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Laboratory Evaluation of Nondestructive Methods to Measure Moisture in Built-Up Roofing Systems

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Lawrence Knab
Robert Mathey
David Jenkins

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

Prepared for:
Directorate of Engineering and Services
U.S. Air Force
Washington, DC 20330

U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, Secretary
Jordan J. Baruch, Assistant Secretary for Productivity, Technology and Innovation
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Cover: An important consideration in roof maintenance is the detection of moisture by nondestructive methods.

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CONVERSION FACTORS TO METRIC (SI) UNITS

Since the roofing industry generally uses conventional U.S. units, the following table is provided for converting to metric units.

Physical Quantity	To Convert From	To	Multiply By
Length	ft	m	3.05×10^{-1}
Area	ft^2	m^2	9.29×10^{-2}
Volume	ft^3	m^3	2.83×10^{-2}
Temperature	Fahrenheit	Celsius	$T_C = (T_F-32)/1.8$
Temp. Diff.	Fahrenheit	Kelvin	$K = (\Delta T_F)/1.8$
Density	lbm/ft^3	kg/m^3	$1.602 \times 10^{+1}$
Mass per Unit Area	lbm/ft^2	kg/m^2	4.88

LABORATORY EVALUATION OF NONDESTRUCTIVE METHODS TO MEASURE MOISTURE IN BUILT-UP ROOFING SYSTEMS

by

L. I. Knab,* R. G. Mathey,* and D. R. Jenkins**

ABSTRACT

This laboratory study investigated the reliability and accuracy of three types of nondestructive evaluation (NDE) methods to quantitatively determine the moisture content of the insulation in built-up roofing specimens. These methods were electrical capacitance, nuclear backscatter, and infrared thermography. Thirty-six roofing specimens, which consisted of five types of rigid-board roof insulations, with attached bituminous built-up membranes were tested over both concrete and steel decks. A wide range of moisture contents was induced into the specimens by maintaining a constant water vapor pressure difference across them.

Two performance characteristics of the NDE methods were evaluated: (a) the minimum moisture content a method could detect, and (b) the relationship between NDE response and moisture content beyond the minimum detectable moisture content. The two performance characteristics were assessed through normalization parameters defined in terms of the NDE response and its scatter about a fitted curve. There were differences in the performance characteristics, the magnitude of which depended on the NDE method, the specimen composition, and the deck type used.

Keywords: Built-up roofing, electrical capacitance, infrared thermography, insulation, moisture detection, moisture measurement, nondestructive evaluation, nondestructive testing, nuclear backscatter, roofing systems.

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* Center for Building Technology, National Bureau of Standards, Washington, D.C.

** Professor of Engineering, University of Central Florida, Orlando, Florida, on assignment to the National Bureau of Standards under provisions of the Intergovernmental Personnel Act.

EXECUTIVE SUMMARY

I. BACKGROUND, PURPOSE, AND SCOPE

Moisture in insulated built-up roofing systems causes many premature roof failures and unwanted energy losses. A promising approach for improving the reliability of roof inspection and maintenance is through the use of nondestructive evaluation (NDE) methods that can detect moisture in the interior of roofing systems. Electrical capacitance, nuclear backscatter, and infrared thermography are the most common commercially available NDE methods used to detect moisture. Since considerable uncertainty existed in the use of these methods, a comprehensive laboratory study was carried out to determine the accuracy and reliability of these methods in order to establish their moisture detection capabilities.

The purpose of this study was to conduct a controlled laboratory investigation of the most common NDE methods to determine their ability to quantitatively detect moisture in the insulation of built-up roofing systems. The methods, number of instruments, and construction variables investigated are shown in the following table.

	Construction Variables				
			Insulation		
NDE Method	Surface	Asphalt Thickness	Type	Nominal Thickness	Deck
Electrical Capacitance (three instruments) and Nuclear Backscatter (two instruments)	Gravel	"Standard" and "Heavy"	Glass Fiber Perlite Fiberboard Polystyrene Polyurethane	1, 2 in. 1, 2 in. 1, 2 in. 1, 2 in. 1 in.	Concrete and Steel
Infrared Thermography (one instrument)	Gravel and Smooth	"Standard"	Glass Fiber Perlite Polystyrene	1, 2 in. 1, 2 in. 1, 2 in.	Steel

As noted in the table, there were significantly fewer tests conducted using infrared thermography as compared to the other two methods. This is due to differences in testing procedure requirements for the infrared method.

Moisture was induced in thirty-six 2 x 2 ft. built-up roofing specimens by maintaining a vapor pressure difference across them. Instrument readings were taken on specimens with moisture content (percent by volume of insulation) levels ranging from "room dry", corresponding to storage conditions of about 70°F and 50 percent relative humidity, to a moisture content of about 60 percent. Specimens containing moisture levels exceeding the "room dry" level (resulting from moisture induction) are denoted "wet". For each specimen, instrument readings were taken at the "room dry" condition and at many (about 10 to 20 or more) "wet" moisture content levels. The readings were taken with the specimens resting on both concrete and steel decks for the electrical capacitance and nuclear backscatter methods and on steel deck only for the infrared method.

II. DATA ANALYSIS

The "adjusted NDE response," as measured by the "wet" minus the "room dry" instrument readings versus moisture content, was analyzed. Quadratic curves (least squares fit) were fitted to each adjusted NDE response versus moisture content data set; the residual standard deviation of the data about the fitted curve was used to normalize the data set and its fitted curve.

Two performance characteristics were assessed for each instrument and combination of construction variables (construction variable refers to either specimen composition, i.e. surface, asphalt thickness, and insulation, or deck used - see previous table). The first performance characteristic, referred to as the "threshold moisture," was the minimum moisture content a method could quantitatively detect. The "threshold moisture" was defined as that moisture content for which the fitted curve for the adjusted NDE response ("wet" minus "room dry") versus moisture content exceeded the zero ("room dry") response by three residual standard deviation values. This definition is equivalent to normalizing the adjusted NDE response by dividing by a scatter constant (three times the residual standard deviation) thus enabling the comparison of "threshold moisture" among the NDE methods.

The second performance characteristic was the moisture content beyond the "threshold moisture" which a method could quantitatively detect. Moisture content beyond the "threshold moisture" was measured by the sensitivity, defined as the ratio of the slope of the fitted curve for the adjusted NDE response versus moisture content to the residual standard deviation. Sensitivity values were determined only for moisture contents at and beyond the "threshold moisture". Large (positive) sensitivity values indicate a correlated increase in the NDE response with an increase in moisture content. Sensitivity values near zero indicate poor correlation between the NDE response and the moisture content. Negative sensitivity values indicate a decrease in response with an increase in moisture content. The "threshold moisture" and sensitivity are called indicators, because they are used to indicate or measure the two performance characteristics. In general, smaller "threshold moisture" contents and higher sensitivity values are indicative of better performance. The indicators were used to measure instrument effects, that is, to assess differences between instruments of a given type and between instrument types.

III. FINDINGS AND CONCLUSIONS

The findings and conclusions presented are based on a controlled laboratory study which utilized the NDE methods and construction variables as shown in the table in section I.

Minimum Detectable Moisture (Threshold Moisture Content)

All three methods were able to detect "threshold moisture." The three methods detected "threshold moisture" values of less than 10 percent in about 40 to 60 percent of the cases; "threshold moisture" values less than 20 percent were detected in 55 to 90 percent of the cases (table 12).

In general, the response of the nuclear backscatter instruments gave as low or lower "threshold moisture" contents as compared to the electrical capacitance and infrared thermography methods (table 13). In some cases, the electrical capacitance instruments could not detect a "threshold moisture" value up to the maximum moisture content induced in the specimen. Infrared thermography detected a "threshold moisture" for eight of the nine specimens tested. In all cases, the nuclear instruments were able to detect the "threshold moisture" content. These differences in detecting "threshold moisture" among the NDE methods were not considered to be significant.

Detection of Moisture Beyond the Threshold Moisture

In general, the nuclear backscatter and infrared thermography methods had sensitivity values which considerably exceeded zero and which exceeded the corresponding sensitivity values for the capacitance method. Depending on the capacitance instrument, from 11 to 22 percent of the sensitivity values were negative, indicating a decrease in the adjusted NDE response as the moisture content increased.

For specimens containing perlite and fiberboard insulations, many of the adjusted NDE response versus moisture content data sets (figures A13 to A24, appendix A) for the capacitance method showed the following trend: the adjusted NDE responses rose sharply at moisture contents of about 10 percent or less and then leveled off or decreased with increasing moisture. Thus, for these cases, it was not possible to distinguish between relatively low moisture contents and larger moisture contents.

Many of the adjusted NDE response versus moisture content data sets and their fitted curves tended to be concave downward for the capacitance method (figures A1 through A36, appendix A). This is in contrast to an almost linear (that is, slightly concave downward), linear, or concave upward trend for the nuclear (figures A37 through A60) and infrared (figures A61 through A69) methods. These trends are supported by the higher percentages (11 to 22 percent) of negative sensitivity values at and beyond the threshold moisture content for the capacitance method as compared to all positive sensitivity values for the nuclear and infrared methods.

It is concluded that the nuclear backscatter method was able to determine the moisture content beyond the "threshold moisture" more reliably (always having positive sensitivity values) and, for most construction variable combinations (table 14), more accurately (larger sensitivity values) than the electrical capacitance method.

Based on the limited infrared thermography data, the following conclusions are drawn. As compared to electrical capacitance, the infrared thermography method was able to determine the moisture content beyond the "threshold moisture" more reliably (always having positive sensitivity values) and more accurately (larger sensitivity values, table 13) than for the electrical capacitance method. It is concluded that no significant difference existed between the ability of the nuclear backscatter and infrared thermography methods to detect moisture beyond the "threshold moisture" content, because the sensitivity values for both methods were positive and about the same in magnitude (table 13).

IV. FACTORS AFFECTING NDE FIELD SURVEYS

This report deals solely with a laboratory evaluation of three commonly used NDE methods to detect moisture in built-up roofing systems. The laboratory study was conducted under controlled conditions and did not consider all variables or factors which may be encountered in actual field surveys. Factors which were not investigated in this study and therefore not discussed in the report include:

- moisture distribution through the thickness of the roofing system
- layers of water either on the surface or within the roofing system
- surface moisture
- volume of roofing system affecting instrument response
- point or grid measurements (capacitance and nuclear methods) as compared to full-field measurements (infrared method)
- gravel thickness
- distance between instrument and moisture (capacitance and nuclear methods)
- anything that affects surface temperature (infrared method)

These factors along with others which affect the response of the NDE methods are discussed in detail in reference [3]. This reference recommends that nondestructive evaluation should always be accompanied by visual inspection of the roof and by the taking of cores to verify moisture contents. In addition to the factors listed above, the following must also be considered in selecting an NDE method:

- Cost of equipment, personnel, and data analysis.
- Skill of personnel required to operate equipment and to collect and analyze data.
- Knowledge of the roofing system and the effects of the construction and environmental variables on the NDE method response.
- Purpose of moisture survey (routine maintenance, re-roofing evaluation, etc.).
- Reliability and quality required in survey results.
- Combination of more than one NDE methods.

It has been pointed out that the selection of an NDE method to measure the moisture in built-up roofing systems depends on many factors. Thus, the information on the reliability and accuracy of the NDE methods for the roof construction variables investigated in this study is an important consideration in selecting an NDE method.

Facing Page: Moisture can be introduced in the insulation of a roofing system during construction.

1. INTRODUCTION

1.1 BACKGROUND

Moisture in insulated built-up roofing systems causes many premature roof failures. For example, moisture in the insulation of roofs will reduce the useful life of a membrane by causing premature failures, such as blistering, splitting, wrinkling, and deterioration of the membrane [1]*. Also moisture can significantly increase the thermal conductance [2] of a roof, causing unwanted energy losses.

Early detection of moisture in roofs is required if premature deterioration is to be prevented. The traditional inspection methods for moisture are slow, costly, require cutting samples from the roof, and seldom provide conclusive results.

A promising approach for improving the reliability of inspection and maintenance procedures is through the use of nondestructive evaluation (NDE) methods that can detect moisture in the interior of roofing systems. There are currently a number of promising, commercially available, NDE methods being used to detect moisture in roofing systems. They are primarily the nuclear backscatter, electrical capacitance, and infrared thermography methods. These methods detect moisture by indirect means. They can be used to estimate the moisture content with an accuracy which appears to depend on the equipment characteristics, composition of the roof, environmental conditions, operator skill, and several other factors [3]. A comprehensive study was carried out to compare the accuracy and reliability of these methods so that their proper role in roofing inspection, maintenance, and repair could be established.

1.2. PURPOSE AND SCOPE

1.2.1 Purpose

The purpose was to conduct a controlled laboratory study to investigate NDE methods for:

- their ability to quantitatively detect a minimum moisture content (threshold moisture content, TVP)

- their ability to quantitatively detect moisture beyond the threshold moisture content (change in NDE response per change in moisture content).

1.2.2 Scope

Two nuclear instruments (N1 and N2), three electrical capacitance instruments (C1, C2, and C3), and one infrared thermography instrument were investigated. The instruments or services using the instruments are commercially available.

Thirty-six built-up roofing (BUR) specimens, measuring 2 x 2 ft. and consisting of five different insulations, in one and two in. nominal

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* Numbers in brackets refer to references at the end of this report.

thicknesses, were used to evaluate the NDE methods on both concrete and steel decks. All the specimens used with the capacitance and nuclear instruments were gravel-surfaced. Since there was essentially no difference in infrared instrument response between comparable gravel and smooth-surfaced specimens, most of the specimens used with the infrared instrument were smooth-surfaced. Two interply asphalt thicknesses were investigated. The gravel surfacing weight per unit area was, in general, greater for the thicker asphalt. Moisture was induced in the roofing specimens by imposing a constant vapor pressure difference across the specimens. The response data for the NDE methods were taken over a wide range of moisture contents, varying from near zero to about 60 percent by volume for some insulation types.

Facing Page: Roofing specimen fabrication - application of asphalt flood coat and gravel surfacing.

2. SPECIMENS, DECKS, AND ENVIRONMENT

2.1 SPECIMENS

NDE responses (readings) were taken on "room dry" roofing insulation boards with attached BUR membranes. The thirty-six "room dry" specimens were stored at room conditions at approximately 70°F and 50 percent relative humidity (RH). The moisture contents of the "room dry" insulation boards and roofing felts used to construct the specimens were determined gravimetrically after oven drying. After obtaining the NDE responses for the "room dry" specimens, moisture was induced into the specimens, and NDE responses were taken on the "wet" specimens. All specimens were nominally 2 by 2 ft. square. Five types of rigid board roof insulations, in 1 and 2 in. nominal thicknesses, were included in the study; they were glass fiber, perlite board, fiberboard, expanded polystyrene, and foamed polyurethane. The BUR specimens were fabricated by a roofing contractor under the supervision of National Bureau of Standards' personnel (figure 1). The BUR membranes consisted of four plies of type 15 asphalt saturated, organic felts (Type I - ASTM D 226-77 [4]). The felts were applied to the insulation boards in sandwich fashion by application of hot, Type III asphalt (ASTM D 312-77 [5]). Both gravel and smooth-surfaced specimens were included. The rounded gravel, which was embedded in a hot asphalt floodcoat, was a 3/4 in. maximum size. Figure 2 shows a schematic of the composition of a roofing specimen; figure 3 shows typical gravel and smooth-surfaced specimens.

Table 1 gives the average measured properties for the insulation, felt, and asphalt used in the fabrication of the test specimens. The glass fiber board had an asphaltic facing sheet over which the BUR membrane was applied. In this study, the facing was considered as part of the membrane. The polyurethane board originally had asphaltic facing sheets on both sides. In order to increase the rate of moisture introduction, the asphaltic facing sheets were removed from both sides with a band saw to provide the required 1 and 2 in. thicknesses. The thickness of the polyurethane boards before cutting was 2.25 in. for the 1 in. specimens and 3.25 in. for the 2 in. specimens. The batch from which the 1 in. thick specimens were cut was probably different from the batch from which the 2 in. specimens were cut. This is supported by the difference in density (table 1) and visual difference; i.e. the 2 in. thick boards appeared less uniform in texture than the 1 in. thick boards.

Table 2 presents the gravel-surfaced specimens for which "room dry" and subsequent "wet" NDE tests were performed. The specimens were taken apart and the following thicknesses were measured: total specimen thickness, combined membrane and gravel thickness, and the membrane thickness. The table gives average values for total specimen thickness, the membrane and gravel thicknesses, and the membrane and gravel weight per unit area. The insulation thickness shown was taken as the difference between the measured total specimen thickness and the combined membrane and gravel thickness. The gravel thickness was taken as the difference between the measured combined membrane and gravel thickness and the membrane thickness. The weight per unit area of the membrane included the weight of the floodcoat, including the floodcoat which adhered to the gravel. The weight of the floodcoat which adhered to the gravel was determined by weighing the gravel before and after it was washed in a solvent.

Table 2 also identifies the smooth-surfaced BUR specimens for which "room dry" and subsequent "wet" NDE tests were performed. The table gives average measured values for total specimen thickness and membrane thickness and weight per unit area for specimens which had been taken apart. The insulation thickness was taken as the difference between the total specimen and the membrane thicknesses.

Thickness and weight per unit area measurements were performed after the "wet" NDE tests had been completed. The values of the individual membrane thicknesses in table 2 are the averages of nine measurements. In some cases, as noted in table 2, the total thickness of the specimen could not be measured because the insulation had deformed. Therefore, the total specimen thickness had to be estimated using the membrane and gravel thicknesses (table 2) and the insulation thickness given in table 1. Some melting and consequent reduction in the thickness of the polystyrene insulation occurred during application of the hot asphalt and roofing felts. When handling the gravel-surfaced specimens, some loose gravel fell off. As a result, this lost gravel was not included in the thickness and weight per unit area measurements given in table 2.

As table 2 indicates, there was considerable variability in the data for membrane thickness and weight per unit area. Table 3 presents the data for the membrane weight per unit area for specimens tested using the capacitance and nuclear methods. Because these methods may be influenced by interply asphalt thickness, it was necessary to introduce asphalt thickness as a variable ("standard" and "heavy"). The membrane weight per unit area data were judged to be more consistent and reliable than the membrane thickness measurements; hence weight per unit area data are used to compare the "standard" and "heavy" asphalt thickness levels in table 3. It is apparent that for specimens containing different insulations there was a considerable range in the weight per unit area values for the "standard" and "heavy" asphalt thicknesses. It can be seen, however, for 1 and 2 in. insulation thicknesses, that the weight per unit area for the "heavy" asphalt exceeded the "standard" for each type of insulation. Table 2 also presents the membrane weight per unit area values for specimens (nos. 51, 61, 113, 141, 143, 145, 733, 751, 155) with "standard" asphalt thickness and tested using the infrared method. The information in tables 2 and 3 needs to be consulted when determining the effect of "standard" as compared to "heavy" asphalt thickness on the NDE response as given later in this report. It is noted that the gravel surfacing weight per unit area was, in general, greater for the "heavy" asphalt thickness.

2.2 DECKS AND ENVIRONMENT

For the nuclear and capacitance instruments, the specimens were placed on 2.5 by 2.5 ft. square decks. Both concrete and steel decks were used; the decks were elevated approximately two feet above a 6 ft. thick concrete-steel structural test floor. After the specimens were centered on the decks, the NDE readings were taken at ambient conditions of approximately 70°F and 50 percent RH. Figure 3 shows NDE readings being taken on the specimen-deck assemblages. For all specimens placed on the steel deck and for "room dry" and "wet" specimens containing polystyrene and also polyurethane insulations, a 1 in. "room dry" perlite board was placed between the specimen and the deck. To prevent moisture from being absorbed into the 1 in. perlite board, a 3 mil polyethylene sheet was used between the specimen insulation surface and the 1 in. perlite board. The reason for using the 1 in. perlite board was that in current construction practice, composite boards using foam plastic and mineral board are used for reasons of fire safety.

Due to differences in the testing procedure requirements for the infrared method, a special test setup, using a steel deck only, was used with controlled environmental conditions. The details of the infrared method are presented in chapter 7.

The concrete deck was a 5 in. thick structural concrete slab with no. 4 steel reinforcing bars in one direction spaced 12 in. on the top and no. 3 bars spaced 12 in. in both directions on the bottom. After curing, the concrete deck was sealed with a two component epoxy paint to insure that the moisture content in the concrete deck did not change during the testing program.

A fluted steel deck (light, 22 gage) was used.

Facing Page: Ponded water on roof surfaces may lead to moisture introduction in the roofing system.

3. MOISTURE INTRODUCTION, MEASUREMENT, AND GAIN

3.1 MOISTURE INTRODUCTION

The NDE tests were performed on specimens containing a wide range of moisture contents. Moisture was induced in the specimens by controlling temperature and relative humidity conditions on each side of the specimens as indicated in figure 4. Specimens were placed on the top of insulated wooden chambers, as shown in figures 4 and 5. The inside of each of the two large insulated chambers, 8 x 16 ft. in area, was maintained at 100°F

($\pm$7°F) and 100 percent RH by means of four pools (each about 25 ft^2) containing heated water. The two insulated chambers were in an environmental laboratory which was maintained at 50°F ($\pm$4°F) and 25 percent ($\pm$5 percent) RH. Thus, the insulation (bottom) side of the specimens was subjected to 100°F and 100 percent RH while the membrane (top) side of the specimens was subjected to 50°F and 25 percent RH. The calculated vapor pressure difference was 1.84 in. of Hg for the environmental conditions under which the specimens were exposed. The intent of using this relatively large vapor pressure difference was to induce moisture into the specimens at a rapid rate; usually, much lower vapor pressure differences exist under actual field environmental conditions.

A wooden frame, approximately 2 x 2 ft., with a continuous wooden ledge at the bottom, was used to support the individual specimens (figure 4). The ledge provided about a 1/2 in. width of support at the bottom on all four specimen edges. When additional support was needed because of deterioration due to moisture, aluminum angle, 1/2 in. in width, spanned the center of the wooden frame in both directions. To promote one-dimensional moisture migration, the edges of the specimens for all insulations except the perlite boards were sealed with an impervious, vinyl, vapor-barrier paint. A wax was used to seal the edges of the perlite board specimens. Due to handling, some specimen edge seals cracked or fell off during the moisture introduction and testing of the specimens.

In an attempt to determine the moisture distribution through the insulation thickness, 0.91 in. diameter cores were taken from the insulation of some of the specimens. These cores were generally taken as far away from the center of the specimens as possible so as to not affect the NDE instrument responses. The coring procedures and some coring data related to thermal conductance are presented in reference[2]. The coring data for this NDE study are considered preliminary and, in general, cores were not taken for most moisture contents corresponding to NDE testing. Thus the coring data are not presented.

3.2 MOISTURE MEASUREMENT

Before the specimens were placed into chambers in the environmental room, they were weighed ("room dry" weight) and measured. When the specimens were removed from the chambers, the time was recorded and the specimens weighed ("out" weight). With the exception of the specimens containing glass fiber insulation, the surface of the insulation was wiped with paper towels to remove any free or condensed surface water prior to weighing. Distinct areas of visible free water, particularly for higher moisture contents, were observed on the surface of the warm side of the glass fiber insulation. It appeared that the lateral distribution of moisture in these specimens varied considerably. At some times during handling, particularly at higher moisture contents, considerable free water was lost from these specimens.

Since some gravel fell from the specimens during handling (removal and return to moisture chambers and during testing), the following procedure was used to determine the moisture weight gain for all gravel-surfaced specimens:

$$\text{moisture gain} = \text{"out" weight} - \text{"room dry" weight} + \text{estimated cumulative gravel weight loss} \quad (1)$$

where the last term (estimated cumulative gravel weight loss) was determined by summing the gravel weight loss during each previous handling.

The gravel weight loss per handling was estimated for all specimens as follows. Since the "room dry" moisture contents were relatively low (table 1), the total gravel loss (for all handlings) was measured for 19 of the 30 gravel-surfaced specimens (table 2) as the difference between the "room dry" weight and the oven dried weight after all testing was completed. The gravel weight loss per handling was determined for these 19 specimens by dividing the total gravel loss by the number of handlings. The average total gravel weight loss for each of the 19 specimens was about 1.6 lb. and the average gravel loss per handling was about 0.08 lb. The gravel weight loss per handling for 7 of the 30 specimens (nos. 11, 16, 18, 21, 23, 26, and 29-table 2) was estimated as 0.08 lb., with the corresponding estimated total gravel weight losses ranging from 0.62 to 1.5 lb. The weight loss per handling for specimen 41 was taken as 0.05 lb. and was based on an assumed total gravel loss of 1.6 lb., since specimen 41 was handled more times than most of the other specimens.

The gravel weight loss per handling for the three specimens (nos. 51, 61, 113) used for the infrared measurements was assumed to be insignificant. These specimens were tested under different conditions than for the capacitance and nuclear measurements and were handled a fewer number of times.

The gravel adjustment procedures applied were judged to be reasonable, since in general it was observed that during testing only a small quantity of gravel was lost during each handling.

The values of moisture gain for the gravel-surfaced specimens are approximate but believed to be reasonable estimates of the moisture gain. The uncertainty in the approximate moisture gain values is most likely greater for the lower moisture content values.

For smooth-sufaced specimens, the difference in weight between the "out" weight and "room dry" weights was taken as the moisture gain.

3.3 RATE OF MOISTURE GAIN

The rate of moisture gain varied depending on the type and thickness of insulation in the roofing specimens. The exposure time ranged from about 10 to 100 days, depending on the type of insulation. There was interruption in the introduction of moisture in some specimens because the desired moisture contents had been reached and because of maintenance of the laboratory facilities. Therefore, some specimens were stored in plastic bags at room temperature before testing.

Figure 6, taken from the companion thermal conductance study [2], shows the insulation moisture content, V_p, in terms of the elapsed time in the chambers for ten smooth-surfaced specimens which were fabricated from the same materials used in this study. Specimen numbers given in figure 6 pertain to the thermal conductance study [2] and are not found in the tables in this report. The moisture content, V_p^*, in the specimen insulation is expressed as the percent by volume of water in the insulation; V_p was based on the average moisture gain for the entire specimen. The volume of insulation was determined from the insulation thickness (table 2) and the actual overall specimen dimensions (about 2 x 2 ft.). The volume of water was determined from the weight gain of the specimen (62.4 lb. = 1 ft^3).

Moisture gain plots for gravel-surfaced specimens were not included since some gravel fell from the specimens during handling. It is judged, however, that the moisture gain characteristics for the smooth and gravel-surfaced specimens were similar, since both surface types were subjected to the same vapor pressure difference.

Near or at the maximum moisture content, the insulation of some of the specimens, particularly perlite and fiberboard, cracked, delaminated, or fell apart. For specimen 16, which contained 2 in. thick perlite insulation, delamination of the specimen occurred at a moisture content of about 18 percent. The specimen was adhered together using a hot glue and testing continued until the maximum moisture content was reached (about 25 percent). The corners of specimens containing 1 in. polyurethane insulation (nos. 41 and 43) warped (turned up, away from deck surface) as much as three inches at their higher moisture content values. Since specimens containing 2 in. polyurethane took on very little moisture, they were not included in the analyses in this report.

$$^* V_p = \left(\frac{\text{Volume of moisture}}{\text{Volume of insulation}}\right) \times 100$$

Facing Page: Asphalt flood coat and mineral aggregate surfacing serves as a protective barrier to resist weathering of the membrane and moisture intrusion into the roofing system.

4. DATA ANALYSIS

This chapter presents the definitions and techniques used to present and analyze the NDE data. Included are the procedures used for data plotting, curve fitting, and outlier identification, and the definitions of the sensitivity criterion, performance characteristics, and indicators used to measure the performance of the NDE methods.

4.1 DATA PLOTTING AND CURVE FITTING

The adjusted NDE response is defined as the "wet" instrument response, R_W, minus the "room dry" instrument response, R_D. The terms "room dry" and "wet" refer to roofing specimens at "room dry" conditions (table 1) and those having induced moisture in the insulation, respectively. The adjusted NDE response versus moisture content, V_P, data sets are plotted in figures A1 through A36 in appendix A for the three capacitance instruments; figures A37 through A60 for the two nuclear instruments; and figures A61 through A69 for the infrared instrument. The "KEY" on the right side of each figure identifies the symbol (e.g. "TRI" = triangle, "DIAM" = diamond) with each specimen number (see figure A1).

To assist the reader to follow the data more easily in figures A1 through A60, the data points were connected by straight lines. For about 30 percent of the total number of moisture content values at which R_W readings were taken, either two or four repeated R_W readings were taken. These multiple R_W readings did not exhibit as much scatter as expected. In many cases the standard deviation of these readings was considerably less than the corresponding residual standard deviation (eqn. 3) resulting from the curve fitting procedures. It was concluded that the scatter in these readings included only part of the variability normally associated with replicate readings, primarily because the specimen was not repositioned between readings and the times at which the readings were taken were usually very close together. For these reasons the multiple readings were not believed to be statistically independent of one another, and hence not true replicates. Thus it was not reasonable to treat each mutliple reading separately as though it were a truly independent data point. Hence, these multiple R_W readings were averaged and that average was equally weighted with the single R_W values taken at other V_P values.

Table 4 provides "room dry" (R_D) responses for 18 of the 27 roofing specimens for the capacitance and nuclear methods; these responses are discussed in chapters 5 and 6.

Table 5 gives the construction variables for each specimen, including the deck type, insulation type and nominal thickness, and asphalt thickness. To compare the effects of the construction variables, one scale for the adjusted NDE response was used with each instrument (figures A1 through A69).

Initially, linear, quadratic, and cubic polynomial forms were arbitrarily selected and fitted to the NDE instrument response versus moisture content data sets. This initial study showed that, in many cases, the quadratic form represented a significant improvement in fit as compared to the linear form. The cubic form, however, was judged not to represent a significant improvement in fit as compared to the quadratic form. Thus the following quadratic form, though somewhat arbitrary, was chosen as best suited for the variety of shapes of NDE data sets observed.

$$Y_{est} = (R_W - R_D)_{est} = a_0 + a_1 V_P + a_2 V_P^2 \tag{2}$$

where:

Y_{est} = estimated $R_W - R_D$ response

R_W = "wet" NDE reading (at a given "wet" V_P value)

R_D = "room dry" NDE reading (at the "room dry" V_P value)

$(R_W - R_D)_{est}$ = estimated $R_W - R_D$ response

V_P = moisture content, percent by volume of insulation

a_0, a_1, a_2 = least squares coefficients

Based on eqn. 2, the residual standard deviation, RSD was calculated by:

$$RSD = \left[\frac{\sum_{i=1}^{n} (Y_{obs} - Y_{est})^2}{n-P} \right]^{1/2} \tag{3}$$

where:

n = total number of $R_W - R_D$ observations

Y_{obs} = observed $R_W - R_D$ response, including 0 (i.e. $R_W = R_D$)

Y_{est} = estimated $R_W - R_D$ response (eqn. 2)

P = number of parameters estimated; for a quadratic form, P = 3.

The RSD value reflects the inherent scatter in the data as well as the uncertainty in the model (quadratic form) used to fit the data. The relatively few data points which were separated from their fitted curve by more than three RSD values were treated as outliers. The outliers are labelled in figures A1 through A60 but were not included in any analysis of the data. There were more outliers for specimens containing polystyrene insulation than for the other insulation types.

An example of the procedure used to analyze the $R_W - R_D$ (adjusted NDE response) vs. V_P data sets and obtain fitted curves is as follows. The response of instrument N1 (nuclear instrument, discussed in chapter 6) on specimen 11 (1 in. thick perlite insulation with "standard" asphalt thickness) on a steel deck was chosen. First the "wet" responses, R_W, were obtained by adjusting the responses for time effects (eqn. 10, chapter 6). (This adjustment was required only on instrument N1.) Then the "room dry" response, R_D, was substracted from each R_W value. In this case R_D was equal to 193 counts. As previuously discussed, for a given V_P value, if there were multiple R_W responses, the multiple R_W responses were averaged so as to be weighted equally with single R_W responses taken at other V_P values. The $R_W - R_D$ vs. V_P data set for the case being illustrated is shown in figure A46, appendix A. A best fit quadratic curve (eqn. 2) was then fitted to the $R_W - R_D$ vs. V_P data set as shown in figure 7. Once the fit was made, the residual standard deviation value, RSD, was computed (eqn. 3).

A variety of shapes and scatter patterns occurred for the $R_W - R_D$ vs. V_P data sets for the three NDE methods studied. Examples of fitted quadratic curves are shown in figures 7 through 16 and figures A61 through A69, appendix A. The intent of these figures is to show the variety of shapes and scatter patterns which were observed. The reader is referred to chapters 5 through 8 for an assessment of the various NDE methods.

Tables A1 through A5, A11 through A15, and A21 in appendix A present a summary of the $R_W - R_D$ vs. V_P data for the capacitance, nuclear, and infrared instruments respectively. The tables show the $R_W - R_D$ response at V_P values of 0, 10, 20, 30, 40, 50, and 60 percent based on a best fit quadratic curve fitted to the points of each $R_W - R_D$ vs. V_P data set. Also shown in the tables are values of "3RSD", that is, 3 times the residual standard deviation (RSD) and the threshold moisture content (TVP) for each fitted curve. The values of 3RSD were used to determine the threshold moisture content, which is discussed in the section 4.3.

4.2 SENSITIVITY CRITERION

A thorough search and study was made on how to define a sensitivity criterion to compare the variety of NDE methods used in this study. There are many possible ways to define sensitivity including normalizing the response by the local or maximum response. For example, a recent comparative study [6] of nuclear moisture and density instruments, defined sensitivity, S, as:

$$S = \frac{\frac{\Delta r}{r}}{\frac{\Delta w}{w}} \tag{4}$$

where:

$\Delta r/r$ = relative change in count rate

$\Delta w/w$ = relative change in moisture

In the current study, the three NDE methods investigated and analyzed had vastly different fitted curve shapes ($R_W - R_D$ vs. V_P) and also different associated scatter (see figures A1 through A69, appendix A). The three instrument types operated with completely different mechanisms and widely different $R_W - R_D$ response scales. For example, the minimum and maximum $R_W - R_D$ scale values used for the different instruments were:

	$R_W - R_D$	
Instrument	Minimum Scale Value	Maximum Scale Value
Capacitance		
C1	0	100
C2	0	200
C3	0	8
Nuclear		
N1	0	80
N2	0	300
Infrared	0	0.2

In addition, a variety of construction variables, including two deck types, five insulation types, two insulation thicknesses and two asphalt thicknesses were investigated. Because of the many variables and the wide ranges of the variables involved, it was necessary to normalize the $R_W - R_D$ data in order to assess the performance charcteristics (discussed in section 4.3) within and among instrument types.

Due to the large difference in the shape and scatter patterns of the data sets, and the many variables and wide ranges of the variables, it was decided that the normalization process would be based on the fitted curve and that it would include a measure of scatter of the $R_W - R_D$ vs. V_P data set about its fitted curve. That is, two fitted curves which were very similar as normalized by a definition such as eqn. 4, but had significantly different scatter (residual standard deviation), needed to be distinguished, since the associated uncertainty in the response would be larger for the curve with more scatter. A sensitivity criterion, such as that given by eqn. 4, though perhaps suitable for a single method (nuclear) was not deemed appropriate for the current study.

Mandel and Stiehler [7] present an approach to quantitatively determine the sensitivity of a test method. They define the sensitivity, S, as the absolute value of the ratio of the slope, m, of the response curve to the standard deviation, s, i.e.:

$$S = |m|/s \qquad (5)$$

This definition of sensitivity (eqn. 5) was chosen because it is a rational definition which incorporates scatter and was believed to be the best suited for quantitatively comparing the results of the NDE methods. Their criterion has also been used for other applications [8, 9].

In this report, the slope was taken to be the change in the adjusted NDE response ($\Delta(R_W - R_D)_{est}$) as predicted from the fitted curve (eqn. 2) per unit change in moisture content (ΔV_P). The standard deviation in eqn. 5 was approximated by the residual standard deviation (RSD, eqn. 3) of the $R_W - R_D$ vs. V_P data set about its fitted curve. Ideally, values of the standard deviation at each V_P value should have been used to define the sensitivity; however, data were not available to do this.

The sensitivity, S, can then be written as:

$$S = \left(\frac{\Delta(R_W - R_D)_{est}}{\Delta V_P} \right) / RSD \qquad (6)$$

Use of the sensitivity, then, implies normalizing the $R_W - R_D$ data by dividing by RSD. That is, the sensitivity can be written as:

$$S = \frac{\dfrac{\Delta(R_W - R_D)_{est}}{RSD}}{\Delta V_P} \qquad (7)$$

From eqn. 7 it can be seen that the sensitivity is the slope of the $(R_W - R_D)_{est}/RSD$ vs. V_P curve.

Use of the sensitivity to assess the performance of the NDE methods is discussed in the next section.

4.3 PERFORMANCE CHARACTERISTICS AND INDICATORS

Two performance characteristics were chosen to evaluate the NDE methods. The following performance characteristics were determined for each $R_W - R_D$ vs. V_P data set and corresponding fitted curve:

- o the minimum amount of moisture, called the threshold moisture content (TVP), that an instrument could quanitatively detect for a specified reliability; and

- o ability of the instrument to quantitatively detect moisture beyond the TVP value.

The first performance characteristic, TVP, was defined to be that V_P value at which the fitted curve [$(R_W - R_D)_{est}$, eqn. 2] deviated from (exceeded) the zero ("room dry") response by 3 RSD values. This definition is equivalent to normalizing the $R_W - R_D$ responses by dividing them by a multiple of the scatter (3RSD), thus permitting the comparison of threshold moisture values within and among the NDE methods. The multiple of 3, which was chosen for analysis purposes and which was somewhat arbitrary, was found to be a reasonable condition and requirement for computing and comparing threshold moisture contents in a consistent manner. It was found that the intercept for the $(R_W - R_D)_{est}$ fitted curve (obtained by setting $V_P = 0$ in eqn. 2) in most cases differed somewhat from zero, and in some cases, differed significantly from zero (for example, see figures 7 through 16 and tables A1-A5, A11-A15, A21, appendix A). It was decided to measure the deviation of 3 RSD values (used in TVP definition) from zero and not from the intercept of the fitted curve. The reason for choosing zero was that the zero value of $R_W - R_D$ was measured and hence was known with certainty. Also the uncertainty in the V_P values caused by gravel loss during testing probably increased the uncertainty of the $R_W - R_D$ vs. V_P points near the origin (see section 3.2). The TVP values were obtained by setting the right hand side of eqn. 2 equal to 3RSD and solving for V_P. An example of the TVP determination is illustrated in figure 7, where 3RSD was equal to 8.45 (table 5) and the resultant TVP value was 7.11 percent. If the ordinate of the fitted curve (eqn. 2) never equalled or exceeded 3RSD up to the maximum moisture content in the specimen, no TVP existed. This condition was referred to as: "TVP not attained". The TVP values for the capacitance and nuclear instruments are given in table 5. Also listed in table 5 is the maximum V_P value attained in each specimen and three times the RSD value (3RSD). Table 6 presents information similar to that in table 5 for the infrared instrument.

The threshold moisture content is called an indicator because it is used as a measure of the ability (or performance) of a method to detect a minimum moisture content. In general, smaller TVP values are indicative of better performance.

Table 7 presents, for the capacitance and nuclear instruments, a summary of the percentage of the TVP values in table 5 which were:

- o less than 10 percent
- o less than 20 percent
- o not attained up to the maximum V_P of the specimen (called "TVP not attained")

For example, the top left entry of "11" in table 7 means that 2 of the 18 (11 percent) TVP values for instrument C1 for specimens containing glass fiber insulation in table 5 were less than 10 percent. The entries given in table 7 are for the three capacitance and two nuclear instruments and for each of the five insulation types tested. Table 7 also presents entries for the instruments for all insulations combined. Information similar to that in table 7 is shown in table 8 for the infrared instrument. The entries in tables 7 and 8 for "TVP less than 10 percent" and "TVP less than

20 percent" are based on the total number of tests performed, including those tests for which a TVP value was not attained.

The TVP values for which percentages are summarized in tables 7 and 8 (less than 10 percent, less than 20 percent, or "not attained") were chosen to emphasize trends which are discussed in chapters 5, 6, 7, and 8.

The second performance characteristic (ability to detect moisture beyond the TVP) was measured by the following indicators:

- o the value of the sensitivity, S, (eqn. 6) at and beyond the TVP value.
- o the value of the slope, SS, of the S vs. V_P curve at and beyond the TVP value.

The sensitivity values, S, were determined from eqn. 6, based on the secant slope, for V_P ranges, called "moisture content ranges" of 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and 50 to 60 percent as follows:

$$S = \frac{(R_W \text{ at } V_P) - (R_W \text{ at } [V_P - 10])}{10 \text{ RSD}} \tag{8}$$

where:

$(R_W$ at $V_P)$ = instrument response at the higher moisture content (i.e., for example 30 percent) in a given "moisture content range" (i.e., for example 20 to 30 percent),

$(R_W$ at $[V_P - 10])$ = instrument response at the lower moisture content (i.e., for example 20 percent) in a given "moisture content range", (i.e., for example 20 to 30 percent)

RSD = residual standard deviation of the fitted curve.

Values of S were determined only for moisture content ranges which either included or exceeded the TVP value; S values were not computed for moisture content values exceeding 60 percent nor for cases when the TVP was not attained up to the maximum moisture content of the specimen.

For example, an S value of 0.10 over the moisture content range of 10 to 20 percent would mean that the $R_W - R_D$ fitted curve increased 1.0 residual standard deviation.

Tables A6 through A10, A16 through A20, and A22 in appendix A give S values for each $R_W - R_D$ vs. V_P fitted curve for the capacitance, nuclear, and infrared instruments respectively.

In table 5, the S values are summarized by three values: S(TVP), S(MID), and S(MAX). The S(TVP) value is the S value in the moisture content range in which the TVP occurs, while S(MAX) is the S value in the moisture content range preceding the range containing the maximum moisture content. The S(MID) value is the average of the S values for the moisture content ranges between the range containing the TVP and the range preceding the range containing the maximum moisture content. Figure 17 shows a schematic $R_W - R_D$ vs. V_P fitted curve and examples of S(TVP), S(MID), and S(MAX). For any specimen, S(TVP), S(MID), and S(MAX) may or may not exist as follows:

o TVP was not attained ("TVP not attained") up to the maximum moisture content of the specimen	Neither S(TVP), S(MID) or S(MAX) exist
o TVP (e.g. 14 percent) occurred in the moisture content range (e.g. 10 to 20 percent) containing the maximum moisture content.	S(TVP) only exists
o TVP (e.g. 22 percent) occurred in the moisture content range (e.g. 20 to 30 percent) preceding the moisture content range (e.g. 30 to 40 percent) containing the maximum moisture content.	S(TVP) and S(MAX) exist; S(MID) does not exist.
o At least two moisture content ranges (e.g. 20 to 30, 30 to 40 and 40 to 50 percent) exist beyond the moisture content range (e.g. 10 to 20 percent) containing the TVP value.	S(TVP), S(MID) and S(MAX) exist

For cases where the TVP existed but the maximum V_P value in the specimen was less than the next higher multiple of 10 V_P (e.g. TVP = 12 percent and the maximum V_P in the specimen was 18 percent), the computation of S(TVP) was modified as follows: the S(TVP) value was based on a reduced moisture content range measured from the maximum moisture content to the next lower multiple of 10 V_P (for example, a reduced moisture content range of 10 to 18 percent if the TVP was 12 percent and the maximum moisture content was 18 percent).

To examine and compare the effects of the major factors in the study (NDE method, insulation type and thickness, asphalt thickness and deck type), plots of all the S values at or beyond the TVP value were made for each specimen. These plots are called S vs. V_P plots and are shown in figures A70 through A105, appendix A. The scale for the S axis was constructed as follows (see figure A70). A continuous linear scale was used for S values between 0.0 and 0.4, since most of the S values occurred in this range. Discrete ranges of S were used for values exceeding 0.4 (0.40 to 0.49; 0.50 to 0.59; 0.60 to 0.69; 0.70 to 0.99; > 1.0) and for S values less than 0.0 (0.0 to -0.049; -0.050 to -0.10; < -0.10). If no TVP value was attained up to the maximum V_P value of the specimen (called "TVP not attained"), a single point appears at a labelled location near the bottom of the S axis and is plotted at the midrange of the moisture content range in which the maximum V_P occurred. Values of S are plotted at the midrange of the moisture content ranges used to compute S. For example, for a moisture content range of 10 to 20 percent, the S value would be plotted at 15 percent. The first point (S, V_P coordinates) on each specimen curve also represents the TVP for that specimen, with the TVP plotted at the midrange of the moisture content range in which the TVP occurred. For example, a TVP of 17 percent would be plotted at the midrange of the 10 to 20 percent moisture content range or a 15 percent V_P value. For the special case where the TVP existed but the maximum V_P value was less than the next multiple of 10 V_P, the S value was plotted at the midrange of the reduced moisture content range (e.g. TVP = 12 percent, maximum V_P = 18 percent, S based on moisture content range of 10 to 18 percent and TVP and S plotted at V_P of 14 percent). Tables A6 through A10, A16 through A20, and A22 show the S values used in the S vs. V_P plots for each specimen, deck, and instrument combination. The S values for each specimen were connected by straight lines on the S vs. V_P plots. For a given deck and instrument, there were in some cases more than one specimen tested resulting in more than one S vs. V_P plot.

The purpose of figures A70 through A105 is to emphasize instrument response differences in the S vs. V_P curves for particular combinations of construction variables. The S vs. V_P curves are shown for all instruments on each figure. The "KEY" on the right side of each figure identifies the symbol (e.g. TRI=triangle, "DIAM"-diamond) with each instrument (IR=infrared).

Table 9 shows a summary of the percentages of the S values (at and beyond the TVP) which were less than 0.0 and 0.2 for the capacitance and nuclear instruments for each of the five insulations. Table 9 also presents percentages for all insulations combined. Information similar to that in table 9 is presented in table 8 for the infrared instrument.

The S values for which the percentages are summarized in table 9 (less <u>0.0</u>, less than <u>0.2</u>) were chosen to emphasize trends presented in later chapters. Values of S less than 0.0 correspond to a concave downward shape and, more important, indicate that both the $R_W - R_D$ and $(R_W-R_D)/RSD$ responses are decreasing with increasing moisture content. The S value of 0.2 is significant because about 90 percent of the S values for the nuclear instruments exceeded 0.2 while over 75 percent of the S values for the capacitance instruments were less than 0.2. In general, higher S values are indicative of better performance.

The slope, SS, of the S vs. V_P curve was also used as an indicator to measure the ability to detect moisture beyond the threshold moisture content. The SS values were found from:

$$SS = (2a_2)/RSD \qquad (9)$$

where a_2 is a quadratic curve coefficient appearing in eqn. 2.

Thus SS is a constant for each $R_W - R_D$ vs. V_P fitted curve; a single SS value was determined for each fitted curve whenever S values (eqn. 8) were determined. (Neither S nor SS values were determined for cases when the TVP was not attained.)

Table 10 gives a summary of the percentages of the SS values (at and beyond the TVP) which were less than -0.015 and 0.0 for the capacitance and nuclear instruments and for each of the five insulations. Percentages for all insulations combined are also given in table 10. Information similar to that in table 10 is shown in table 8 for the infrared instrument.

The values of SS for which percentages are summarized in table 10 were selected to illustrate trends. Values of SS less than about -0.015 correspond to a sharp drop in the S vs. V_P curve (for example, this was a strong trend for the capacitance instruments for fiberboard insulation - see figures A86 through A93). In general, S vs. V_P curves which do not have sharp decreases, are indicative of better performance.

To aid in interpreting the S vs. V_P curves shown in figures A70 through A105, the graphical relationship between the $R_W - R_D$ vs. V_P fitted curve and the corresponding S vs. V_P curve are illustrated in figure 18. In figure 18a, the $R_W - R_D$ vs. V_P curve is essentially linear (small quadratic component); the S values are positive and the SS values close to zero. Figure 18b shows a concave downward $R_W - R_D$ vs. V_P curve, resulting in more than a single V_P value for one $R_W - R_D$ value. Here the S value is relatively large and positive at A; at B the S value is zero; and at C the S value is less than zero. The SS value (a constant) is negative (figure 18b). In figure 18b, the S vs. V_P curve is linear, but appears broken because of the discrete ranges chosen for the extreme S values. In figure 18c, the $R_W - R_D$ vs. V_P curve is concave upward, corresponding to linearly increasing S values with increasing moisture content. Again note the break in the S vs. V_P curve. For this case (figure 18c), the constant SS value is positive.

Although the general shape of the $R_W - R_D$ vs. V_P fitted curve and the corresponding $((R_W - R_D)/RSD)$ vs. V_P curve will be similar, the magnitude of the slope of the two curves could be significantly different. Thus one of the characteristics of normalizing (dividing) by the RSD value is that the slope (corresponds to S, see equation 6) of the normalized curve $((R_W - R_D)/RSD)$ usually differs from the slope of the $R_W - R_D$ curve. For example, although two fitted $R_W - R_D$ curves may appear similar in slope, their normalized curves will not have similar slopes (S values) if they have significantly different RSD values.

The indicators TVP, S, and SS are used in subsequent chapters to measure instrument effects, that is, to assess differences between instruments of a given type (method) and between instrument types.

An example is:

- o A significant difference in TVP, S, or SS values among the capacitance, nuclear, and infrared methods for one or more combinations of construction variables (construction variable refers to specimen composition and deck used, e.g. 1 in. thick glass fiber insulation, "standard" asphalt thickness, steel deck).

These indicators were also used to measure construction variable effects which occurred both within and between instrument types. An example is:

- o A significant difference in TVP, S, or SS values for a particular instrument or between two instrument types used on concrete as compared to steel deck (deck effect).

There are several factors which contribute to the uncertainty in estimating the TVP, S, and SS values including:

- o Lack of fit of model (quadratic used); for most of the data the quadratic model appeared reasonable. In certain cases, however, it was not. For example, the $R_W - R_D$ vs. V_P data sets for instrument C2 with perlite board and fiberboard are closer to a bilinear than a quadratic shape (figures A15, 16, 21, 22, appendix A and figure 11).

- o Choice of normalization and sensitivity criteria, and definition of TVP.

- o Using the RSD as an average estimate of the standard deviation at each moisture content.

- o Uncertainty in the TVP value due to uncertainty in the moisture content caused by gravel loss during testing (see section 3.2) as well as the measurement of the deviation of 3RSD (used in the TVP definition) from zero and not from the intercept of the $(R_W - R_D)_{est}$ fitted curve.

These uncertainties must be recognized when using the TVP, S, and SS values to measure instrument performance and to determine instrument and construction variable effects. Thus, significant differences in the TVP, S, and SS values are needed for reliable conclusions regarding instrument performance and instrument and construction variable effects.

Facing Page: Three types of electrical capacitance instruments were used in this study.

5. ELECTRICAL CAPACITANCE METHOD

5.1 MECHANISM OF OPERATION

Electrical capacitance-radio frequency instruments respond to changes in either the dielectric constant, which is a measure of the ability of material to store electrical energy, or in the dielectric loss factor, which is related to the energy lost in an alternating electric field. Operation of electrical capacitance-radio frequency instruments is given in detail in reference [3]. Electrical insulators can be characterized by their dielectric properties as well as by their electrical resistances. Detection of roof moisture is based on the principle that either the dielectric constant or the loss factor for the roofing system with moisture will be significantly different than for the roofing system without moisture. Radio frequencies (1 x to 30 x 10^6 Hz) are used in most moisture determination instruments. However, when large moisture contents are encountered, frequencies in the VHF range, (100 x to 300 x 10^6 Hz) can be used. Using radio frequencies, equipment is commercially available which measures dielectric constant in some cases and dielectric loss factor in others.

Electrical capacitance instruments have been used for about 40 years by paper mills, textile mills, and wall board producers to measure moisture in their products. Some manufacturers' literature indicates that moisture content readings should be accurate to less than $\pm$ 2 percent. The various items of equipment are in an advanced state of development and have taken advantage of recent developments in electronics to enhance their dependability and portability. Available instruments make use of various electrode configurations. These electrodes, which are attached to a constant frequency alternating current source, establish a field in the material to be tested and determine the depth of penetration of the field. Current flow or power loss can be measured.

The presence of moisture on the surface can greatly influence the response and prevent obtaining information on the moisture content beneath the surface. Moisture may also have a profound effect on the "shape" of the electrical field which can be established in the material. Regions of high dielectric constant, such as wet regions, distort the field so that the spacing of the field lines is closer there than in dry regions. Cases where the moisture is not uniformly distributed or where discontinuities exist in the material (such as joints) could lead to errors in interpretation, since most interpretations are based on the assumption that the material is homogeneous. In addition to the field distortion, some instruments have limited penetration depths, which could prevent the detection of moisture below a certain distance from the surface.

5.2 INSTRUMENT DESCRIPTION

Two typical, commercially available capacitance-radio frequency instruments (not specifically sold for roofing applications) designated as C1 and C2 and one proprietary instrument, designated as C3, for which a roof survey service is commercially available were investigated. During testing the instruments were approximately centered on the surface of the specimens and the dial reading recorded.

Instrument C1 (figure 3) contained a power loss circuit which operated at 10 Megahertz. Button-shaped electrodes covered an area 3 in. in diameter. Instrument C1 was claimed by the manufacturer to have a penetration depth of 3/4 in. The scale on the dial ranged from 0 to 50 units and could be extended to a range of 0 to 100; scale divisions were marked: 0, 1, 2, 3 ...., 50. There were four moisture ranges; only moisture range 4, the most sensitive moisture range, was used in this study.

Similar to instrument C1, instrument C2 (figure 3) used a power loss circuit and operated at 10 Megahertz. The electrodes of the C2 instrument were two rollers, 3 5/8 in. wide and spaced 5 1/4 in. apart. The penetration depth was claimed by the manufacturer as 2 in. The scale on the dial ranged from 0 to 100 and could be extended to 200 units; scale divisions were marked: 0, 1, 2, ... 100. There were three moisture sensitivity ranges; only the "High", which was the most sensitive moisture range, was reported in this study.

Instrument C3 (figure 19) used two capacitor plates mounted at the bottom of the meter. A spray or fringe electrostatic field was formed between the plates. The scale on the dial ranged from 0 to 25 units; scale divisions were marked on each half unit: 0, 0.5, 1.0, 1.5, 2.0 ...., 24.5, 25.0. There were two instrument settings, one for gravel-surfaced and the other for smooth-surfaced roofs. The gravel setting was used in this study because the instrument was used only on gravel-surfaced specimens. The manufacturer recommends that instrument C3 should not be used on gravel thicknesses greater than 5/8 in.

5.3 INSTRUMENT CALIBRATION

Calibration readings on the three instruments were usually taken at the beginning of each day of testing. This was done to determine if the meters were operating properly and to detect any change in meter response with time which may have occurred during the testing period, which lasted about 150 days. The readings were taken on a piece of 1 1/8 in. thick polymethylmethacrylate mounted on a wooden stand about 6 in. high. Plots of the calibration readings vs the elapsed time for each of the instruments are shown in figures 20, 21, and 22.

Because of instrument operating difficulties, instrument C2 was replaced during the testing program after about 60 days. As shown in figure 21, the calibration readings for both C2 instruments were in reasonable agreement, indicating that the two C2 instruments appeared to be similar in their response. In general, limited data from both C2 instruments for specimens containing moisture also indicated similar response. It is noted that there was more scatter in the calibration curve for the C2 instrument which was replaced (figure 21).

The calibration curves for instruments C2 and C3 (figures 21 and 22) appear to be relatively constant with time. Therefore, no adjustments were made for the response of instruments C2 and C3 for specimens containing moisture. For instrument C1 (figure 20), there was a maximum change of about 3 scale units during the 150 day testing period. The change in response of instrument C1 with time was for the calibration condition, that is, without moisture. Because the change was considered small, and since it was not known what change would have occurred on specimens containing moisture, no adjustment of the response for instrument C1 was made for specimens containing moisture.

5.4 TEST RESULTS

As discussed in chapter 4, the adjusted NDE response vs. moisture content data sets for the three capacitance instruments are plotted in figures A1 through A36 in appendix A. The data are for gravel-sufaced specimens.

The "room dry" responses for instruments C1, C2, and C3 for specimens 6 and 31 were estimated by the "room dry" responses for specimens of similar composition. The "room dry" responses for specimen 56 were assumed for specimen 6. As table 2 shows, the compositions of specimens 6 and 56 were similar. The asphalt and gravel thickness and weight per unit area measurements were not determined for the specimen from which the "room dry" responses for specimen 31 were estimated. However, both specimens were gravel-surfaced, contained nominal 1 in. thick polystyrene insulation, and had similar total specimen weights. Table 4, which presents "room dry" responses, shows that the assumed "room dry" responses for specimens 6 (i.e. see specimen 56) and 31 appear to be reasonable compared to other "room dry" responses for the corresponding insulation type.

In some cases the response of instruments C1 and C2 for specimens containing moisture exceeded the maximum scale reading. In these cases, the maximum scale readings of 100 for instrument C1 and 200 for instrument C2 were used for R_W. For instrument C2, most perlite specimens (nos. 11, 16, 66, and 18 - see figures A15 and A16) and fiberboard specimens (nos. 21, 658, 26, and 29 - see figures A21 and A22) had many responses which exceeded the maximum scale reading of 200 for both concrete and steel decks.

5.5 TRENDS

A discussion of the analysis techniques used are presented in chapter 4.

5.5.1 Detection of Minimum Moisture Content (TVP)

As table 7 indicates, instrument C1, as compared to C2 and C3, in general had as low or lower percentages of TVP values less than 10 percent for each of the insulations and for all insulations combined. A similar trend is seen for percentages of TVP values less than 20 percent.

Of the five insulations, perlite board and fiberboard had the highest average percentages of TVP values less than 10 percent for the three instruments (table 7). A similar statement can be made for percentages of TVP values less than 20 percent. This trend for perlite and fiberboard correlates with the steep initial rise of the $R_W - R_D$ vs. V_P data sets (figures A13 to A24, appendix A), particularly for instrument C2.

Instrument C1, as compared to C2 and C3, had the highest average percentage (38 percent, table 7) of TVP values not attained for all insulations; of the five insulations, polystyrene and polyurethane had the higher percentages (50 to 70 percent) of TVP values not attained for instrument C1.

Instrument C2 had the lowest percentage (2 percent, table 7) of TVP values not attained for all insulations.

As indicated in table 5 for instruments C1 and C3, many specimens with "heavy" asphalt thickness had higher TVP values or did not attain TVP values as compared to specimens with "standard" asphalt thickness. It is noted that the gravel thickness was, in general, greater for the thicker asphalt. Only 7 of the 52 (14 percent) TVP values for specimens with "heavy" asphalt thickness were less than 10 percent as compared to 28 of the 54 (52 percent) TVP values for "standard" asphalt thickness which were less than 10 percent. (These percentages are based on the total number of tests, including tests for which a TVP value was not attained). For instrument C1, there were no TVP values less than 10 percent for polystyrene and polyurethane insulations. If polystyrene and polyurethane insulations are excluded, a trend for instruments C1 and C3 similar to that above was observed. (That is, only 19 percent of the TVP values for specimens with "heavy" asphalt thickness were less than 10 percent as compared to 55 percent for "standard" asphalt thickness.) With instrument C1, TVP values were not attained for 16 of the 26 (62 percent) tests for specimens with "heavy" asphalt thickness as compared to only 4 of the 26 (15 percent) tests with "standard" asphalt thickness for which TVP values were not attained. For instrument C3, all cases (5 out of 26, 19 percent) in which TVP values were not attained occurred in tests with "heavy" asphalt thickness.

Table 5 also shows that the TVP values were not attained primarily for specimens with:

- "Heavy" asphalt thickness for all insulations for instrument C1.

- "Heavy" asphalt thickness for glass fiber, polystyrene, and polyurethane insulations for instrument C3.

As evident from table 2, larger gravel thickness values correlated with larger membrane weight per unit area and larger gravel weight per unit area values. All 8 (100 percent) of the specimens with gravel thickness values exceeding 0.60 in. had "heavy" asphalt thickness as compared to only 5 of the 19 (26 percent) specimens with gravel thickness values less than 0.60 in. which had "heavy" asphalt thickness. All 14 specimens having "standard" asphalt thickness had gravel thickness values less than 0.60 in. The trend observed with instruments C1 and C3 for the "heavy" versus "standard" asphalt thickness (larger TVP values and more TVP values not attained for "heavy" asphalt thickness) may, in general, be attributed to either gravel thickness, asphalt thickness, or a combination of both. Since the specimens with the "heavy" asphalt thickness also had, in general, larger gravel thickness, the relative significance of these two variables was not determined. During specimen fabrication, it was intended to have a typical amount of gravel as recommended by the National Roofing Contractors Association. The values of gravel thickness given in table 2 were determined after testing was completed. During handling and testing, some gravel fell from the specimens (see section 3.2). Since gravel thickness was not controlled during testing, the trend of higher TVP values and more TVP values not attained for larger gravel thickness as compared to smaller gravel thickness is not known with certainty.

With instruments C2 and C3, many tests with specimens containing 1 in. thick insulation had higher TVP values than tests with specimens containing 2 in. thick insulation. Only 18 of the 60 (30 percent) tests with 1 in. thick insulation had TVP values less than 10 percent as compared to 35 of the 48 (73 percent) tests with 2 in. insulation which had TVP values less than 10 percent.

For instrument C1, TVP values were not attained for 12 of the 22 (54 percent) tests with specimens containing 2 in. thick insulation as compared to TVP values not being attained for only 8 of the 30 (27 percent) tests with specimens containing 1 in. insulation. With instrument C3, all cases (5 out of 30, 17 percent) in which TVP values were not attained occurred in tests with 1 in. thick insulation.

Hence, insulation thickness appeared to be a significant factor in affecting TVP values and causing TVP values not to be attained, depending on the instrument.

With instrument C3, all 5 cases for which TVP values were not attained occurred on specimens with "heavy" asphalt thickness and 1 in. thick insulation.

There were no significant deck effects (concrete vs. steel).

5.5.2 Detection of Moisture Content Beyond the TVP

Table 9 indicates that the capacitance instruments had their smallest average percentage (0 percent) of S values less than 0.0 for glass fiber insulation. Perlite board and fiberboard insulations had the largest percentages (35 and 29 percent) of S values less than 0.0. For all insulations combined, instrument C3 had the smallest (11 percent) percentage of S values less than 0.0; a similar trend is evident with instrument C3 for percentages of S less than 0.2. As previously discussed in section 5.4, the response for instrument C2 exceeded the maximum scale reading on most perlite and fiberboard specimens on both concrete and steel decks (figures A15, A16, A21, and A22) thus making interpretation of $R_W - R_D$ data difficult beyond the lower V_P values. The relatively large percentages of S values less than 0.0 and 0.2 for intrument C2 in table 9 for perlite and fiberboard insulations are attributable, at least in part, to the flatness of the $R_W - R_D$ vs. V_P data sets. Based on all insulations and the three capacitance instruments, over 75 percent (table 9) of the S values were less than 0.2.

Thus, in general, for some construction variable combinations, the S trends given in tables 5 and 9 indicate that the capacitance instruments were unable to detect moisture quantitatively at higher moisture contents beyond the TVP.

In general for the S indicator and for the three capacitance instruments, there were no significant deck effects (concrete vs. steel), insulation thickness effects (1 in. vs. 2 in.), and asphalt thickness effects ("standard" vs. "heavy").

As indicated in table 10, the three capacitance instruments had their lowest percentages of SS values less than -0.015 with polyurethane (0 percent) and glass fiber (12 percent) and their highest percentage with fiberboard (92 percent). That is, fiberboard had more sharp drops in the S vs. V_P curves (figures A86 through A93, appendix A) as compared to the other insulation types.

5.5.3 Shape of Data Sets and Their Fitted Curves

Many of the $R_W - R_D$ vs. V_P data sets (figures A1 through A36, appendix A) and their fitted curves tended to be concave downward for the capacitance instruments. This trend is supported by relatively large percentages (11 to 22 percent, table 9) of S values less than 0.0. The concave downward trend was particularly strong for perlite and fiberboard insulations.

For specimens containing perlite and fiberboard insulations, many of the adjusted NDE response versus moisture content data sets (figures A13 to A24, appendix A) for the capacitance instruments showed the following trend: the adjusted NDE responses rose sharply at moisture contents of about 10 percent or less and then leveled off or decreased with increasing moisture. Thus, for these cases, it was not possible to distinguish between relatively low moisture contents and larger moisture contents. The trend of flatness due to off-scale responses for instrument C2 with specimens containing perlite (figures A15 and A16) and fiberboard (figures A21 and A22) has been discussed in section 5.5.2.

5.5.4 "Room Dry" Response

Table 4 shows, for 18 roofing specimens, the "room dry" responses for the "standard" and "heavy" asphalt thicknesses with concrete and steel decks for the three capacitance instruments. Also shown is the difference in "room dry" responses between the "heavy" and "standard" asphalt thicknesses. Two specimens were chosen for each insulation type and thickness combination. Where possible, the specimens were chosen such that (a) the "room dry" readings were taken not more than seven days apart and (b) the membrane weight per unit area difference between "standard" and "heavy" was as large as possible.

As evident from table 4, in general the response for the "heavy" asphalt thickness exceeded the "standard" by a relatively small amount. For the most part, the absolute value of the response for the "heavy" asphalt thickness minus the "standard" asphalt thickness (absolute value of "Hvy-Std") values were less than the 3RSD values shown in table 5 for each instrument. Instruments C1 and C2 had very large responses for specimen 18 tested on both concrete and steel decks as compared to the other specimen responses. The reason for this was not determined.

5.5.5 Additional Considerations

Several factors should be noted with regard to uncertainty introduced in the laboratory study. In general, efforts were made to maintain visibly surface dry specimens. At times during testing, however, the surfaces of the specimens may have had small amounts of moisture thus affecting the instrument response. The few outliers (see section 4.1) may have been the result of surface moisture.

Gravel loss from the specimens (discussed in section 3.2) may have effectively reduced the distance from the capacitance instruments to the specimens and their decks. Thus as testing progressed and the gravel loss occurred, the instrument responses may have been affected.

Facing Page: Nuclear backscatter instruments used in this investigation.

6. NUCLEAR BACKSCATTER METHOD

6.1 MECHANISM OF OPERATION

The mechanism of operation of the nuclear backscatter method is described in detail in reference [3]. Briefly, a radioactive isotope source emits fast neutrons into a sample. The neutrons are scattered and slowed down, primarily due to collisions with the nuclei of hydrogen atoms. The slowed down or backscattered neutrons are counted by a detector and are related to the number of hydrogen atoms present in the sample. The presence of water in a sample, such as a roofing system, furnishes hydrogen nuclei for this slowing process. However, other materials in the roof system, such as hydrocarbons (asphalt, felts, insulation, concrete deck, etc.), also contain hydrogen. Since the activity in the detector is related to the total amount of hydrogen present in the volume of the sample being monitored, the interpretation of the detector reading as being due to moisture alone may not be valid.

6.2 INSTRUMENT DESCRIPTION

Due to the limited scope of this study, only two of the commercially available nuclear instruments used in roof surveys were evaluated. The two nuclear instruments used were referred to as N1 (figure 19) and N2 (figure 3). The instruments were placed approximately on the center of the specimen and neutron counting was initiated. When the neutron counting ended, the digital response was recorded. The radioactive neutron source for both instruments was americium beryllium, 40 millicures. The neutron source was sealed for both meters. In instrument N1, polyethylene neutron moderator shielding was used, whereas in instrument N2, no moderator shielding was used. The time period for each reading was 30 seconds for instrument N1; instrument N2 had 15 second, 60 second and 4 minute settings. During this study, the 60 second setting was used. The output for both instruments was displayed digitally to the nearest count.

6.3 INSTRUMENT CALIBRATION

In general, calibration readings on both instruments were taken at the beginning of each day of testing. This was done to determine if the instruments were operating properly and to detect any change in instrument response that may have occurred in the testing period which lasted about 150 days. The calibration readings were taken on a reference platform (provided by the manufacturers), which was placed over one location on a concrete floor. Plots for each instrument of the response vs. the elapsed time are shown in figures 23 and 24. In general, each point in figures 23 and 24 was based on 4 minutes of counting for each meter.

There was a definite trend of increasing instrument response with elapsed time for instrument N1 (figure 23) but not for instrument N2 (figure 24). In addition to the calibration response taken on reference platforms, calibration responses for instruments N1 and N2 were periodically taken directly on the surface of the concrete and steel decks used in testing the roofing specimens. The decks were in their same positions as used when testing roofing specimens but without roofing specimens on them. A definite trend of increasing instrument response with elapsed time was again observed for responses taken on the decks for instrument N1 but not for instrument N2.

For instrument N1 and for a given elapsed time interval, the ratio of the calibration responses taken at the beginning and end of the time interval was about the same for responses taken on the reference platform and on the concrete and steel decks. This ratio, which did not change over a wide range of instrument response values, was used to adjust the response of instrument N1 for time effects. That is, the following equation was used to account for a change in instrument response during the elapsed time interval between when the "room dry" and subsequent "wet" NDE responses were taken on the roofing specimens:

$$R_W = R \times \frac{C_D}{C_W} \qquad (10)$$

where R_W = corrected NDE "wet" response for which the time interval between "room dry" and "wet" responses is accounted for,

R = unadjusted "wet" NDE response,

C_D = calibration response (figure 23) on reference platform for when "room dry" NDE response was taken,

C_W = calibration response (figure 23) on reference platform for when "wet" NDE response was taken.

The values of C_D and C_W used were based on weekly averages, which were found by averaging the calibration readings (up to 7, figure 23) for each week.

Equation (10) was used only for instrument N1, since no definite trend for calibration response occurred for instrument N2.

6.4 TEST RESULTS

As discussed in chapter 4, the adjusted NDE response vs. moisture content curves for the two nuclear instruments are plotted in figures A37 through A60 in appendix A. The data are for gravel-surfaced specimens.

For instruments N1 and N2 and for specimens 6 and 31, the "room dry" responses were estimated as the initial "wet" responses, which corresponded to the lowest V_P values (V_P of 0.3 percent for specimen 6 and 0.9 percent for specimen 31). Since the V_P values corresponding to the initial "wet" responses were near the "room dry" V_P values, the estimated "room dry" responses are believed to be reasonable.

6.5 TRENDS

A discussion of the analysis techniques used are discussed in chapter 4.

6.5.1 Detection of Minimum Moisture Content (TVP)

Table 7 shows that, for all insulations except glass fiber, at least 50 percent of the TVP values were less than 10 percent for each nuclear instrument. Table 7 indicates that all TVP values were attained for both nuclear instruments and that all TVP values were less than 20 percent for all insulations except glass fiber, for which about 70 percent of the TVP values were less than 20 percent.

As evident from table 5, with both nuclear instruments many tests with specimens containing 1 in. thick insulation had higher TVP values as compared to tests with specimens containing 2 in. thick insulation. Only 27 of the 60 (45 percent) TVP values for specimens with 1 in. insulation were less than 10 percent as compared to 38 of the 48 (79 percent) TVP values for specimens with 2 in. insulation which were less than 10 percent.

In many cases with instrument N2, specimens tested on the steel deck had higher TVP values than specimens tested on the concrete deck. Only 13 of the 27 (48 percent) TVP values for specimens tested on the steel deck had TVP values less than 10 percent as compared to 21 of the 27 (78 percent) TVP values for specimens tested on the concrete deck which had TVP values less than 10 percent.

There were no significant asphalt thickness effects ("standard" vs. "heavy").

6.5.2 Detection of Moisture Content Beyond the TVP

As table 9 indicates, the percentages of S values less than 0.2 were less for instrument N2 than N1 for all insulations. However, all S values were positive and, in general, considerably exceeded zero for both instruments and for all insulations. For both instruments, an average of 87 percent of the S values for all insulations exceeded 0.2 (table 9). The following table shows the percentages of S values less than 0.2, 0.3, and 0.4 for each insulation type for instruments N1 and N2 taken together.

	Glass Fiber	Perlite	Fiberboard	Polystyrene	Polyurethane
$S < 0.2$	25	5.1	4.2	20	7.3
$S < 0.3$	62	20	8.5	33	24
$S < 0.4$	78	38	19	51	51

As indicated by the table, lower S values occurred for glass fiber and higher S values for fiberboard as compared to the other insulation types.

Table 11 shows for instruments N1 and N2 the significant deck, insulation thickness, and asphalt thickness effects which occurred based on the S indicator. The corresponding figure numbers of the S vs. V_P plots on which the effects are based are also shown. For example, the top left entry for instrument N1, "1", Std, PU" under the column "Concrete S > Steel S" means that for instrument N1 and the construction variables of 1 in. thick, polyurethane insulation and "standard" asphalt thickness, the S values corresponding to the concrete deck significantly exceeded the S values for the steel deck. This effect can be seen by comparing the S vs. V_P curves for instrument N1 in figures A102 and A103.

From table 11, the following trends for the deck effects are apparent:

- o With both instruments, all but one deck effect occurred with 1 in. thick insulation.

- o With one exception, for instrument N1, the S values for the steel deck exceeded those for the concrete deck, while for instrument N2, the S values for the concrete deck exceeded those for the steel deck.

Trends in table 11 for both instruments for the insulation thickness effects are:

- o All insulation thickness effects occurred only for the case where the S values for the 2 in. thick insulation exceeded those for the 1 in. thick insulation.

- o Seven of the nine cases occurred with "heavy" asphalt thickness.

Trends in table 11 for both instruments for asphalt thickness effects are:

- o All asphalt thickness effects occurred only for the case where the S values for the "standard" asphalt thickness exceeded those for the "heavy" asphalt thickness.

- o Eight of the ten cases occurred with 1 in. thick insulation.

No significant construction variable effects in table 11 were observed for glass fiber insulation.

As apparent from table 10, most SS values exceeded -0.015 for both instruments.

6.5.3 Shape of Data Sets and their Fitted Curves

In general, the $R_W - R_D$ vs. V_P data sets (figures A37 through A60) for both nuclear instruments were approximately linear in shape.

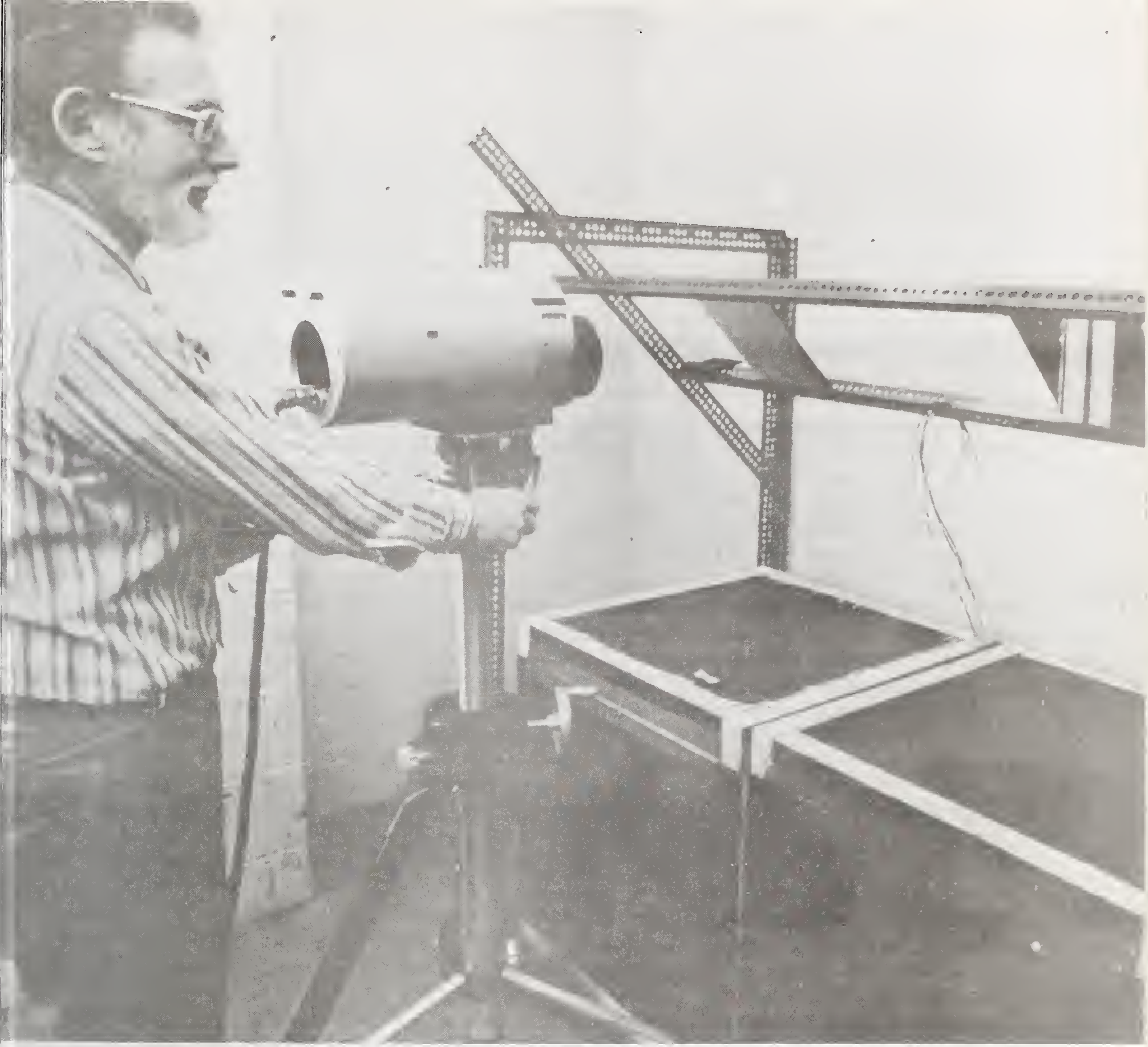
6.5.4 "Room Dry" Response

As discussed previously, the nuclear response can be strongly affected by any hydrogen bearing material, such as asphalt and concrete. Thus, if the hydrogen content of the roof construction varies and is not accounted for, it will add uncertainity to the moisture determination. Table 4 presents responses for both nuclear instruments for 18 specimens with "standard" and "heavy" asphalt thicknesses and tested on concrete and steel decks for the "room dry" moisture content. The response for the "heavy" asphalt thickness minus the "standard" asphalt thickness ("Hvy-Std") values, with one exception, were always positive. With each instrument and in most cases, the "Hvy-Std" values exceeded the 3RSD values in table 5. In some cases, the "Hvy-Std" values were considerably larger than the 3RSD values of each instrument. Thus, variable asphalt content, similar to the "standard" and "heavy" asphalt thicknesses of this study, could confound the response and appear to be water, as defined by the TVP definition (3RSD) used in this study. Coring would be needed to account for variability of this magnitude in the asphalt content.

6.5.5 Additional Considerations

Several factors should be mentioned with regard to the uncertainty introduced in the laboratory testing. At times during testing, responses were taken on adjacent specimens resulting in the two nuclear instruments being separated from each other by about 2 ft. (figure 3). During these times, each instrument could affect the other's response. However, due to the distance of separation, this effect was not believed to have a significant effect on the responses. Gravel loss from the specimens (discussed in section 3.2) may have effectively reduced the distance from the nuclear instruments to the hydrogen sources (asphalt, moisture, concrete deck, etc.). Thus, as testing progressed and the gravel loss accumulated, the nuclear instruments would tend to have somewhat higher readings. However, this gravel loss effect is believed to be insignificant because the gravel loss occurred gradually throughout testing and because the gravel thickness decrease due to gravel loss was probably relatively small.

Facing Page: Infrared thermography instrument and test setup used in testing.



7. INFRARED THERMOGRAPHY METHOD

7.1 MECHANISM OF OPERATION

The physical principles involved in the operation of infrared thermography systems and the factors involved in the response of this instrumentation to moisture in roofing systems are described in detail in reference [3]. Briefly, an infrared thermography system consists of an infrared sensor or camera-like unit and a display unit which is much like a TV-monitor. The infrared camera responds to radiation which is either emitted from or reflected from a roof surface. For given environmental conditions, the intensity of emitted radiation depends on the surface temperature and the emittance of the roofing system while the intensity of reflected radiation depends on the incident solar and sky radiation and the reflectance of the roof surface. By definition, emittance is a measure of radiation efficiency of a real surface and it is equal to the absorptance if the surface can be characterized as a "grey body". The sum of the reflectance, or the fraction of incoming radiation which is reflected, and the absorptance, or the fraction of incoming radiation which is absorbed, is equal to unity.

The heat transfer modes which affect the roof surface temperature are: conduction through the roofing system, convection at the roof surface, absorption of solar and night sky radiation, and absorption of radiation from neighboring buildings. Since the roofing system consists of a structural deck, insulation, and a built-up membrane, the heat conductance (and heat capacity for transient conditions) of each of these components influences heat conduction through the roofing system. If water or water vapor is present in the insulation or one of the other components, then conductance is increased and the surface temperature is changed. Such changes in the surface temperature are detected as differences in infrared radiation intensity and displayed. The different shades of grey associated with the different radiation intensities over wet regions allows these regions to be identified. A picture (thermogram) of the display can be taken.

Variations in roofing system construction can also lead to variations in surface temperatures. Examples are variations in the:

- thickness of built-up membrane
- thickness of insulation
- thickness of structural deck
- major structural members, such as beams and joists

Heat sources under the roof or on the roof surface can have a similar effect. Thus, careful interpretation of thermograms is necessary to insure that moisture is the cause of the surface temperature differences indicated by the thermograms.

7.2 INSTRUMENT DESCRIPTION

Because of the similarity in method of operation of the various commercially available infrared thermography systems, only one system was evaluated. This system is shown in figure 25.

The sensor or camera-like unit (right side, figure 25) consists of infrared transparent lenses, a mechanical-optical scanner and an infrared radiation detector. The radiation detector is relatively small (0.35 mm diameter) and responds to radiation in the 2.0×10^{-6} to 5.6×10^{-6} m wavelength band.

Other systems have detectors which operate in the 8.0×10^{-6} to 14.0×10^{-6} m band.

The mechanical-optical scanner consists of rotating prisms, or mirrors, which provide a vertical and horizontal scan of the field of view. Different points in the field are sequentially aligned with the detector by the scanning elements and in this way the radiant flux from each point or small region of the surface of the roof is read by the detector. The amplified voltage output of the radiation detector is used to modulate the beam intensity of a cathode ray tube in the display unit (left side, figure 25). By coordinating the scanning systems in the camera unit and the cathode ray tube, a black and white monochrome image is produced whose grey tones correspond to the point-by-point radiation intensities. These intensities are different for surface points over wet insulation compared to surface points over dry insulation.

The image displayed on the cathode ray tube screen has a reference grey scale at the bottom. In addition, so-called isotherms can be superposed on the image. Isotherms are produced by causing an arbitrarily selected intensity to show as white on the image and on the reference grey scale. If two isotherms corresponding to different intensities are used, the difference in intensity between points under the isotherms can be determined within ± 0.2°F when using the most accurate scale.

Infrared wavelengths rather than wavelengths in the visual range are employed because surfaces at temperatures in the 0°F to 180°F range have a much greater radiation intensity in the infrared region. Substantial intensity in the visual region would not occur until the temperature is increased to about 1000°F or until the wavelength viewed is incandescent. The temperature range from 0°F to 180°F is considered to be typical of roof surface temperatures under practical viewing conditions.

The observed radiation intensity differences between regions in the field of view can be converted to a temperature difference, but in the field of view an apparent radiance temperature difference rather than an actual temperature difference is obtained. This is because the sensor responds to both emitted and reflected radiation. If there is no incident radiation, as in the laboratory, or if it is constant during measurement, only emitted radiation is significant. Under the latter conditions, the apparent radiance temperature difference and the actual temperature difference are the same if the correct emittance and intensity-temperature law are used.

When the response of a given specimen was being determined, the difference in temperature or radiation intensity was observed between the center of a specimen subjected to a steady-state heat flux (described in section 7.3) and a reference pad at room temperature. An isotherm capability of the instrument was used by which the intensity difference measurement was determined by observing the number of tonal differences in the grey scale on the displayed image of the reference pad and specimen surface. Calibration curves furnished with the instrument simplify the conversion from grey scale units to temperature.

7.3 DECK AND TESTING ENVIRONMENT

Because of lengthy experimental runs required to reach the appropriate conditions for measurement, fewer specimens were subjected to infrared thermography as compared to the other two NDE methods and all specimens were placed over a steel deck (same deck type as used for the capacitance and nuclear testing).

As is evident from the discussion of section 7.1, moisture in the insulation or in the built-up membrane alters the thermal conductance. To cause this alteration in conductance to affect the surface temperature, it was necessary to impress a heat flux through the specimen. The experimental arrangement for impressing the heat flux is shown in figure 26.

Roofing specimens with various levels of moisture were placed on the steel deck which formed the top of an insulated box. The upper portions of the two boxes are shown in figure 26. The interior of each box was maintained at approximately 100°F by continuous operation of a variable resistance controlled incandescent lamp and a low-speed fan. The boxes were located in an environmental room that was maintained at 50°F and 10 percent relative humidity. Specimens were allowed to come to steady-state conditions in this environment. Boundary conditions were consequently "radiation" boundary conditions since a roofing specimen was used on the steel deck in contact with a medium at 100°F nominal on the deck side and a medium at 50°F nominal on the built-up membrane side. One dimensional heat flow conditions were attained at the center of the specimen.

Thermocouples were attached to the built-up membrane surface of the specimen in all cases. The temperature in the interior of the insulated box was read by a thermocouple positioned about 3 in. below the specimen center. The temperature in the environmental room was determined from a thermocouple embedded in the membrane surface of a temperature reference pad. This temperature reference pad was a 10 in. by 10 in. piece of polyurethane insulation with a built-up membrane attached. Two pads were actually used, one with a smooth asphalt surface and one with gravel surfacing. The pads can be seen in figure 26 at the extreme left end and right end of the supporting structure over the roofing specimens.

To provide normal incidence viewing of the specimens without tilting the infrared camera unit, observations were made through a mirror with high infrared reflectance mounted at 45°. These are shown in figure 26 next to the temperature reference pads.

For all thermography observations, thermocouple readings were taken of the specimen surface temperature, the interior temperature of the insulated box, and the reference pad temperature or room temperature. The specimen surface temperature measured by the thermocouples provided a check on the temperature measured by use of the thermographic system. Although the data are not reported here, the agreement was good in all cases.

Thermographic temperatures were reduced from the measured data by means of the equation.

$$T_S^{1.4} = T_P^{1.4} + 7.2574\ \Delta I \tag{11}$$

where T_S = surface temperature (°C),

T_P = reference pad or room temperature (°C),

ΔI = change in intensity represented by the product of the number of grey scale units and the sensitivity setting.

Since only radiation in the 2.0 x 10^{-6} to 5.6 x 10^{-6} m band is "seen" by the thermography system, the usual fourth power of the temperature law is not correct. Equation 11 is a curve fitted to an instrument calibration curve for temperatures from 0°C to 30°C.

The results in this report are in the form of normalized temperatures since the temperature gradient across the specimen and the room temperature were allowed to vary somewhat from specimen to specimen. The normalized temperature parameter, R, is given by:

$$R = (T_S - T_P)/(T_B - T_P) \tag{12}$$

where T_B is the interior temperature in the insulated box

and $T_B - T_P$ is the temperature gradient across the specimen. The above equation is derived from the steady-state heat flow equation which is:

$$H_S(T_S - T_P) = C_T\ (T_B - T_P) \tag{13}$$

where H_S is the exterior surface heat transfer coefficient, and

C_T is the total thermal conductance of the exterior surface layer, built-up membrane, insulation, deck, and interior surface layer.

Since moisture in a specimen would increase the thermal conductance of either the insulation or the built-up membrane, C_T would be altered by moisture but H_S would not. The parameter R is directly proportional to C_T and the variation of R is related to moisture in the same way (except for a constant multipler) as C_T.

R_W is the value of R obtained from eqn. 12 when T_S is measured on a specimen containing moisture and R_D is the value of R when T_S is measured on a "room dry" specimen. As with the other NDE methods discussed, the adjusted NDE response (R_W-R_D) is reported.

7.4 TEST RESULTS

The adjusted NDE response vs. moisture content and their corresponding fitted curves are shown in figures A61 through A69 in appendix A.

Because it was necessary to subject each specimen to a steady-state heat flux before readings were taken, it was not possible to cover the full range of construction variables with the infrared instrumentation. As already noted, one deck type (steel) was used. The full range of moisture contents, V_P, was investigated for roofing specimens having perlite, glass fiber, and polystyrene insulations. With smooth-surfaced specimens, both 1 in. and 2 in. insulation thicknesses were tested. However, for gravel-surfaced specimens only the 1 in. insulation thickness was investigated. All specimens had a "standard" asphalt thickness.

The response of the thermographic system to smooth-surfaced and to gravel-surfaced specimens was similar. This means that for a smooth-surfaced specimen and a gravel-surfaced specimen at the same surface temperature as measured by a thermocouple on the asphalt surface, the image intensities on the display unit were almost identical. Thus, in comparing the response from the different instrument types (chapter 8), results for smooth-surfaced specimens were interpreted as though these results were for gravel-surfaced specimens.

7.5 TRENDS

A discussion of the analysis techniques used are presented in chapter 4.

7.5.1 Detection of Minimum Moisture Content (TVP)

The following trends were observed (table 6):

- For a given insulation type, the TVP values for the 2 in. thick insulations were less than for the 1 in. thick insulations.
- For a given insulation thickness, the TVP values for perlite insulation were lower than glass fiber and polystyrene insulations.
- All TVP values were: for perlite less than 15 percent; for glass fiber less than 33 percent; and for two of the three TVP values for polystyrene, less than 27 percent.

In one out of nine TVP values, the TVP was not attained up to the maximum V_P (17 percent) of the specimen, which contained 1 in. thick polystyrene insulation (table 6).

7.5.2 Detection of Moisture Content Beyond the TVP

All S values (table A22) were positive and, in general, considerably exceeded 0.0 for all three insulations. For the three insulations combined 62 percent of the S values exceeded 0.2 (table 8).

With specimens containing 2 in. thick insulation, the S values for perlite (figure A83) and polystyrene (based on only one S value, figure A99) exceeded those for glass fiber (figure A75).

Two of the eight SS values for the infrared instrument were less than -0.015 (specimen 61, figure A79 and specimen 733, figure A83). These two occurrences were not considered significant because the corresponding S values were relatively large.

7.5.3 Shape of Data Sets and Their Fitted Curves

In general, the shape of the $R_W - R_D$ vs. V_P data sets (figures A61 to A69) were approximately linear.

7.5.4 Additional Considerations

When comparing the various NDE methods, it should be noted that the infrared thermography system produces more information than is represented by R_W or R_D. Since an infrared picture of the roof surface is presented, it is possible to define the boundaries of "hot" or wet areas whereas the capacitance and nuclear methods yield only a point reading.

Facing Page: Intrusion of moisture in roofing systems can cause premature failures.

8. COMPARISON AND INTERPRETATION OF RESULTS AND TRENDS FOR CAPACITANCE, NUCLEAR, AND INFRARED METHODS

The "EXECUTIVE SUMMARY" presents the findings and conclusions of this study. This chapter presents a comparison and discussion of the findings for the three NDE methods investigated.

8.1 SUMMARY OF RESULTS

Table 12 summarizes the results for the capacitance, nuclear, and infrared instruments for all insulations for the TVP, S, and SS indicators presented in chapters 5, 6, and 7. Table 13 summarizes the instrument effects for specimens with the "standard" asphalt thickness and tested on steel deck with the capacitance, nuclear, and infrared instruments. In table 13, the following symbols are used:

C = capacitance instruments C1, C2, and C3
N = nuclear instruments N1 and N2
IR = infrared instrument
≈ = approximately equal to

For example, the top left entry of "C < N" in table 13 is for the indicator TVP and for 1 in. thick glass fiber insulation. It means that the TVP values for the capacitance instruments were, in general, less than the TVP values for the nuclear instruments. Some subjectivity was introduced in determining the entries in table 13. None the less, it is believed that the subjectivity introduced is minimal and should not affect the general trends shown in table 13. Table 13 shows the figure numbers for the S vs. V_p plots on which the S table entries are based. The TVP indicator entries were based on table 5 and table A21. Infrared instrument trends shown in tables 12 and 13 are based on results from specimens containing "standard" asphalt thickness and glass fiber, perlite, and polystyrene insulations tested on steel deck.

Table 14 presents the construction variable sets* for the instrument effects between capacitance and nuclear instruments as measured by the TVP and S indicators. For example, for the instrument effect "Nuclear < Capacitance" measured by the TVP indicator, the construction variable set for glass fiber is: 1", 2", Hvy, C,S. This means that the TVP values for the nuclear instruments were in general less than the capacitance instruments for specimens containing 1 and 2 in. thick glass fiber insulation, for "heavy" asphalt thickness, and tested on concrete and steel decks. As discussed for table 13, some subjectivity, which was judged to be minimal, was introduced in assigning the entries for table 14. Table 14 gives the figure numbers for the S vs. V_p plots on which the construction variable set entries for S are based. The construction variable sets for the TVP indicator are based on table 5.

Table 15 presents the percentages of TVP values less than 10 percent, less than 20 percent, and "not attained" for the "standard" versus "heavy" asphalt thicknesses and for 1 in. versus 2 in. thick insulations. As previously noted, gravel thickness was, in general, greater for the "heavy"

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* The term construction variable set means a combination of one or more construction variables (for example, specimen containing 1 in. thick, glass fiber insulation, with "standard" asphalt thickness and tested on a steel deck).

asphalt thickness. The purpose of table 15 is to illustrate asphalt and insulation thickness effects with the capacitance and nuclear instruments.

8.2 DETECTION OF MINIMUM MOISTURE CONTENT (TVP)

In general for each insulation type, the percentages of TVP values less than 10 percent for nuclear instruments equalled or exceeded the corresponding percentages for the capacitance instruments (table 7) and the infrared instrument (table 8). A similar trend is seen for percentages of TVP values less than 20 percent.

As given in table 12, in general, for all insulations combined, the nuclear instruments had higher percentages of TVP values less than 10 percent than did the capacitance and infrared instruments. A similar statement can be made for percentages of TVP values less than 20 percent.

With glass fiber, perlite and polystyrene insulations, the percentages of TVP values less than 10 percent were not significantly different for the capacitance instruments C2 and C3 (table 7) and the infrared instrument (table 8). The percentages of TVP values less than 10 percent for glass fiber, perlite, and polystyrene insulations were significantly lower for instrument C1 as compared to instruments C2 and C3 (table 7) and the infrared instrument (table 8).

For the capacitance instruments C2 and C3, the TVP was not attained for 2 to 9 percent of the tests (table 12) as compared to the nuclear instruments, for which TVP values were always attained. Instrument C1 had a significantly larger percentage (38 percent, table 12) of TVP values not attained as compared to instruments C2, C3, N1, N2, and the infrared instrument. With the infrared instrument, 1 TVP value in 9 tests (11 percent) was not attained. However, the significance of this result for the infrared instrument is not known due to the limited infrared data.

The TVP instrument effect trends based on table 13 are:

- With one exception, the TVP values for the nuclear and infrared instruments were about the same for the three insulations.

- For glass fiber insulation, the TVP values for the capacitance instruments were less than or about equal to the nuclear and infrared instruments.

- With perlite and polystyrene insulations, the TVP values for the nuclear and infrared instruments were less than or about equal to the capacitance instruments.

Based on table 14, the following instrument trends for nuclear and capacitance instruments are apparent:

- The TVP values for the nuclear instruments were less than the capacitance instruments for the construction variable sets shown; there were one or more construction variable sets for all insulation types.

- Only for 1 and 2 in. glass fiber insulation, with "standard" asphalt thickness, and for steel deck were the TVP values for the capacitance instruments less than the nuclear instruments.

The entries in table 14 correlate with the as large or larger percentages of TVP values less than 10 percent for nuclear as compared to capacitance instruments with perlite, polystyrene, and polyurethane insulations as given in table 7. A similar statement can be made for the TVP values less than 20 percent. As evident from table 15, with "standard" asphalt thickness the percentages of TVP values less than 10 percent for the capacitance instruments C2 and C3 were about the same as compared to the nuclear instruments. A similar statement can be made for percentages of TVP values less than 20 percent. Instrument C1 for "standard" asphalt thickness had a significantly lower percentage of TVP values less than 10 percent as compared to instruments C2, C3, N1, and N2.

With the "heavy" asphalt thickness, the nuclear instruments had significantly larger percentages of TVP values less than 10 percent as compared to capacitance instruments C1 and C3. A similar trend is evident for percentages of TVP values less than 20 percent. As discussed in chapter 5, because specimens with "heavy" asphalt thickness may have had, in general, larger gravel thicknesses during testing, the relative significance of the asphalt and gravel thickness variables could not be determined. This confounding of the gravel and asphalt thickness needs to be recognized when comparing the capacitance instruments with the nuclear instruments.

Table 15 indicates that instruments C2, C3, N1 and N2 had significantly larger percentages of TVP values less than 10 percent for specimens with 2 in. as compared to 1 in. thick insulation. A similar but weaker trend is seen for percentages of TVP values less than 20 percent.

8.3 DETECTION OF MOISTURE CONTENT BEYOND THE TVP

Perhaps the most significant effect between the capacitance, nuclear, and infrared instruments was that effect which was measured by the percentage of S values less than 0.0. As table 12 indicates, from about 10 percent (instrument C3) to 20 percent (instruments C1 and C2) of the S values for the capacitance instruments were less than 0.0 as compared to no S values (0 percent) less than 0.0 for the nuclear and infrared instruments. The trend of the S values less than 0.0 for the capacitance instruments was strongest for the perlite and fiberboard insulations; no values of S were less than 0.0 for the capacitance instruments for glass fiber insulation (table 9). The significance of the S values less than 0.0 is that the adjusted NDE responses, $R_W - R_D$, and $(R_W - R_D)/RSD$, are decreasing per increase in V_p (figure 18b). Also most (76 percent, table 9) of the S values for the capacitance instruments were less than 0.2, compared to 38 percent (table 8) of the S values for the infrared instrument being less than 0.2. These are in contrast to most (87 percent, table 9) of the S values for the nuclear instruments being greater than or equal to 0.2. For all construction variable combinations, the S trends given in tables 5, 8, 9, and 12 indicate that the nuclear and infrared instruments were able to detect moisture quantitatively at higher moisture contents beyond the TVP (no S values less than 0.0). The capacitance instruments, for some construction variable combinations, could not detect moisture quantitatively at higher moisture contents beyond the TVP.

As indicated in table 12, 33 percent of the SS values for the capacitance instruments were less than -0.015 as compared to 25 percent of the infrared SS values and 5 percent of the nuclear values. The significance of the SS values less than -0.015 is that the S vs. V_p curve drops sharply. With the capacitance instruments, values of SS less than -0.015 occurred most often (92 percent, table 10) for specimens containing fiberboard insulation (figures A86 through A93). The occurrences of SS values less than -0.015 for the infrared and nuclear instruments were not considered significant because, in general, the corresponding S values were relatively large.

Based on table 13, the instrument effect trends for the capacitance, nuclear, and infrared instruments for the S indicator are:

- o For the three insulations, the S values for the nuclear instruments exceeded the S values for the capacitance instruments and were about the same (with one exception) as the S values for the infrared instrument.

- o For glass fiber and perlite insulations, the infrared S values exceeded the capacitance S values.

The instrument effect trends for the capacitance and nuclear instruments as taken from table 14 are:

- o The S values for the nuclear instruments exceeded those for the capacitance instruments for all combinations of construction variables investigated except for 1 in. thick glass fiber insulation with "heavy" asphalt thickness tested on concrete and steel decks. (The lack of S values for the capacitance instruments for 1 in. polystyrene insulation with "heavy" asphalt thickness and tested on steel deck prevented determining an instrument effect trend for this combination.)

- o There were no construction set entries for which the capacitance instrument S values exceeded the nuclear instrument S values.

These trends are in agreement with the relatively large percentages of S values less than 0.0 and 0.2 (table 9) for the capacitance instruments as compared to the nuclear instruments for each of the five insulations. One exception to this was that there were no S values less than 0.0 for glass fiber insulation for the capacitance instruments.

Of all the insulations, glass fiber S values appeared to be the most similar for the capacitance and nuclear methods. This trend is indicated by the results in table 9.

8.4 SHAPE OF DATA SETS AND THEIR FITTED CURVES

Many of the $R_W - R_D$ vs. V_P data sets and their fitted curves tended to be concave downward for the capacitance method (figures A1 through A36, appendix A). This is in contrast to an almost linear (i.e., slightly concave downward), linear, or concave upward trend for the nuclear (figures A37 through A60) and infrared (figures A61 through A69) methods. These trends are supported by the higher percentages (11 to 22 percent) of S values less than 0.0 for the capacitance method as compared to the nuclear and infrared methods, for which there were no S values less than 0.0 (table 9). The concave downward trend was particularly strong for the capacitance method for perlite and fiberboard insulations (again note the relatively large percentages of S values less than 0.0 in table 9).

For specimens containing perlite and fiberboard insulations, many of the adjusted NDE response versus moisture content data sets (figures A13 to A24, appendix A) for the capacitance method showed the following trend: the adjusted NDE responses rose sharply at moisture contents of about 10 percent or less and then leveled off or decreased with increasing moisture. Thus, for these cases, it was not possible to distinguish between relatively low moisture contents and larger moisture contents. The trend of flatness due to off-scale responses for instrument C2 with specimens containing perlite (figures A15 and A16) and fiberboard (figures A21 and A22) has been discussed in section 5.5.2.

8.5 INTERPRETATION OF EFFECTS AND TRENDS AS RELATED TO PERFORMANCE CHARACTERISTICS

As discussed in chapter 4, this study was primarily concerned with the evaluation of the two performance characteristics:

- quantitative detection of the minimum moisture content (TVP)
- quantitative detection of the moisture content beyond the TVP.

These two performance characteristics were quantitatively evaluated for the three instrument types through the use of the indicators TVP, S, and SS. When using the indicators, one instrument or construction variable combination may have a more favorable indicator value than another instrument or construction variable combination. When interpreting the indicator values, however, it is important for the user to recognize that, although one instrument may have a more favorable indicator value than another, both instruments could possibly be used to detect or determine moisture content. Also, depending on the use, only the performance characteristic for the minimum amount of moisture (TVP) may be important; in this case more significance should be given to the TVP indicator than to the S or SS indicators.

8.6 ADDITIONAL CONSIDERATIONS-"ON THE ROOF" UNCERTAINTY

The reported trends are for a controlled laboratory study designed to determine the effect of insulation type and thickness, asphalt thickness, and deck type on the ability of the three NDE methods investigated to quantitatively detect and measure the moisture content. Thus, the uncertainties associated with the construction variable effects were, in part, accounted for in a systematic, controlled, manner. On an actual roof, however, the uncertainty associated with one or more of the construction variables (effects) may not be able to be accounted for easily. For example, it is well known that nuclear instruments are affected by any hydrogen bearing material, such as asphalt. Thus, variations in asphalt thickness can cause changes in the nuclear instrument response (see table 4). In this study, however, asphalt thickness was (at least in part) accounted for by subtracting the "room dry" response from the "wet" response ($R_W - R_D$). On an actual roof, asphalt thickness may not be able to be accounted for and could be misinterpreted as moisture. Thus, the asphalt thickness variability may need to be measured by taking cores. The uncertainties associated with the construction variable effects for each type of instrument can accumulate on an actual roof, unless they can be accounted for by coring, for example. In reference [3], a thorough discussion of the advantages and limitations of the capacitance, nuclear, and infrared methods is presented. Thus the information in reference [3], which is not in this report, needs to be combined with the information presented in this report with regard to method choice, usage, and data interpretation and analysis.

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GLOSSARY OF TERMS

Adjusted NDE Response = "wet" NDE response minus the "room dry" NDE response

Adjusted NDE Response vs. Moisture Content Data Set = set of "wet" minus "room dry" NDE responses vs. moisture content

Adjusted NDE Response vs. Moisture Content Fitted Curve = refers to the quadratic best fit curve fitted to the adjusted NDE response vs. moisture content data set.

Construction Variable = refers to the composition of the specimen (for example, insulation type and thickness and asphalt thickness) and the type of deck (concrete or steel) the specimen was tested on.

Construction Variable Set = refers to a combination of one or more construction variables

Moisture Content = percent of moisture by volume of insulation (see V_P)

Moisture Content Range = Ranges of moisture content: 0 to 10 percent; 10 to 20 percent; 20 to 30 percent; etc. used in the determination of S values (see eqn. 8)

NDE = nondestructive evaluation

"Room dry" = refers to moisture condition in insulation in roofing specimens at approximately 70°F and 50 percent relative humidity

"Room dry" NDE response = NDE response obtained for roofing specimen containing only "room dry" moisture

RSD = Residual Standard Deviation = measure of scatter (eqn. 3) of the adjusted NDE response about its fitted curve

Sensitivity = $\left(\frac{\Delta(R_W - R_D)_{est}}{\Delta V_P}\right)/RSD$

Sensitivity vs. V_P (S vs. V_P) Curve = refers to the sensitivty versus moisture content curve

Threshold Moisture Content = the minimum moisture content which an instrument could detect. Defined to be that value of the moisture content (V_P) at which the fitted curve [$(R_W - R_D)_{est}$, eqn. 2] deviated from (exceeded) the zero ("room dry") response by 3 residual standard deviation (RSD) values.

"TVP Not Attained" = refers to the case when the deviation of the fitted curve $[(R_W-R_D)_{est}]$ from zero does not reach three residual standard deviation values.

"Wet" = refers to specimen containing induced moisture

"Wet" NDE response = NDE response obtained for roofing specimen containing induced moisture

NOTATION

BUR = built-up roofing

C_T = total thermal conductance (eqn. 13)

H_S = exterior surface heat transfer coefficient (eqn. 13)

R_D = "room dry" NDE instrument response

R_W = "wet" NDE instrument response

$R_W - R_D$ = adjusted NDE response

$R_W - R_D$ vs. V_P Data Set = adjusted NDE response versus moisture content data points

$R_W - R_D$ vs. V_P Fitted Curve = adjusted NDE response versus moisture content fitted curve

$(R_W - R_D)_{est}$ = estimated or predicted response based on the adjusted NDE response versus moisture content fitted curve (eqn. 2). Values of TVP and S were based on $(R_W-R_D)_{est}$.

RSD = residual standard deviation (eqn. 3)

S = sensitivity (eqns. 6, 7, and 8)

S(MAX) = S value in the moisture content range preceding the range containing the maximum moisture content. (S values were not computed for moisture content values exceeding 60 percent.)

S(MID) = average of the S values for the moisture content ranges between the range containing the TVP and the range preceding the range containing the maximum moisture content.

S(TVP) = S value for the moisture content range in which the TVP occurs.

S vs. V_P Curve = sensitivity versus moisture content curve; refers to the S value plotted at midrange of each moisture content range

SS = slope of the S vs. V_P curve (eqn. 9)

T_B = interior temperature of the insulated box used in the infrared thermography testing and analysis (eqn. 12)

T_P = reference pad or room temperature (eqn. 11)

T_S = surface temperature (eqn. 11)

NOTATION (Continued)

TVP = threshold moisture content

V_P = moisture content by volume of water in the insulation = $\left(\frac{\text{Volume of Moisture}}{\text{Volume of Insulation}}\right) \times 100$

W_P = moisture content by weight of insulation = $\left(\frac{\text{Weight of Moisture}}{\text{Weight of Dry Insulation}}\right) \times 100$

ΔI = change in intensity used in infrared analysis (eqn. 11)

Table 1. Properties of Roofing System Components

Material	Thickness (in)			Density (lb/ft^3)			Moisture Content "room dry"[c] Percent by Volume			$(W_p/V_p)^d$
	Average	COV[a] (%)	N[b]	Average (oven dry)	COV (%)	N	Average	COV (%)	N	
Glass fiber 1 in[e]	0.75	4.72	7	9.56	11.9	7	0.0733	60.7	7	6.53
Glass fiber 2 in[e]	2.07	1.94	7	8.17	4.78	7	0.0348	48.0	7	7.64
Perlite board 1 in	1.02	2.18	6	10.4	3.15	6	0.222	18.5	9	5.99
Perlite board 2 in	2.06	1.59	6	9.47	3.70	6	0.295	17.6	9	6.59
Fiberboard 1 in	1.00	--	3	16.4	--	3	1.32	2.96	6	3.80
Fiberboard 2 in	2.00	--	3	15.2	--	3	1.41	2.10	6	4.12
Polystyrene 1 in	0.99	1.53	6	1.30	9.71	6	0.00245	160.	9	48.1
Polystyrene 2 in	1.99	0.643	6	1.13	9.05	6	0.00128	154.	9	55.6
Polyurethene 1 in	0.97	4.56	9	1.59	4.93	9	0.101	20.8	12	39.2
Polyurethene 2 in	2.16	8.90	9	1.86	9.37	9	0.0357	38.1	12	33.5
Roofing Felt, ASTM Type 15	0.035	--	2	.122[f] lb/ft^2	9.1	4	2.0[g]	--	2	--
Asphalt[h] ASTM Type III	--	--	--	about 62.4	--	--	--	--	--	--

[a] Coefficient of variation in percent, defined as the standard deviation divided by the mean.

[b] Number of specimens.

[c] Refers to storage at room conditions at approximately 70°F and 50% relative humidity.

[d] Ratio of moisture content expressed as percent by dry weight of insulation to moisture content expressed as percent by volume of insulation.

[e] Excludes asphalt facing sheet. Facing was treated as part of the membrane - see table 2.

[f] Weight per unit area.

[g] Moisture content - percent by dry weight of felt.

[h] Average softening point of 187°F based on 16 measurements (COV=1.7%).

Table 2. Composition by Thickness and Weight Per Unit Area of Gravel-Surfaced Roofing Specimens

Specimen No.	Insulation Type	Nominal Thickness (in.)	Asphalt Thickness	Membrane Thickness Avg.(in.)	Membrane Weight Per Unit Area Avg.(lb/ft^2)	Gravel Thickness Avg.(in.)	Gravel Weight Per Unit Area Avg.(lb/ft^2)	Insulation Thickness Avg.(in.)	Total Specimen Thickness Avg.(in.)
1	Glass Fiber	1	Standard[a]	0.38	2.12	0.49	1.36	0.75[c]	1.62[d]
51	Glass Fiber	1	Standard	0.42	2.50	0.46	1.49	0.91	1.79
2	Glass Fiber	1	Standard	0.39	2.19	0.43	1.31	0.80	1.62
52	Glass Fiber	1	Heavy[b]	0.44	3.24	0.38	0.98	0.77	1.59
4	Glass Fiber	1	Heavy	0.45	3.28	0.63	2.53	0.72	1.80
54	Glass Fiber	1	Heavy	0.47	3.30	0.61	2.37	0.77	1.85
6	Glass Fiber	2	Standard	0.33	1.97	0.52	1.77	2.07[c]	2.92[d]
56	Glass Fiber	2	Standard	0.44	2.20	0.37	1.72	1.82	2.63
8	Glass Fiber	2	Heavy	0.46	3.26	0.64	2.40	2.17	3.27
58	Glass Fiber	2	Heavy	0.53	3.62	0.71	2.46	2.12	3.36
62	Perlite	1	Standard	0.34	2.01	0.50	1.34	1.02	1.86
61	Perlite	1	Standard	0.38	2.23	0.38	1.25	1.01	1.77
11	Perlite	1	Standard	0.32	1.79	0.30	.91	1.06	1.68
14	Perlite	1	Heavy	0.48	3.56	0.75	3.13	1.05	2.28
66	Perlite	2	Standard	0.38	2.14	0.40	.63	2.03	2.81
16	Perlite	2	Standard	0.31	1.92	0.45	1.48	2.06[c]	2.82[d]
18	Perlite	2	Heavy	0.39	2.34	0.39	1.31	2.06[c]	2.84[d]
658	Fiberboard	1	Standard	0.28	1.49	0.44	1.27	1.00[c]	1.72[d]
21	Fiberboard	1	Standard	0.22	1.20	0.37	1.19	1.00[c]	1.59[d]
23	Fiberboard	1	Heavy	0.50	3.01	0.52	1.75	1.00[c]	2.02[d]
26	Fiberboard	2	Standard	0.25	1.60	0.41	1.72	2.00[c]	2.66[d]
29	Fiberboard	2	Heavy	0.37	2.34	0.42	1.41	2.00[c]	2.79[d]
31	Polystyrene	1	Standard	0.36	2.10	0.46	.96	0.79	1.61
113	Polystyrene	1	Standard	0.35	2.12	0.47	1.45	0.93	1.75
34	Polystyrene	1	Heavy	0.57	3.82	0.98	3.89	0.48	2.03
36	Polystyrene	2	Standard	0.24	1.36	0.45	.77	1.70	2.39
38	Polystyrene	2	Heavy	0.44	3.50	0.72	2.22	1.76	2.92
39	Polystyrene	2	Heavy	0.36	2.49	0.51	1.54	1.98	2.85
41	Polyurethane	1	Standard	0.31	1.89	0.36	1.07	0.81	1.48
43	Polyurethane	1	Heavy	0.45	3.14	0.78	2.09	0.97[c]	2.20[d]
141[e]	Glass Fiber	1	Standard	0.46	2.47	--[e]	--	0.88	1.34
143[e]	Glass Fiber	2	Standard	0.43	2.24	--	--	2.13	2.56
145[e]	Perlite	1	Standard	0.38	2.00	--	--	0.99	1.37
733[e]	Perlite	2	Standard	0.32	1.67	--	--	2.06[c]	2.38[f]
751[e]	Polystyrene	1	Standard	0.38	1.76	--	--	0.78	1.16
155[e]	Polystyrene	2	Standard	0.40	2.06	--	--	1.89	2.29

[a] About 0.25 lb/ft^2 interply asphalt thickness.
[b] About 0.40 lb/ft^2 interply asphalt thickness.
[c] Based on table 1.
[d] Based on sum of insulation thickness (table 1) and the combined thickness of the membrane and gravel.
[e] Smooth-surfaced specimens.
[f] Based on sum of insulation thickness (table 1) and the membrane thickness.

Table 3. Comparison of Membrane Weight Per Unit Area for "Standard" and "Heavy" Asphalt Thicknesses

Insulation Type and Nominal Thicknness	(in.)	Asphalt Thickness	Weight Per Unit Area (lb/ft^2)		
Glass Fiber	1	Standard	2.12 (1)[a]	2.19 (2)	
	1	Heavy	3.24 (52)	3.28 (4)	3.30 (54)
	2	Standard	1.97 (6)	2.20 (56)	
	2	Heavy	3.26 (8)	3.62 (58)	
Perlite	1	Standard	1.79 (11)	2.01 (62)	
	1	Heavy	3.56 (14)		
	2	Standard	1.92 (16)	2.14 (66)	
	2	Heavy	2.34 (18)		
Fiberboard	1	Standard	1.20 (21)	1.49 (658)	
	1	Heavy	3.01 (23)		
	2	Standard	1.60 (26)		
	2	Heavy	2.34 (29)		
Polystyrene	1	Standard	2.10 (31)		
	1	Heavy	3.82 (34)		
	2	Standard	1.36 (36)		
	2	Heavy	2.49 (39)	3.50 (38)	
Polyurethane	1	Standard	1.89 (41)		
	1	Heavy	3.14 (43)		

[a] Specimen numbers shown in parentheses; these specimens were tested with capacitance and nuclear instruments.

Table 4. "Room Dry" Responses (R_D) for 18 Roofing Specimens for the Capacitance and Nuclear Instruments with "Standard" and "Heavy" Asphalt Thicknesses on Concrete and Steel Decks

Specimen Numbers (table 2)	Insulation Type and Thickness	(in.)	Difference in Membrane Wt. per Unit Area Between "Std" and "Hvy" (lb/ft^2)	Deck	Instrument: C1 Response, R_D Std	C1 Hvy	C1 Hvy-Std	C2 Response, R_D Std	C2 Hvy	C2 Hvy-Std	C3 Response, R_D Std	C3 Hvy	C3 Hvy-Std	N1 Response, R_D Std[a]	N1 Hvy[a]	N1 Hvy-Std	N2 Response, R_D Std	N2 Hvy	N2 Hvy-Std
1, 4	Glass Fiber	1	1.16	Conc.	7.9	10.5	2.6	20.0	25.5	5.5	2.8	2.5	-0.3	241	240	-1	110	140	30
		1	1.16	Steel	6.5	9.0	2.5	12.5	15.5	3.0	1.8	3.0	1.2	196	221	25	39	65	26
56, 58		2	1.42	Conc.	6.2	7.5	1.3	12.0	13.5	1.5	2.5	3.8	1.3	218	249	31	76	124	48
		2	1.42	Steel	5.0	7.0	2.0	9.7	11.5	1.8	1.7	3.0	1.3	196	231	35	38	80	42
62, 14	Perlite	1	1.55	Conc.	6.8	8.5	1.7	40.0	23.5	-16.5	2.5	3.0	0.5	241	271	30	114	203	89
		1	1.55	Steel	8.0	7.0	-1.0	16.5	19.0	2.5	2.8	3.5	0.7	194	230	36	40	84	44
16, 18		2	0.42	Conc.	7.0	79.0	70.0	21.0	117	96	2.0	4.5	2.5	220	247	27	92	126	34
		2	0.42	Steel	6.8	75.0	68.2	23.0	109	86	1.8	4.5	2.7	194	218	24	39	62	23
21, 23	Fiberboard	1	1.81	Conc.	10.8	9.8	-1.0	37.0	34.0	-3.0	4.0	3.2	-0.8	249	276	27	138	233	95
		1	1.81	Steel	11.5	9.2	-2.3	26.0	25.5	-0.5	4.0	3.9	-0.1	193	226	33	35	84	49
26, 29		2	0.74	Conc.	15.5	29.0	13.5	37.0	42.0	5.0	2.5	3.5	1.0	240	254	14	144	178	34
		2	0.74	Steel	17.5	27.5	10.0	28.5	42.0	13.5	3.0	4.2	1.2	209	225	16	47	75	28
31, 34	Polystyrene	1	1.72	Conc.	8.0[b]	10.3	2.3	19.0[b]	25.8	6.8	2.5[b]	4.0	1.5	251[c]	266	15	134[c]	227	93
		1	1.72	Steel	6.0[b]	9.5	3.5	14.0[b]	21.0	7.0	1.8[b]	3.5	1.7	197[c]	228	31	44[c]	82	38
36, 38		2	2.14	Conc.	7.5	7.0	-0.5	17.5	15.5	-2.0	1.8	3.2	1.4	211	250	39	84	171	87
		2	2.14	Steel	8.0	6.8	-1.2	17.5	7.0	-10.5	1.5	2.0	0.5	180	226	46	26	80	54
41, 43	Polyurethane	1	1.25	Conc.	7.5	11.0	3.5	19.0	23.0	4.0	2.3	3.4	1.1	245	268	23	111	196	85
		1	1.25	Steel	6.8	9.4	2.6	12.0	13.0	1.0	1.5	2.4	0.9	199	226	27	37	73	36

[a] Responses adjusted to account for increased instrument response with elapsed time (figure 23).
[b] Response not from specimen 31, but from specimen of similar composition.
[c] Response estimated from initial "wet" response (V_p = 0.9 percent).

TABLE 5. SUMMARY OF SPECIMENS, CONSTRUCTION VARIABLES, 3RSD, TVP, AND S VALUES FOR THE CAPACITANCE AND NUCLEAR INSTRUMENTS

SPECIMEN[a]				MAX[b] VP	INSTRUMENT C1					INSTRUMENT C2					INSTRUMENT C3				
NO.	INS.	ASP.	DECK		3RSD[c]	TVP[d]	S[e] FOR TVP	S[e] FOR MID	S[e] FOR MAX	3RSD[c]	TVP[d]	S[e] FOR TVP	S[e] FOR MID	S[e] FOR MAX	3RSD[c]	TVP[d]	S[e] FOR TVP	S[e] FOR MID	S[e] FOR MAX
1	GF	1	STD	CON	39.42	3.98	18.89	.182		.217	39.07	15.43	.181		.183	1.00	10.61	.271		.268
2	GF	1	STD	CON	58.81	4.62	19.37	.148	.141	.134	37.72	18.47	.160	.114	.068	1.88	36.62	.080		.071
1	GF	1	STD	STL	39.42	5.51	17.14	.161		.150	45.03	17.73	.160		.147	2.44	16.13	.121		.129
2	GF	1	STD	STL	58.81	7.56	27.57	.101	.066	.031	39.27	18.48	.155	.105	.054	1.34	20.34	.123	.114	.105
4	GF	1	HVY	CON	45.70	4.78	41.62	.285			27.52	24.13	.144		.151	1.65	21.42	.050		.023
54	GF	1	HVY	CON	46.50	5.44	46.50*	*			60.56	38.26	.113			.93	40.38	.239		
52	GF	1	HVY	CON	37.65	4.71	12.43	.277		.360	30.23	14.52	.293		.384	.74	13.53	.193		.268
4	GF	1	HVY	STL	45.70	6.38	44.71	.135			23.26	17.83	.153	.156	.160	1.60	37.60	.093		
54	GF	1	HVY	STL	46.50	12.93	46.50*	*			68.29	40.44	.126			1.88	46.50*	*		
52	GF	1	HVY	STL	37.65	6.47	14.70	.211		.214	54.12	20.27	.252			1.70	30.51	.205		
6	GF	2	STD	CON	21.95	6.94	5.88	.264		.097	40.05	2.15	.518		.268	1.16	9.73	.335		.019
56	GF	2	STD	CON	37.24	6.91	10.77	.128		.097	71.58	8.76	.220	.152	.083	1.68	9.46	.261	.185	.109
6	GF	2	STD	STL	21.95	4.63	1.24	.493		.126	37.92	1.79	.513		.266	1.66	6.61	.213		.074
56	GF	2	STD	STL	37.24	10.66	16.65	.073		.067	76.60	9.40	.207	.134	.061	1.92	5.09	.314	.174	.035
8	GF	2	HVY	CON	34.35	7.99	27.49	.107			25.55	3.60	.420	.259	.098	1.61	19.45	.131		.063
58	GF	2	HVY	CON	29.29	10.18	29.29*	*			39.12	4.88	.236		.134	1.40	27.77	.136		
8	GF	2	HVY	STL	34.35	7.31	22.51	.140			28.22	6.31	.400	.260	.120	1.10	23.11	.106		
58	GF	2	HVY	STL	29.29	8.75	29.29*	*			37.25	3.96	.241		.124	1.53	12.59	.099		
11	PR	1	STD	CON	44.60	22.73	8.94	.120	.020	-.080	137.68	6.31	.122	.033	-.055	3.62	8.17	.183	.068	-.047
62	PR	1	STD	CON	70.13	24.15	11.88	.062	-.003	-.068	132.98	12.87	.047	-.011	-.069	2.95	12.74	.096	.045	-.005
11	PR	1	STD	STL	39.20	29.73	39.20*	*			168.59	10.42	.041		-.032	5.26	19.90	.078		.048
62	PR	1	STD	STL	70.13	23.07	14.51	.068	.003	-.062	152.55	17.37	.024	-.018	-.061	3.09	14.68	.136	.050	-.036
14	PR	1	HVY	CON	44.61	5.78	12.28	.093	-.002	-.096	67.47	12.21	-.000	-.040	-.080	1.38	17.63	.115	.073	.032
14	PR	1	HVY	STL	44.61	7.09	12.16	.056	-.028	-.113	70.78	8.28	.050	-.026	-.103	1.49	36.73	.087		
16	PR	2	STD	CON	24.78	21.17	4.20	.248		.020	144.10	3.63	.176		.000	2.37	3.92	.310		.113
66	PR	2	STD	CON	31.72	f					186.82	10.06	.039		-.060	3.61	3.74	.394	.099	-.197
16	PR	2	STD	STL	24.78	20.64	3.76	.248		.004	141.38	3.45	.179		-.005	2.92	4.50	.266		.097
66	PR	2	STD	STL	31.72	f					190.84	10.39	.043		-.062	3.47	4.09	.384	.115	-.153
18	PR	2	HVY	CON	29.92	60.54	29.92*	*			75.47	7.82	.147		.040	1.96	3.51	.395		.129
18	PR	2	HVY	STL	29.92	40.28	29.92*	*			81.36	7.10	.158		.033	1.84	3.13	.397		.159
21	FB	1	STD	CON	25.31	38.52	25.31*	*			99.36	5.26	.545		.083	3.19	5.29	.659		.079
658	FB	1	STD	CON	32.34	17.18	6.76	.565	.148	-.268	69.51	5.19	.723	.258	-.208	1.51	6.13	.615	.295	-.026
21	FB	1	STD	STL	25.31	28.88	9.96	.346		.005	108.42	5.49	.530		.074	2.89	4.85	.699		.101
658	FB	1	STD	STL	32.34	25.88	7.90	.478	.144	-.189	77.48	5.42	.727	.245	-.237	.93	3.79	.972	.425	-.121
23	FB	1	HVY	CON	39.77	10.26	8.95	.368	.167	-.034	123.64	9.56	.284	.099	-.085	1.68	6.20	.351	.182	.012
23	FB	1	HVY	STL	39.77	13.13	9.57	.222	.137	-.048	151.14	15.27	.070		-.060	1.86	10.28	.163		.016
26	FB	2	STD	CON	30.36	41.59	14.19	.057		-.160	133.40	8.22	.288	.084	-.121	3.19	7.89	.419	.169	-.081
26	FB	2	STD	STL	30.36	42.75	30.36*	*			130.01	7.01	.318	.074	-.170	3.49	9.64	.369	.117	-.135
29	FB	2	HVY	CON	20.44	58.36	20.44*	*			100.99	4.85	.606		-.094	1.91	3.82	.886		-.177
29	FB	2	HVY	STL	20.44	72.49	20.44*	*			98.93	4.83	.620		-.115	1.55	3.93	1.102		-.121
31	PS	1	STD	CON	50.54	7.37	25.48	.093	.065	.037	26.95	12.95	.164	.111	.057	1.28	7.70	.478	.219	-.040
31	PS	1	STD	STL	50.54	3.59	22.20	.085	.047	.009	31.56	50.54*	*			1.05	7.19	.496	.265	.034
34	PS	1	HVY	CON	86.25	8.04	86.25*	*			13.99	19.96	.138	.077	.016	1.81	86.25*	*		
34	PS	1	HVY	STL	86.25	8.30	86.25*	*			17.71	62.01				1.68	86.25*	*		
36	PS	2	STD	CON	36.01	20.16	10.10	.118		-.026	91.71	5.70	.381	.152	-.077	1.65	3.59	.595	.310	.025
36	PS	2	STD	STL	36.01	33.62	36.01*	*			91.64	6.02	.355	.143	-.069	1.84	4.48	.499	.282	.066
38	PS	2	HVY	CON	33.14	9.03	33.14*	*			19.01	15.41	.128		.031	2.06	32.32	.121		
39	PS	2	HVY	CON	28.81	9.19	28.81*	*			22.35	14.41	.123			1.81	11.11	.185		
38	PS	2	HVY	STL	33.14	4.97	33.14*	*			16.98	7.98	.196	.098	-.000	1.62	10.83	.162		.105
39	PS	2	HVY	STL	28.81	7.05	28.81*	*			23.92	24.68	.119			1.33	11.61	.272		
41	PU	1	STD	CON	64.34	9.49	30.66	.053	.036	.019	30.37	6.72	.247	.091	-.066	1.72	10.64	.197	.117	.037
41	PU	1	STD	STL	64.34	9.83	43.76	.034		.024	34.67	11.40	.116	.058	.000	1.50	6.44	.317	.157	-.004
43	PU	1	HVY	CON	53.73	6.84	53.73*	*			27.23	12.72	.082	.017	-.048	2.43	53.73*	*		
43	PU	1	HVY	STL	53.73	6.90	53.73*	*			17.77	6.58	.147	.081	.014	2.49	53.73*	*		

[a] No. = specimen number; INS. = insulation type: GF = glass fiber, PR = perlite, FB = fiberboard, PS = polystyrene, PU = polyurethane; 1 = 1 in., 2 = 2 in.; ASP. = asphalt thickness: STD = "standard", HVY = "heavy"; DECK = deck used: CON = concrete, STL = steel.

[b] Maximum moisture content induced in the specimen.

[c] Three times the residual standard deviation.

[d] Threshold moisture content.

[e] S(TVP) = S value in the moisture content range in which the TVP occurred; S(MAX) = S value in the moisture content range preceding the range containing the maximum moisture content; S(MID) = average of the S values for the moisture content ranges between the moisture content range containing the TVP and the range preceding the range containing the maximum moisture content.

[f] Data not included because the quadratic fitted curve was inappropriate.

* TVP not attained up to the maximum moisture content of the specimen.

TABLE 5. SUMMARY OF SPECIMENS, CONSTRUCTION VARIABLES, 3RSD, TVP, AND S VALUES FOR THE CAPACITANCE AND NUCLEAR INSTRUMENTS

SPECIMEN[a]					MAX[b] VP	INSTRUMENT N1					INSTRUMENT N2				
NO.	INS.		ASP.	DECK		3RSD[c]	TVP[d]	S[e] FOR TVP	S[e] FOR MID	S[e] FOR MAX	3RSD[c]	TVP[d]	S[e] FOR TVP	S[e] FOR MID	S[e] FOR MAX
1	GF	1	STD	CON	39.42	8.58	17.60	.227		.313	19.25	11.25	.327		.407
2	GF	1	STD	CON	53.81	7.63	28.86	.189	.218	.246	25.27	23.13	.194	.268	.342
1	GF	1	STD	STL	39.42	9.72	15.21	.226		.288	11.95	18.89	.167		.249
2	GF	1	STD	STL	58.81	11.20	43.04	.208			10.21	30.90	.263		.356
4	GF	1	HVY	CON	45.70	17.80	4.15	.124	.096	.068	30.08	6.31	.147	.189	.230
54	GF	1	HVY	CON	46.50	9.45	28.68	.143		.192	17.72	23.30	.361		.538
52	GF	1	HVY	CON	37.65	11.24	21.33	.195			16.91	7.81	.253	.288	.322
4	GF	1	HVY	STL	45.70	5.23	18.36	.183	.227	.272	17.92	25.27	.167		.235
54	GF	1	HVY	STL	46.50	7.64	31.02	.291			13.00	27.93	.298		.462
52	GF	1	HVY	STL	37.65	9.12	7.08	.194	.205	.216	12.66	25.41	.205		
6	GF	2	STD	CON	21.95	6.24	6.24	.491		.458	9.46	6.66	.499		.643
56	GF	2	STD	CON	37.24	11.66	11.04	.188		.172	23.29	15.72	.237		.331
6	GF	2	STD	STL	21.95	7.79	13.96	.423			8.85	12.12	.304		
56	GF	2	STD	STL	37.24	12.92	14.13	.171		.150	10.10	14.63	.289		.436
8	GF	2	HVY	CON	34.35	10.93	19.17	.206		.231	24.59	8.79	.368	.418	.468
58	GF	2	HVY	CON	29.29	10.54	14.93	.221			17.03	1.85	.478		.529
8	GF	2	HVY	STL	34.35	9.60	5.90	.370	.329	.288	12.26	6.10	.421	.636	.851
58	GF	2	HVY	STL	29.29	8.53	15.36	.281			14.26	8.99	.345		.463
11	PR	1	STD	CON	44.60	9.37	3.49	.503	.431	.359	18.02	5.13	.621	.783	.944
62	PR	1	STD	CON	70.13	11.72	7.85	.420	.291	.163	17.29	2.91	.911	.794	.677
11	PR	1	STD	STL	39.20	8.45	7.11	.346	.393	.439	16.49	13.22	.249		.322
62	PR	1	STD	STL	70.13	8.94	8.00	.417	.342	.267	12.33	8.75	.338	.486	.635
14	PR	1	HVY	CON	44.61	9.14	14.15	.246	.228	.209	36.08	6.44	.437	.314	.192
14	PR	1	HVY	STL	44.61	10.96	15.24	.202	.177	.152	17.64	6.96	.462	.356	.251
16	PR	2	STD	CON	24.78	8.62	2.48	.631		.626	11.30	2.69	1.627		1.999
66	PR	2	STD	CON	31.72	13.75	1.28	.634	.466	.297	17.20	2.33	1.118	1.378	1.637
16	PR	2	STD	STL	24.78	5.06	3.69	.997		1.073	6.14	3.79	.962		1.687
66	PR	2	STD	STL	31.72	11.76	4.29	.503	.477	.451	10.87	6.06	.503	1.085	1.666
18	PR	2	HVY	CON	29.92	7.25	3.79	1.048		.774	23.56	3.83	1.026		.931
18	PR	2	HVY	STL	29.92	10.07	7.26	.528		.550	13.70	6.35	.740		.963
21	FB	1	STD	CON	25.31	7.18	5.19	.846		.461	9.99	3.84	1.218		1.337
658	FB	1	STD	CON	32.34	5.74	10.29	.565		.938	23.16	10.52	.582		.966
21	FB	1	STD	STL	25.31	6.67	5.70	.693		.613	14.59	10.08	.268		
658	FB	1	STD	STL	32.34	6.82	9.63	.305	.492	.679	7.13	16.88	.591		1.267
23	FB	1	HVY	CON	39.77	11.06	19.22	.167		.167	15.69	6.90	.602	.608	.613
23	FB	1	HVY	STL	39.77	6.21	5.47	.417	.350	.283	12.63	9.99	.389	.438	.487
26	FB	2	STD	CON	30.36	8.47	6.88	.558	.553	.548	5.56	2.38	2.840	3.039	3.236
26	FB	2	STD	STL	30.36	5.40	6.29	.810	.981	1.151	9.89	3.88	.720	1.127	1.535
29	FB	2	HVY	CON	20.44	10.65	9.62	.413		.356	14.05	3.76	.975		.957
29	FB	2	HVY	STL	20.44	7.47	3.03	.557		.372	11.11	4.95	.888		.793
31	PS	1	STD	CON	50.54	9.79	10.39	.381	.343	.304	24.60	8.07	.517	.486	.456
31	PS	1	STD	STL	50.54	7.07	8.49	.468	.421	.375	11.58	14.96	.349	.432	.515
34	PS	1	HVY	CON	86.25	8.30	16.84	.222	.159	.097	23.69	11.26	.330	.255	.179
34	PS	1	HVY	STL	86.25	5.46	19.55	.165	.165	.166	15.50	13.24	.227	.198	.170
36	PS	2	STD	CON	36.01	6.79	3.17	.823	.727	.631	14.53	6.59	.605	.830	1.055
36	PS	2	STD	STL	36.01	8.90	6.77	.436	.451	.465	10.48	4.47	.235	.378	.521
38	PS	2	HVY	CON	33.14	11.66	3.56	.447	.312	.177	15.70	2.15	1.112	1.033	.954
39	PS	2	HVY	CON	28.81	7.32	3.81	.851		.591	7.87	1.95	1.852		1.875
38	PS	2	HVY	STL	33.14	11.05	7.70	.356	.307	.257	12.54	2.07	.783	.786	.788
39	PS	2	HVY	STL	28.81	6.70	7.61	.480		.589	27.05	16.35	.240		
41	PU	1	STD	CON	64.34	7.16	8.24	.511	.437	.362	21.08	5.20	.461	.546	.631
41	PU	1	STD	STL	64.34	8.27	14.44	.311	.332	.353	11.75	16.43	.247	.473	.699
43	PU	1	HVY	CON	53.73	12.03	8.58	.283	.188	.093	32.21	3.10	.472	.357	.242
43	PU	1	HVY	STL	53.73	8.21	11.52	.374	.288	.202	17.85	6.29	.406	.404	.403

[a] No. = specimen number; INS. = insulation type: GF = glass fiber, PR = perlite, FB = fiberboard, PS = polystyrene, PU = polyurethane; 1 = 1 in., 2 = 2 in.; ASP. = asphalt thickness: STD = "standard", HVY = "heavy"; DECK = deck used: CON = concrete, STL = steel.

[b] Maximum moisture content induced in the specimen.

[c] Three times the residual standard deviation.

[d] Threshold moisture content.

[e] S(TVP) = S value in the moisture content range in which the TVP occurred; S(MAX) = S value in the moisture content range preceding the range containing the maximum moisture content; S(MID) = average of the S values for the moisture content ranges between the moisture content range containing the TVP and the range preceding the range containing the maximum moisture content.

[f] Data not included because the quadratic fitted curve was inappropriate.

* TVP not attained up to the maximum moisture content of the specimen.

Table 6. Summary of Maximum Moisture Content, 3RSD, TVP and S Values for Specimens[a] Used with the Infrared Instrument

Specimen No.	Surface	Insulation Type and Nominal Thickness	(in.)	Maximum V_P (%)	3RSD	TVP	S(TVP)	S(MID)	S(MAX)
51	Gravel	Glass Fiber	1	41.4	0.053	21.6	0.201	---[b]	0.231
141	Smooth	Glass Fiber	1	54.0	0.071	31.8	0.099	---	0.091
143	Smooth	Glass Fiber	2	37.8	0.053	8.9	0.402	0.262	0.122
61	Gravel	Perlite	1	46.4	0.009	2.6	1.034	0.799	0.565
145	Smooth	Perlite	1	66.4	0.043	14.2	0.225	0.145	0.066
733	Smooth	Perlite	2	32.0	0.018	2.4	0.791	0.630	0.469
113	Gravel	Polystyrene	1	17.3	0.055	17.3[c]	---	---	---
751	Smooth	Polystyrene	1	38.4	0.052	25.7	0.190	---	---
155	Smooth	Polystyrene	2	12.6	0.011	5.1	1.016	---	---

[a] All specimens were "standard" asphalt thickness and tested on a steel deck.
[b] No entry.
[c] TVP not attained up to the maximum moisture content.

Table 7. Percentages of TVP Values Less than 10 percent, 20 percent, or "Not Attained"[a] for Capacitance and Nuclear Instruments

Instrument	TVP for Fiber Glass			TVP for Perlite			TVP for Fiberboard			TVP for Polystyrene			TVP for Polyurethane			TVP for All Insulations		
	< 10%	< 20%	Not Attained	< 10%	< 20%	Not Attained	< 10%	< 20%	Not Attained	< 10%	< 20%	Not Attained	< 10%	< 20%	Not Attained	< 10%	< 20%	Not Attained
C1	11	50	22	30	70	30	50	60	40	0	10	70	0.0	0.0	50	19	44	38
C2	44	78	0.0	50	100	0.0	90	100	0	30	70	10	50	100	0	52	87	1.8
C3	22	50	5.5	58	92	0.0	90	100	0	40	70	20	25	50	50	46	72	9.3
Avg: C1, C2, C3	26	59	9.3	47	88	8.8	77	87	13	23	50	33	25	50	33	39	68	16
N1	22	72	0.0	83	100	0.0	80	100	0	70	100	0	50	100	0	57	91	0.0
N2	39	67	0.0	92	100	0.0	70	100	0	60	100	0	75	100	0	63	89	0.0
Avg: N1, N2	30	69	0.0	88	100	0.0	75	100	0	65	100	0	62	100	0	60	90	0.0

[a] TVP not attained up to the maximum moisture content.

Table 8. Percentages of TVP Values Less than 10 percent, 20 percent, or "Not Attained" and Percentages of S Values Less than 0.0 and 0.2 and SS less than -0.015 and 0.0 for the Infrared Instrument

Indicator	Insulation			
	Glass Fiber	Perlite	Polystyrene	All Insulations
TVP < 10 percent	33	67	33	44
TVP < 20 percent	33	100	33	55
TVP not Attained	0	0	33	11
S < 0.0	0	0	0	0
S < 0.2	43	33	50	38
SS < -0.015	0	67	0	25
SS < 0.0	67	100	0	63

Table 9. Percentages of S values Less than 0.0 and 0.2 for Capacitance and Nuclear Instruments

Instrument	S for Glass Fiber		S for Perlite		S for Fiberboard		S for Polysystrene		S for Polyurethane		S for All insulations	
	< 0.0	< 0.2	< 0.0	< 0.2	< 0.0	< 0.2	< 0.0	< 0.2	< 0.0	< 0.2	< 0.0	< 0.2
C1	0	70	46	92	31	69	12	100	0	100	21	81
C2	0	64	49	100	32	56	14	91	20	95	22	80
C3	0	71	15	82	24	56	4.8	48	9.1	82	11	68
Avg: C1, C2, C3	0	68	35	91	29	59	9.8	74	14	92	18	76
N1	0	39	0	7.7	0	8.3	0	29	0	15	0	21
N2	0	13	0	2.5	0	0.0	0	12	0	0	0	6.3
Avg: N1, N2	0	25	0	5.1	0	4.2	0	20	0	7.3	0	13

Table 10. Percentages of SS Values Less than −0.015 and 0.0 for Capacitance and Nuclear Instruments

Instrument	SS for Glass Fiber		SS for Perlite		SS for Fiberboard		SS for Polystyrene		SS for Polyurethane		SS for All Insulations	
	< −0.015	< 0.0	< −0.015	< 0.0	< −0.015	< 0.0	< −0.015	< 0.0	< −0.015	< 0.0	< −0.015	< 0.0
C1	14	50	29	100	100	100	0.0	100	0.0	100	31	78
C2	17	61	17	100	90	100	22	89	0.0	100	30	85
C3	5.9	65	50	92	90	100	25	87	0.0	100	37	84
Avg: C1, C2, C3	12	59	32	97	92	100	20	90	0.0	100	33	83
N1	0.0	28	17	75	20	60	10	70	0.0	75	9.3	55
N2	0.0	0	0.0	33	0	30	0.0	40	0.0	50	0.0	24
Avg: N1, N2	0.0	14	8.3	54	10	45	5.0	55	0.0	63	4.6	40

Table 11. Construction Variable Effects[a] for Nuclear Instruments

Nuclear Instrument	Deck Effect		Insulation Thickness Effect	Asphalt Thickness Effect
	Concrete S > Steel S	Steel S > Concrete S	2"S > 1"S	"Standard" S > "Heavy" S
N1	1",Std,PU[b] (A102, A103)[c]	1",Std,PS (A94, A95) 1",Hvy,FB (A88, A89) 1",Hvy,PU (A104, A105)	Std,Con,PS (A94, A98) Hvy,Con,PR (A80, A84) Hvy,Con,FB (A88, A92) Hvy,Stl,PR (A81, A85) Hvy,Stl,PS (A97, A101)	1",Con,FB (A86, A88) 1",Con,PS (A94, A96) 1",Con,PU (A102, A104) 2",Con,FB (A90, A92) 1",Stl,PR (A79, A81) 1",Stl,PS (A95, A97) 2",Stl,FB (A91, A93)
N2	1",Std,PR (A78, A79) 1",Hvy,PS (A96, A97) 2",Std,PS (A98, A99)		Hvy,Con,PR (A80, A84) Hvy,Con,PS (A96, A100) Std,Stl,PR (A79, A83) Hvy,Stl,PR (A81, A85)	1",Con,PR (A78, A80) 1",Con,PS (A94, A96) 1",Stl,PS (A95, A97)

[a] Construction variables are listed for which significant differences in S occurred with respect to the effects of deck, insulation thickness, and asphalt thickness.

[b] Abbreviations for construction variables are the same as those used in table 5.

[c] Figure numbers for the S vs. V_P plots on which the effect was based.

Table 12. Summary of Percentages for All Insulations of TVP Less Than 10 percent, 20 percent , and "Not Attained"; S Less than 0.0 and 0.2; and SS Less than −0.015 and 0.0 for Capacitance, Nuclear, and Infrared Instruments

Instrument Type		TVP			S		SS	
		< 10%	< 20%	Not Attained	< 0.0	< 0.2	< −0.015	< 0.0
Capacitance[a]	C1	19	44	38	21	81	31	78
	C2	52	87	2	22	80	30	85
	C3	46	72	9	11	68	37	84
Avg. of C1, C2, and C3		39	68	16	18	76	33	83
Nuclear[a]	N1	57	91	0	0	21	9	55
	N2	63	89	0	0	6	0	24
Avg. of N1 and N2		60	90	0	0	13	5	40
Infrared[b]		44	55	11	0	38	25	63

[a] Based on "standard" and "heavy" asphalt thicknesses, glass fiber, perlite, fiberboard, polystyrene, polyurethane insulations and concrete and steel decks.

[b] Based on: "standard" apshalt thickness, glass fiber, perlite, and polystyrene insulations and steel deck only.

Table 13. Instrument Effects[a] for the Capacitance, Nuclear, and Infrared Methods Based on the TVP and S Indicators

	Insulation					
	Glass Fiber (Figs. A71 and A75)		Perlite (Figs. A79 and A83)		Polystyrene (Figs. A95 and A99)	
Indicator	1"	2"	1"	2"	1"	2"
TVP	C < N C < IR IR ≈ N	C < N C ≈ IR IR ≈ N	N < C IR < C IR ≈ N	C ≈ N C ≈ IR IR ≈ N	N < C C ≈ IR N < IR	N < C IR < C IR ≈ N
S	N > C IR > C N > IR	N > C IR > C IR ≈ N	N > C IR > C IR ≈ N	N > C IR > C IR ≈ N	N > C b b	N > C b b

[a] For "standard" asphalt thickness and steel deck. The following definitions are used: "C" represents the capacitance instruments (C1, C2, C3); "N" represents the nuclear instruments (N1, N2); "IR" represents the infrared instrument; "≈" means approximately equal to.

[b] Entries not determined because only one S value occurred for the infrared instrument.

Table 14. Instrument Effects for Capacitance and Nuclear Methods Based on the TVP and S Indicators

		Insulation				
Indicator	Nuclear, Capacitance Instrument Effects	Glass Fiber (Figs. A70 to A77)	Perlite (Figs. A78 to A85)	Fiberboard (Figs. A86 to A93)	Polystyrene (Figs. A94 to A101)	Polyurethane[d] (Figs. A102 to A105)
TVP	Nuclear < Capacitance	1",2",Hvy,C,S[a]	1",Std,Hvy,S 2",Hvy,C	2",Std,S	1",2",Std,Hvy,S, 1",2",Hvy,C	1",Std,Hvy,C 1",Hvy,S
	Capacitance < Nuclear	1",2",Std,S	None[b]	None	None	None
S	Nuclear > Capacitance	1",2",Std,C,S 2",Hvy,C,S	1",2",Std,Hvy,C,S (i.e., all possible combinations)	1",2",Std,Hvy,C,S (i.e., all possible combinations)	1",2",Std,Hvy,C 1",2",Std,S[c] 2",Hvy,S	1",Std,Hvy,C,S
	Capacitance > Nuclear	None	None	None	None	None

[a] Construction variable entries are abbreviated as follows: 1", 2" are nominal 1 and 2 in. insulation thicknesses; Std, Hvy are "Standard" and "Heavy" asphalt thicknesses; C, S are concrete and steel decks. For example, a construction variable combination of 1", 2", Std, C, S refers to specimens with 1 and 2 in. thick insulation, with "standard" asphalt thickness, and tested on concrete and steel deck.

[b] No construction variable set entries.

[c] No S values existed for 1 in., "heavy" asphalt, steel deck for polystyrene for instruments C1, C2 and C3; thus no instrument effect could be determined.

[d] Entries for 1 in. insulation thickness.

Table 15. Percentages of TVP Values Less than 10 Percent, 20 Percent, and "Not Attained" for "Standard" and "Heavy" Asphalt Thicknesses and 1 in. and 2 in. Insulation Thicknesses.

Instrument	Asphalt Thickness[a]						Insulation Thickness					
	TVP < 10%		TVP < 20%		TVP Not Attained		TVP < 10%		TVP < 20%		TVP not Attained	
	Standard	Heavy	Standard	Heavy	Standard	Heavy	1 in.	2 in.	1 in.	2 in.	1 in.	2 in.
C1	31	7.7	65	23	15	62	20	18	50	36	27	54
C2	57	46	96	77	3.6	0	30	79	80	96	3.3	0
C3	71	19	93	50	0	19	30	67	60	87	17	0
Avg: C1, C2, C3	54	24	85	50	6.1	27	27	56	63	74	15	17
N1	64	50	93	88	0	0	43	75	83	100	0	0
N2	54	73	93	85	0	0	47	83	80	100	0	0
Avg: N1, N2	59	61	93	87	0	0	45	79	82	100	0	0

[a] Gravel thickness was, in general, greater for the "heavy" asphalt thickness. Table 2 gives values of gravel thickness and gravel weight for the specimens.

Figure 1. Fabrication of roofing specimens. Felts being applied to insulation board with hot asphalt.

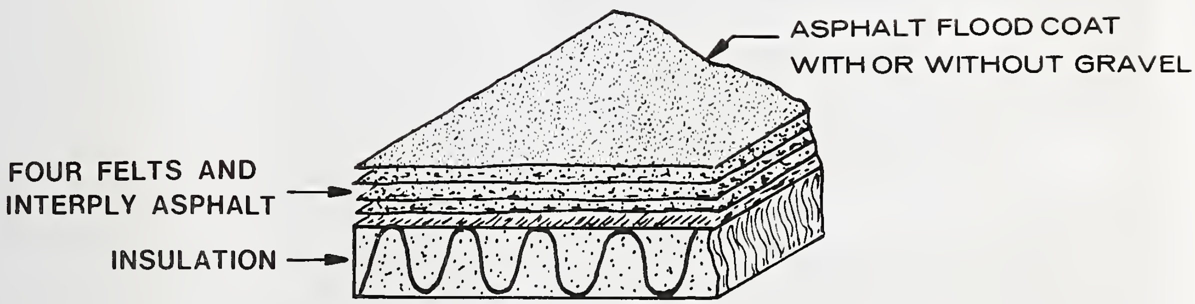


Figure 2. Roofing specimen composition.

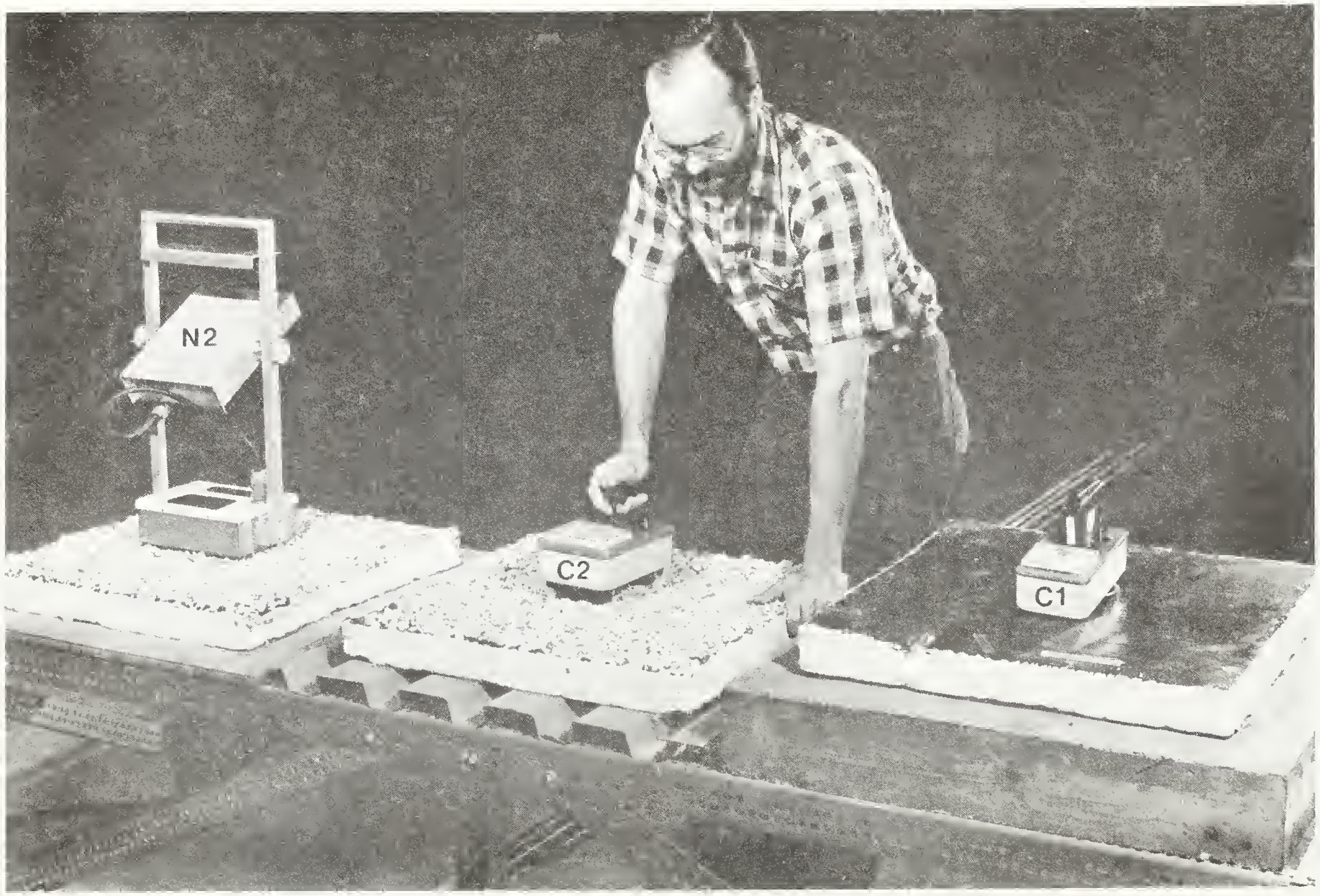


Figure 3. Typical gravel and smooth-surfaced specimens in testing position for the capacitance and nuclear instruments on the concrete (right side) and steel (center) decks. Instruments C1 (right side), C2 (center), and N2 (left side) are shown.

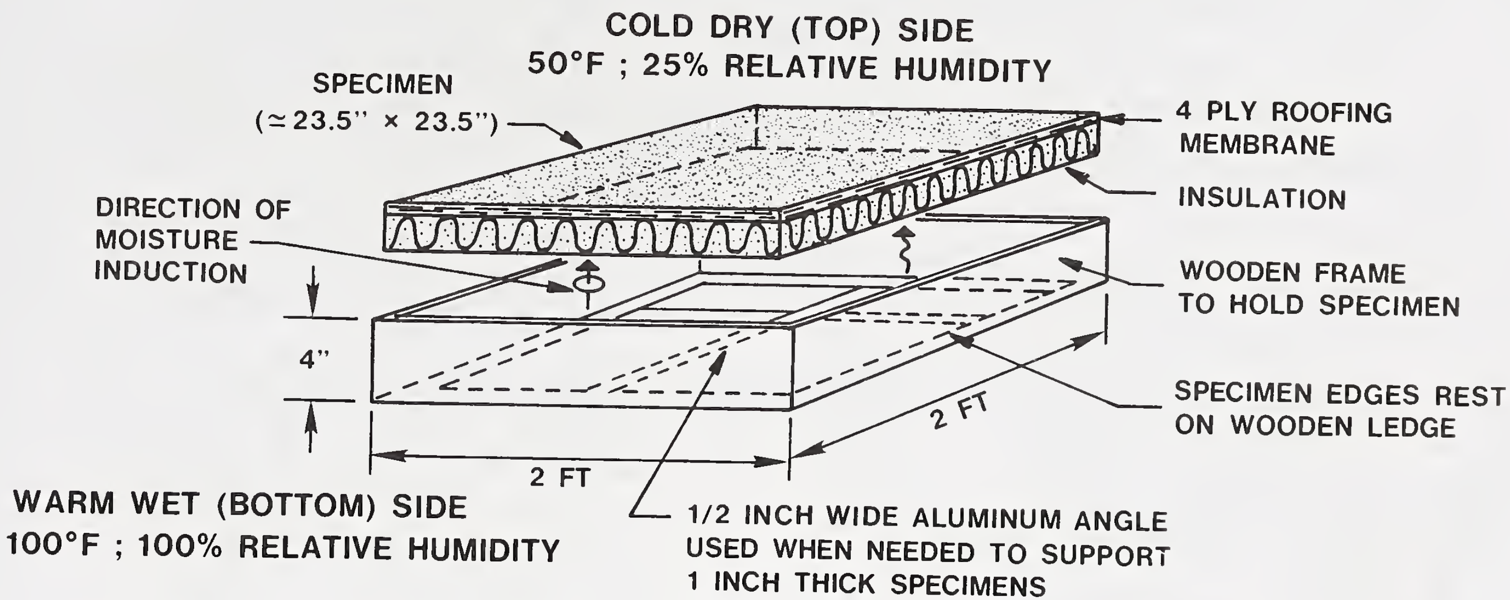
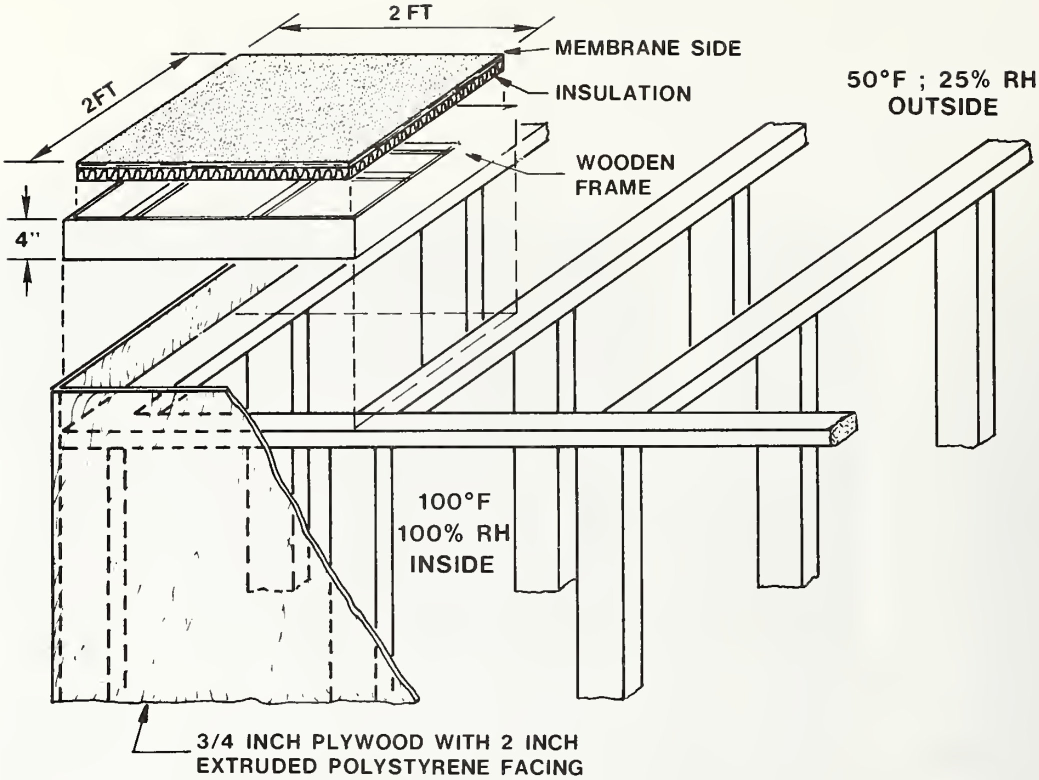
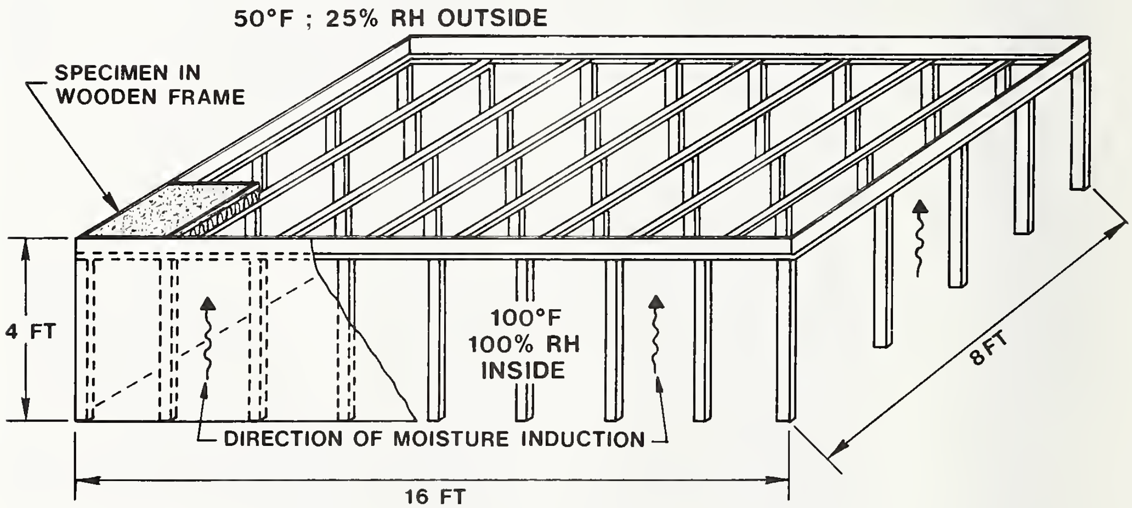


Figure 4. Roofing specimen, wooden supporting frame and the environmental conditions used to induce moisture.



Detail View



Overall View

Figure 5. Insulated wooden chambers used to induce moisture in the roofing specimens.

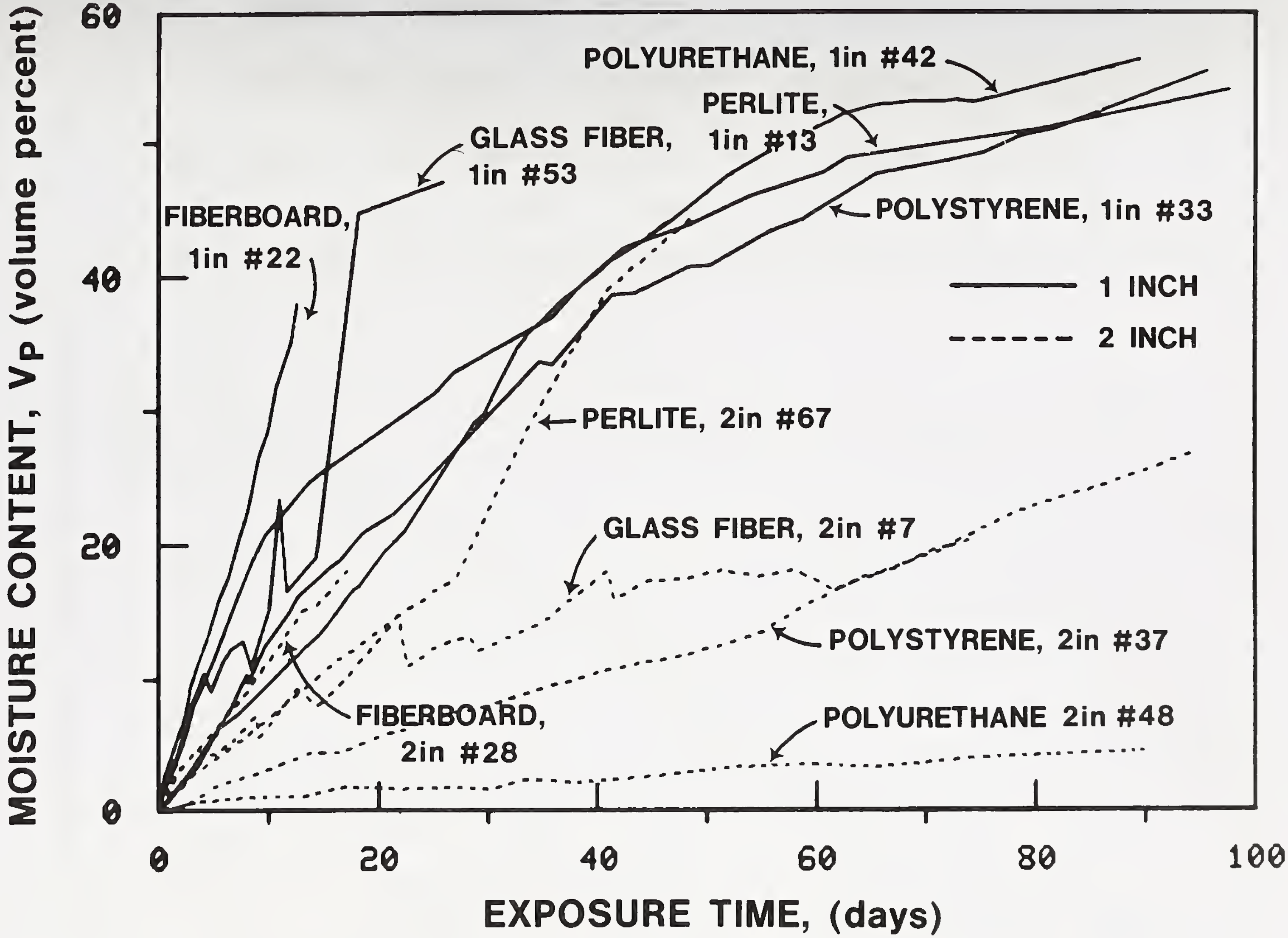


Figure 6. Moisture gain in roofing specimens.

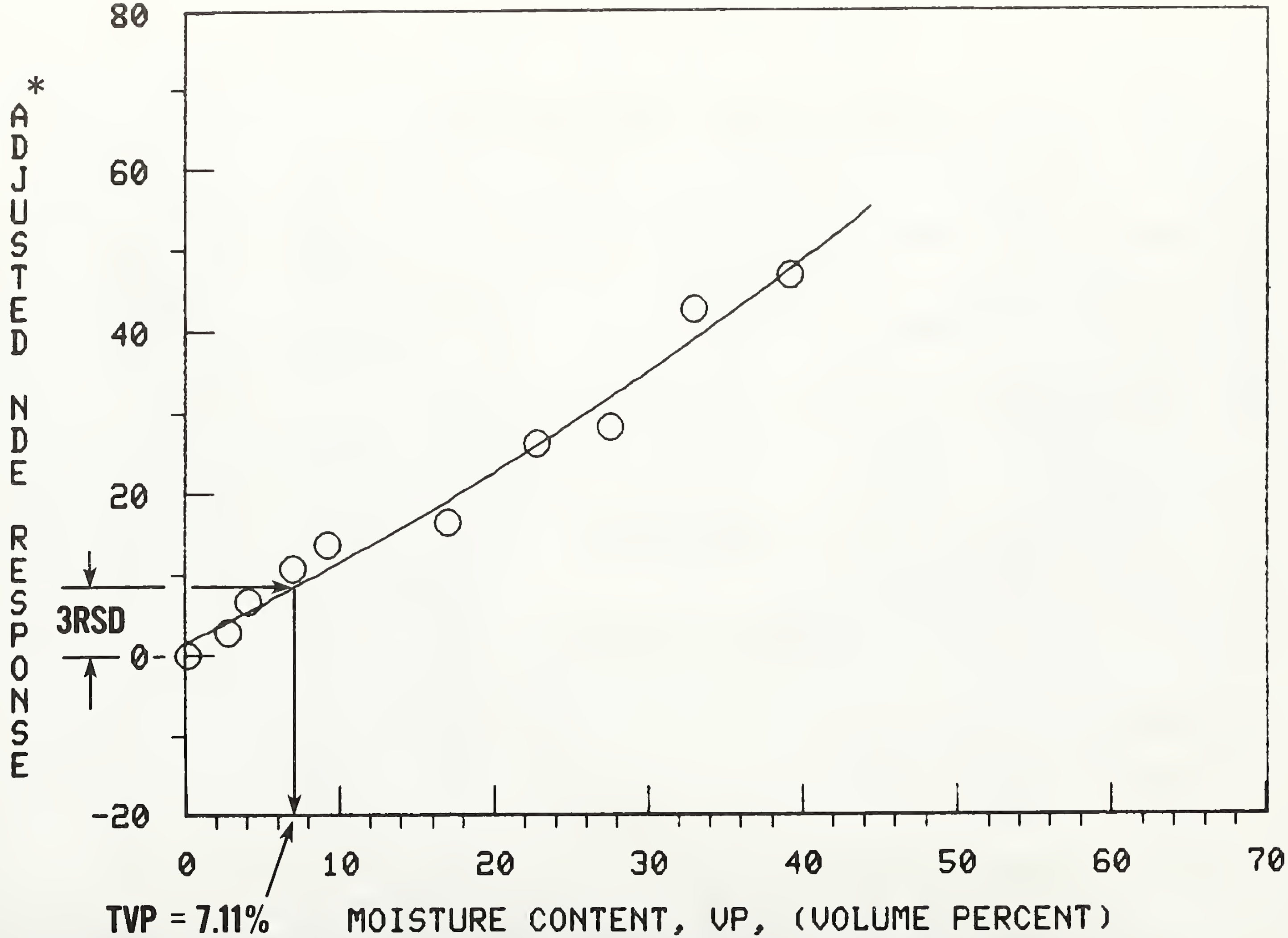


FIGURE 7 PERLITE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT N1, SPEC #11

* $R_W - R_D$ = adjusted NDE response

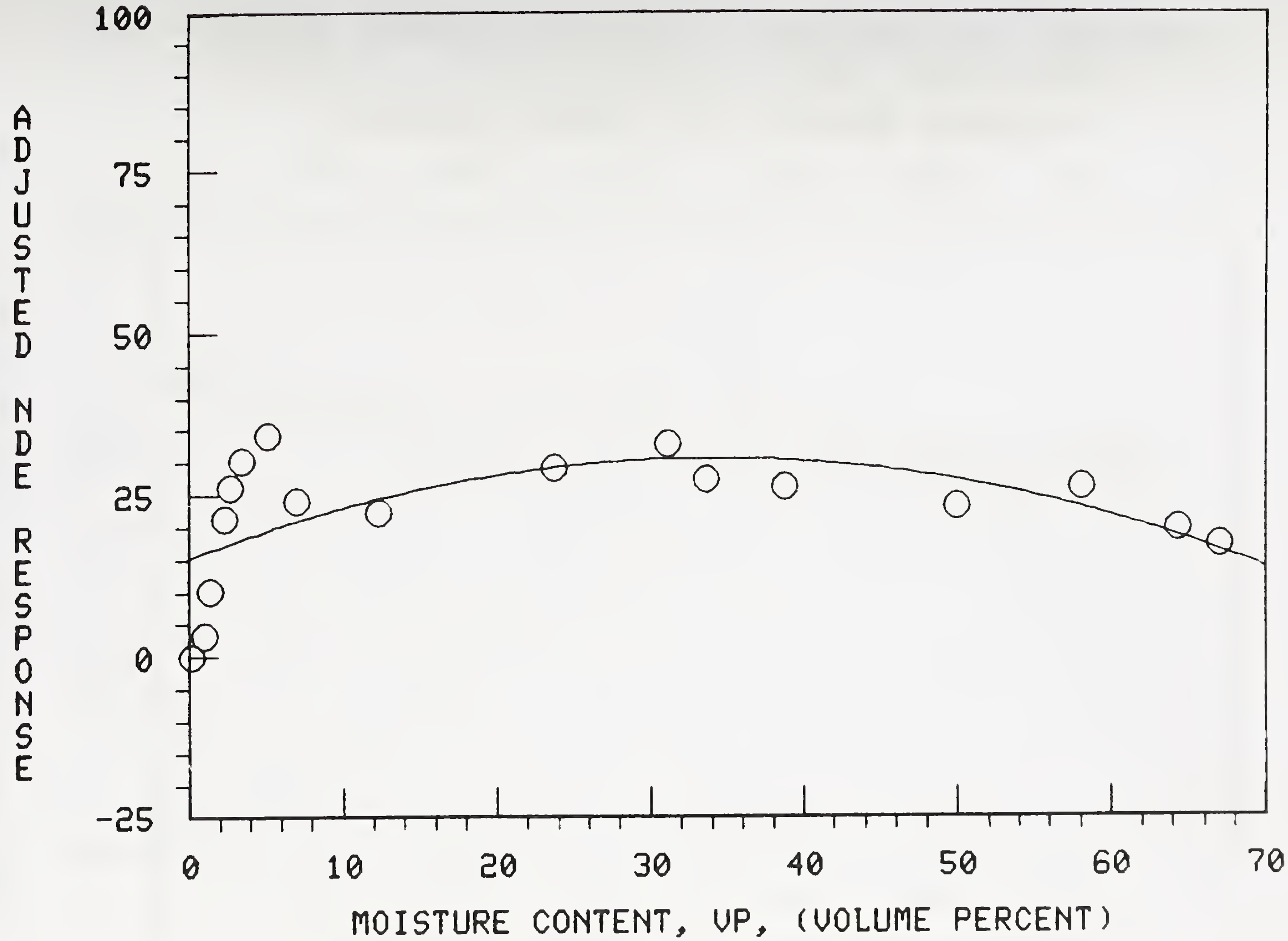


FIGURE 8 PERLITE, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT C1, SPEC #62

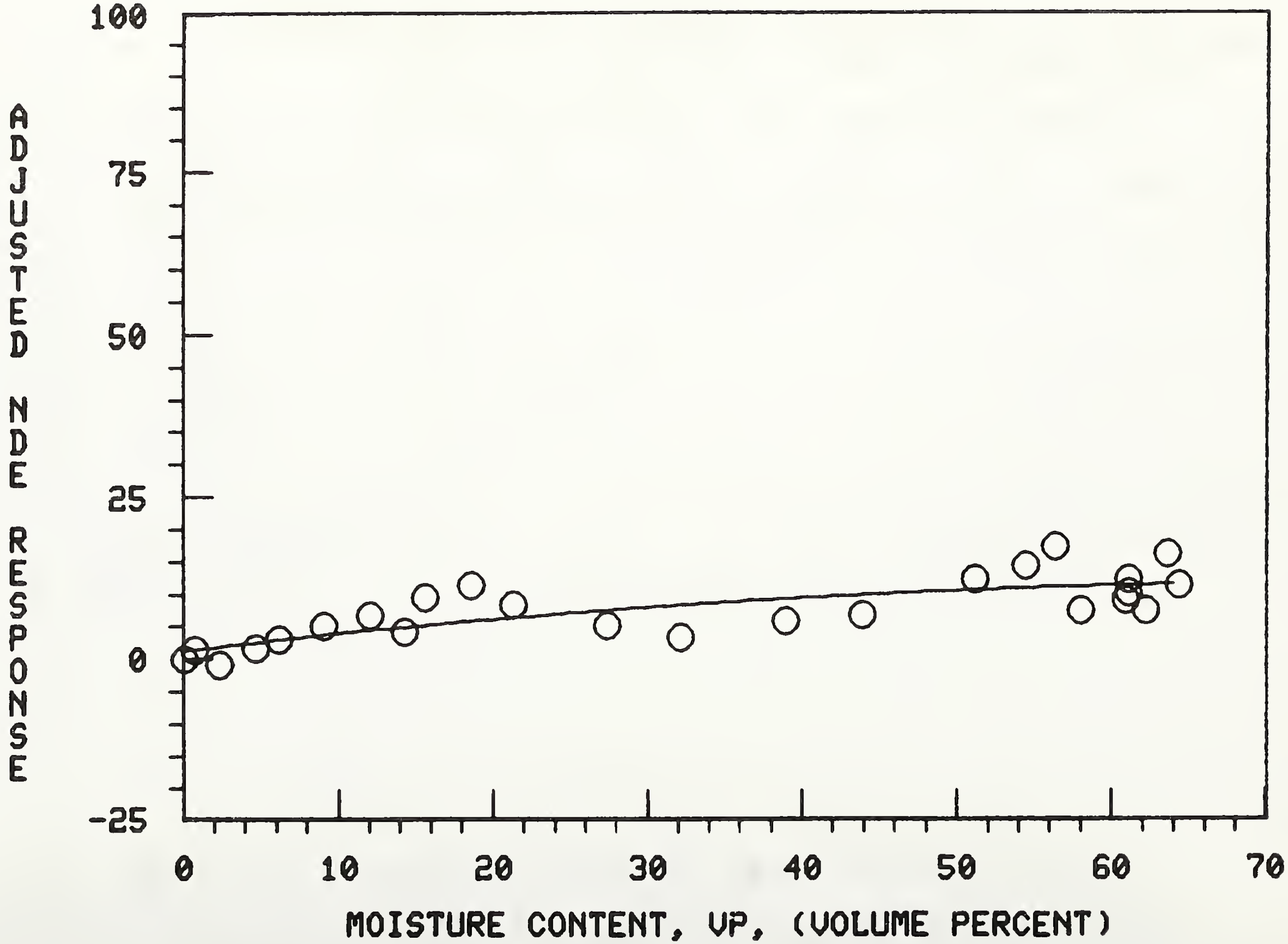


FIGURE 9 POLYURETHANE, 1 INCH, STEEL DECK,
STANDARD ASPHALT THICKNESS, INSTRUMENT C1, SPEC #41

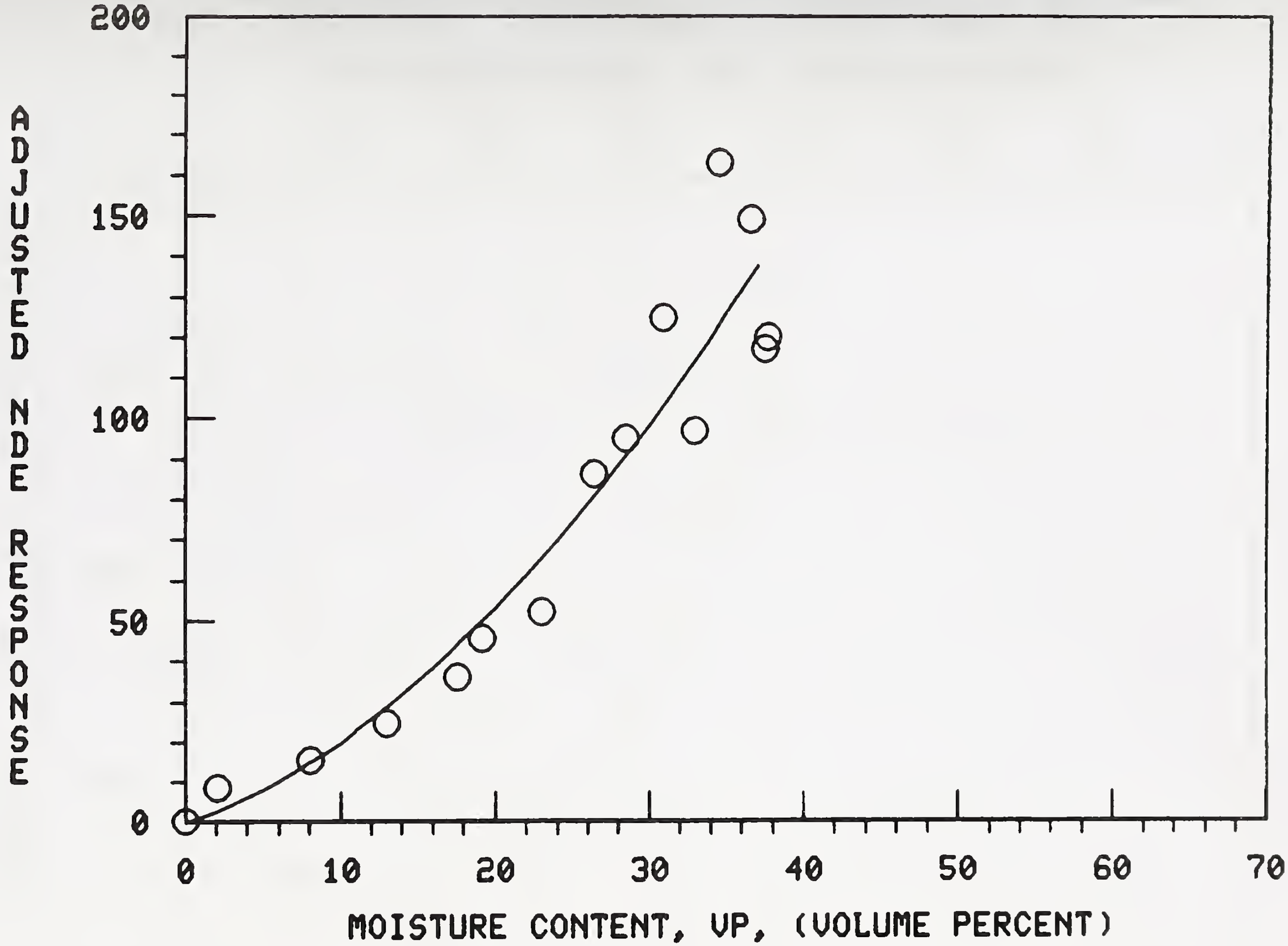


FIGURE 10 GLASS FIBER, 1 INCH, STEEL DECK,
HEAVY ASPHALT THICKNESS, INSTRUMENT C2, SPEC #52

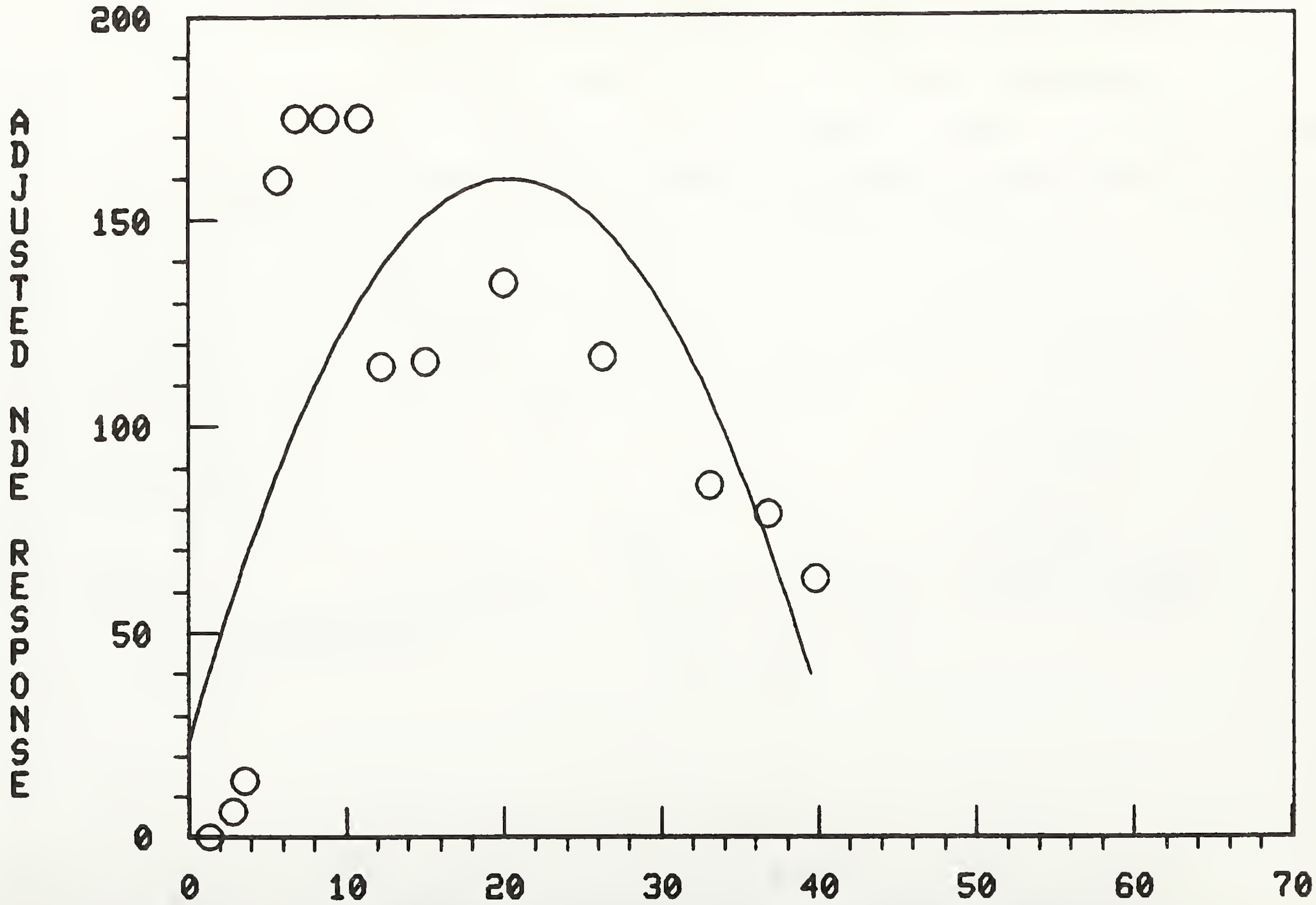


FIGURE 11 FIBERBOARD, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS, INSTRUMENT C2, SPEC #23

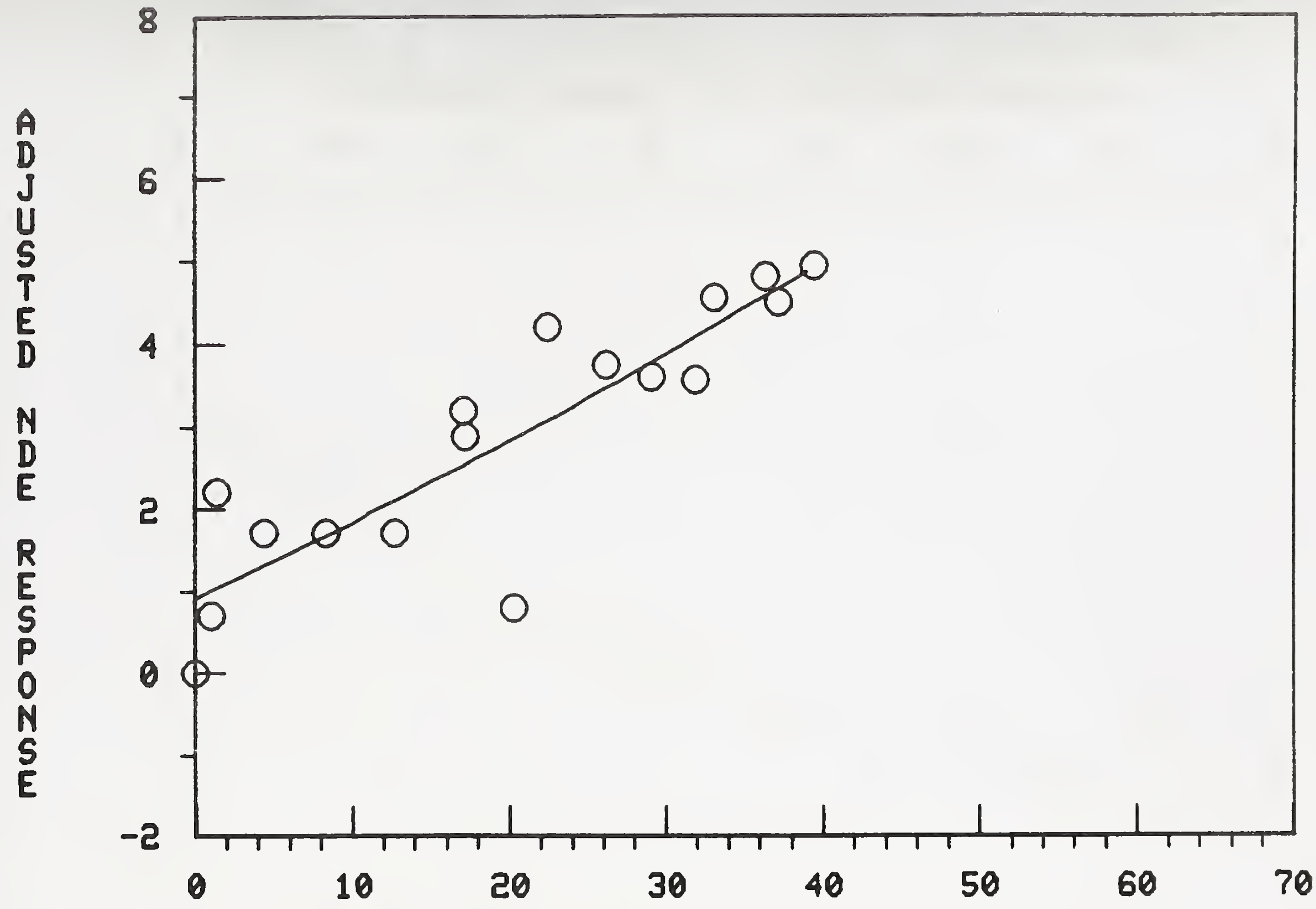


FIGURE 12 GLASS FIBER, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT C3, SPEC #1

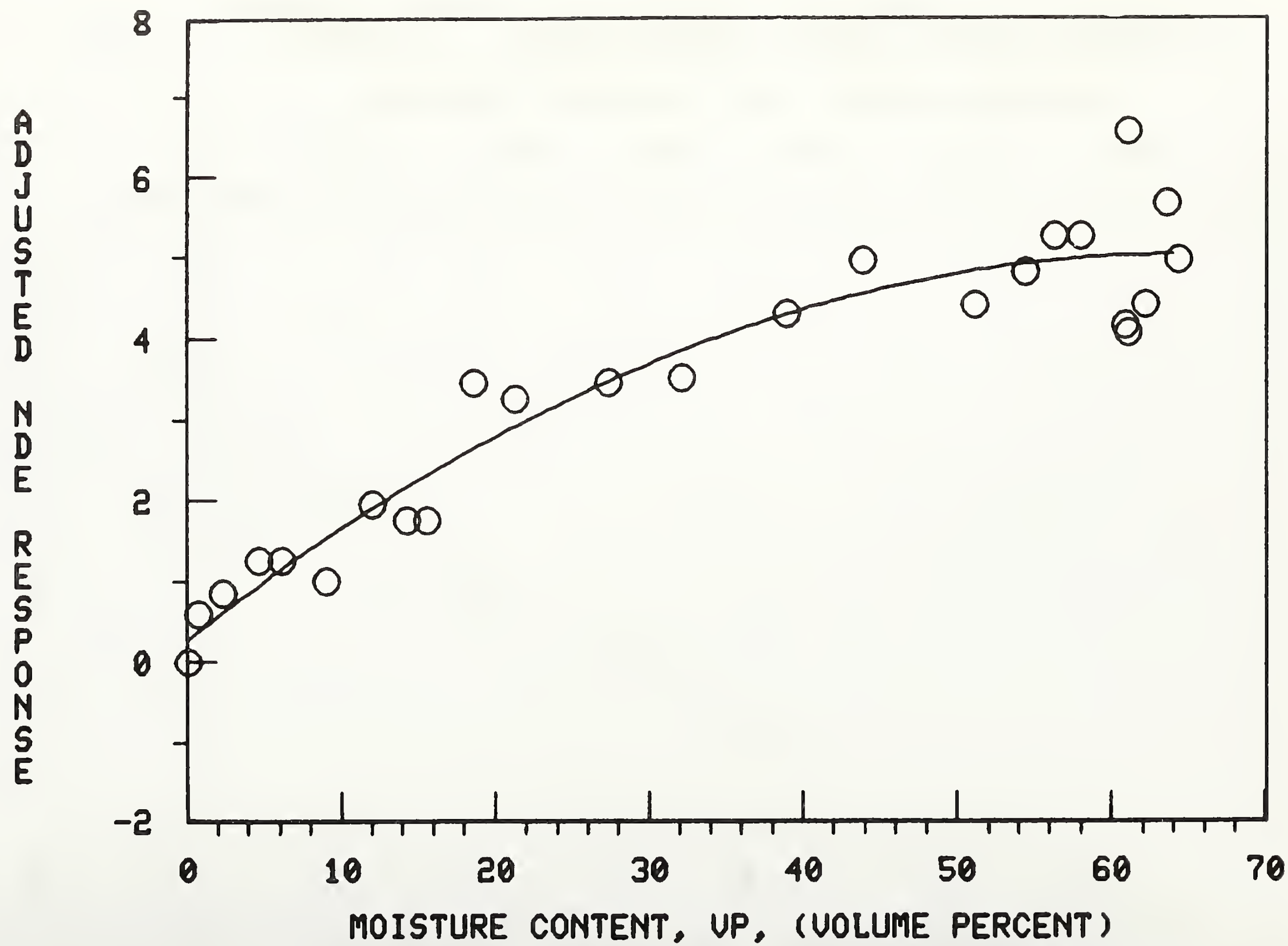


FIGURE 13 POLYURETHANE, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT C3, SPEC #41

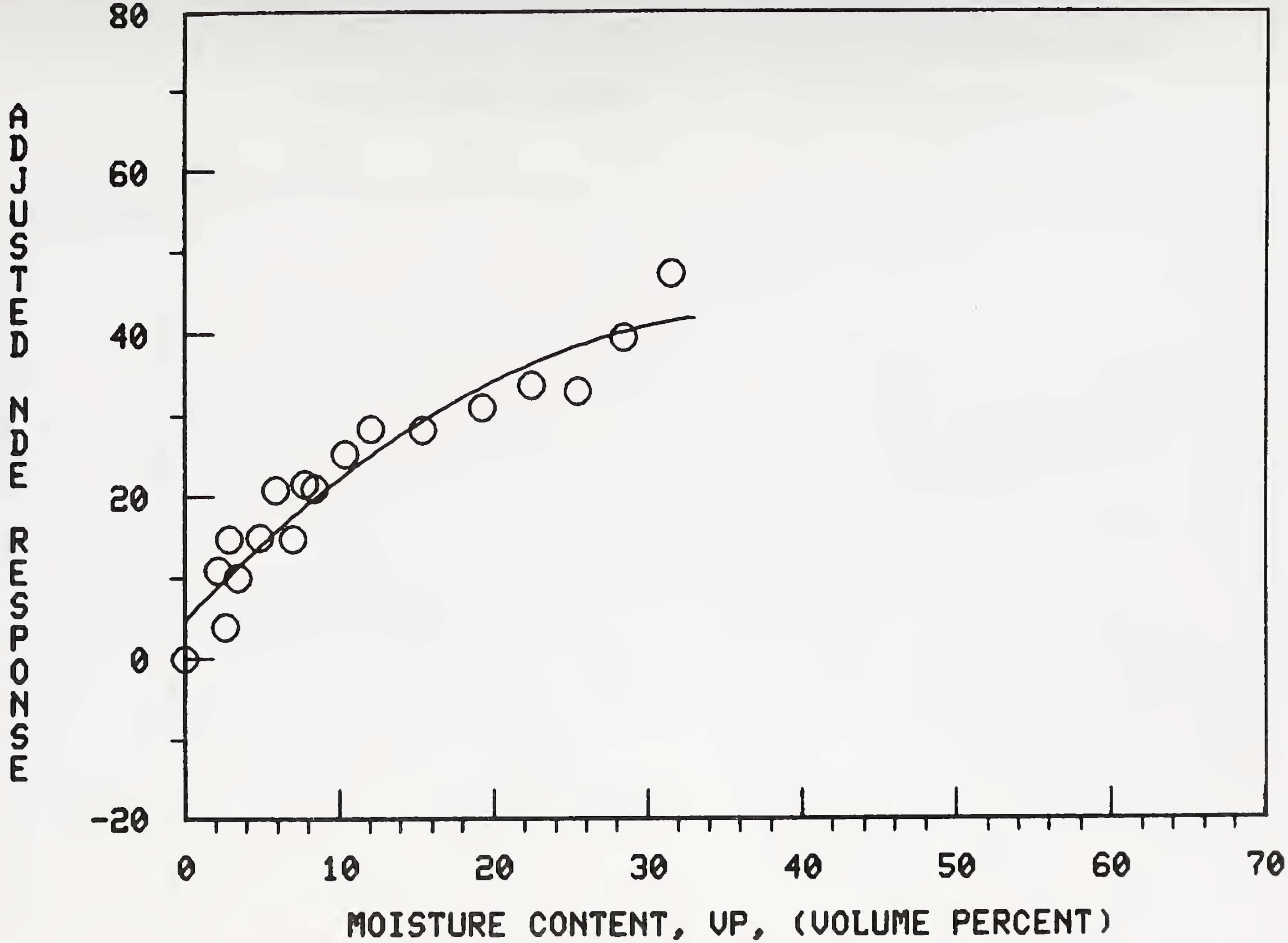


FIGURE 14 POLYSTYRENE, 2 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS, INSTRUMENT N1, SPEC #38

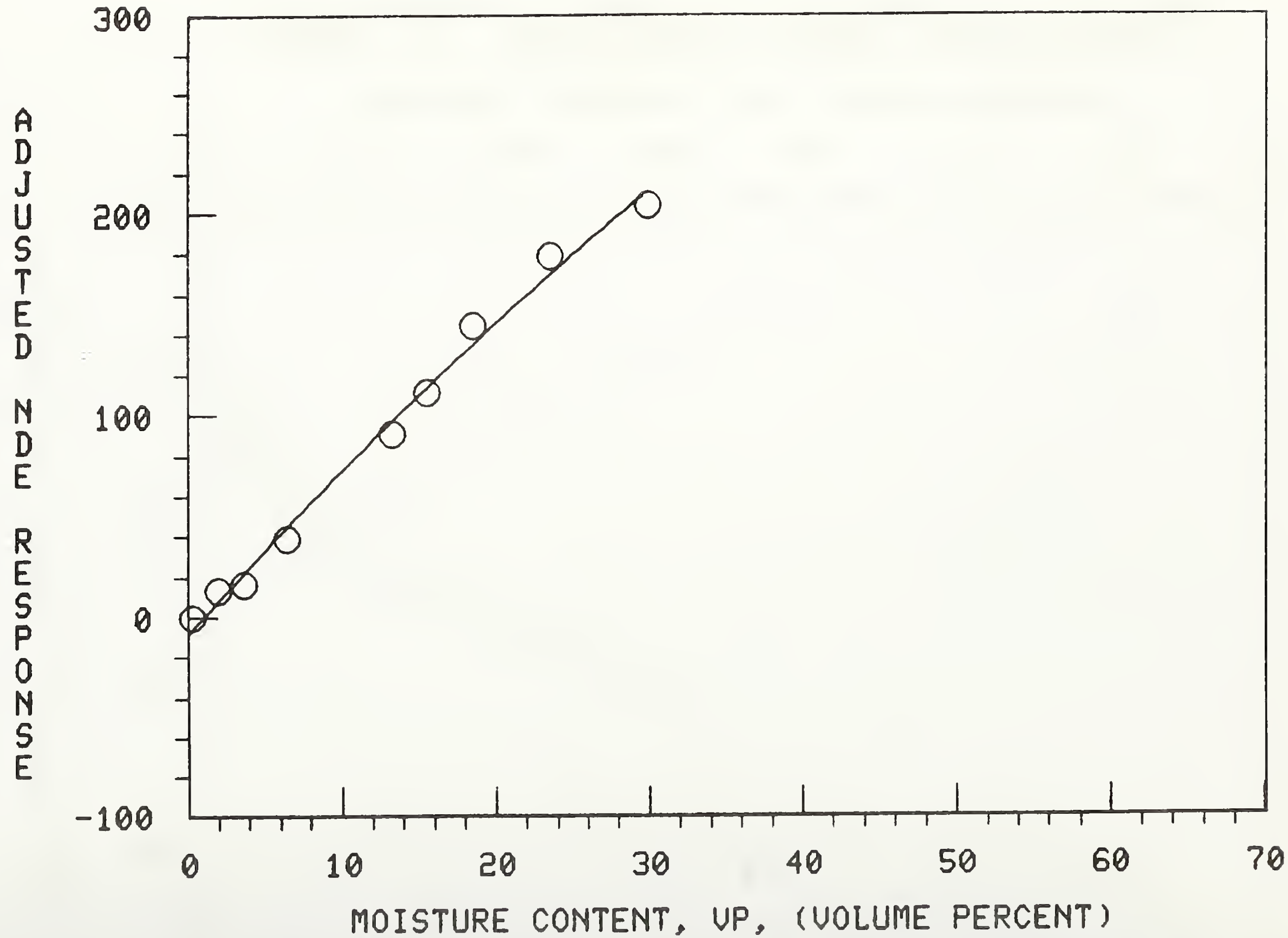


FIGURE 15 PERLITE, 2 INCH, CONCRETE DECK,
HEAVY ASPHALT THICKNESS, INSTRUMENT N2, SPEC #18

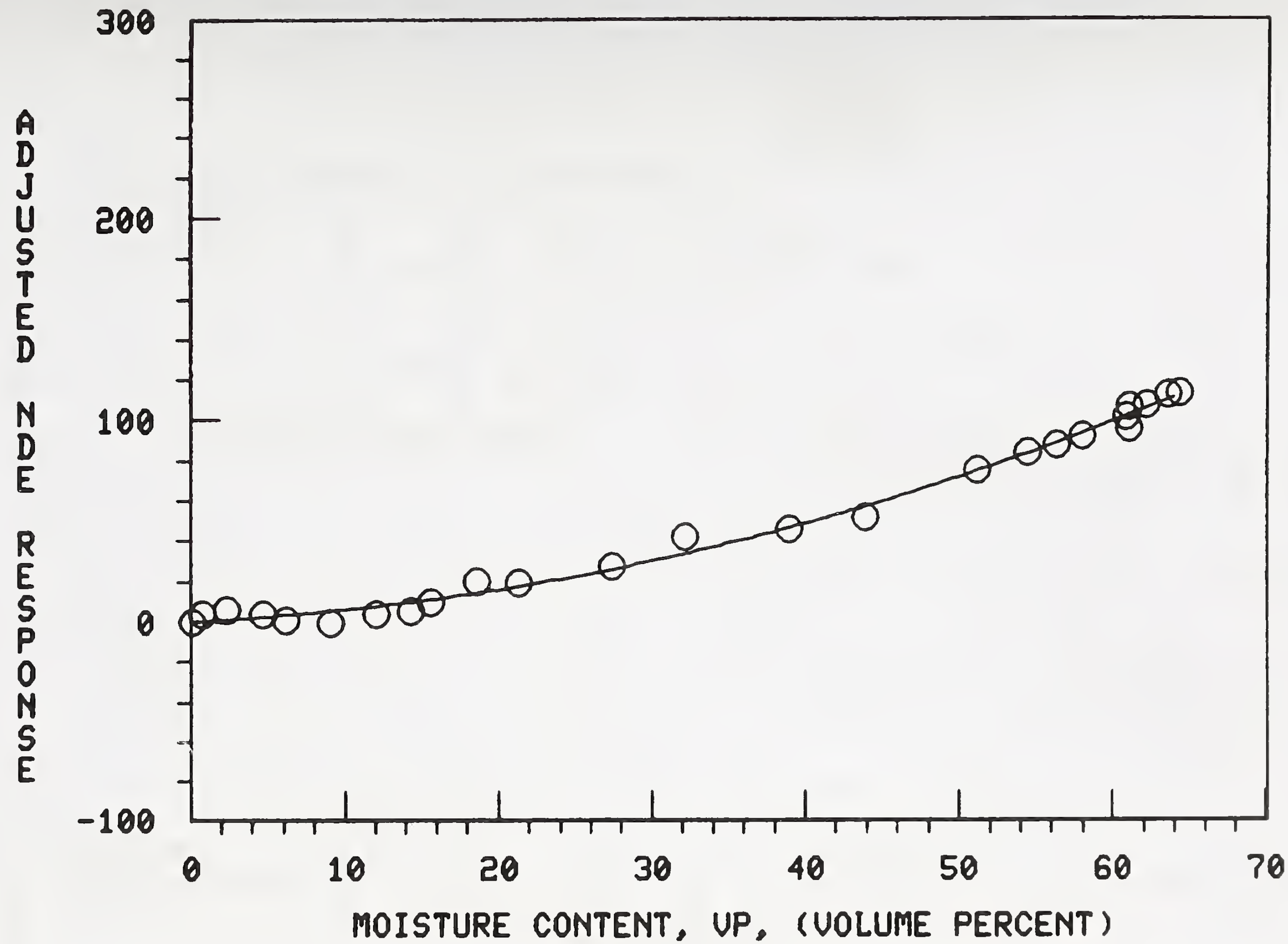
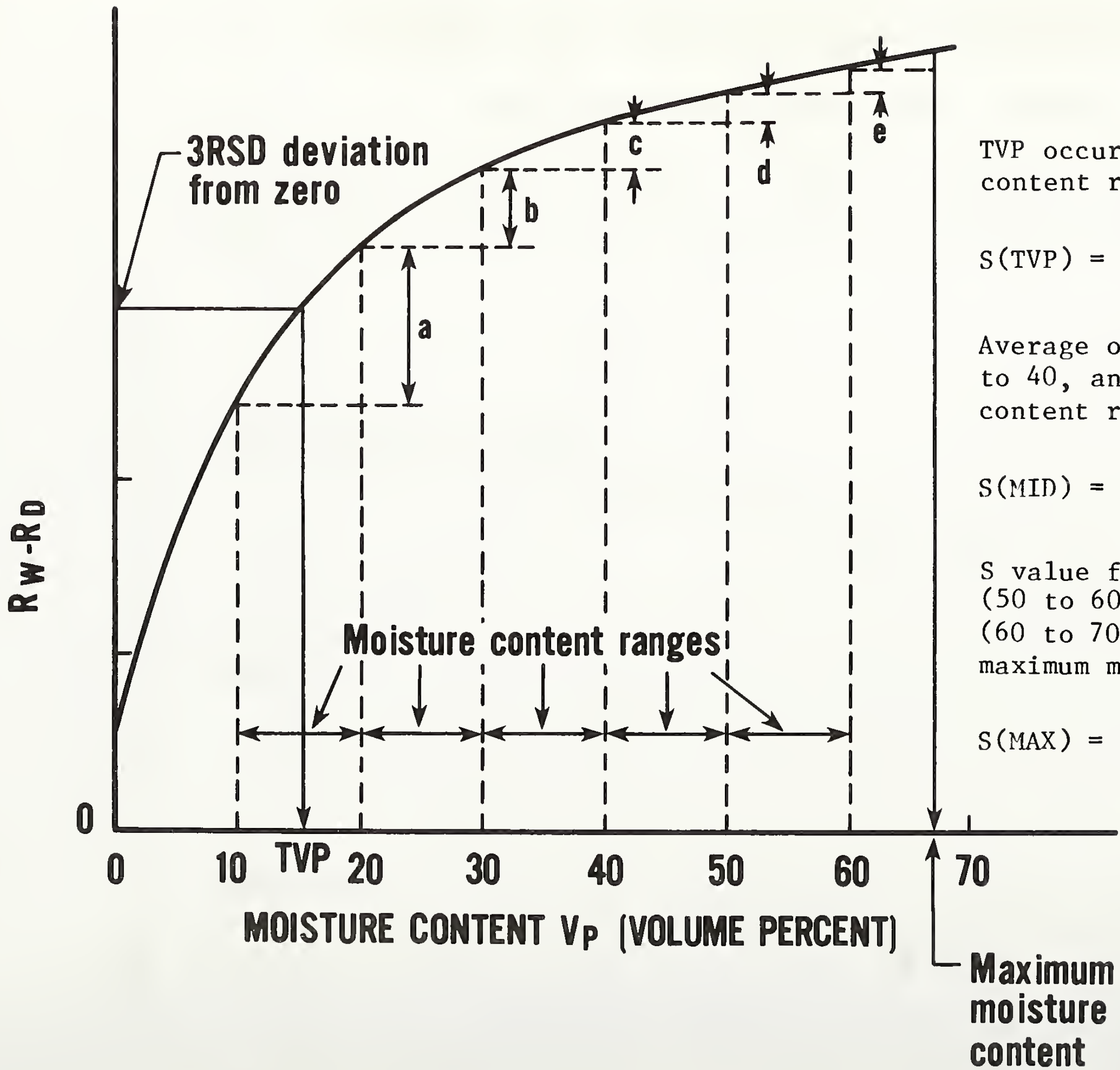


FIGURE 16 POLYURETHANE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT N2, SPEC #41



TVP occurs in 10 to 20 percent moisture content range:

$$S(TVP) = \frac{a}{10\ RSD}$$

Average of S values for 20 to 30, 30 to 40, and 40 to 50 percent moisture content ranges:

$$S(MID) = \left(\frac{b}{10\ RSD} + \frac{c}{10\ RSD} + \frac{d}{10\ RSD}\right)/3$$

S value for moisture content range (50 to 60 percent) preceding the range (60 to 70 percent) containing the maximum moisture content:

$$S(MAX) = \frac{e}{10\ RSD}$$

Figure 17. Schematic representation of $R_W - R_D$ vs. V_P fitted curve showing determination of S(TVP), S(MID), S(MAX).

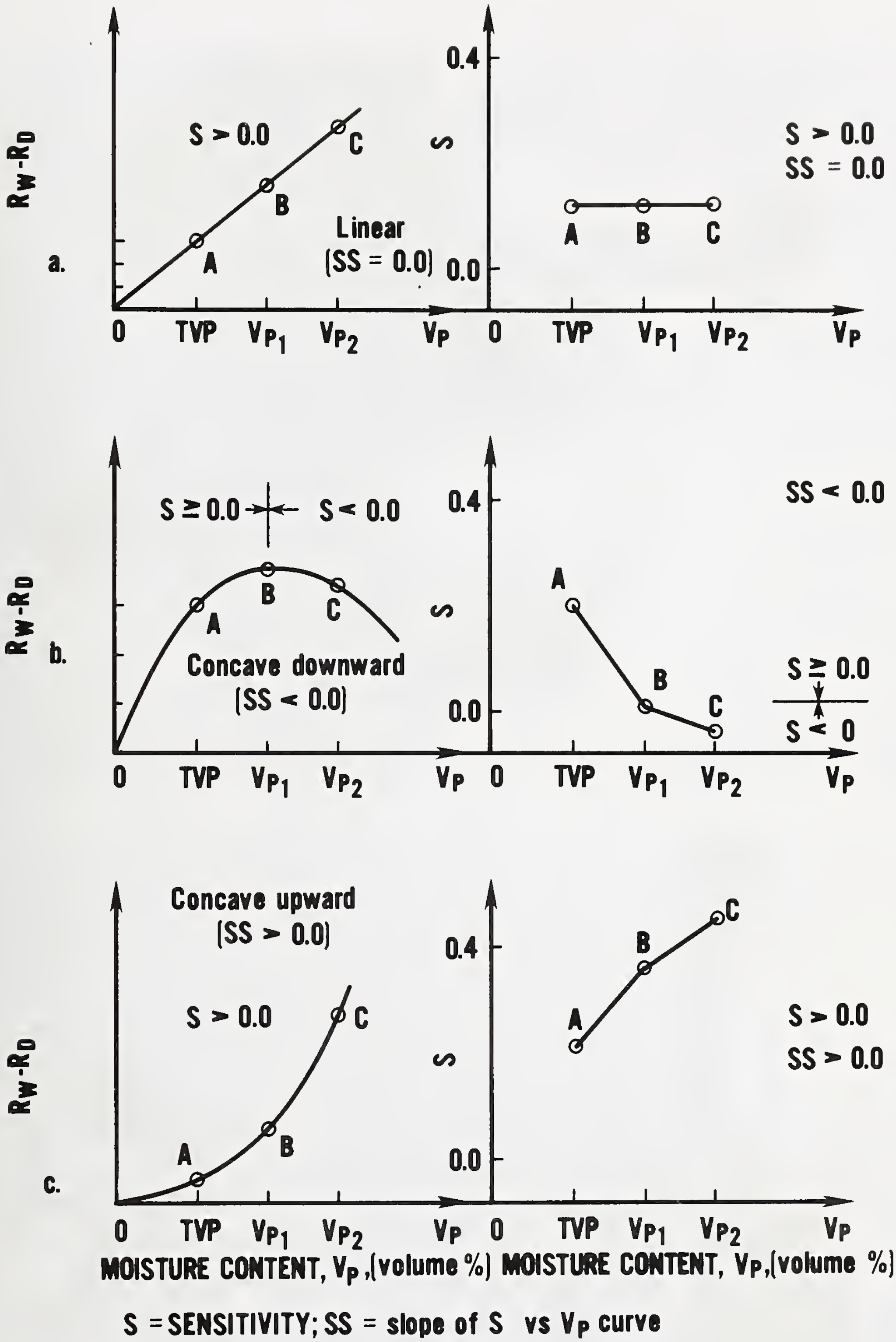


Figure 18. Typical Relationships between $R_W - R_D$ vs. V_P Fitted Curves and their corresponding S vs. V_P curves.

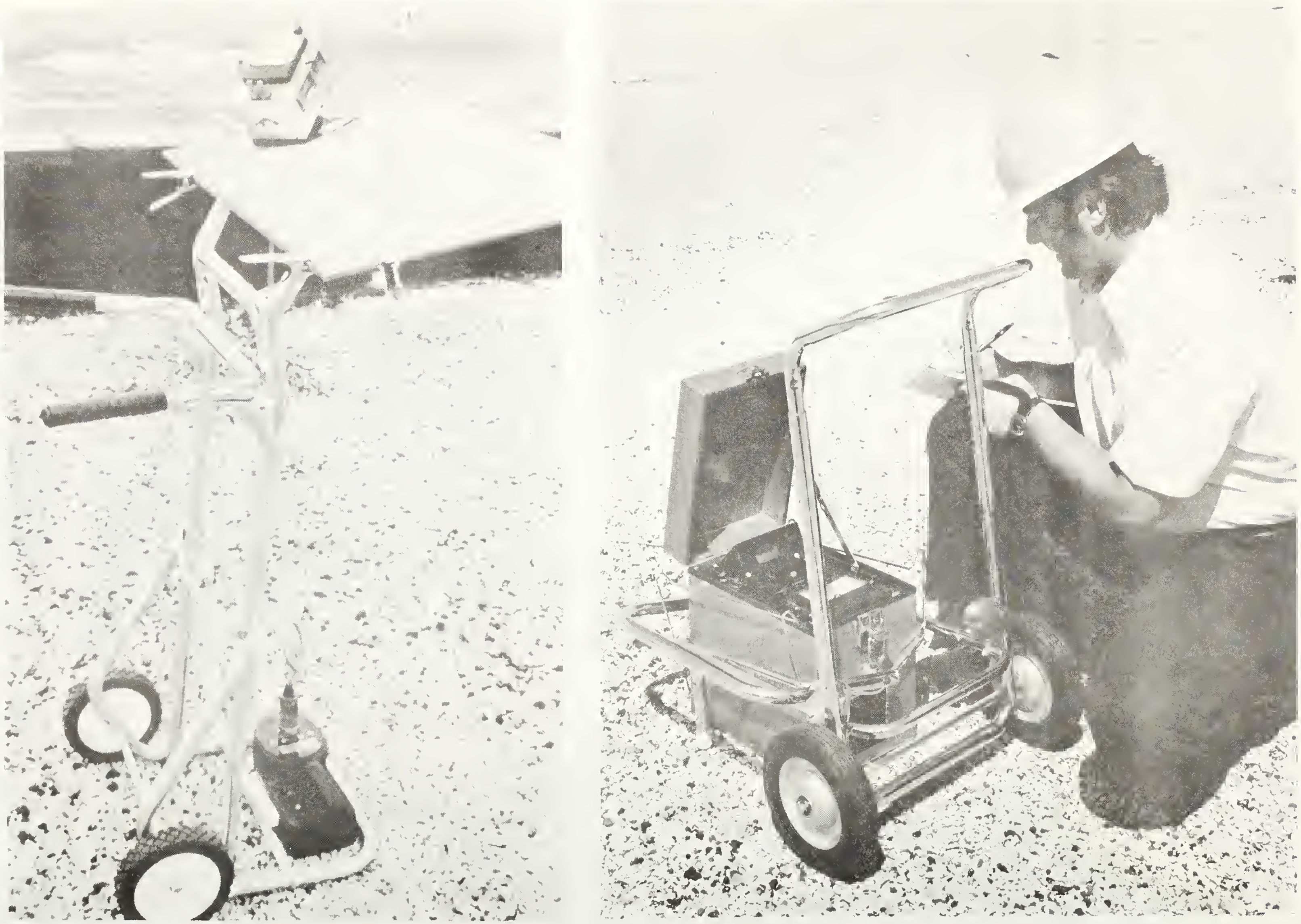


Figure 19. Left: Instrument C3 (bottom of cart) and readout (top of cart)
Right: Instrument N1
(Carts not used in laboratory testing.)

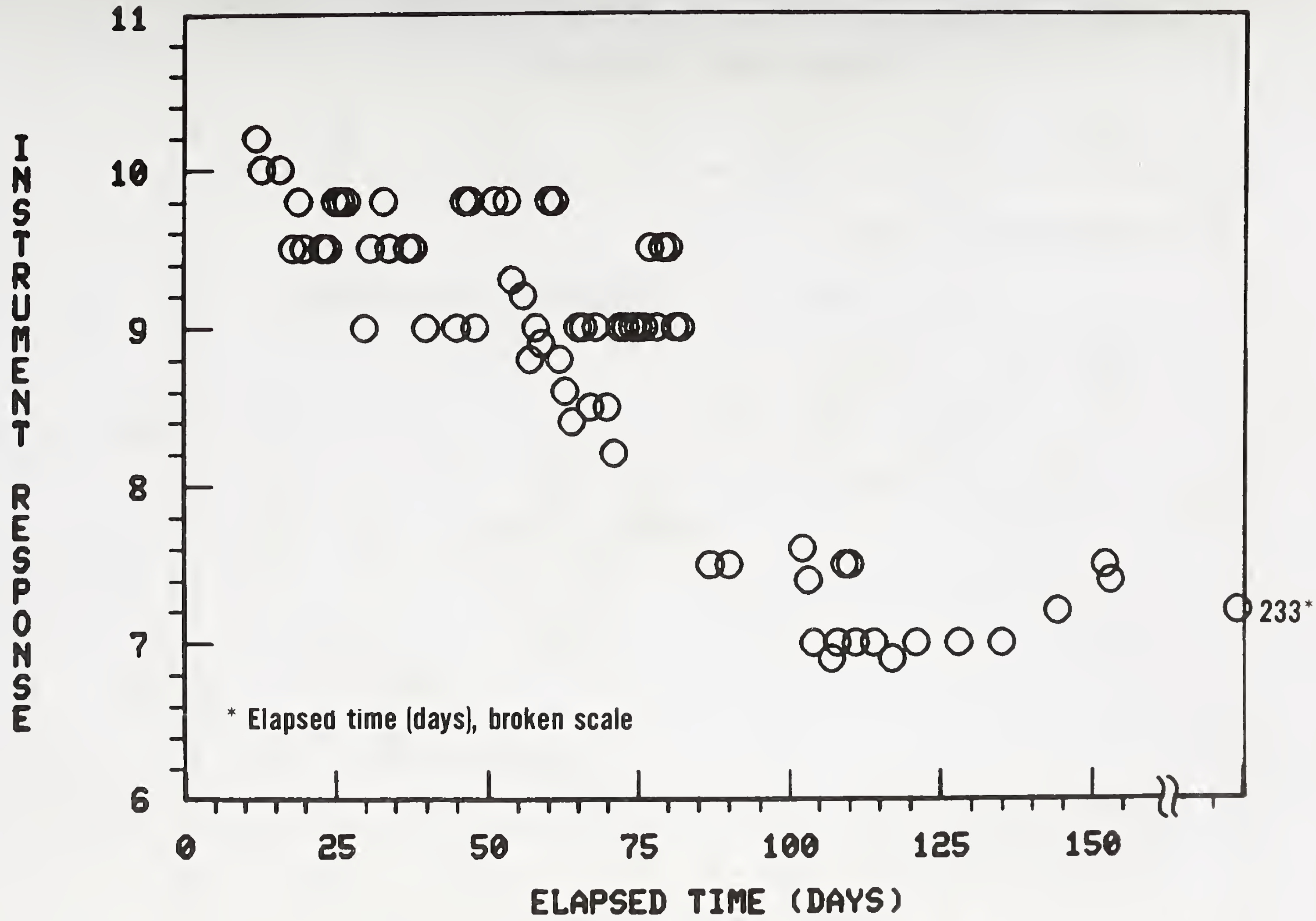


FIGURE 20. ELECTRICAL CAPACITANCE INSTRUMENT RESPONSE VERSUS ELAPSED TIME FOR INSTRUMENT C1, RANGE 4.

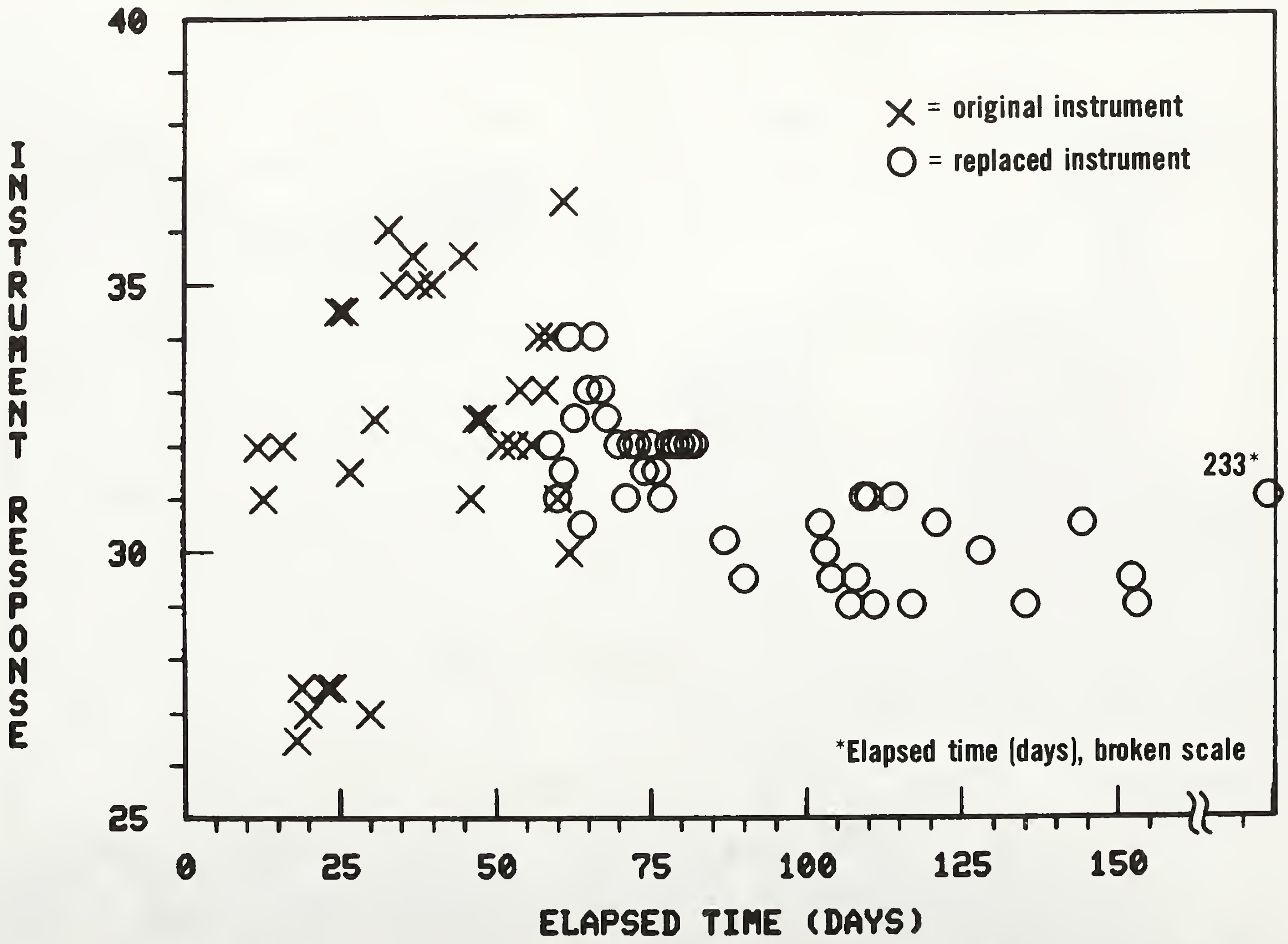


FIGURE 21. ELECTRICAL CAPACITANCE INSTRUMENT RESPONSE VERSUS ELAPSED TIME FOR INSTRUMENT C2, "HIGH" RANGE.

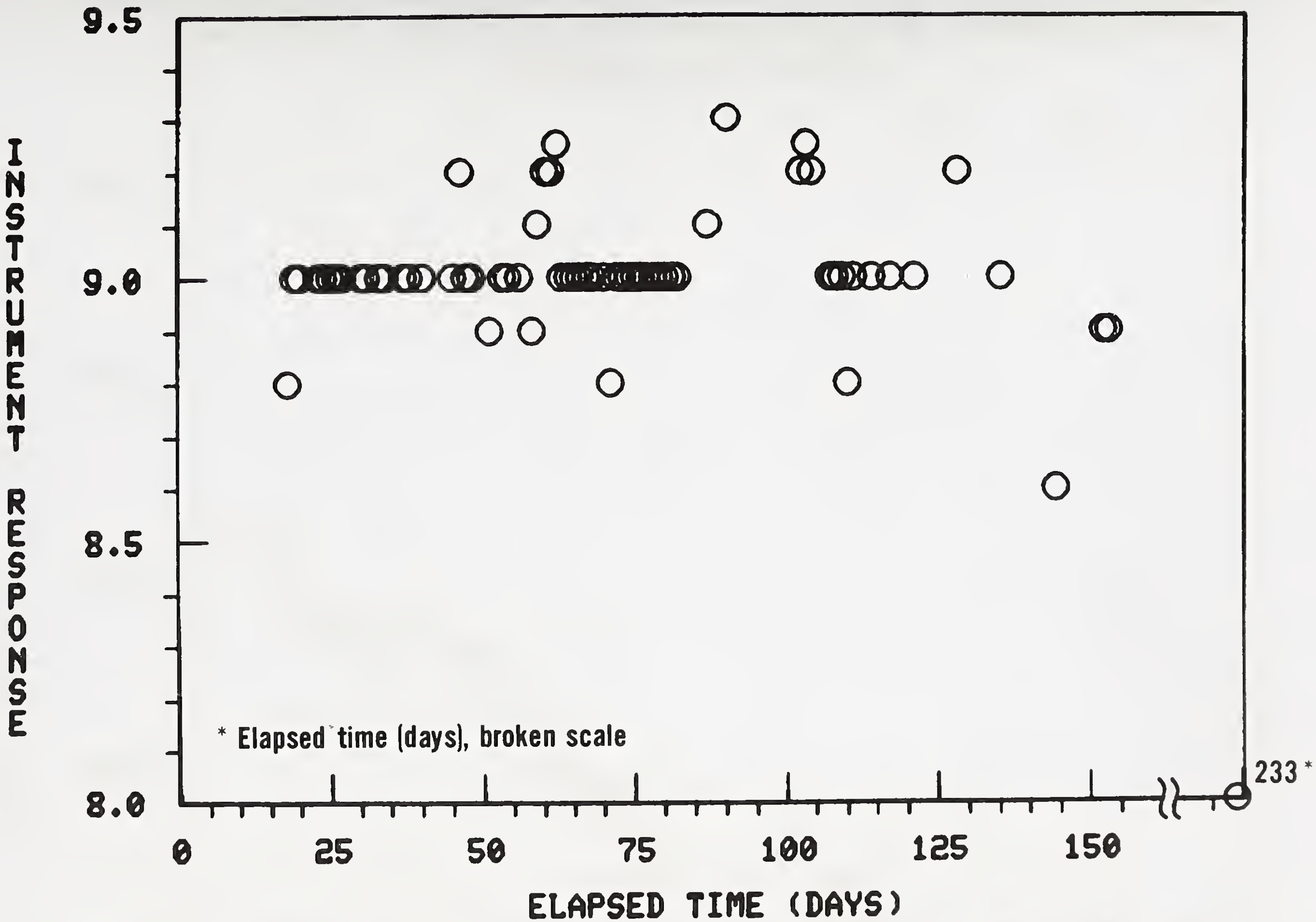


FIGURE 22. ELECTRICAL CAPACITANCE INSTRUMENT RESPONSE VERSUS ELAPSED TIME FOR INSTRUMENT C3, GRAVEL SETTING.

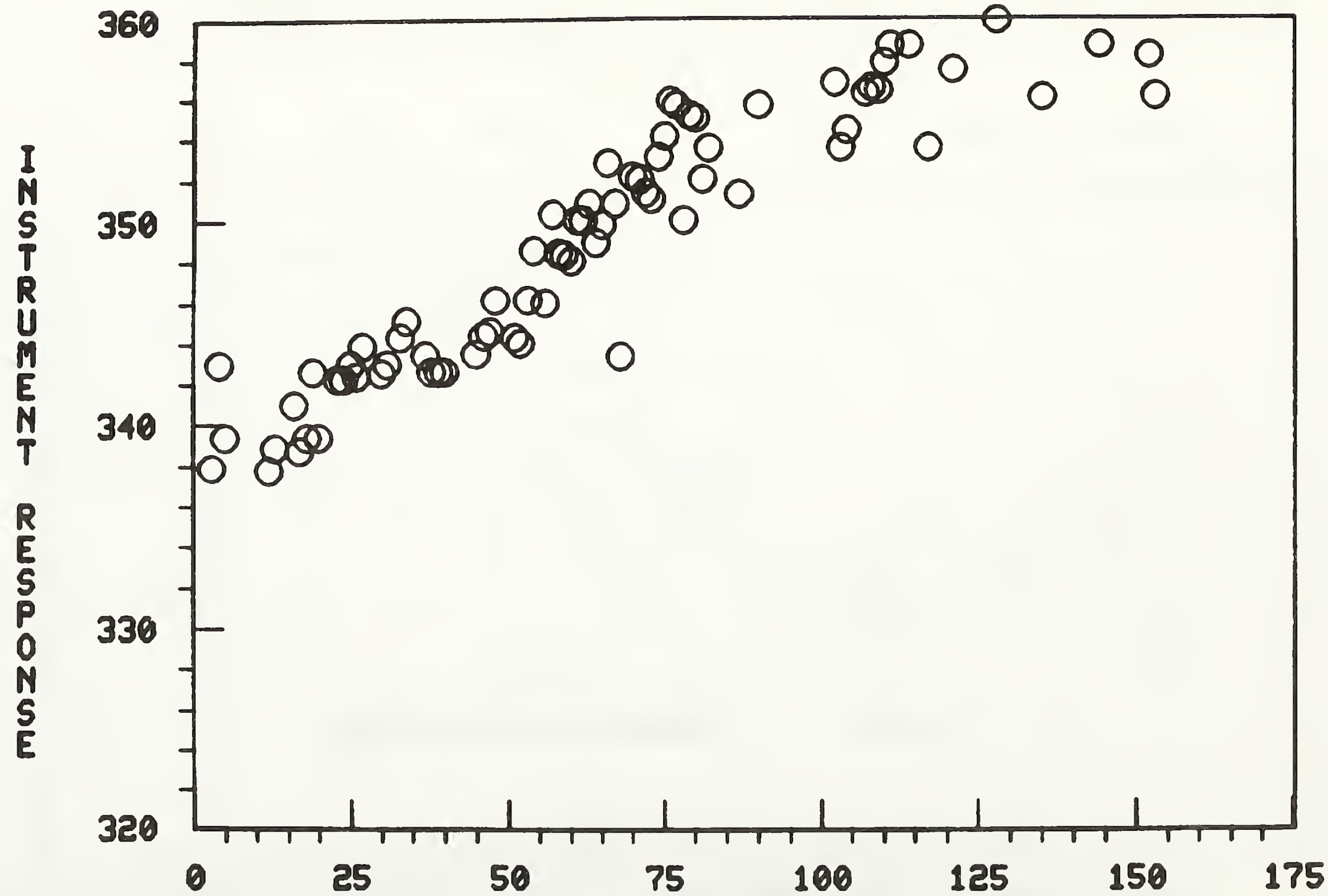


FIGURE 23. NUCLEAR INSTRUMENT RESPONSE VERSUS ELAPSED TIME FOR INSTRUMENT N1.

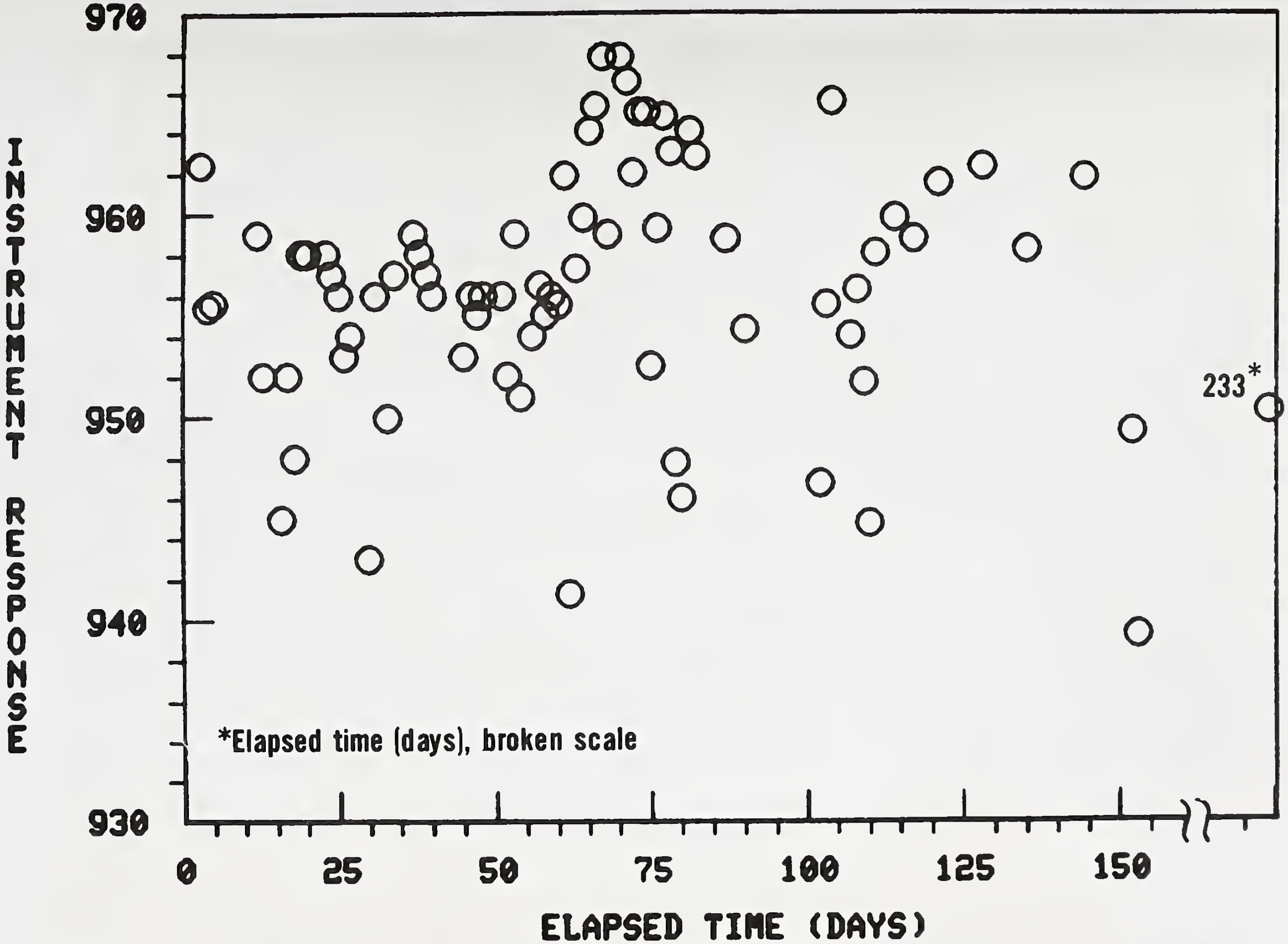


FIGURE 24. NUCLEAR INSTRUMENT RESPONSE VERSUS ELAPSED TIME FOR INSTRUMENT N2.

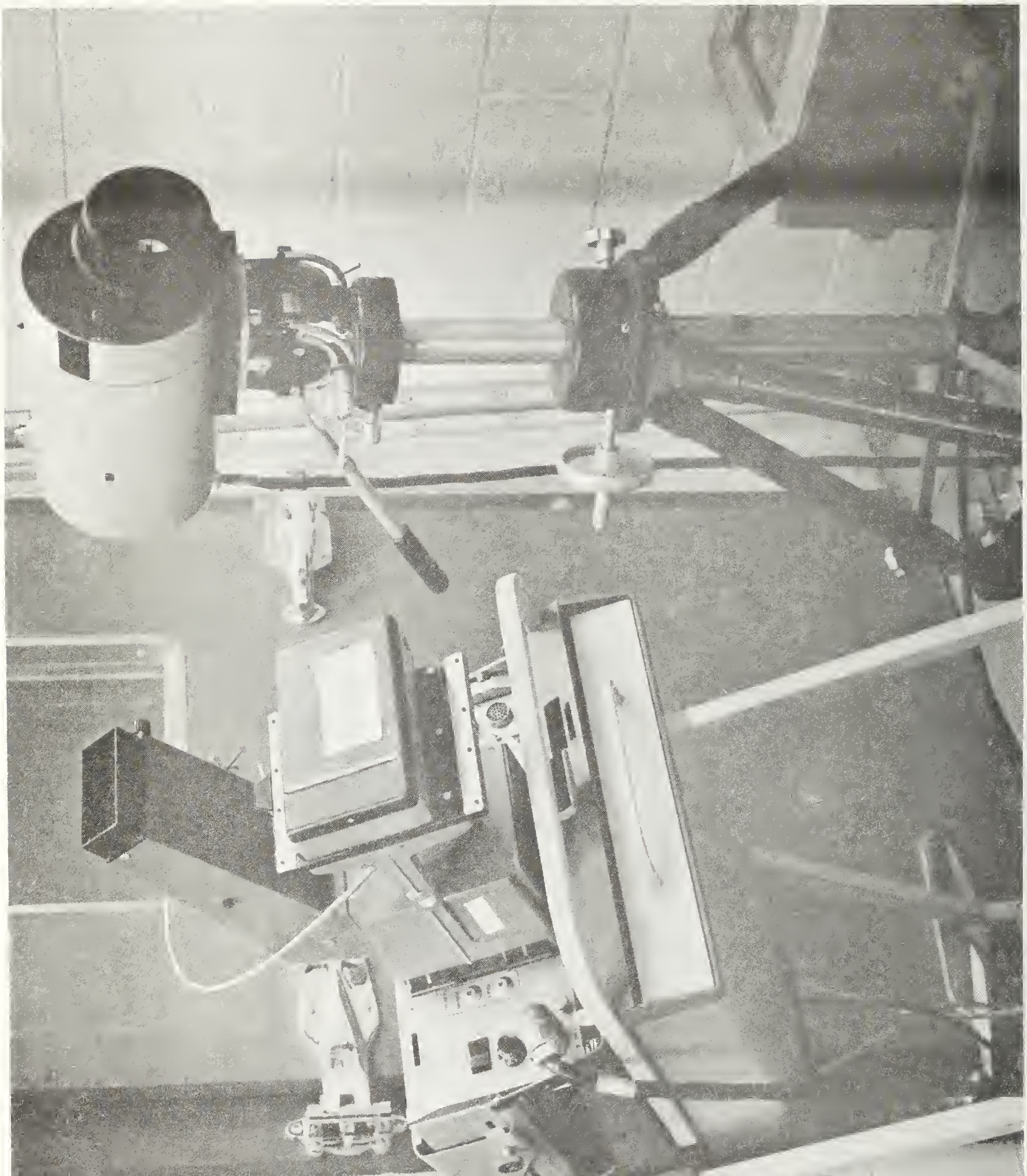


Figure 25. Infrared thermography system.

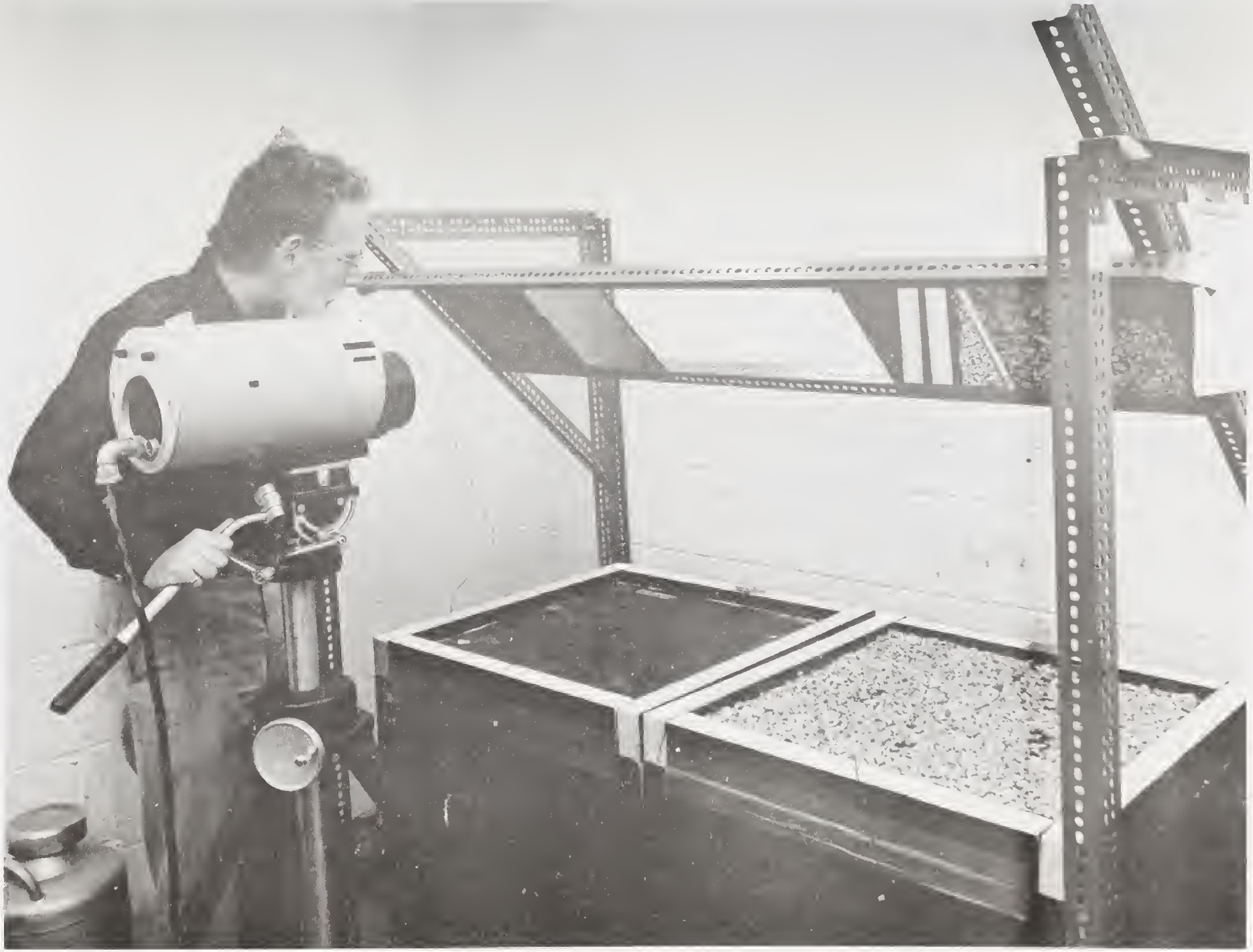


Figure 26. Infrared thermography experimental apparatus.

APPENDIX A

COMPILATION AND ANALYSIS OF NDE DATA

TABLE A1. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR GLASS FIBER INSULATION

INSTRUMENT C1

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
1	C1S	-.09[b]	1.86	4.28	7.2	******	******	******	4.0	19.9
2	C1S	.13	2.48	4.77	7.0	9.1	11.2	******	4.6	19.4
52	C1H	.71	3.77	8.12	13.8	******	******	******	4.7	12.4
4	C1H	-1.13	-1.95	-1.35	.7	4.1	******	******	4.8	41.6
54	C1H	-.74	-.22	.66	1.9	3.5	******	******	5.4	46.5*
6	C2S	2.88	8.98	11.23	******	******	******	******	6.9	5.9
56	C2S	3.00	6.65	9.60	11.8	******	******	******	6.9	10.8
6	C2H	2.83	3.95	5.94	8.8	******	******	******	8.0	27.5
59	C2H	3.75	3.81	4.04	******	******	******	******	10.2	29.3*
1	S1S	.22	2.38	6.34	9.1	******	******	******	5.5	17.1
2	S1S	-2.22	2.11	5.55	8.1	9.8	10.6	******	7.6	27.6
52	S1H	-.14	4.34	8.89	13.5	******	******	******	6.5	14.7
4	S1H	-1.03	-.39	.83	2.6	5.0	******	******	6.4	44.7
54	S1H	-1.06	-.02	1.60	3.8	6.6	******	******	12.9	46.5*
6	S2S	3.38	11.00	12.95	******	******	******	******	4.6	1.2
56	S2S	6.25	9.08	11.72	14.2	******	******	******	10.9	16.7
8	S2H	2.86	4.18	6.55	10.0	******	******	******	7.3	22.5
58	S2H	3.42	4.77	5.65	******	******	******	******	3.7	29.3*

INSTRUMENT C2

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%[c]	10%	20%	30%	40%	50%	60%	3RSD	TVP
1	C1S	2.99	26.3	49.9	73.7	******	******	******	39.1	15.4
2	C1S	-3.53	20.4	40.5	56.8	69.2	77.8	******	37.7	18.5
52	C1H	-2.29	19.0	47.5	86.2	******	******	******	30.2	14.5
4	C1H	-2.38	9.6	22.1	35.3	49.2	******	******	27.5	24.1
54	C1H	6.11	12.7	24.7	42.1	64.9	******	******	60.6	39.3
6	C2S	22.35	91.6	127.3	******	******	******	******	40.0	2.1
56	C2S	24.72	77.2	113.4	133.2	******	******	******	71.6	8.8
6	C2H	11.10	46.9	68.9	77.2	******	******	******	25.6	3.6
59	C2H	22.44	53.2	70.7	******	******	******	******	39.1	4.9
1	S1S	.51	26.3	50.3	72.4	******	******	******	45.0	17.7
2	S1S	-2.39	21.8	42.1	58.0	69.5	76.6	******	39.3	18.5
52	S1H	-.27	20.1	53.1	98.5	******	******	******	54.1	2[illegible].3
4	S1H	2.47	14.0	25.9	38.0	50.4	******	******	23.7	17.8
54	S1H	2.59	10.6	24.0	42.9	67.1	******	******	69.3	40.4
6	S2S	24.36	89.2	122.8	******	******	******	******	37.9	1.7
56	S2S	26.32	79.3	113.5	129.1	******	******	******	76.6	9.4
8	S2H	2.96	40.6	65.0	76.3	******	******	******	28.2	6.3
58	S2H	23.66	53.6	69.0	******	******	******	******	37.3	4.0

a NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

b $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

c Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

TABLE A1. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR GLASS FIBER INSULATION

INSTRUMENT C3										
SPECIMEN[a]		RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP[c]
1	C1S	.03[b]	.94	1.84	2.7*****	*****	*****	*****	1.0	10.6
2	C1S	-.30	.37	.98	1.5	2.0	2.5*****	*****	1.9	36.6
52	C1H	.30	.59	1.07	1.7*****	*****	*****	*****	.7	13.5
4	C1H	.61	1.18	1.60	1.9	2.0*****	*****	*****	1.6	21.4
54	C1H	-.01	-.11	.01	.3	.9*****	*****	*****	.9	40.4
6	C2S	-.12	1.18	1.26*****	*****	*****	*****	*****	1.2	9.7
56	C2S	.28	1.75	2.79	3.4*****	*****	*****	*****	1.7	9.5
8	C2H	-.13	.94	1.64	2.0*****	*****	*****	*****	1.6	19.5
58	C2H	.09	.42	.91*****	*****	*****	*****	*****	1.4	27.8
1	S1S	.93	1.84	2.82	3.9*****	*****	*****	*****	2.4	16.1
2	S1S	.10	.73	1.32	1.9	2.4	2.8*****	*****	1.3	20.7
52	S1H	.46	.45	.84	1.6*****	*****	*****	*****	1.7	30.5
4	S1H	.09	.41	.79	1.2	1.7*****	*****	*****	1.6	37.6
54	S1H	.16	.69	1.12	1.5	1.7*****	*****	*****	1.9	46.5*
6	S2S	.79	1.97	2.38*****	*****	*****	*****	*****	1.7	6.6
56	S2S	.79	2.80	3.91	4.1*****	*****	*****	*****	1.9	5.1
4	S2H	-.13	.47	.97	1.4*****	*****	*****	*****	1.1	23.1
58	S2H	.51	1.36	1.87*****	*****	*****	*****	*****	1.5	12.6

a NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

b $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_p) values less than or equal to the maximum moisture content.

c Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

TABLE A2. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR PERLITE INSULATION

INSTRUMENT C1

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]
11	C1S	14.34[b]	23.46	27.51	26.5	20.4	****	****	22.7	8.9
62	C1S	15.39	23.02	28.03	30.4	30.2	27.3	22.	24.2	11.9
14	C1H	1.61	5.21	6.59	7.0	5.1	****	****	5.8	12.3
16	C2S	11.86	29.39	30.61	****	****	****	****	21.2	4.2
66	C2S	[e] ****	****	****	****	****	****	****	****	****
18	C2H	-10.74	-11.81	-16.81	****	****	****	****	60.5	29.9*
11	S1S	16.11	24.38	27.26	24.1	****	****	****	29.7	39.2*
62	S1S	12.67	20.40	25.63	28.4	28.6	26.3	22.	23.1	14.5
14	S1H	3.27	6.59	7.92	7.2	4.6	****	****	7.0	12.2
16	S2S	12.28	29.32	29.61	****	****	****	****	20.6	3.8
65	S2S	[e] ****	****	****	****	****	****	****	****	****
18	S2H	-3.93	-6.06	-12.93	****	****	****	****	40.3	29.9*

INSTRUMENT C2

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
11	C1S	99.27	155.2	184.1	185.9	160.7	****	****	137.7	6.3
62	C1S	92.59	126.6	147.7	155.8	150.9	133.1	102.	134.0	12.9
14	C1H	57.79	66.7	66.6	57.6	39.6	****	****	67.5	12.2
16	C2S	103.70	188.2	188.3	****	****	****	****	144.1	3.6
66	C2S	100.71	186.5	210.8	173.7	****	****	****	186.8	10.1
18	C2H	44.28	81.2	91.3	****	****	****	****	75.5	7.8
11	S1S	102.43	166.8	190.0	171.9	****	****	****	168.6	10.4
62	S1S	119.31	142.4	154.7	156.3	147.0	127.0	96.	152.6	17.4
14	S1H	60.17	72.0	71.7	59.5	35.3	****	****	70.8	8.3
16	S2S	102.41	186.9	184.4	****	****	****	****	141.4	3.5
65	S2S	93.60	188.5	216.2	176.4	****	****	****	190.8	10.4
18	S2H	47.51	90.3	99.1	****	****	****	****	81.4	7.1

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

[d] Value rounded to nearest whole number.

[e] Data not included because the quadratic fitted curve was inappropriate.

TABLE A2. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR PERLITE INSULATION

INSTRUMENT C3											
SPECIMEN[a]		RW-RD AT VP OF									
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
11	C1S	1.75[b]	3.96	5.25	5.6	5.0************			7.6	8.2
62	C1S	1.49	2.66	3.60	4.3	4.7	4.9	5.	2.9	12.7
14	C1H	.24	.96	1.49	1.8	2.0************			1.4	17.6
15	C2S	1.22	3.57	4.56*************************					2.4	3.9
66	C2S	1.42	6.17	7.37	5.0******************				3.6	3.7
18	C2H	.86	3.44	4.29*************************					2.0	3.5
11	S1S	2.01	3.90	5.27	6.1	***************			5.3	19.9
62	S1S	.54	2.38	3.78	4.7	5.2	5.3	5.	3.1	14.7
14	S1H	.18	.48	.82	1.2	1.6************			1.5	36.7
16	S2S	1.55	4.13	5.08*************************					2.9	4.5
66	S2S	1.28	5.72	7.05	5.3******************				3.5	4.1
18	S2H	.92	3.35	4.32*************************					1.8	3.1

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_p) values less than or equal to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A3. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR FIBERBOARD INSULATION

SPECIMEN[a]		INSTRUMENT C1									INSTRUMENT C2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP[c]	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
21	C1S	-1.41[b]	31.62	28.79	******	******	******	******	38.5	25.3*	-14.71	165.9	193.6	******	******	******	******	99.4	5.3
658	C1S	-7.27	25.06	33.56	18.2	******	******	******	17.2	6.8	-30.26	137.3	197.1	149.0	******	******	******	69.5	5.1
23	C1H	-1.34	11.25	16.98	15.8	******	******	******	10.3	9.0	10.33	127.2	168.1	133.1	******	******	******	123.6	9.6
26	C2S	-3.31	34.63	42.51	20.3	******	******	******	41.6	14.2	21.57	149.5	186.7	133.1	******	******	******	133.4	9.2
29	C2H	-21.61	40.38	-1.24	******	******	******	******	58.4	20.4*	-27.41	176.5	144.9	******	******	******	******	101.0	4.9
21	S1S	-4.40	28.95	29.39	******	******	******	******	28.9	10.0	-16.34	175.0	201.9	******	******	******	******	108.4	5.5
658	S1S	-9.10	32.15	44.61	23.3	******	******	******	25.9	7.9	-39.75	148.1	211.5	150.2	******	******	******	77.5	5.4
23	S1H	-.50	13.57	19.56	17.5	******	******	******	13.1	9.6	23.56	124.4	159.6	129.3	******	******	******	151.1	15.3
26	S2S	5.63	34.63	38.75	18.0	******	******	******	42.8	30.4*	22.32	160.2	192.3	118.5	******	******	******	130.0	7.0
29	S2H	-20.23	44.26	12.25	******	******	******	******	72.5	20.4*	-29.93	174.4	136.6	******	******	******	******	98.9	4.8

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_p) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

TABLE A3. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR FIBERBOARD INSULATION

INSTRUMENT C3										
SPECIMEN [a]		RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
21	C1S	-1.28 [b]	5.73	6.56************************					3.2	5.3
658	C1S	-.58	2.52	4.01	3.9******************				1.5	6.1
23	C1H	.35	2.32	3.34	3.4******************				1.7	6.2
26	C2S	-.54	3.91	5.70	4.8******************				3.2	7.9
29	C2H	-1.04	4.59	3.47************************					1.9	3.8
21	S1S	-1.10	5.64	6.61************************					2.9	4.9
658	S1S	-.41	2.60	3.91	3.5******************				.9	3.8
23	S1H	-.10	1.82	2.83	2.9******************				1.9	10.3
26	S2S	-.70	3.59	4.95	3.4******************				3.5	9.6
29	S2H	-1.44	4.26	3.63************************					1.6	3.9

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

TABLE A4. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYSTYRENE INSULATION

SPECIMEN[a]		INSTRUMENT C1									INSTRUMENT C2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]
31	C1S	-.64[b]	3.04	6.03	8.3	9.9	10.8	******	7.4	25.5	4.35	22.3	37.0	48.5	56.9	62.0	******	26.9	12.9
34	C1H	.51	.62	.74	.9	1.0	1.1	1.	9.0	86.2*	-.26	7.6	14.0	19.0	22.6	24.8	26.	14.0	20.0
36	C2S	2.51	20.03	27.93	26.2	******	******	******	20.2	10.1	16.72	133.2	179.7	156.2	******	******	******	91.7	5.7
38	C2H	-.51	2.02	3.30	3.3	******	******	******	5.0	33.1*	-.35	13.9	22.0	23.9	******	******	******	19.0	15.4
39	C2H	.32	3.09	5.10	******	******	******	******	9.2	28.8*	4.49	17.8	26.9	******	******	******	******	22.3	14.4
31	S1S	-.04	1.87	3.33	4.3	4.9	5.0	******	3.6	22.2	5.74	15.9	22.9	26.8	27.7	25.5	******	31.6	50.5*
34	S1H	.93	.72	.58	.5	.5	.6	1.	8.3	86.2*	4.57	7.2	9.7	11.9	14.0	15.8	17.	17.7	62.0
36	S2S	3.11	24.16	32.08	26.8	******	******	******	33.6	36.0*	18.70	127.0	170.6	149.5	******	******	******	91.6	6.0
38	S2H	-.03	1.21	2.11	2.7	******	******	******	4.9	33.1*	7.69	18.8	24.3	24.3	******	******	******	17.0	8.0
39	S2H	.38	.93	2.07	******	******	******	******	7.1	28.8*	5.09	11.8	19.7	******	******	******	******	23.9	24.7

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A4. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYSTYRENE INSULATION

INSTRUMENT C3											
SPECIMEN[a]		RW-RD AT VP OF									
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]
31	C1S	-.34[b]	1.70	3.19	4.1	4.5	4.3******		1.3	7.7
34	C1H	.78	.38	.09	-.1	-.2	-.1	0.	1.8	86.2*
36	C2S	.30	3.57	5.28	5.4******************				1.7	3.6
38	C2H	-.34	.34	1.08	1.9******************				2.1	32.3
39	C2H	.42	1.68	2.79************************					1.8	11.1
31	S1S	-.24	1.50	2.83	3.8	4.3	4.4******		1.1	7.2
34	S1H	.83	.45	.17	-.0	-.1	-.0	0.	1.7	86.2*
36	S2S	.30	3.36	5.09	5.5******************				1.8	4.5
38	S2H	.35	1.54	2.42	3.0******************				1.6	10.8
39	S2H	-.31	1.12	2.32************************					1.3	11.6

a NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

b $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

c Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

d Value rounded to nearest whole number.

TABLE A5. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYURETHANE INSULATION

SPECIMEN[a]		INSTRUMENT C1									INSTRUMENT C2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
41	C1S	1.07[b]	4.35	7.10	9.3	11.0	12.1	13.	9.4	30.7	12.87	37.9	56.5	68.9	74.9	74.6	68.	30.4	6.7
43	C1H	-.45	.38	1.04	1.5	1.8	2.0	******	6.8	53.7*	13.39	24.8	32.3	35.8	35.4	31.0	******	27.2	12.7
41	S1S	1.48	3.96	6.11	7.9	9.4	10.5	11.	9.8	43.8	15.33	32.6	46.0	56.1	62.8	66.2	66.	34.7	11.4
43	S1H	-.53	.72	1.72	2.5	3.0	3.2	******	6.9	53.7*	11.82	20.5	27.3	32.0	34.9	35.7	******	17.8	6.6

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A5. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYURETHANE INSULATION

INSTRUMENT C3										
SPECIMEN[a]		RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP[c]
41	C1S	.28[b]	1.64	2.78	3.7	4.3	4.8	5.	1.7	10.6
43	C1H	.16	.61	.93	1.1	1.2	1.1	******	2.4	53.7*
41	S1S	.44	2.03	3.29	4.2	4.9	5.2	5.	1.5	6.4
43	S1H	.96	1.34	1.61	1.8	1.8	1.8	******	2.5	53.7*

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A6. SUMMARY OF S[a] VALUES FOR THE CAPACITANCE INSTRUMENTS FOR GLASS FIBER INSULATION

SPECIMEN[b]		INSTRUMENT C1						INSTRUMENT C2						INSTRUMENT C3					
		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
1	C1S	******	.182[c]	.217	******	******	******	******	.181	.183	******	******	******	******	.271	.268	******	******	******
2	C1S	******	.148	.143	.138	.134	******	******	.160	.129	.099	.068	******	******	******	******	.080	.071	******
52	C1H	******	.277	.360	******	******[d]	******	******	.293	.384	******	******	******	******	.193	.268	******	******	******
4	C1H	******	******	******	******	.285	******	******	******	.144	.151	******	******	******	******	.050	.023	******[d]	******
54	C1H	******	******	******	******	******	******	******	******	******	.113	******	******	******	******	******	******	.239	******
6	C2S	.264	.097	******	******	******	******	.518	.268	******	******	******	******	.335	.019	******	******	******	******
56	C2S	******	.123	.097	******	******	******	.220	.152	.083	******	******	******	.261	.185	.109	******	******	******
8	C2H	******	******	.107	******	******	******	.420	.259	.098	******	******	******	******	.131	.063[d]	******	******	******
58	C2H	******	******	******	******	******	******	.236	.134	******	******	******	******	******	******	.136	******	******	******
1	S1S	******	.161	.150	******	******	******	******	.160	.147	******	******	******	******	.121	.129	******	******	******
2	S1S	******	******	.101	.066	.031	******	******	.155	.121	.088	.054	******	******	******	.123	.114	.105	******
52	S1H	******	.211	.214	******	******[d]	******	******	******	.252	******	******	******	******	******	******	.205[d]	******	******
4	S1H	******	******	******	******	.135	******	******	.153	.156	.160	******[d]	******	******	******	******	.093	******	******
54	S1H	******	******	******	******	******	******	******	******	******	******	.126	******	******	******	******	******	******	******
6	S2S	.493	.126	******	******	******	******	.513	.266	******	******	******	******	.213	.074	******	******	******	******
56	S2S	******	.073	.067	******	******	******	.207	.134	.061	******	******	******	.314	.174	.035	******	******	******
8	S2H	******	******	.140	******	******	******	.400	.260	.120	******	******	******	******	******	.106	******	******	******
58	S2H	******	******	******	******	******	******	.241	.124	******	******	******	******	******	.099	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

[d] TVP and maximum moisture content occurred in the same moisture content range; S based on reduced moisture content range (less than 10 percent - see chapter 4).

TABLE A7. SUMMARY OF S[a] VALUES FOR THE CAPACITANCE INSTRUMENTS FOR PERLITE INSULATION

SPECIMEN[b] NO.	TYPE	INSTRUMENT C1 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
11	C1S	.120[c]	.053	-.014	-.080	******	******
62	C1S	******	.062	.030	-.003	-.036	-.068
14	C1H	******	.093	-.002	-.096	******	******
16	C2S	.248	.020	******	******	******	******
66	C2S	[e] ******	******	******	******	******	******
18	C2H	******	******	******	******	******	******
11	S1S	******	******	******	******	******	******
62	S1S	******	.068	.035	.003	-.030	-.062
14	S1H	******	.056	-.028	-.113	******	******
16	S2S	.248	.004	******	******	******	******
66	S2S	[e] ******	******	******	******	******	******
18	S2H	******	******	******	******	******	******

SPECIMEN[b] NO.	TYPE	INSTRUMENT C2 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
11	C1S	.122	.063	.004	-.055	******	******
62	C1S	******	.047	.018	-.011	-.040	-.069
14	C1H	******	-.000	-.040	-.080	******	******
16	C2S	.176	.000	******	******	******	******
66	C2S	******	.039	-.060	******	******	******
18	C2H	.147	.040	******	******	******	******
11	S1S	******	.041	-.032	******	******	******
62	S1S	******	.024	.003	-.018	-.039	-.061
14	S1H	.050	-.001	-.052	-.103	******	******
16	S2S	.179	-.005	******	******	******	******
66	S2S	******	.043	-.062	******	******	******
18	S2H	.158	.033	******	******	******	******

SPECIMEN[b] NO.	TYPE	INSTRUMENT C3 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
11	C1S	.183	.107	.030	-.047	******	******
62	C1S	******	.096	.070	.045	.020	-.005
14	C1H	******	.115	.073	.032	******	******
16	C2S	.310	.113	******	******	******	******
66	C2S	.394	.099	-.197	******	******	******
18	C2H	.395	.129	******	******	******	******
11	S1S	******	.078	.048	******	******	******
62	S1S	******	.136	.093	.050	.007	-.036
14	S1H	******	******	******	.087	******	******
16	S2S	.266	.097	******	******	******	******
66	S2S	.384	.115	-.153	******	******	******
18	S2H	.397	.159	******	******	******	******

a S = sensitivity

b NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

c S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

e Data not included because the quadratic fitted curve was inappropriate.

TABLE A8. SUMMARY OF S[a] VALUES FOR THE CAPACITANCE INSTRUMENTS FOR FIBERBOARD INSULATION

SPECIMEN[b]		INSTRUMENT C1						INSTRUMENT C2						INSTRUMENT C3					
		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
21	C1S	******[c]	******	******	******	******	******	.545	.083	******	******	******	******	.659	.079	******	******	******	******
658	C1S	.565	.149	-.268	******	******	******	.723	.258	-.208	******	******	******	.615	.295	-.026	******	******	******
23	C1H	.368	.167	-.034	******	******	******	.284	.099	-.085	******	******	******	.351	.182	.012	******	******	******
26	C2S	******	.057	-.160	******	******	******	.288	.084	-.121	******	******	******	.419	.169	-.081	******	******	******
29	C2H	******	******	******	******	******	******	.606	-.094	******	******	******	******	.886	-.177	******	******	******	******
21	S1S	.346	.005	******	******	******	******	.530	.074	******	******	******	******	.699	.101	******	******	******	******
658	S1S	.478	.144	-.189	******	******	******	.727	.245	-.237	******	******	******	.972	.425	-.121	******	******	******
23	S1H	.322	.137	-.048	******	******	******	******	.070	-.060	******	******	******	******	.163	.016	******	******	******
26	S2S	******	******	******	******	******	******	.318	.074	-.170	******	******	******	.369	.117	-.135	******	******	******
29	S2H	******	******	******	******	******	******	.620	-.115	******	******	******	******	1.102	-.121	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

TABLE A9. SUMMARY OF S[a] VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYSTYRENE INSULATION

		INSTRUMENT C1						INSTRUMENT C2						INSTRUMENT C3					
SPECIMEN[b]		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
31	C1S	******	******	.093[c]	.065	.037	******	******	.164	.128	.093	.057	******	.478	.348	.219	.089	-.040	******
34	C1H	******	******	******	******	******	******	******	.138	.107	.077	.047	.016	******	******	******	******	******	******
36	C2S	******	.118	-.026	******	******	******	.381	.152	-.077	******	******	******	.595	.310	.025	******	******	******
38	C2H	******	******	******	******	******	******	******	.128	.031	******	******	******	******	******	******	.121[d]	******	******
39	C2H	******	******	******	******	******	******	******	.123	******	******	******	******	******	.185	******	******	******	******
31	S1S	******	******	.065	.047	.009	******	******	******	******	******	******	******	.496	.381	.265	.149	.034	******
34	S1H	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
36	S2S	******	******	******	******	******	******	.355	.143	-.069	******	******	******	.499	.282	.066	******	******	******
38	S2H	******	******	******	******	******	******	.196	.098	-.000[d]	******	******	******	******	.162	.105	******	******	******
39	S2H	******	******	******	******	******	******	******	******	.115	******	******	******	******	.272	******	******	******	******

a S = sensitivity

b NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

c S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

d TVP and maximum moisture content occurred in the same moisture content range; S based on reduced moisture content range (less than 10 percent - see chapter 4).

TABLE A10. SUMMARY OF S[a] VALUES FOR THE CAPACITANCE INSTRUMENTS FOR POLYURETHANE INSULATION

		INSTRUMENT C1						INSTRUMENT C2						INSTRUMENT C3					
SPECIMEN[b]		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
41	C1S	******	******	******	.053[c]	.036	.019	.247	.184	.122	.059	-.003	-.066	******	.197	.157	.117	.077	.037
43	C1H	******	******	******	******	******	******	******	.082	.039	-.005	-.048	******	******	******	******	******	******	******
41	S1S	******	******	******	******	.034	.024	******	.116	.087	.058	.029	.000	.317	.253	.189	.124	.060	-.004
43	S1H	******	******	******	******	******	******	.147	.114	.081	.048	.014	******	******	******	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

TABLE A11. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE NUCLEAR INSTRUMENTS FOR GLASS FIBER INSULATION

SPECIMEN[a]		INSTRUMENT N1									INSTRUMENT N2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
1	C1S	-.12[b]	4.07	10.85	20.2*****************				9.0	17.6	1.04	16.9	37.9	64.1*****************				19.2	11.2
2	C1S	-4.08	-.70	3.40	9.2	13.8	20.0******		7.6	28.9	6.78	10.7	20.8	37.2	59.8	88.7******		25.3	23.1
52	C1H	-.64	4.24	10.34	17.7*****************				11.2	21.3	5.93	20.2	36.4	54.6*****************				16.9	7.8
4	C1H	14.60	21.98	28.24	33.4	37.4************			17.8	4.2	21.09	35.8	53.4	73.7	96.7************			30.1	6.3
54	C1H	1.29	2.68	5.63	10.1	16.2************			9.4	28.7	.49	.9	11.8	33.2	64.9************			17.7	23.3
6	C2S	-.21	10.00	19.55***********************					6.2	6.2	-.51	15.2	35.5	***********************				9.5	6.7
56	C2S	2.94	10.87	18.18	24.9*****************				11.7	11.0	2.49	13.6	32.1	57.8*****************				23.3	15.7
8	C2H	-2.48	4.09	11.58	20.0*****************				10.9	19.2	-1.68	28.4	62.7	101.1*****************				24.6	8.8
58	C2H	3.02	7.16	14.94***********************					10.5	14.9	12.22	39.4	69.4	***********************				17.0	1.9
1	S1S	.84	6.16	13.47	22.8*****************				9.7	15.2	2.82	6.2	12.8	22.8*****************				11.9	18.9
2	S1S	-2.43	-2.49	-.60	3.2	9.0	16.8******		11.2	43.0	1.73	1.2	3.8	9.5	18.5	30.6******		10.2	30.9
52	S1H	4.97	10.87	17.12	23.7*****************				9.1	7.1	1.68	3.3	8.4	17.1*****************				12.7	25.4
4	S1H	.23	2.63	5.81	9.8	14.5************			5.2	18.4	5.24	7.2	13.2	23.2	37.2************			17.9	25.3
54	S1H	1.10	.34	2.31	7.0	14.4************			7.6	31.0	-1.04	-2.4	3.4	16.3	36.3************			13.0	27.9
6	S2S	-4.02	3.81	14.79***********************					7.8	14.0	.52	7.1	16.1	***********************				8.9	12.1
56	S2S	1.48	9.76	17.14	23.6*****************				12.9	14.1	1.43	6.2	15.9	30.6*****************				10.1	14.6
8	S2H	2.45	14.30	24.82	34.0*****************				9.6	5.9	2.81	20.0	46.0	80.8*****************				12.3	6.1
58	S2H	-1.07	4.54	12.53***********************					8.5	15.4	-.24	16.2	38.2	***********************				14.3	9.0

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

TABLE A12. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE NUCLEAR INSTRUMENTS FOR PERLITE INSULATION

INSTRUMENT N1

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
11	C1S	3.71[b]	19.42	33.64	46.3	57.6	******	******	9.4	3.5
62	C1S	-1.33	15.08	29.49	41.9	52.3	60.6	67.	11.7	7.8
14	C1H	-2.10	5.96	13.45	20.4	26.7	******	******	9.1	14.2
16	C2S	4.11	22.22	40.21	******	******	******	******	8.6	2.5
66	C2S	9.59	38.66	60.01	73.6	******	******	******	13.8	1.3
18	C2H	-3.13	22.19	40.90	******	******	******	******	7.2	3.8
11	S1S	1.65	11.40	22.46	34.8	******	******	******	9.4	7.1
62	S1S	-1.07	11.36	22.89	33.5	43.3	52.1	60.	8.9	8.0
14	S1H	-1.35	6.97	14.37	20.8	26.4	******	******	11.0	15.2
16	S2S	-1.00	15.83	33.94	******	******	******	******	5.1	3.7
66	S2S	3.16	22.90	41.60	59.3	******	******	******	11.8	4.3
18	S2H	-2.74	15.00	33.44	******	******	******	******	10.1	7.3

INSTRUMENT N2

SPECIMEN[a] NO.	TYPE	RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
11	C1S	-.32	37.0	80.8	131.1	187.8	******	******	18.0	5.1
62	C1S	1.73	54.2	104.0	151.2	195.6	237.3	276.	17.3	2.9
14	C1H	1.09	53.7	96.4	129.3	152.3	******	******	36.1	6.4
16	C2S	-3.83	57.4	132.7	******	******	******	******	11.3	2.7
66	C2S	.57	64.7	143.6	237.5	******	******	******	17.2	2.8
18	C2H	-8.22	72.4	145.5	******	******	******	******	23.6	3.8
11	S1S	2.83	12.5	26.2	43.9	******	******	******	16.5	13.2
62	S1S	.30	14.2	30.5	49.3	70.5	94.2	120.	12.3	8.8
14	S1H	-1.68	25.5	48.5	67.4	82.1	******	******	17.6	7.0
16	S2S	.42	20.1	54.6	******	******	******	******	6.1	3.8
66	S2S	2.34	20.6	59.9	120.2	******	******	******	10.9	6.1
18	S2H	-6.57	27.2	71.2	******	******	******	******	13.7	6.3

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A13. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE NUCLEAR INSTRUMENTS FOR FIBERBOARD INSULATION

SPECIMEN[a]		INSTRUMENT N1									INSTRUMENT N2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP	0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
21	C1S	-4.48[b]	15.76	26.80	******	******	******	******	7.2	5.2	-5.10	35.5	80.0	******	******	******	******	10.0	3.8
658	C1S	1.87	5.53	16.34	34.3	******	******	******	5.7	10.3	6.20	21.5	66.5	141.1	******	******	******	23.2	10.5
23	C1H	-.75	5.39	11.54	17.7	******	******	******	11.1	19.2	-6.01	25.5	57.3	89.3	******	******	******	15.7	6.9
26	C2S	-2.39	13.37	28.99	44.5	******	******	******	8.5	6.9	-6.65	46.0	102.3	162.3	******	******	******	5.6	2.4
29	C2H	-3.57	11.38	24.27	******	******	******	******	10.9	9.6	-3.20	42.5	87.3	******	******	******	******	14.0	3.8
21	S1S	-2.40	13.47	27.50	******	******	******	******	6.9	5.7	-.43	14.5	27.5	******	******	******	******	14.6	10.1
658	S1S	.22	7.15	18.34	33.8	******	******	******	6.8	9.6	1.22	-.8	13.2	43.3	******	******	******	7.1	16.9
23	S1H	1.32	9.95	17.20	23.1	******	******	******	6.2	5.5	-3.73	12.6	31.1	51.6	******	******	******	12.6	10.0
26	S2S	-3.41	11.17	28.83	49.6	******	******	******	5.4	6.3	2.28	26.0	63.2	113.8	******	******	******	9.9	3.9
29	S2H	-4.02	9.84	19.11	******	******	******	******	7.5	8.0	-5.59	27.3	56.6	******	******	******	******	11.1	4.9

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_p) values less than or equal to the maximum moisture content.

TABLE A14. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE NUCLEAR INSTRUMENTS FOR POLYSTYRENE INSULATION

		INSTRUMENT N1									INSTRUMENT N2								
SPECIMEN[a]		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
31	C1S	-3.96[b]	9.29	21.71	33.3	44.1	54.0	******	9.8	10.4	-9.72	32.7	73.8	113.7	152.3	189.7	******	24.6	8.1
34	C1H	-2.98	4.01	10.14	15.4	19.8	23.4	26.	8.3	16.9	-8.83	20.2	46.3	69.4	89.5	106.7	121.	23.7	11.3
36	C2S	.65	19.27	35.73	50.0	******	******	******	6.8	3.2	-3.55	25.8	66.0	117.1	******	******	******	14.5	6.6
38	C2H	4.84	22.05	34.05	40.9	******	******	******	11.6	3.6	2.33	61.0	115.1	165.0	******	******	******	15.7	2.2
39	C2H	-1.35	19.42	33.84	******	******	******	******	7.3	3.8	-1.55	47.1	96.3	******	******	******	******	7.9	1.9
31	S1S	-2.33	8.70	19.18	29.1	38.5	47.4	******	7.1	8.5	-6.19	5.2	18.6	34.3	52.0	71.9	******	11.6	15.0
34	S1H	-.40	2.59	5.59	8.6	11.6	14.6	18.	5.5	19.6	-.94	11.6	23.3	34.3	44.6	54.1	63.	15.5	13.2
36	S2S	.19	13.13	26.50	40.3	******	******	******	8.9	6.8	7.44	15.6	28.8	47.0	******	******	******	10.5	4.5
38	S2H	.78	13.91	25.20	34.7	******	******	******	11.0	7.7	5.79	38.5	71.4	104.3	******	******	******	12.5	2.1
39	S2H	-1.23	9.48	22.64	******	******	******	******	6.7	7.6	-4.89	13.7	35.3	******	******	******	******	27.0	16.4

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A15. SUMMARY OF RW-RD VERSUS VP DATA AND TVP VALUES FOR THE NUCLEAR INSTRUMENTS FOR POLYURETHANE INSULATION

SPECIMEN[a]		INSTRUMENT N1									INSTRUMENT N2								
		RW-RD AT VP OF									RW-RD AT VP OF								
NO.	TYPE	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP	0%	10%	20%	30%	40%	50%	60%[d]	3RSD	TVP
41	C1S	-2.93[b]	9.26	20.74	31.5	41.6	50.9	60.	7.2	8.2	4.52	36.9	71.7	108.9	148.5	190.4	235.	21.1	5.2
43	C1H	1.76	13.11	22.55	30.1	35.7	39.5	******	12.0	9.0	15.84	66.6	111.1	149.4	181.5	207.5	******	32.2	3.1
41	S1S	-3.80	4.50	13.08	21.9	31.1	40.5	50.	8.3	14.4	.75	6.0	15.7	29.8	48.4	71.3	99.	11.8	16.4
43	S1H	-5.25	6.55	16.76	25.4	32.5	38.1	******	8.2	11.5	2.67	26.8	50.9	75.0	99.0	123.0	******	17.9	6.3

[a] NO. = specimen number; TYPE = specimen type: C = concrete deck, S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[d] Value rounded to nearest whole number.

TABLE A16. SUMMARY OF S[a] VALUES FOR THE NUCLEAR INSTRUMENTS FOR GLASS FIBER INSULATION

SPECIMEN[b]		INSTRUMENT N1						INSTRUMENT N2					
		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
1	C1S	******	.227[c]	.313	******	******	******	******	.327	.407	******	******	******
2	C1S	******	******	.189	.218	.246	******	******	******	.194	.268	.342	******
52	C1H	******	******	.195	******	******	******	.253	.288	.322	******	******	******
4	C1H	.124	.106	.087	.068	******	******	.147	.175	.202	.230	******	******
54	C1H	******	******	.143	.192	******	******	******	******	.361	.538	******	******
6	C2S	.491	.458	******	******	******	******	.499	.643	******	******	******	******
56	C2S	******	.188	.172	******	******	******	******	.237	.331	******	******	******
8	C2H	******	.206	.231	******	******	******	.368	.418	.468	******	******	******
58	C2H	******	.221	******	******	******	******	.478	.529	******	******	******	******
1	S1S	******	.226	.288	******	******	******	******	.167	.249	******	******	******
2	S1S	******	******	******	******	.208	******	******	******	******	.263	.356	******
52	S1H	.194	.205	.216	******	******	******	******	******	.205	******	******	******
4	S1H	******	.183	.227	.272	******	******	******	******	.167	.235	******	******
54	S1H	******	******	******	.291	******	******	******	******	.298	.462	******	******
6	S2S	******	.423	******	******	******	******	******	.304	******	******	******	******
56	S2S	******	.171	.150	******	******	******	******	.289	.436	******	******	******
8	S2H	.370	.329	.288	******	******	******	.421	.636	.851	******	******	******
58	S2H	******	.281	******	******	******	******	.345	.463	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value.

TABLE A17. SUMMARY OF S[a] VALUES FOR THE NUCLEAR INSTRUMENTS FOR PERLITE INSULATION

SPECIMEN[b]		INSTRUMENT N1						INSTRUMENT N2					
		MOISTURE CONTENT (VP%) RANGE						MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
11	C1S	.503[c]	.455	.407	.359	******	******	.621	.729	.837	.944	******	******
62	C1S	.420	.369	.317	.266	.214	.163	.911	.864	.817	.771	.724	.677
14	C1H	******	.246	.228	.209	******	******	.437	.355	.273	.192	******	******
16	C2S	.631	.626	******	******	******	******	1.627	1.999	******	******	******	******
66	C2S	.634	.466	.297	******	******	******	1.118	1.378	1.637	******	******	******
18	C2H	1.048	.774	******	******	******	******	1.026	.931	******	******	******	******
11	S1S	.346	.393	.439	******	******	******	******	.249	.322	******	******	******
62	S1S	.417	.387	.357	.327	.297	.267	.338	.397	.457	.516	.575	.635
14	S1H	******	.202	.177	.152	******	******	.462	.391	.321	.251	******	******
16	S2S	.997	1.073	******	******	******	******	.962	1.687	******	******	******	******
66	S2S	.503	.477	.451	******	******	******	.503	1.085	1.666	******	******	******
18	S2H	.528	.550	******	******	******	******	.740	.963	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value.

TABLE A18. SUMMARY OF S[a] VALUES FOR THE NUCLEAR INSTRUMENTS FOR FIBERBOARD INSULATION

SPECIMEN[b]		INSTRUMENT N1 MOISTURE CONTENT (VP%) RANGE						INSTRUMENT N2 MOISTURE CONTENT (VP%) RANGE					
NO.	TYPE	0-10	10-20	20-30	30-40	40-50	50-60	0-10	10-20	20-30	30-40	40-50	50-60
21	C1S	.846[c]	.461	******	******	******	******	1.218	1.337	******	******	******	******
658	C1S	******	.565	.938	******	******	******	******	.582	.966	******	******	******
23	C1H	******	.167	.167	******	******	******	.602	.608	.613	******	******	******
26	C2S	.558	.553	.548	******	******	******	2.840	3.038	3.236	******	******	******
29	C2H	.413	.356	******	******	******	******	.975	.957	******	******	******	******
21	S1S	.693	.613	******	******	******	******	******	.268	******	******	******	******
658	S1S	.305	.492	.679	******	******	******	******	.591	1.267	******	******	******
23	S1H	.417	.350	.283	******	******	******	.389	.438	.487	******	******	******
26	S2S	.810	.981	1.151	******	******	******	.720	1.127	1.535	******	******	******
29	S2H	.557	.372	******	******	******	******	.888	.793	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value.

TABLE A19. SUMMARY OF S[a] VALUES FOR THE NUCLEAR INSTRUMENTS FOR POLYSTYRENE INSULATION

SPECIMEN[b] NO.	TYPE	INSTRUMENT N1 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60	INSTRUMENT N2 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
31	C1S	******	.381[c]	.355	.330	.304	******	.517	.502	.486	.471	.456	******
34	C1H	******	.222	.190	.159	.128	.097	******	.330	.293	.255	.217	.179
36	C2S	.823	.727	.631	******	******	******	.605	.830	1.055	******	******	******
38	C2H	.447	.312	.177	******	******	******	1.112	1.033	.954	******	******	******
39	C2H	.851	.591	******	******	******	******	1.852	1.875	******	******	******	******
31	S1S	.468	.444	.421	.398	.375	******	******	.349	.404	.459	.515	******
34	S1H	******	.165	.165	.165	.166	.166	******	.227	.213	.198	.184	.170
36	S2S	.436	.451	.465	******	******	******	.235	.378	.521	******	******	******
38	S2H	.356	.307	.257	******	******	******	.783	.786	.788	******	******	******
39	S2H	.480	.589	******	******	******	******	******	.240	******	******	******	******

a S = sensitivity

b NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

c S values determined only for moisture content ranges which included or exceeded the TVP value.

TABLE A20. SUMMARY OF S[a] VALUES FOR THE NUCLEAR INSTRUMENTS FOR POLYURETHANE INSULATION

SPECIMEN[b] NO.	TYPE	INSTRUMENT N1 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60	INSTRUMENT N2 MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
41	C1S	.511[c]	.481	.451	.422	.392	.362	.461	.495	.529	.563	.597	.631
43	C1H	.283	.235	.183	.141	.093	******	.472	.415	.357	.299	.242	******
41	S1S	******	.311	.322	.332	.343	.353	******	.247	.360	.473	.586	.699
43	S1H	******	.374	.317	.260	.202	******	.406	.405	.404	.404	.403	******

a S = sensitivity

b NO. = specimen number; TYPE = specimen type: C = concrete deck; S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness, H = "heavy" asphalt thickness.

c S values determined only for moisture content ranges which included or exceeded the TVP value.

Table A21. Summary of $R_W - R_D$ Versus V_P Data and TVP Values for the Infrared Instrument for Glass Fiber Insulation

SPECIMEN[a] NO.	TYPE	INSTRUMENT IR RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
51	S1S	-.0079[b]	.0170	.0471	.082	.123************			.053	21.64
141	S1S	-.0149	.0143	.0416	.067	.091	.112*******		.071	31.76
143	S2S	-.0113	.0604	.1070	.129******************				.053	8.85

Table A21. Summary of $R_W - R_D$ Versus V_P Data and TVP Values for the Infrared Instrument for Perlite Insulation

SPECIMEN[a] NO.	TYPE	INSTRUMENT IR RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%	3RSD	TVP
61	S1S	.0005[b]	.0325	.0597	.082	.100************			.009	2.61
145	S1S	-.0090	.0288	.0609	.087	.108	.123	.133	.043	14.19
733	S2S	.0057	.0540	.0924	.121******************				.018	2.42

Table A21. Summary of $R_W - R_D$ Versus V_P Data and TVP Values for the Infrared Instrument for Polystyrene Insulation

SPECIMEN[a] NO.	TYPE	INSTRUMENT IR RW-RD AT VP OF 0%	10%	20%	30%	40%	50%	60%	3RSD	TVP[c]
113	S1S	.0004[b]	-.0269******************************						.055	17.34*
751	S1S	-.0239	.0033	.0332	.066******************				.052	25.73
155	S2S	-.0059	.0307******************************						.011	5.09

[a] NO. = specimen number; TYPE = specimen type: S = steel deck; 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness.

[b] $R_W - R_D$ based on fitted curve (eqn. 2); $R_W - R_D$ values shown only for moisture content (V_P) values less than or equal to the maximum moisture content.

[c] Value (maximum moisture content) followed by asterisk (*) indicates that TVP not attained up to the maximum moisture content.

Table A22. Summary of S[a] Values for the Infrared Instrument for Glass Fiber Insulation

SPECIMEN[b] NO.	TYPE	INSTRUMENT IR MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
51	S1S	******	******	.201[c]	.231	******	******
141	S1S	******	******	******	.099	.051	******
143	S2S	.402	.262	.122	******	******	******

Table A22. Summary of S[a] Values for the Infrared Instrument for Perlite Insulation

SPECIMEN[b] NO.	TYPE	INSTRUMENT IR MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
61	S1S	1.034[c]	.877	.721	.565	******	******
145	S1S	******	.225	.185	.145	.106	.066
733	S2S	.791	.630	.469	******	******	******

Table A22. Summary of S[a] Values for the Infrared Instrument for Polystyrene Insulation

SPECIMEN[b] NO.	TYPE	INSTRUMENT IR MOISTURE CONTENT (VP%) RANGE 0-10	10-20	20-30	30-40	40-50	50-60
113	S1S	******	******	******[c]	******	******	******
751	S1S	******	******	.190	******	******	******
155	S2S	1.016	******	******	******	******	******

[a] S = sensitivity

[b] NO. = specimen number; TYPE = specimen type: S = steel deck: 1 = 1 in., 2 = 2 in. insulation thickness; S = "standard" asphalt thickness.

[c] S values determined only for moisture content ranges which included or exceeded the TVP value. If the TVP was not attained up to the maximum moisture content then no S values are shown.

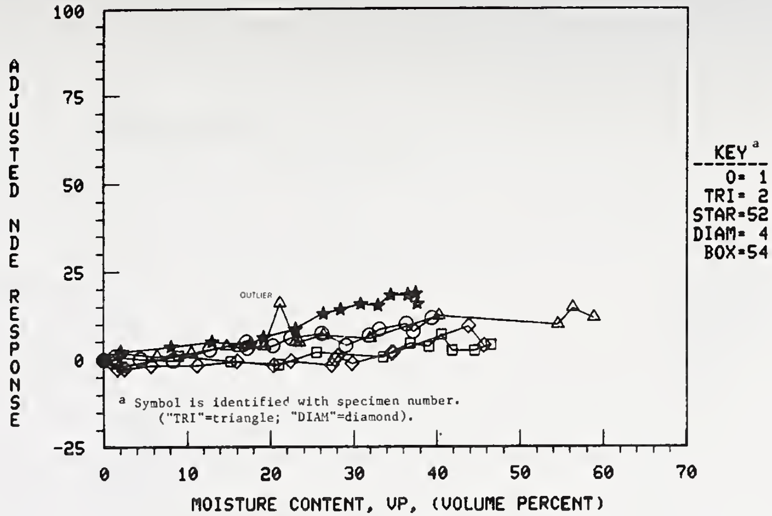


FIGURE A1. GLASS FIBER, 1 INCH, CONCRETE DECK, INSTRUMENT C1

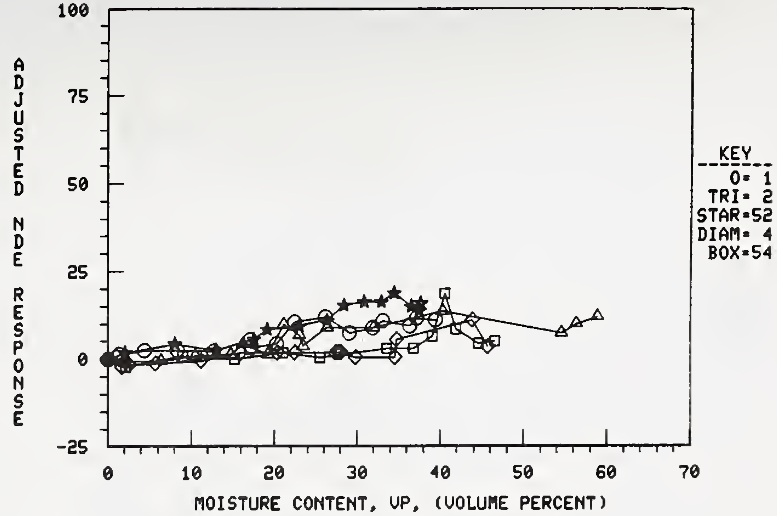


FIGURE A2. GLASS FIBER, 1 INCH, STEEL DECK, INSTRUMENT C1

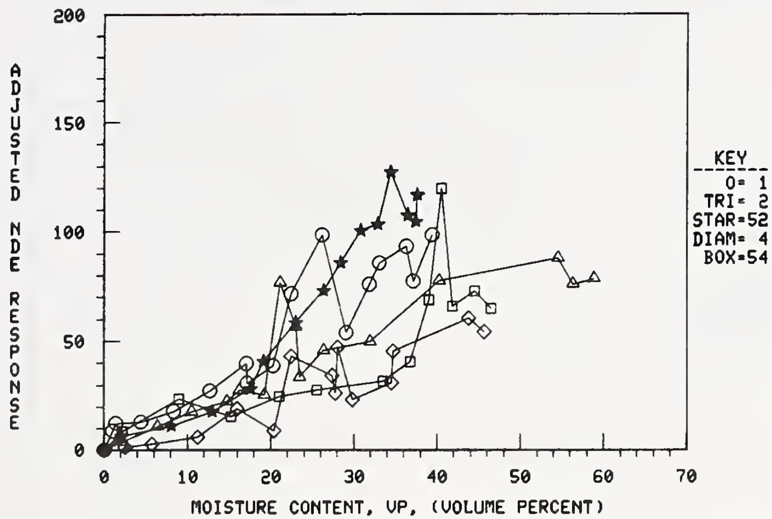


FIGURE A3. GLASS FIBER, 1 INCH, CONCRETE DECK, INSTRUMENT C2

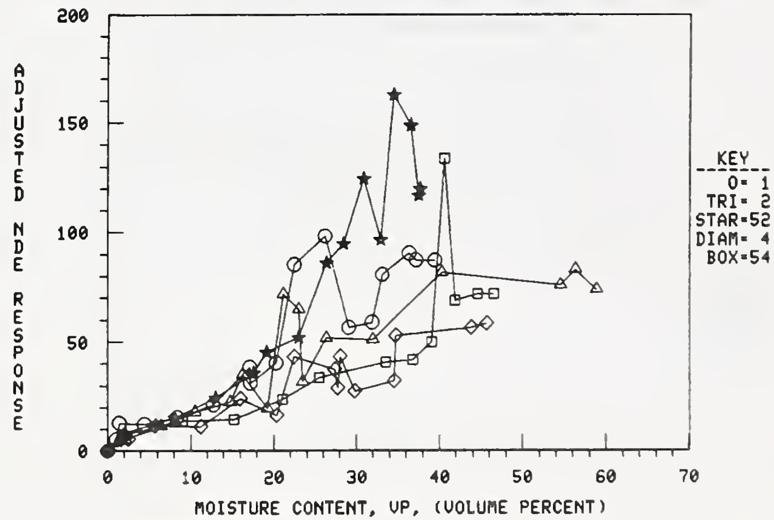


FIGURE A4. GLASS FIBER, 1 INCH, STEEL DECK, INSTRUMENT C2

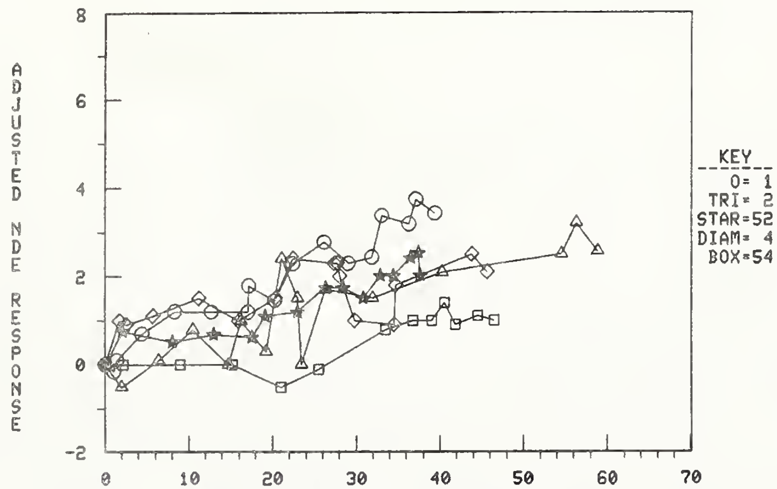


FIGURE A5. GLASS FIBER, 1 INCH, CONCRETE DECK, INSTRUMENT C3

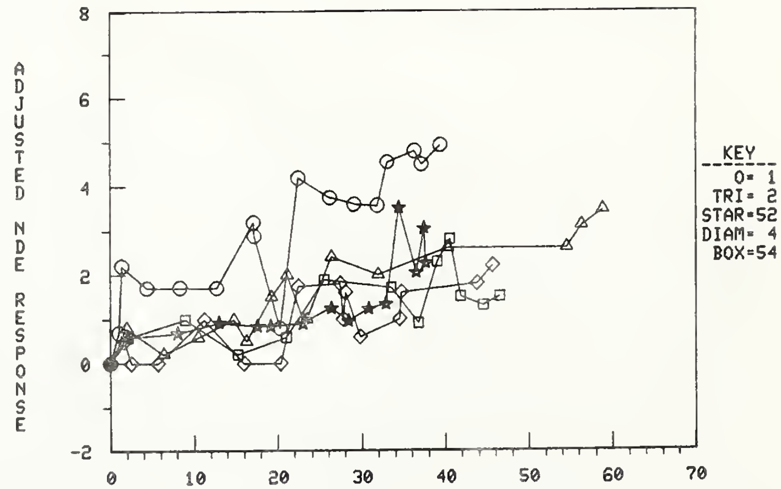


FIGURE A6. GLASS FIBER, 1 INCH, STEEL DECK, INSTRUMENT C3

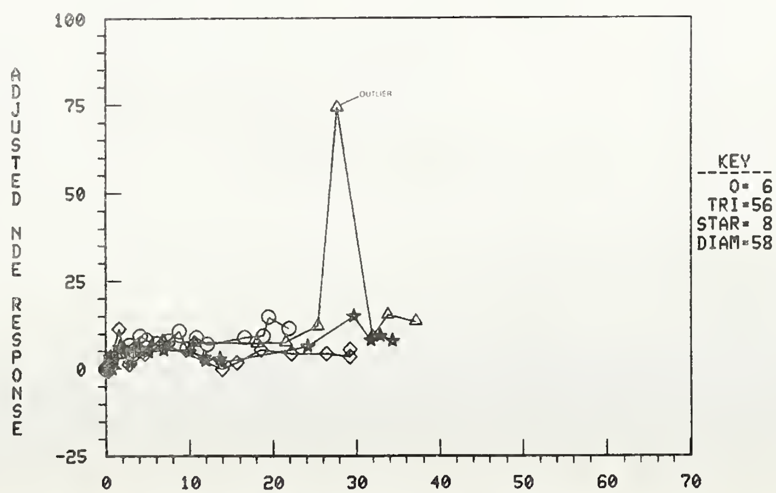


FIGURE A7. GLASS FIBER, 2 INCH, CONCRETE DECK, INSTRUMENT C1

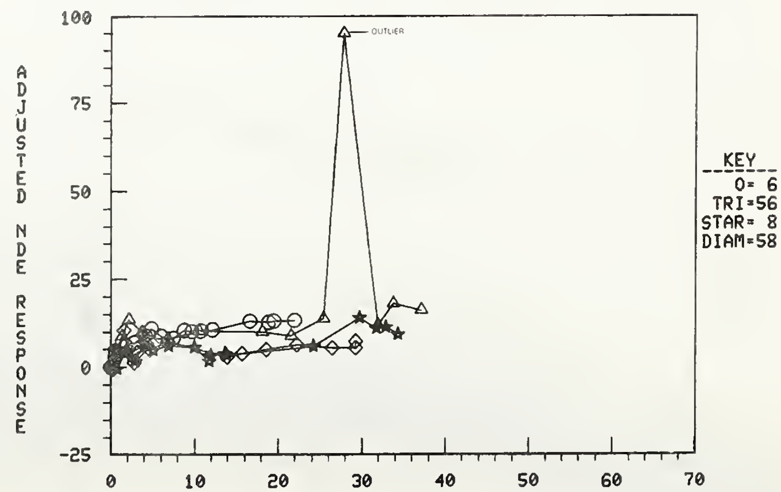


FIGURE A8. GLASS FIBER, 2 INCH, STEEL DECK, INSTRUMENT C1

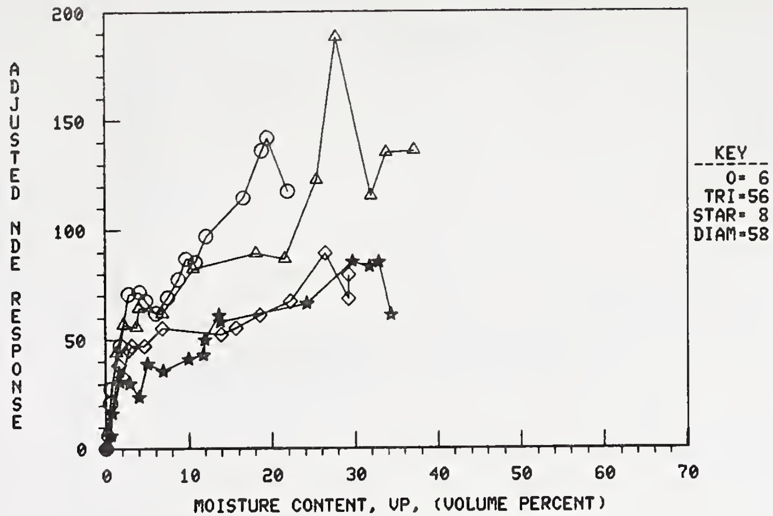


FIGURE A9. GLASS FIBER, 2 INCH, CONCRETE DECK, INSTRUMENT C2

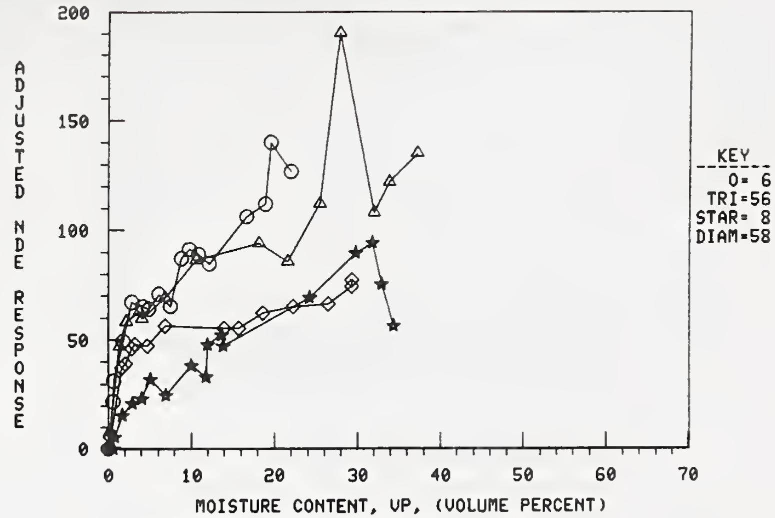


FIGURE A10. GLASS FIBER, 2 INCH, STEEL DECK, INSTRUMENT C2

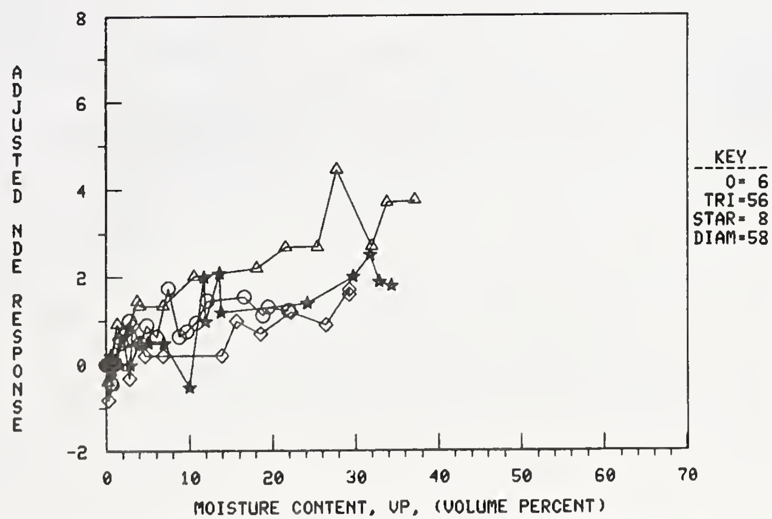


FIGURE A11. GLASS FIBER, 2 INCH, CONCRETE DECK, INSTRUMENT C3

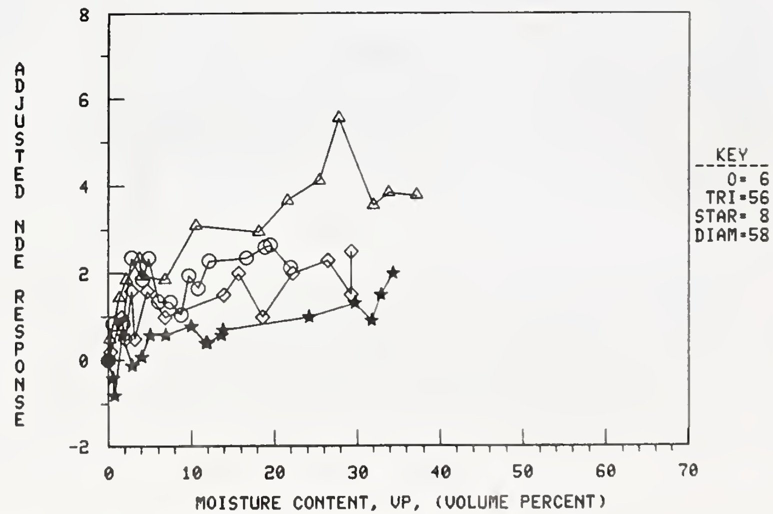


FIGURE A12. GLASS FIBER, 2 INCH, STEEL DECK, INSTRUMENT C3

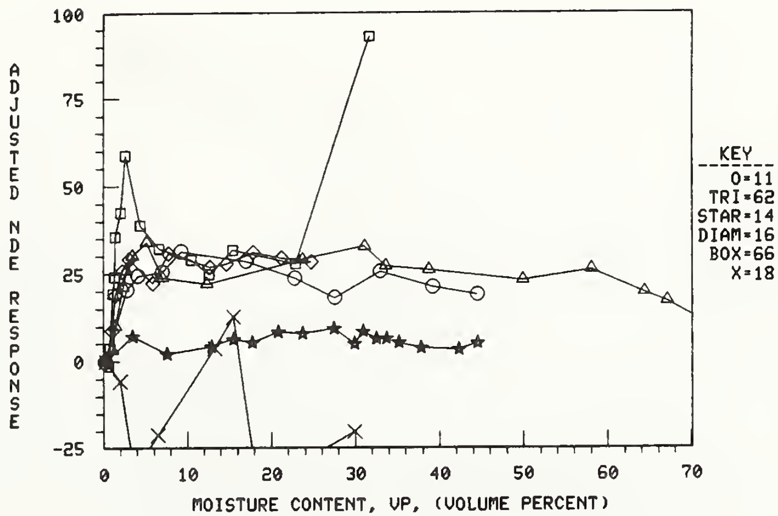


FIGURE A13. PERLITE, CONCRETE DECK, INSTRUMENT C1

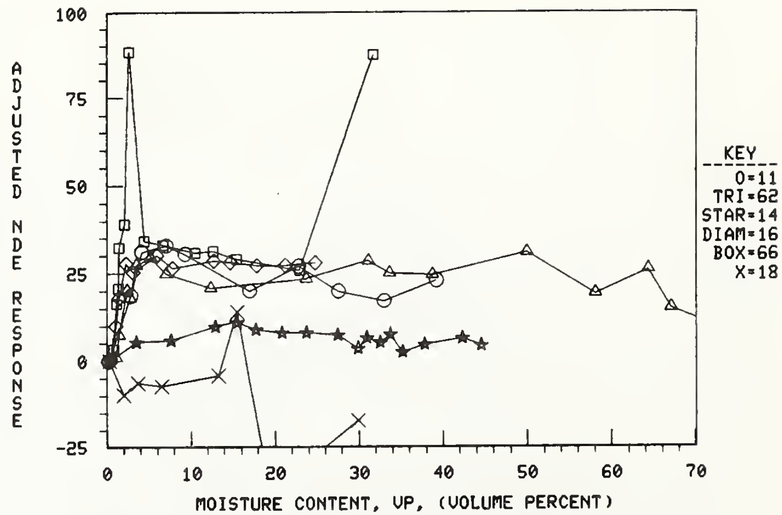


FIGURE A14. PERLITE, STEEL DECK, INSTRUMENT C1

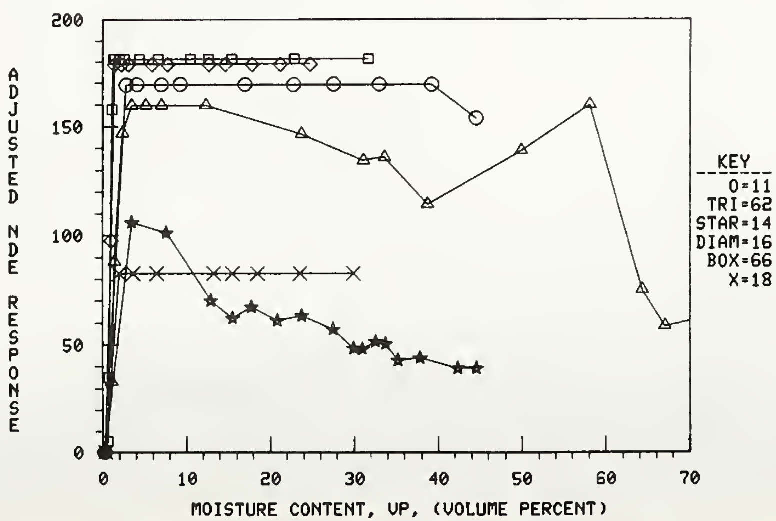


FIGURE A15. PERLITE, CONCRETE DECK, INSTRUMENT C2

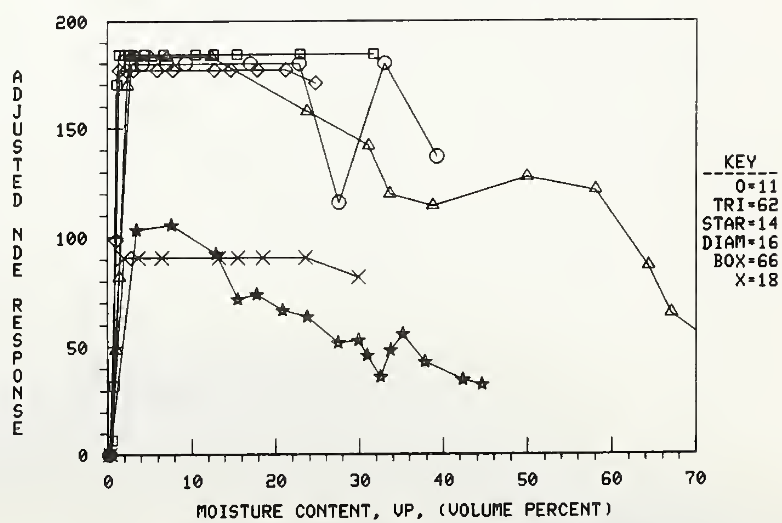


FIGURE A16. PERLITE, STEEL DECK, INSTRUMENT C2

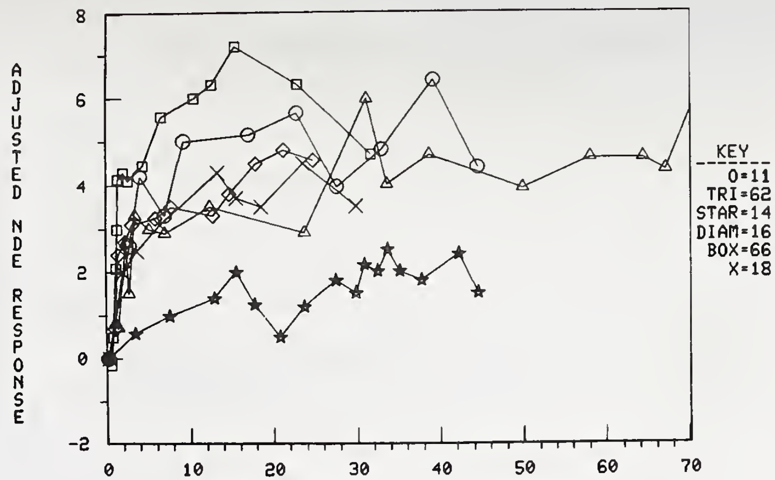


FIGURE A17. PERLITE, CONCRETE DECK, INSTRUMENT C3

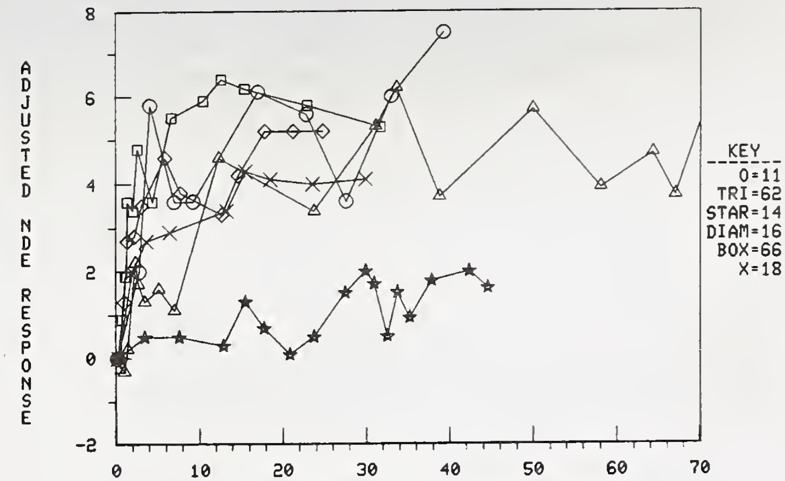


FIGURE A18. PERLITE, STEEL DECK, INSTRUMENT C3

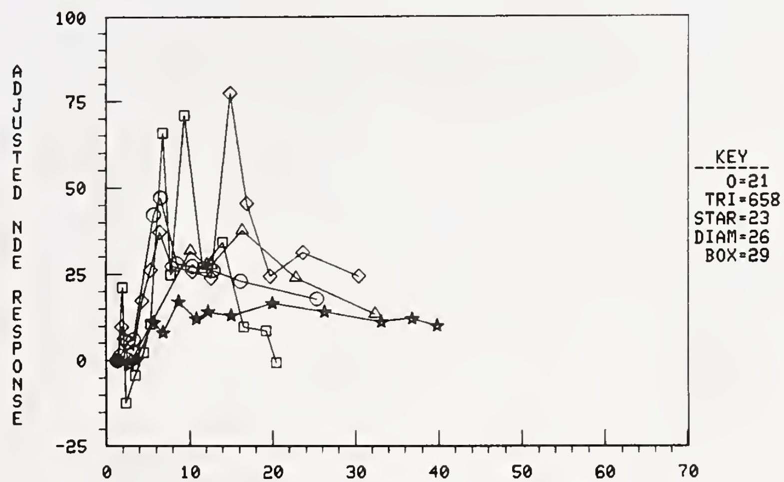


FIGURE A19. FIBERBOARD, CONCRETE DECK, INSTRUMENT C1

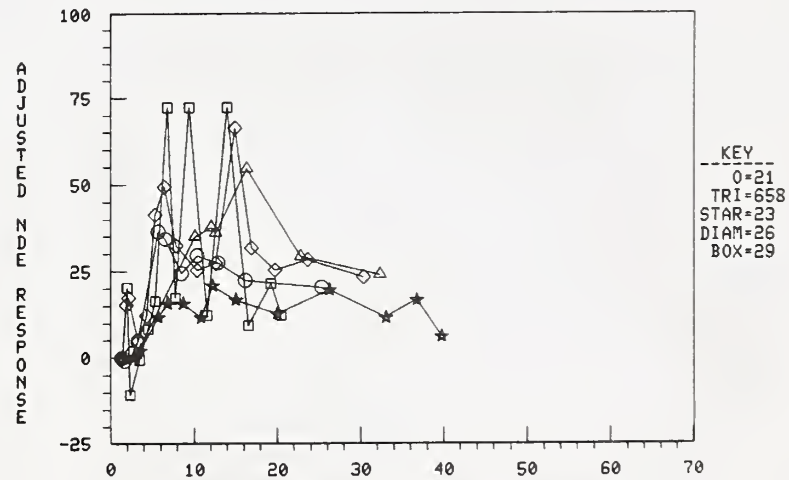


FIGURE A20. FIBERBOARD, STEEL DECK, INSTRUMENT C1

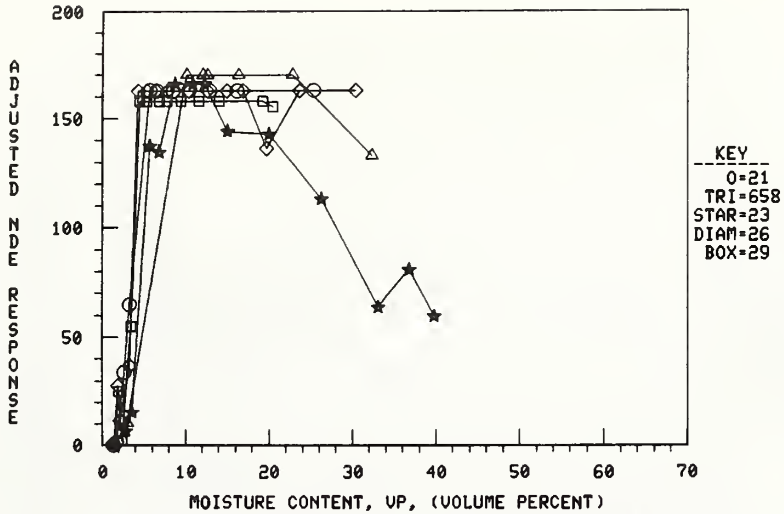


FIGURE A21. FIBERBOARD, CONCRETE DECK, INSTRUMENT C2

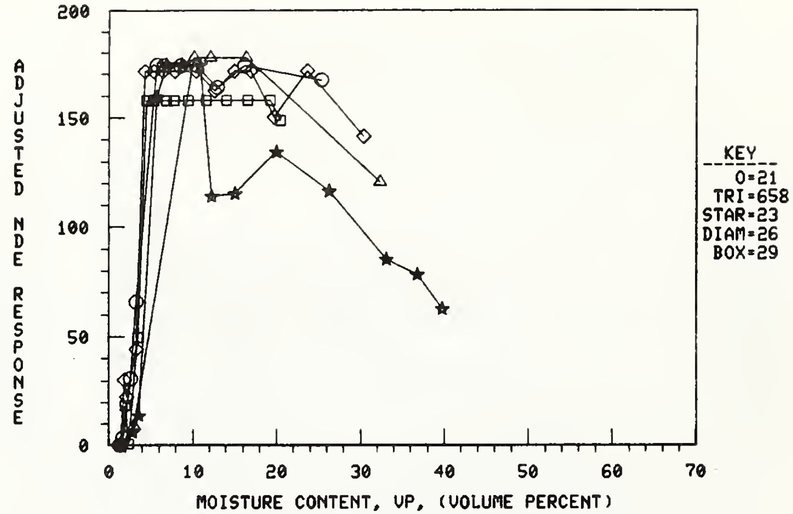


FIGURE A22. FIBERBOARD, STEEL DECK, INSTRUMENT C2

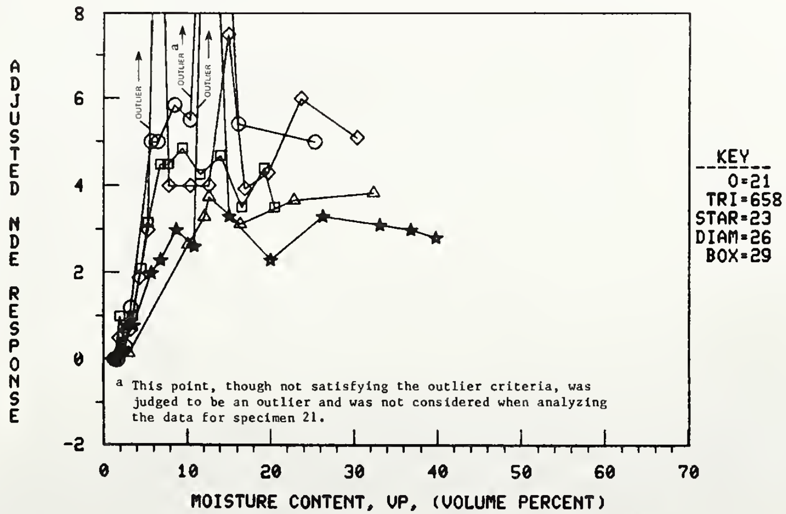


FIGURE A23. FIBERBOARD, CONCRETE DECK, INSTRUMENT C3

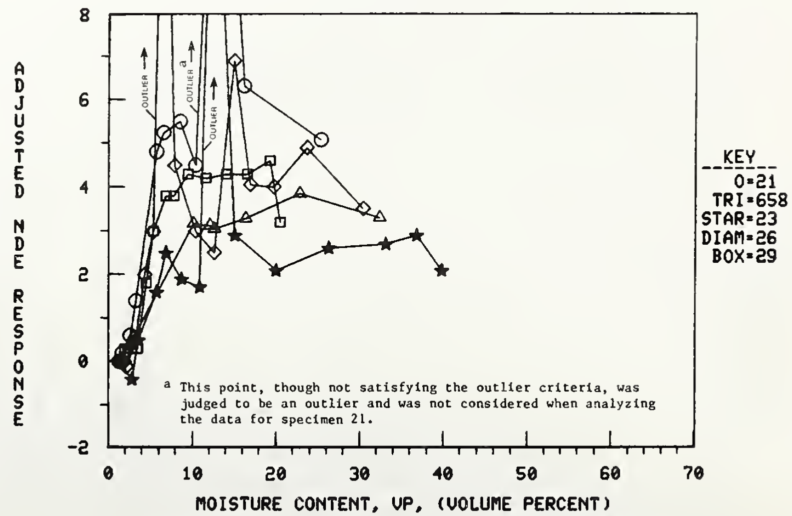


FIGURE A24. FIBERBOARD, STEEL DECK, INSTRUMENT C3

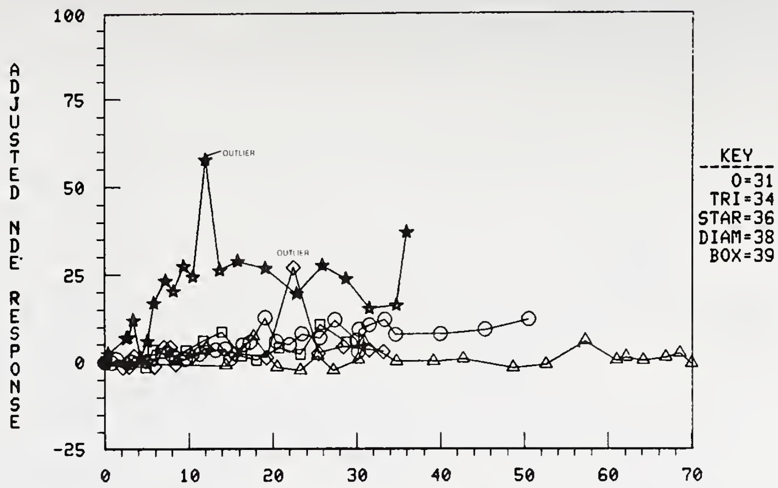


FIGURE A25. POLYSTYRENE, CONCRETE DECK, INSTRUMENT C1

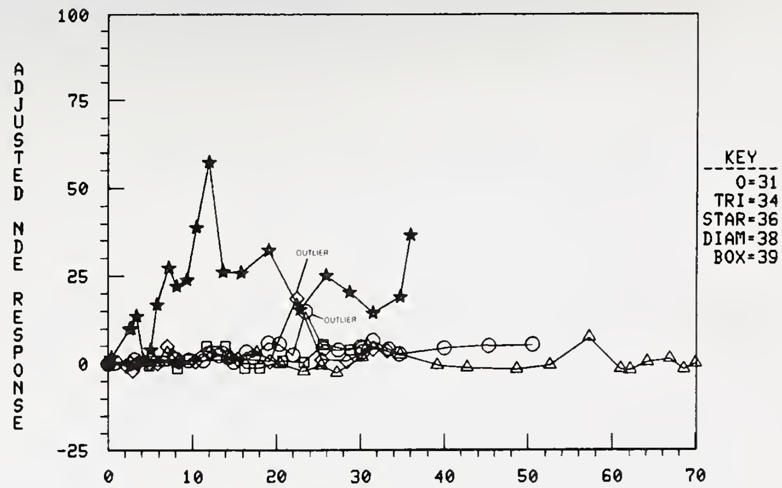


FIGURE A26. POLYSTYRENE, STEEL DECK, INSTRUMENT C1

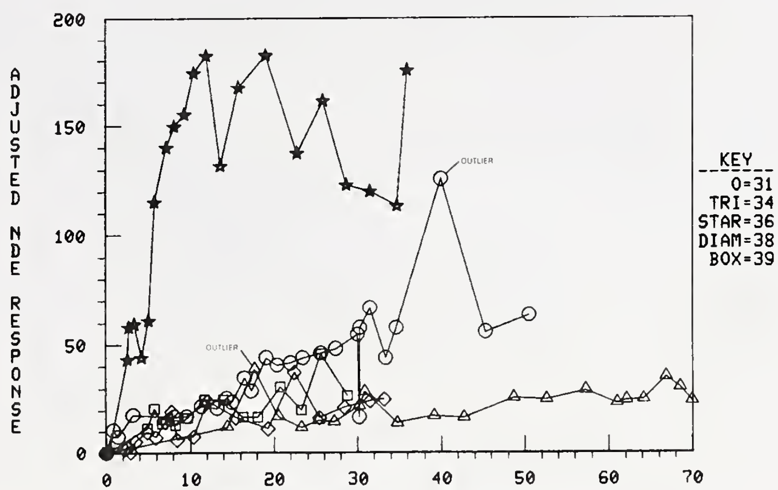


FIGURE A27. POLYSTYRENE, CONCRETE DECK, INSTRUMENT C2

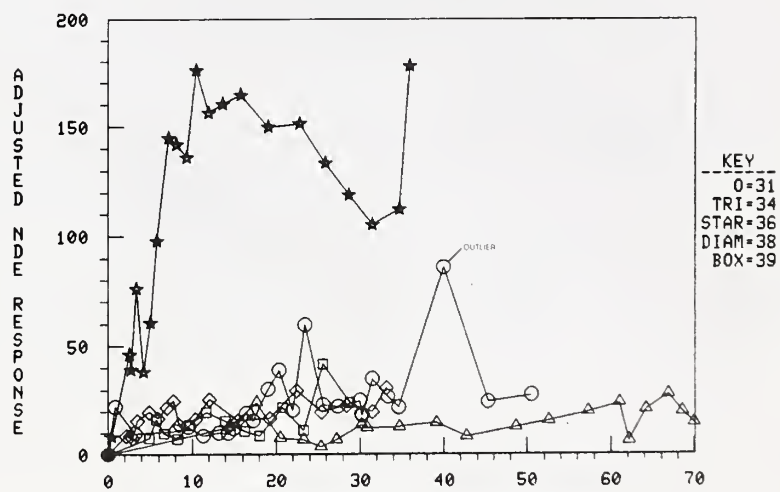


FIGURE A28. POLYSTYRENE, STEEL DECK, INSTRUMENT C2

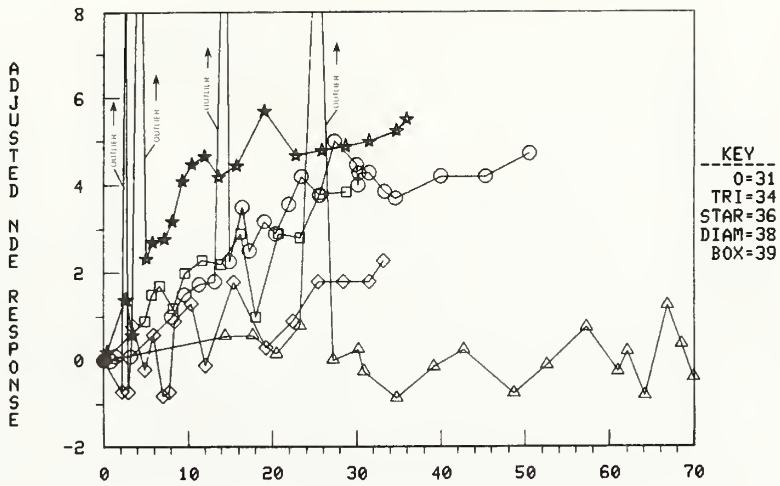


FIGURE A29. POLYSTYRENE, CONCRETE DECK, INSTRUMENT C3

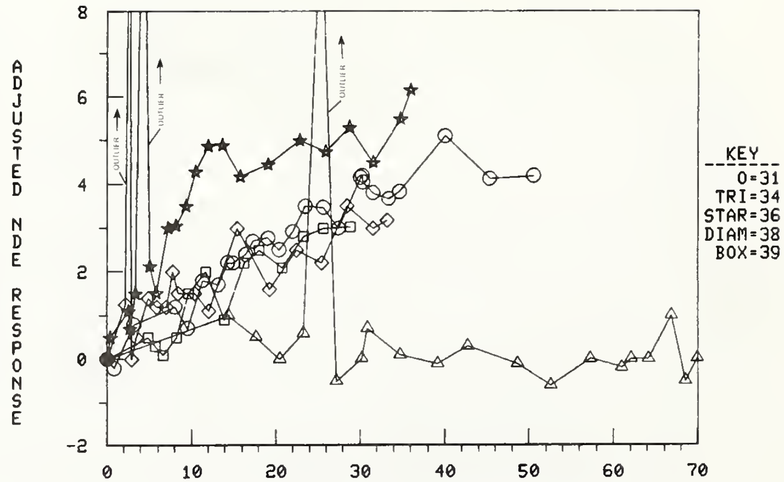


FIGURE A30. POLYSTYRENE, STEEL DECK, INSTRUMENT C3

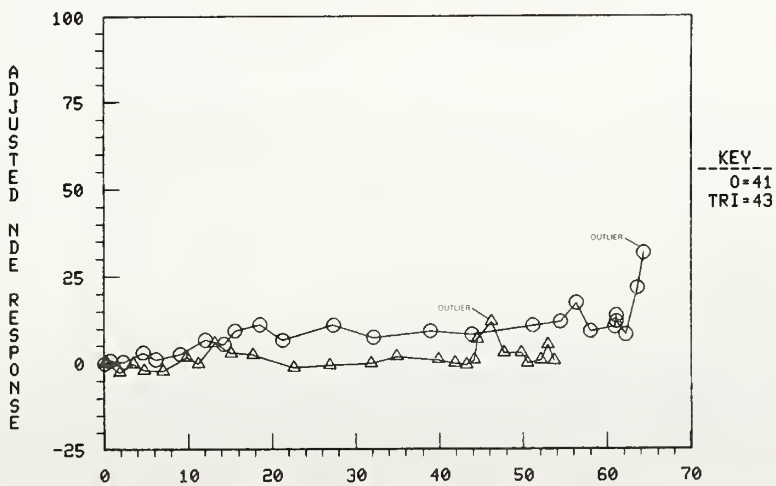


FIGURE A31. POLYURETHANE, CONCRETE DECK, INSTRUMENT C1

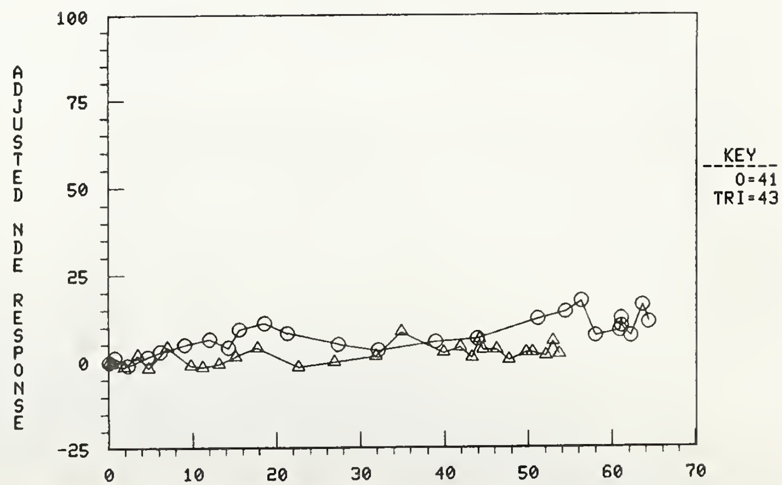


FIGURE A32. POLYURETHANE, STEEL DECK, INSTRUMENT C1

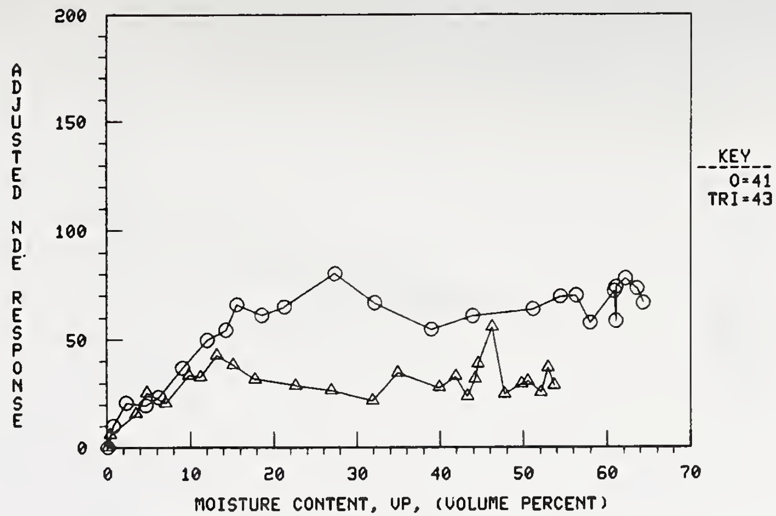


FIGURE A33. POLYURETHANE, CONCRETE DECK, INSTRUMENT C2

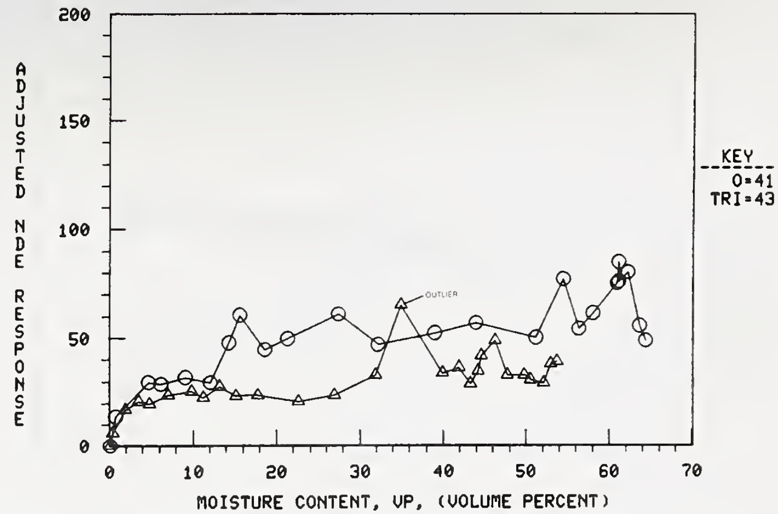


FIGURE A34. POLYURETHANE, STEEL DECK, INSTRUMENT C2

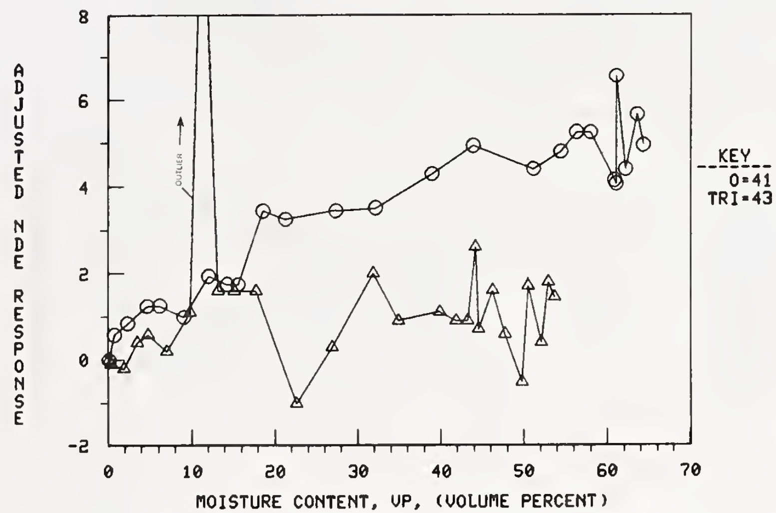


FIGURE A35. POLYURETHANE, CONCRETE DECK, INSTRUMENT C3

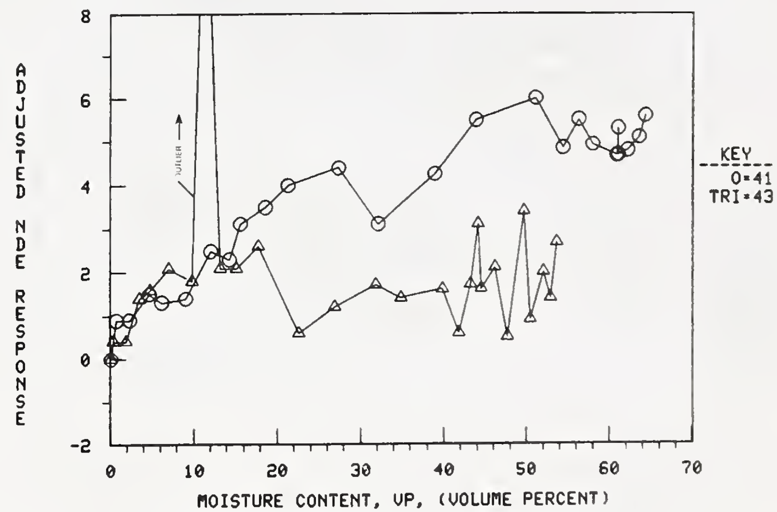
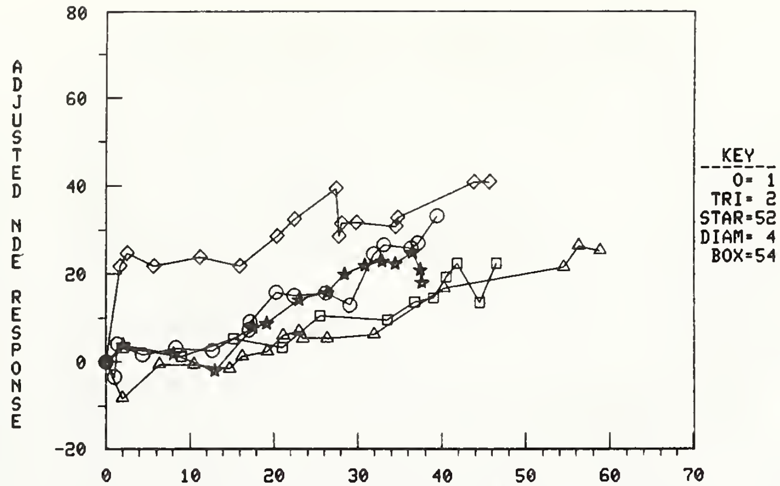
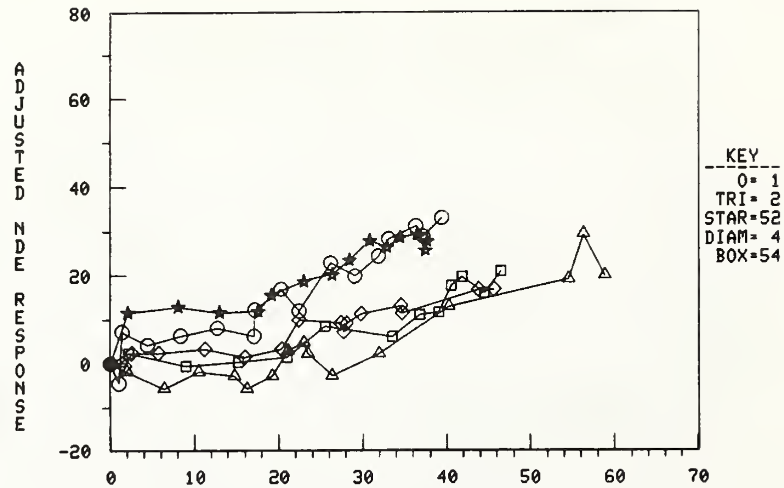


FIGURE A36. POLYURETHANE, STEEL DECK, INSTRUMENT C3



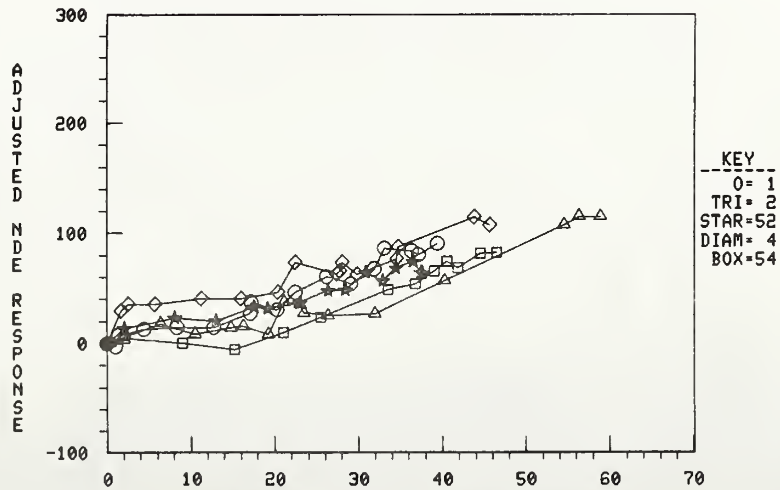
MOISTURE CONTENT, VP, (VOLUME PERCENT)

FIGURE A37. GLASS FIBER, 1 INCH, CONCRETE DECK, INSTRUMENT N1



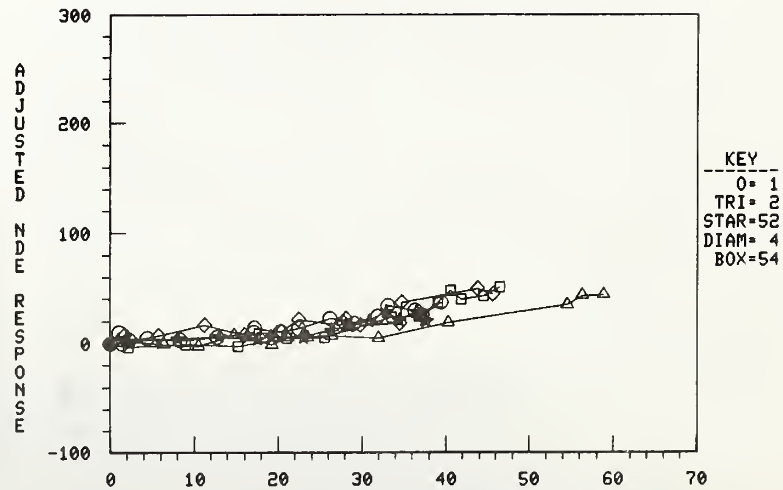
MOISTURE CONTENT, VP, (VOLUME PERCENT)

FIGURE A38. GLASS FIBER, 1 INCH, STEEL DECK, INSTRUMENT N1



MOISTURE CONTENT, VP, (VOLUME PERCENT)

FIGURE A39. GLASS FIBER, 1 INCH, CONCRETE DECK, INSTRUMENT N2



MOISTURE CONTENT, VP, (VOLUME PERCENT)

FIGURE A40. GLASS FIBER, 1 INCH, STEEL DECK, INSTRUMENT N2

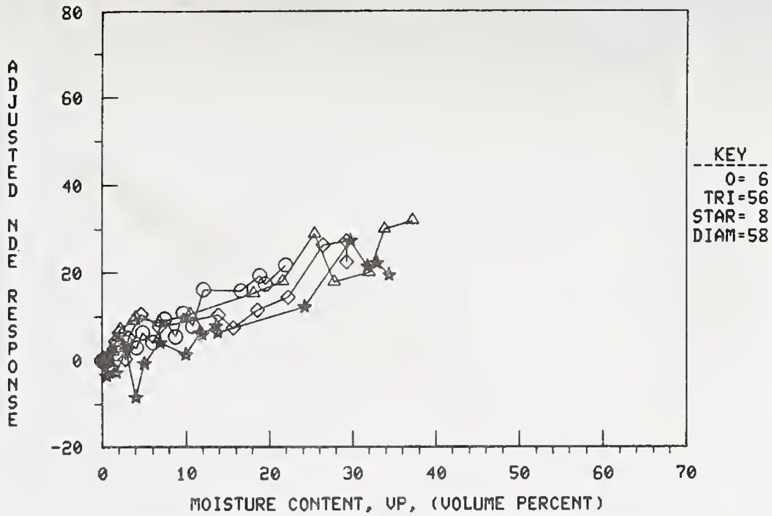


FIGURE A41. GLASS FIBER, 2 INCH, CONCRETE DECK, INSTRUMENT N1

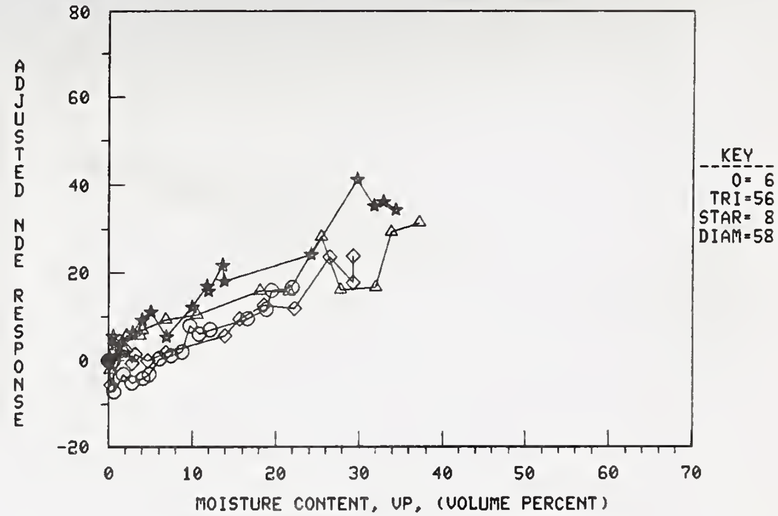


FIGURE A42. GLASS FIBER, 2 INCH, STEEL DECK, INSTRUMENT N1

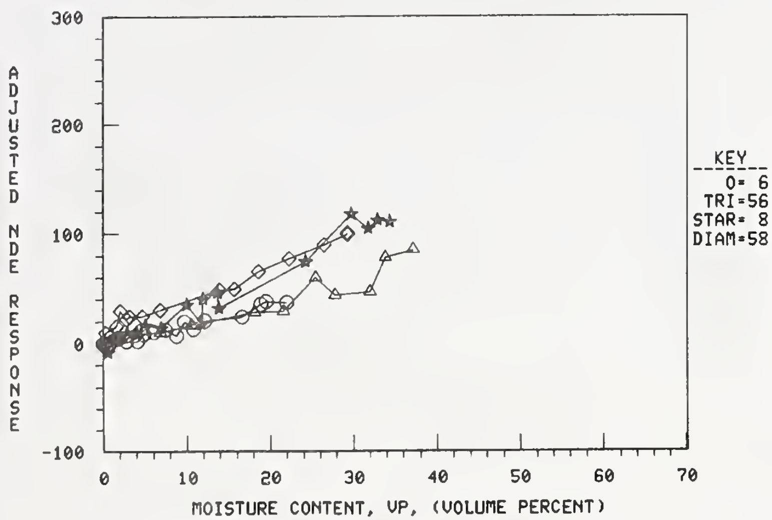


FIGURE A43. GLASS FIBER, 2 INCH, CONCRETE DECK, INSTRUMENT N2

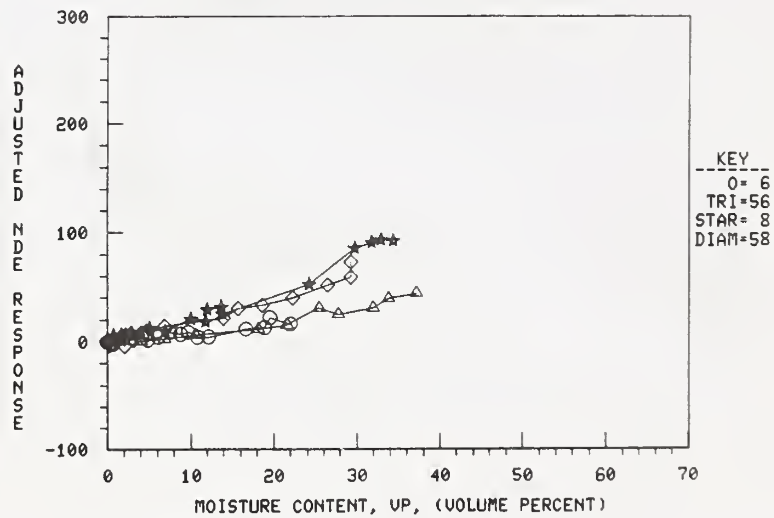


FIGURE A44. GLASS FIBER, 2 INCH, STEEL DECK, INSTRUMENT N2

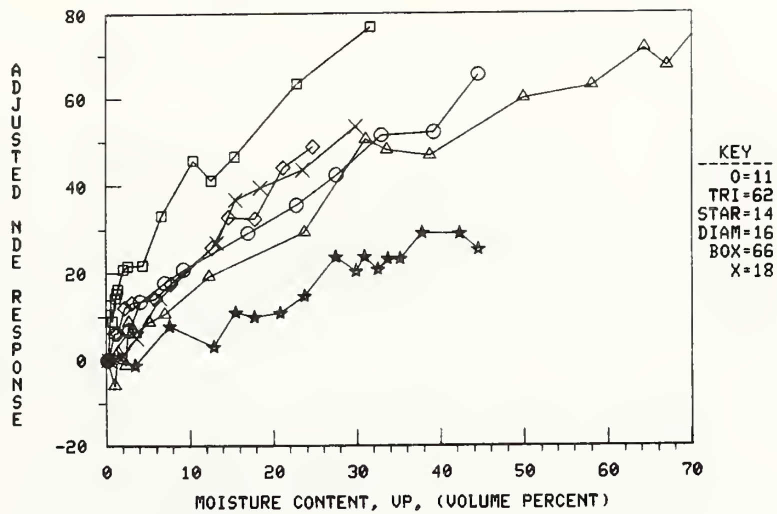


FIGURE A45. PERLITE, CONCRETE DECK, INSTRUMENT N1

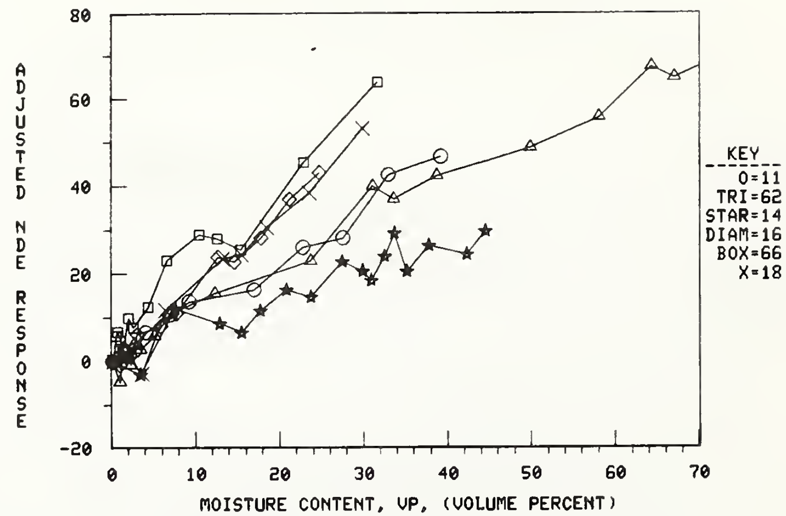


FIGURE A46. PERLITE, STEEL DECK, INSTRUMENT N1

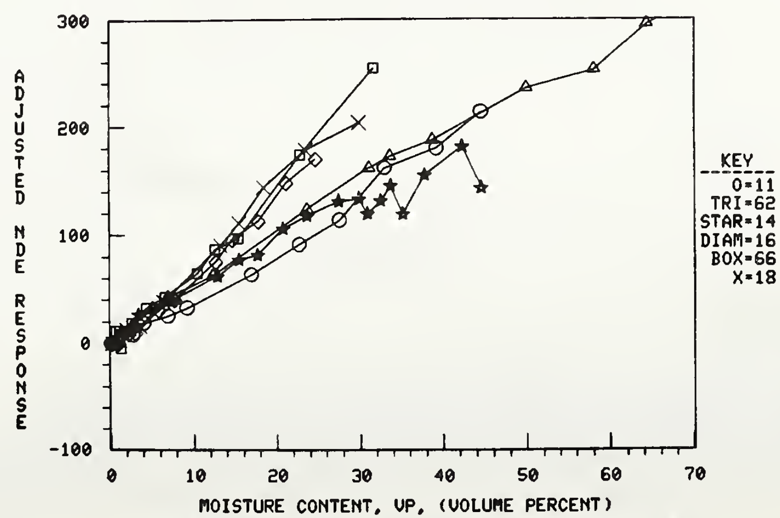


FIGURE A47. PERLITE, CONCRETE DECK, INSTRUMENT N2

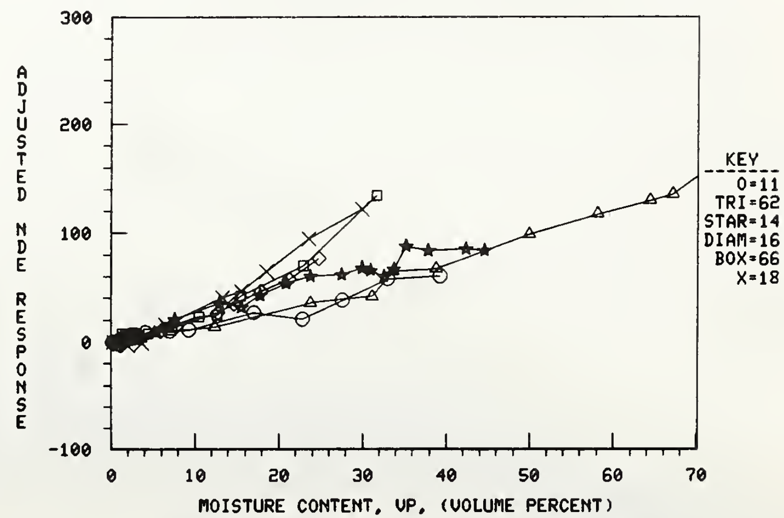


FIGURE A48. PERLITE, STEEL DECK, INSTRUMENT N2

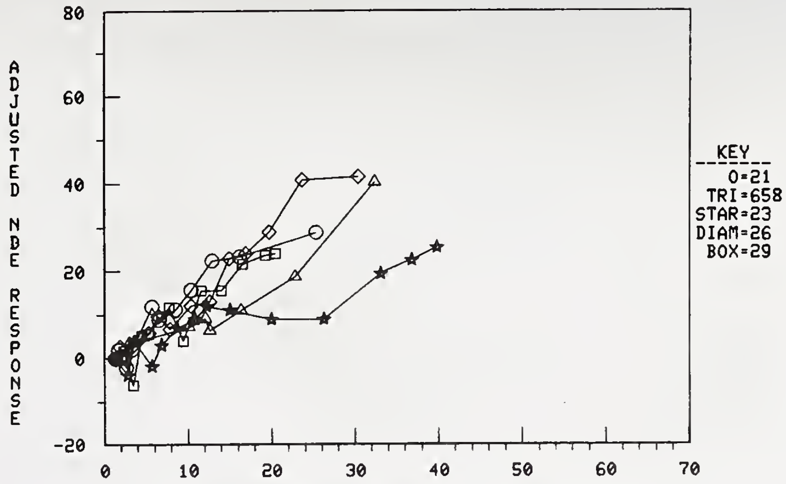


FIGURE A49. FIBERBOARD, CONCRETE DECK, INSTRUMENT N1

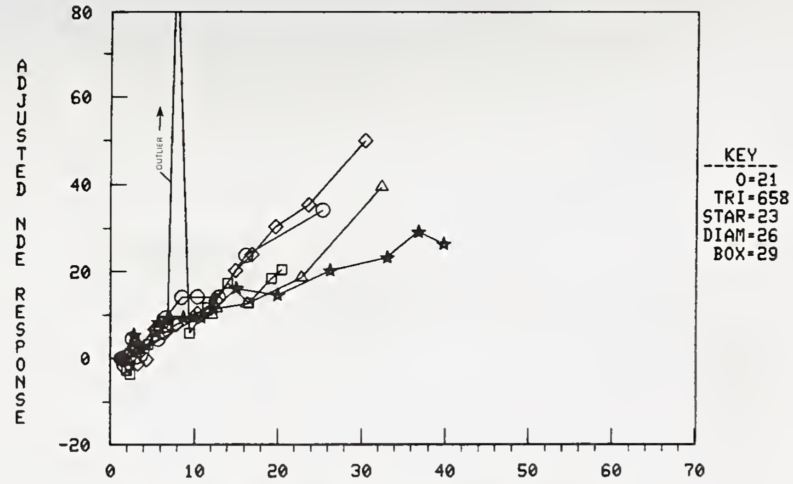


FIGURE A50. FIBERBOARD, STEEL DECK, INSTRUMENT N1

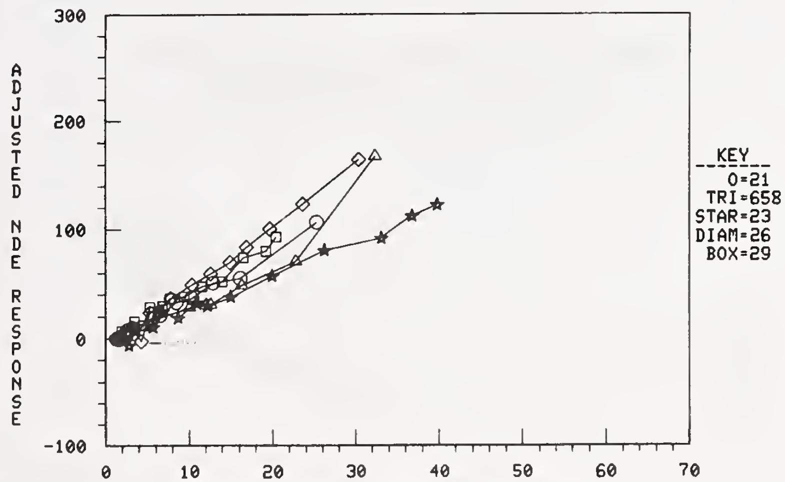


FIGURE A51. FIBERBOARD, CONCRETE DECK, INSTRUMENT N2

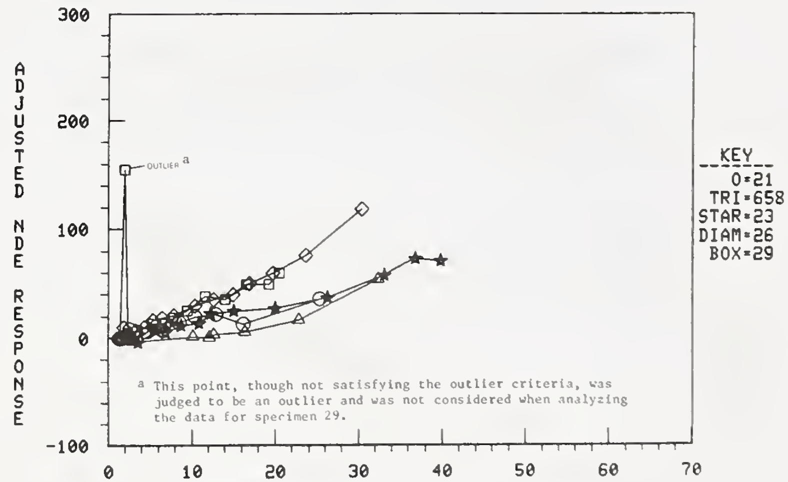


FIGURE A52. FIBERBOARD, STEEL DECK, INSTRUMENT N2

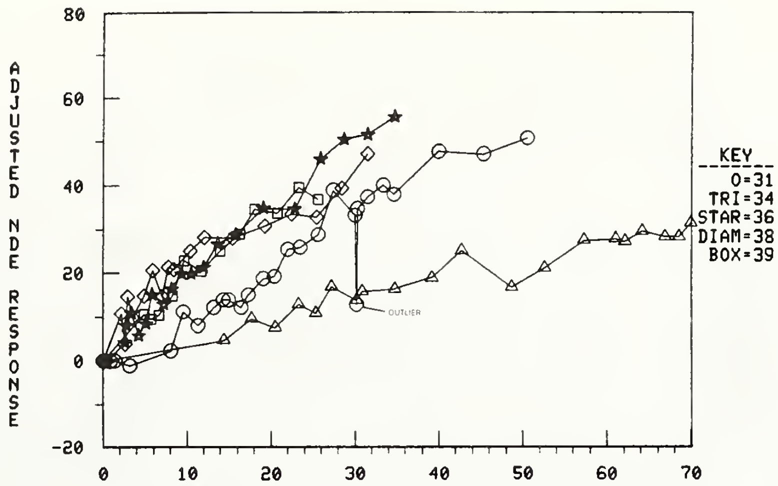


FIGURE A53. POLYSTYRENE, CONCRETE DECK, INSTRUMENT N1

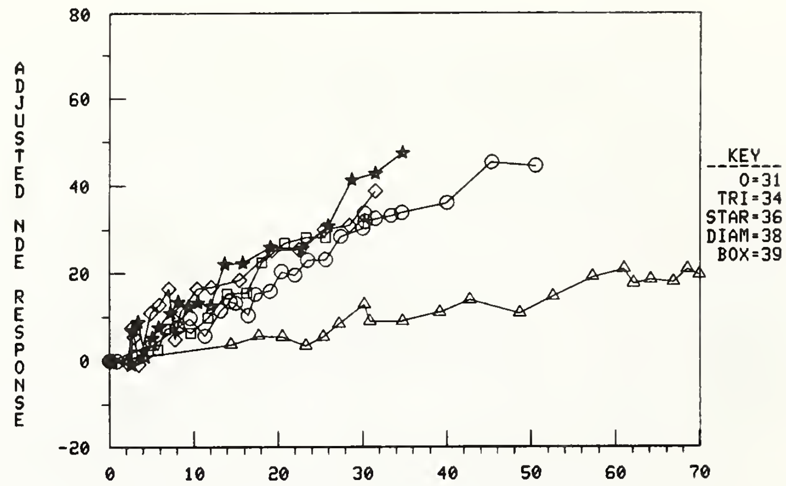


FIGURE A54. POLYSTYRENE, STEEL DECK, INSTRUMENT N1

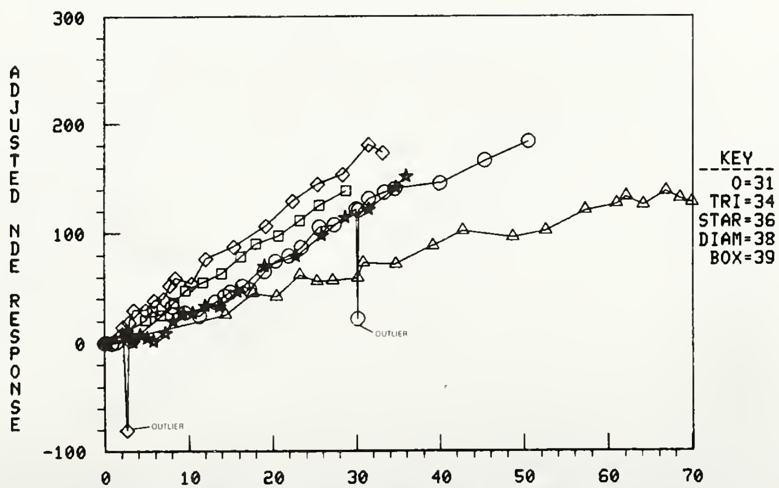


FIGURE A55. POLYSTYRENE, CONCRETE DECK, INSTRUMENT N2

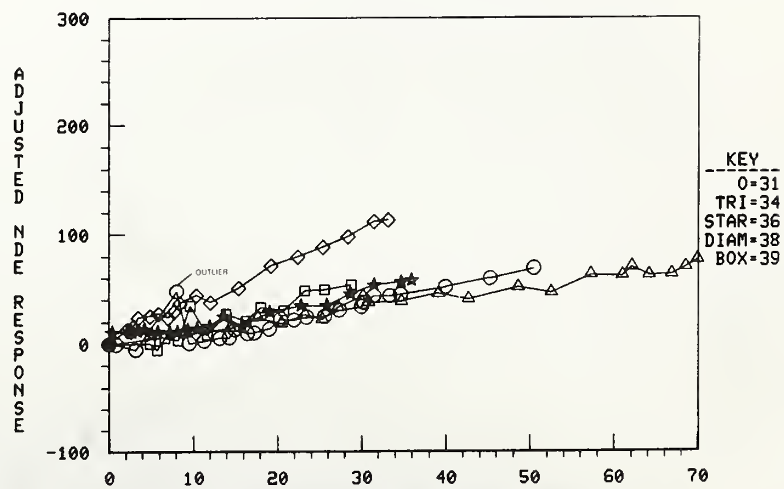


FIGURE A56. POLYSTYRENE, STEEL DECK, INSTRUMENT N2

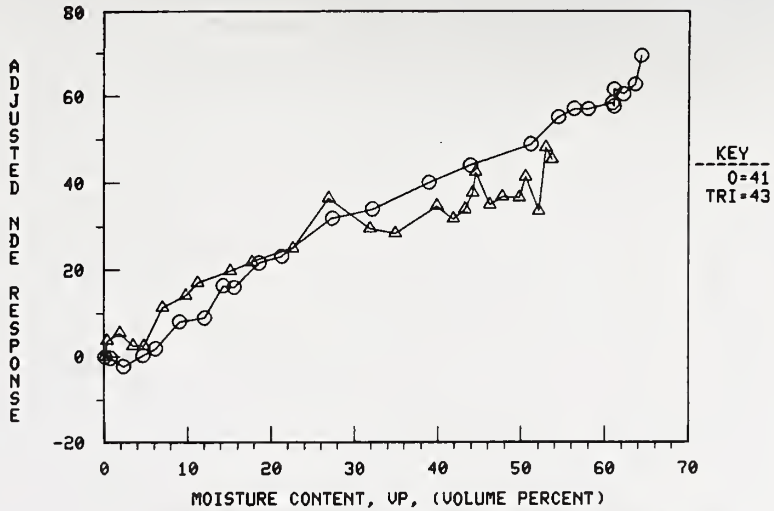


FIGURE A57. POLYURETHANE, CONCRETE DECK, INSTRUMENT N1

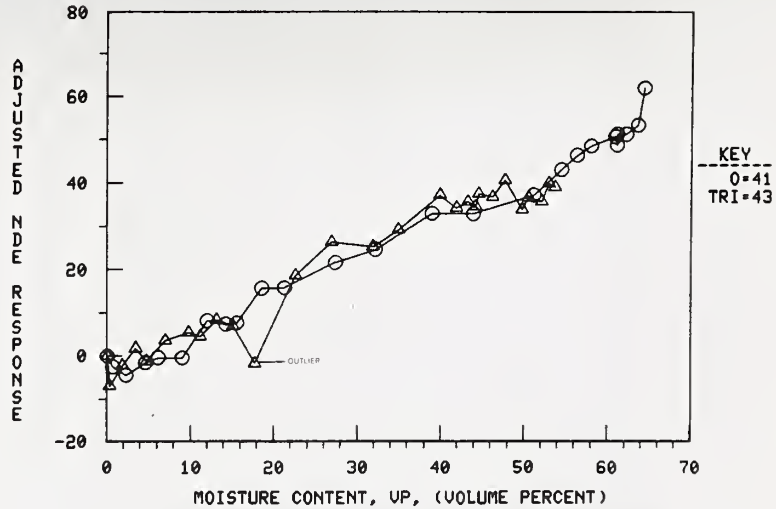


FIGURE A58. POLYURETHANE, STEEL DECK, INSTRUMENT N1

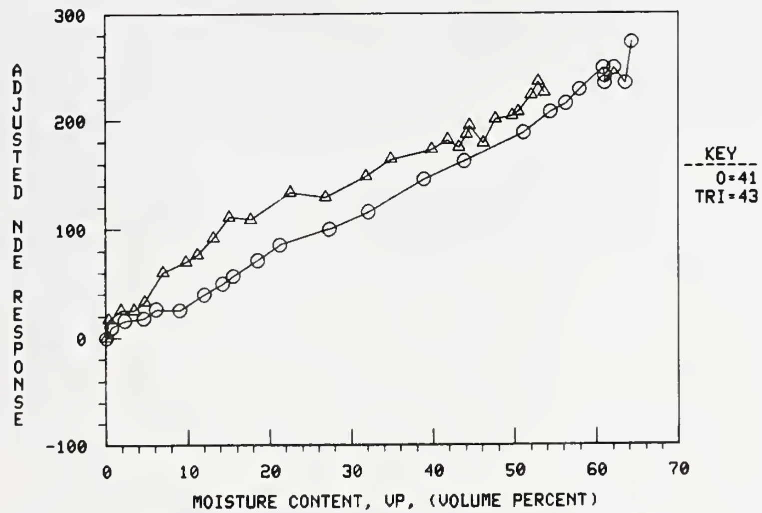


FIGURE A59. POLYURETHANE, CONCRETE DECK, INSTRUMENT N2

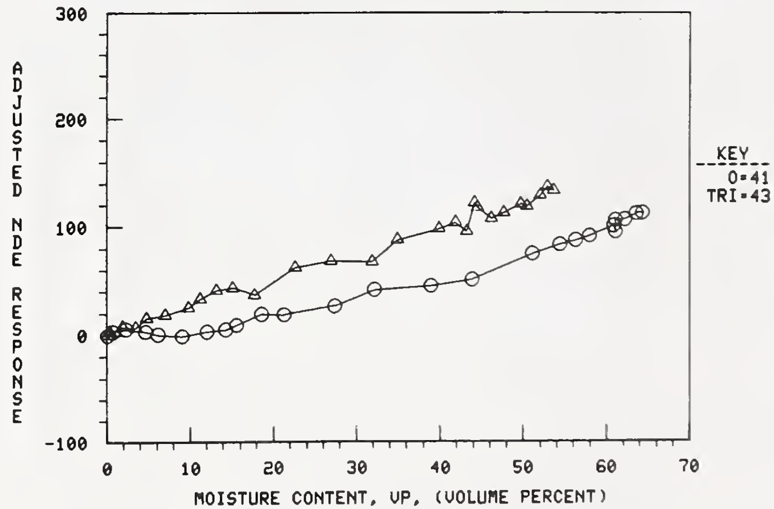


FIGURE A60. POLYURETHANE, STEEL DECK, INSTRUMENT N2

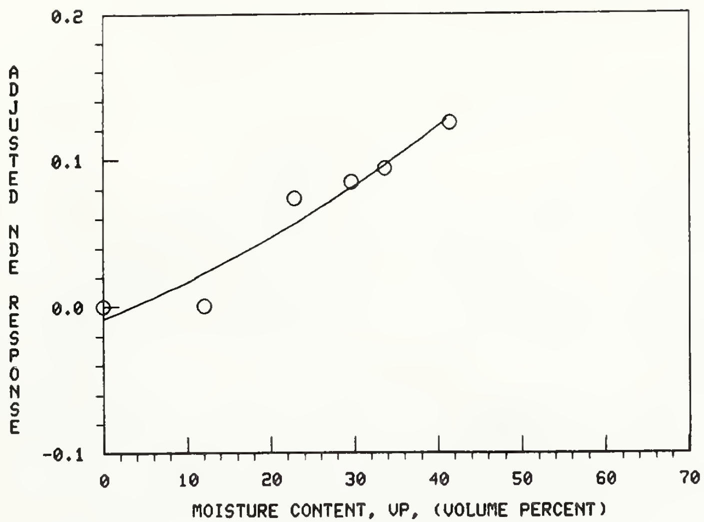


FIGURE A61. GLASS FIBER, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #51

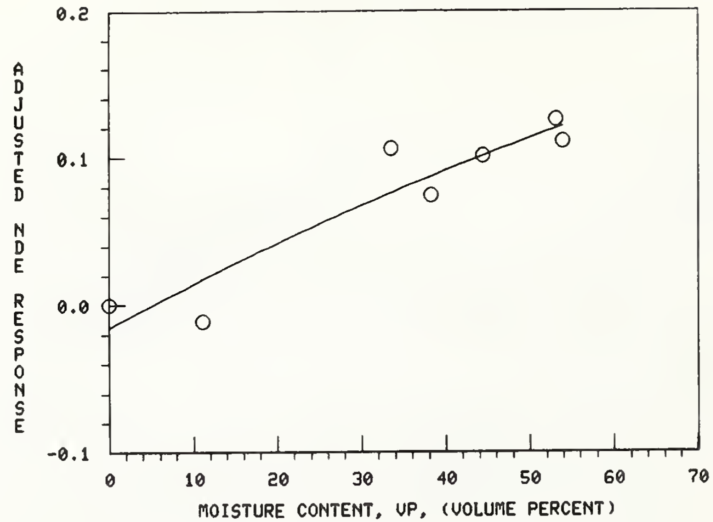


FIGURE A62. GLASS FIBER, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #141

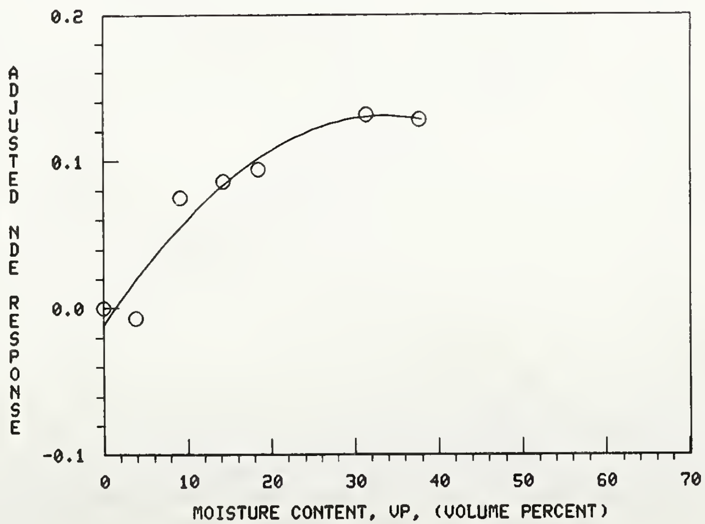


FIGURE A63. GLASS FIBER, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #143

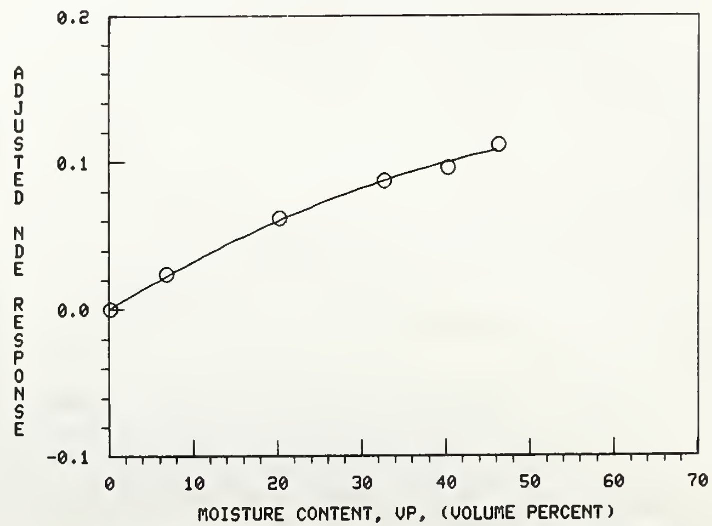


FIGURE A64. PERLITE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #61

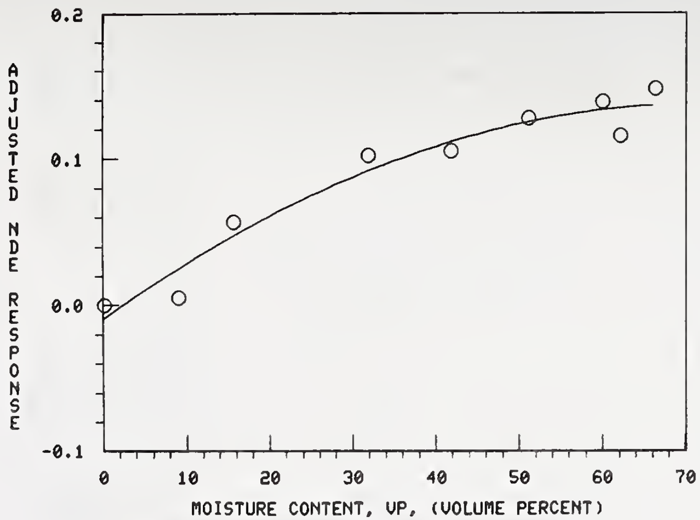


FIGURE A65. PERLITE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #145

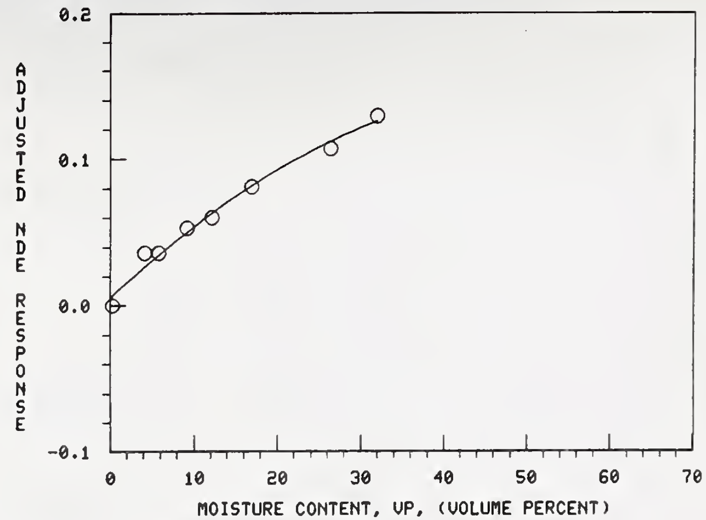


FIGURE A66. PERLITE, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #733

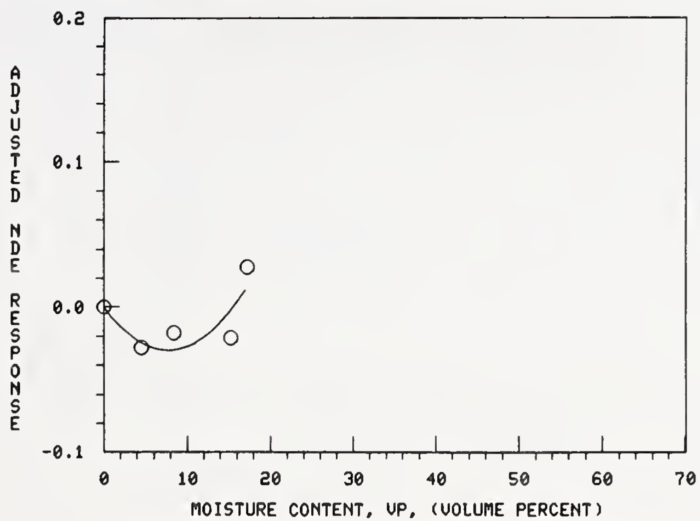


FIGURE A67. POLYSTYRENE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #113

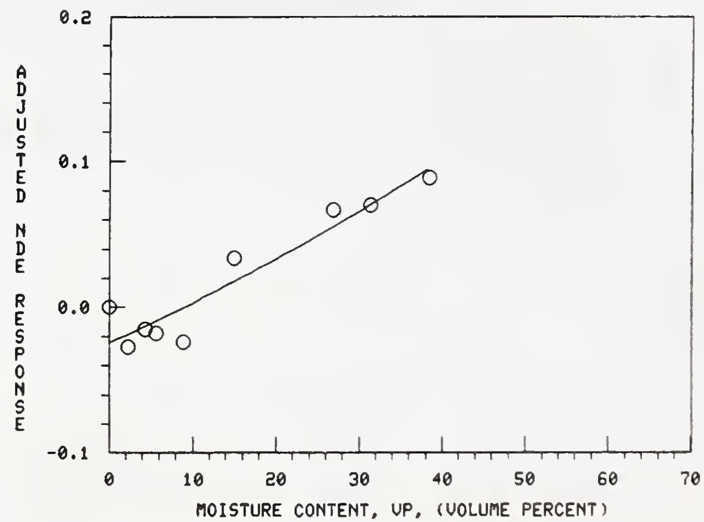


FIGURE A68. POLYSTYRENE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #751

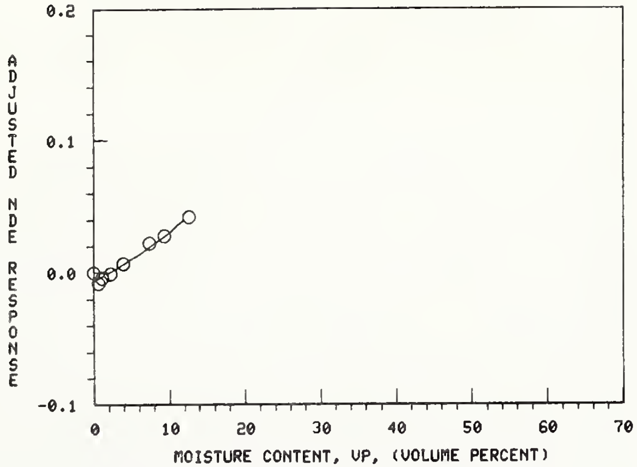


FIGURE A69. POLYSTYRENE, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS, INSTRUMENT IR, SPEC #155

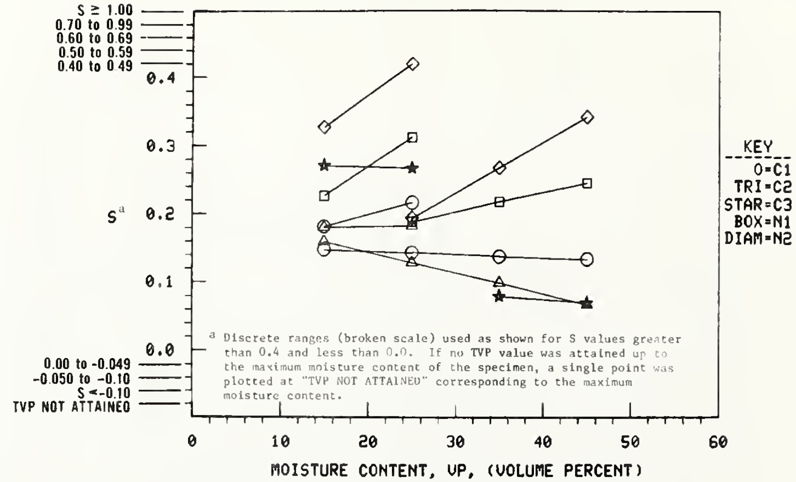


FIGURE A70. GLASS FIBER, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

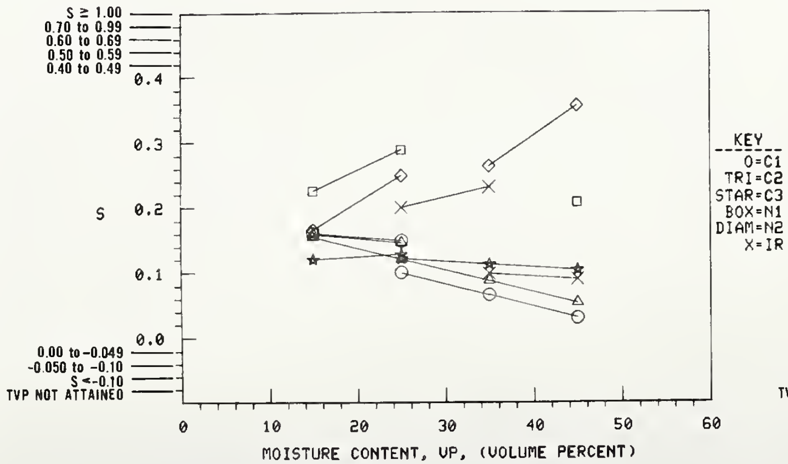


FIGURE A71. GLASS FIBER, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

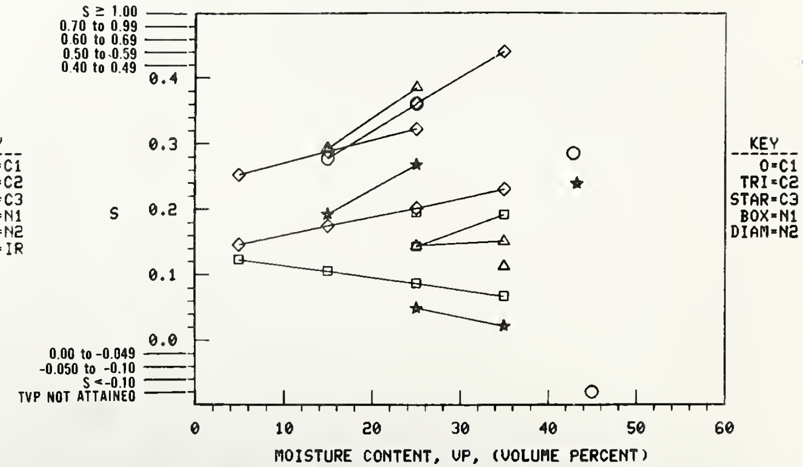


FIGURE A72. GLASS FIBER, 1 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

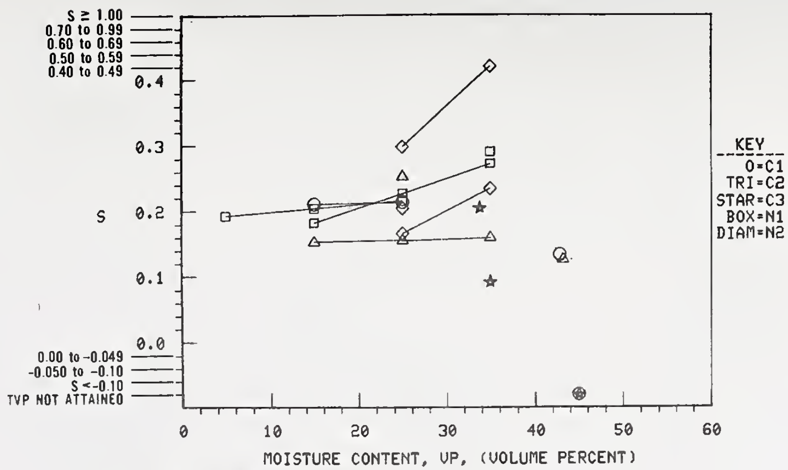


FIGURE A73. GLASS FIBER, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

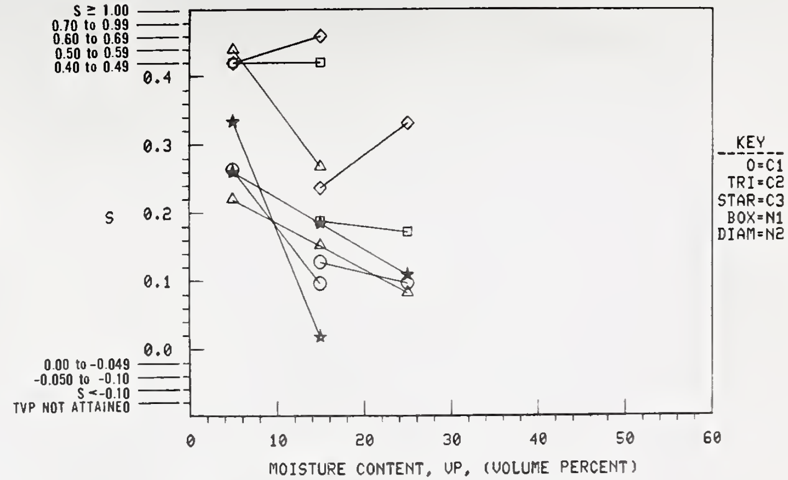


FIGURE A74. GLASS FIBER, 2 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

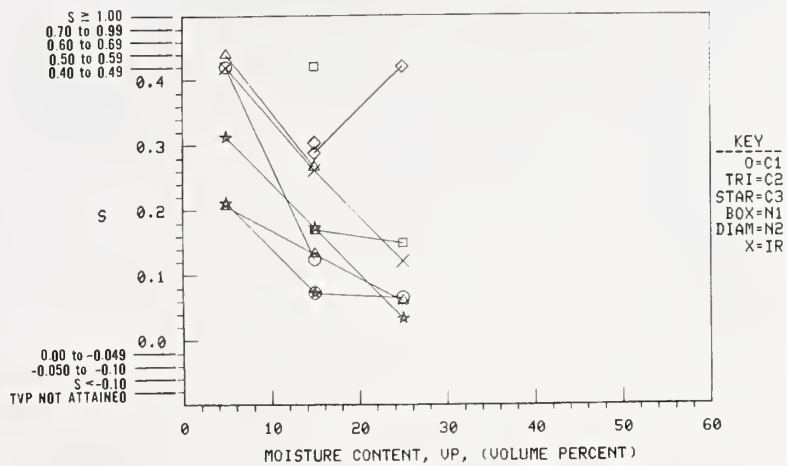


FIGURE A75. GLASS FIBER, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

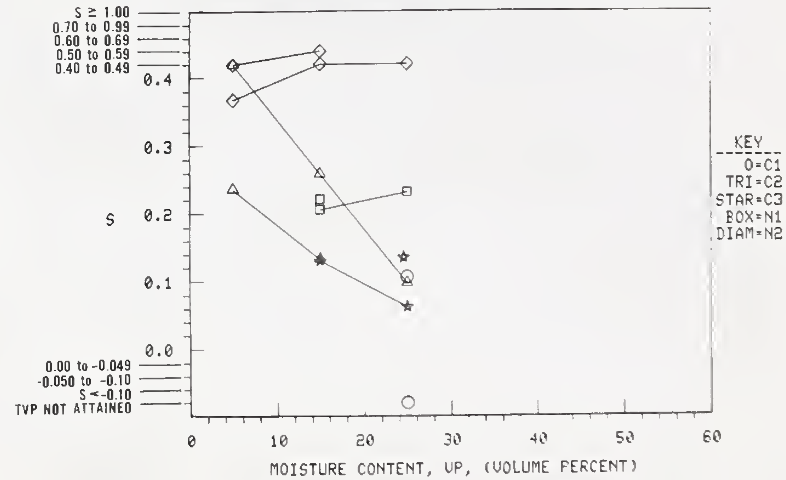


FIGURE A76. GLASS FIBER, 2 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

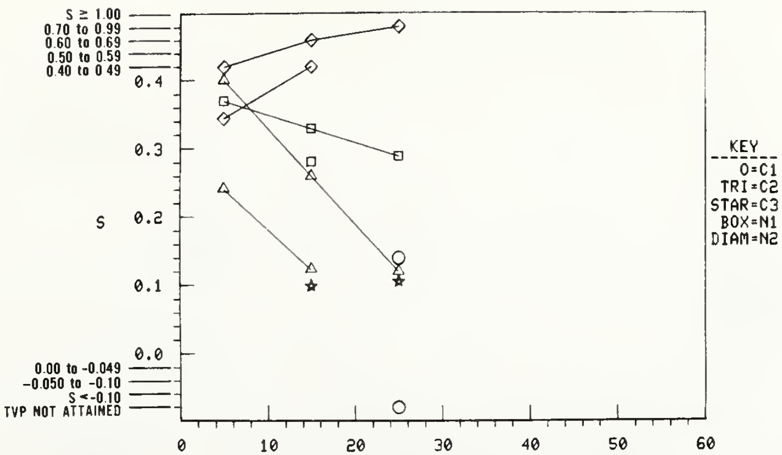


FIGURE A77. GLASS FIBER, 2 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

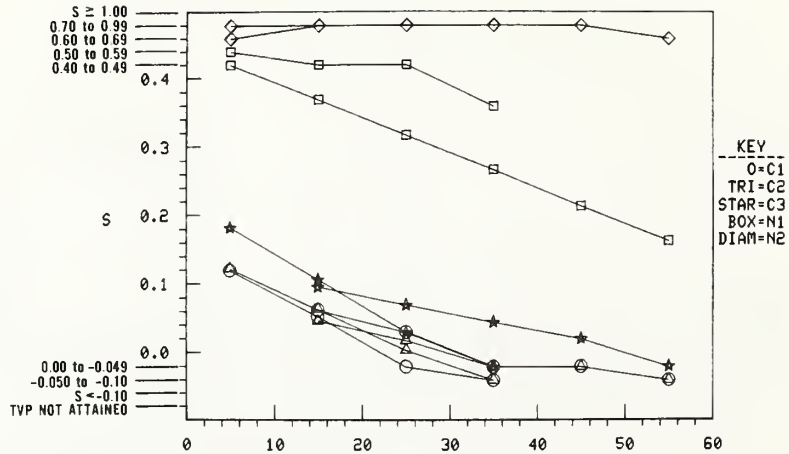


FIGURE A78. PERLITE, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

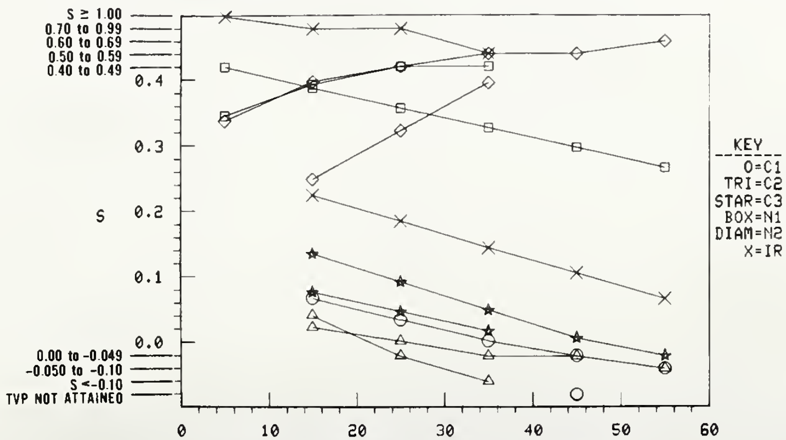


FIGURE A79. PERLITE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

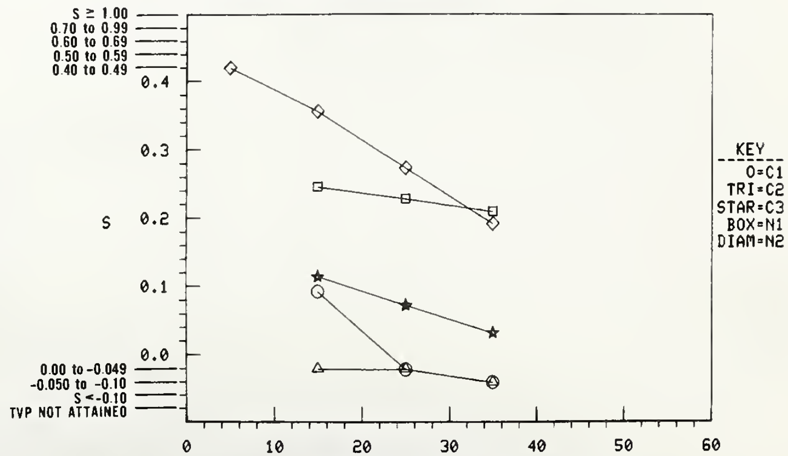


FIGURE A80. PERLITE, 1 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

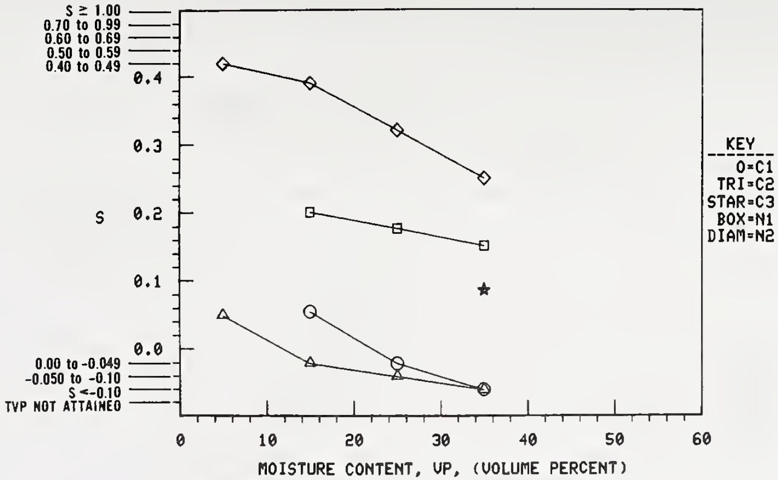


FIGURE A81. PERLITE, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

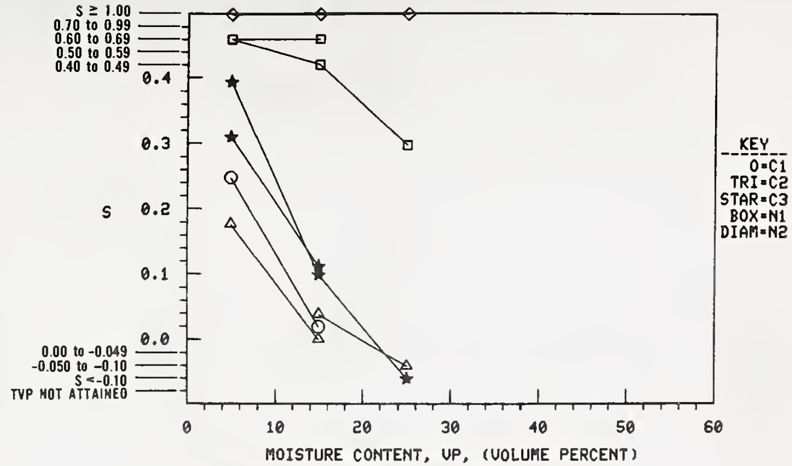


FIGURE A82. PERLITE, 2 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

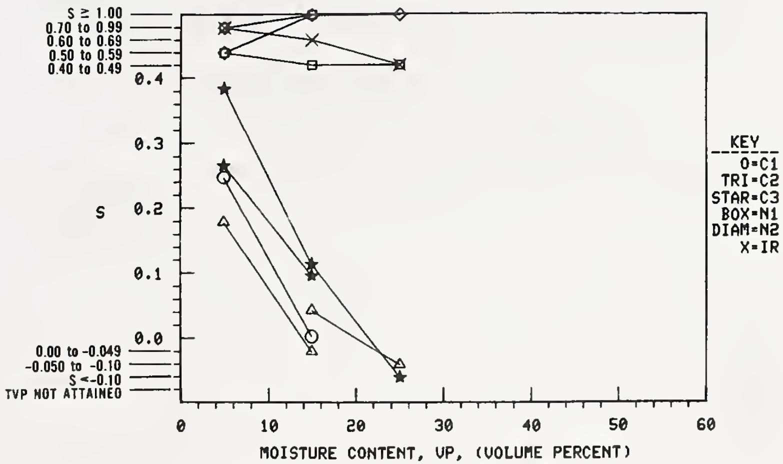


FIGURE A83. PERLITE, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

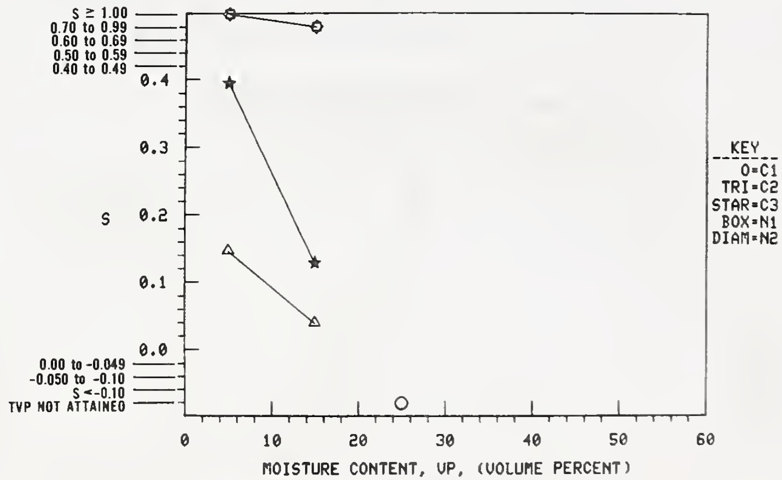


FIGURE A84. PERLITE, 2 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

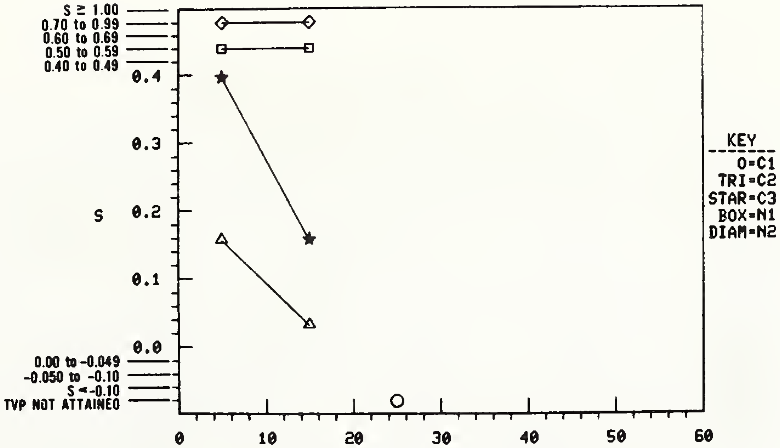


FIGURE A85. PERLITE, 2 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

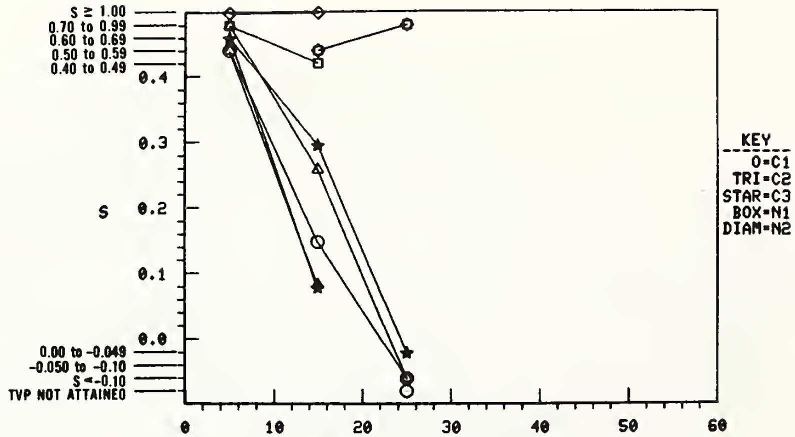


FIGURE A86. FIBERBOARD, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

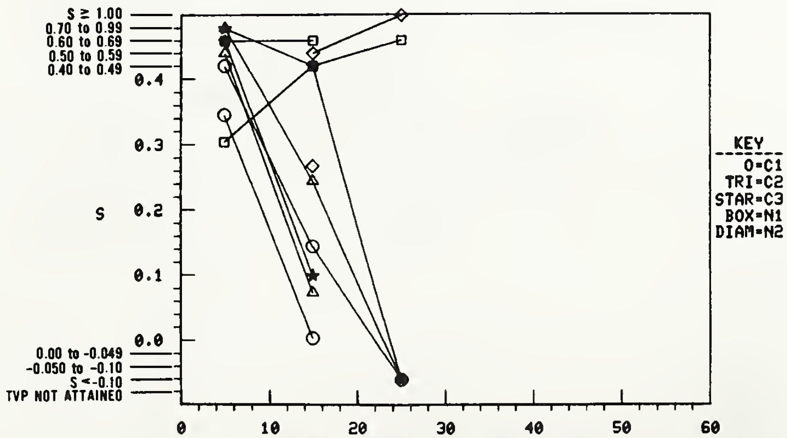


FIGURE A87. FIBERBOARD, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

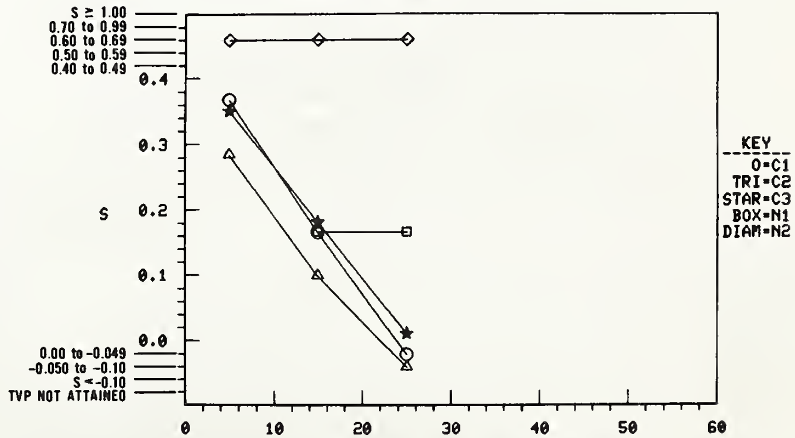


FIGURE A88. FIBERBOARD, 1 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

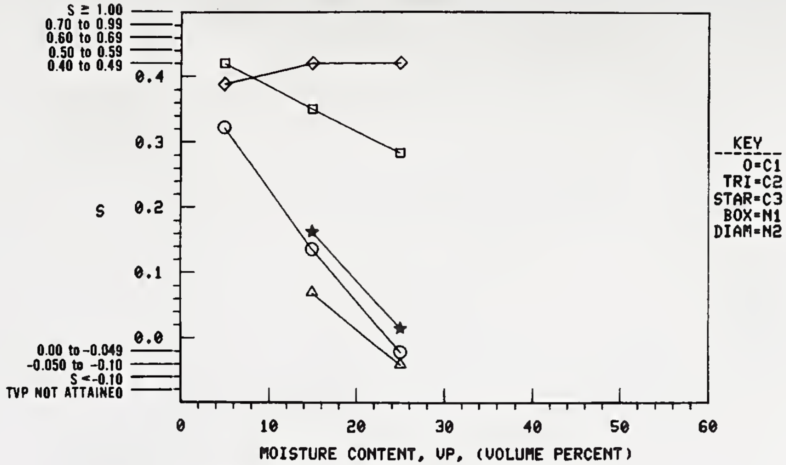


FIGURE A89. FIBERBOARD, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

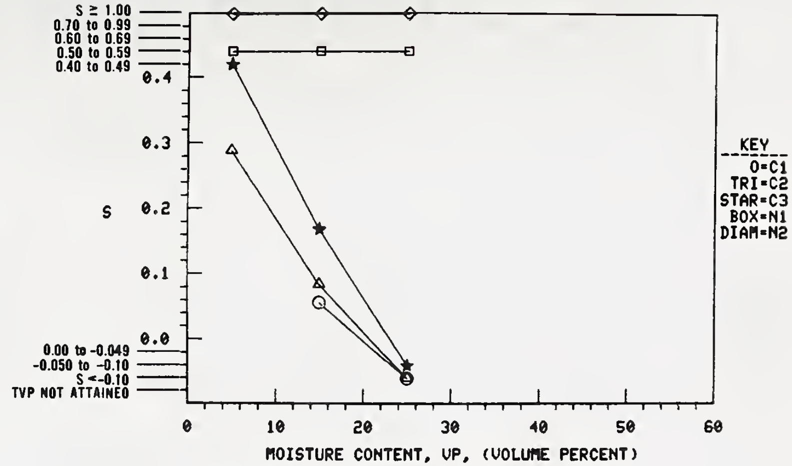


FIGURE A90. FIBERBOARD, 2 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

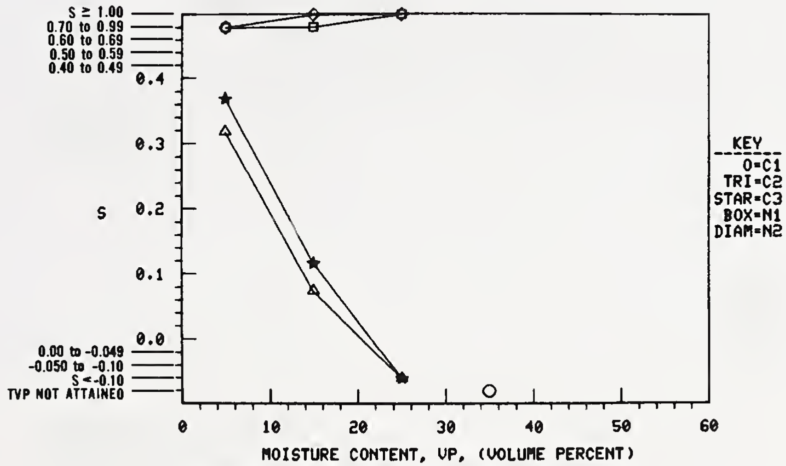


FIGURE A91. FIBERBOARD, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

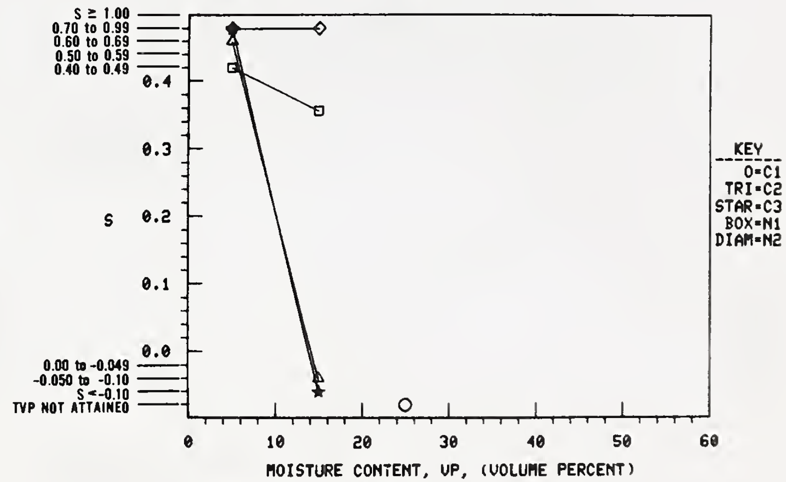


FIGURE A92. FIBERBOARD, 2 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

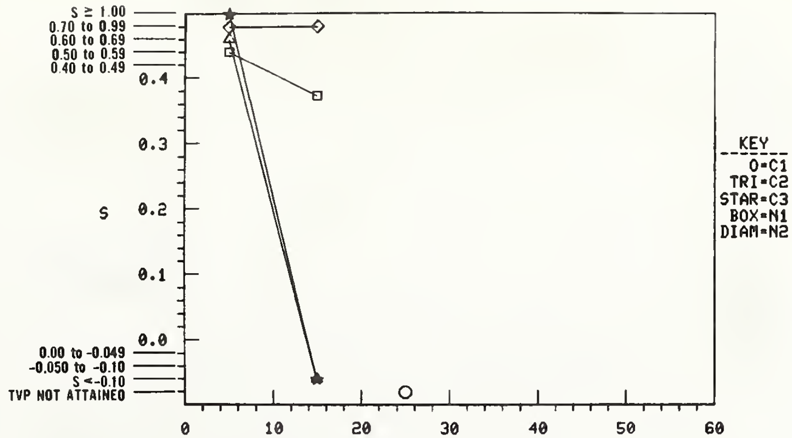


FIGURE A93. FIBERBOARD, 2 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

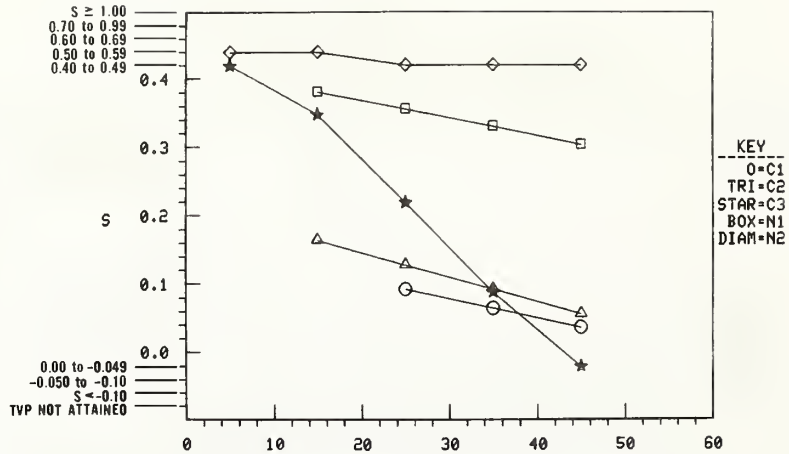


FIGURE A94. POLYSTYRENE, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

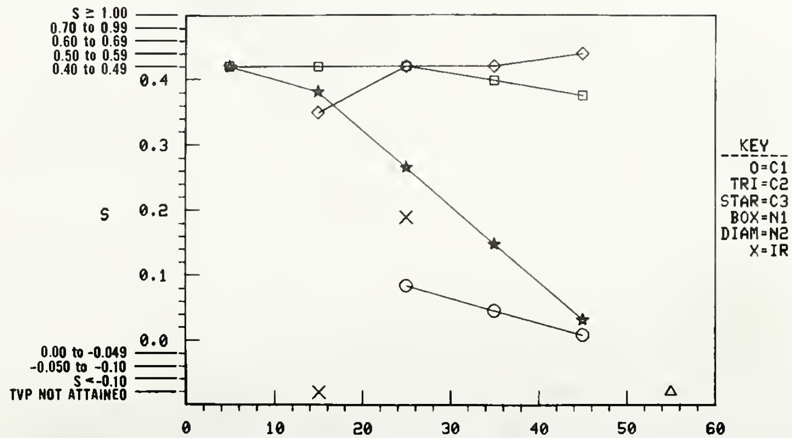


FIGURE A95. POLYSTYRENE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

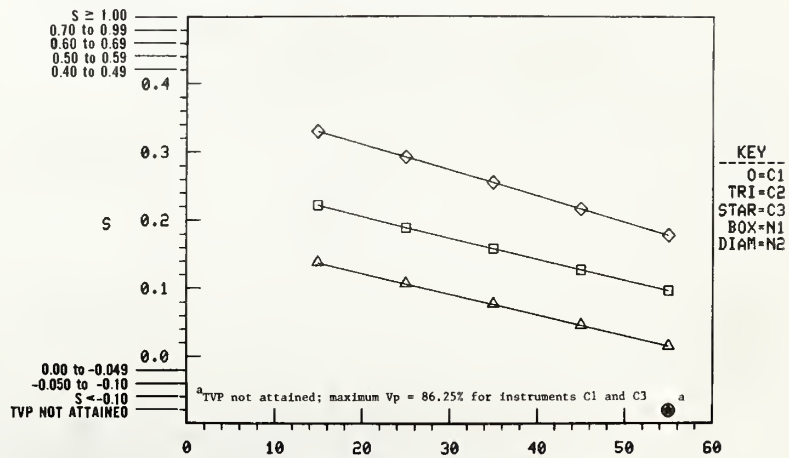
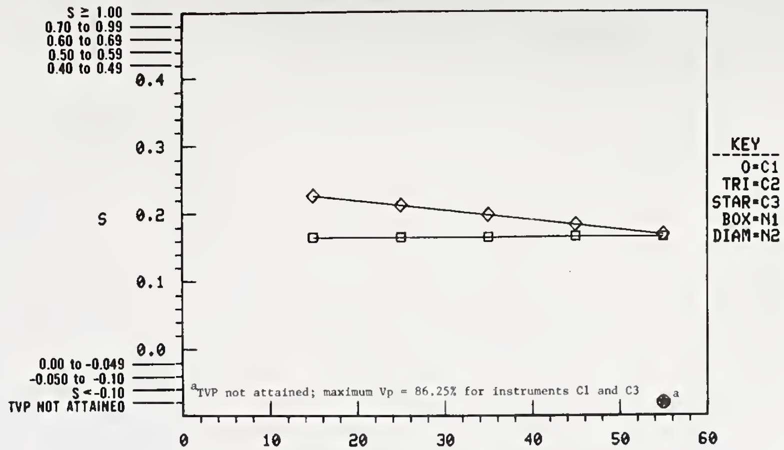


FIGURE A96. POLYSTYRENE, 1 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS



[a] TVP not attained; maximum Vp = 86.25% for instruments C1 and C3

FIGURE A97. POLYSTYRENE, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

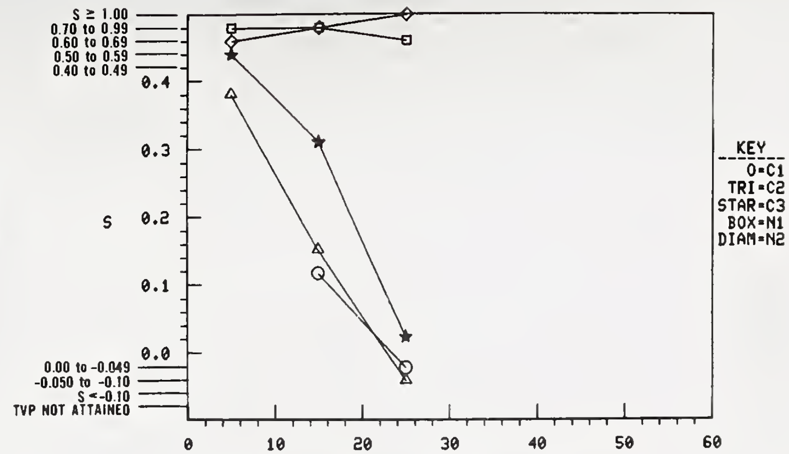


FIGURE A98. POLYSTYRENE, 2 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

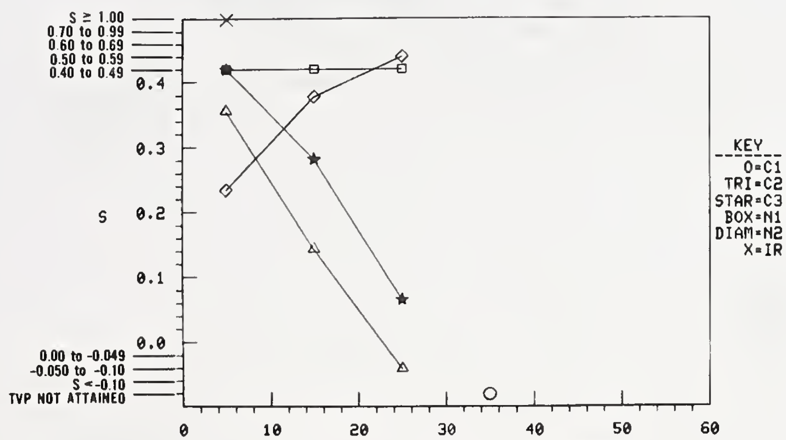


FIGURE A99. POLYSTYRENE, 2 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

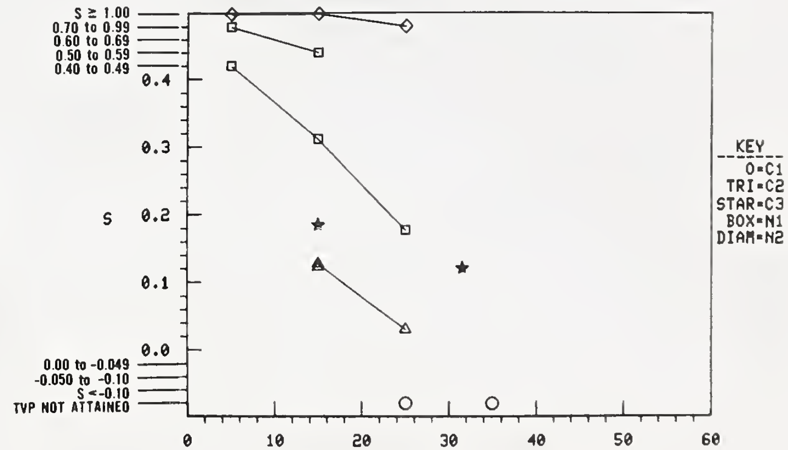


FIGURE A100. POLYSTYRENE, 2 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

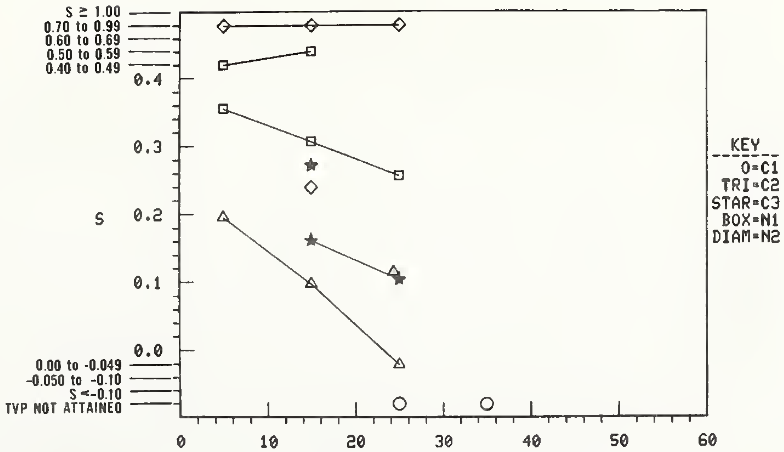


FIGURE A101. POLYSTYRENE, 2 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

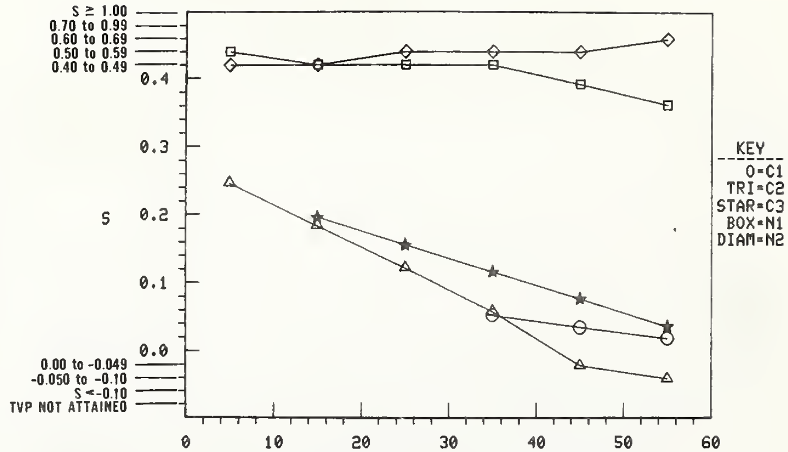


FIGURE A102. POLYURETHANE, 1 INCH, CONCRETE DECK, STANDARD ASPHALT THICKNESS

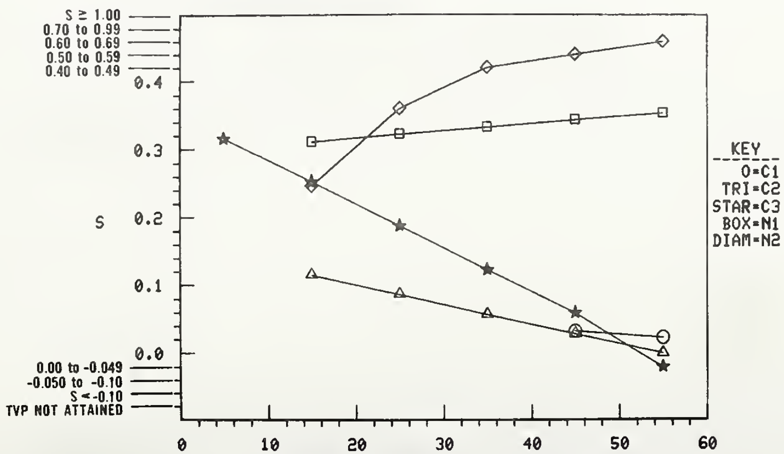


FIGURE A103. POLYURETHANE, 1 INCH, STEEL DECK, STANDARD ASPHALT THICKNESS

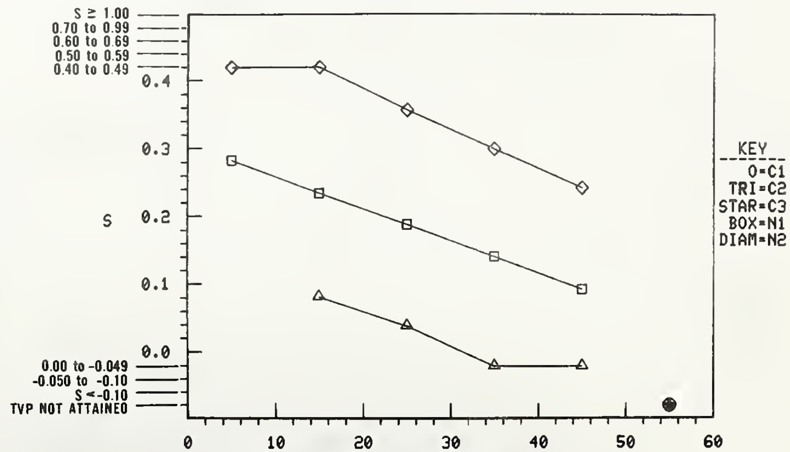


FIGURE A104. POLYURETHANE, 1 INCH, CONCRETE DECK, HEAVY ASPHALT THICKNESS

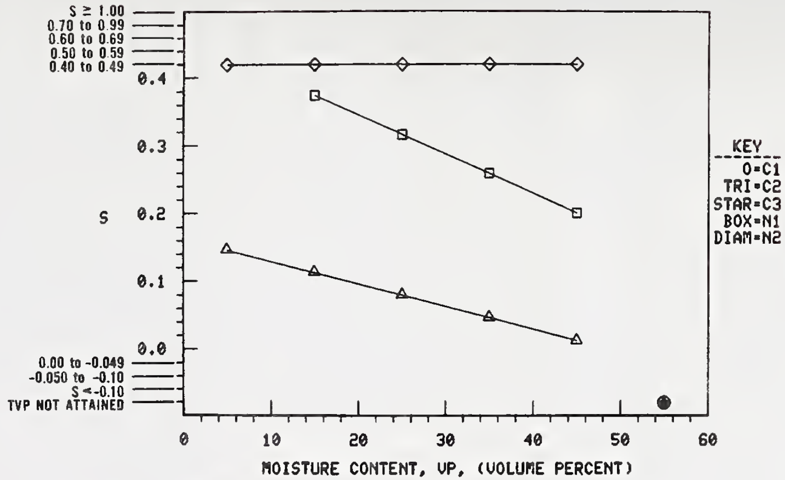


FIGURE A105. POLYURETHANE, 1 INCH, STEEL DECK, HEAVY ASPHALT THICKNESS

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This laboratory study investigated the reliability and accuracy of three types of nondestructive evaluation (NDE) methods to quantitatively determine the moisture content of the insulation in built-up roofing specimens. These methods were electrical capacitance, nuclear backscatter, and infrared thermography. Thirty-six roofing specimens, which consisted of five types of rigid-board roof insulations with attached bituminous built-up membranes, were tested over both concrete and steel decks. A wide range of moisture contents was induced into the specimens by maintaining a constant water vapor pressure difference across them.

Two performance characteristics of the NDE methods were evaluated: (a) the minimum moisture content a method could detect, and (b) the relationship between NDE response and moisture content beyond the minimum detectable moisture content. The two performance characteristics were assessed through normalization parameters defined in terms of the NDE response and its scatter about a fitted curve. There were differences in the performance characteristics, the magnitude of which depended on the NDE method, the specimen composition, and the deck type used.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Built-up roofing electrical capacitance; infrared thermography; insulation; moisture detection; moisture measurement; nondestructive evaluation; nondestructive testing; nuclear backscatter; roofing systems.

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