so that their top surfaces are flush with the top of the underlying insulation boards. The membrane is then installed.

The electronics of the sensor are housed in a plastic case, which provides protection from careless handling at the work site and from static loads of as much as 350 lb. The sensor has also been designed to withstand temperature extremes of -40 to +90 °C.

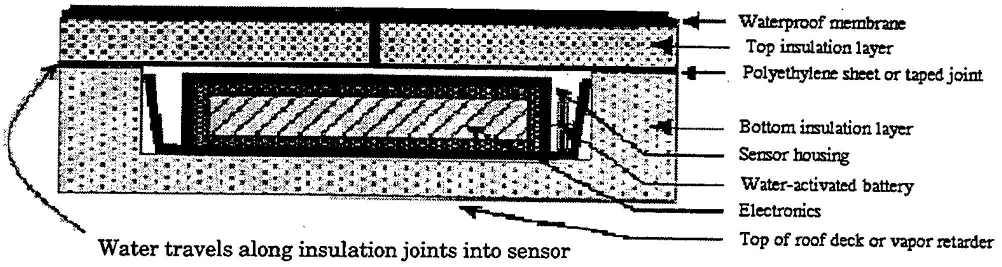
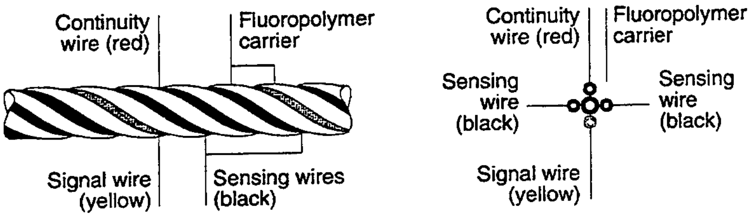


Figure 5. Cross-sectional view of water-activated battery/transmitter.

Water-sensing Cable

After completion of Phase I, the researchers learned of a marketed system which detects and locates water and other unwanted liquids within buildings (i.e., under flooring systems and pipelines, and around equipment). Like the moisture-detection tape, the sensor—a water-sensing cable (Raychem 1991)—also serves as the transmission medium. The cable is approximately 1/4 in. in diameter (Figure 6). It is constructed of two sensing wires, a signal wire and a continuity wire, all of which are wrapped around a fluoropolymer carrier rod. Pooled water completes a circuit between the sensing wires, triggering an alarm at the signal processing unit.

The signal processing unit needs no calibration and has the ability to resolve the location of leaks while monitoring up to 5,000 ft of continuous cable. If a leak is detected, the unit continues to monitor and will re-alarm if subsequent leak water is detected by the water-sensing cable. The signal processing unit also has the ability to log a history of more than 300 events. Available cable connection accessories make the system modular by allowing the sensing cables to be networked into various configurations to meet desired coverages.



(Source: Raychem Corporation. Used with permission.)

Figure 6. Water-sensing cable.

3 Laboratory Investigation, Phase I

The purpose of Phase I of the laboratory investigation was to measure the degradation of sensor performance and changes in signal responses with time. In addition, sensor placement location, ease of installation, and sensitivity of the sensors when exposed to water intrusion were also examined.

Sensors were placed in laboratory-constructed roof samples and exposed to four different temperature/humidity environments for a period of 30 weeks. Two types of roof samples were tested: one without water and one with water added at various times to simulate leak water intrusion. For each sample, there were five test variables: sensor type, insulation type, membrane attachment, module type (water added/no water added) and temperature/humidity conditions of the accelerated aging environment (Table 1). Sensor signals were recorded daily during the test period. Once the tests were completed, the sensors were inspected for corrosion and damage, and the signal readings were analyzed to evaluate sensor performance.

Table 1. Variables for test samples.

Variable	Acronym	Description
Sensor	RS	resistance probe
	WP	wooden probe
	PD	plywood disc
	MT	moisture-detection tape
	WB	water-activated battery/transmitter
Insulation	PER	perlite
	EPS	expanded polystyrene
	ISO	polyisocyanurate
	CMP	composite board (iso/perlite)
Membrane Attachment	F	fully adhered
	M	mechanically fastened/ballasted
Module	D	sensor and roof sample assembly
	W	sensor and roof assembly with water added
Lab Condition	1	158 °F - ambient humidity
	2	158 °F - 90% humidity
	3	70 °F - ambient humidity
	4	40 °F - ambient humidity

Note that only four of the five sensor types used electrical signals and required electrical wire for their transmission medium. The water-activated battery sensor uses a radio signal, and once activated, it is no longer functional. Therefore, samples containing these sensors were not monitored during the 30-week exposure period but were tested at the end of this period.

Test Sample Assembly

The 1 ft by 1 ft square test samples, which were fabricated to house the sensors, simulated actual roofing system configurations. Each sample included, from the bottom up: 20-gage galvanized steel decking, 1/2-in.-thick wood fiberboard substrate, laminated asphalt/kraft paper vapor retarder, insulation, and a 45-mil-thick nonreinforced ethylene-propylene-diene monomer (EPDM) membrane covering (Figure 7). The general procedures for assembling the test samples are herein described. First, researchers attached a 1 ft by 1 ft piece of wood fiberboard to the steel deck using two 1-5/8-in. self-tapping screws (Figure 8). The vapor retarder was cut into a 16 in. by 16 in. sheet and 2 in. squares were removed from each corner. The notched corners allowed enough vapor retarder material to seal the sides of the insulation. The vapor retarder was centered on the substrate with the insulation board placed on top. Both were then attached to the wood fiberboard/steel deck assembly using insulation plates and screws of adequate length to penetrate the bottom flanges of the steel deck. The insulation layer in each test sample assembly was comprised of three pieces—one 12 in. by 6 in. piece and two 6 in. by 6 in. pieces, with the larger piece placed parallel to the deck flutes (Figure 9).

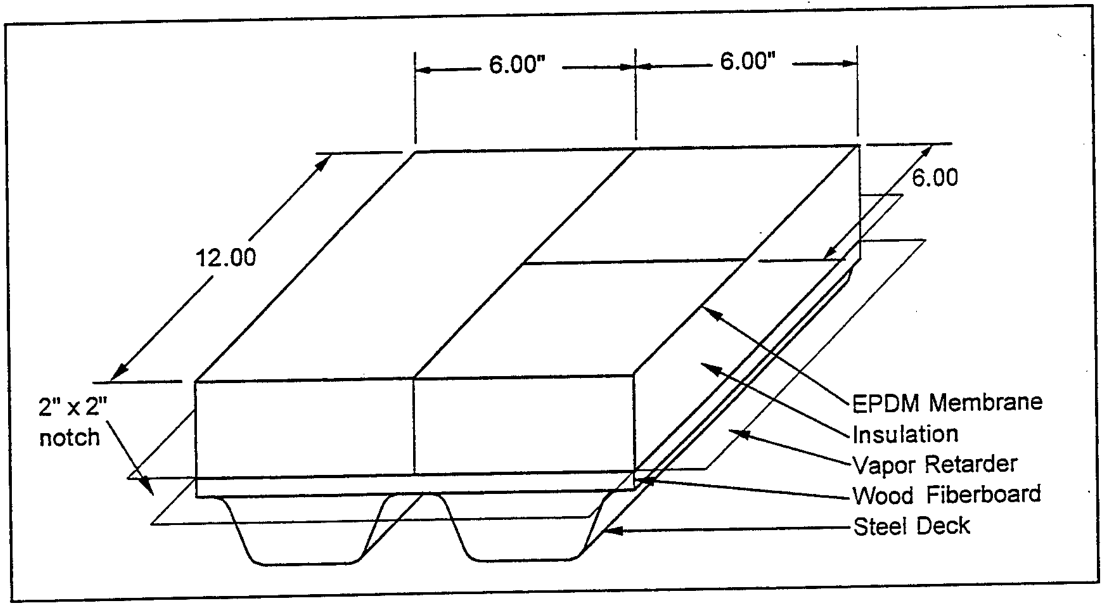


Figure 7. Test sample assembly.

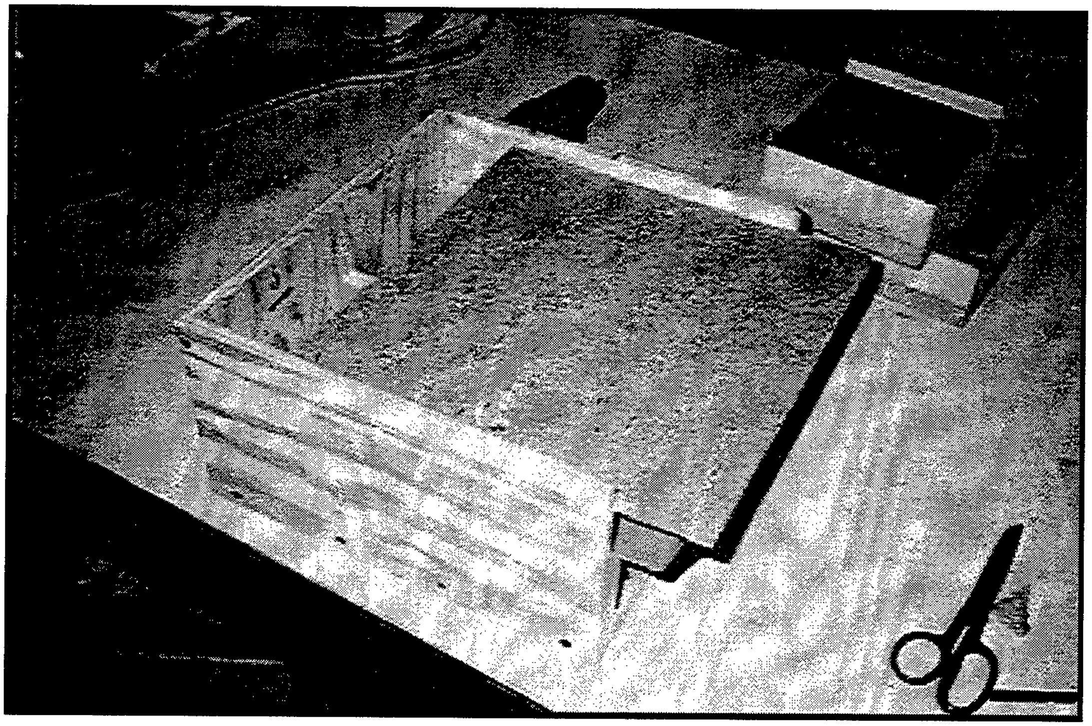


Figure 8. Wood fiberboard attached to steel decking with screws.

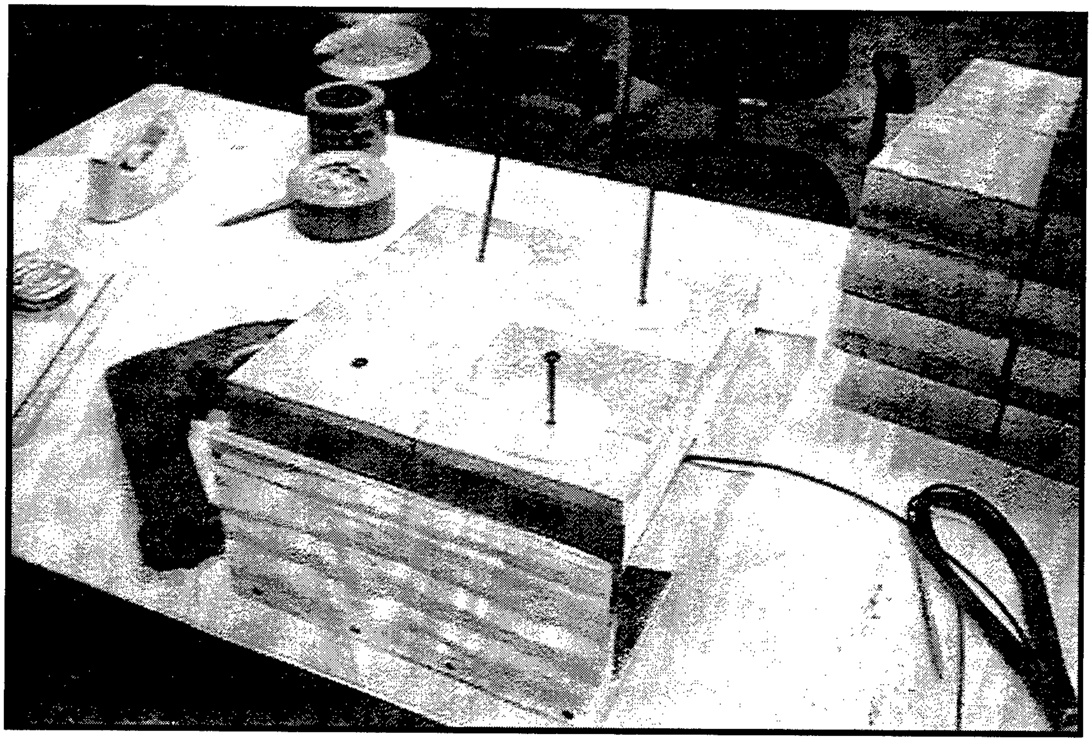


Figure 9. Placement of screws in three insulation pieces.

Finally, researchers adhered the EPDM membrane to the insulation using a bonding adhesive applied to both surfaces. For the samples simulating ballasted /mechanically fastened membrane systems, the membrane was only adhered along a 2-in. width at the perimeter; for samples simulating fully adhered systems, the entire 1-ft-square area of membrane was adhered.

For those samples that were to have water added, additional construction steps were needed. A 2-in.-diameter polyvinyl chloride (PVC) pipe column was adhered to the membrane with silicone sealant. The center of the pipe was placed 3 in. from the outer edge of the large piece of insulation. Prior to placing the pipe, a small hole was drilled through the membrane to a depth of 1/2 in. with a 5/64-in. bit.

Placement of the sensors in each type of test sample is described below.

Resistance Probe

The test samples were constructed as described with the sensor being inserted after the membrane was adhered. Two holes about 3/4 in. apart were drilled through the membrane with a 1/16-in. bit to an approximate depth of 3/4 in. The metal pins of the resistor were inserted into the holes, and the sensor was covered with a 1-1/2 in. by 2 in. patch of self-adhering, uncured EPDM (Figure 10). Finally, a 3 in. by 6 in. patch of the same material was placed over the remaining wire and sensor patch (Figure 11).

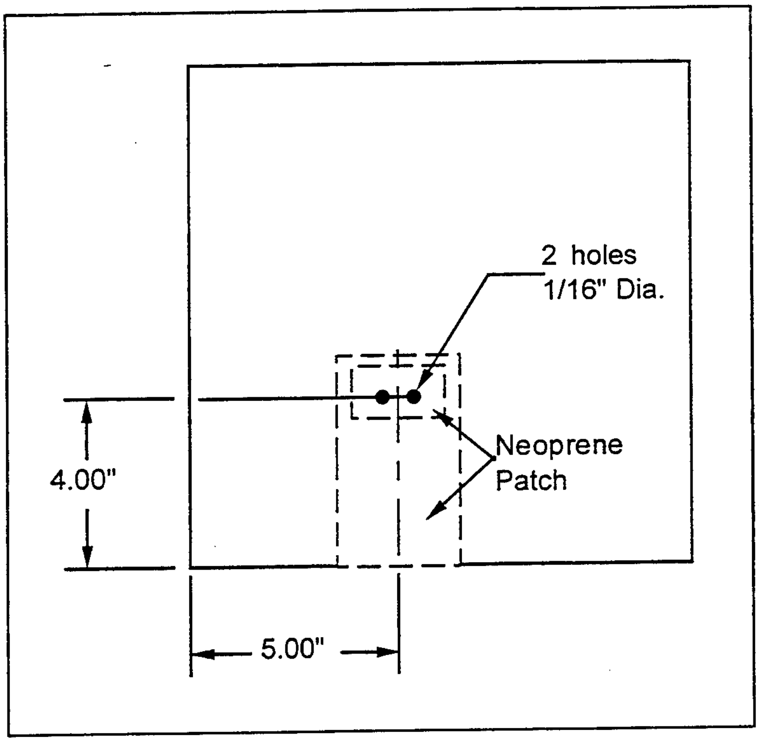


Figure 10. Placement of resistance probe.

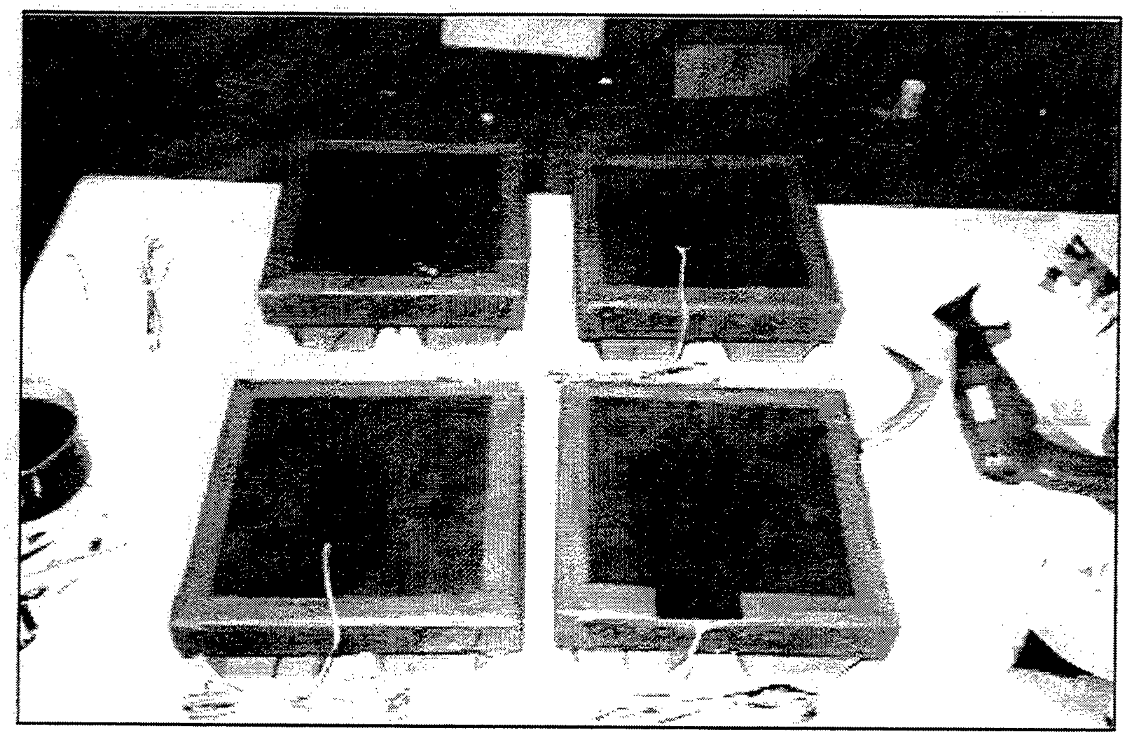


Figure 11. Test sample assemblies for resistance probes.

Wooden Probe

The wooden probe was inserted into the 12 in. by 6 in. piece of attached insulation, as shown in Figure 12. Using a 3/16-in. drill bit, a 1-in. deep hole was bored by hand 3/4 in. up from the bottom and 4 in. from the front edge of the insulation. The sensor was placed in the hole with the wires exiting the sample from the front of the assembly. The remaining two pieces of insulation were then installed and the membrane was adhered to the insulation.

Plywood Disc

A notch was cut into the base of the 12 in. by 6 in. piece of insulation to provide a tight fit for the plywood disc. With the disc inserted into the notch, the insulation was fastened to the substrate assembly. The remaining two pieces of insulation were installed (see Figure 13).

Moisture-detection Tape

Before attaching the insulation, the moisture-detection tape was centered on the vapor retarder 4 in. from the front edge of the sample (Figure 14) and held in place by masking tape. The insulation was then fastened to the substrate assembly. The screws were placed well away from the tape position.

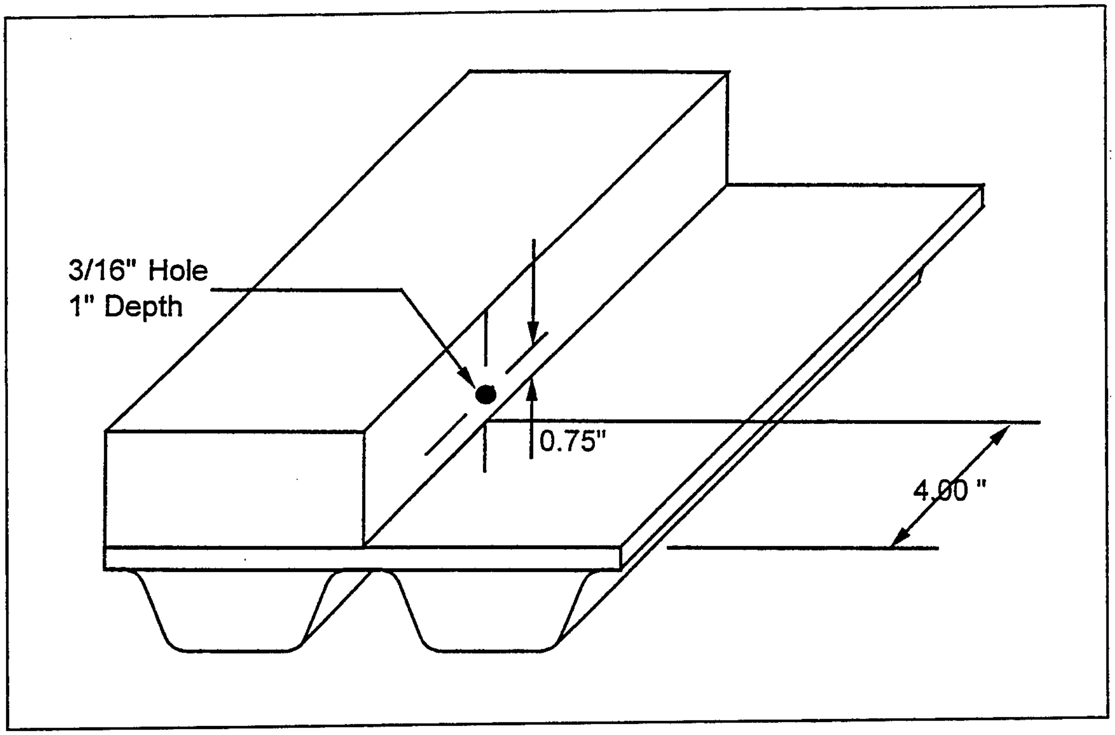


Figure 12. Placement of wooden probe.

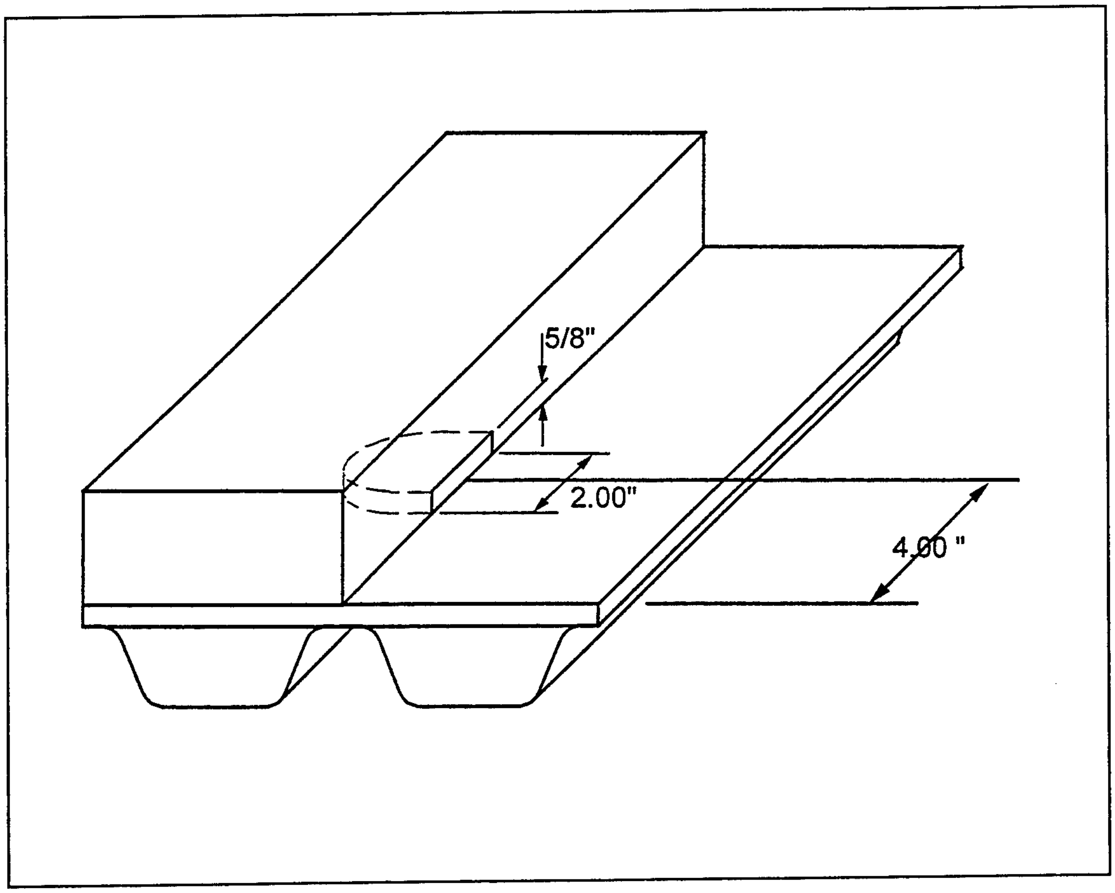


Figure 13. Placement of plywood disc.

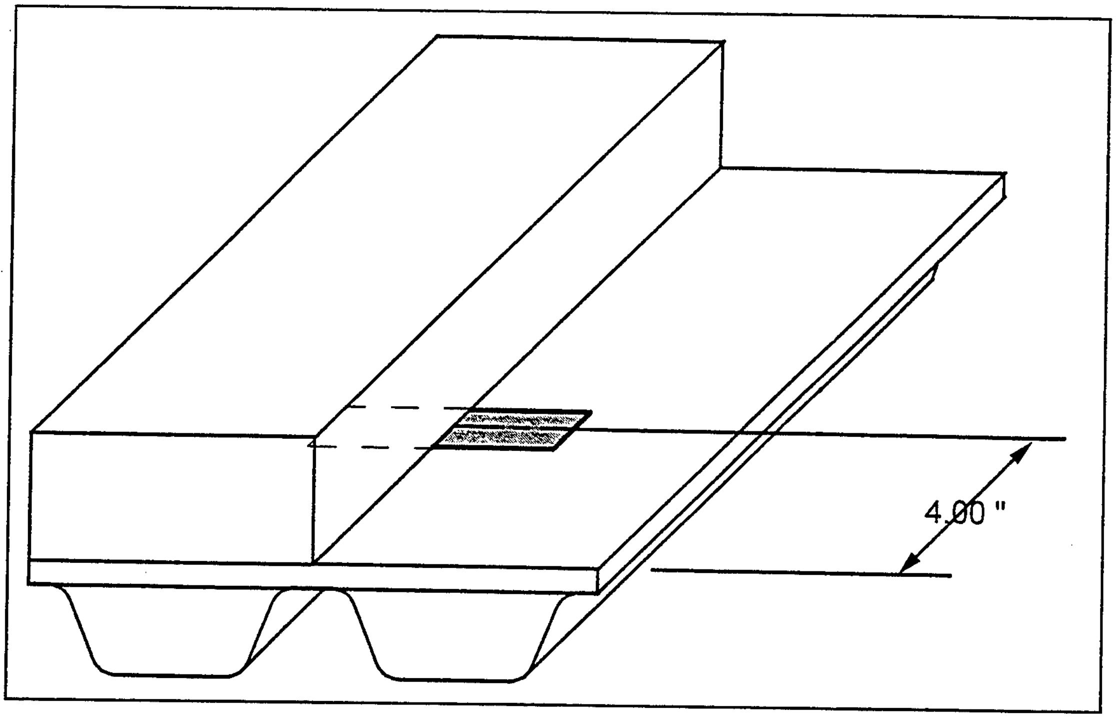


Figure 14. Placement of moisture-detection tape.

Water-activated Battery/Transmitter

Unlike the test samples for the other four sensors, a vapor retarder and second layer of insulation board were placed underneath the top layer of insulation. After the bottom board was fastened to the substrate by screws, a hole large enough to accommodate the sensor was bored into its center using a special tool provided by the sensor manufacturer. A hole of the same size was then cut from the center of the top vapor retarder sheet. The vapor retarder was placed over the insulation, and the water-activated battery was fitted into the hole. The assembly was then covered by the standard three pieces of top insulation, which were screwed into position. Figure 15 shows one phase of the construction.

Data Acquisition System

Figure 16 shows the hardware schematic of the data acquisition system used to process and record the data. Two such setups were necessary because the scanner was limited to 80 data channels. Each sensor was connected to the scanner, which was connected to a power supply and multimeter. The scanner and multimeter were controlled by a personal computer through a standard IEEE-GPIB data acquisition card.

Figure 15. Placement of water-activated battery/transmitter.

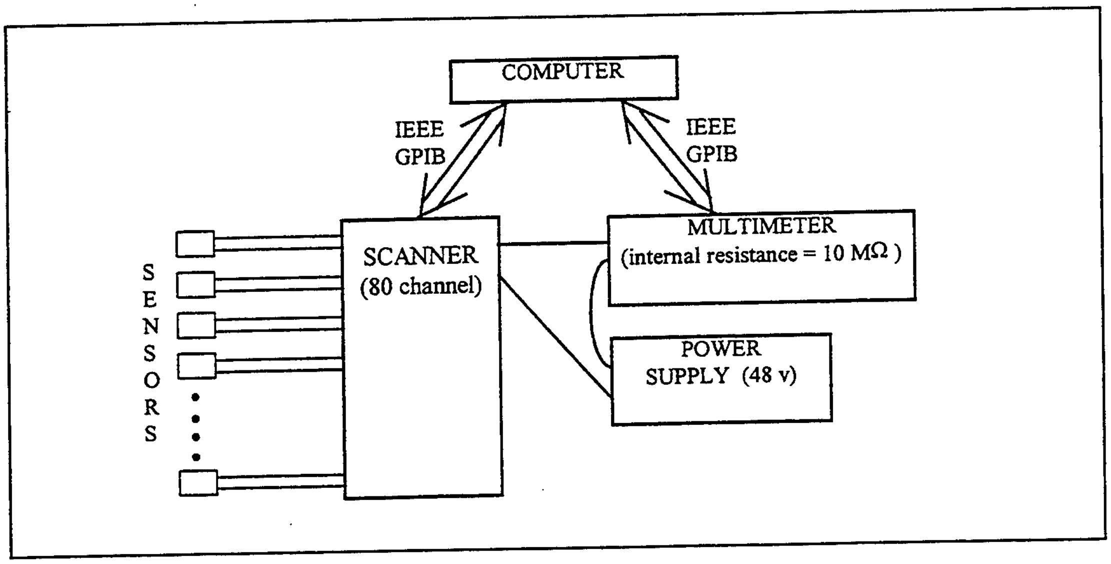


Figure 16. Hardware schematic of data acquisition system.

Because the resistances of most of the sensors were very high (10^9 to 10^{12} ohms in the dry state), the multimeter could not be used in the standard resistance measurement configuration. Instead, the set-up shown in Figure 17 was used. It was necessary to place the multimeter in series with the sensor and power supply and measure the voltage across the internal resistor within the multimeter. The computer converted the voltage reading to a resistance value for the sensor through the use of Equation 2.

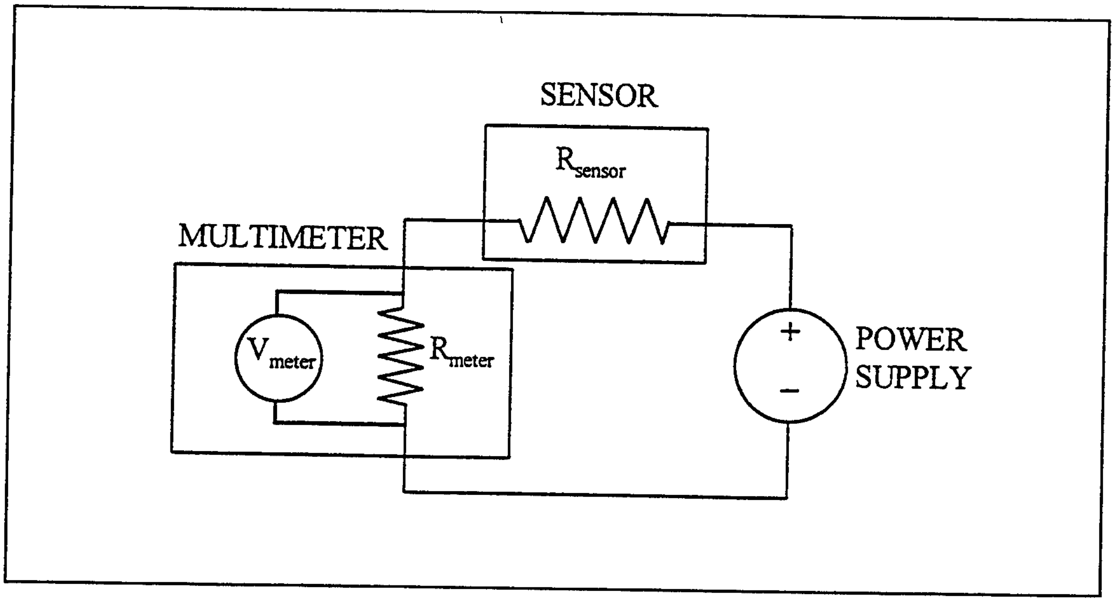


Figure 17. Schematic of resistance measurement circuit.

$$R_{sensor} = \frac{V_{PS} - V_{meter}}{V_{meter} / R_{meter}} \quad \text{[Eq 2]}$$

The uncertainty for extremely high resistances (>10^8 ohms) is roughly ± 20 percent, which is due mostly to the signal noise. For smaller resistance values (<10^7 ohms) the uncertainty is less than 5 percent. Considering that most of the resistances change over more than one order of magnitude, the seemingly large uncertainty is not significant as long as some threshold value can be established to signify the presence of water.

Test Program

Once the wiring was completed and the data acquisition system determined to be operating correctly, all test samples were placed on wood shelves inside the environmental chambers (Figure 18). A total of 144 test samples were used (see Table 2). Along with the sensors placed into the test samples, one free sensor of each type was also placed in each chamber to serve as a control.

A computer program was executed that recorded resistance readings from each sensor on a daily basis. In addition, the test samples in chambers 1 and 3 were subjected every 7 days to a freeze-thaw cycle, which consisted of setting the chambers to 20 °F for approximately 8 hours and then returning them to their normal operating temperatures. Water was added to the module "W" samples according to the schedule in Table 3.

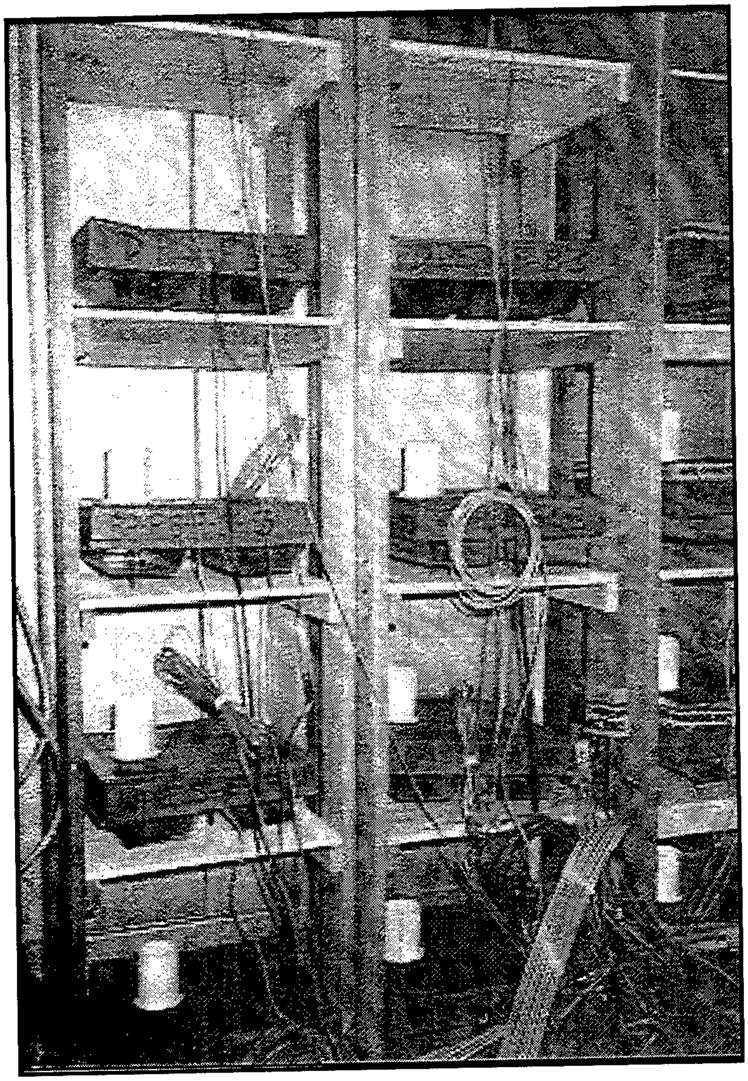


Figure 18. Test sample assemblies placed on wooden shelves in environmental chamber.

Table 2. Array of constructed test samples.

Resistance Probe (RP) Wooden Probe (WP) Plywood Disc (PD) Identification Code	Moisture-detection Tape (MT) Identification Code	Water-activated Battery (WB) Identification Code
XX-A-(1,2,3,4)	MT-A-(1,2,3,4)	WB-A-(1,2,3,4)
XX-ISO-F-D-(1,2,3,4)	MT-PER-M-D-(1,2,3,4)	WB-ISO-M-W-(1,2,3,4)
XX-ISO-F-W-(1,2,3,4)	MT-EPS-M-D-(1,2,3,4)	WB-EPS-M-W-(1,2,3,4)
XX-PER-F-D-(1,2,3,4)	MT-EPS-M-W-(1,2,3,4)	WB-CMP-M-W-(1,2,3,4)
XX-CMP-F-W-(1,2,3,4)	MT-CMP-M-D-(1,2,3,4)	WB-PER-M-W-(1,2,3,4)
XX-CMP-M-D-(1,2,3,4)	MT-CMP-M-W-(1,2,3,4)	WB-CMP-F-W-(1,2,3,4)
XX-CMP-M-W-(1,2,3,4)	MT-CMP-F-D-(1,2,3,4)	
	MT-CMP-F-W-(1,2,3,4)	

Table 3. Schedule for water addition.

Time (days)	Time Period	Time (days)	Time Period
0	D	82	B
7	A	89	D
14	A	96	D
19	A	103	B
26	A	110	D
33	A	117	D
40	A	124	D
47	D	131	D
54	D	138	D
61	A	145	D
68	D	152	D
75	D	159	D

A: Add 1/2 in. of water (approximately 3.6 oz)
B: Add 3/4 in. of water (approximately 5.4 oz)
D: No water added

The W modules containing the water-activated battery sensors were treated differently. Because these sensors are no longer functional after being activated, no water was added to them during the course of the experiment. After completion of the 30 weeks of exposure, the samples were removed from the chambers, and water was continually added to each of the water battery samples until sensor activation.

Discussion of Results

Because of the large amount of data generated, only the beginning weeks and the last week of data for each sensor are presented.

As is often the case with experiments of this length, problems occurred during the 30-wk test period. Power outages caused gaps in the data and temporarily changed the temperature and humidity in the affected environmental chambers. Both the chamber set at 40 °F/ambient humidity and the chamber set at 160 °F/90 percent humidity malfunctioned and had to be shut down temporarily during the experiment. The high temperature/high humidity chamber had other problems. Early in the experiment, the high humidity caused water to liquify on the exposed terminal strips to which all of the sensors were connected. This water formation shorted the contacts and produced invalid measurements. The problem resulted in another period where the chamber had to be shut down for a few days to allow the chambers to partially dry. During the last weeks of the experiment, corrosion of the terminal strips in the same chamber resulted in invalid sensor readings.

Three main characteristics of the data were investigated. First, the resistances of the sensors in test samples without water added (D modules) were examined to determine the degradation of the sensor signals over exposure time. Secondly, the readings from these sensors defined the nominal resistance levels for each environmental condition. Finally, the resistance histories of the sensors in the test samples with water added (W modules) were examined to determine their sensitivity to induced moisture as well as to define the characteristic threshold resistance values. The threshold resistance for this study was defined as the resistance level that indicated the presence of liquid water in the insulation system.

Nominal and Threshold Resistances

From examination of the data, nominal resistance values were established for the different sensor types (resistance probe: 50×10^3, wooden probe: 1×10^9, plywood disc: 1×10^8, moisture-detection tape: 5×10^8). The threshold resistance for the resistance probe was set at 45×10^3 ohms, and the threshold resistances for the other three sensors were set at 5×10^7 ohms.

Resistance Probe

Figure 19 shows the response of the resistance probes in the four different roofing system configurations. The probe in the fully adhered composite insulation at room temperature and ambient humidity was the only one to register a significant decrease in resistance, which indicated an increase in moisture content of the insulation (as was shown by comparing the readings at 21 days and after 142 days). It is possible that the probe in polyisocyanurate exposed to high temperature and ambient humidity registered the presence of a leak, but data are inconclusive. The probe in the mechanically fastened composite insulation at high temperature and humidity read a drop in resistance before water was added to the system, indicating that the high humidity environment was the cause for the insulation moisture content to rise. The readings from the remaining probes were nearly constant over the duration of the experiment, with minor fluctuations attributable to signal noise. Except for the cases previously mentioned, the sensors did not measure any noticeable increase in moisture content of the insulation, despite the addition of water to some of the test samples. The resistance probes were inserted on top of the insulation, and, because the water introduced into the W modules would flow downward, it is highly probable that the insulation near the sensors absorbed very little water.

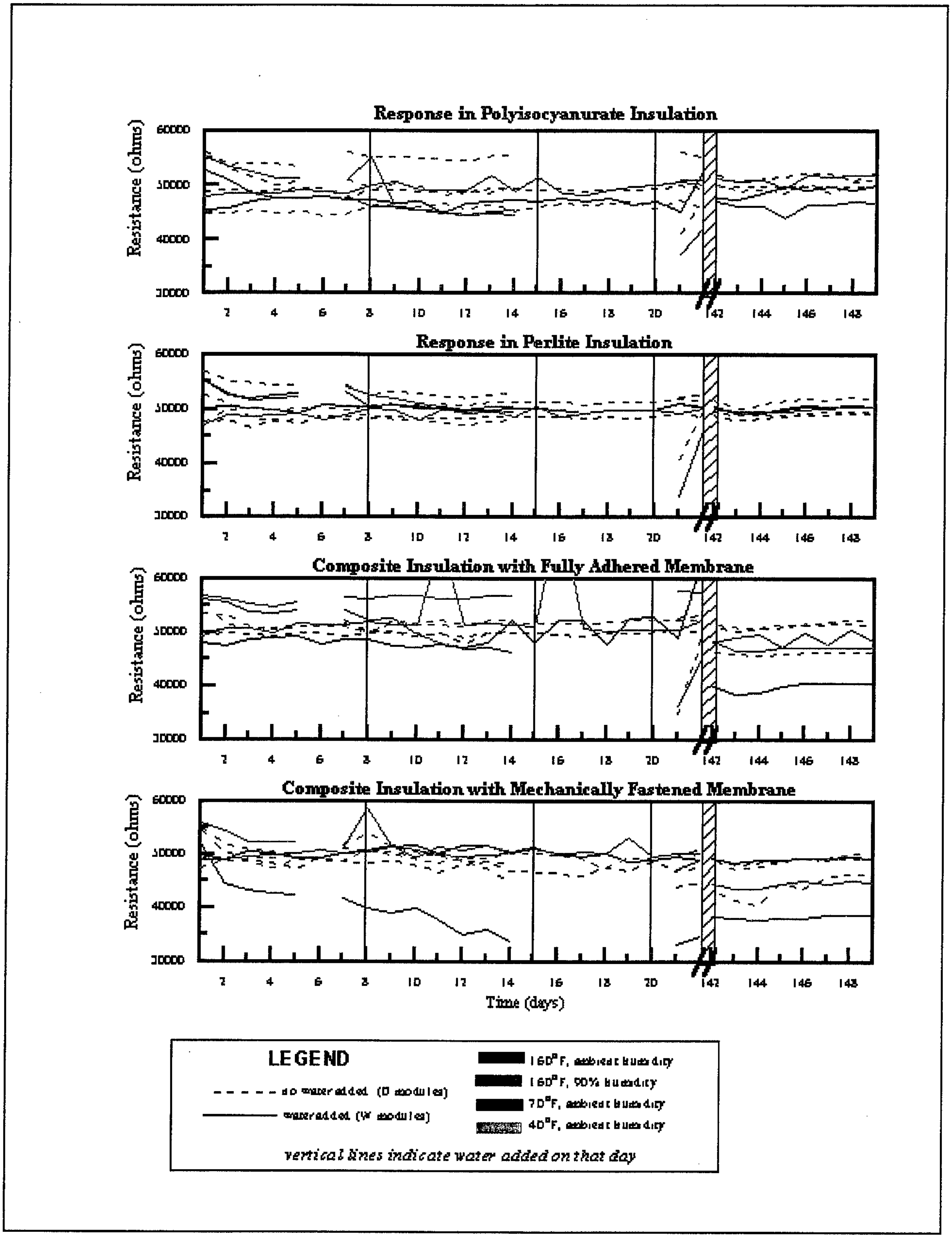


Figure 19. Results for resistance probe.

Wooden Probe

The responses of the wooden probes are presented in Figure 20, and Table 4 summarizes the following analysis. With regard to nominal resistance, a slight drop in resistance was indicated for all of the D-module test samples through the duration of the experiment, which might have been caused by the normal increase in ambient humidity from when the experiment started in March to when it ended in August. Based on a comparison between the modules with and without water added, it was determined that a resistance decrease of about two orders of magnitude is necessary to indicate a sensor detected the presence of water. In addition, the sensors in the W modules at the high temperature/high humidity conditions recorded a larger initial resistance decrease than those in the D modules prior to day 8—when water was first added. A possible cause was that the holes made for allowing water entry in the membrane of the W modules permitted the intrusion of humidity while the D modules were tightly sealed. This difference made it almost impossible to determine if these sensors were detecting extremely high humidity or the presence of a leak.

For the test samples with polyisocyanurate, the sensors in the W modules at room temperature and at 40 °F recorded drops in resistance of between 2 and 3 orders of magnitude, indicating the increase of moisture in the probe. The resistance decrease for the sensor at room temperature came on day 15, the second time water was added. The resistance of both sensors returned to the level of those in the D modules after 142 days, indicating that the modules were able to dry out.

For the perlite insulation configuration, the wooden probe in the cold chamber may have detected the presence of a leak; the data are inconclusive. The consistently low readings also indicate faulty probes in the W modules of the high temperature/ambient humidity and the room temperature chambers.

The majority of the wooden probes in the composite insulation with either the mechanically fastened or fully adhered membrane did not detect any water. Only the sensor in the cold chamber with the fully adhered membrane and the sensor in the room temperature chamber with the mechanically fastened membrane showed a significant drop in resistance, indicating water absorption. The sensor in the cold chamber with the mechanically fastened membrane possibly registered the presence of water, but the response was extremely slow and the resistance did not drop below the threshold level. The reason for the unusual increase in resistance of the probe in the mechanically fastened composite insulation at high temperature and high humidity is unknown.

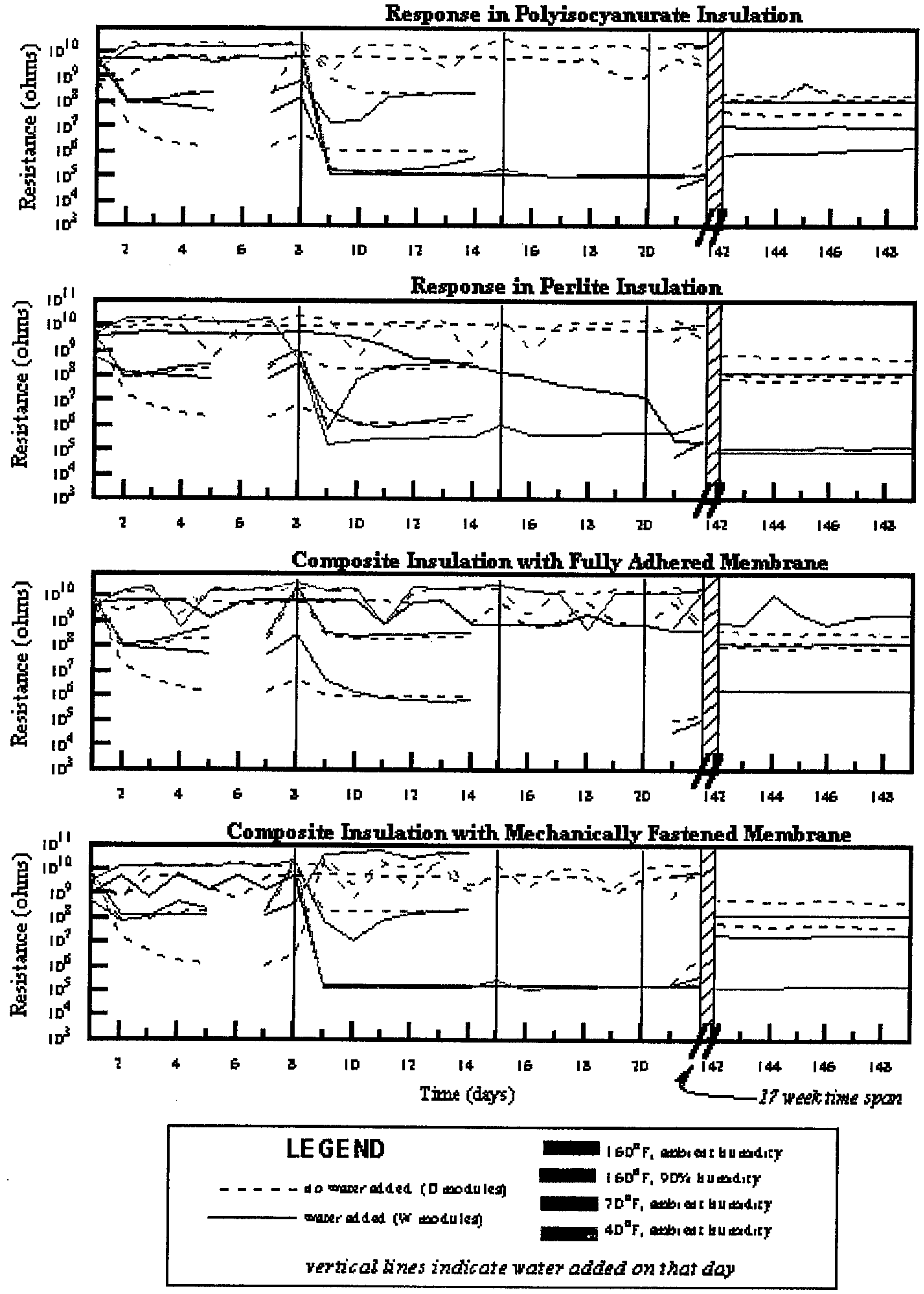


Figure 20. Results for wooden probe.

Table 4. Responses for wooden probes.

Insulation Type	Chamber Conditions	Water Detected	Comments
polyisocyanurate	160 °F, amb. hum.	--	resistance did not go below threshold
	160 °F, 90% hum.	uncertain	insufficient data due to chamber problems
	70 °F, amb. hum.	yes	resistance dropped after second addition of water
	40 °F, amb. hum.	yes	drying effects can be seen
perlite	160 °F, amb. hum.	--	faulty sensor: possible short in the system
	160 °F, 90% hum.	uncertain	insufficient data due to chamber problems
	70 °F, amb. hum.	uncertain	
	40 °F, amb. hum.	uncertain	probably some random signal fluctuations
composite—fully adhered	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	--	
	40 °F, amb. hum.	yes	slow response—significant drop at 15 days
composite—mechanically fastened	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	yes	slow response—no significant quick drop in R
	40 °F, amb. hum.	probably	possible slow response (see Appendix)

Plywood Disc

Figure 21 shows the resistance measurement histories for the plywood disc sensors. The sensor signals displayed decreases in nominal resistance of slightly less than two orders of magnitude from beginning to end. As with the wooden probes, these decreases might also have been caused by the expected increase in ambient humidity. Even with these decreases, the nominal resistance values were still significantly higher than resistance values of several W modules after water was added. Figure 22 shows that the resistances of the D-module sensors at high humidity decreased during the initial stages of the experiment. The reason for this initial resistance decrease is unknown. Because of this decrease, however, comparisons between the water-added and the no-water-added modules in high temperature/high humidity environment cannot be made. Because the plywood disc sensors were located on the bottom of the insulation, it is possible that more water reached them compared to the resistance and wooden probes, which were surrounded by the insulation. The vertical placement must be considered when any comparisons between sensor types are made.

All of the W-module plywood disc sensors in the polyisocyanurate with the induced leak detected water. For sensors in the cold and room-temperature chambers, the addition of water into the samples was indicated by a large drop in resistance. The resistance of the W module sensor in the high temperature/ambient humidity chamber only decreased by one order of magnitude, but it was lower the any of the readings recorded by the D module sensor in the same insulation configuration. Similar results are seen for the sensors in perlite

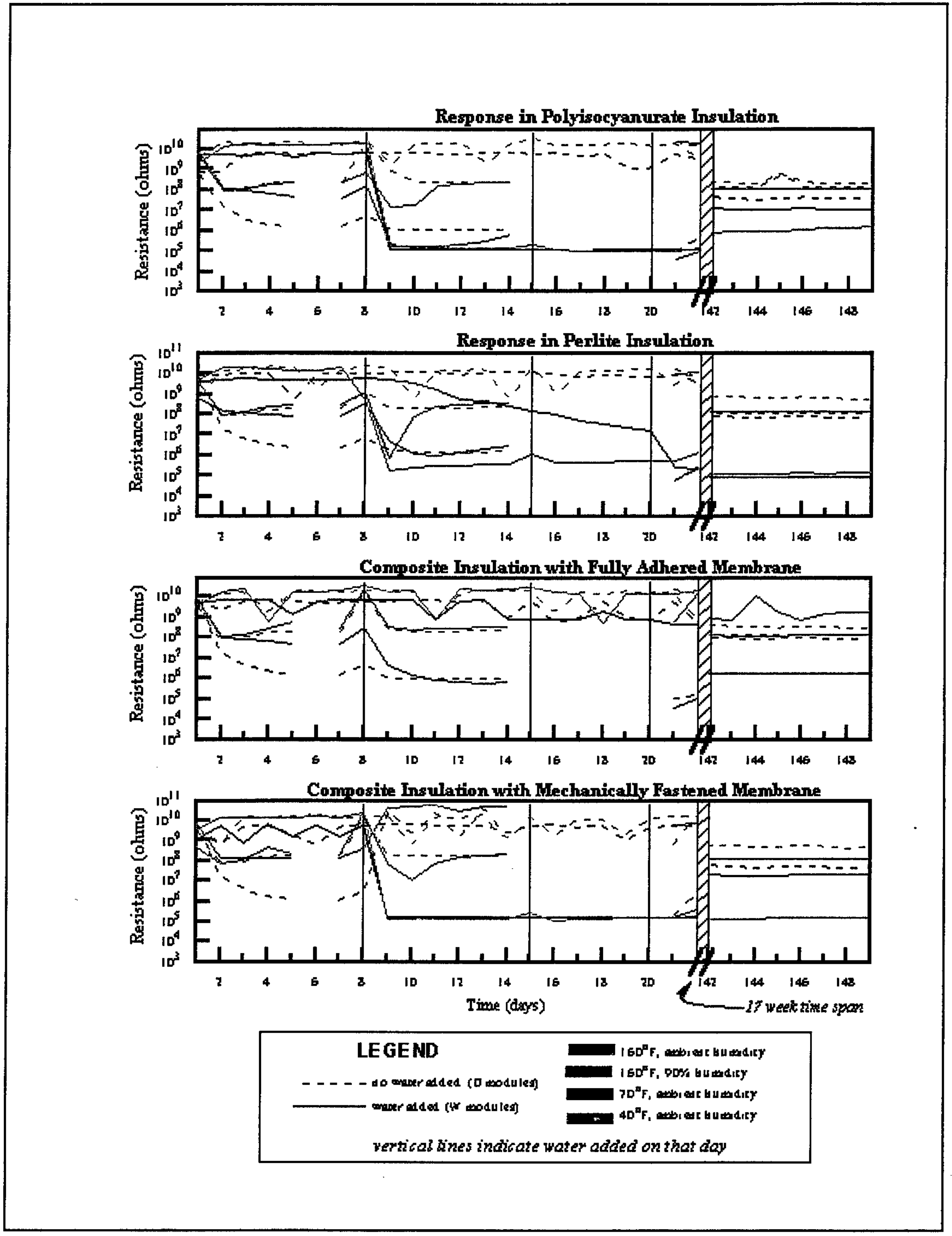


Figure 21. Results for plywood disc probe.

insulation configuration. Similar results are seen for the sensors in perlite insulation, though the response of the sensor at room temperature was considerably slower. Also, slight differences in the drying characteristics occurred between the plywood disc sensors in the polyisocyanurate and perlite insulations. Those sensors in the polyisocyanurate exhibited some drying effects, but those in perlite did not.

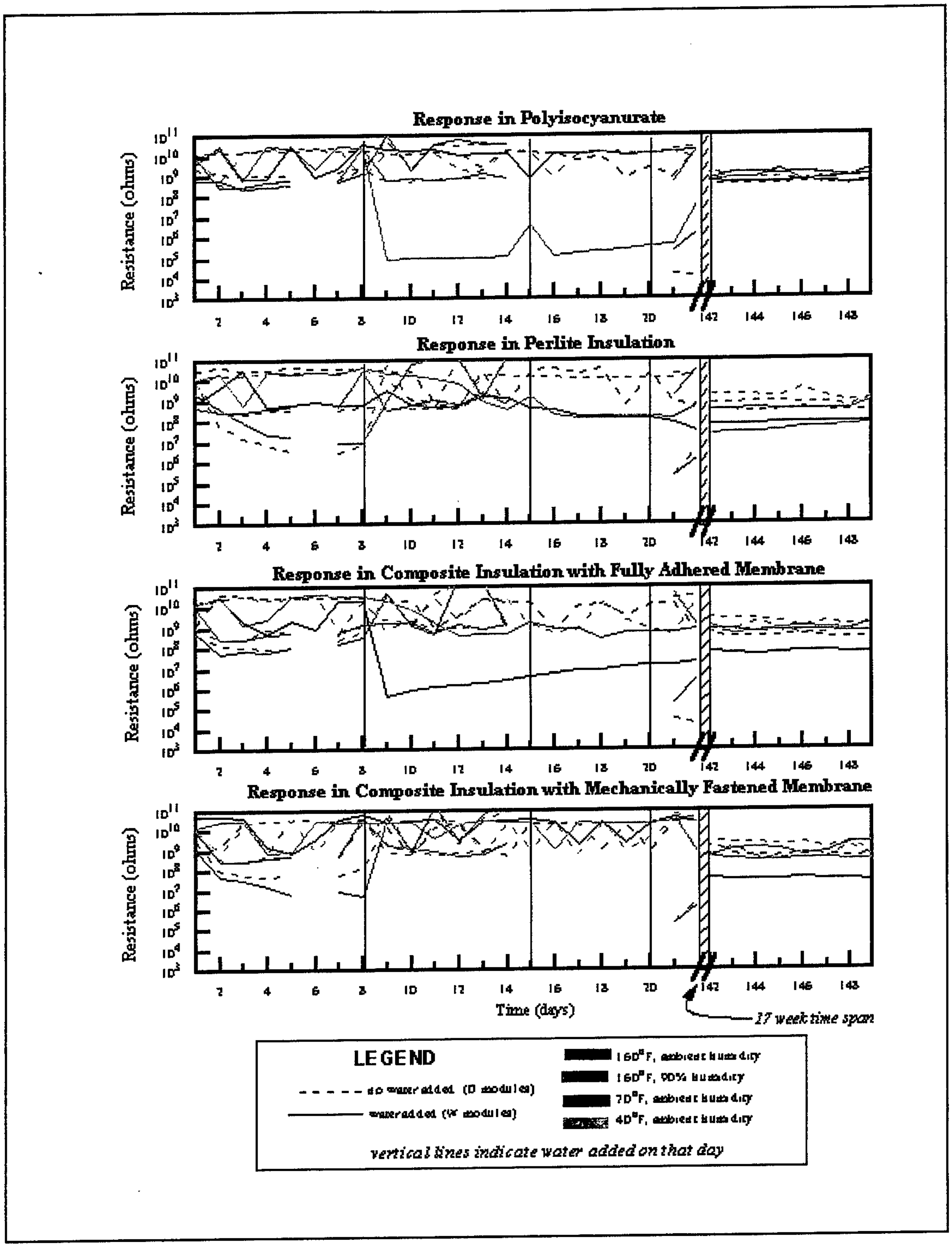


Figure 22. Results for moisture-detection tape.

For the composite insulation assemblies, it appears that the plywood disc at room temperature with the fully adhered membrane eventually detected water, but the response was a few weeks after the first introduction of leak water into the system. The sensors in the composite insulation with the mechanically fastened membrane in the cold and room-temperature chambers detected an increased moisture content at a much faster rate. Both recorded a significant drop in resistance the first time water was added. The sensor in the mechanically fastened membrane module at in the high temperature/ambient humidity chamber probably also detected the leak, but the decrease was only one order of magnitude below the apparent nominal value; therefore, the data are inconclusive. Table 5 summarizes the entire set of results for the plywood discs.

Moisture-detection Tape

The response characteristics of the moisture-detection tape sensors are presented in Figure 22, and Table 6 summarizes the following analysis. In the W modules, the sensors of only two roof assembly/chamber conditions clearly detected the addition of water. These detections were evident by the sudden large drop in resistance by the tapes in the polyisocyanurate at 40 °F and in the composite insulation with the fully adhered membrane at room temperature. The response of the two sensors at cold and room temperatures in perlite show a slow decrease in resistance that could be caused by the presence of water, but the expected response of the tape to water is a quick drop in resistance. For all of the D modules, the nominal resistances of the sensors over the 30 weeks decreased by roughly one order of magnitude, irrespective of environment.

Table 5. Responses for plywood discs.

Insulation Type	Chamber Conditions	Water Detected	Comments
Polyisocyanurate	160 °F, amb. hum.	probable	noticeable but small resistance decrease
	160 °F, 90% hum.	--	invalid data
	70 °F, amb. hum.	yes	sharp drop; some drying seen
	40 °F, amb. hum.	yes	sharp drop; very little drying
perlite	160 °F, amb. hum.	yes	sharp drop; quick drying
	160 °F, 90% hum.	--	invalid data
	70 °F, amb. hum.	yes	slow response, no drying
	40 °F, amb. hum.	yes	sharp drop; no drying
composite--fully adhered	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	invalid data
	70 °F, amb. hum.	yes	slow response (see Appendix)
	40 °F, amb. hum.	--	
composite--mechanically fastened	160 °F, amb. hum.	uncertain	small drop
	160 °F, 90% hum.	--	invalid data
	70 °F, amb. hum.	yes	some drying
	40 °F, amb. hum.	yes	no drying

Table 6. Responses for moisture-detection tapes.

Insulation Type	Chamber Conditions	Water Detected	Comments
polyisocyanurate	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	--	
	40 °F, amb. hum.	yes	freeze-thaw effect at day 15; drying
perlite	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	possibly	slow response; not the characteristic sharp drop
	40 °F, amb. hum.	possibly	slow response; not the characteristic sharp drop
composite--fully adhered	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	--	
	40 °F, amb. hum.	--	
composite--mechanically fastened	160 °F, amb. hum.	--	
	160 °F, 90% hum.	--	insufficient data due to chamber problems
	70 °F, amb. hum.	yes	almost no drying
	40 °F, amb. hum.	--	

Water-activated Battery/Transmitter

After 30 weeks of exposure, all of the sensors were successfully triggered except those exposed to the high temperature and humidity conditions and the sensor in composite insulation with the mechanically fastened membrane in the high temperature/ambient humidity chamber (Table 7).

Table 7. Responses for water-activated battery/transmitters.

Insulation Type	Chamber Conditions	Water Detected	Comments
polyisocyanurate	160 °F, amb. hum.	yes	>200 mL water
	160 °F, 90% hum.	--	highly corroded
	70°F, amb. hum.	yes	≈150 mL water
	40 °F, amb. hum.	--	sensor casing was not sealed properly—corroded
perlite	160 °F, amb. hum.	yes	≈150 mL water
	160 °F, 90% hum.	--	highly corroded
	70 °F, amb. hum.	yes	>200 mL water
	40 °F, amb. hum.	--	damaged circuit board
composite—fully adhered	160 °F, amb. hum.	yes	>200 mL water
	160 °F, 90% hum.	--	highly corroded
	70 °F, amb. hum.	yes	>200 mL water
	40 °F, amb. hum.	yes	>200 mL water
composite—mechanically fastened	160 °F, amb. hum.	--	unknown reason for sensor failure
	160 °F, 90% hum.	--	highly corroded
	70 °F, amb. hum.	yes	>200 mL water
	40°F, amb. hum.	yes	≈100 mL water
expanded polystyrene	160 °F, amb. hum.	yes	≈30 mL water
	160 °F, 90% hum.	--	highly corroded
	70 °F, amb. hum.	yes	≈30 mL water
	40 °F, amb. hum.	yes	≈100 mL water

The sensors that failed to activate were removed from the insulation and a 9-V power supply was attached to their transmitter circuit boards. In all cases, the sensors again failed to trigger. Even with the proper power source attached to the circuit board, the sensors failed to trigger. Note that the levels of water vapor present in the high temperature/high humidity chamber were much higher than can be expected in typical roofing systems. Examination of the sensors showed the circuit boards within the plastic casings to be highly corroded. It is speculated that the sensor casing in the mechanically fastened composite insulation at high temperature and ambient humidity must not have been completely sealed to allow for the degree of corrosion found.

Summary

Except for the water-activated battery/transmitter in the high temperature/high humidity chamber, all of the sensors endured the 30 weeks of accelerated aging conditions fairly well. The resistance sensors (resistance probe, wooden probe, and plywood disc) and the moisture-detection tape exhibited little change in their nominal readings through 30 weeks of different exposures. The slight drop over time of the resistance readings from the wooden probe and plywood disc were likely due to an increase in ambient relativity humidity within the chambers.

For all but the resistance probe, some occurrences of leak water were detected. The lack of detections from the resistance probes were possibly because of: (1) placement of the sensor in the top face of the insulation board instead of near the underlying vapor retarder where the leak water accumulated and (2) requirement for the insulation to absorb large amounts of moisture to achieve noticeable drops in resistance. Placement of these sensors was further investigated in Phase II.

4 Laboratory Investigation, Phase II

The purposes of Phase II were to assess sensor and overall PRLDS performance and to evaluate sensor placement and other variables such as insulation material type and roofing system configuration.

The sensors were placed in test setups that consisted of a 168-sq-ft sloped test roof supported by a plywood deck. Each setup included three variables: sensors, insulation type, and membrane attachment. A leak was simulated in the test roof, allowing water to penetrate the roofing system. Sensor signals were monitored for several days until the sensor signals and/or water flow indicated stabilization of water migration within the system.

Test Setup

The test setup included a 14 ft by 12 ft table with a deck constructed of 3/4 in. plywood. Wood joist framing and 4 in. by 4 in. posts at the corners comprised the supporting structure for the deck. The 14 ft dimension was sloped at 1 inch per foot (Figure 23). The overlying roofing system consisted of a polyethylene vapor retarder, insulation, and a 45-mil nonreinforced EPDM membrane covering. During application of the roofing system components, the sensors were placed at different locations on the table. Using a supply carboy, plastic tub, and float valve, water was maintained at a constant level over a hole created in the membrane at the upslope side and allowed to penetrate the roofing system. Drainage at the downslope edge of the table aided in channeling excess water out of the system.

Different membrane attachments were studied in the investigations. A non-adhered membrane was used to simulate loose-laid and mechanically fastened systems. For test setups with these membranes, the EPDM sheet was laid over the insulation and ballasted with a concrete block placed near each corner. For the test setups simulating fully adhered systems, the EPDM membrane was attached to the insulation using a bonding adhesive applied to both the top of the insulation and the underside of the sheet (Figure 24). The different types of insulation board stock used in the test setups included 2-in. expanded polystyrene (EPS), 2-in. polyisocyanurate, and 1-in. perlite. In all setups, the polyethylene vapor retarder was taped to the deck and the insulation boards attached using insulation plates and screws.

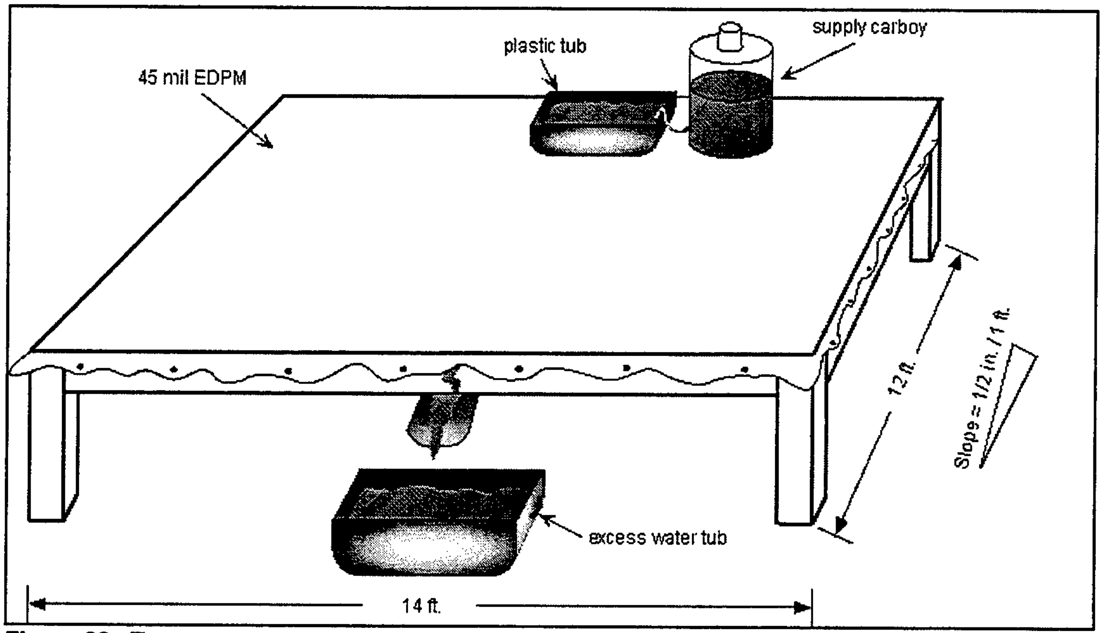


Figure 23. Test setup.

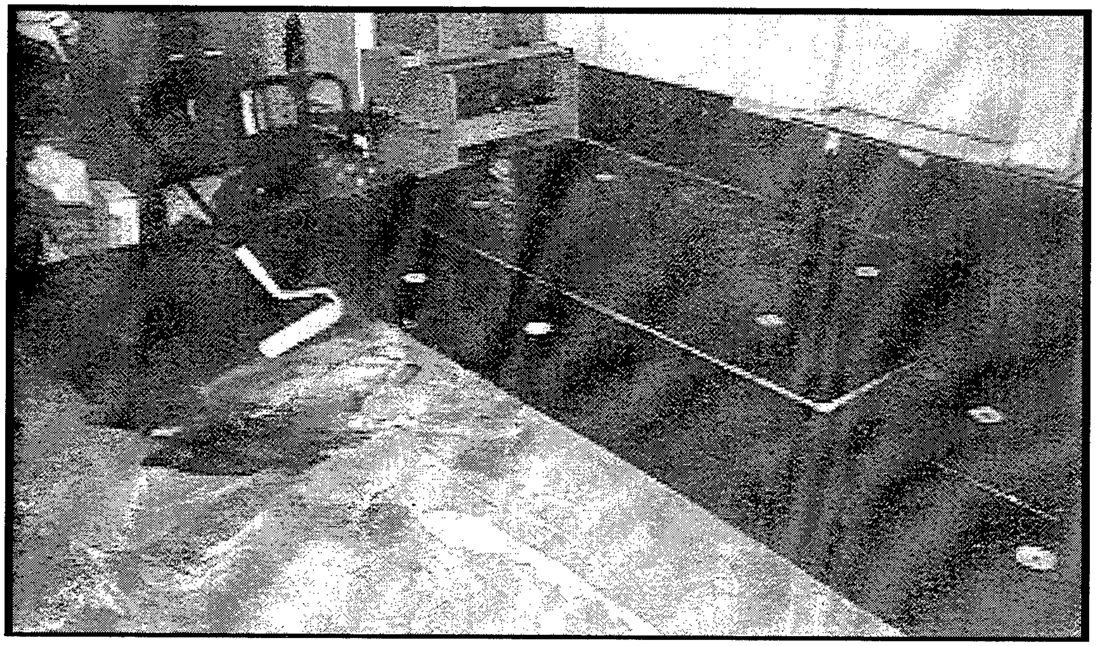


Figure 24. Application of bonding adhesive to back of EPDM membrane.

Sensor Group A

The four sensors requiring resistance measurements (resistance probe, wooden probe, plywood disc, and moisture-detection tape) made up sensor group A. These sensors were evaluated in five separate test setups, each having different roofing system design configurations. These configurations included nonadhered membranes over single layers of EPS, polyisocyanurate, and perlite insulation, and fully adhered membranes over single layers of polyisocyanurate and perlite insulation.

For each setup, a bundle of sensors was placed at five different locations on the table. Each bundle included two resistance probes, two wooden probes, a plywood disc and a 6-in. length of moisture-detection tape. The sensors were installed in the same manner for each bundle. For each resistance probe, two holes were made through the insulation about 3/4 in. apart and to a depth of 3.4 in. using a 1/16-in. drill bit. The metal pins of the sensor were inserted into the holes in the insulation and held in place by masking tape. One resistance probe was installed through the top face of the insulation, and the other through the edge face. The wooden probes were placed in 3/16-in. diameter holes, which were bored into the edge face of the insulation to a depth of approximately 1 in. One probe was placed in the top half of the board, and the other was placed in the bottom half. For the plywood discs, a notch was cut from the bottom face of the insulation to provide a tight fit for the sensor. With the disc inserted into the notch, the wire was taped to the substrate assembly. The moisture-detection tape was placed onto the vapor retarder in a position perpendicular to and centered around the joint between insulation boards.

The pairs of conductive wires from each sensor were placed on top of the insulation for the setups having nonadhered membranes (Figure 25). For the setups with fully adhered membranes, a flat ribbon cable was placed below the insulation layer. The conductive wires were connected to a data acquisition system similar to the one used in Phase I, with a new computer program written to record resistance readings every hour.

Except for the resistance probe, the values for nominal and threshold resistance listed in the "Discussion of Results" (Chapter 3) were used to identify leak detection in Phase II. For the data acquisition setup for Phase II, the nominal resistance for the resistance probes was determined to be 44×10^3 ohms and the threshold limit was set at 40×10^3 ohms. The lower nominal reading, as compared with 50×10^3 ohms for Phase I, is likely due to absorption of moisture in the insulation boards during storage. Until used, the boards were kept stacked in a room without air conditioning during the hot, humid months of July and August.

Sensor Group B

Sensor group B (water-activated battery/transmitter and water-sensing cable) was evaluated in three separate test setups, each of which had nonadhered membranes with double layers of insulation board. One setup used EPS insulation, one used polyisocyanurate, and the third used EPS with a second vapor retarder of polyethylene sheeting placed between the two layers of insulation. In all cases, the two layers of insulation were placed with staggered joints. For the two setups with the single vapor retarder, the board joints of the bottom insulation layer were taped along the top surface to restrict water from flowing vertically at the joints.

Two water-activated battery/transmitter sensors were placed at different positions in each setup. As instructed by the company, the sensors were installed on the top side of the bottom insulation layer below board joints in the top layer. For each sensor, a plug of proper depth and diameter was cut and removed from the top face of the insulation board. The sensor was then placed in the remaining hole, and its surrounding outer lip was sealed to the insulation using a silicon sealant. For the setup having the second vapor retarder between insulation layers, an "X" was cut into the polyethylene sheet to allow for installation of the sensor.

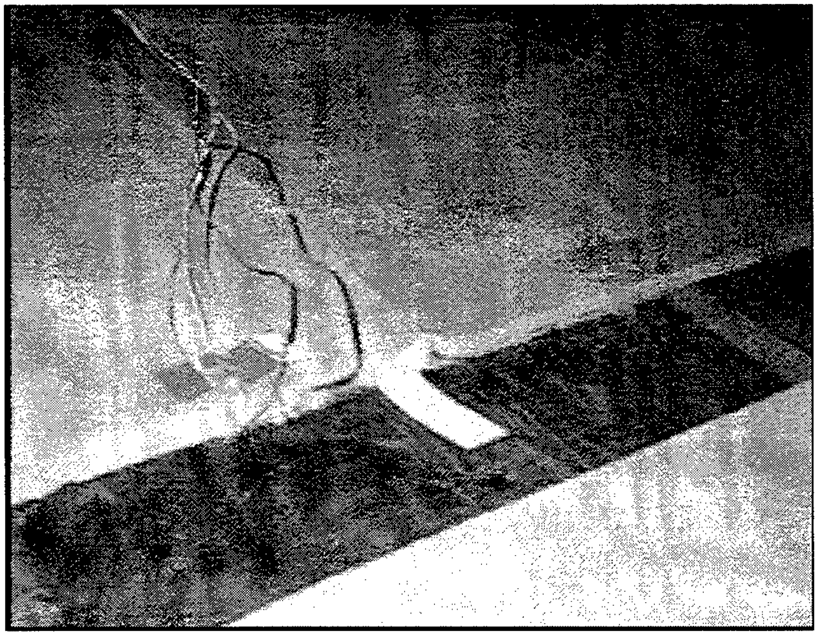


Figure 25. Conductive wires placed on top of insulation for setups with nonadhered membranes.

For all three setups, the water-sensing cables were placed in "V" shaped channels, which were cut into the underside of the insulation board (Figure 26). These channels accommodated the cables while ensuring a flat, even substrate. They were cut with a utility knife, which was a tedious operation. Two cables were placed below the top layer of insulation and two cables below the bottom layer. Accessories provided by the system manufacturer, such as "T" connectors/adapters and end termination caps, were used with the cable to simulate a cable network used in actual field implementations of the system.

The signal processing unit for both the water-activated battery/transmitter sensors and water-sensing cable system were placed adjacent to the test setup. For the water-sensing cable system, the signal processing unit identifies the distance (in lineal feet) from the point along the cable where the first leak is detected to the origin of the cable. When leaks occur at more than one point along the cable, an effective length is computed by the unit. During evaluation of the system prior to the Phase I investigation, the researchers were unable to successfully locate multiple detection points based on effective length readings. For this reason, the location is provided only for the first leak detected by the water-sensing cable for each setup.

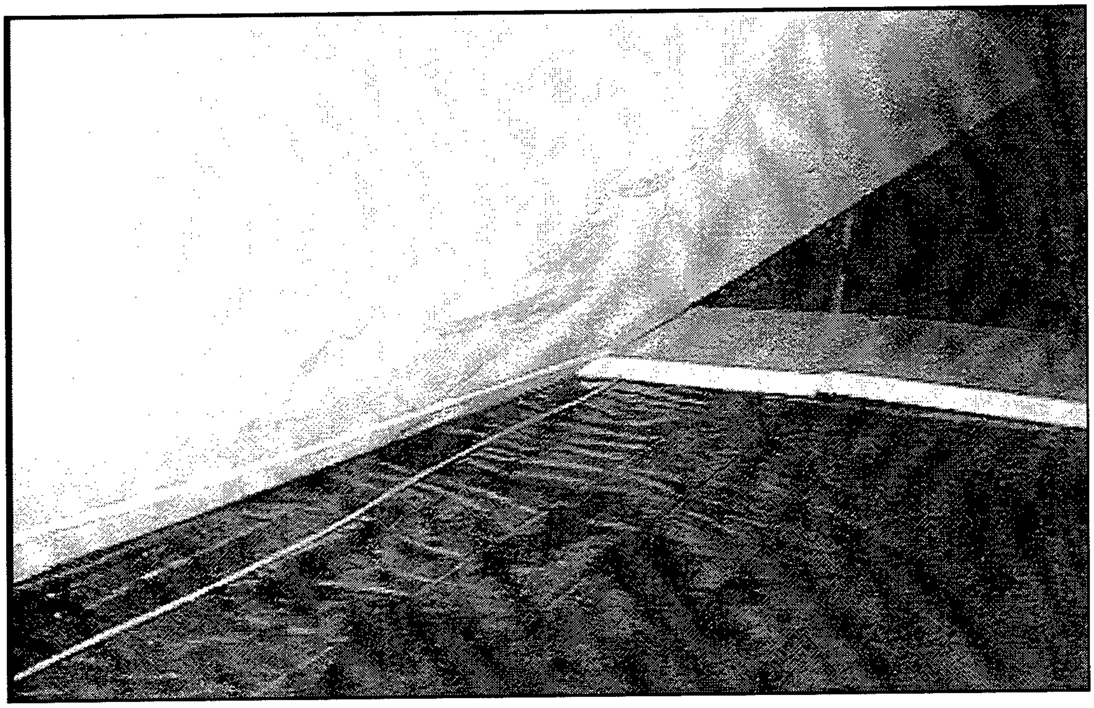


Figure 26. V-shaped channel cut in bottom of EPS board for receiving water-sensing cable.

Discussion of Results

After construction of a setup was completed, the test was initiated by opening the stopcock to a carboy and allowing water to flow into a retention tub (Figure 27). The retention tub had a large hole cut in the bottom, which was placed over the membrane hole. The edges of the tub around the hole were sealed to the membrane with EPDM flashing tape. A float valve was used to maintain a head of approximately 2-1/2 in. above the leak hole in the membrane. The sensor readings and flow rates of water into and out of the roofing system were monitored regularly.

For all the setups, the rate of the leak water intrusion into the roofing systems was in no way constant with time. In several instances, the initial rate of water flow into the system was too slow. When this occurred, the insulation just below the membrane hole was reamed to achieve a faster flow rate. For this reason, the relative order of sensor detection at different positions is important, but not absolute elapsed times of detection.

After completion of each test, the researchers carefully removed the membrane and insulation layers to investigate and record the areas of water accumulation between component layers (Figure 28).

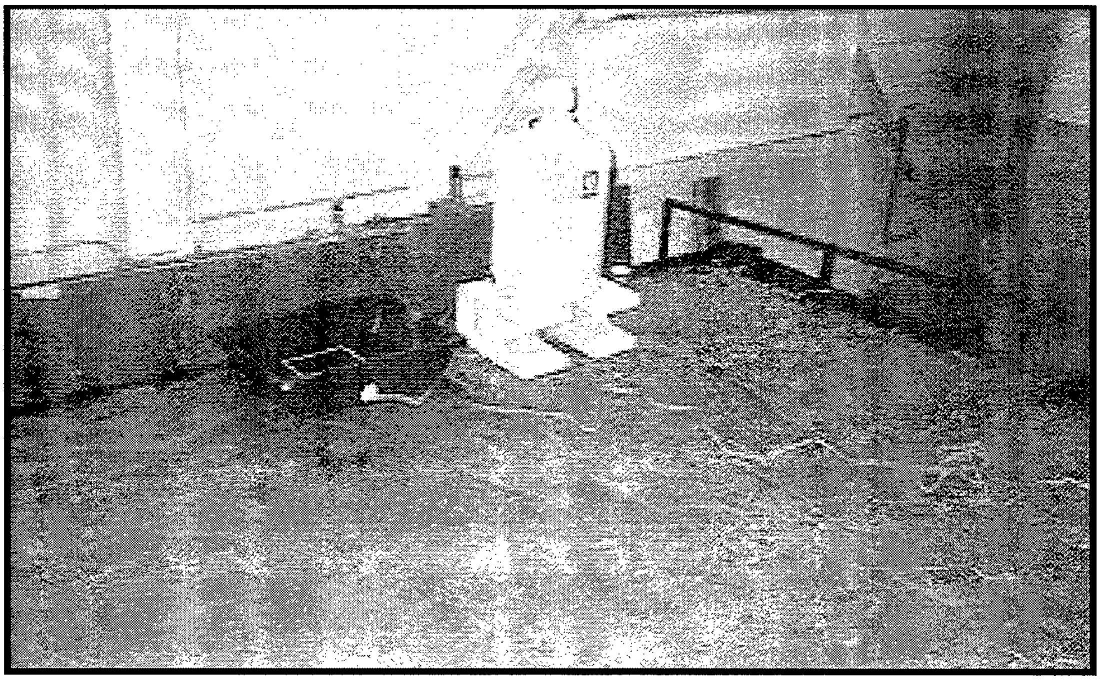


Figure 27. Water supply carboy and retention tub placed over membrane hole.

Figure 28. Evidence of water accumulation between membrane and perlite board observed during disassembly of test setup.

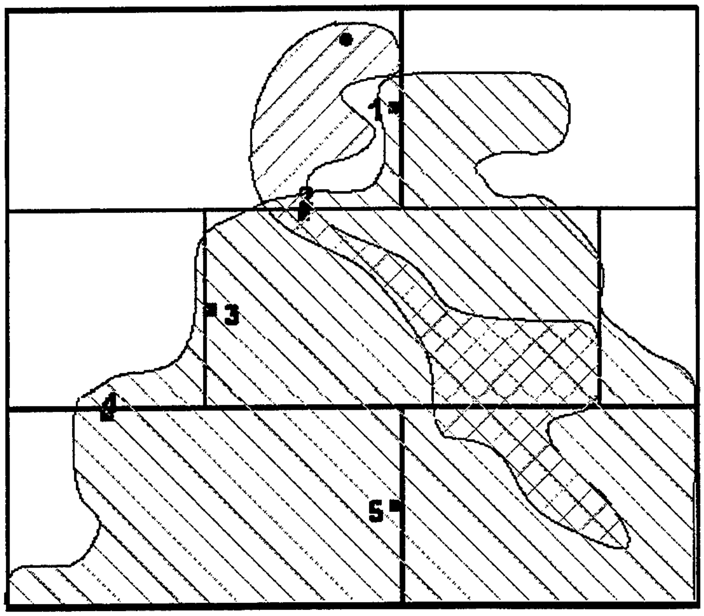
Sensor Group A — Non-adhered Membrane With EPS Insulation

Because the expanded EPS is an open-celled insulation, the majority of the leak water passed vertically down through the insulation to the polyethylene vapor retarder. From there, it flowed downslope with a tendency to follow the insulation board joints (Figure 29). The area of water migration below the insulation encompassed all of the sensor positions. The insulation was saturated throughout its thickness in a circular area (approximately 1-in. diameter) about the membrane hole. The top surface of the insulation showed no evidence of water flowing on it.

Not surprisingly, without the indication of water flow on the top of the EPS insulation, none of the topside resistance probes detected water. However, none of the bottom resistance probes detected water either, indicating a lack of absorption of the insulation from the bottom up. Except for the moisture-detection tape at position 4, the remaining sensors detected water at about the same time for each position. The sensors at position 1 were the first to reach their threshold levels, at between 58 and 92 hr. Table 8 lists results for this test group.

Sensor Group A — Nonadhered Membrane With Polyisocyanurate Insulation

Examination of the insulation during disassembly showed that most of the leak water flowed below the insulation, and that the water on top of the insulation was puddled and did not appear to be soaking into the insulation at a noticeable rate (Figure 30). Unlike the EPS insulation, the polyisocyanurate is closed cell, making it much more resistant to water penetration. The area of water migration below the insulation encompassed all of the sensor positions. Water was retained on top of the insulation at position 2 only.



Legend

● hole in membrane

#■ resistance bundle

— insulation board joints

Water paths

▨ on top of insulation

▧ below insulation

Figure 29. Water accumulation in sensor group A setup with nonadhered membrane and EPS insulation.

Table 8. Elapsed time(hr) for detection for Sensor Group A - nonadhered membrane with EPS insulation.

	High Wooden Probe	Low Wooden Probe	Plywood Disc	Moisture-detection tape	High Resistance	Low Resistance
Position 1	92	75	58	58	N	N
Position 2	110	101	110	115	N	N
Position 3	103	103	100	100	N	N
Position 4	179	152	220	100	N	N
Position 5	125	120	116	112	N	N

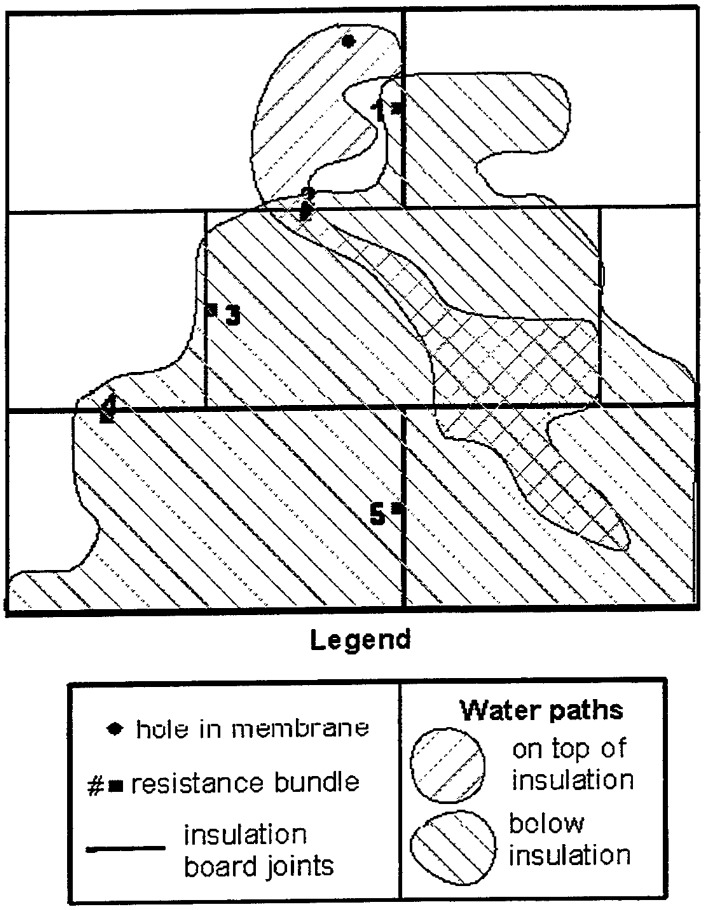


Figure 30. Water accumulation in sensor group A setup with nonadhered membrane and polyisocyanurate insulation.

Only one of the resistance probes, the lower sensor at position 1, had a signal which dropped to the threshold level, indicating detection of a leak. The signals from the two resistance probes at position 2 showed noticeable resistance drops but stabilized before reaching their threshold value.

At positions 1, 2, and 4, all of the wooden probes, plywood discs, and moisture-detection tapes detected water within 33 hr; with all but two of them triggering within 12 hr. The sensors at position 5 triggered between 38 and 95 hr. Interestingly, the sensors at position 3 triggered much later than those at position 4, which appears to be further down the water path from the leak source. The plywood disc at this position detected first at 71 hr, and the lower wooden probe detected last at 165 hr. A possible explanation for this is that the sensors at position 3 are located at a board joint parallel to the roof slope. Water can be expected to flow with little obstruction along the joint. At position 4, the sensors are placed at a board joint that is transverse to the roof slope, possibly allowing the water to accumulate and soak into the insulation and wood sensors. Table 9 lists results for this test group.

Sensor Group A — Nonadhered Membrane With Perlite Insulation

Perlite insulation has the ability to absorb large quantities of water. This characteristic allowed the water to soak vertically through the insulation and spread downslope along the insulation/vapor retarder interface. The water that did not soak through the board flowed downslope over the top surface of insulation, with very little spread perpendicular to the slope. As shown in Figure 31, no evidence showed water reaching position 1, and no sensors at this location triggered. As at all positions in this setup, the resistance probes at position 2 did not reach the threshold level. The other sensors at this position detected water at elapsed times ranging from 5 to 18 hr. With the insulation at position 3 completely soaked, the moisture tape and plywood disc had quick responses of 4 and 5 hr, respectively. The wooden probes had delayed threshold readings of 49 hr for the low placement and 95 hr for the high placement. No water had accumulated at position 4; however, water was on the vapor retarder nearby. The lower resistance probe exhibited a drop in resistance from its nominal level but did not reach its threshold value. The moisture-detection tape and plywood disc had a simultaneous trigger at the 12-hr mark. The lower wooden probe was triggered at 14 hr and the high wooden probe was triggered at 19 hr. As with position 4, the moisture tape and plywood discs at position 5 detected water before the wooden probes (12 hr vs 24 hr). See Table 10 for results.

Sensor Group A — Fully Adhered Membrane With Polyisocyanurate Insulation

The polyisocyanurate insulation had fibrous glass facers. With the membrane fully adhered, negligible water passed through the membrane hole and into the roofing system. After 2 weeks of exposure and attempts to expedite water penetration by enlarging the cavity in the insulation below the membrane hole, the test was terminated.

Table 9. Elapsed time (hr) for detection for Sensor Group A - nonadhered membrane with polyisocyanurate insulation.

	High Wooden Probe	Low Wooden Probe	Plywood Disc	Moisture-detection tape	High Resistance	Low Resistance
Position 1	12	9	4	4	N	110
Position 2	11	5	24	3	?	?
Position 3	134	165	71	98	N	N
Position 4	33	10	6	5	N	N
Position 5	95	44	38	44	N	N

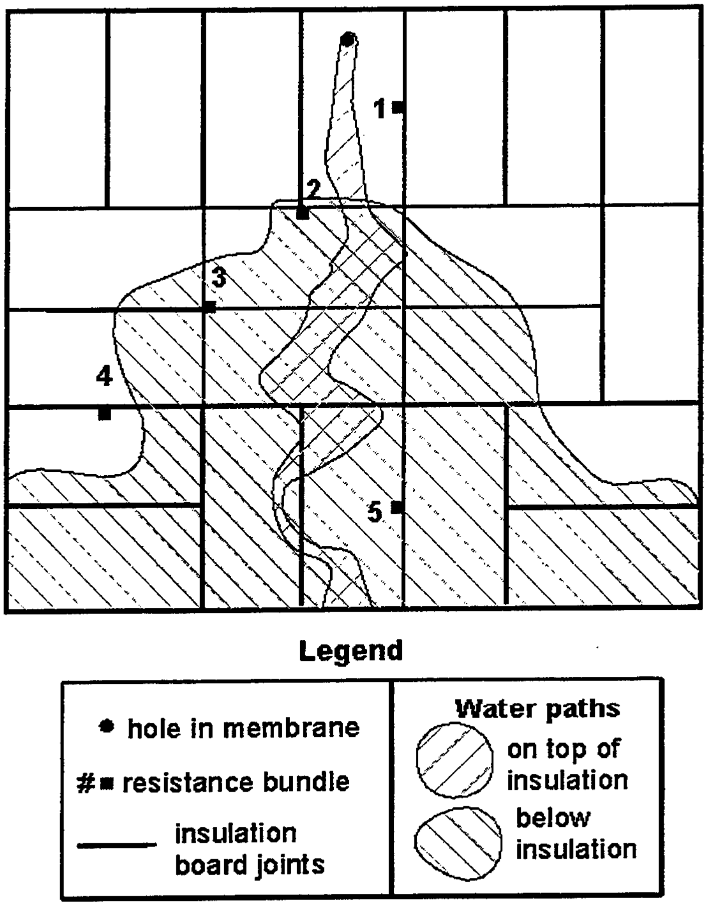


Figure 31. Water accumulation in sensor group A setup with nonadhered membrane and perlite insulation.

Table 10. Elapsed time (hr) for detection for Sensor Group A - nonadhered membrane with perlite insulation.

	High Wooden Probe	Low Wooden Probe	Plywood Disc	Moisture-detection tape	High Resistance	Low Resistance
Position 1	N	N	N	N	N	N
Position 2	13	18	10	5	N	N
Position 3	95	49	5	4	N	N
Position 4	19	14	12	12	N	N
Position 5	50	63	24	24	N	N

Sensor Group A — Fully adhered Membrane with Perlite Insulation

Like the test setup for the nonadhered membrane with EPS insulation, the leak water passed vertically down through the perlite insulation until it was impeded by the vapor retarder. The water traveled downslope between the vapor retarder and insulation with some tendency to follow the board joints (Figure 32). Based on inspection during disassembly of the setup, evidence of water reaching all sensor locations was visible except at position 5, and the insulation had absorbed considerable amounts of moisture at positions 1, 2, and 3. Despite this, the resistance probes at all five positions did not trigger. At position 1, the plywood disc and moisture tape triggered at the same time, 120 hr, and both wooden probes reached their threshold value at 133 hr. As with the other four positions, the resistance probes did not detect water at this position. At position 2, all of the sensors, except for the resistance probes, triggered at 122 hr. At position 3, the resistance probes did have noticeable drops in resistance readings but did not reach their threshold values. At this same location, the plywood disc detected water at 123 hr, and the moisture tape triggered at 129 hr. The low and high wooden probes reached their threshold values at 170 hr.

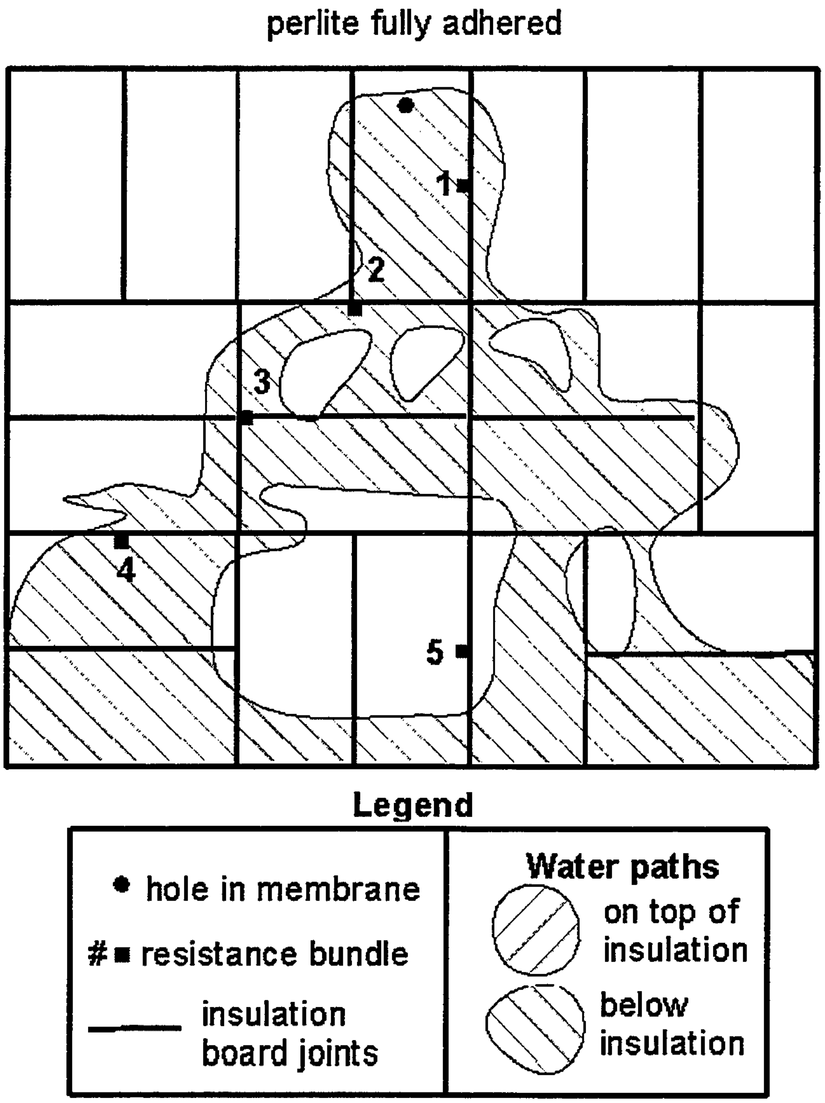


Figure 32. Water accumulation in sensor group A setup with fully adhered membrane and perlite insulation.

At position 4, the plywood disc, moisture tape, and the high wooden probe all triggered at 123 hr. The high wooden probe returned to its nominal "dry" reading after 1 hr. The low wooden probe never triggered. Despite no evidence of pooled water at position 5, the moisture tape detected water at 134 hr followed by the low wooden probe at 220 hr. Table 11 lists results for this test group.

Sensor Group B — Nonadhered Membrane With Polyisocyanurate Insulation

In the test on the polyisocyanurate insulation, the first leak was detected by the water-sensing cable system at 68 ft (Figure 33). The water accumulation found during disassembly indicated flow between the two layers of insulation following the board joints of the top insulation boards. Nine hours after the first detection by the sensing cable, the water-activated battery/transmitter sensor at position 1 triggered. The water-sensing cable re-alarmed 15 hr after its first detection. The water battery sensor at position 2 was activated another 16 hr later.

Sensor Group B — Nonadhered Membrane with Expanded Polystyrene Insulation

As shown in Figure 34, some of the leak water flowed between the top insulation board and overlying membrane. Once it reached the first board joint downslope from the leak hole, it traveled vertically down to the top surface of the underlying insulation board. From there it spread laterally, resulting in an initial detection by the water sensing cable at 61 ft. However, much of the leak water ran vertically down through both insulation board layers to the vapor retarder, where it spread downslope with a tendency to follow the board joints. Because of this tendency, the water battery sensors, located on the top of the bottom layer of insulation, were never triggered. The sensing cable was re-alarmed 52 hr after initial detection and twice again within the following hour. From the reference distance readings, it is hypothesized that water followed the path of the cable sensor to the end of the table.

Table 11. Elapsed time (hr) for detection for Sensor Group A - fully adhered membrane with perlite insulation.

	High Wooden Probe	Low Wooden Probe	Plywood Disc	Moisture-detection tape	High Resistance	Low Resistance
Position 1	133	133	120	120	N	N
Position 2	122	122	122	122	N	N
Position 3	170	170	123	129	N	N
Position 4	123	N	123	123	N	N
Position 5	N	220	N	134	N	N

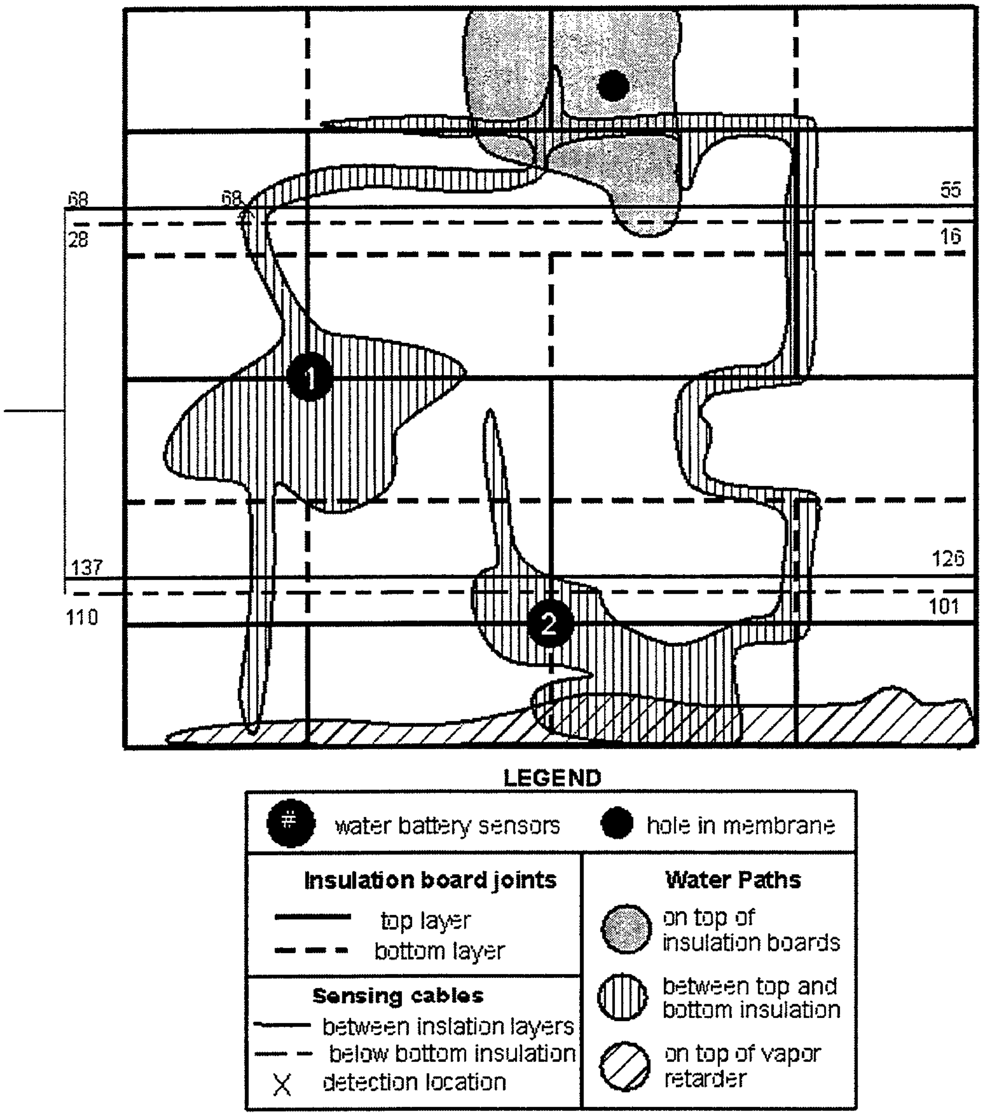


Figure 33. Water accumulation in sensor group B setup with nonadhered membrane and polyisocyanurate insulation.

Sensor Group B — Nonadhered Membrane With Expanded Polystyrene Insulation and Intermediate Vapor Retarder

A second setup with a second vapor retarder placed between the two layers of polystyrene insulation was tested. In this test, once the leak water reached the first board joint running perpendicular to the slope, it flowed vertically down to the intermediate vapor retarder (Figure 35). From here, the water traveled on top of the vapor retarder and downslope. The water-sensing cable was first alarmed at approximately 60 ft. The water-activated battery/transmitter sensor at position 2 alarmed 51 hr later. The sensor at position 1 never alarmed because of a crack in the seal which was found during disassembly between the sensor and vapor retarder during disassembly. The crack allowed water to flow beneath the vapor retarder and down to the bottom vapor retarder.

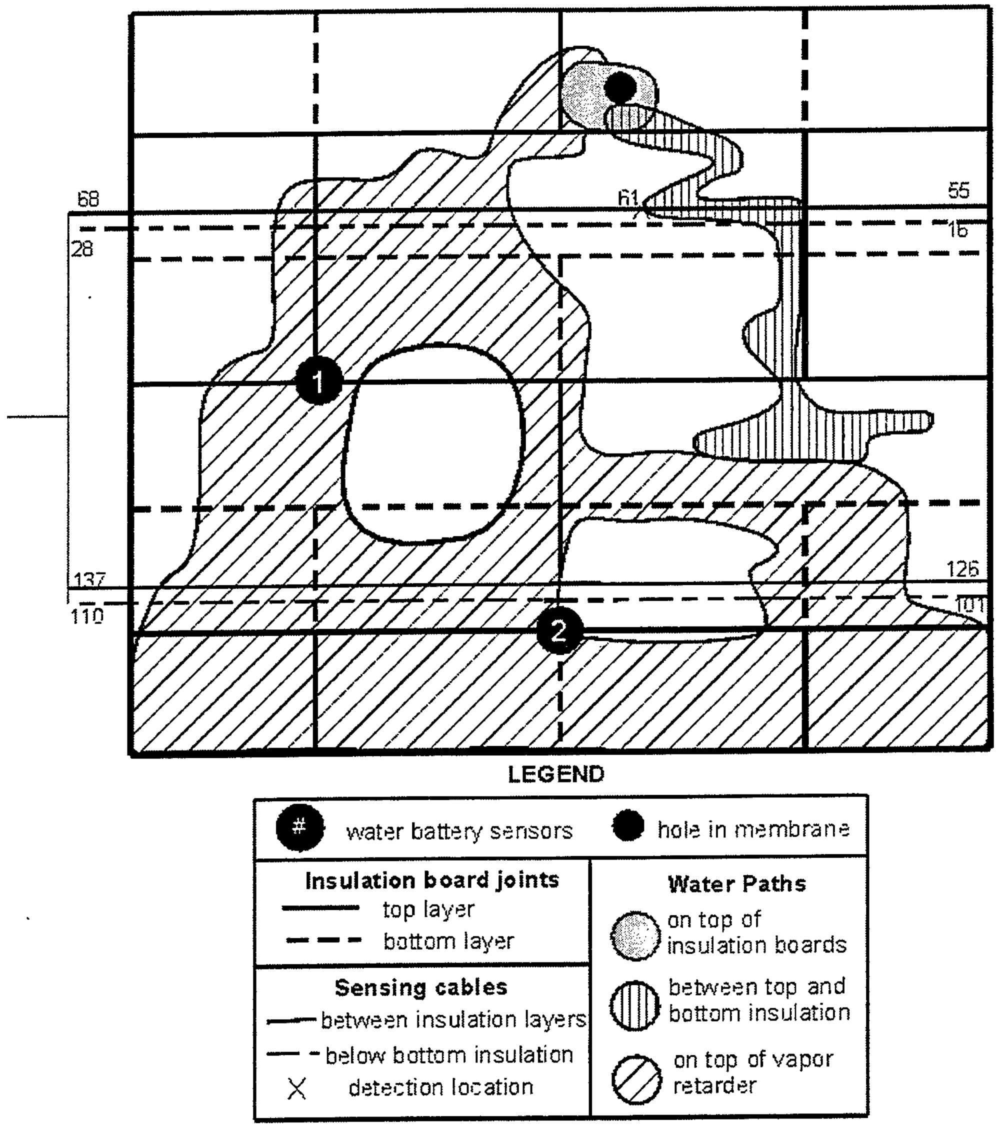


Figure 34. Water accumulation in sensor group B setup with nonadhered membrane and EPS insulation.

Summary

For the test setups evaluated in Phase II, the following observations were made:

- Leak water that penetrated the roofing membrane hole had a tendency to flow (1) vertically down through open-cell insulation such as expanded EPS or perlite, and (2) on the surface of closed-cell insulation such as polyisocyanurate until it reached an open board joint, where it could flow vertically down to the underlying substrate. Once water reached an impermeable surface such as a vapor retarder or top surface of polyisocyanurate insulation with taped board joints, it tended to flow downslope and along the board joints in the overlying insulation.

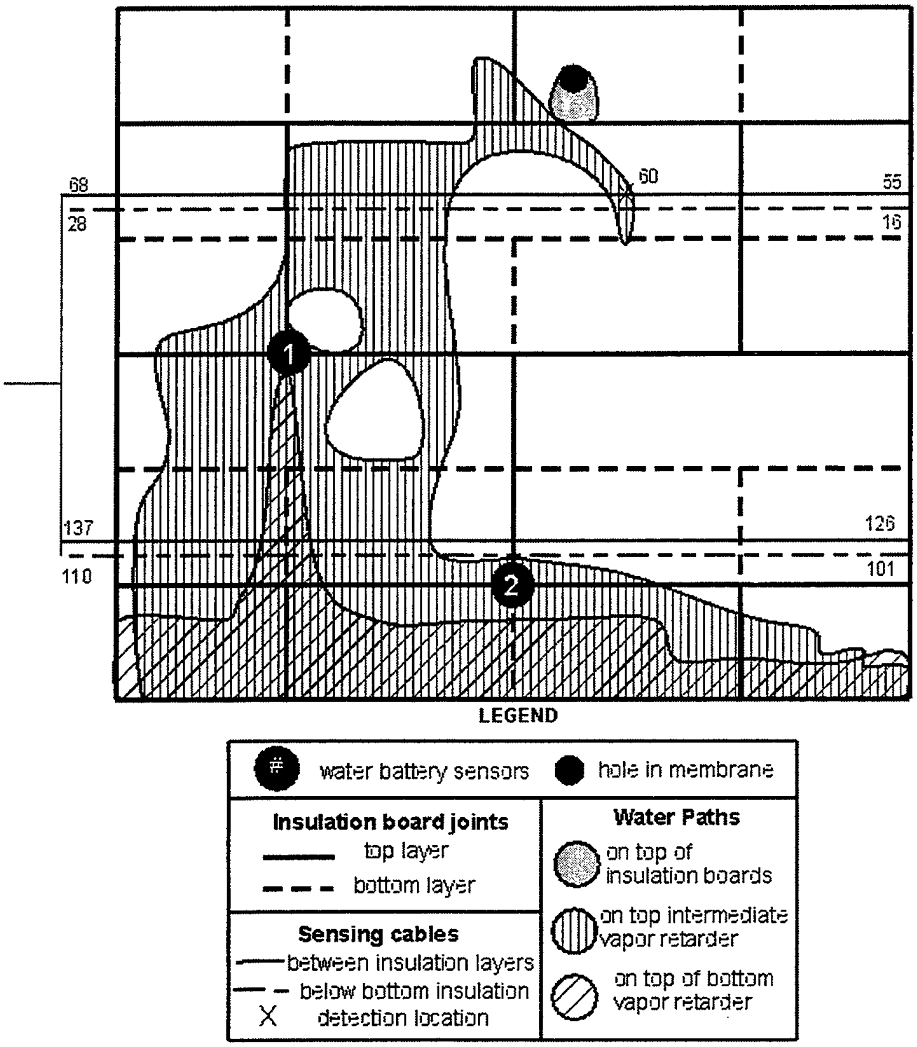


Figure 35. Water accumulation in sensor group B setup with nonadhered membrane, EPS insulation, and intermediate vapor retarder.

- Of the resistance sensors, good leak detection performance was experienced with the wooden probe and plywood disc. Both of these sensors use wood as the medium across which resistance measurements are taken; as opposed to the resistance probe, which uses the roof insulation as the resistance medium. Regardless of the placement, only on one occasion did a resistance probe reach its threshold level to indicate leak detection. The water-activated battery/transmitter and the water-sensing cable were equally effective in detecting leaks. However, discerning between multiple leak locations with the sensing cable in a given setup proved to be very difficult.

- For sensors with electrical wiring as their transmission medium, the Phase II results seemed to indicate that, when water flow is impeded by a wire transmission medium, the water tends to travel along the wire until it reaches an obstruction such as the connected sensor.

- When placed on closed-cell insulations such as polyisocyanurate, fully adhered membrane configurations may provide greater impedance to water infiltration through small holes occurring in the membrane. This effect would likely be less for larger defects and diminish over time as a result of damage from freeze-thaw cycling and other phenomenon that might adversely affect the adherence or integrity of the insulation.

5 Conclusions and Recommendations

The results of the Phase I evaluation indicated that all five sensors studied (resistance probe, wooden probe, plywood disc, water-activated battery/transmitter, and moisture-detection tape) can be expected to exhibit adequate durability performance when placed in typical roofing system environments.

Except for the resistance probe, all of the sensors that require electrical conduit as a transmission medium performed reasonably well in detecting leak water within the simulated roofing system. However, the capability of the water-sensing cable to identify the locations of multiple leaks is questionable. The water-activated battery/transmitter sensor also performed well. The resistance probe requires absorption of considerable amounts of water by the insulation to be able to detect water intrusion. For the cases tested in Phase II, this absorption did not occur.

It is paramount that integration of PRLDS components into the roof construction process does not compromise the quality of the finished roofing system. Based on experience in fabricating the setups, the placement of wire and cable used for the transmission medium will require extra care and planning during construction of the roofing system. This care and planning is especially true for those sensors and/or transmission medium with high profiles such as the water-sensing cable. A system that uses a sensor not requiring the use of wire or cable, such as the water-activated battery/transmitter, has a notable constructibility advantage in this regard.

An effective placement of the sensor for leak detection appears to be at the bottom surface of the insulation board, which is placed on an impermeable substrate such as a vapor retarder or a layer of polyisocyanurate boards with taped joints. For both optimal positioning and ease of installation, sensors that are embedded in the insulation should be placed at the edge face of the board. Those sensors that are not embedded should be placed at board joints of an overlying insulation layer. Although none of the setups included fully adhered insulation, it became apparent that placement of the sensors and transmission medium would cause major interruption and delay in the roof construction process. This delay could possibly eliminate the ability to apply a fully adhered membrane, unless the components were placed after installation of the membrane, such as required in the resistance-probe system.

A loose-laid and ballasted roofing system, which often incorporates a loose-laid or mechanically fastened insulation system, cannot be visually inspected for membrane anomalies without the removal of stones or pavers. This disadvantage makes it an excellent candidate for a PRLDS.

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Appendix A: Construction Specification for Passive Roof Leak Detection Systems (PRLDS)

PART 1 GENERAL

This guide specification covers the requirements for passive roof leak detection systems (PRLDS) which use sensors placed into a membrane roofing system during roof construction to provide early detection of water intrusion.

1.1 GENERAL REQUIREMENTS

NOTE: If relevant, show locations of sensors on roof section plans.

The placement of the sensors and transmission medium can cause major interruption and delay in the roof construction process and possibly eliminate the ability to apply a fully adhered membrane, unless the components are placed after installation of the membrane. A loose-laid and ballasted roofing system, which incorporates a loose-laid or mechanically fastened insulation system, has the disadvantage of not being able to be visually inspected for membrane anomalies without the removal of stones or pavers, making it an excellent candidate for a PRLDS.

1.1.1 Standard Products

Components, material, and equipment shall be the standard products of a manufacturer/system supplier regularly engaged in the supply of the products and shall be items that have been in satisfactory use as parts of a PRLDS for at least [2] [___] years prior to bid opening. Equipment shall be supported by a service organization that can provide service within 48 hours.

1.1.2 Nameplates

Major components or equipment, other than those placed within the roofing system, shall have the manufacturer/system supplier's name and address, and the system's type or style, on labels that are securely attached to the equipment.

1.1.3 Verification of Dimensions

The Contractor shall become familiar with all details of the work, verify all dimensions in the field, and advise the Contracting Officer of any discrepancy before performing the work.

1.1.4 Manufacturer/System Supplier's Services

Services of a manufacturer/system supplier's representative who is experienced in the installation, adjustment, testing, and operation of the components and equipment specified shall be provided. The representative shall supervise the installation, adjustment, and testing of the components, equipment, and completed system.

1.2 SYSTEM DESIGN

1.2.1 Operation

The PRLDS shall be a complete system. The system shall activate a visual alarm when a sensor detects a leak mode by actuation of a graphical display at the signal processing unit. The system shall remain in the alarm mode until a system operator resets the system.

The signal processing unit shall be an addressable microcomputer (microprocessor or microcontroller) based system. Sufficient memory shall be provided to perform as specified. Individual identity of each addressable sensors shall be provided for the following conditions:

- leak detection
- faulty sensor
- faulty transmission medium.

All addressable sensors shall have the capability of being individually disabled or enabled from the signal processing unit.

1.2.2 Operational Features

The system shall have the following operational features:

a. Procedures and processes for monitoring all sensors on demand to determine if leak detection has occurred or sensor or transmission medium has malfunctioned.

b. One-person test mode to assess operability of all sensors.

1.2.3 Leak Detection Functions

A positive leak detection event shall automatically initiate transmission of a signal from the sensor to the signal processing unit. Visual indications of the triggered sensor shall be displayed at the signal processing unit.

1.2.4 Power Loss Protection

Leak detection system and detection occurrence data storage and retrieval shall be protected from loss of electrical or battery power. Loss of AC power shall not cause the loss of recorded signals via the leak detection system upon restoration of power.

1.3 SUBMITTALS

> *NOTE: Submittals must be limited to those necessary for adequate quality control. The importance of an item to the project should be one of the primary factors in determining if a submittal for the item should be required.*
>
> *Indicate submittal classification in the blank space using "AR" when the submittal requires approval or "FIO" when the submittal is for information only.*

Approval is required for submittals with an "AR" designation; submittals having an "FIO" designation are for information only.

1.3.1 Data

Manufacturer/System Suppliers Catalog Data, which includes a complete list of components, equipment, and material included in the PRLDS. This material shall include manufacturer/system supplier's descriptive and technical literature.

1.3.2 Drawings

Roof Leak Detection System;[____]

Detail drawings approved and signed by both the leak detection manufacturer/ system supplier and the roofing system manufacturer. Note that the contract drawings show layouts based on typical sensors. The contractor shall check the layout based on the sensors to be installed and make any necessary revisions. The detail drawings shall contain system layout including location of sensors and transmission medium, complete wiring and schematic diagrams for the equipment furnished, equipment layout, and any other details required to demonstrate that the system has been coordinated and will properly function as a unit.

1.3.3 Instructions

System Operation; AR

[Two] [____] copies of operating instructions outlining step-by-step procedures required for system startup, operation, and shutdown. The instructions shall include the manufacturer's name, the model number, service manual, parts list, and a brief description of all equipment and their basic operating features. [Two] [____] copies of maintenance instructions listing routine maintenance procedures, possible breakdowns and repairs, and troubleshooting guide. Instructions shall be approved prior to training.

System Installation; [____]

Manufacturer/system supplier's instructions for installing the roof leak detection system, including all associated components

1.3.4 Statements

Test Procedures; [____]

Detailed test procedures, signed by the manufacturer/system supplier for the roof leak detection system, [60] [____] days prior to performing system tests.

1.3.5 Reports

Testing; [____]

Test reports in booklet form showing all field tests performed. Each test report shall document nominal "dry" readings for each sensor and establish the threshold reading that indicates leak detection.

1.3.6 Certificates

Installer; [_____]

The Contractor shall provide documentation demonstrating that its roof leak detection system installer has been regularly engaged in the installation of roof leak detection systems for a minimum of 2 years immediately preceding commencement of this contract. Such documentation shall specifically include proof of satisfactory performance on at least two projects similar to that required by these specifications, including the names and telephone numbers of using agency points of contact for each of these projects. Documentation shall indicate the type of each system installed and include written certification that each system has performed satisfactorily in the manner specified for a period of not less than 12 months following completion.

Roofing System Manufacturer Approval; [_____]

The contractor shall provide written certification from the roofing system manufacturer stating that the roof leak detection system is approved for use with the roofing system being installed and its standard roofing warranty is available.

1.3.7 Samples

Sensors; [_____]

One sample of each sensor type.

Transmission Medium; [_____]

One piece of each type to be used, 2 feet long.

1.4 DELIVERY AND STORAGE

All equipment delivered and placed in storage shall be stored with protection from the weather, humidity and temperature variation, dirt and dust, and any other contaminants.

PART 2 PRODUCTS

2.1 SENSORS AND TRANSMISSION MEDIUM

NOTE: Choose sensor configuration (point or line) and sensor type (wire or wireless), which are most suited for the application and roof system design.

Sensors shall have the ability to detect pooled water or increase in moisture content of a standard medium consistent with the absorption of free water in 48 hr. Sensors shall have a [point] [or] [line] configuration. The sensors shall transmit [an electrical signal which requires a transmission medium of electrical wire conductors] [or] [a radio wave signal which is received by a remote antenna and requires no hardwire transmission medium]. Each sensor shall have a unique identification label. The sensors and transmission medium shall be capable of withstanding temperatures between -40 and 180 °F without degradation of response.

2.2 SIGNAL PROCESSING UNIT

A signal processing unit shall provide for storage and retrieval requiring battery back-up for a minimum of up to 256 events. The signal processing unit shall be 115/120 V, 60 Hz powered.

PART 3 EXECUTION

3.1 INSTALLATION

NOTE: The installation of the leak detection system must be integrated with the roof construction process. Procedures and operations must be pre-established with the roofing contractor to ensure proper coordination of all activities.

An effective placement of the sensor for leak detection can be at the bottom surface of the insulation board, which is placed on an impermeable substrate such as a vapor retarder or a layer of polyisocyanurate boards with taped joints. For both optimal positioning and ease of installation, sensors that are embedded in the insulation should be placed at the edge face of the board. Those sensors that are not *embedded shall be placed at board joints of an overlying insulation layer.*

3.1.1 General

Installation shall comply with the manufacturer/system supplier's approved instructions and as per submitted and approved detail drawings except as otherwise specified. The Contractor shall provide marked locations of sensors and transmission medium and identification of sensors on the approved detail drawing.

3.1.2 Sensors

Sensors shall be of [point] [line] configuration and placed on [___] feet centers in the field of the roof and as shown on the detail drawings. Placement at wall flashings, roof edge flashings, curbed flashings, and flashed penetrations shall be as shown on drawings.

Sensor locations may be changed to conform to roof construction process and insulation board layout, end-of-day water cutoffs, and placement of rooftop curbs, penetrations, and other obstructions, if approved.

Sensors shall be placed and marked so as not to be damaged by roofing system fasteners.

3.1.3 Transmission Medium

Transmission medium shall be fixed to the underlying substrate through taping or brackets and placed so as not to be damaged by the roofing system fasteners.

Where transmission medium penetrates and exits the membrane, it must be flashed as per roofing system manufacturer recommendations. Transmission medium shall be grouped at exiting points to the greatest extent possible to minimize the number of membrane penetrations.

3.1.4 Signal Processing Unit and Peripheral Equipment and Accessories

Wall mounted signal processing units and associated electrical boxes shall be mounted so that no part of the enclosing cabinet is less than [300 mm] [12 in.] nor more than [2 m] [78 in.] above the finished floor. All manually operable controls shall be between [900 mm] [36 in.] to [1.1 m] [42 in.] above the finished floor. Panel shall be installed to comply with the requirements of [UL 864].

The signal processing unit shall be installed in a dry location where the temperature is between 32 and 120 F and the relative humidity is between 5 and 95 percent.

3.2 TESTING

The Contracting officer shall be notified [30] [ ] days before the acceptance tests are to be conducted. The Contractor shall furnish instruments and trained personnel as required for the tests. The tests shall be conducted on all equipment and components in accordance with the approved test plan and procedures, to determine that the system meets the operational requirements specified. If any deficiencies are revealed during any test, such deficiencies shall be corrected and tests repeated.

3.3 FIELD TRAINING

The Contractor shall conduct training for operating and maintenance staffs as designated by the Contracting Officer. The training period, for a total of [ ] hours of normal working time, shall start after the system is functionally completed but prior to final acceptance tests. Training shall cover all of the items contained in the operating and maintenance manuals.

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SETAF
ATTN: AESE-EN-D 09613
ATTN: AESE-EN 09630
Supreme Allied Command
ATTN: ACSGEB 09703
ATTN: SHIHB/ENGR 09705

INSCOM
ATTN: IALOG-I 22060
ATTN: IAV-DPW 22186

USA TACOM 48397-5000
ATTN: AMSTA-XE

Defense Distribution Region East
ATTN: ASCE-WI 17070-5001

Defense Distribution Region West
ATTN: ASCW-WG 95296-0100

HQ XVIII Airborne Corps 28307
ATTN: AFZA-DPW-EE
4th Infantry Div (MECH) 80913-5000
ATTN: AFZC-FE

US Army Materiel Command (AMC)
Alexandria, VA 22333-0001
ATTN: AMCEN-F
Installations: (20)

FORSCOM
Forts Gillem & McPherson 30330
ATTN: FCEN
Installations: (22)

TRADOC
Fort Monroe 23651
ATTN: ATBO-G
Installations: (20)

Fort Belvoir 22060
ATTN: CETEC-IM-T
ATTN: CETEC-ES 22315-3803
ATTN: Water Resources Support Ctr

USA Natick RD&E Center 01760
ATTN: STRNC-DT
ATTN: AMSSC-S-IMI

US Army Materials Tech Lab
ATTN: SLCMT-DPW 02172

USARPAC 96858
ATTN: DPW
ATTN: APEN-A

SHAPE 09705
ATTN: Infrastructure Branch LANDA

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

HQ USEUCOM 09128
ATTN: ECJ4-LIE

CEWES 39180
ATTN: Library

CECRL 03755
ATTN: Library

USA AMCOM
ATTN: Facilities Engr 21719
ATTN: AMSMC-EH 61299
ATTN: Facilities Engr (3) 85613

USAARMC 40121
ATTN: ATZIC-EHA

Military Traffic Mgmt Command
ATTN: MT-LOF 20315
ATTN: MTE-SU-FE 28461

Fort Leonard Wood 65473
ATTN: ATSE-DAC-LB (3)
ATTN: ATZT
ATTN: ATSE-CFLO
ATTN: ATSE-DAC-FL
ATTN: Australian Liaison Office

Military Dist of WASH
Fort McNair
ATTN: ANEN-IS 20319

USA Engr Activity, Capital Area
ATTN: Library 22211

US Army ARDEC 07806-5000
ATTN: AMSTA-AR-IMC

Engr Societies Library
ATTN: Acquisitions 10017

Defense Nuclear Agency
ATTN: NADS 20305

Defense Logistics Agency
ATTN: MMBIR 22060-6221

Walter Reed Army Medical Ctr 20307

National Guard Bureau 20310
ATTN: NGB-ARI

US Military Academy 10996
ATTN: MAEN-A
ATTN: Facilities Engineer
ATTN: Geography & Envr Engrg

Naval Facilities Engr Command
ATTN: Facilities Engr Command (8)
ATTN: Division Offices (11)
ATTN: Public Works Center (8)
ATTN: Naval Constr Battalion Ctr 93043
ATTN: Naval Facilities Engr Service Center
93043-4328

8th US Army Korea
ATTN: DPW (11)

USA Japan (USARJ)
ATTN: APAJ-EN-ES 96343
ATTN: HONSHU 96343
ATTN: DPW-Okinawa 96376

416th Engineer Command 60623
ATTN: Gibson USAR Ctr

US Army MEDCOM
ATTN: MCFA 78234-6000
Fort Detrick 21702-5000
ATTN: MCHS-IS
Fort Sam Houston 78234-5000
ATTN: MCFA-PW
Walter Reed Army Medical Ctr 20007-5001
ATTN: MCHL-PW

Tyndall AFB 32403
ATTN: HQAFCESA/CES
ATTN: Engrg & Srvc Lab

USA TSARCOM 63120
ATTN: STSAS-F

American Public Works Assoc. 64104-1806

US Army CHPPM
ATTN: MCHB-DE 21010

US Gov't Printing Office 20401
ATTN: Rec Sec/Deposit Sec (2)

Nat'l Institute of Standards & Tech
ATTN: Library 20899

Defense General Supply Center
ATTN: DGSC-WI 23297-5000

Defense Construction Supply Center
ATTN: DCSC-WI 43216-5000

Defense Tech Info Center 22304
ATTN: DTIC-O (2)

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11/97