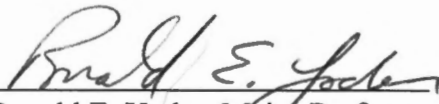
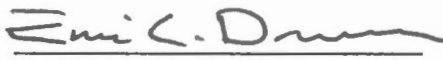


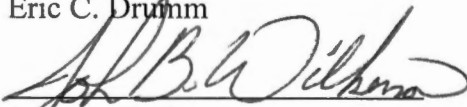
To the Graduate Council:

I am submitting herewith a thesis written by Wesley Carl Wright entitled "*In Situ* Water Content Measurement of Compacted Highway Subgrades Using Time Domain Reflectometry." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.


Ronald E. Yoder, Major Professor

We have read this thesis
and recommend its acceptance:


Eric C. Drumm


John B. Wilkerson

Accepted for the Council:


Associate Vice Chancellor and
Dean of the Graduate School

***In Situ* Water Content Measurement of Compacted Highway
Subgrades Using Time Domain Reflectometry**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Wesley Carl Wright
May 1998

Ag-Vet Med.

Thesis
98
.w75

Dedication

To:

My wife Angela Machelles and son Wesley Austin
for their love, understanding, and support.

ACKNOWLEDGMENTS

The author wishes to express sincere gratitude and appreciation to the following:

The Department of Agricultural and Biosystems Engineering and its Department Head, Dr. Roland Mote, for accepting me into the department and making the departmental resources available.

To Dr. Ronald Yoder, major professor, for his patience, guidance, and advice during my studies.

Appreciation is also extended to Dr. Eric Drumm for his time and friendship.

Sincere thanks for technical support, guidance, and friendship is extended to Nathan Randy Rainwater.

A special thank you to the Tennessee Department of Transportation for the funding of this research project.

To Dr. John Wilkerson, committee member, for his time and advice.

To Mr. Paul Elliot, shop manager, for his mechanical advice and friendship.

To my fellow graduate students Teffany Rich, Scott Glover, Cole Reagan, and Chris Wheeler for their friendship and assistance during my graduate studies.

To my mother and father for supporting me in my academic endeavors.

ABSTRACT

The water content is a principle factor of subgrade soil stability in shallow foundation pavement systems. Currently data do not exist for seasonal subgrade water content changes in Tennessee pavement systems. Four test sites across the state were instrumented with equipment to monitor subgrade and flexible asphalt pavement water content and temperature, water infiltrated through the pavement layers, and climatic conditions. These data will later be used to develop a rational method of flexible asphalt pavement design that accounts for environmental factors and seasonal water content changes.

Five-segment TDR probes, manufactured by *Environmental Sensors*, were installed in the soil subgrade, the stone base, and the asphalt stabilized base. Single-segment TDR probes, constructed in the laboratory, were installed in the asphaltic concrete. The multiple-segment TDR probes allow changes in water content to be tracked two-dimensionally, between the probes and along probe segments. Temperature sensors were installed at depths corresponding to the soil subgrade and the stone base TDR probes. Three temperature sensors were also installed in the top 20 cm of the pavement. A weather station was installed at each test site to monitor air temperature, relative humidity, solar radiation, wind speed, and rainfall.

The *Moisture Point* TDR system, manufactured by *Environmental Sensors*, was

designed for use in agricultural soils. The materials in which the TDR probes were installed at each test site are quite dissimilar from agricultural soils. For this reason, a calibration study was performed with the *Moisture Point* TDR equipment using test site subgrade soils and a single crusher run gravel sample. Ten previously published TDR calibration equations were evaluated to determine which equation most accurately predicts water content for the subgrade soils and for crusher run gravel.

The relationship between inverse signal velocity and water content proposed by Herkelrath et al. (1991) most accurately predicted water content for all subgrade soils; however, this relationship requires the derivation of a soil specific slope and intercept. The three- and four-phase dielectric mixing models, proposed by Dobson et al (1985) and rewritten to calculate volumetric water content by Weitz et al. (1997), provided results within the accuracy of the *Moisture Point* equipment for subgrade soils. The equation proposed by Baran (1994) most accurately predicted water contents for the crusher run gravel.

The use of brand names does not imply consent by *The University of Tennessee* or the
Tennessee Department of Transportation

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
Subgrade Water Content Measurements	1
Time Domain Reflectometry Calibration	3
Objectives	4
II. REVIEW OF THE LITERATURE	6
Principles of Time Domain Reflectometry	6
TDR Calibration	11
Empirical Models	11
Topp et al.	12
Baran	14
Ledieu et al.	15
Malicki et al.	15
Jacobsen and Schjonning	18
Herkelrath et al.	19
Hook and Livingston (and the <i>Moisture Point</i> Equation) ..	20
Dielectric Mixing Models	22
Hallikainen et al. and Dobson et al.	22
Roth et al.	26
Dirksen and Dasberg	28
Wietz et al.	30
TDR Calibration Methods	33
TDR Technique Improvements	34
Previous Flexible Pavement Subgrade Water Content Studies	35
III. MATERIALS AND PROCEDURES	45
Field Instrumentation and Installation	45
Site Location	44
Time Domain Reflectometry Equipment	47
Soil Subgrade Instrumentation	50
Stone Base Material Instrumentation	53
Underground Vault and Instrumentation Cable Routing	54
Pavement Instrumentation	58
Climatological Data Monitoring	64
Concrete Vault Instrumentation and Data Logging Equipment ..	65
Falling Weight Deflectometer Testing	68
Subsurface Investigation	68
Data Collection and Processing	70
<i>Moisture Point</i> Type III TDR Probe Calibration	71
Calibration Setup and Procedure	71
Time to Equilibrium	78

	Calibration Data Analysis	80
	Propagation Time Correction	80
	Calibration Equation Evaluation	82
IV.	RESULTS AND DISCUSSION	85
	Field Instrumentation	85
	Moisture Point TDR System Calibration	86
	Moisture Point TDR System Noise	86
	Moisture Point TDR Calibration Data Analysis	87
	Statistical Analysis of Calibration Data	90
	TDR Calibration Equation Performance for Test site Materials	98
	Soil	98
	Crusher Run Gravel	99
	Individual Calibration Equation Performance	99
	Herkelrath et al.	99
	Moisture Point Equation	100
	Three-Phase Dielectric Mixing Model (Weitz et al.)	102
	Four-Phase Dielectric Mixing Model (Weitz et al.)	102
	Topp et al.	103
	Malicki et al.	104
	Jacobsen and Schjønning	105
	Ledieu et al.	105
	Maxwell Equation (Weitz et al.)	105
	Baran	106
V.	SUMMARY AND CONCLUSIONS	107
	Summary	107
	Conclusions	109
VI.	RECOMMENDATIONS	112
	TDR Calibration Equation for High Density Pavement Systems	112
	Future Research	113
	LITERATURE CITED	114
	APPENDICES	122
	APPENDIX A	123
	APPENDIX B	142
	APPENDIX C	157
	APPENDIX D	173
	APPENDIX E	176
	APPENDIX F	181
	APPENDIX G	226
	APPENDIX H	237
	APPENDIX I	242
	VITA	247

LIST OF FIGURES

	PAGE
Figure 1. Plot of a standard time domain reflectometry signal trace.	9
Figure 2. Four locations of the pavement monitoring test sites in Tennessee.	46
Figure 3. <i>Moisture Point</i> Type III five-segment TDR probe with diode control wire color code.	48
Figure 4. Design of a two-prong, single-segment TDR probe utilizing a switching diode.	49
Figure 5. A cross section of a typical test site showing TDR probe locations.	62
Figure 6. Water delivery apparatus and aluminum test box used to calibrate TDR equipment to test site soils and crusher run gravel	75
Figure 7. Time to equilibrium of test material water content in calibration box (Segment 4)	79
Figure 8. Noise in the <i>Moisture Point</i> five-segment TDR probe (Segment 4).	88

LIST OF PLATES

	PAGE
Plate 1. Installation of five-segment TDR probes in the soil subgrade.	52
Plate 2. Subgrade compaction using a jumping jack style compactor	55
Plate 3. Subsurface concrete vault that contains instrumentation and tipping bucket gages for pan lysimeters.	56
Plate 4. Junction box filled with silicone caulk to protect the cable connections of the <i>Moisture Point</i> five-segment TDR probe head.	57
Plate 5. Conduit to route pavement instrumentation leads to subsurface concrete vault	59
Plate 6. Applying a thermally conductive epoxy to a 108/B <i>CSI</i> thermistor, during pavement thermistor installation.	63
Plate 7. Instrument panel with data loggers and <i>Moisture Point</i> TDR equipment inside the subsurface concrete vault	66
Plate 8. The <i>Moisture Point</i> five-segment TDR probe calibration box with the water delivery apparatus mounted on top. The setup was being continuously weighed by a digital scale.	74

LIST OF TABLES

	PAGE
Table 3-1. Segment correction constants for <i>Moisture Point</i> Type III five-segment probe.	82
Table 3-2. TDR calibration equations evaluated for the <i>Moisture Point</i> five-segment probe	83
Table 4-1. Minimum and maximum volumetric water contents from test site data, 1997	89
Table 4-2. Mean absolute differences of volumetric water content by model for all ranges, probe segments, repetitions, and test site soils	92
Table 4-3. Mean absolute differences of volumetric water content by model for all ranges, probe segments, and repetitions for crusher run test material	93
Table 4-4. Mean absolute differences of high volumetric water content range by model and soil	94
Table 4-5. Mean absolute differences of high volumetric water content range by model for all ranges, probe segments, repetitions, and soils.	96
Table 4-6. Mean absolute differences of high and medium volumetric water content range by model for all probe segments and repetitions of crusher run gravel data	97
Table 4-7. Slopes and intercepts derived from calibration data for the Herkelrath equation	99

CHAPTER I

INTRODUCTION

Subgrade Water Content Measurements

The *AASHTO Road Test*, conducted in the late 1950s and early 1960s, is the basis for current asphaltic pavement design procedures (Yoder and Witczak, 1975). Water content is one of the principle factors of soil stability and is of special significance to shallow foundation pavement systems (Guinee, 1958; Marks and Haliburton, 1969; Russam, 1970; Vaswani, 1975; Rada et al., 1994; Kotdawala et al., 1994; Janoo et al., 1994; van Schelt et al., 1994; Sargand, 1994; Hossain et al., 1997). Drumm et al. (1996) found that a soil compacted at optimum water content (27.1% by mass) and maximum dry density (1.47 Mg m^{-3}) and later subjected to a 3% increase in water content had a resilient modulus decrease from 130 MPa to about 70 to 80 MPa. Methods of water content measurement that offer accurate results, long equipment life spans, continuous monitoring, or safe ways of data acquisition have not been available (van Schelt et al., 1994). This changed with the introduction of time domain reflectometry (TDR)

technology. The applicability of TDR systems for measurement of pavement subgrade water contents has been well documented (Rada et al., 1994; Kotdawala et al., 1994; Look et al., 1994; Janoo et al., 1994; Baran, 1994; van Schelt et al., 1994). Previous studies of pavement subgrade water content have concluded with mixed results. This is probably due to geographical differences in test sites, differences in soil types, accuracy of equipment, incomplete data, possible effects of destructive installation techniques, and/or pavement not being under actual “in use” conditions. These studies also failed to find a correlation between variations in subgrade water content, environmental factors, traffic loading, and/or soil types, although some of these studies concluded there was variation in subgrade water content (Guinnee, 1958; Marks and Haliburton, 1969; Kotdawala et al., 1994; Baran, 1994).

With the design of multiple segment TDR probes by Hook et al. (1992), probes can be installed to examine water content variations two-dimensionally. Multi-segment TDR probe technology has not been previously applied to pavement subgrade systems. Also, with the use of an automated multiplexed system, the interval for data acquisition can be reduced to every few hours rather than a few days in a year, monthly, or every three months as data has been collected in the past.

Time Domain Reflectometry Calibration

Time domain reflectometry is a method of measuring high-frequency signal propagation times. The signal velocity is a function of the ability of a cable to transmit the signal and of the dielectric properties of the material surrounding the cable. TDR is applied to the measurement of soil water content by installing two or three exposed stainless steel waveguides of a probe into the soil. Reflections in the transmission signal are caused at the head of the probe by the abrupt change in dielectric constant, due to the soil, and another stronger reflection is caused when the signal reaches the end of the probe. A cable tester measures the time between the two reflections. From this travel time, the signal velocity can be determined, indicating the apparent dielectric constant of the soil. Topp et al. (1980) found a relationship between the apparent dielectric constant of the soil system and the volumetric water content. Data was gathered from the calibration of four mineral soils. From this data, an empirical relationship was derived that they believed was almost independent of soil type, soil properties, salt content, and temperature. They concluded that only organic matter content and magnetic properties of the soil affected the calibration.

Later work has shown that the apparent dielectric constant is not nearly as independent of soil texture, soil density, and temperature as was first thought (Hellikainen et al., 1985; Dobson et al., 1985; Roth et al., 1990; Herkelrath et al., 1991; Dasberg and Hopmans, 1992; Jacobsen and Schjonning, 1993; Dirksen and Dasberg,

1993; Heimovaara et al., 1994; Pepin et al., 1995; Hook and Livingston, 1996; Weitz et al., 1997). Dobson et al. (1985) showed that fine textured soils had a lower apparent dielectric constant than that of a coarse textured soil at the same water content. They presented two dielectric mixing models to demonstrate the complex interaction between water and clay particles, referred to as bound or absorbed water. Bound water is believed to have a dielectric constant similar to that of ice or soil (Roth et al., 1990; Dasberg and Hopmans, 1992). Dirksen and Dasberg (1993) found that the volume of bound water was very similar to the volume of hygroscopic water, water that remains in air dried soil, which can be as high as $0.11 \text{ m}^3 \text{ m}^{-3}$ for high clay soils. Also, temperature has a measurable effect on the apparent dielectric constant of the soil system. Pepin et al. (1995) found that volumetric water contents (θ_v) measured by TDR should be adjusted for temperature by $0.001750(\theta_v) \text{ }^\circ\text{C}^{-1}$. For this reason, there is a need to adjust the constants of Topp's relationship for a particular soil or to use a more complex relationship to calculate the apparent dielectric constant (Herkelrath et al., 1991; Hook and Livingston, 1996).

Objectives

The objectives of this project were to:

- Install automated highway subgrade monitoring systems at four sites in Tennessee.

- ✓
 - Compare TDR volumetric water contents of the test site soil subgrade to those of soil cores from each site corresponding to each probe depth.
- Perform a calibration study with *Moisture Point*® multiple segment TDR probes to evaluate previously published TDR calibration equations.
 - From this data determine which model is best suited for application in high density test site soils and in a stone base sample (crusher run gravel).

CHAPTER II

REVIEW OF THE LITERATURE

Principles of Time Domain Reflectometry

Time domain reflectometry (TDR) has become a widely accepted method of measuring soil water content and bulk electrical capacitance, due to its fast, precise, and nondestructive *in situ* measurement (Topp et al., 1980; Dasberg and Dalton, 1985; Yanuka et al., 1988; Roth et al., 1990). TDR was originally developed for detecting faults in electrical cables and was later adapted to the measurement of soil water content primarily through the use of empirical relationships. In soil applications, TDR measures the apparent dielectric constant (ϵ) of the soil volume in which the waveguides are inserted. This technique works because the apparent dielectric constant of the soil system is primarily a function of the water content.

The dielectric constant of a material is a measure of its insulating capabilities. It is equal to the ratio of the electrostatic capacity of condenser plates separated by a given material to that of the same condenser plates separated by a vacuum (Scullion and Saarenketo, 1996). In the application of TDR, the dielectric constant is equal to the

electrostatic capacity of the probe waveguides separated by a soil system. When the dielectric constant of a soil system is measured, in reality the average (which can be expressed as apparent or composite also) dielectric constant of the four major soil components is measured according to the proportion of each in the soil system. The four major soil components are air, soil solids, bound water, and free water (Heimovaara et al., 1994). Since the water content of a soil system is constantly changing, the dielectric is not really a constant but rather a variable. The dielectric of a soil system could be considered a constant at only the specific water content and temperature at which the measurement was taken. The apparent dielectric constant of a material is frequency-dependent, therefore the sensitivity of TDR is frequency-dependent. The most sensitive frequency range, for moist soils, is between 50 MHz and 10 GHz. At frequencies below 50 MHz, the apparent dielectric constant of moist soils depends strongly on the soil type; at frequencies above 10 GHz, the apparent dielectric constant drops off due to water relaxation (Roth et al., 1990). At 1 GHz and 20 °C the dielectric constant of pure water is 80.36, while that of a mineral soil particle ranges from 2 to 5, and the constant for air is typically defined as 1 (Dasberg and Dalton, 1985).

The apparent dielectric constant of the soil system is determined by measuring the propagation time of a voltage pulse signal along a coaxial cable transmission line connected to a probe embedded in the soil. The components of the soil act as a dielectric medium surrounding the probe. The amplitude and velocity of the signal are dependent on the electrical properties of the transmission line and the dielectric medium surrounding the waveguides of a probe. Typically the initial signal velocity, transmission line length,

and waveguides lengths are known. The basic TDR equipment setup consists of a cable tester and a probe embedded in the soil with a connecting transmission line of coaxial cable; the coaxial cable has little effect on results for lengths less than 27 m (Herkelrath et al., 1991).

The cable tester produces a fast rise-time-step increase in voltage, typically measured in picoseconds, that triggers an oscilloscope scan. The signal wave travels through an impedance-matching transformer balun, to offset the cable length, and along the coaxial cable until it reaches the soil. Due to an impedance mismatch at the soil surface, caused by a rapid change in dielectric constant, part of the original signal is reflected back to the cable tester, and the rest of the signal proceeds down the probe. The signal propagates along the waveguides as a plane wave until the signal reaches the end of the waveguides and is reflected back to the cable tester. Upon arrival at the cable tester, the signal is identified by the change in voltage (Figure 1). The cable tester may repeat this process several times to get a stable picture on the oscilloscope. From the arrival times of the signal reflections, the transit velocity, which is indicative of the apparent dielectric constant of the soil, can be computed by equation [1] (Herkelrath et al., 1991).

$$v = \frac{2 l}{\Delta t} \quad [1]$$

where, v - signal velocity in waveguides in meters per second

l - length of waveguides in meters

t - time of transit in seconds.

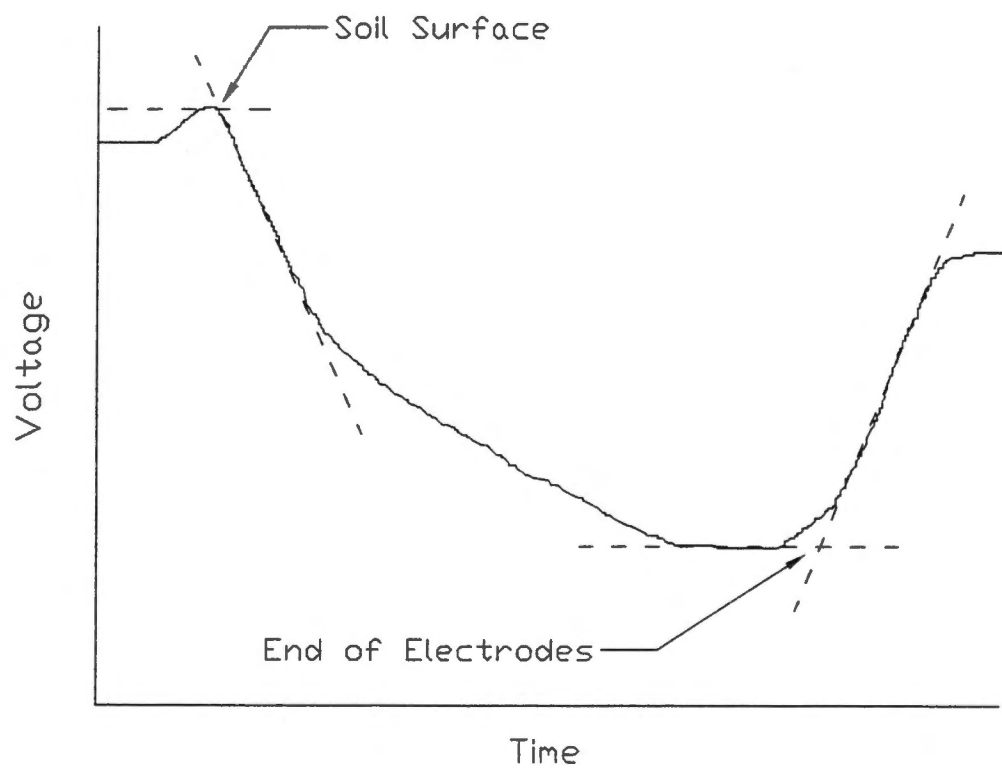


Figure 1. Plot of standard time domain reflectometry signal trace.

By incorporating the signal velocity through the waveguides into equation [2] the apparent dielectric constant (ϵ) of the soil can be computed (Dasberg and Dalton, 1985; Heimovaara and Bouten, 1990).

$$\epsilon = \left[\frac{c}{v} \right]^2 = \left[\frac{c \Delta t}{2 l} \right]^2 \quad [2]$$

where, c - 3×10^8 meters per second (velocity of light in free space)
 t - time of transit in nanoseconds
 l - length of waveguide in meters
 ϵ - apparent dielectric constant (K_a).

Probes are typically two or three parallel waveguides separated by only a few centimeters (Topp et al., 1982). Topp and Davis (1985b) concluded that as the length of waveguides and the spacing between waveguides increase, the resolution decreases. The area of influence around parallel waveguides that make up a probe is about 1.4 times the spacing between the waveguides (Topp and Davis, 1985b). Petersen et al. (1995) found that waveguides spaced 5 cm apart gave a cross-sectional area of influence of about 38 cm², which supports Topp and Davis' finding. The choice of waveguide configuration depends on the medium into which the probe will be inserted (Topp and Davis, 1985a).

TDR Calibration

Empirical Models

There have been two primary approaches to relate apparent dielectric constant to volumetric soil water content. The first approach fits empirical relationships to experimental data. This method has yielded satisfactory results but has no physical justification. The validity of these relationships has been questioned, due to the inability of empirical models to fit the data derived from a wide range of soil types (Jacobsen and Schjonning, 1993).

At wave frequencies of 1 to 20 GHz, fine textured soils have been found to have lower apparent dielectric constant values than coarse textured soils at the same water content (Roth et al., 1990; Dasberg and Hopmans, 1992). This is believed to be caused by interactions between water molecules and clay particles (bound water). The water within a soil system exists as either bound water or free water. Clay minerals tend to have a natural negative charge, which varies depending on the clay mineralogy. The water molecules are systematically arranged toward the negatively charged surface of a clay mineral and form an electrical bond between the hydrogen atoms of the water and the negative charge of the clay mineral surface. The primary bound water layer has been measured to be 10 to 20 angstroms thick, has a high density, and is tightly bound. The outer bound water layer around the clay mineral can extend to 100 angstroms depending on the clay mineralogy and the specific surface area (Scullion and Saarenketo, 1996).

The bonding forces decrease with distance from the clay mineral surface and are sensitive to changes in temperature and pressure. The layers of bound water closest to the clay particle are dielectrically similar to soil and ice, having a dielectric constant of approximately 3.2 (Roth et al., 1990; Dasberg and Hopmans, 1992). Bound water has an dielectric constant in the range of 20 to 40, depending on the clay mineralogy, when the dielectric constants of all bound water layers are averaged (Dobson et al., 1985). The effect of bound water on the apparent dielectric constant is that it disproportionately weights the dielectric constant of water, which is 80.36 at 20 °C, in the soil system. For this reason, some researchers indicate a need to collect empirical data to adjust polynomial constants when using TDR in a research application where absolute measurements of soil water content are required (Herkelrath et al., 1991; Werkhoven, 1994).

Topp et al.

The most widely used empirical relationship between apparent dielectric constant (ϵ) and volumetric soil water content (θ_v = volume of water over total volume) is known as Topp's Universal Equation ([3]) (Topp et al., 1980).

$$\theta_v = -0.053 + 0.0293\epsilon - 0.00055\epsilon^2 + 0.0000043\epsilon^3 \quad [3]$$

The coefficients for this equation were derived using laboratory calibration data from four mineral soils and from glass beads. The textural classes for the four soils were a sandy loam (9% clay), clay loam (34% clay), clay loam (36% clay), and a heavy clay (66% clay). The dry bulk densities (dry bulk density is the ratio of dry solids over total volume) of the soils ranged from 1.3 to 1.4 Mg m⁻³ and the volumetric water contents ranged from 0.1 to 0.5 m³ m⁻³. Topp et al. (1980) concluded that individual soils within these ranges of water content and density do not require specific calibration so long as they are derived from a mineral parent material. Also, the apparent dielectric constant is almost independent of soil density, texture, and salt content, and there is no significant dependence on temperature. The apparent dielectric constant ranged from 3 to 40 for a volumetric soil water content change of 0 to 0.55 m³ m⁻³ in mineral soils used in this study. Topp et al (1980) also concluded that the apparent dielectric constant was weakly dependent on operating frequencies between 20 MHz and 1 GHz.

Topp's equation is not suitable for high bulk density clay soils (Dasberg and Hopmans, 1992; Dirksen and Dasberg, 1993), soils high in organic matter (Topp et al., 1980; Herkelrath et al., 1991), or soils with very low or high bulk density (Dirksen and Dasberg, 1993). Topp and Davis (1985a) found the standard deviation of the differences between TDR, using Topp's equation, and gravimetric samples to be ± 0.02 m³ m⁻³ when the measured locations were the same.

There is a debate on whether salinity has a significant effect on apparent dielectric measurements. Salinity was not found to have a significant effect on the dielectric properties of soil by Topp et al. (1980) and Roth et al. (1990), but Dasberg and Dalton

(1985) concluded the affect of salinity on the dielectric properties of the soil is significant enough to affect TDR measurements. Due to large differences in dielectric constants, soils high in organic matter, vermiculite clay, and soils with magnetic properties like those that contain maghemite and magnetite will substantially influence TDR apparent dielectric constant measurements (Topp et al., 1980; Herkelrath et al., 1991; Roth et al., 1990; Dirksen and Dasberg, 1993).

Baran

Baran (1994) found that Topp's Universal equation was valid for loosely compacted crushed gravel (dry bulk density: 1.5 Mg m⁻³) and for clay subgrade material (dry bulk density: 1.85 Mg m⁻³), but the Topp Universal equation is unsuitable for high density samples of crushed rock. Baran developed a new relationship (Equation [4]), relating the apparent dielectric constant and volumetric soil water content for dense paving materials.

$$\theta_v = -0.062164 + 0.023831\epsilon - 0.000598\epsilon^2 + 0.000006\epsilon^3 \quad [4]$$

(for apparent dielectric constants 5 < ϵ < 25)

Ledieu et al.

Ledieu et al. (1986) established a calibration relationship predicting soil volumetric water content using wave transit time and soil bulk density. Plastic columns 150 mm in length and 100 mm in diameter were packed at 0.04 m³ m⁻³ volumetric water content with a loam soil that passed a 2-mm sieve. The soil was compacted using vibration and hydraulic jacks. The resulting dry bulk densities ranged from 1.38 Mg m⁻³ to 1.78 Mg m⁻³. The soil columns were saturated using a Marriotte flask and were drained using a vacuum pump. The volumetric soil water content of the soil columns varied between 0.10-0.38 m³ m⁻³. The exact water content was determined by weighing the soil columns. Two TDR probes were placed in each sample. The resulting relationship including dry bulk density, which was found to have a small effect, is equation [5].

$$\theta_v = 5.688t - 3.38\delta - 15.29 \quad [5]$$

where, t - transit time in nanoseconds

δ - dry bulk density (Mg m⁻³).

Malicki et al.

Roth et al. (1992) concluded a single calibration equation for mineral soil and a separate equation for organic soils could be developed. They suggested that site specific

calibration is unnecessary if an absolute error of $0.015 \text{ m}^3 \text{ m}^{-3}$ for mineral soils is acceptable. The presence of magnetic properties in the soil were not found to significantly effect TDR results.

A later publication by this research team (Malicki et al., 1996) provides empirical relationships that account for porosity or dry bulk density. Soil particle dielectric constant and particle density were assumed to be relatively stable between different soils. Malicki et al. (1996) concluded that changes in the volumetric soil water content due to the soil solid phase is primarily a result of degree of compaction. Sixty-two materials were used to test the effect of the solid matrix on TDR measurements of apparent dielectric constant. The test materials consisted of mineral soils with different textures and dry bulk densities, organic soils with different amounts of organic material, potting soils, peat-loess and peat-sand mixtures, sea and river sands, forest litter, and wood products (bark, shavings, and sawdust).

Soil samples were air dried and passed through a 2-mm sieve. The samples were moistened in five to eight steps, to cover a range of water contents. The moistened soil samples were packed into beakers that were 60 mm in diameter by 80 mm in height. Forest materials were packed into beakers that were 100 mm in diameter by 150 mm in height. TDR probes were inserted into the beakers and the apparent dielectric constant was determined for each material. After TDR results were recorded, a sample was taken from each beaker for an independent determination of volumetric soil water content, dry bulk density, and particle density. A total of 894 data points were collected for apparent dielectric constant, volumetric soil water content, dry bulk density, and particle density.

Dry bulk density and porosity were found to cause a similar amount of error in TDR measurements of apparent dielectric constant. Malicki et al. (1996) concluded that a universal calibration equation for all soils could not exist without including a physical parameter for the soil matrix. The error caused by influences of the soil matrix could be accounted for by including a parameter for dry bulk density or porosity in a conversion function. The resulting conversion equation accounting for dry bulk density is equation [6] or when accounting for porosity is equation [7].

$$\theta_v = \frac{\sqrt{\varepsilon} - 0.819 - 0.168\rho - 0.159\rho^2}{7.17 + 1.18\rho} \quad [6]$$

where, ε - apparent dielectric constant from equation [2]
 ρ - dry bulk density (Mg m^{-3}).

$$\theta_v = \frac{\sqrt{\varepsilon} - 3.47 + 6.22\eta - 3.82\eta^2}{7.01 + 6.89\eta - 7.83\eta^2} \quad [7]$$

where, ε - apparent dielectric constant from equation [2]
 η - porosity.

These equations allow inclusion of factors related to the soil matrix. Malicki et al. (1996) determined either of the conversion equations reduced the root mean square error to $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$.

Jacobsen and Schjonning

Jacobsen and Schjonning (1993) derived a new empirical relationship for soil sampled from five sites. The soil was sieved, air dried, and separated into several sub-samples. The sub-samples were moistened to different volumetric water contents in steps of approximately $0.025 \text{ m}^3 \text{ m}^{-3}$. After the application of water, the soil sub-samples were allowed to equilibrate for several days. The soil sub-samples of each water content were then packed into PVC cylinders. Due to the difficulty of packing the soil to the original field dry bulk density, the actual values of dry bulk density obtained in the PVC cylinders were used to determine volumetric water content. The resulting empirical equation from this calibration was a third-order polynomial (Equation [8]).

$$\theta_v = -7.01 \times 10^{-2} + 3.47 \times 10^{-2} \epsilon - 11.6 \times 10^{-4} \epsilon^2 + 18.0 \times 10^{-6} \epsilon^3 \quad [8]$$

By comparing results from equation [8] and Topp's equation [3], Jacobsen and Schjonning (1993) concluded that neither gave satisfactory results at volumetric soil water contents above $0.28 \text{ m}^3 \text{ m}^{-3}$. A multiple linear regression was performed with volumetric soil water content as the dependent variable and ϵ , ϵ^2 , ϵ^3 , dry bulk density in Mg m^{-3} , organic matter, and particle size as the explanatory variables. By inclusion and elimination of the variables, dry bulk density, clay content, and organic matter significantly improved the calibration equation ($R^2 = 0.989$, $SD = 0.0097$) (Equation [9]).

$$\theta_v = -3.41 \times 10^{-2} + 3.45 \times 10^{-2} \epsilon - 11.4 \times 10^{-4} \epsilon^2 + 17.1 \times 10^{-6} \epsilon^3 \quad [9]$$

$$- 3.70 \times 10^{-2} \rho_b + 7.36 \times 10^{-4} \% \text{ clay} + 47.7 \times 10^{-4} \% \text{ organic matter}$$

where, ρ_b - dry bulk density (Mg m^{-3}).

Herkelrath et al.

Herkelrath et al. (1991) indicated there is a linear fit between the reciprocal of the signal velocity (v) (Equation [2]) and volumetric soil water content. Using this linear fit, they derived a linear model to calculate volumetric soil water content. Experimental data were obtained using five undisturbed soil cores approximately 100 mm in diameter by 510 mm long. The cores were collected using polyvinyl chloride pipe (PVC) driven into the ground and then extracted by digging around the outer circumference of the pipe. The PVC pipe was then glued to a plexiglass base that contained a screen to keep the soil sample intact. TDR probes with 3-mm waveguides, separated by 50 mm and 500 mm in length, were installed vertically into the columns. The columns were saturated with tap water and a suction was applied from the bottom of the column to remove water and to draw air through the columns.

TDR measurements were taken to determine the signal velocity along the waveguides, and the column weights corresponding to TDR measurements were recorded. When suction no longer removed a substantial amount of water, the columns

were oven dried at 105 °C for seventy-two hours to determine the remaining gravimetric water content and the dry bulk density of the soil column. The gravimetric soil water content of the soil column, corresponding to each TDR measurement, was determined by the difference between measured column mass and oven-dry mass. Volumetric soil water content, at each of these points, was determined as the ratio between gravimetric water content and the dry bulk density of the soil column. Like other empirical relationships, this method requires soil specific calibration to determine a new slope and intercept in the linear model.

Hook and Livingston (and the Moisture Point Equation)

Hook and Livingston (1996) derived a physically based linear model in which TDR measurements are expressed as a ratio of the signal propagation time in soil (T_s) to that in air (T_{air}). The model predicts a linear relationship between T_s/T_{air} and the volumetric soil water content in non-clay soils. The relationship has a slope of $1/(K_w^{0.5} - 1)$, where K_w is the dielectric constant of water. The slope does not vary between soils, but is slightly temperature dependent and at 20 °C is 0.1256. The intercept of T_s/T_{air} can be obtained experimentally, or a published value can be selected. Most agricultural soils have a T_s/T_{air} that ranges from 1.4 to 1.7. The expression proposed by Hook and Livingston (1996) is:

$$\theta_v = \frac{(t * c) / (2 * l)}{K_w^{0.5} - 1} \quad [10]$$

where,

t - transit time in seconds

c - 3×10^8 meters per second (velocity of light in free space)

l - waveguide length

K_w - dielectric constant of water at 20 °C.

Hook and Livingston (1996) indicate that the model can be applied to clay soils to determine free water and that the difference between predicted and gravimetrically determined volumetric soil water content represents bound water. For this reason, they specify that their model is mainly limited to non-clay soils. Soils high in clay, with a substantial amount of bound water, may require a more complex model.

The *Moisture Point* equation (Young, 1995a) for the five-segment probes is based on the Hook & Livingston equation. The adjusted form is:

$$\theta_v = \frac{[(T_{mc} * c) / (2 * L) - T_s / T_a]}{[(K_w^{0.5}) - 1]} \quad [11]$$

where,

T_{mc} - corrected propagation time in seconds

c - 3×10^8 meters per second (velocity of light in free space)

L - probe segment length in meters

T_s - corrected propagation time in oven dried soil

T_a - corrected propagation time in air

K_w - dielectric constant of water.

Dielectric Mixing Models

To more accurately explain the apparent dielectric constant of soil, the second approach relating apparent dielectric constant to volumetric soil water content has been to incorporate soil physical characteristics into a semi-empirical and physically based three- or four-component dielectric mixing model. The three-component mixing model accounts for the volume and dielectric constant of air, soil solids, and water. Incorporating the dielectric differences between bound and free water, the four-component mixing model goes a step further by separating these into different components.

Hallikainen et al. and Dobson et al.

In the first of a two-part research effort, Hallikainen et al. (1985) were among the first to evaluate the effect of bound and free water, temperature, and soil textural composition on apparent dielectric constant behavior of the soil system. The study focused on signal wave frequencies between 1.4 and 18 GHz. Soil texture was found to have a significant effect on dielectric behavior, especially at frequencies below 5 GHz. Two dielectric mixing models were later presented to account for these behaviors. In the second part of the research, Dobson et al. (1985) presented a physically based four-component dielectric mixing model to calculate the apparent dielectric constant of the soil system, which is written:

$$\varepsilon = \frac{3\varepsilon_s + 2\theta_{fw}(\varepsilon_{fw} - \varepsilon_s) + 2\theta_{bw}(\varepsilon_{bw} - \varepsilon_s) + 2\theta_a(\varepsilon_a - \varepsilon_s)}{3 + \theta_{fw}\left(\frac{\varepsilon_s}{\varepsilon_{fw}} - 1\right) + \theta_{bw}\left(\frac{\varepsilon_s}{\varepsilon_{bw}} - 1\right) + \theta_a\left(\frac{\varepsilon_s}{\varepsilon_a} - 1\right)} \quad [12]$$

where, φ - percent porosity (volume of air / total volume)

ε - apparent dielectric constant

bw - subscript for bound water

fw - subscript for free water

a - subscript for air

s - subscript for soil solid phase

θ - volume fraction of each parameter in $\text{m}^3 \text{m}^{-3}$.

This is a theoretical model based on the Maxwell equation, describing a homogeneous mixture of one or more substances, randomly distributed in a medium, with different dielectric constants (de Loor, 1964). The Maxwell equation was rewritten by Dobson et al. (1985) as a four-component soil-water system, with dry soil solids as the host medium, containing randomly distributed and randomly oriented disc-shaped inclusions of bound water, free water, and air. This theoretical soil-water system model uses only physical soil parameters without any other fitting parameters. Dobson et al. (1985) found the theoretical model yields values that correlate well with observed results. The observed results were derived from TDR wave scans that were converted to apparent dielectric constants using equation [2]. The Maxwell equation was not intended as a

TDR calibration equation. The purpose was to explain why fine textured soils have lower apparent dielectric constants than do coarse textured soils of equal water content.

The major problem with this model is that there are systematic prediction errors caused by the uncertainty in assigning values to the volume fraction of bound water and its average dielectric constant (Dobson et al., 1985; Dirksen and Dasberg, 1993). To separate the volume of bound water from the volume of free water, an appropriate soil model must be selected based on the available measured soil physical characteristics.

Dobson et al. (1985) used a soil physical model that assumes a plate-model of bound water around the clay particle. The plate model treats the soil particle as planar with a net specific surface area units of $\text{m}^2 \text{g}^{-1}$. The bound water layer, also referred to as the Gouy layer, is assumed to have a maximum thickness of 3 angstroms. The number most difficult to obtain is the clay particle specific surface area. The clay particle specific surface area is readily measurable by absorption techniques, but this method is not readily available to most researchers. The specific surface area can be estimated from tables with knowledge of the clay mineralogy and soil particle size distribution. Dobson et al. (1985) suggested refinements could be made to the plate-model results by using soil absorption techniques to measure the specific surface area of the clay particles and by including interactions between clay particles when the separation is small.

A second dielectric mixing model was derived from the Birchak semi-empirical mixing model by Dobson et al. (1985). The Birchak model is based on the assumption that the total is equal to the sum of the volumetric mixing of each of the inputs. Dobson et al. (1985) applied the Birchak mixing model to moist soil to obtain:

$$\varepsilon^{\alpha} = \theta_s \varepsilon_s^{\alpha} + \theta_a \varepsilon_a^{\alpha} + \theta_{fw} \varepsilon_{fw}^{\alpha} + \theta_{bw} \varepsilon_{bw}^{\alpha} \quad [13]$$

where,

ε - apparent dielectric constant

bw - subscript for bound water

fw - subscript for free water

a - subscript for air

s - subscript for soil solid phase

ϕ - percent porosity (volume air / total volume)

θ - volume fraction of each parameter in $\text{m}^3 \text{m}^{-3}$

α - curve fitting parameter.

The α is a curve fitting parameter related to the geometry of the medium with relation to the applied electric field (Roth et al., 1990; Dirksen and Dasberg, 1993).

The curve fitting parameter α allows flexibility in the input parameters of bound water volume and average dielectric constant. These parameters become approximations and estimates based on the textural composition of the soil. Dobson et al. (1985) found the best fit value of α to be 0.65 in a four-phase system that contained bound water. Roth et al. (1990) found the α value to be closer to the theoretical value proposed by Birchak, which was 0.5, when they used a three-phase system that disregarded bound water. Roth et al., (1990) felt this discrepancy was mainly caused by differences between operating frequencies. Dobson et al. (1985) were working primarily at frequencies higher than 4

GHz, because the semi-empirical model was believed to perform best in that range of frequencies. At frequencies higher than 4 GHz, the effects of clay content, and subsequently bound water, become less significant due to the dielectric relaxation of bound water.

Roth et al.

The semi-empirical dielectric mixing model (Equation [13]) was presented by Dobson et al. (1985) as an alternative equation to explain the effect of soil bulk density and texture on the apparent dielectric constant of the soil system. The semi-empirical model was later developed into a TDR calibration equation by Roth et al. (1990). The resulting calibration equation was derived from the three-component form of the semi-empirical model. This approach disregards the effects of bound water but does include bulk density. The method uses the apparent dielectric constant, computed from the TDR propagation time (Equation [2]), and converts it to an apparent dielectric constant that is relative to the dielectric constant of water at 20 °C. The TDR propagation time in soil is divided by the propagation time in pure water. The resulting ratio does not depend on the cable tester nor the cable tester calibration ([14]).

$$\zeta_c = \frac{\epsilon_c}{\epsilon_w} = \left(\frac{L}{L_w}\right)^2 \quad [14]$$

where,

- ζ_c - relative dielectric constant of soil
- ϵ_c - apparent dielectric constant of soil
- ϵ_w - dielectric constant of water at 20 °C
- L - signal propagation time along probe in soil
- L_w - signal propagation time along probe in pure water.

The volumetric water content can then be calculated from equation [15]. The dielectric values for each parameter are relative to the dielectric constant of water at 20 °C.

$$\theta_v = \frac{\zeta_c^\alpha - (1 - \eta)\zeta_s^\alpha - \eta\zeta_a^\alpha}{\zeta_w^\alpha - \zeta_a^\alpha} \quad [15]$$

where,

- ζ_c^α - relative apparent dielectric constant (Eq. [14])
- η - percent porosity (volume of air / total volume)
- ζ_s^α - relative dielectric constant of soil (0.048)
- ζ_a^α - relative dielectric constant of air (0.012)
- ζ_w^α - relative dielectric constant of water (1.0)
- α - fitting parameter

(Dobson et al. 1985, $\alpha=0.65$ and Roth et al. 1990, $\alpha=0.5$)

Roth et al. (1990) estimated that equation [15] predicted volumetric soil water content with an uncertainty (root mean square error) not to exceed $0.013 \text{ m}^3 \text{ m}^{-3}$. This precision is comparable to the thermogravimetric method. The accuracy of the results may be improved by more accurately determining the apparent dielectric constant ζ_c^α , the dielectric constant of the soil ζ_s^α , and the porosity η . Using a temperature correction for the dielectric constant of water should also be considered since it is the easiest parameter to measure.

Dirksen and Dasberg

Dirksen and Dasberg (1993) compared apparent dielectric constant values obtained from Topp's Equation [3] (when used to derive apparent dielectric constant instead of water content), the Maxwell-De Looze model, and the semi-empirical model using the α curve fitting parameter. The assumed standard apparent dielectric constant was derived by inserting the TDR propagation time into equation [2]. They used eleven soils that ranged texturally from a sandy loam to an almost pure clay. The soils were air dried, sieved to 2 mm, wetted and mixed at a variety of water contents, and packed into ceramic cylinders. After TDR scans were taken at each water content, the true volumetric soil water content was calculated from oven dry soil mass and the bulk density of each cylinder. This procedure was repeated in an attempt to duplicate the results. Assuming one monomolecular water layer, the volume of bound water was calculated using:

$$\theta_{bw} = l \Upsilon \rho_b S \quad [16]$$

where,

- θ_{bw} - volume of bound water
- l - number of layers (typically set to one monomolecular layer, therefore $l = 1$)
- Υ - thickness of one monomolecular layer ($\Upsilon = 3 \times 10^{-10}$ m)
- ρ_b - dry bulk density (Mg m^{-3})
- S - specific surface area of clay mineral ($\text{m}^2 \text{g}^{-1}$).

The hygroscopic water content (air dried volumetric soil water content) was found to be very similar to the volumetric water content of bound water and was therefore suggested for use instead of the calculated value. The dielectric constant of bound water was assumed to be that of ice (3.2). The α value for the semi-empirical equation was derived as a best fit value for each soil. The values ranged from -0.10 to 0.81.

The resulting apparent dielectric constant data derived from each equation was compared, using linear regression, to that determined by TDR. The resulting R^2 was used to compare the fit of data from each equation to the actual apparent dielectric constant data. After comparison of the equations, Topp's equation was found to be valid for soils with low clay contents and typical dry bulk densities ($1.35\text{-}1.50 \text{ Mg m}^{-3}$). Dirksen and Dasberg (1993) felt that deviations from Topp's equation were due to lower dry bulk densities associated with finer textured soils rather than to bound water with a lower

dielectric constant. The Maxwell-De Looor model resulted in a satisfactory fit with the experimental data for seven of the eleven test soils. Topp's equation fit data better on the two soils with the lowest clay fraction. The Maxwell-De Looor model broke down at volumetric soil water contents above $0.30 \text{ m}^3 \text{ m}^{-3}$. Dobson et al. (1985) suggested this is a short coming of this model. The semi-empirical α model yielded data similar to the Maxwell-De Looor model, but because α varies from soil to soil, is not measurable, and is insensitive to anomalous behavior, it was concluded the semi-empirical model is inferior to the Maxwell-De Looor model.

Weitz et al.

Weitz et al. (1997) compared Topp's equation [3] to the three- and four-phase α models and the Maxwell-De Looor model, which were developed by Dobson et al. (1985). The three- and four-phase α models and the Maxwell-De Looor model were rewritten to calculate the volumetric soil water content instead of the apparent dielectric constant. The data were collected with a *Tektronix*® 1502B cable tester, a *Campbell Scientific, Inc.*® (CSI) SDM152 interface, and a CSI CR10 data logger. The probe design consisted of two 3.2-mm stainless steel rod waveguides with a 300-mm length and a 30-mm spacing between waveguide centers. The rod ends were encased in epoxy. The stainless steel soil calibration box held a 0.35 by 0.13 by 0.07-m undisturbed soil sample that was excavated by hand. The box was found to have no significant effects on the TDR signal propagation. The undisturbed soil blocks were covered to prevent evaporation losses and

were saturated over a three-week period. After each calibration test, the box was uncovered and allowed to dry by means of evaporation. Daily box weights and corresponding TDR scans were recorded. The soil blocks required two to three weeks to air dry, after which they were placed in an oven at 105 °C for 48 hours to determine the final gravimetric soil water content. The daily volumetric soil water contents of the soil block were then calculated based on the final gravimetric water content and the field dry bulk density.

The three-phase dielectric mixing model was rewritten into the following expression to calculate the volumetric water content:

$$\theta_v = \frac{[K_a^\alpha - (1 - \varphi)\epsilon_s^\alpha - \varphi\epsilon_a^\alpha]}{(\epsilon_w^\alpha - \epsilon_a^\alpha)} \quad [17]$$

where,

ϵ_w - dielectric constant of water

ϵ_a - dielectric constant of air

ϵ_s - dielectric constant of soil solid phase

φ - percent porosity (volume air / total volume)

α - curve fitting parameter

K_a - apparent dielectric constant (Equation [2]).

The semi-empirical four-phase dielectric mixing model rewritten to calculate volumetric water content is:

$$\theta_v = \frac{[K_a^\alpha - \theta_{bw}(\epsilon_{bw}^\alpha - \epsilon_{fw}^\alpha) - (1 - \varphi)\epsilon_s^\alpha - \varphi\epsilon_a^\alpha]}{(\epsilon_{fw}^\alpha - \epsilon_a^\alpha)} \quad [18]$$

where, ϵ_{bw} - dielectric constant of bound water
 θ_{bw} - volume fraction of bound water
 (Other subscripts are the same as above).

The Maxwell equation arranged to calculate volumetric water content is:

$$\theta_v = \frac{[3(\epsilon_s - K_a) - 2\theta_{bw}(\epsilon_{bw} - \epsilon_{fw}) + 2\varphi(\epsilon_a - \epsilon_s) + K_a\theta_{bw}(\epsilon_s\epsilon_{fw}^{-1} - \epsilon_s\epsilon_{bw}^{-1}) - K_a\varphi(\epsilon_s\epsilon_a^{-1} - 1)]}{[K_a(\epsilon_s\epsilon_{fw}^{-1} - \epsilon_s\epsilon_a^{-1}) + 2(\epsilon_a - \epsilon_{fw})]} \quad [19]$$

where, (All subscripts are the same as above).

The root mean square error was calculated for actual water contents derived from gravimetric measurements and the corresponding water contents were estimated using each of the calibration models. The three-phase α model (Equation [17]) with a fitting parameter of 0.47 and assuming a bound water dielectric constant of 4 performed better than the other models for a variety of low density soils.

TDR Calibration Methods

The traditional method of single-segment probe TDR calibration has involved wetting a soil sample with de-ionized water or a solution of water with a low concentration of calcium sulfate. The water was typically applied to the soil using a spray bottle to reduce soil clumping. The soil was then mixed and placed into a sealed container for at least twenty-four hours to cure. This ensured an even distribution of water in the calibration soil. The soil was then packed into a steel or PVC column to a specified dry bulk density. After several TDR wave scans were recorded, the soil column was oven dried to verify the volumetric water content. This method has been employed by many researchers working on TDR calibration (e.g., Topp et al., 1980; Dirksen and Dasberg, 1993; Jacobsen and Schjonning, 1993; Noborio et al., 1994; Malicki et al., 1996).

Herkelrath et al. (1991) inserted a single-segment TDR probe into a column of continuously weighed saturated soil, and removed water from the soil by applying suction at the base of the column. As the column dried, mass and the corresponding apparent dielectric constants were recorded. The soil was drained as much as possible by suction, and was oven dried to determine the volumetric water content for each apparent dielectric constant. This method worked well for single segment-probes, because the water content did not have to be evenly distributed in the column to obtain accurate results. The single-segment TDR probe scan was an average of the conditions in the column and this gave

the correct average volumetric water content.

Young et al. (1997) continuously forced water into a soil column. This method is also based on the theory that the average apparent dielectric constant would be the same as the apparent dielectric constant of soil with evenly distributed water. The mass of a soil column was continuously weighed and recorded, while corresponding TDR scans were performed and recorded. These scans were performed every three minutes and continued from seven to thirteen hours. At the same time, a six channel syringe pump forced water into the base of the soil column. When free water was observed on the top of the soil column, the volumetric water content was determined by oven drying the column. This method was found to compare very well with the traditional method of TDR calibration.

TDR Technique Improvements

Pepin et al. (1995) focused on the effect of temperature on apparent dielectric constant measurement of soils. The dielectric constant of water is much more sensitive to temperature than is the dielectric constant of soil and air. Since water has the greatest influence on apparent dielectric constant, small changes in the dielectric constant of water can have significant effects on the subsequent calculated volumetric soil water content. To obtain the highest measurement accuracy, Pepin et al. (1995) suggested using a temperature correction of $0.001750(\theta_v) ^\circ\text{C}^{-1}$.

Hook et al. (1992) showed that remotely switched diodes in combination with differential detection techniques produced reflected signals with larger amplitudes and distinctive reflection wave signatures. The sharper returns at the points of discontinuity allowed for reduction of background noise. When a diode is closed, a strong negative reflection is created at that point. When the diode is open, the electromagnetic pulse continues along the waveguide unaffected until another discontinuity is reached. With the use of multiple switching diodes, segmented probes can be constructed with diodes at the beginning and end of each segment. This type of probe is used in the current research.

Previous Flexible Pavement Subgrade Water Content Studies

The *AASHTO Road Test*, conducted in the late 1950s and early 1960s, is the basis for current asphaltic pavement design procedures (Yoder and Witczak, 1975). Water content is the fundamental variable of soil stability and is of special significance to shallow foundation pavement systems (Guinnee, 1958; Marks and Haliburton, 1969; Russam, 1970; Vaswani, 1975; Rada et al., 1994; Kotdawala et al., 1994; Janoo et al., 1994; van Schelt et al., 1994; Sargand, 1994; Hossain et al., 1997). Methods of water content measurement that offer accurate results, long equipment life spans, continuous monitoring, or safe ways of data acquisition have not been available (van Shelt et al.,

1994). Advances in electronic sensors, material testing techniques, and automated data acquisition systems make it possible to monitor the asphaltic pavement systems in a nondestructive manner.

The *Missouri State Highway Department* was one of the first agencies to undertake a long term study of pavement subgrade water content and temperature. The Missouri highway study allowed for soil samples to be taken manually (Guinnee, 1958). After each sample was taken, the soil had to be replaced in the core hole, tamped to the correct density, and capped with concrete. The high amount of labor and the destructive testing technique allowed the project team to only take samples in three-month intervals. The project engineers later used ceramic plate resistance cells, which were much less labor intensive but proved to be inaccurate and expensive to install, to measure soil water content. The project was discontinued due to the short life span of these cells. Although data were collected for seven years, the project ended with more questions than answers due to incomplete and inaccurate data. The conclusion that was drawn from the seven years of data collection was that some sites showed seasonal variations in water content as high as 25%. On average from all the sites, over the course of seven years, there was no substantial seasonal variation.

Marks and Haliburton (1969), of *Oklahoma State University*, undertook a six year study of Oklahoma pavement to correlate subgrade water content variations to soil type, climate, and pavement conditions. The water content measurement tool chosen was a neutron depth moisture and density gauge. The water content data were collected from fifty sites at an interval of six to eight weeks. Density data were collected every six

months. The conclusions drawn from this study were:

“moisture variations were found to occur in an annual cycle with maximum moisture contents occurring during winter months; high moisture contents occurred during cold seasons and decreased during summer months, but variations could not be correlated to temperature; variations in moisture content resulting from infiltration of runoff lagged rainfall by 4 to 6 weeks; sealed shoulders reduced infiltration, resulting in smaller variations; soil type was found to have no noticeable effect on subgrade moisture variations beneath Oklahoma pavements; subgrade moisture contents appear to be gradually increasing beneath pavements with no stable conditions indicated.”

In 1975, Virginia addressed the problem of water content variations in pavement subgrades. Vaswani (1975) reported the study examined pavements from new to 10 years old in an attempt to correlate temperature gradients to soil water contents. The water content measurement tool used was a neutron probe. Data were collected over a period of two years at an interval of every two months. The study focused on the potential differences between cut and fill locations due to differences in foundation material, drainage, density, etc. Cut locations were found to increase in gravimetric soil water content by about 3 to 5% during the nine months of new road construction. The fill locations accumulated as much as a 20% increase in gravimetric soil water content, which was thought to be due to the lower density of the fill material as compared to the rocky subgrade of the cut locations. After construction was complete, the rate of water content increase was almost unnoticeable. In the interior areas of the ten-year old pavement, it was concluded that there is almost no change in subgrade water content.

The *Federal Highway Administration's (FHWA's) Long Term Pavement Performance (LTPP)* study program began a study in 1991 referred to as the *Seasonal Monitoring Program (SMP)* (Janoo et al., 1994; Rada et al., 1994). The objective of this project was to collect data needed to understand the effects of variations in temperature, water content, and traffic. Sixty-four test sites across North America were equipped with TDR systems. The TDR configuration was chosen through a trial comparison, at three sites, between three TDR probe designs and a *Troxler® (Sentry 2000)* system.

The *Troxler (Sentry 2000)* is a capacitance probe. The capacitance theory of soil water content measurement also uses soil dielectric properties to calculate water content. The *Sentry 2000* probe is placed in an access tube and does not come into direct contact with the soil. The probe consists of two electrodes separated by an insulating spacer, similar to a capacitor. The electromagnetic field created by the electrodes penetrates the soil at a certain frequency. The dielectric properties of the soil surrounding the access tube change the frequency output. The affect is measured and a correlation is made to determine the water content. Capacitance measurements can be greatly influenced by the care taken during installation of the access tube, which is typically a two-inch diameter schedule 40 PVC pipe. Over compaction and void spaces are the main sources of inaccuracies. Preferential flow around the access tube may also interfere with accuracy.

The TDR system was chosen over the *Troxler* capacitance probe for several reasons. The TDR supplied reasonable and reliable water contents and was not greatly affected by salinity as was the capacitance probe, and the capacitance operator must stand in the road to acquire data, which requires traffic control. Problems maintaining the

integrity and water tightness of the capacitance probe access hole were also contributing factors to the choice. The TDR probe design chosen was a flat three-waveguide, single-segment probe. These probes were installed vertically in existing pavement sections through auger holes. The holes were refilled with soil, stone, and asphalt and compacted to the original densities. Volumetric water content was calculated using Topp's Universal Equation. Ten probes were installed at each site and data were recorded with *Campbell Scientific, Inc.* CR10X data loggers. *Seasonal Monitoring Program* data were collected on twelve to fourteen "test days" each year, with each probe scanned on four-hour intervals. It was found that for clay subgrades, the difference between TDR and gravimetric method readings of soil water content varied as much as 10%. At the time of this report, data collection was incomplete so final conclusions have not been drawn.

Look et al. (1994), engineers with the *Materials and Geotechnical Services Branch of Queensland Transport (QT)*, reported on field experiences, accuracies, and inaccuracies of using TDR to measure pavement subgrade water content at their testing facility in Australia. Topp's Universal Equation was accepted as reliable and accurate for clays. This was later disproved by Baran (1994), a member of the *QT* team, after he showed Topp's Universal Equation to be inaccurate in high density materials such as crushed rock and highly compacted clays.

The TDR probes were installed vertically in test pavement subgrades. The subgrade was treated as any other construction site, including compacting the soil with a 10-tonne vibrating compactor. Upon completion of the site, it was found that only seven of the twelve probes survived construction. Initial TDR readings were taken two to four

days after completion of installation. These readings were compared to volumetric soil water contents from samples taken at the time of probe installation, which showed the TDR readings to be 5-7% lower. This was thought to be due to the delay in taking initial readings. Later test sites produced better results between “as constructed” water content readings and the initial TDR readings. The conclusions drawn from this study were that their latest probe design gave satisfactory results for engineering purposes, where ease of monitoring and the change in water content rather than the accurate water content were the important factors influencing design and construction.

In 1993, the *Kansas Department of Transportation (KDOT)* initiated a research project with *Kansas State University* to correlate seasonal variation in water contents of subgrades with the structural response (FWD-measured deflections) of pavements (Kotdawala et al., 1994). The state was divided into three zones using thirty years of precipitation and temperature data. Using a general soil map, seven 150-m long test sites were chosen in the middle zone, which was assumed to represent average climatic conditions for the state of Kansas. The general soil type of the seven sites is a silty clay.

The project team concluded that neutron probes were a secondary choice to TDR probes due to the need for access holes and traffic control. The TDR probes were a three rod-type manufactured by *Soilmoisture Equipment Corporation®*. The probes were installed 76 m apart at each site. A 100-mm core hole was drilled to the soil subgrade in the outer wheel path of the travel lane. TDR probe rods were driven approximately 200 mm into the subgrade. The probe head was approximately 460 mm below the pavement surface. A saw cut was made from the probe to the pavement edge. The access hole and

saw cut were later recompact and sealed.

Soil water content measurements were made, at least monthly at each site, using a *Tektronix*® Model 1502 cable tester. TDR volumetric soil water contents, determined with Topp's Universal Equation, were found to agree within $\pm 0.02 \text{ m}^3 \text{ m}^{-3}$ of oven dried gravimetric soil water contents of samples taken at the time of TDR probe installation. This study confirmed that TDR technology is suitable for pavement subgrade water content measurement. The need for soil-specific TDR calibration and salinity, caused by heavy road salting for ice removal, was thought to be a possible source of error in the TDR water content measurements.

Asphalt pavements in Kansas experience relatively constant moisture condition during most of the year, with the exception of the northeast part of the state which shows a slightly higher variation (Hossain et al., 1997). Overall, the water contents changed 3 to 6% by mass, but the asphalt pavements with a granular subgrade had fluctuations in moisture content that exceeded 10% (Hossain et al., 1997). Despite frequent precipitation, it appeared that soil water content did not change significantly with precipitation at any site, and soil water movement was virtually negligible during the dry winter months in Kansas. Most subgrade water contents did not change significantly over a one-year period, but many sites showed individual readings that had a significant variation (Hossain et al., 1997).

The *Ohio Department of Transportation*, in conjunction with the *Federal Highway Administration* as part of its *Strategic Highway Research Program (SHRP)*, constructed a test highway section to develop an empirical design procedure for pavement

systems. The general statements made below were reported by Sargand (1994) and SHRP (1997). The three mile long test road was constructed in the pre-existing 170-ft median of US-23 approximately 25 miles north of Columbus, OH in Delaware County. New north and south bound lanes were constructed. The north bound lanes were constructed of portland concrete, and the southbound lanes were constructed of asphaltic concrete.

When construction was completed, all traffic was diverted to the test road, and the existing roadway was maintained for local traffic and mainline traffic in the event a repair to the test road was required. Data were collected on the response of different pavement designs to seasonal conditions and traffic loading. The test sections were constructed from a combination of materials and layer thicknesses and were divided into four categories. These categories were structural factors for flexible pavement, structural factors for rigid pavement, environmental effects in the absence of heavy traffic, and asphalt program field verification studies. Different types and combinations of pavement base were used to construct the test road. These bases include dense graded aggregate base, asphalt treated base, permeable asphalt treated base, permeable cement treated base, and lean concrete base.

Of the forty test sections, thirty-four were instrumented by civil engineering departments from six universities in Ohio. Environmental parameter and pavement response instruments were installed in twenty test sections. The environmental parameters measured were temperature, water content, frost depth, soil suction, and water table elevation, and pavement response parameters included strain, pressure,

displacement, and joint opening. Only pavement response instruments were installed in another fourteen test sections, and six test section were not instrumented with pavement response and environmental sensors.

An on-site weather station was installed to collect air temperature, precipitation, wind speed and direction, relative humidity, and incoming solar radiation. *Federal Highway Administration* TDR mini-probes, produced by *Campbell Scientific, Inc.*, were used to measure the water content of the granular base layer and soil subgrade. Ten probes were installed in each test section. Temperatures were measured using *Measurement Research Corporation®* thermistor probes. Three to four thermistors were installed in the surface layers and as many as fifteen were installed in the base and subgrade layers. Resistivity probes, developed by the *Cold Regions Research and Engineering Laboratory* of the *Corps of Engineers*, were used to monitor frost depth. Each resistivity probe consists of thirty-six ring wire electrodes, spaced 51 mm (2 in.) apart and mounted on a polyvinyl chloride (PVC) rod. Water table elevations are monitored using a piezometer.

The installation of the TDR probes, thermistors, and resistivity probes required boring a 300-mm (12-in.) diameter hole through the base before the placement of asphalt or concrete. The bore hole was located in the outer wheel path, which was 600 to 900 mm (2 to 3 ft) from the edge of the pavement. Pavement and concrete joints were avoided by at least 1.2 m (4 ft) to avoid surface water infiltration. The bore hole was drilled to a depth of approximately 2.1 m (7 ft) below the surface of the stabilized base layer. The thermistor and resistivity probes were installed at a depth of approximately 51

mm (2 in.) below the bottom of the lowest stabilized layer. The first TDR probe was placed at mid-depth of the granular base layer. The subsequent probes were installed at 150-mm (6 in.) intervals except for the last two probes, which were installed at 300 mm (12 in.) intervals. At the time of this publication, conclusions had not been drawn from the data.

CHAPTER III

MATERIALS AND PROCEDURES

Field Instrumentation and Installation

Site Location

The four sites chosen for instrumentation are located in four different physiographic regions of Tennessee (Blount County, I-140, Ridge and Valley; Overton County, state Route 42, Eastern Highland Rim; Sumner County, state Route 139, Central Basin; and McNairy County, US-45, Southern Coastal Plain) (Figure 2). The four test sites represent the variety of climatic and geotechnical conditions that exist across the State of Tennessee. Only sites that were under construction, with no asphalt in place, were considered for instrumentation. This allowed the monitoring equipment to be installed with minimal disturbance to the natural conditions of the subgrade and asphalt layers. Initially only subgrade instruments were installed, and the other instruments were installed as construction progressed.

The State of Tennessee

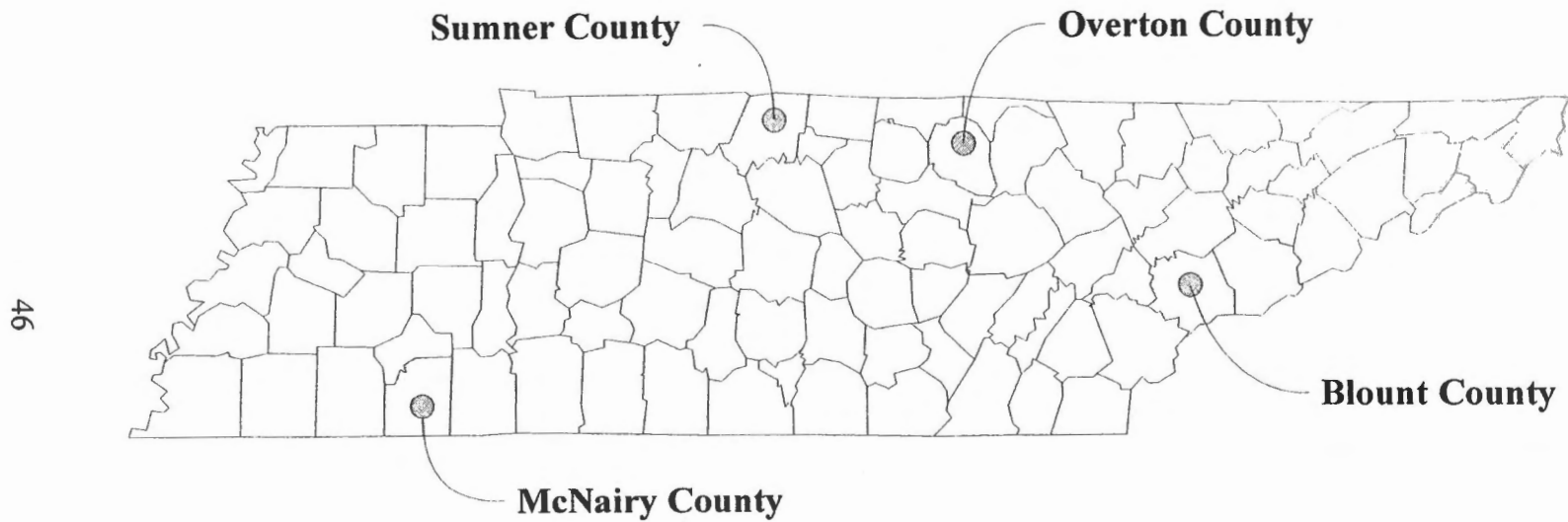


Figure 2. Four locations of the pavement monitoring test sites in Tennessee.

Time Domain Reflectometry Equipment

The TDR method of water content measurement was used because probes could be installed with minimal disturbance of the surrounding subgrade material, and because five-segment TDR probes allow for the two-dimensional tracking of water movement vertically between probes and horizontally along the probe segments. Other water content measuring techniques require the use of access holes, radioactive materials, or have a short life expectancy, all of which were unacceptable for this project. *Moisture Point* five-segment TDR probes (Figure 3) produced by *Environmental Sensors*® are used to monitor the volumetric water content of the subgrade and of some asphalt layers. These probes have segments that are 300 mm in length. The waveguides are stainless steel plates approximately 12.7 mm ($\frac{1}{2}$ in.) wide by 3.2 mm ($\frac{1}{8}$ in.) thick, separated by 12.7 mm of high density plastic and epoxy.

The five segments are electrically separated by *Motorola*® MPN 3404 PIN switching diodes encased in the epoxy and high density plastic. The diodes are switched by control wires with each control wire acting on a pair of diodes. These diodes mimic the end of the probe, causing a strong reflection, and separate the segments on solid waveguides. Based on research by Hook and Livingston (1992), this increases the accuracy and precision of the equipment to measure the signal propagation time.

Single-segment probes, fabricated in the laboratory, were used to measure water content in some asphalt layers (Figure 4). Two 3.2-mm ($\frac{1}{8}$ -in.) stainless steel rods, 400 mm in length, and a nylon terminal block were used to construct these probes. These

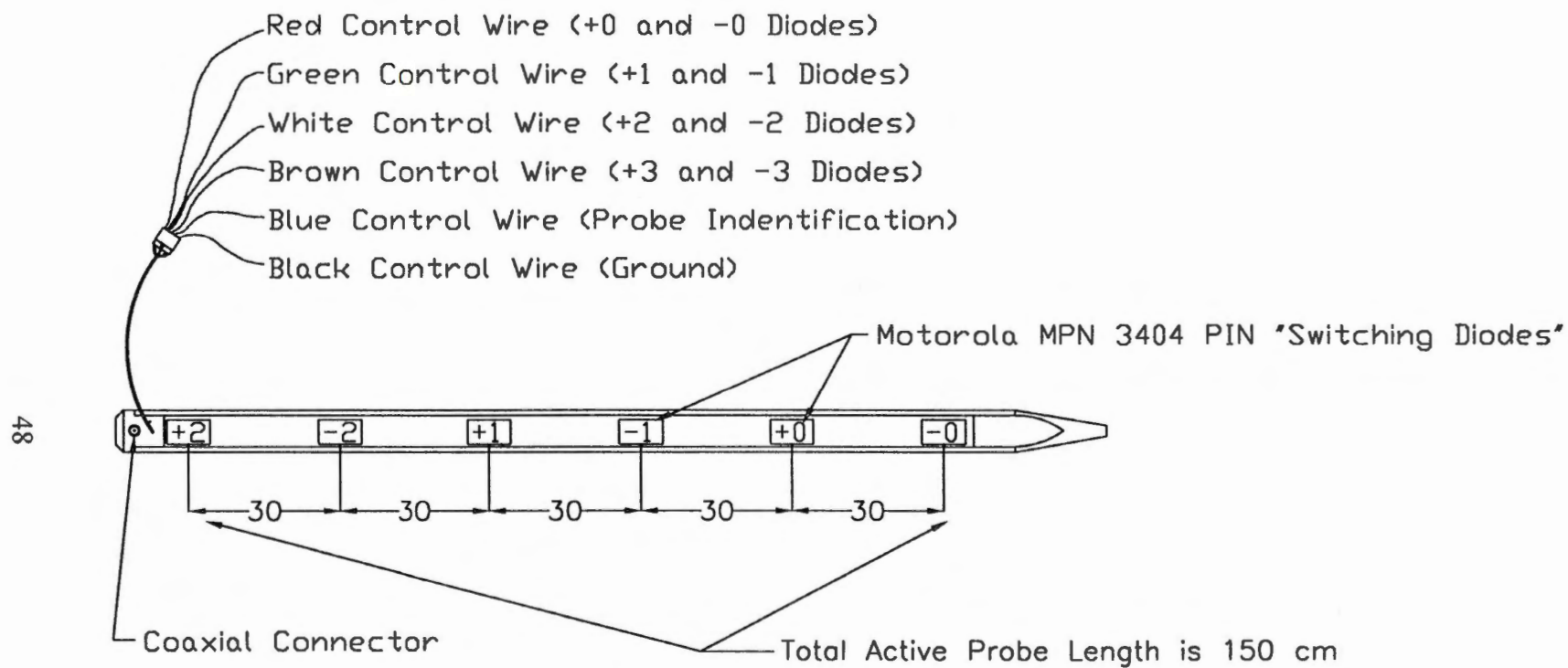
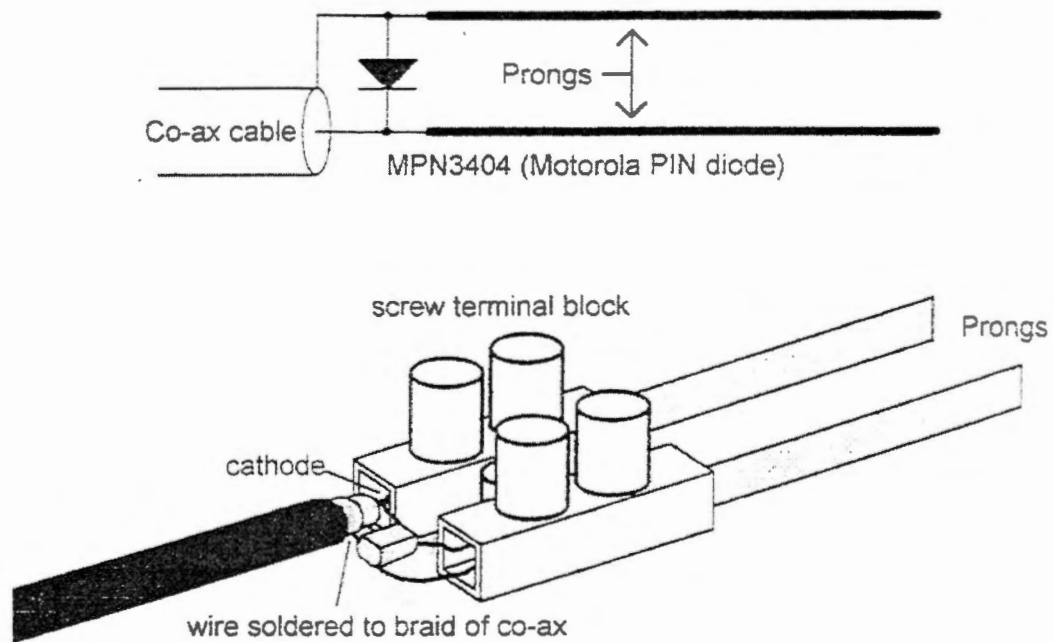


Figure 3. *Moisture Point* Type III five-segment TDR probe with diode control wire color code.



Encapsulate terminal block with silicon sealant to make connections water proof.

Figure 4. Design of a two-prong, single-segment TDR probe utilizing a switching diode (Young 1995a).

single-segment probes use a single *Motorola MPN 3404 PIN* switching diode at the head of the probe. This diode serves to mark the head of the probe with a strong reflection rather than depending on a sudden change in impedance at the soil interface, which only causes a small reflection (Young, 1995a).

The signal detection device used to measure signal propagation times was the *Moisture Point MP-917*, which is produced by *Environmental Sensors*. The *Moisture Point MP-917* utilizes signal discrimination and processing techniques. These techniques help reduce noise in the signal, make waveform detection and discrimination clearer, and apply signal validation that is specific to TDR applications in uncompacted soil. The MP-917 can be used in a multiplexed system allowing data acquisition from probes at a maximum distance of 100 m (Young, 1995b). This cable tester was specifically designed for the use of multiple segment probes and controls the switching diodes corresponding to the segment being scanned.

Soil Subgrade Instrumentation

The TDR probes were installed in the outer 1 m of the travel lane. This was based on research by Chu and Humphries (1972) that suggests the water content under asphalt pavement is rather constant except for a zone under the outer wheel path of the travel lane. To differentiate between the different subgrade layers, all TDR probes were installed in a horizontal position perpendicular to the direction of travel.

In order to install the soil subgrade TDR probes with minimal disturbance, a 1 m

(36 in.) wide by 1.5-m (60-in.) deep trench was excavated with a backhoe. The trench started at the edge of pavement, which is just outside the white line of the travel lane, and was excavated perpendicular to the travel lane to approximately 4 m (13 ft) from the edge of the pavement. Using the vertical cut face at the edge of pavement, the soil subgrade was fitted with three five-segment probes (Plate 1). The five-segment probes have an overall length of approximately 1.8 m (6 ft), making them too fragile to be driven into the dense soil subgrade without being damaged. A solid steel pilot rod, the same shape as the probe but slightly undersized, was first driven into the soil subgrade by hand. Using the hydraulics of the backhoe boom, the pilot rod was extracted without deforming the sides of the pilot hole. The five-segment probe was then lubricated with water and hammered back into the pilot hole until it was firmly seated. This procedure was repeated for the other two soil subgrade probes. The three probes installed in the soil subgrade were at depths of approximately 1200 mm (48 in.), 500 mm (19 in.), and 15 mm (6 in.) below the surface of the soil subgrade. Due to debris encountered while driving the pilot rod, these depths vary slightly from site to site. Actual probe depths are given in Table G-11.

At corresponding depths of the three, five-segment TDR probes, *Campbell Scientific Incorporated (CSI) 107/B* thermistors were installed to monitor soil subgrade temperature. A steel dowel rod was used to make a shallow pilot hole, before the thermistors were installed in the soil subgrade. Soil was pushed tightly around the thermistors to ensure solid soil contact.



Plate 1. Installation of five-segment TDR probes in the soil subgrade.

Stone Base Material Instrumentation

The first layer of base material on the soil subgrade was approximately 250 to 300 mm (10 in.) of crusher run gravel. Crusher run gravel is a mixture of lime and fine to coarse magnesium and/or calcium carbonate gravel at all test sites. Two, five-segment TDR probes were installed in the crusher run gravel. The first probe was located just above the bottom of the layer, which was near the interface of the soil subgrade and stone base. The second probe was located close to the top, which was near the interface of stone base and the first layer of asphaltic base. The Sumner test site also has two five-segment probes located under the longitudinal joint between the travel lanes at the same depths as the other probes in the stone base. The probes were installed in the gravel by hand digging a trench just large enough for the probe. Two CSI 107/B thermistors were also placed at corresponding locations of the probes.

The exact amount of water infiltrating through the pavement layers is also of interest. Two 1-m² stainless steel pan lysimeters were installed at Overton and McNairy test sites. The Blount test site was not instrumented with pan lysimeters because the roadway construction progressed before the pan lysimeters could be installed. Four pan lysimeters were installed at the Sumner test site; two of which were installed under the longitudinal joint. The pan lysimeters are 76 mm deep at the back, sloping to 102 mm deep at the front where an approximately 10-mm ($\frac{3}{8}$ -in.) inside diameter drain is located. The top edge of the pan lysimeter side walls were positioned so that they were even with the top surface of the stone base. This ensured that only water moving through the

asphalt layers would enter the pan lysimeters. The pan lysimeters were placed some distance from the TDR probes to avoid effecting water content results. A jumping jack style compactor (Plate 2) was used to compact the crusher run gravel and soil to pre-installation densities. Most test sites were also compacted with a twelve-ton vibrating compactor before the first layer of asphalt was placed.

Underground Vault and Instrumentation Cable Routing

A 1.8 m (6 ft) by 1.8 m by 1.8 m inside dimension concrete vault was installed at the end of the 4-m (13-ft) trench (Plate 3). The vault (similar to a septic tank) was constructed by *Precast Concrete Company* of Powell, TN in two sections. The vault was designed to be traffic capable, since it would be located just off the shoulder of the roadway and may need to support vehicles. An aluminum door was placed in the top of the vault to allow user entrance. There are three major cable access holes, fitted with schedule 40 polyvinyl chloride (PVC) couplings, located in the sides of the vault to provide entrance for instrumentation cables. A hole was excavated to a sufficient depth, using a backhoe, that the top surface of the vault would be even with surrounding material when pavement construction was finished. A drain pipe was installed in the bottom of each vault. The drain allowed water that collected inside the vault to flow out by gravity rather than by pumping.

The five-segment TDR probe heads were outfitted with electrical junction boxes, which were filled with caulk, to protect cable to probe connections (Plate 4) from



Plate 2. Subgrade compaction using a jumping jack style compactor.



Plate 3. Subsurface concrete vault that contains instrumentation and tipping bucket gages for pan lysimeters.



Plate 4. Junction box filled with silicone caulk to protect the cable connections of the *Moisture Point* five-segment TDR probe head.

environmental damage. The junction boxes were equipped with 19-mm ($\frac{3}{4}$ -in.) coupling type connectors. The TDR probe coaxial and control wire cable were routed through this connector into 19-mm ($\frac{3}{4}$ -in.) flexible PVC conduit to a common schedule 40 PVC conduit leading into the concrete vault. Each TDR probe and thermistor cable was routed through a separate flexible conduit to the main conduits. There were two main conduits entering the side of the vault facing the roadway. The lower main conduit was located in the lower right corner of the concrete vault and was used to route the soil subgrade and stone base TDR probe and thermistor cables into the vault (Plate 5). The upper main conduit was used to route the asphalt TDR probe cables and the pan lysimeter drain tubes into the vault. However, at the Sumner test site, two of the four pan lysimeter drain tubes entered the lower main conduit. The upper main conduit was installed when the vault, soil subgrade and stone base TDR probes and thermistors, and pan lysimeters were installed. A steel pull cable was left in the upper main conduit to pull the other TDR probe cables through later, during other pavement construction phases.

Pavement Instrumentation

The first layer of asphalt placed was the asphaltic stabilized base which serves as the drainage layer of asphalt. This layer, approximately 75 mm (3 in.) thick, is comprised of approximately 10- to 20-mm magnesium and/or calcium carbonate gravel loosely bound together by asphalt. Site specific pavement thickness is given in Table H-1. The McNairy test site was constructed using mainly Cretaceous gravel in the asphalt mixes.

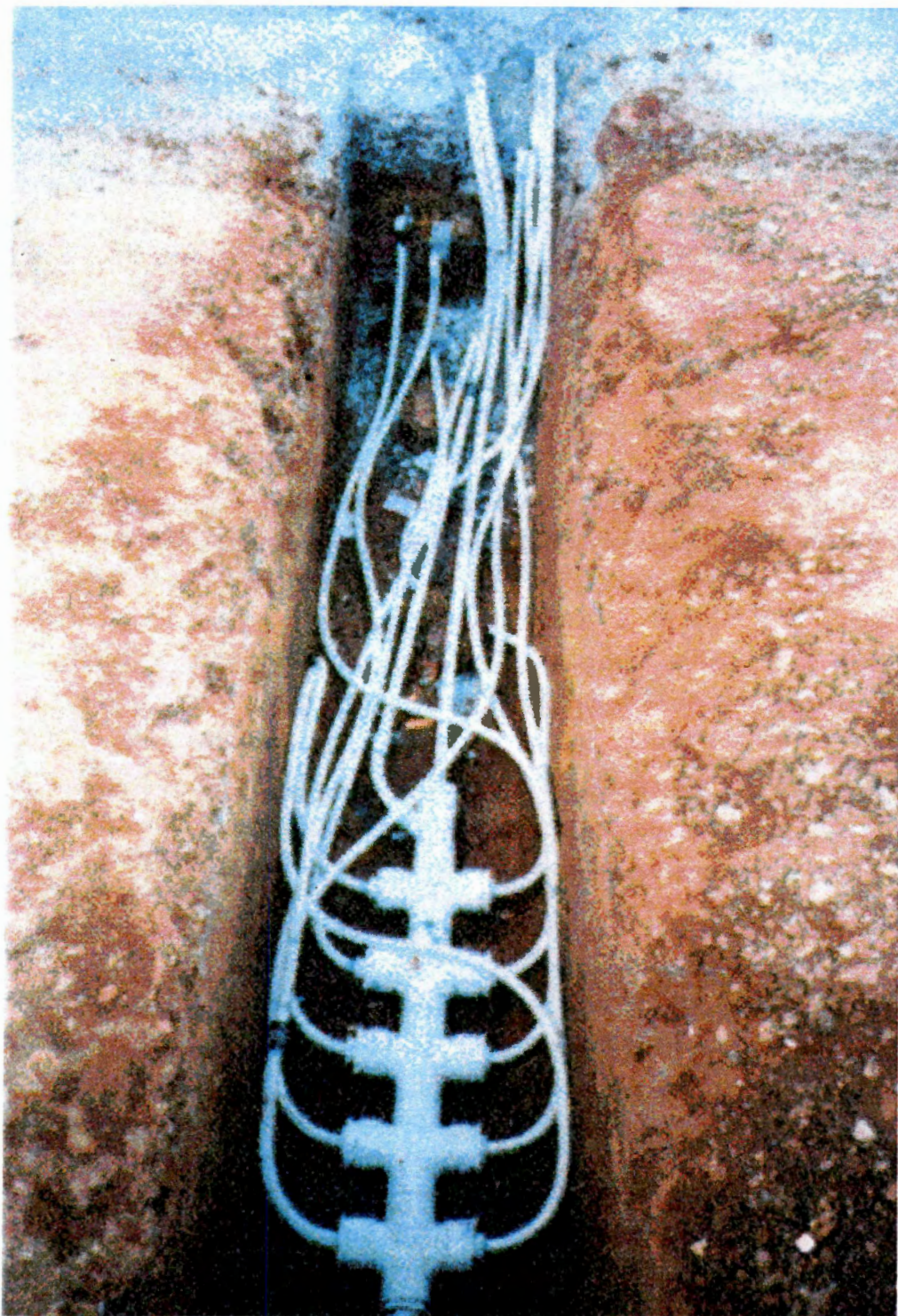


Plate 5. Conduit to route pavement instrumentation leads to subsurface concrete vault.

The stabilized base layer extends past the edge of the pavement to an aggregate under drain. The aggregate under-drain is a trench located within in the stone base, approximately 150 mm (6 in.) wide, filled with 10- to 20-mm magnesium and/or calcium carbonate gravel. A 100-mm (4-in.) corrugated pipe with holes to collect water, leads to a drain that carries drainage water off the side of the roadway. The aggregate under drain was in place before the asphaltic stabilized base layer was placed.

A five-segment probe was placed in the asphaltic stabilized base. This required being on location when the paving machine passed the test site. Before the asphalt was compacted by the twelve-ton vibrating compactor, a trench was dug with a shovel, and the probe was placed in the center of the layer. After the layer was compacted, water was poured on the asphalt to cool it. The switching diodes of the TDR probes can not withstand high temperatures for extended periods of time without causing permanent damage. The diodes have a temperature limit of 150 °F, and the epoxy that surrounds the diodes begins to melt at about 200 °F. When the asphalt was placed, the temperature ranged from 275 to 325 °F.

The second layer of asphalt placed was the asphaltic concrete base, referred to as the AC-base. The AC-base layer consists of 9- to 15-mm magnesium and/or calcium carbonate gravel bonded by asphalt and is approximately 120 mm (5 in.) thick. Two single-segment TDR probes were placed in the AC-base. The technique for the installation of the single-segment probes was the same as for the five-segment probe in the asphaltic stabilized base layer. The AC-base TDR probe cables were routed through flexible conduit to the upper main conduit. The steel pull cable, left in place during the

initial installation, was used to route these cables into the concrete vault. A cross section of a typical flexible pavement test site cross-section is illustrated in Figure 5 (this figure does not show the pan lysimeters).

Two final layers of asphalt were placed on the AC-base layer. The B-modified binder layer was placed over the AC-base. This layer is approximately 45 mm (1.75 in.) thick and contains much finer aggregates than the AC-base and serves as a transition layer between the AC-base and the very fine aggregate surface layer. The surface layer is the final pavement layer and is also approximately 45 mm (1.75 in.) thick. The shoulders of the roadway are also paved at each site. An asphalt referred to as E-mix, comprised of medium aggregates, was placed from the edge of pavement to approximately 2.5 m (8 ft) from the edge of the pavement.

Three *CSI 108/B* thermistors were placed in the asphalt layers when construction was near completion. A core hole was drilled approximately 7.5 m (25 ft) from the location of the other instrumentation. These thermistors were not located at the same location as the other equipment, because the core hole might influence the other instrumentation results. The core hole, approximately 100 mm (4 in.) in diameter, was drilled through all asphalt layers to the stone base. A 90° angle drill was used to bore three holes into the asphalt layers. The three thermistors were placed at various depths (given in Table G-10) from site to site. The thermistors were coated and placed in the bore holes using a thermally conductive epoxy to ensure asphalt to thermistor contact (Plate 6). A concrete saw was used to cut a groove, wide enough and deep enough to accommodate the thermistor cables, from the core hole to the edge of the paved shoulder.

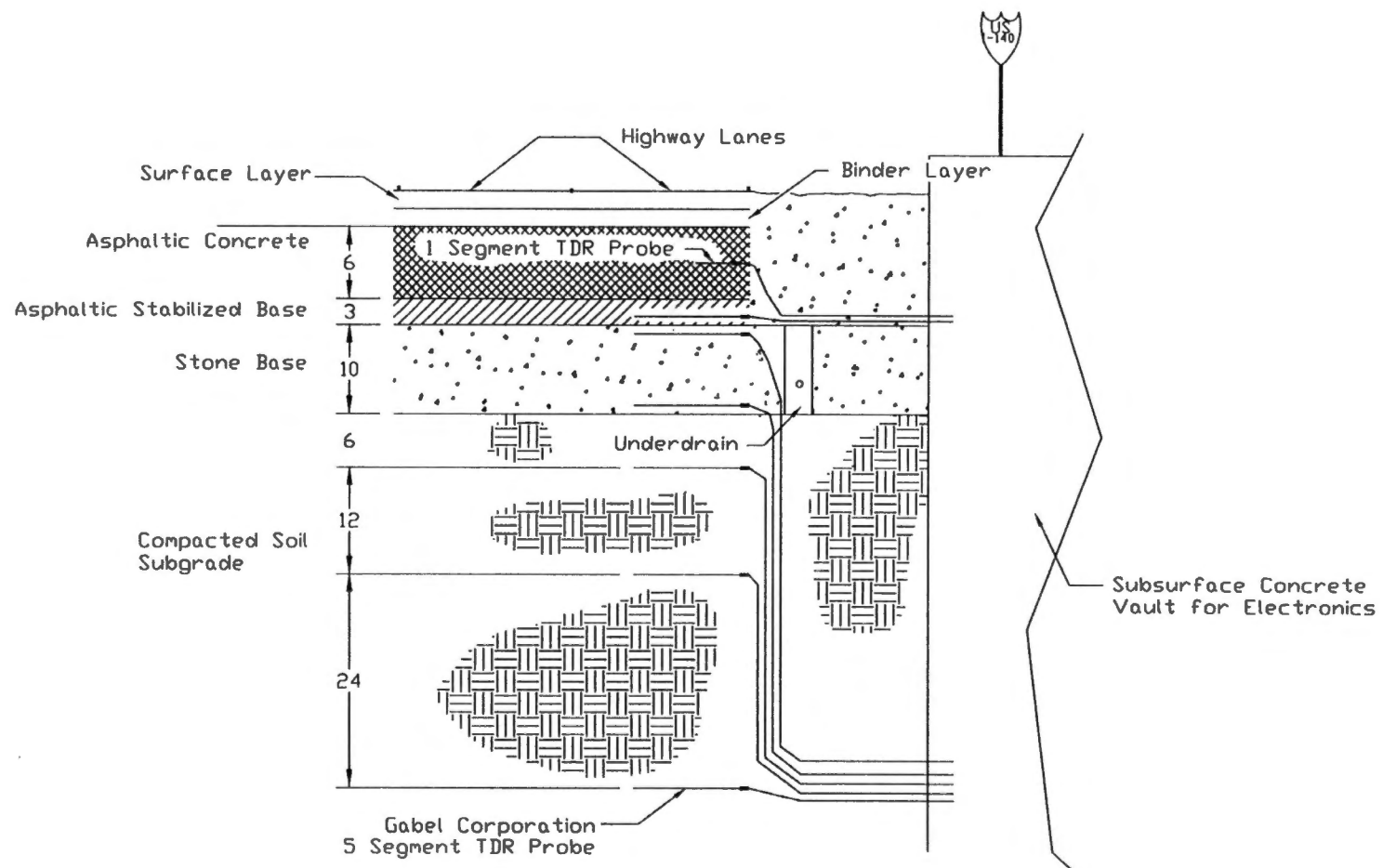


Figure 5. A cross-section of a typical test site showing the TDR probe locations (units are in inches).



Plate 6. Applying a thermally conductive epoxy to a 108/B *CSI* thermistor, during pavement thermistor installation.

The core hole and groove were filled with asphalt pavement patch and were compacted to the original density of the pavement. The thermistor cables were routed through underground conduit to the PVC coupling at the rear of the concrete vault.

Climatological Data Monitoring

A CSI CM10 tripod weather station was erected at each site to monitor environmental conditions. Each weather station contains a *Vaisala*® HMP35C temperature/relative humidity probe in a UT12VA gill radiation shield, a *LI-COR*® Model LI-200SZ solar radiation pyranometer, a *RM Young*® 03001 wind sentry unit for wind speed and direction (only wind speed data were logged), and a *Texas Electronics*® TE525 tipping bucket rain gage. The weather station tripod also holds a CSI MSX20R solar panel to recharge the system battery and a CSI DC1765 cellular telephone antenna for remote data downloads. The weather stations are housed within a 3-m (10-ft) by 3-m chain link fence with barb wire around the top. The chain link fence, which has 2.5-m (8-ft) sides, is used to protect the weather station from possible vandalism, since all test sites are in isolated locations. The chain link fence lot also encloses the system power supply, a deep cycle, twelve-volt marine battery.

The cables from the weather station instrumentation are routed into a junction box mounted on the weather station tripod. The junction box has a PVC coupling in the bottom that was used to route the cables to an underground conduit. The conduit enters the concrete vault through the same PVC coupling containing the three pavement thermistors.

Concrete Vault Instrumentation and Data Logging Equipment

Texas Electronics TE525 tipping bucket rain gages were mounted on the wall inside of each vault to quantify water infiltrating through the pavement layers to the pan lysimeters. The Overton and McNairy test sites each have two tipping bucket gages, and the Sumner test site has four tipping bucket gages installed, one for each pan lysimeter. The pan lysimeter drain tubes enter the vault through the PVC coupling and are run along the vault wall to the respective tipping bucket gages. A sheet metal hood was mounted on the frame that holds the tipping bucket gages to shed condensation water that collects on the ceiling of the vault. The condensation was found to be influencing the infiltration data.

A *NEMA*® IV stainless steel enclosure, 1220 mm (48 in.) by 910 mm (36 in.) by 305 mm (12 in.), houses the data logging equipment inside the concrete vault. The instrumentation cables enter the side of the enclosure through compression fittings. The compression fittings contain rubber seals that were squeezed around the cables when tightened. The enclosure contains a heavy rubber seal in the door frame that makes it water tight when closed. The compression fittings and door seal are required to keep damaging condensation away from the electronics. Desiccant packs that are changed every few months are also used to control moisture inside the enclosure.

The data logging equipment is mounted on a panel inside the enclosure (Plate 7). The MP-917 multiplexed data logging system utilizes a *Moisture Point* MP-917 TDR cable tester, a *CSI* CR10X data logger, a *CSI* CR500 data logger, two *CSI* AM-416

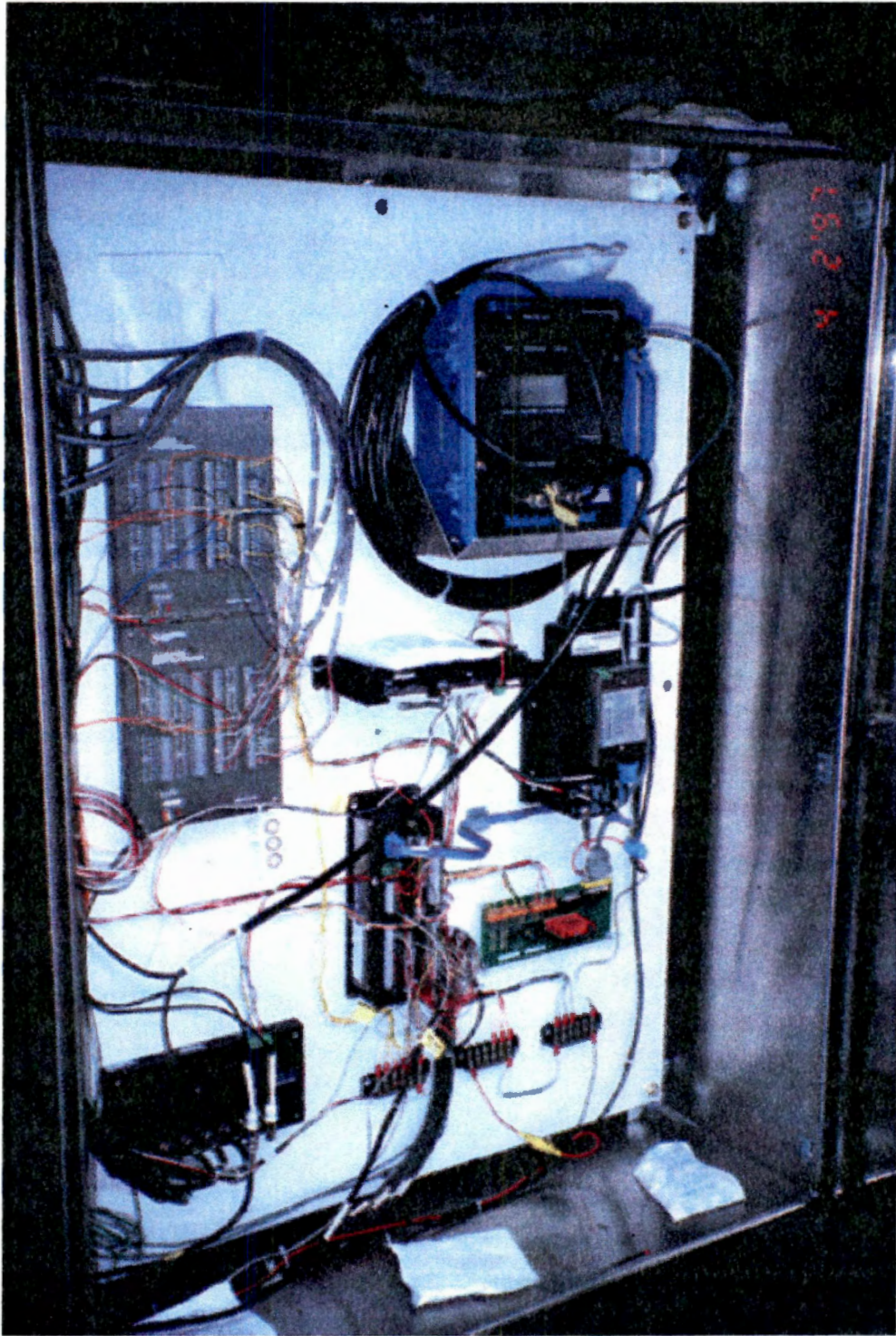


Plate 7. Instrument panel with data loggers and *Moisture Point* TDR equipment inside the subsurface concrete vault.

multiplexers, a *CSI* SDMX50 coaxial multiplexer, a *Moisture Point* data logger to MP-917 interface card, and a *CSI* DC1765 cellular telephone package which allows offsite data downloads by computer with the assistance of *CSI* PC208W software. At the Sumner test site two *CSI* CR10X data loggers and SDMX50 coaxial multiplexers were used because extra TDR probes and pan lysimeters were installed. The CR10X records TDR scans, subgrade and asphalt temperature, depth of infiltrating water from one pan lysimeter, rainfall, air temperature, relative humidity, and solar radiation. The CR10X also controls the two AM-416 multiplexers and the SDMX50 coaxial multiplexer, which switches the diode control wires and coaxial cables of the TDR probes respectively.

Due to the input/output lines of the CR10X being filled to capacity, a CR500 data logger is used to monitor wind speed, depth of infiltrating water from one pan lysimeter, and to power-up of the cellular telephone transceiver. At the Sumner test site, the second CR10X data logger replaces the CR500 data logger. The CR500 data logger is not hooked into the cellular telephone system, therefore it is manually downloaded periodically. Specific equipment for each test site are illustrated in Appendix G, and data logger programs are listed in Appendix F.

TDR probes are scanned every six hours. Each scan consists of three repetitions. The climatological sensor data are collected every sixty seconds with hourly totals or averages placed in final storage.

Falling Weight Deflectometer Testing

Nondestructive falling weight deflectometer (FWD) tests was performed periodically at each test site by the Tennessee Department of Transportation. The falling weight deflectometer test is performed with a device that drops a weight from various heights, and the deflection of the flexible pavement is measured by a series of pressure transducers in contact with the pavement surface. Assuming the pavement deflection is the same in all directions, the spacing of the transducers gives measurements of deflection at radial distances from the falling weight. The pavement strength is controlled by pavement temperature and the strength of the subgrade material. If the subgrade strength is low, the pavement surface may become uneven and wavy when the pavement temperature is warm. During cold weather, the pavement becomes more rigid and less flexible, and this may cause the pavement to crack if the subgrade does not give adequate support. Therefore, this test was performed to correlate pavement performance with environmental conditions and subgrade water content.

Subsurface Investigation

Two bore holes at each site were drilled by *S & ME Engineering* of Alcoa, TN with a hollow stem auger. The first bore hole was drilled at approximately 610 mm (2 ft) from the shoulder of the roadway and 7.5 m (25 ft) from the test site equipment. From bore hole one, undisturbed Shelby tube samples, which were approximately 76 mm (3 in.) in diameter by 610 mm (2 ft) in length, were collected to a depth of 7.5 m (25 ft). At

intervals of 1.5 m (5 ft), soil strength samples were collected. These samples were sealed in air tight jars and were later used for Atterburg limits testing. Auger cuttings were bagged, labeled, and archived. Bore hole one was then developed into a piezometer with a 50-mm (2-in.) diameter well casing and a 1.5-m (5-ft) long slotted well casing at the bottom. The slotted well casing was surrounded by clean washed sand, and a 610-mm (2-ft) bentonite clay plug was installed above the sand. The remainder of the bore hole was filled with grout. A locking well cover was put over the well casing. Bore hole one at the Blount test site was not developed into a piezometer because no water or evidence of saturation was found.

The second bore hole was located in the outside wheel path of the travel lane 7.5 m (25 ft) below the test site. Undisturbed Shelby tube samples were collected to a depth of 7.5 m (25 ft) for later soil resilient modulus tests by *The University of Tennessee, Civil Engineering Department*. Parts of these samples were also used to develop a water retention curve by *The University of Tennessee, Agricultural and Biosystems Engineering Department*. Auger cuttings were bagged, labeled, and archived for future TDR calibration studies.

Three 76-mm (3-in.) samples were cut from the Shelby tubes in the field. These samples corresponded to the depths of the three soil subgrade five-segment TDR probes. Each 76-mm (3-in.) sample was measured and removed from the Shelby tube using a portable band saw. The soil samples were then cut into several pieces and wet weights for each were recorded in the field. The soil samples were later oven dried for seventy-two hours at 105 °C. From these samples, dry bulk density and volumetric water content

were calculated, and the volumetric water contents were compared to the TDR data for the corresponding time. These results are given in Table H-4 through H-7. These same soil samples were also later used for particle size analysis. When bore hole two was complete, the hole was filled with grout to the top of the crusher run gravel, and an asphalt pavement patch was used to fill the hole completely.

Data Collection and Processing

The cellular telephone for offsite data collection is only powered during certain hours of the day, which limits the drain on the system power supply. With the use of *CSI* PC208W software for *Windows*®, a personal computer, located at the Knoxville, *University of Tennessee* campus, is scheduled to automatically download data nightly from each test site. The raw data are processed by a *QBASIC*® program Appendix F-5 and F-6. This program corrects raw TDR propagation times, calculates volumetric and gravimetric water contents from the corrected TDR propagation times, calculates repetition and daily averages of TDR scans, separates outlier data points, and separates daily climatological data. These data are archived for later processing in a *COREL* *Quattro Pro*® (Release 7) spreadsheet file.

Moisture Point Type III TDR Probe Calibration

Calibration Setup and Procedure

The review of literature on TDR calibration suggested three particular methods for calibrating single-segment TDR probes. Two of these methods were determined to be inapplicable for our equipment. Herkelrath et al. (1991) calibrated a single-segment TDR probe placed in a column of continuously weighed saturated soil, by applying suction to remove water from the soil. This method worked well for single-segment probes because the water content did not have to be evenly distributed in the column to obtain accurate results. The single-segment TDR probe scan was an average of the conditions in the column giving the correct average volumetric water content. Young et al. (1997) continuously forced water into a soil column. This method is also based on the theory that the average apparent dielectric constant would be the same as the apparent dielectric constant of soil with evenly distributed water.

The traditional method of single-segment probe TDR calibration has involved wetting a soil sample with de-ionized water, or with a solution of water with a low concentration of calcium sulfate. This method could be used to calibrate the five-segment probe, but a much larger volume of soil would be required than for a single-segment probe. The large amount of soil, the amount of time required, and the variation in soil conditions due to repacking were determined to be unacceptable for this study.

The method used to calibrate the five-segment *Moisture Point* Type III TDR probe was, however, similar to the traditional single-segment probe calibration. An aluminum box with inside dimensions of 6.35 cm (2.5 in.) wide by 8.9 cm (3.5 in.) high by 182.88 cm (72 in.) long, was constructed to hold the test material and a five-segment TDR probe. Soils were collected from each of the four test sites and sieved through a 2-mm screen. One crusher run gravel sample was purchased from *American Limestone Mines* in Knox County, TN to represent the stone base.

For each test the material was packed into the box in three layers to ensure uniform compaction. The three test material layers were 0 to 2 cm, 2 to 5 cm, and 5 to 6.35 cm. Reference marks were made at 2 cm, 5 cm, and 6.35 cm inside the aluminum calibration box. The volume was computed for each layer of the box, allowing for the volume of the probe in the middle layer, and verified by filling the respective test box layers with water and recording the volume.

Using the computed volume and the dry bulk densities derived from field data, the dry mass of the test material was determined for each layer. The test box was placed on an *OHAUS*® (Model I-10) 25-kg scale. The dry mass of test material for the first layer was added to the box and compacted to the reference marks inside the test box. This procedure was repeated for the other two layers. A sample of the test material was oven dried for seventy-two hours at 105 °C to determine the gravimetric water content of the soil or crusher run gravel when it was placed in the box. Multiplying the gravimetric water content by the actual bulk density of the material in the test box, the initial volumetric water content was determined.

A water delivery apparatus (Plate 8) was constructed using two 915-mm (3-ft) long pieces of 25-mm (1-in.) diameter schedule 40 PVC pipe. The two pieces were attached in the center using a T-type PVC coupling. The ends of the PVC pipe were sealed with PVC caps so the PVC pipe served as a water reservoir. The open end of the T-type coupling was oriented upward and was used to fill the reservoir with the desired amount of water to be applied to the test material. To prevent evaporation from the reservoir, a rubber stopper was used to plug the T-type coupling hole between additions of water to the calibration box.

Water from the PVC reservoir was delivered to the test soil through fifteen 38-mm (1.5-in.) long, 18-gauge hypodermic needles (Figure 6). Fourteen holes, which were 38 mm ($\frac{3}{8}$ in.) in diameter, were drilled through the top of the PVC reservoir and fourteen corresponding 6.4-mm ($\frac{1}{4}$ -in.) holes were drilled through the bottom of the PVC reservoir to provide access to install the hypodermic needles. A fifteenth hole was drilled through the bottom of the T-type coupling, which did not require an upper hole because of the inlet opening. The hypodermic needles were inserted through the top holes of the PVC reservoir and inserted through the bottom holes until a raised 6.4-mm ($\frac{1}{4}$ - in.) ledge at the base of the needles fit snugly through the bottom holes. A lip at the base of the raised ledge was seated firmly against the inside of the PVC reservoir. Silicone caulk was applied around the needles to prevent leakage. The upper holes were sealed with tape.

Four mounts were made from 19 mm ($\frac{3}{4}$ in.) wide by 3.2-mm ($\frac{1}{8}$ -in.) thick aluminum flat metal. The flat metal was cut long enough so that 9.5-mm ($\frac{3}{8}$ -in.) flanges

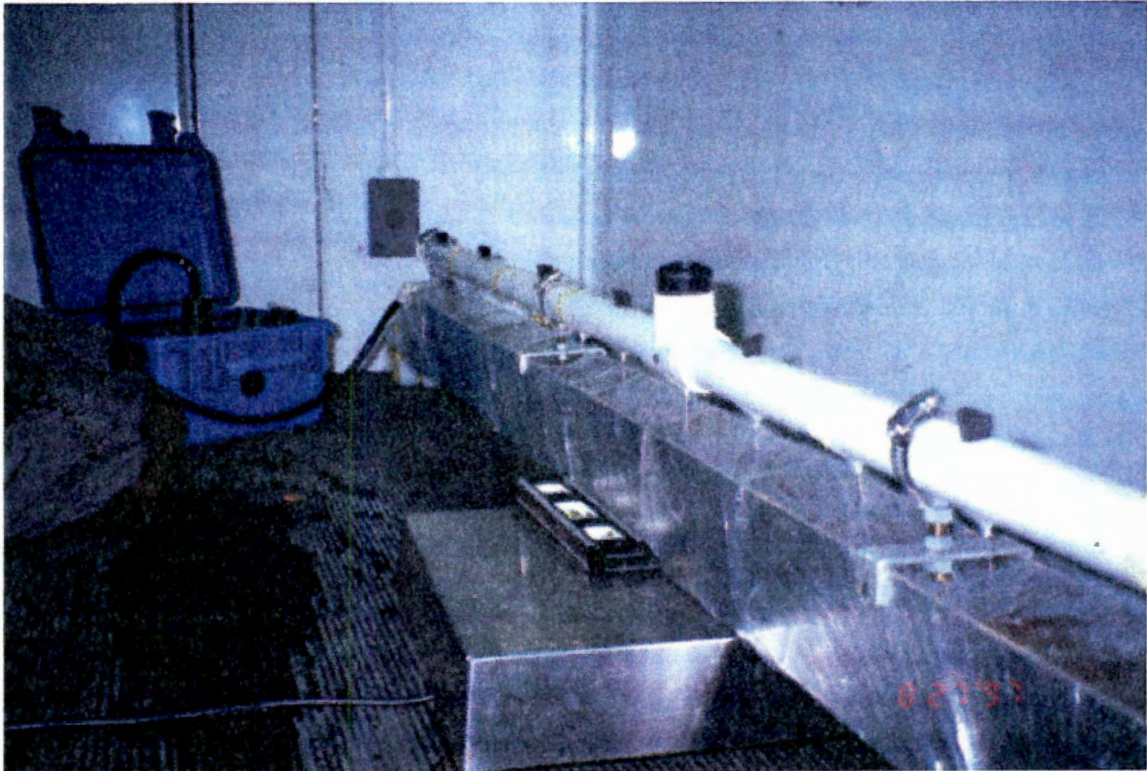


Plate 8. The *Moisture Point* five-segment TDR probe calibration box with the water delivery apparatus mounted on top. The setup was being continuously weighed by a digital scale.

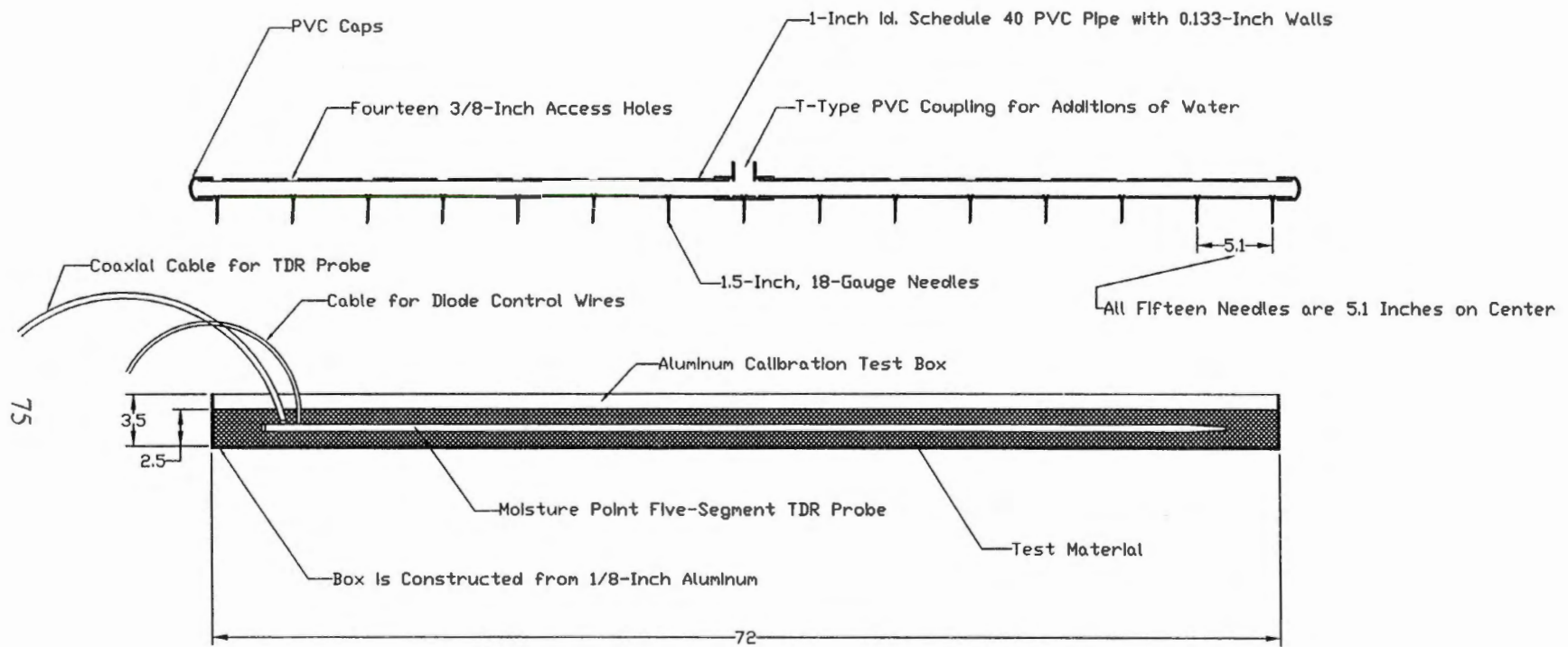


Figure 6. Water delivery apparatus and aluminum test box used to calibrate TDR equipment to test site soils and crusher run gravel.

could be bent on the ends to fit over the sides of the calibration box, holding the water delivery apparatus in place. Holes were drilled in the center of the mounts, and pieces of 6.4-mm (¼-in.) diameter thread-all rod were inserted through the holes. The thread-all rod was locked in place using nuts. Holes were drilled in four 38-mm (1.5-in.) hose clamps. The thread-all rod was inserted through these holes in the clamps and locked in place using nuts. The hose clamps fit around the PVC reservoir to hold it in place. Using the thread-all rod and nuts, the PVC reservoir could be leveled ensuring a uniform depth of water in the PVC reservoir.

The delivery of water through each needle was checked to ensure that water would be evenly applied to the soil in the calibration box. The apparatus was leveled on a laboratory bench with cups under each needle, and 345 grams of de-ionized water was poured into the PVC reservoir. An addition of 345 grams of water to the calibration box increases the volumetric water content of the test material by approximately $5 \text{ m}^3 \text{ m}^{-3}$. When all water from the reservoir had been delivered to the collection cups, the mass of water in each cup was measured. Three repetitions were performed for both apparatuses. The mean standard deviation of water mass delivered through the needles from the three repetitions was 2.4 grams for apparatus one and 3 grams for apparatus two. The results are given in Appendix B-3 and B-4.

The water delivery apparatus was mounted on the top of the test box and leveled. Saran wrap was wrapped around the test box and water delivery apparatus to prevent water loss due to evaporation and the entire apparatus was placed on a 25-kg digital scale inside a *Hotpack*® (Model TK-3578-WF-L) walk-in environmental chamber. The

temperature of the environmental chamber was set to 20 °C, and the relative humidity was adjusted to 68%. The dielectric constant of water (80.36 at 20 °C) changes with temperature; by setting the temperature of the environmental chamber to 20 °C, temperature corrections were not necessary.

The initial mass of the test material and water within the box was recorded, and a TDR scan was performed. When the TDR scan was completed, a predetermined amount of de-ionized water was delivered to the test material through the water delivery apparatus. The water was allowed to equilibrate throughout the test material for several hours. The mass of the test material and the water was again recorded, and a second TDR scan was performed. The change of mass between the two readings was assumed to be due to the addition of water, and the change in water mass was used to determine the change in volumetric water content of the test material. This procedure was repeated until the test material was saturated.

Two calibration setups were used to perform three repetitions for each of the four test soils and for the crusher run gravel sample. During the first repetition, the water content was increased by intervals of $0.05 \text{ m}^3 \text{ m}^{-3}$. During the second and third repetitions, the water content was increased by $0.05 \text{ m}^3 \text{ m}^{-3}$ until the water content reached a predetermined level for each test material and was then increased by $0.025 \text{ m}^3 \text{ m}^{-3}$. The procedure for the second and third repetitions increased the number of data points for the range of interest.

Time to Equilibrium

The time required for the applied water to equilibrate throughout the test material in the calibration box was determined by continuous TDR scans. The MP-917 cable tester, with an internal data logger, can be setup to continuously scan at a user defined time interval. The calibration box was packed with soil from the Overton test site, and the volumetric water content was initially increased to $0.30 \text{ m}^3 \text{ m}^{-3}$.

The calibration box was placed in the environmental chamber on the digital scale, and the cable tester was set to scan at ten-minute intervals. After allowing three days for the water content of the soil to initially equilibrate, water was added to the box. Separated by three twenty-four hour intervals, two additions of water required to increase the volumetric water content of the soil by $0.05 \text{ m}^3 \text{ m}^{-3}$ and one of $0.025 \text{ m}^3 \text{ m}^{-3}$ were added to the calibration box. Using the graphic representation of the results (Figure 7), the required time between water additions was determined by measuring the time between the addition of water until the water content appeared to stop changing. The results from segment four were used to determine the time to equilibrium because the amount of noise was much less for this segment than the other segments. The time for an addition of water to the calibration box to reach equilibrium in the test material is a minimum of eight hours. The results for all probe segments are given in Appendix B-1 through B-6. The volumetric water content determined by the *Moisture Point* equation from measured TDR times continued to decrease beyond this time, but the additional decrease appeared to be less than $0.01 \text{ m}^3 \text{ m}^{-3}$.

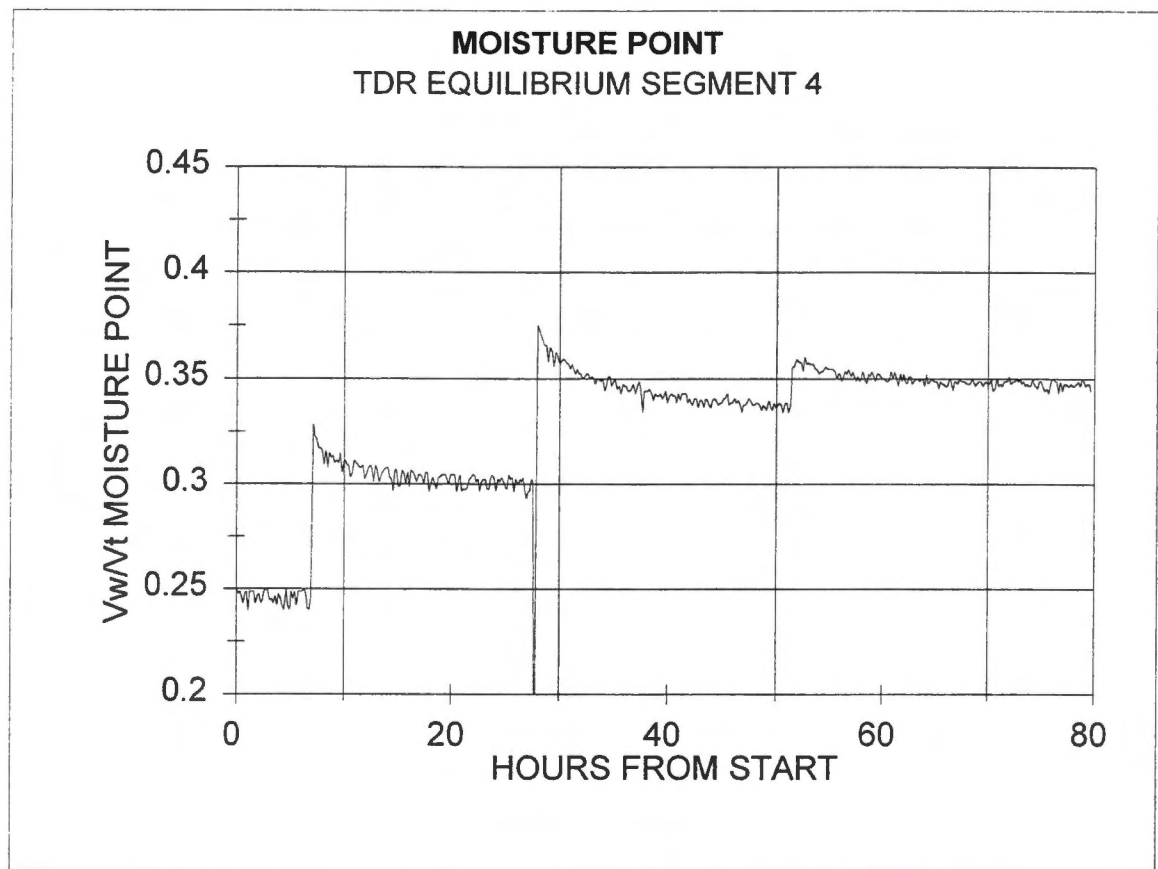


Figure 7. Time to equilibrium of test material water content in calibration box (Segment 4).

Calibration Data Analysis

Propagation Time Correction

The epoxy and high density plastic that separate the five-segment waveguides of the multiple-segment *Moisture Point* TDR probe cause an incomplete interaction between the waveguides and the soil which affects the measured propagation time. The manufacturer determined a linear relationship between measured propagation time and corrected propagation time. Using the correction constants supplied by the manufacturer for each segment, the corrected propagation times did not match between segments when the propagation times for water and air were measured.

New correction constants for each segment were determined by using the Blount test site soil calibration data. The four-phase, semi-empirical dielectric mixing model (Equation [13]) proposed by Dobson et al. (1985) was used to calculate the apparent dielectric constant for each actual volumetric water content.

$$\varepsilon^{\alpha} = \theta_s \varepsilon_s^{\alpha} + \theta_a \varepsilon_a^{\alpha} + \theta_{fw} \varepsilon_{fw}^{\alpha} + \theta_{bw} \varepsilon_{bw}^{\alpha} \quad [13]$$

where,

ε - apparent dielectric constant

bw - subscript for bound water

fw - subscript for free water

a - subscript for air

s - subscript for soil solid phase

ϕ - percent porosity (volume air / total volume)

θ - volume fraction of each parameter in $\text{m}^3 \text{m}^{-3}$

α - curve fitting parameter.

The curve fitting parameter α was assumed to be 0.5 (Roth et al., 1990; Weitz et al., 1997), and the dielectric of air was assumed to be 1. Since the calibration was performed at 20 °C, the dielectric of water was assumed to be 80.36, and the dielectric of soil was assumed to be 3.9. The porosity of the soil was 42%, which was based on a dry bulk density of 1.54 Mg m^{-3} . These composite dielectric results were used to back calculate propagation times corresponding to each actual volumetric water content using Equation [2]. Linear regression was performed between the MP-917 propagation times and the calculated propagation times resulting in a new slope and a new intercept for each segment. The new segment correction constants are shown in Table 3-1.

Table 3-1. Segment correction constants for *Moisture Point* Type III five-segment probe.

$T = T_{mc}/B - A$					
Segment	B^*	A^*	R^2 (T by T_{mc})	B^*	A^*
1	0.727	1.721	0.971	0.629	2.336
2	0.662	2.054	0.965	0.667	1.879
3	0.645	1.091	0.972	0.653	1.244
4	0.779	0.485	0.956	0.7	1.346
5	0.803	0.649	0.955	0.678	1.622

*Default values (Young 1995a)

★Calculated Values

Calibration Equation Evaluation

The calibration data were grouped by soil, probe segment, and repetition and were further divided into three equal volumetric water content ranges which are specific to each test material. Due to apparent physical differences between the crusher run gravel and soil, statistical analysis was performed separately on these data. Calibration data derived from laboratory tests were fit to models presented by other researchers (Table 3-2).

Table 3-2. TDR calibration equations evaluated for the *Moisture Point* five-segment probe.

Model	Reference	Equation
Topp	Topp et al. (1980)	$\theta_v = -0.053 + 0.0293\varepsilon - 0.00055\varepsilon^2 + 0.0000043\varepsilon^3$
Baran	Baran (1994)	$\theta_v = -0.062164 + 0.023831\varepsilon - 0.000598\varepsilon^2 + 0.000006\varepsilon^3$
Herkelrath	Herkelrath et al. (1991)	$\theta_v = \text{slope}(1/v) + \text{intercept}$
Ledieu	Ledieu et al. (1986)	$\theta_v = 5.688t - 3.38\delta - 15.29$
Malicki	Malicki et al. (1996)	$\theta_v = [\varepsilon^{0.5} - 0.819 - 0.168\rho(0.159\rho^2)] / [7.17 + 1.18\rho]$
Jacobsen	Jacobsen and Schjonning (1993)	$\theta_v = -7.01 \times 10^{-2} + 3.47 \times 10^{-2}\varepsilon - 11.6 \times 10^{-4}\varepsilon^2 + 18.0 \times 10^{-6}\varepsilon^3$
<i>Moisture Point</i>	Young (1995a)	$\theta_v = [(T_{mc} * c) / (2 * L) - T_s/T_a] / [(K_w^{0.5}) - 1]$
3 - phase	[†] Weitz et al. (1997)	$\theta_v = [K_a^\alpha - (1 - \varphi)\varepsilon_s^\alpha - \varphi\varepsilon_a^\alpha] / (\varepsilon_w^\alpha - \varepsilon_a^\alpha)$
4 - phase	[†] Weitz et al. (1997)	$\theta_v = [K_a^\alpha \theta_{bw}(\varepsilon_{bw}^\alpha - \varepsilon_{fw}^\alpha) - (1 - \varphi)\varepsilon_s^\alpha - \varphi\varepsilon_a^\alpha] / (\varepsilon_{fw}^\alpha - \varepsilon_a^\alpha)$
Maxwell	[†] Weitz et al. (1997)	$\theta_v = [3(\varepsilon_s - K_a) - 2\theta_{bw}(\varepsilon_{bw} - \varepsilon_{fw}) + 2\varphi(\varepsilon_a - \varepsilon_s) + K_a\theta_{bw}(\varepsilon_s\varepsilon_{fw}^{-1} - \varepsilon_s\varepsilon_{bw}^{-1}) - K_a\varphi(\varepsilon_s\varepsilon_a^{-1} - 1)] / [K_a(\varepsilon_s\varepsilon_{fw}^{-1} - \varepsilon_s\varepsilon_a^{-1}) + 2(\varepsilon_a - \varepsilon_{fw})]$

[†] These equations were originally proposed by Dobson et al. (1985) to calculate apparent dielectric instead of volumetric water content

Corrected propagation times and predicted volumetric water contents were calculated using *Corel Quattro Pro* (Release 8). Absolute differences between the actual volumetric water contents and predicted volumetric water contents were computed using *Statistical Analysis Systems*® (SAS version 6.12) software for *Windows*. The use of absolute difference values reduces prediction errors caused by over-predicted values canceling under-predicted values of volumetric water content.

The independent variables were model, soil, probe segment, and water content range. Paired t-tests (Schlotzhauer and Littell, 1987) were performed using the PROC MIXED procedure on the absolute difference values to derive mean absolute difference values for specific combinations of independent variables. The residuals were evaluated using PROC UNIVARIATE NORMAL to test the normality of the data for each model. The SAS programs used to evaluate data can be reviewed in Appendix F-6 and F-7.

CHAPTER IV

RESULTS AND DISCUSSION

Field Instrumentation

The *Moisture Point* five-segment TDR probes were not designed to be installed in high density compacted subgrades below pavement systems, but during probe installation, only two probes were damaged. In both instances, while installing the probes into the pilot holes, the epoxy between the stainless steel waveguides that holds the switching diodes cracked and separated from the waveguides. The damage was discovered during installation, and these probes were replaced. The heat of the AS base asphalt also permanently damaged probe six at the Blount test site. Probe four at the Overton test site failed to operate when the system was brought online, possibly because the coaxial cable or control wires were pulled loose from the probe head during construction activities after probe installation.

Several other probes and probe segments have failed since the systems were brought on-line. The loss of probe segments appears to be associated with the failure of switching diodes that separate the probe segments. The cause of the diode failure may be

due to the intense data acquisition rate, but since the probes are in a harsh field environment there may be physical factors involved. The overall five-segment probe survival rate is currently 85%, and the segment survival rate is currently 78%. This survival rate is considered acceptable based on geotechnical instrumentation survival rates are typically between 60 -75% (Dunnicliff, 1988). Two of the original seven single-segment probes have failed since installation. A record of probes and probe segments that have failed are shown in Appendix E-5.

Moisture Point TDR System Calibration

In order to evaluate the capability of the various models to predict volumetric water content from TDR propagation times, the TDR equipment error must be taken into account. As stated by the manufacture, the *Moisture Point* TDR system has the ability to predict volumetric water content with an accuracy of $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$ for agricultural type soils (Young, 1995a).

Moisture Point TDR System Noise

Through electronic mail conversations with technical representatives of *Environmental Sensors*, it was learned that some segments of the *Moisture Point* multiple segment probe give more repeatable results than others, especially in high clay soils or in

soils near saturation. To quantify this noise, the calibration box was packed with Blount test site soil, and the volumetric water content of the soil was increased to $0.30 \text{ m}^3 \text{ m}^{-3}$. After allowing seventy-two hours for the water content to reach an equilibrium, the *Moisture Point* MP-917 was set up to continuously scan at ten-minute intervals with no further water content change in the test box soil. Scans continued for a little more than thirty hours with 182 data points taken for each probe segment. The corrected propagation times were calculated using the new A and B constants from Table 3-1. The volumetric water contents were calculated using the *Moisture Point* equation with a T_s/T_a value of 1.55. Graphical illustrations of this data are given in Appendix B-2. The graphical results show that the soil volumetric water content remains constant. Segments 1 and 2 seem to have the least amount of repeatability with range of approximately $0.05 \text{ m}^3 \text{ m}^{-3}$, while segments 3 and 5 have a range of approximately $0.026 \text{ m}^3 \text{ m}^{-3}$. Segment 4 gave very consistent results with a range of $0.009 \text{ m}^3 \text{ m}^{-3}$ (Figure 8).

Moisture Point TDR Calibration Data Analysis

Preliminary minimum and maximum test site data from 1997 (Table 4-1) show the soil subgrades for each test site to have a volumetric water content in the high volumetric water content range. The monthly average volumetric water contents for each test and probe are given in Appendix I. The high, medium, and low volumetric water content range for each test site soil and crusher run gravel were determined by dividing the full range of laboratory volumetric water content for each material into three equal size ranges.

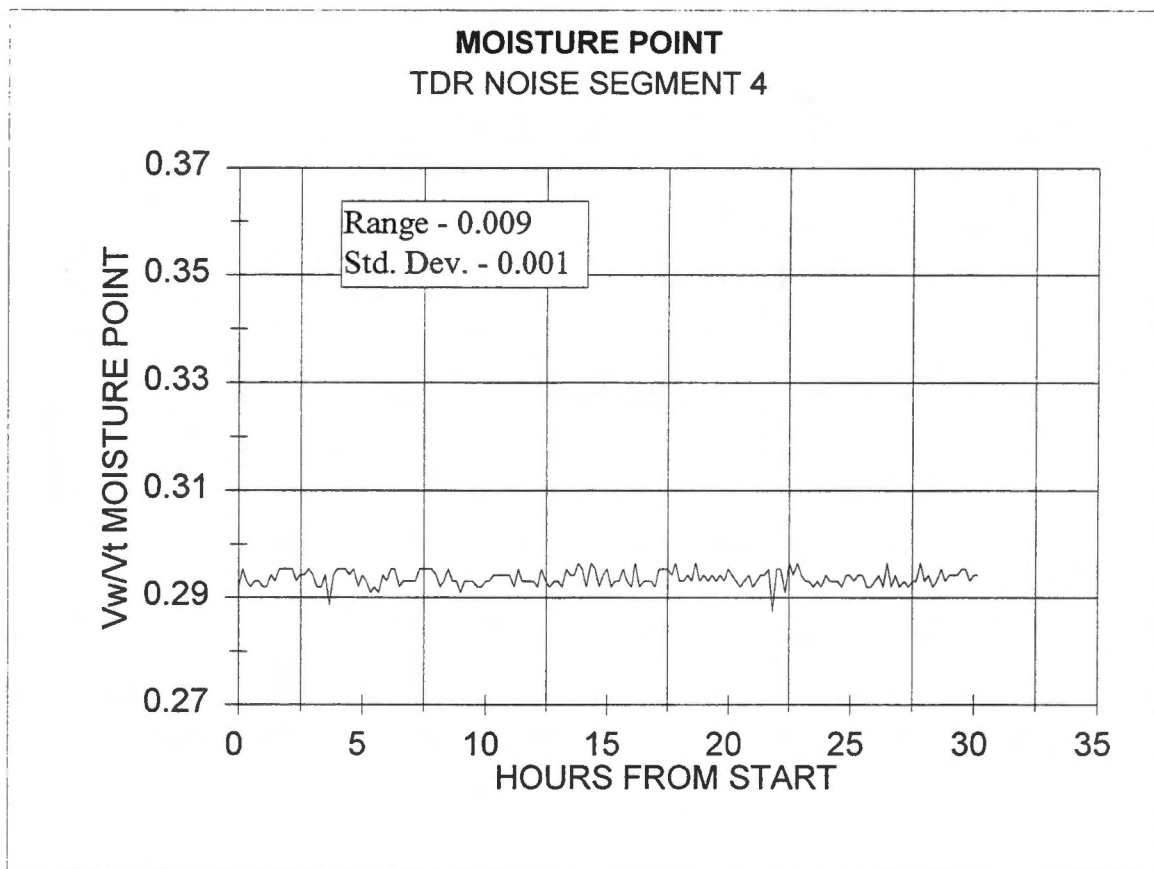


Figure 8. Noise in *Moisture Point* five-segment TDR probe (Segment 4).

Table 4-1. Minimum and maximum volumetric water contents from test site data, 1997.

Test Site		Soil Subgrade Probes			Stone Base Probes			
		Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 9	Probe 10
Blount	Min	0.40	0.43	0.40	0.18	0.15	Not Installed	Not Installed
	Max	0.41	0.47	0.43	0.27	0.17	Not Installed	Not Installed
Overton	Min	0.38	0.39	0.34	Failed	0.20	Not Installed	Not Installed
	Max	0.41	0.42	0.36		0.21	Not Installed	Not Installed
Sumner	Min	0.34	0.42	0.44	0.19	0.19	0.19	0.18
	Max	0.39	0.46	0.48	0.20	0.24	0.20	0.18
McNairy	Min	0.30	0.31	0.30	0.25	0.20	Not Installed	Not Installed
	Max	0.32	0.32	0.31	0.27	0.23	Not Installed	Not Installed

Note: Currently field data volumetric water contents are computed with Topp's Equation in units of $\text{m}^3 \text{m}^{-3}$.

Note: Soil subgrade probe depths can be reviewed in Table G-11. Probe 4 is in the bottom of the crusher run layer, and probe 5 is in the top. Probes 9 and 10 are respectively at the same depths but located under the longitudinal joint of the travel lanes at Sumner County.

Note: Overton and McNairy County test sites were not brought online until March.

Note: Sumner County test site was not brought online until October.

This method makes the ranges specific for each test material. Although the field data volumetric water contents were calculated using Topp's equation, the prediction error using Topp's equation is not great enough for the actual volumetric water contents to be outside the high water content range for each soil. The probes in the stone base show most volumetric water contents were in the high water content range, but some volumetric water content results were in the upper medium range.

Based on the field data, the TDR calibration equations from Table 3-2 were primarily evaluated on their performance within the high range of water content for the subgrade soils and the high and medium water content range for crusher run gravel, but overall performance was taken into account since volumetric water contents in the field may change over time.

Statistical Analysis of Calibration Data

Statistical analysis began by testing the data for normality. The residuals of actual water content minus the predicted water content of each model were analyzed using the PROC UNIVARIATE procedure of SAS. The soil and crusher run data appeared normal for each model. Therefore it was assumed that statistical procedures would be valid.

The PROC MIXED procedure of SAS was used to calculate mean absolute difference values for various groupings of independent variables, which were soil, probe segment, repetition, and water content range. A paired difference t-test was used to rank the model performance by T groupings which indicate the results from models with the

same letter are not significantly different at the 95 percent confidence level. The T groupings are alphabetized with the lowest prediction error being A.

Table 4-2 illustrates how each model performed overall in subgrade soils when all independent variables were considered. This table also specifies the minimum and maximum prediction error, the standard deviation of the prediction error from the actual water contents for each model, and the T groupings were also included in the table. Table 4-3 gives these same results for the crusher run gravel.

In Table A-1 the independent variables are listed to give a clearer indication of how each model performed by soil, probe segment, and water content range. The equivalent results for the crusher run gravel are given in Table A-2.

Since the overall performance of a model may not be indicative of the model performance by water content range, the mean absolute difference for each model is given for only the high water content range for each test site soil in Table 4-4 and for all soils in Table 4-5. The mean absolute difference values for the high and medium water content range along with T groupings for crusher run gravel are illustrated in Table 4-6.

Table 4-2. Mean absolute differences of volumetric water content by model for all ranges, probe segments, repetitions, and test site soils.

Model	Mean Absolute Difference [†]	Std. Dev.	Minimum	Maximum	T Grouping [*]
Herkelrath	0.025	0.020	0	0.151	A
Moisture Point	0.028	0.024	0	0.122	B,A
3-phase	0.028	0.025	0	0.121	B
4-phase	0.029	0.021	0	0.140	B
Topp	0.034	0.028	0	0.133	C
Malicki	0.036	0.028	0	0.141	C
Jacobsen	0.046	0.034	0	0.143	D
Ledieu	0.061	0.035	0.001	0.168	E
Maxwell	0.065	0.035	0	0.174	F
Baran	0.097	0.053	0	0.215	G

* T groupings with same letter are not significantly different at the 95% confidence level.

[†] Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

Table 4-3. Mean absolute differences of volumetric water content by model for all ranges, probe segments, and repetitions for crusher run test material.

Model	Mean Absolute Difference[†]	Std. Dev.	Minimum	Maximum	T Grouping[*]
Baran	0.021	0.013	0	0.059	A
Herkelrath	0.022	0.014	0	0.062	A
Maxwell	0.037	0.028	0	0.120	B
Ledieu	0.042	0.036	0	0.149	C
Malicki	0.044	0.033	0	0.138	C
Jacobsen	0.066	0.031	0.006	0.155	D
3-phase	0.080	0.050	0.001	0.215	E
Topp	0.082	0.043	0.006	0.188	E
4-phase	0.082	0.050	0.001	0.218	E
Moisture Point	0.100	0.052	0	0.237	F

* T groupings with same letter are not significantly different at the 95% confidence level.

[†] Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

Table 4-4. Mean absolute differences of high volumetric water content range by model and soil.

Model	Soil	Mean Absolute Difference [†]	T Grouping [*]
Herkelrath	Blount	0.014	A
Moisture Point	Blount	0.014	A
3 - phase	Blount	0.014	A
Topp	Blount	0.026	C,D
4 - phase	Blount	0.028	C,D
Malicki	Blount	0.029	D,E
Jacobsen	Blount	0.058	I
Ledieu	Blount	0.061	I,J,K
Maxwell	Blount	0.064	J,K,L
Baran	Blount	0.14	Q
Herkelrath	Overton	0.035	E,F
4 - phase	Overton	0.035	E,F
Moisture Point	Overton	0.043	G
3 - phase	Overton	0.045	G
Topp	Overton	0.059	I,J
Malicki	Overton	0.066	K,L
Jacobsen	Overton	0.090	M,N
Ledieu	Overton	0.095	M,N,O
Maxwell	Overton	0.096	N,O
Baran	Overton	0.170	R
Herkelrath	Sumner	0.019	A,B
4 - phase	Sumner	0.022	B,C

Table 4-4. Continued.

Model	Soil	Mean Absolute Difference [†]	T Grouping [*]
Moisture Point	Sumner	0.039	G,H
3 - phase	Sumner	0.040	G,H
Topp	Sumner	0.059	I,J
Malicki	Sumner	0.061	I,J,K
Jacobsen	Sumner	0.088	M
Ledieu	Sumner	0.094	M,N,O
Maxwell	Sumner	0.097	O
Baran	Sumner	0.165	R
Herkelrath	McNairy	0.028	C,D
3 - phase	McNairy	0.029	D,E
Moisture Point	McNairy	0.029	D,E
Topp	McNairy	0.031	D,E
4 - phase	McNairy	0.032	D,E
Malicki	McNairy	0.044	G
Jacobsen	McNairy	0.056	I
Ledieu	McNairy	0.066	K,L
Maxwell	McNairy	0.071	L
Baran	McNairy	0.133	P

^{*} T groupings with same letter are not significantly different at the 95% confidence level.

[†] Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

Table 4-5. Mean absolute differences of high volumetric water content range by model for all ranges, probe segments, repetitions, and soils.

Model	Mean Absolute Difference[†]	Std. Dev.	Min. Error	Max. Error	T Grouping[*]
Herkelrath	0.022	0.022	0	0.151	A
4 - phase	0.028	0.022	0	0.140	B
Moisture Point	0.030	0.025	0	0.122	B
3 - phase	0.030	0.026	0	0.121	B
Topp	0.042	0.029	0	0.133	C
Malicki	0.048	0.029	0	0.141	D
Jacobsen	0.072	0.028	0.011	0.143	E
Ledieu	0.078	0.031	0.004	0.168	F
Maxwell	0.081	0.031	0.006	0.174	F
Baran	0.151	0.028	0.086	0.215	G

* T groupings with same letter are not significantly different at the 95% confidence level.

† Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

Table 4-6. Mean absolute differences of high and medium volumetric water content range by model for all probe segments and repetitions of crusher run gravel data.

Model	Range	Mean Absolute Difference [†]	T Grouping [*]
Baran	High	0.020	A
Herkelrath	High	0.023	A
Maxwell	High	0.062	C
Malicki	High	0.075	D
Ledieu	High	0.078	D
Jacobsen	High	0.092	E
Topp	High	0.127	F
3 - phase	High	0.135	F,G
4 - phase	High	0.137	G
Moisture Point	High	0.156	H
Baran	Medium	0.020	A
Maxwell	Medium	0.021	A
Herkelrath	Medium	0.022	A
Ledieu	Medium	0.024	A
Malicki	Medium	0.025	A
Jacobsen	Medium	0.050	B
3 - phase	Medium	0.055	B,C
4 - phase	Medium	0.058	B,C
Topp	Medium	0.059	C
Moisture Point	Medium	0.075	D

* T groupings with same letter are not significantly different at the 95% confidence level.

† Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

TDR Calibration Equation Performance for Test Site Materials

Soil

The Herkelrath equation was ranked as the best prediction model of volumetric water content from *Moisture Point* TDR data in all test site subgrade soils. Some models had a lower prediction error for some soils and ranges, but the prediction error was not significant in any of these cases. The *Moisture Point* equation had the second lowest mean absolute difference when all independent variables were considered, but the error was not significantly different from the three- and four-phase dielectric mixing models. These four models gave comparable results for all soils and water content ranges. This was a strong performance by the *Moisture Point* equation since no physical characteristics of the individual soils were used in calculating volumetric water content. The Herkelrath equation was the only equation that was specifically calibrated for these soils. The three- and four-phase models were specifically calibrated for the individual soils to an extent since the bulk density is taken into account, and the volume of bound water is also considered in the four- phase model. Volumetric water content predictions, using the Herkelrath equation, compared to the actual water content are graphically illustrated in Appendix C-2.

Crusher Run Gravel

The Baran and Herkelrath equations were the only models that accurately predicted the volumetric water content for all ranges of the crusher run gravel. The Baran equation had a lower mean absolute difference, but the results of the Herkelrath equation were not significantly different.

Individual Calibration Equation Performance

Herkelrath et al.

The Herkelrath equation is a simple linear model between the inverse velocity of the TDR voltage pulse and the soil volumetric water content. The equation performs best when a soil specific slope and intercept are derived. The slopes and intercepts derived from each of the test site soils are very similar (Table 4-7), while that of the crusher run gravel is considerably different.

Table 4-7. Slopes and intercepts derived from calibration data for the Herkelrath equation.

Test Material	Slope	Intercept	R²
Blount	37.396	-0.193	0.965
Overton	38.653	-0.186	0.911
Sumner	38.320	-0.171	0.920
McNairy	36.171	-0.178	0.924
Crusher Run	23.089	-0.127	0.888

The Herkelrath equation was more accurate than all other equations for subgrade soils. The mean absolute difference across all independent variables was $0.025 \text{ m}^3 \text{ m}^{-3}$, although this was not significantly different from the prediction error of the *Moisture Point* equation (Table 4-2). The mean absolute difference dropped to $0.022 \text{ m}^3 \text{ m}^{-3}$ when just the high range of water contents for all soils was considered (Table 4-5). Although when the high range of water content for each individual soil is considered, the mean absolute difference varied significantly from soil to soil (Table 4-4).

The Herkelrath equation also performed well in the crusher run gravel. The mean absolute difference when all independent variables were taken into account was the second lowest at $0.022 \text{ m}^3 \text{ m}^{-3}$ and was not significantly different from the best model. When only the high and medium range water contents were considered, the mean absolute difference changed only slightly.

Moisture Point Equation

The *Moisture Point* equation proved to be one of the four best predictors of volumetric water content from *Moisture Point* TDR data in subgrade soils. This model was not specifically calibrated to these soils in any way, which was a strong point of this model over the others. The T_s/T_a value was assumed to be the manufacturer default value of 1.55. The results of this model may be improved if an average value was calculated specifically for these subgrade soils.

The *Moisture Point* equation had the second lowest mean absolute difference in subgrade soils when all independent variables were considered, and the prediction error was not significantly different from the best model. This model performed consistently for all water content ranges for each soil. While significantly different from the Herkelrath equation, the *Moisture Point* equation was ranked in the second highest group when only the high water content range was considered for subgrade soils. However, the accuracy of the equation varied for each soil in the high water content range. The mean absolute difference for the Blount test site soil in the high water content range was $0.013 \text{ m}^3 \text{ m}^{-3}$, which placed this model in the best T grouping, but the model was less accurate for the Sumner and Overton test site soils in all water content ranges. Although many of the other equations predicted water content in the Sumner soil poorly, the mean absolute difference for the *Moisture Point* equation in the Sumner soil was twice that of the two best performers in the high water content range. The prediction error was not as great in the Overton test site soil. Although the difference ranked the *Moisture Point* equation and two best performers in different T groupings, the prediction error is not that substantial.

The paired difference t-test results ranked the *Moisture Point* equation last for all groupings evaluated in the crusher run gravel. The physical differences between subgrade soil and crusher run gravel clearly makes this model incompatible for this material.

Three-Phase Dielectric Mixing Model (Weitz et al.)

The three-phase dielectric mixing model performed very well in this study. The T groupings consistently placed this model among the best and second best prediction models for subgrade soils. The water content range did not appear to affect the accuracy of the volumetric water content predicted with this equation. The mean absolute difference for this model was almost identical to that of the *Moisture Point* equation, including the Sumner test site soil. This model did not perform well in the high density crusher run gravel. This may be because a different α value should be used.

The fitting parameter α was assumed to be 0.5, based on other published work. An α value better suited to these high density soils may have yielded better results. Specific calibration for this model would have to be performed to establish a better value of α . The equation is not specifically calibrated to each soil but does use the individual soil dry bulk density. Therefore, some knowledge of the soils physical characteristics must be known.

Four-Phase Dielectric Mixing Model (Weitz et al.)

The variables of the four-phase dielectric mixing model are nearly identical to those of the three-phase dielectric mixing model. The only difference is the four-phase model accounts for the volume of bound water in each test material. The bound water is the water that is held tightly by the clay particles and can influence water content results derived with dielectric measurement techniques. Based on work by Dirksen and Dasberg

(1993), the hygroscopic water content (air dried water content of the soil) was used for the bound water volume in calculations for this study. The dielectric constant of bound water was assumed to be 3.2, and the α value for this model was also assumed to be 0.5.

The effectiveness of this model to accurately predict volumetric water content was very close to that of the *Moisture Point* equation and the three-phase equation as indicated by the T grouping for subgrade soils. The mean absolute differences for the Sumner and Overton test site soils in the high water content range were significantly lower than for the *Moisture Point* and three-phase equations. The Herkelrath equation was the best predictor of water content in these soils in the high water content range but was not significantly better than the four-phase dielectric mixing model.

The four-phase dielectric mixing model did not perform well in the crusher run gravel. The T grouping ranked this model second from last, but just slightly worse than the three-phase model. An α value better suited to high density stone may improve the performance of this model, but a new α value would require specific calibration for this equation in that material.

Topp et al.

Topp's equation performed well overall in the subgrade soils. Like the *Moisture Point* equation, this was a strong performance considering the equation is not specifically calibrated for these soils in any way. The T groupings consistently ranked the Topp's equation performance for subgrade soils in the third best group, although there were

typically three equations in the second best group. The water content range did appear to effect the results. The prediction error was consistent for all soils in the low water content range but varied from soil to soil in the medium and high water content range.

The mean absolute difference for subgrade soils when all independent variables were considered was $0.034 \text{ m}^3 \text{ m}^{-3}$, which was only $0.01 \text{ m}^3 \text{ m}^{-3}$ different from the best model. When the high water content range was evaluated for subgrade soils, the mean absolute difference was comparable to the best fit models for the Blount and McNairy test site soils, but the prediction error was considerably greater than the best models for the Sumner and Overton test site soils.

Topp's equation does not appear to be suited for use with crusher run gravel. The mean absolute difference was similar to that of the dielectric mixing models and the *Moisture Point* equation, which had the largest prediction error.

Malicki et al.

The Malicki equation which was evaluated incorporates a correction for the soil matrix by including the bulk density of the soil in the calculation of volumetric water content. While the prediction error of the model was always significantly greater than that of Topp's equation, the results were similar for each soil and each water content range.

Prediction errors for the medium water content range of crusher run gravel were not significantly different from the best models, but the mean absolute difference tripled for the high water content range.

Jacobsen & Schjonning

The Jacobsen and Schjonning equation is a polynomial similar to Topp's equation. The model was ranked with the fourth poorest T grouping for subgrade soils when all independent variables were taken into account. The same rank was given for each soil when only the high water content range was considered. This model also does not seem suited for crusher run gravel.

Ledieu et al.

The Ledieu equation which was analyzed accounts for the soil bulk density. The prediction error results for subgrade soils are ranked second to the last if the Baran equation is excluded for subgrade soils. The mean absolute difference for subgrade soils when all independent variables were considered was $0.078 \text{ m}^3 \text{ m}^{-3}$.

The model did give a fairly accurate result for the medium water content range for crusher run gravel, but the prediction error greatly increased in the high water content range.

Maxwell Equation (Weitz et al.)

The Maxwell equation is the most complicated model evaluated. The model accounts for many soil physical characteristics when predicting volumetric water content, which makes the model difficult to use from site to site. The results from this study show the Maxwell equation does not perform consistently between water content ranges for the

same soil. Also the overall prediction error was the largest of all the models evaluated, excluding the Baran equation for subgrade soils.

In crusher run gravel, the model had one of the better performances overall when all independent variables were considered. However, the prediction error for the high water content range was three times as large as the Baran or Herkelrath equation.

Baran

The Baran equation had the highest mean absolute difference for the subgrade soil. This was not unexpected since the equation was developed for highest density rock. The mean absolute difference in the crusher run gravel for all repetitions, ranges, and probe segments was $0.021 \text{ m}^3 \text{ m}^{-3}$. While the Herkelrath equation was not significantly different, no other equation was nearly as accurate when only the high water content range was considered.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Resilient modulus of flexible asphalt pavement subgrade soil is highly dependent on water content. Currently, pavement subgrade water content data do not exist for the State of Tennessee. Four test sites across the state were instrumented with equipment to monitor subgrade and flexible asphalt pavement water content and temperature, infiltration water through the pavement layers, and climatic conditions. This data will later be used to develop a rational method of flexible asphalt pavement design that accounts for environmental factors and seasonal water content changes.

Moisture Point five-segment TDR probes, manufactured by *Environmental Sensors*, were installed in the soil subgrade, in the stone base, and in the asphaltic stabilized base. These multiple segment TDR probes will allow changes in water content to be tracked two-dimensionally between the probes and along probe segments. Single-segment TDR probes, constructed in the laboratory, were installed in the asphaltic concrete. Temperature sensors were installed at corresponding depths of the soil subgrade

and the stone base TDR probes. Three temperature sensors were also installed in the top 20 cm of the pavement. A weather station was installed at each test site to monitor air temperature, relative humidity, solar radiation, wind speed, and rainfall.

Subsurface investigations were performed at three test sites to evaluate soil properties and to collect soil samples. One of the subsurface investigation boreholes was developed into a monitoring well at two of the test sites to monitor the water table elevation. To correlate climatic conditions and subgrade water content to pavement strength, the Tennessee Department of Transportation has been performing monthly falling weight deflectometer tests at each test site.

The *Moisture Point* TDR system, manufactured by *Environmental Sensors*, was designed for use in agricultural soils. The materials in which the TDR probes are installed at each test site are quite dissimilar to agricultural soils. For this reason, a calibration study was performed with the *Moisture Point* TDR equipment using four test site subgrade soils and crusher run gravel, which is used for the stone base at each test site.

Three repetitions were performed on each test material. Each data point was grouped by soil, probe segment, repetition, and volumetric water content range. The calibration data for each test material were divided into three equal volumetric water content ranges which were test material specific according to the respective porosities. Volumetric water contents were calculated from the TDR calibration data using ten previously published equations. These predicted volumetric water contents were compared to the corresponding actual volumetric water contents. The absolute value of

the difference between predicted and actual volumetric water content was calculated to prevent positive and negative differences from canceling each other out when averaged.

Using the *Statistical Analysis System* (SAS), means of the absolute difference values were calculated for several interactions between the independent variables. Based on preliminary test site data, the prediction models were primarily evaluated on performance within the high water content range for subgrade soils and high to medium water content range for crusher run gravel. The prediction models were also analyzed for their overall performance since test site subgrade water contents may change in the future.

Conclusions

Multiple-segment TDR probes offer many advantages over conventional single-segment TDR probes and other means of water content measurement in flexible asphalt pavement subgrades. The incorporation of this equipment into an automated multiplexed system allows the data acquisition time to be reduced to a point where hourly changes in water content can be monitored. The multiple-segment probes also allow the movement of water to be tracked in pavement subgrades. Although four of twenty-six probes and ten other segments have failed, the overall multiple segment probe survival rate was good. The overall five-segment probe survival rate is currently 85%, and the segment

survival rate is currently 78%. Two of the original seven single-segment probes have failed since installation.

The following conclusions were drawn from extensive evaluation of ten TDR calibration equations for predicting volumetric water content from *Moisture Point* TDR system data for flexible asphalt pavement subgrade materials:

- The equation proposed by Herkelrath et al. (1991) proved to be the most accurate prediction model of volumetric water content for all subgrade soils and was not significantly different from the best prediction model in crusher run gravel.
- The equation proposed by Baran (1994) had the lowest prediction error of volumetric water content for all water content ranges of crusher run gravel.
- The *Moisture Point* equation and the three- and four- phase dielectric mixing models proposed by Weitz et al. (1997) gave acceptable volumetric water content predictions for subgrade soils.
- The best prediction models of those evaluated have a prediction error that is less than the $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$ accuracy given by the *Moisture Point* equipment manufacturer.
- There were four prediction models that have a prediction error that was

less than $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$ for all water content ranges in the subgrade soils and two prediction models for the crusher run gravel.

- The physical differences between soil and high density crushed gravel appear to be a significant factor in selecting a TDR water content prediction equation.
- Repeatability errors exist in the *Moisture Point* five-segment TDR probes. Segments one and two have twice as much prediction error from one scan to the next as segments three and five. Segment four has a prediction error that is an order of magnitude less than any of the other segments.

CHAPTER VI

RECOMMENDATIONS

TDR Calibration Equation for High Density Pavement Systems

The approach defined by Herkelrath et al. (1991) to predicting volumetric water content from the inverse signal velocity from TDR equipment proved to be the most simple and accurate for the *Moisture Point* equipment. For this reason, it is recommended for use with the *Moisture Point* TDR equipment to predict volumetric water contents for the subgrade soils and crusher run gravel for each flexible pavement test site.

The dielectric constant of free water appears to be significantly dependent on temperature (approximately $-0.0356\text{ }^{\circ}\text{C}^{-1}$ from 5 to 50 $^{\circ}\text{C}$ at 1 GHz). Pepin et al. (1995) suggested using a temperature correction of $0.001750(\theta_v)\text{ }^{\circ}\text{C}^{-1}$. Although temperature was not evaluated in this study, the affect of temperature on the accuracy of TDR has been well noted. The direct correction of volumetric water content calculated by TDR, suggested by Pepin et al. (1995), offers a good way to correct results from the Herkelrath equation for temperature.

Future Research

The correction constants between measured propagation time and actual propagation time for *Moisture Point* multiple-segment TDR probes should be further analyzed in order to get the most accurate result for each probe segment. A linear relationship appears to exist, but more research needs to be performed to determine if any probe dependence exists. An actual measurement of the apparent dielectric of the soil should be made to get the most accurate slope and intercept.

The one short coming of the Herkelrath method is the need to derive soil specific slope and intercept constants, although the slopes and intercepts derived for soil subgrade calibration data appear to be very consistent. Further studies should be performed to evaluate whether a good average slope and intercept for the Herkelrath equation from several soil calibrations could be as accurate a predictor of water content as any of the more complex models.

LITERATURE CITED

LITERATURE CITED

- Baran, E. 1994. Use of Time Domain Reflectometry for Monitoring Changes in Crushed Rock Pavements: *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.349-356.
- Chu, T. Y. and W. K. Humphries. 1972. Investigations of Subgrade Moisture Conditions in Connection with the Design of Flexible Pavement Structures. *College of Engineering: University of South Carolina*, Columbia, South Carolina.
- Dasberg, S. and J. W. Hopmans. 1992. Time Domain Reflectometry Calibration for Uniformly and Nonuniformly Wetted Sandy and Clayey Loam Soils. *Soil Science Society of America Journal*. 56:1341-1345.
- Dasberg, S. and F. N. Dalton. 1985. Time Domain Reflectometry Field Measurements of Soil Water Content and Electrical Conductivity. *Soil Science Society of America Journal*. 49:293-297.
- De Loor, G. P. 1964. Dielectric Properties of Heterogeneous Mixtures With a Polar Constituent. *Applied Science Research*. 11:310-320.
- Dirksen, C. and S. Dasberg. 1993. Improved Calibration of Time domain Reflectometry Soil Water Content Measurements. *Soil Science Society of America Journal*. 57:660-667.
- Dobson, M. C., F. T. Ulaby, M. T. Hallikainen, and M. A. El-Rayes. 1985. Microwave Dielectric Behavior of Wet Soil - Part II: Dielectric Mixing Models. *IEEE Transactions on Geoscience and Remote Sensing*. GE-23(1):35-46.

- Drumm, E. C., J. S. Reeves, M. R. Madgett, and W. D. Trolinger. 1996. Subgrade Resilient Modulus Correction for Saturation Effects. *ASCE Journal of Geotechnical Engineering*. 123(7):603-670.
- Dunnicliff, J. 1988. Geotechnical Instrumentation for Monitoring Field Performance. *John Wiley and Sons, Inc.*. New York, New York.
- Guinnee, J. W. 1958. Field Studies on Subgrade Moisture Conditions. *Highway Research Board*. Special Report 60.
- Hallikainen, M. T., F. T. Ulaby, M. C. Dobson, M. A. El-Rayes, and L. Wu. 1985. Microwave Dielectric Behavior of Wet Soils - Part I: Empirical Models and Experimental Observations. *IEEE Transactions on Geoscience and Remote Sensing*. GE-23(1):25-34.
- Heimovaara, T. J. and W. Bouten. 1990. A Computer-Controlled 36-Channel Time Domain Reflectometry System for Monitoring Soil Water Contents. *Water Resources Research*. 26(10):2311-2316.
- Heimovaara, T. J., W. Bouten, and J. M. Verstraten. 1994. Frequency Domain Analysis of Time Domain Reflectometry Waveforms: A Four-Component Dielectric Mixing Model for Soils. *Water Resources Research*. 30(2):201-209.
- Herkelrath, W. N., S. P. Hamburg, and F. Murphy. 1991. Automatic, Real-Time Monitoring in a Remote Field Area with Time Domain Reflectometry. *Water Resources Research*. 27(5):857-864.
- Hook, W. R., N. J. Livingston, Z. J. Sun, and P. B. Hook. 1992. Remote Diode Shorting Improves Measurement of Soil Water by Time Domain Reflectometry. *Soil Science Society of America Journal*. 56:1384-1391.

- Hook, W. R. and N. J. Livingston. 1996. Errors in Converting Time Domain Reflectometry Measurements of Propagation Time to Estimates of Soil Water Content. *Soil Science Society of America Journal*. 60(1):35-41.
- Hossain, M., S. J. Kotdwala, B. Long, and A. J. Gisi. 1997. Subgrade Moisture Monitoring Using Time Domain Reflectometry. *Transportation Research Board*. 76th Annual Meeting. Washington D. C. (Preprint).
- Jacobsen, O. H. and P. Schjonning. 1993. A Laboratory Calibration of Time Domain Reflectometry for Soil Water Measurement Including Effects of Bulk Density and Texture. *Journal of Hydrology*. 151:147-157.
- Janoo, V., R. L. Berg, E. Simonsen, and A. Harrison. 1994. Seasonal Changes in Airport and Highway Pavements. *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.357-363.
- Kotdawala, S. J., M. Hossain, and A. J. Gisi. 1994. Monitoring of Moisture Changes in Pavement Subgrades Using Time-Domain Reflectometry (TDR). *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.349-356.
- Ledieu, J., P. De Ridder, P. De Clerck, and S. Dautrebanda. 1986. A Method of Measuring Soil Moisture by Time Domain Reflectometry. *Journal of Hydrology*. 88:319-328.

- Look, B. G., Reeves I. N., and D. J. Williams. 1994. Field Experiences Using Time Domain Reflectometry For Monitoring Moisture Changes In Road Embankments and Pavements. *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.374-385.
- Malicki, M. A., R. Plagge, and C. H. Roth. 1996. Improving the Calibration of Dielectric TDR Soil Moisture Determination Taking Into Account the Solid Soil. *European Journal of Soil Science*. 47:357-366.
- Marks, B. D., III and T. A. Haliburton. 1969. Subgrade Moisture Variations Studied with Nuclear Depth Gages. *Highway Research Board*. Special Report 276.
- Noborio, K., K. J. McInnes, and J. L. Heilman. 1994. Field Measurements of Soil Conductivity and Water Content by Time Domain Reflectometry. *Computers and Electronics in Agriculture*. 11:131-142.
- Pepin, S., N. J. Livingston, and W. R. Hook. 1995. Temperature-Dependent Measurement Errors in Time Domain Reflectometry Determinations of Soil Water. *Soil Science Society of America Journal*. 59:38-43.
- Petersen, L. W., A. Thomsen, P. Moldrup, O. H. Jacobsen; and D. E. Rolsten. 1995. High Resolution Time Domain Reflectometry: Sensitivity Dependency on Probe Design. *Soil Science Society of America Journal*. 159:149-154.

- Rada, G. R., A. Lopez, Jr., and G. E. Elkins. 1994. Monitoring of Subsurface Moisture in Pavements Using Time-Domain Reflectometry. *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.422-433.
- Roth, C. H., M. A. Malicki, and R. Plagge. 1992. Empirical Evaluation of the Relationship Between Soil Dielectric Constant and Volumetric Water Content on the Basis for Calibrating Soil Moisture Measurements by TDR. *Journal of Soil Science*. 43:1-13.
- Roth, K., R. Shulin, H. Fluhler, and W. Attinger. 1990. Calibration of Time Domain Reflectometry for Water Content Measurement Using a Composite Dielectric Approach. *Water Resources Research*. 26(10):2267-2273.
- Russam, K. 1970. Subgrade Moisture Studies by the British Road Research Laboratory: British Road Research Laboratory. *Highway Research Board*. HRR 301.
- Sargand, S. 1994. Development of an Instrumentation Plan for Ohio SPS Test Pavement (DEL-23-17.48), Job No. 14573(0). Final Report for Ohio Department of Transportation and Federal Highway Administration. *Ohio University, Center for Geotechnical and Environmental Research*. Athens, Ohio.
- Schlotzhauer, S. D. and R. C. Littell. 1987. SAS System for Elementary Statistical Analysis. *SAS Institute*. Cary, North Carolina.
- Scullion, T. and T. Saarenketo. 1996. Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials. *Transportation Research Record*. 1577:37-44.

- Strategic Highway Research Program, Ohio Department of Transportation. 1997.
Specific Pavement Studies: Test Road as Constructed. *Ohio University, Center for Geotechnical and Environmental Research*. Athens, Ohio.
- Topp, G. C., J. L. Davis, and A. P. Annan. 1980. Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Lines. *Water Resources Research*. 16(3):574-582.
- Topp, G. C., J. L. Davis, and A. P. Annan. 1982. Electromagnetic Determination of Soil Water Content Using TDR:II. Evaluation of Installation and Configuration of Parallel Transmission Lines. *Soil Science Society of America Journal*. 46:678-684.
- Topp, G. C. and J. L. Davis. 1985a. Measurement of Soil Water Content Using Time Domain Reflectometry (TDR): A Field Evaluation. *Soil Science Society of America Journal*. 49:19-21.
- Topp, G. C. and J. L. Davis. 1985b. Time Domain Reflectometry (TDR) and Its Application to Irrigation Scheduling. *Advances in Irrigation*. 3:107-126.
- van Schelt, W., M. K. Jong-Hanninen, J. P. C. M. van der Aa, and W. K. P. van Loon. 1994. Field and Laboratory Experiments with Time Domain Reflectometry as a Moisture Monitoring System in Road Structures. *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, September 7-9, Evanston, Illinois. US Bureau of Mines, Infrastructure Technology Institute at Northwestern University, Los Alamos National Laboratory. pp.386-397.
- Vaswani, N. K. 1975. Case Studies of Variations in Subgrade Moisture and Temperature Under Road Pavements in Virginia. *TRR*. Special Report 532.

- Weitz, A. M., W. T. Grauel, M. Keller, and E. Veldkamp. 1997. Calibration of Time Domain Reflectometry Techniques Using Undisturbed Soil Samples from Humid Tropical Soils of Volcanic Origin. *Water Resources Research*. 33(6):1241-1249.
- Werkhoven, C. 1994. Time Domain Reflectometry for Detecting Soil Moisture Content. Proceedings of 5th International Conference of Computers in Agriculture : American Society of Agricultural Engineers. February 6-9. Orlando, Florida. *ASAE Publication* 94-03:pp.853-857.
- Yanuka, M., G. C. Topp, S. Zegelin, and W. D. Zebchuck. 1988. Multiple Reflection Attenuation of Time Domain Reflectometry Pulses: Theoretical Considerations for Applications to Soil and Water. *Water Resources Research*. 24(7):939-944.
- Yoder, E. J. and M. W. Witzak. 1975. Principles of Pavement Design, Second Edition. *John Wiley and Sons, Inc.* New York, New York.
- Young, G. D. 1995a. Single-Diode Probes. *Moisture Point MP-917 Technical Brief* 13. *Environmental Sensors, Inc.* San Diego, California.
- Young, G. D. 1995b. Moisture Point TDR System. *Moisture Point MP-917 Technical Brief* 1. *Environmental Sensors, Inc.* San Diego, California.
- Young, M. H., J. B. Fleming, P. J. Wierenga, and A. W. Warrick. 1997. Rapid Laboratory Calibration of Time Domain Reflectometry Using Upward Infiltration. *Soil Science Society of America Journal*. 61(3):707-712.

APPENDICES

APPENDIX A

RESULTS

Table A-1. Mean absolute differences of volumetric water contents for each model, test site soil, probe segment, and range.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Herkelrath	Blount	1	0.017	0.022	0.015
Herkelrath	Blount	2	0.015	0.028	0.013
Herkelrath	Blount	3	0.013	0.018	0.021
Herkelrath	Blount	4	0.012	0.025	0.028
Herkelrath	Blount	5	0.012	0.028	0.024
Herkelrath	Overton	1	0.051	0.047	0.019
Herkelrath	Overton	2	0.027	0.031	0.021
Herkelrath	Overton	3	0.018	0.031	0.033
Herkelrath	Overton	4	0.026	0.030	0.037
Herkelrath	Overton	5	0.035	0.034	0.024
Herkelrath	McNairy	1	0.029	0.017	0.013
Herkelrath	McNairy	2	0.014	0.015	0.012
Herkelrath	McNairy	3	0.022	0.023	0.022
Herkelrath	McNairy	4	0.019	0.025	0.031

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Herkelrath	McNairy	5	0.053	0.039	0.017
Herkelrath	Sumner	1	0.028	0.033	0.033
Herkelrath	Sumner	2	0.021	0.019	0.022
Herkelrath	Sumner	3	0.017	0.016	0.017
Herkelrath	Sumner	4	0.021	0.025	0.045
Herkelrath	Sumner	5	0.026	0.034	0.028
Moisture Point	Blount	1	0.017	0.022	0.015
Moisture Point	Blount	2	0.015	0.028	0.013
Moisture Point	Blount	3	0.012	0.017	0.021
Moisture Point	Blount	4	0.013	0.024	0.029
Moisture Point	Blount	5	0.012	0.029	0.024
Moisture Point	Overton	1	0.041	0.065	0.017
Moisture Point	Overton	2	0.024	0.050	0.017
Moisture Point	Overton	3	0.033	0.030	0.020
Moisture Point	Overton	4	0.050	0.040	0.026

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Moisture Point	Overton	5	0.059	0.039	0.017
Moisture Point	McNairy	1	0.033	0.017	0.009
Moisture Point	McNairy	2	0.018	0.017	0.011
Moisture Point	McNairy	3	0.025	0.024	0.019
Moisture Point	McNairy	4	0.018	0.026	0.028
Moisture Point	McNairy	5	0.050	0.041	0.017
Moisture Point	Sumner	1	0.040	0.058	0.016
Moisture Point	Sumner	2	0.035	0.042	0.013
Moisture Point	Sumner	3	0.042	0.014	0.014
Moisture Point	Sumner	4	0.041	0.031	0.017
Moisture Point	Sumner	5	0.042	0.046	0.014
3 - Phase	Blount	1	0.017	0.022	0.014
3 - Phase	Blount	2	0.015	0.028	0.012
3 - Phase	Blount	3	0.013	0.018	0.019
3 - Phase	Blount	4	0.013	0.026	0.028

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
3 - Phase	Blount	5	0.012	0.028	0.023
3 - Phase	Overton	1	0.041	0.068	0.018
3 - Phase	Overton	2	0.025	0.054	0.017
3 - Phase	Overton	3	0.037	0.030	0.018
3 - Phase	Overton	4	0.053	0.042	0.025
3 - Phase	Overton	5	0.063	0.041	0.017
3 - Phase	McNairy	1	0.030	0.013	0.008
3 - Phase	McNairy	2	0.013	0.017	0.012
3 - Phase	McNairy	3	0.021	0.024	0.016
3 - Phase	McNairy	4	0.021	0.033	0.024
3 - Phase	McNairy	5	0.058	0.045	0.019
3 - Phase	Sumner	1	0.041	0.059	0.015
3 - Phase	Sumner	2	0.036	0.043	0.013
3 - Phase	Sumner	3	0.043	0.015	0.014
3 - Phase	Sumner	4	0.042	0.032	0.017

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
3 - Phase	Sumner	5	0.045	0.047	0.014
4 - Phase	Blount	1	0.029	0.034	0.031
4 - Phase	Blount	2	0.024	0.040	0.031
4 - Phase	Blount	3	0.027	0.022	0.038
4 - Phase	Blount	4	0.028	0.013	0.046
4 - Phase	Blount	5	0.023	0.035	0.043
4 - Phase	Overton	1	0.047	0.048	0.021
4 - Phase	Overton	2	0.023	0.022	0.024
4 - Phase	Overton	3	0.020	0.031	0.034
4 - Phase	Overton	4	0.031	0.030	0.039
4 - Phase	Overton	5	0.039	0.033	0.026
4 - Phase	McNairy	1	0.042	0.025	0.016
4 - Phase	McNairy	2	0.029	0.021	0.012
4 - Phase	McNairy	3	0.029	0.025	0.025
4 - Phase	McNairy	4	0.013	0.017	0.035

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
4 - Phase	McNairy	5	0.041	0.037	0.019
4 - Phase	Sumner	1	0.027	0.035	0.031
4 - Phase	Sumner	2	0.022	0.021	0.019
4 - Phase	Sumner	3	0.020	0.011	0.03
4 - Phase	Sumner	4	0.024	0.023	0.042
4 - Phase	Sumner	5	0.029	0.035	0.025
Topp	Blount	1	0.026	0.022	0.015
Topp	Blount	2	0.029	0.026	0.012
Topp	Blount	3	0.025	0.026	0.019
Topp	Blount	4	0.024	0.040	0.026
Topp	Blount	5	0.028	0.031	0.02
Topp	Overton	1	0.040	0.079	0.022
Topp	Overton	2	0.038	0.066	0.020
Topp	Overton	3	0.058	0.035	0.018
Topp	Overton	4	0.073	0.051	0.023

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Topp	Overton	5	0.082	0.047	0.020
Topp	McNairy	1	0.021	0.01	0.011
Topp	McNairy	2	0.010	0.017	0.015
Topp	McNairy	3	0.02	0.025	0.017
Topp	McNairy	4	0.034	0.041	0.025
Topp	McNairy	5	0.070	0.049	0.021
Topp	Sumner	1	0.058	0.070	0.014
Topp	Sumner	2	0.053	0.056	0.015
Topp	Sumner	3	0.064	0.029	0.014
Topp	Sumner	4	0.062	0.044	0.017
Topp	Sumner	5	0.062	0.059	0.016
Malicki	Blount	1	0.029	0.019	0.017
Malicki	Blount	2	0.032	0.025	0.015
Malicki	Blount	3	0.028	0.024	0.022
Malicki	Blount	4	0.027	0.036	0.030

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Malicki	Blount	5	0.032	0.029	0.025
Malicki	Overton	1	0.047	0.076	0.019
Malicki	Overton	2	0.045	0.064	0.019
Malicki	Overton	3	0.066	0.035	0.019
Malicki	Overton	4	0.081	0.049	0.026
Malicki	Overton	5	0.089	0.045	0.019
Malicki	McNairy	1	0.025	0.015	0.011
Malicki	McNairy	2	0.025	0.022	0.015
Malicki	McNairy	3	0.035	0.025	0.016
Malicki	McNairy	4	0.051	0.047	0.024
Malicki	McNairy	5	0.085	0.054	0.021
Malicki	Sumner	1	0.059	0.064	0.014
Malicki	Sumner	2	0.055	0.049	0.014
Malicki	Sumner	3	0.066	0.024	0.015
Malicki	Sumner	4	0.064	0.038	0.018

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Malicki	Sumner	5	0.063	0.053	0.015
Jacobsen	Blount	1	0.057	0.027	0.014
Jacobsen	Blount	2	0.060	0.027	0.011
Jacobsen	Blount	3	0.058	0.036	0.018
Jacobsen	Blount	4	0.057	0.048	0.026
Jacobsen	Blount	5	0.061	0.036	0.019
Jacobsen	Overton	1	0.070	0.085	0.022
Jacobsen	Overton	2	0.074	0.072	0.020
Jacobsen	Overton	3	0.091	0.042	0.017
Jacobsen	Overton	4	0.103	0.058	0.022
Jacobsen	Overton	5	0.110	0.054	0.020
Jacobsen	McNairy	1	0.034	0.017	0.011
Jacobsen	McNairy	2	0.042	0.024	0.015
Jacobsen	McNairy	3	0.051	0.025	0.016
Jacobsen	McNairy	4	0.063	0.048	0.023

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Jacobsen	McNairy	5	0.093	0.055	0.021
Jacobsen	Sumner	1	0.087	0.076	0.014
Jacobsen	Sumner	2	0.081	0.062	0.015
Jacobsen	Sumner	3	0.093	0.039	0.015
Jacobsen	Sumner	4	0.092	0.052	0.017
Jacobsen	Sumner	5	0.092	0.066	0.015
Ledieu	Blount	1	0.061	0.046	0.031
Ledieu	Blount	2	0.064	0.044	0.032
Ledieu	Blount	3	0.061	0.058	0.026
Ledieu	Blount	4	0.060	0.072	0.026
Ledieu	Blount	5	0.065	0.054	0.027
Ledieu	Overton	1	0.069	0.110	0.042
Ledieu	Overton	2	0.076	0.097	0.036
Ledieu	Overton	3	0.097	0.065	0.025
Ledieu	Overton	4	0.112	0.082	0.025

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Ledieu	Overton	5	0.121	0.077	0.033
Ledieu	McNairy	1	0.041	0.039	0.035
Ledieu	McNairy	2	0.048	0.049	0.041
Ledieu	McNairy	3	0.059	0.046	0.027
Ledieu	McNairy	4	0.075	0.076	0.024
Ledieu	McNairy	5	0.110	0.083	0.038
Ledieu	Sumner	1	0.092	0.010	0.036
Ledieu	Sumner	2	0.086	0.086	0.042
Ledieu	Sumner	3	0.100	0.061	0.033
Ledieu	Sumner	4	0.099	0.075	0.022
Ledieu	Sumner	5	0.098	0.089	0.037
Maxwell	Blount	1	0.064	0.054	0.039
Maxwell	Blount	2	0.067	0.051	0.038
Maxwell	Blount	3	0.065	0.067	0.033
Maxwell	Blount	4	0.063	0.081	0.030

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Maxwell	Blount	5	0.068	0.062	0.034
Maxwell	Overton	1	0.071	0.117	0.044
Maxwell	Overton	2	0.077	0.104	0.039
Maxwell	Overton	3	0.099	0.070	0.027
Maxwell	Overton	4	0.115	0.088	0.029
Maxwell	Overton	5	0.123	0.083	0.036
Maxwell	McNairy	1	0.044	0.045	0.034
Maxwell	McNairy	2	0.053	0.054	0.039
Maxwell	McNairy	3	0.063	0.052	0.028
Maxwell	McNairy	4	0.079	0.081	0.026
Maxwell	McNairy	5	0.115	0.089	0.037
Maxwell	Sumner	1	0.095	0.110	0.044
Maxwell	Sumner	2	0.089	0.095	0.049
Maxwell	Sumner	3	0.103	0.069	0.041
Maxwell	Sumner	4	0.101	0.084	0.031

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Maxwell	Sumner	5	0.100	0.098	0.045
Baran	Blount	1	0.140	0.085	0.038
Baran	Blount	2	0.141	0.083	0.037
Baran	Blount	3	0.140	0.093	0.033
Baran	Blount	4	0.139	0.103	0.032
Baran	Blount	5	0.142	0.090	0.034
Baran	Overton	1	0.153	0.135	0.044
Baran	Overton	2	0.158	0.125	0.041
Baran	Overton	3	0.170	0.101	0.032
Baran	Overton	4	0.178	0.114	0.033
Baran	Overton	5	0.184	0.111	0.038
Baran	McNairy	1	0.114	0.073	0.035
Baran	McNairy	2	0.122	0.082	0.039
Baran	McNairy	3	0.128	0.081	0.030
Baran	McNairy	4	0.138	0.102	0.029

Table A-1. Continued.

Model	Soil	Probe Segment	Mean Absolute Difference by Range*		
			High	Medium	Low
Baran	McNairy	5	0.147	0.098	0.030
Baran	Sumner	1	0.162	0.108	0.038
Baran	Sumner	2	0.162	0.115	0.048
Baran	Sumner	3	0.169	0.096	0.041
Baran	Sumner	4	0.168	0.106	0.033
Baran	Sumner	5	0.168	0.117	0.044

* Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

Table A-2. Crusher run mean absolute differences of volumetric water contents for each model, probe segment, and range.

Model	Probe Segment	Mean Absolute Difference by Range*		
		High	Medium	Low
Baran	1	0.013	0.027	0.015
Baran	2	0.019	0.018	0.021
Baran	3	0.024	0.012	0.026
Baran	4	0.015	0.016	0.035
Baran	5	0.018	0.021	0.018
Herkelrath	1	0.016	0.030	0.015
Herkelrath	2	0.021	0.019	0.020
Herkelrath	3	0.027	0.016	0.025
Herkelrath	4	0.017	0.016	0.034
Herkelrath	5	0.025	0.023	0.018
Maxwell	1	0.05	0.022	0.019
Maxwell	2	0.075	0.022	0.026
Maxwell	3	0.089	0.018	0.034
Maxwell	4	0.063	0.025	0.044
Maxwell	5	0.030	0.020	0.022

Table A-2. Continued.

Model	Probe Segment	Mean Absolute Difference by Range*		
		High	Medium	Low
Ledieu	1	0.065	0.025	0.021
Ledieu	2	0.093	0.024	0.024
Ledieu	3	0.109	0.020	0.028
Ledieu	4	0.079	0.030	0.041
Ledieu	5	0.042	0.020	0.018
Malicki	1	0.063	0.022	0.215
Malicki	2	0.089	0.024	0.030
Malicki	3	0.104	0.025	0.042
Malicki	4	0.076	0.036	0.053
Malicki	5	0.041	0.018	0.025
Jacobsen	1	0.080	0.036	0.039
Jacobsen	2	0.103	0.050	0.053
Jacobsen	3	0.117	0.054	0.068
Jacobsen	4	0.091	0.065	0.080

Table A-2. Continued.

Model	Probe Segment	Mean Absolute Difference by Range [*]		
		High	Medium	Low
Jacobsen	5	0.061	0.043	0.048
3 - Phase	1	0.121	0.041	0.031
3 - Phase	2	0.151	0.055	0.045
3 - Phase	3	0.169	0.06	0.061
3 - Phase	4	0.136	0.073	0.075
3 - Phase	5	0.094	0.046	0.039
Topp	1	0.116	0.043	0.042
Topp	2	0.141	0.060	0.057
Topp	3	0.155	0.064	0.071
Topp	4	0.128	0.077	0.083
Topp	5	0.092	0.051	0.051
4 - Phase	1	0.123	0.043	0.033
4 - Phase	2	0.154	0.058	0.047
4 - Phase	3	0.172	0.063	0.064

Table A-2. Continued.

Model	Probe Segment	Mean Absolute Difference by Range*		
		High	Medium	Low
4 - Phase	4	0.139	0.076	0.078
4 - Phase	5	0.096	0.049	0.041
Moisture Point	1	0.141	0.053	0.047
Moisture Point	2	0.172	0.076	0.065
Moisture Point	3	0.190	0.081	0.082
Moisture Point	4	0.157	0.094	0.096
Moisture Point	5	0.115	0.067	0.059

* Mean absolute differences are in units of $\text{m}^3 \text{m}^{-3}$.

APPENDIX B

B-1-1. Time to equilibrium of test material water content in calibration box.

- Overton County Test Soil
- Bulk Density ρ_b - 1.57 Mg m^{-3}
- Test Material Water Content Initially Increased to $0.30 \text{ m}^3 \text{ m}^{-3}$
- Test Material Water Content Initially Allowed to Equalize for Seventy-Two Hours
- Water Content Increased by Two Steps of $0.05 \text{ m}^3 \text{ m}^{-3}$ and One Step of $0.025 \text{ m}^3 \text{ m}^{-3}$
- Volumetric Water Content Computed Using *Moisture Point* Equation

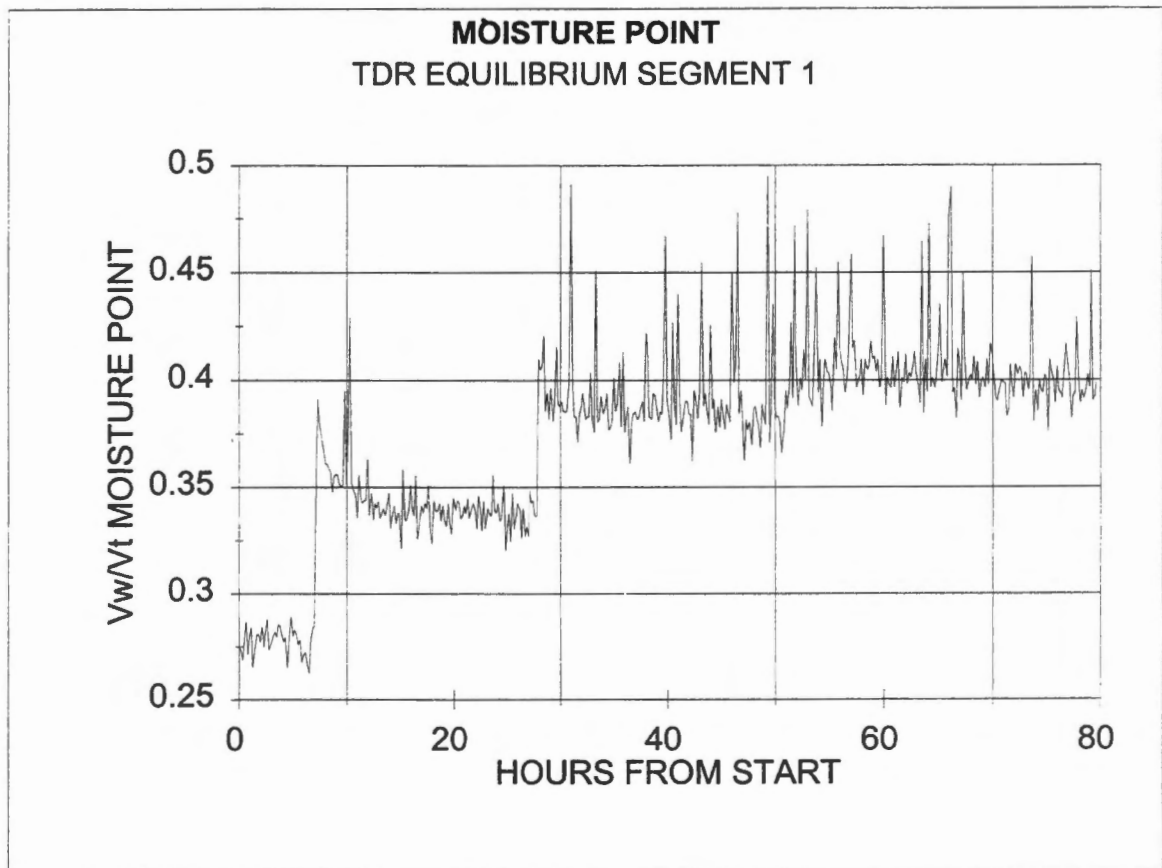


Figure B-1-2. Time to equilibrium of test material water content in calibration box (Segment 1).

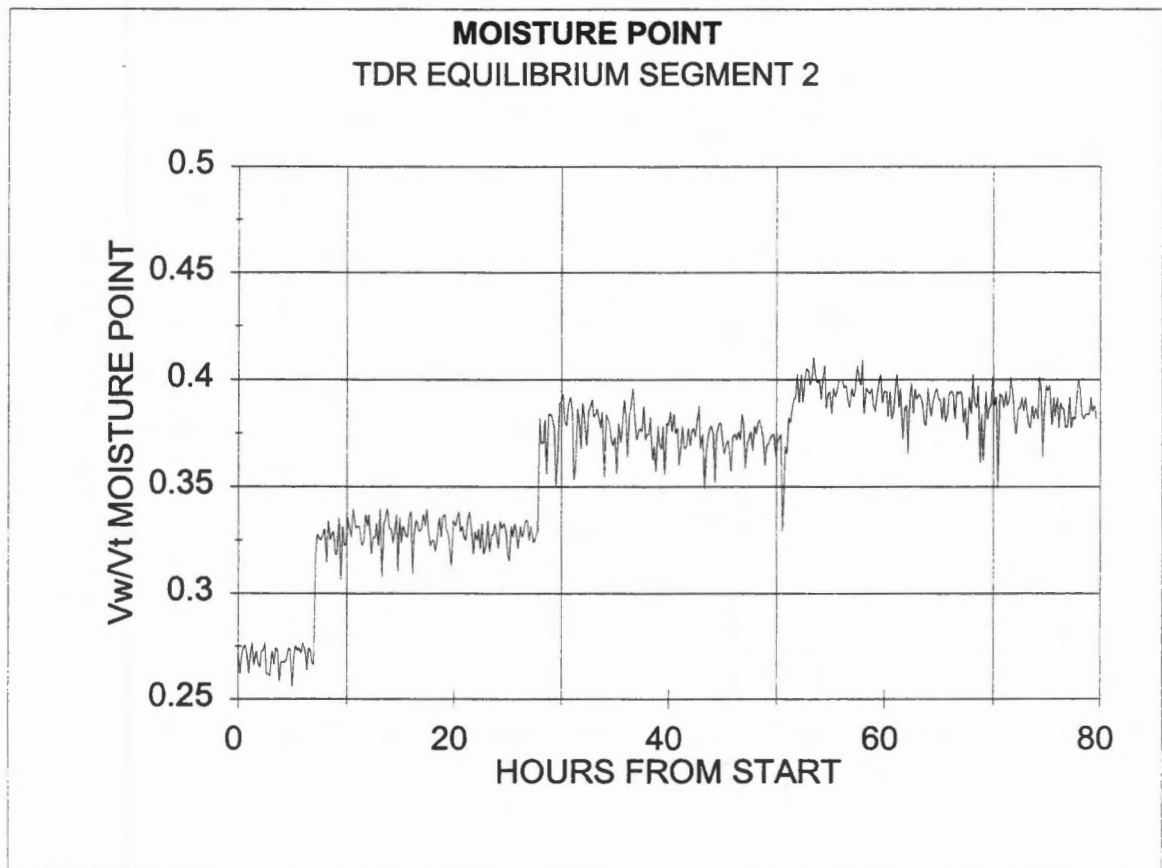


Figure B-1-3. Time to equilibrium of test material water content in calibration box (Segment 2).

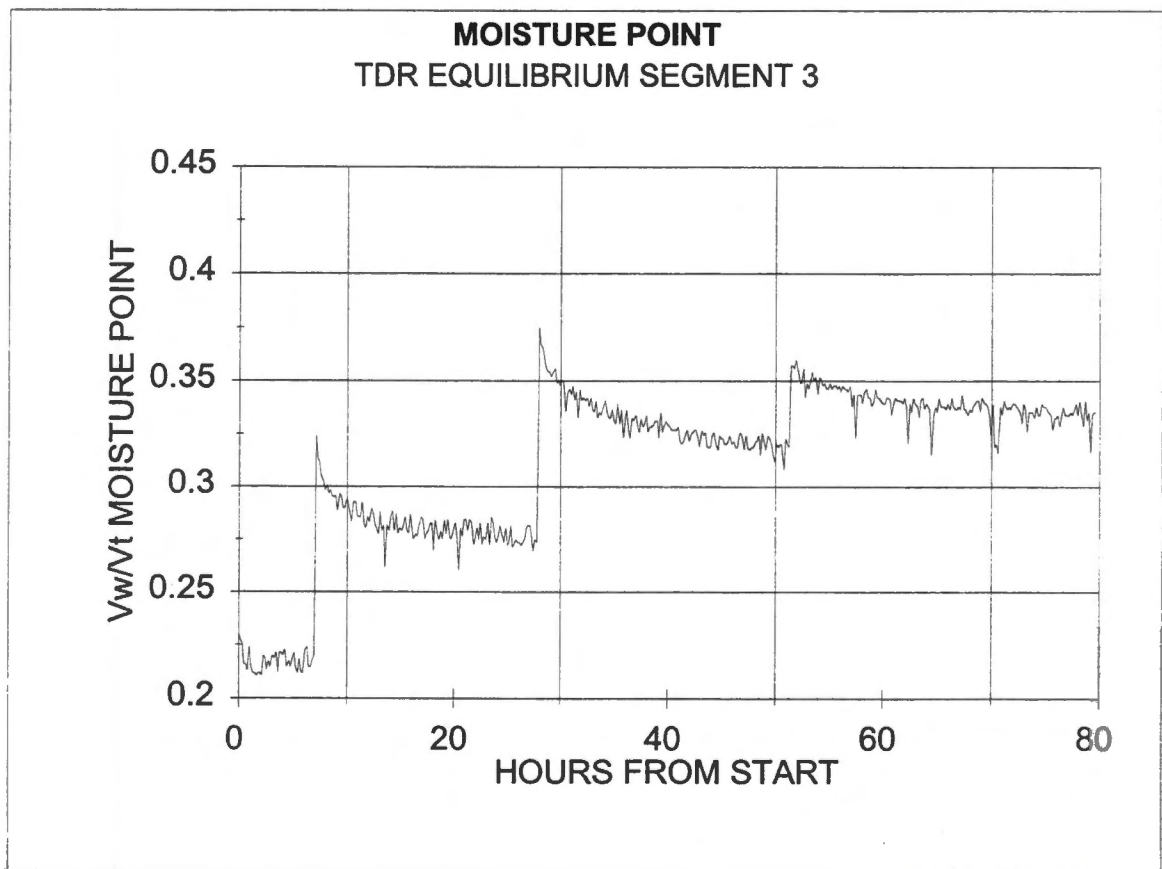


Figure B-1-4. Time to equilibrium of test material water content in calibration box (Segment 3).

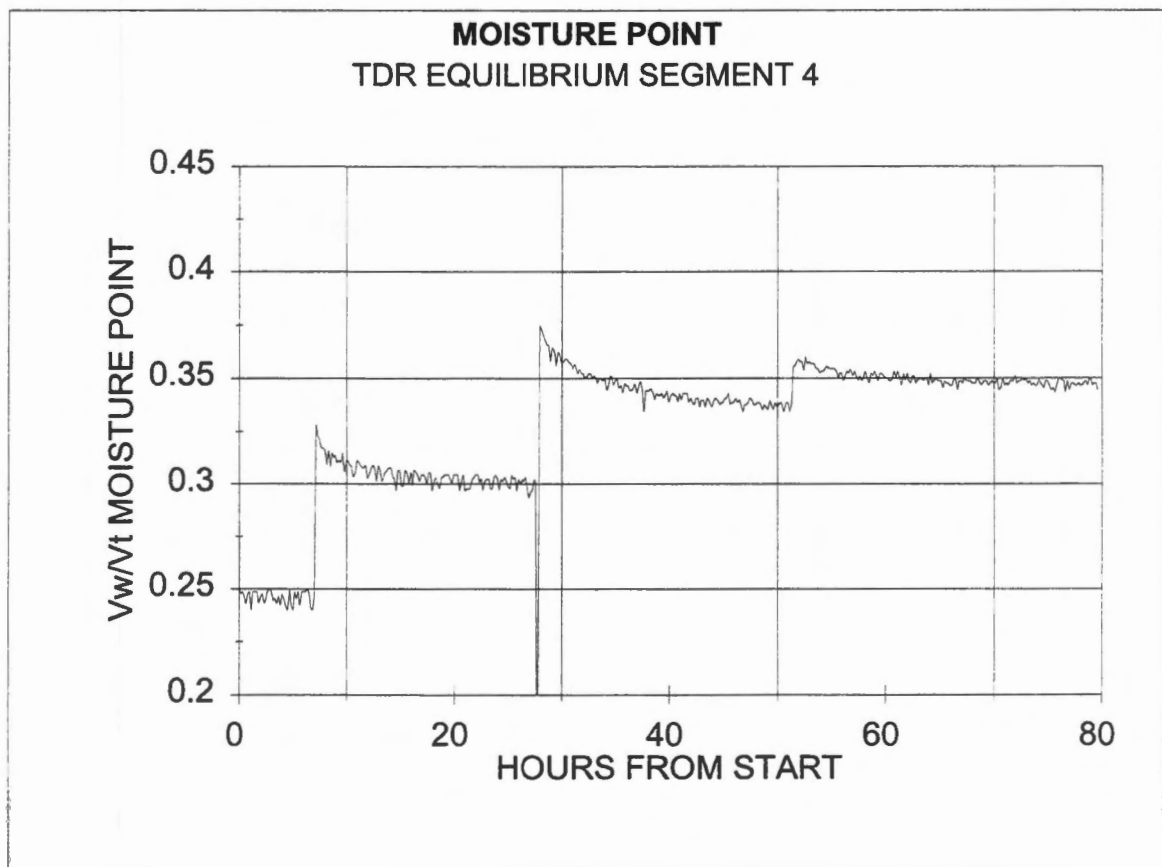


Figure B-1-5. Time to equilibrium of test material water content in calibration box (Segment 4).

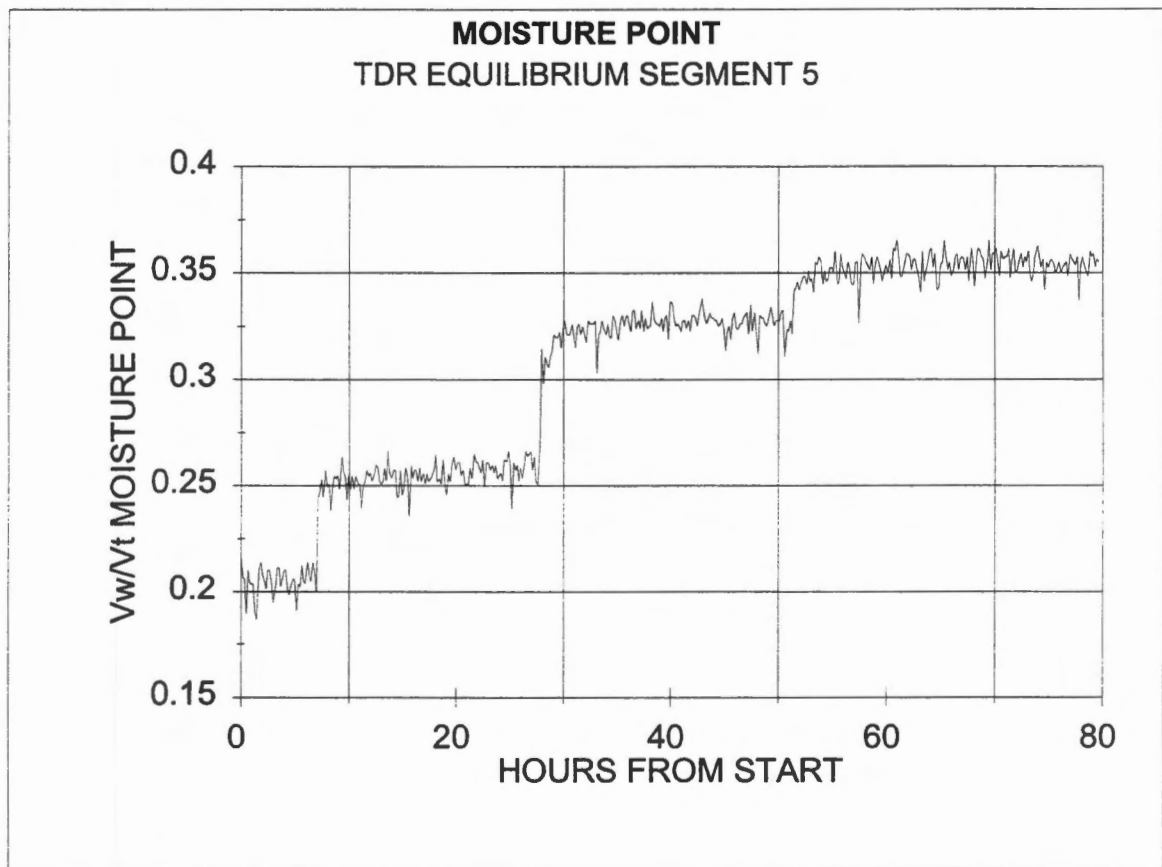


Figure B-1-6. Time to equilibrium of test material water content in calibration box (Segment 5).

B-2-1. Noise in *Moisture Point* five-segment TDR probe.

- Blount County Test Soil
- Bulk Density ρ_b - 1.54 Mg m⁻³
- Test Material Water Content Initially Increased to 0.30 m³ m⁻³
- Test Material Water Content Initially Allowed to Equalize for Seventy-Two Hours
- Volumetric Water Content Computed Using *Moisture Point* Equation

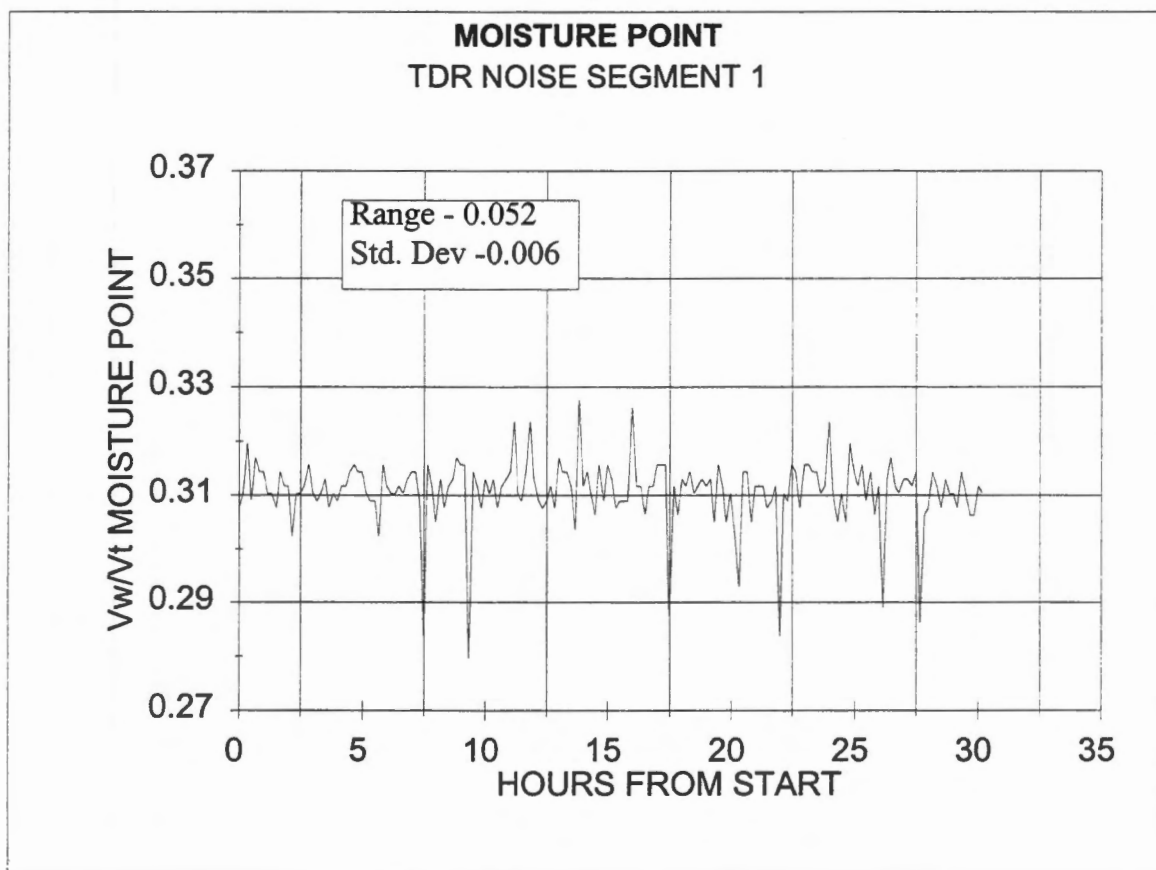


Figure B-2-2. Noise in *Moisture Point* five-segment TDR probe (Segment 1).

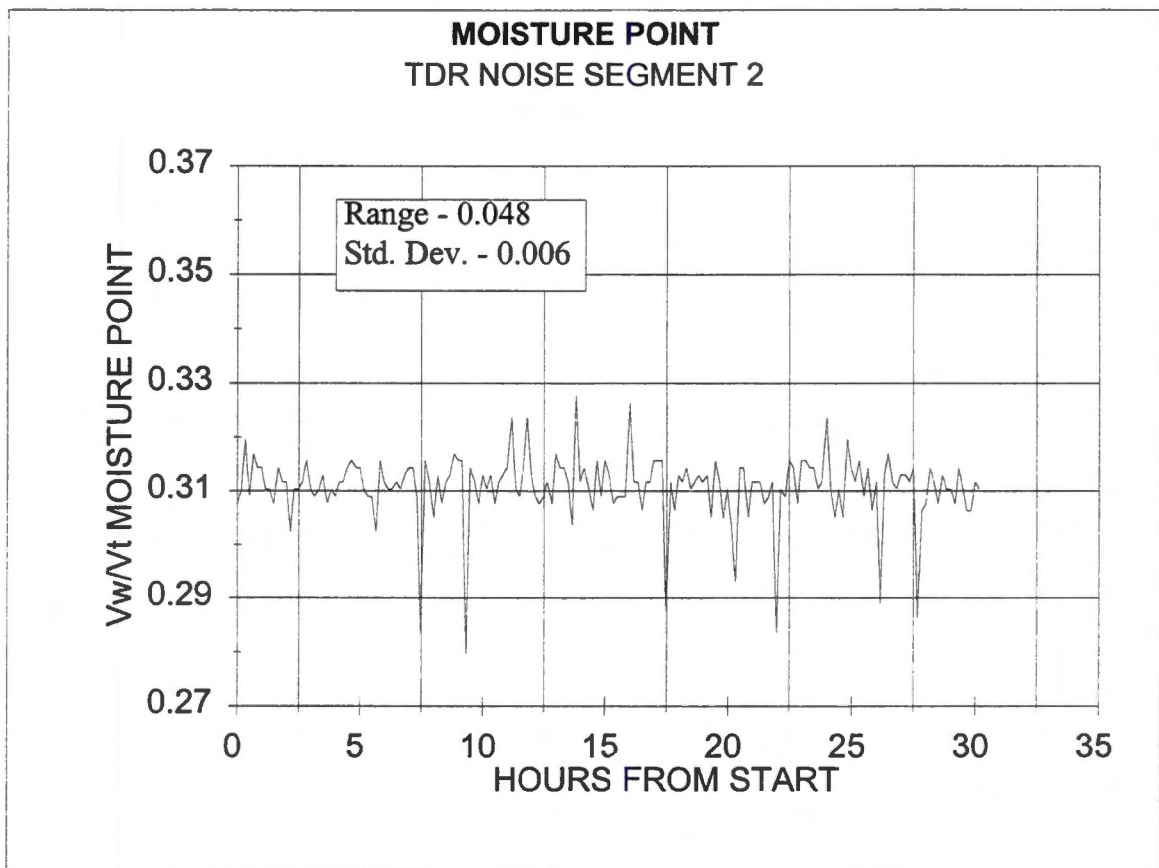


Figure B-2-3. Noise in *Moisture Point* five-segment TDR probe (Segment 2).

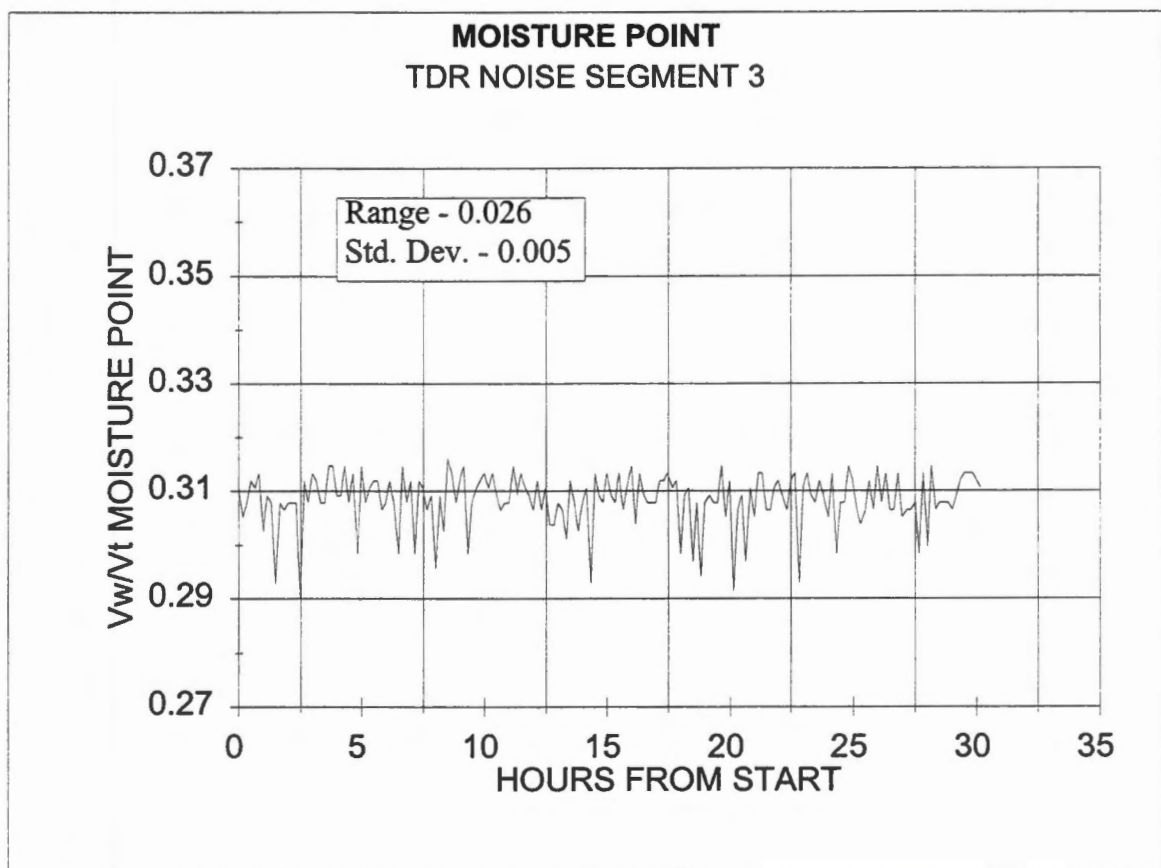


Figure B-2-4. Noise in *Moisture Point* five-segment TDR probe (Segment 3).

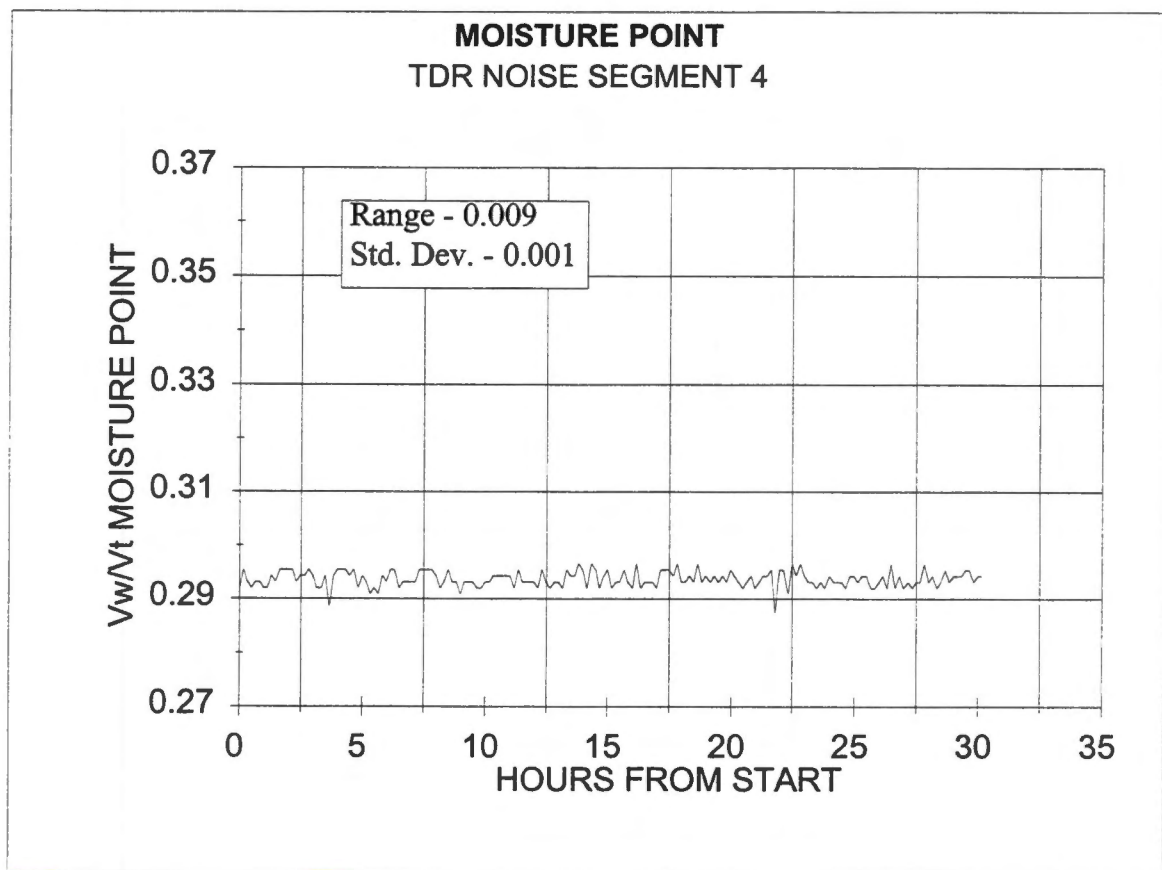


Figure B-2-5. Noise in *Moisture Point* five-segment TDR probe (Segment 4).

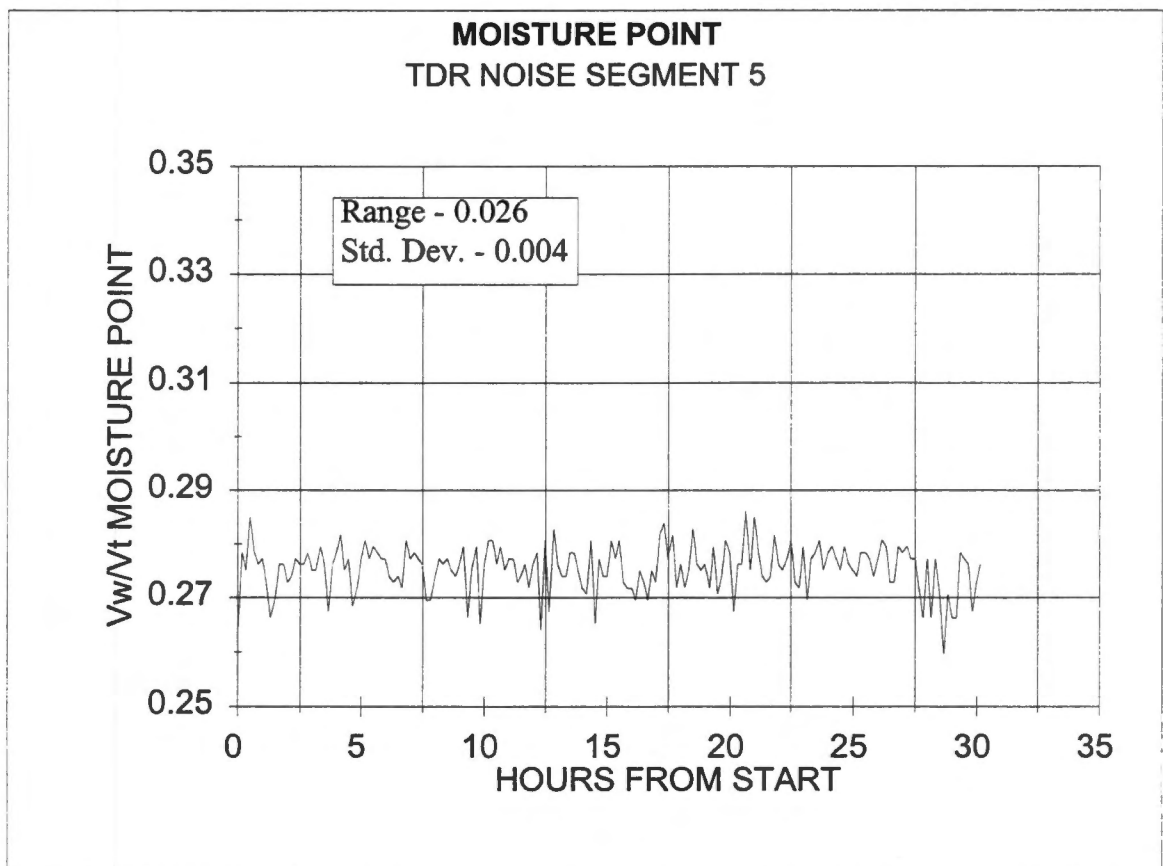


Figure B-2-6. Noise in *Moisture Point* five-segment TDR probe (Segment 5).

Table B-3. Water Delivery Apparatus #1 water delivery distribution.

Cup #	Test 1	Test 2	Test 3
1	21.39	22.36	20.87
2	21.62	21	23.68
3	20.52	19.62	22.36
4	20.66	20.91	21.96
5	23.66	22.08	25.23
6	21.11	21.03	23.27
7	20.06	18.84	22.07
8	27.88	26.27	30.34
9	19.9	17.73	20.42
10	20.92	22	22.35
11	23.86	22.37	25.2
12	23.04	20.35	21.75
13	23.55	20.58	19.6
14	24.65	22.81	24.03
15	16.18	21.62	24.03
Std. Dev.	2.66	1.96	2.58

Note: Results are in grams of water flowing out of the reservoir into a cup under each needle.

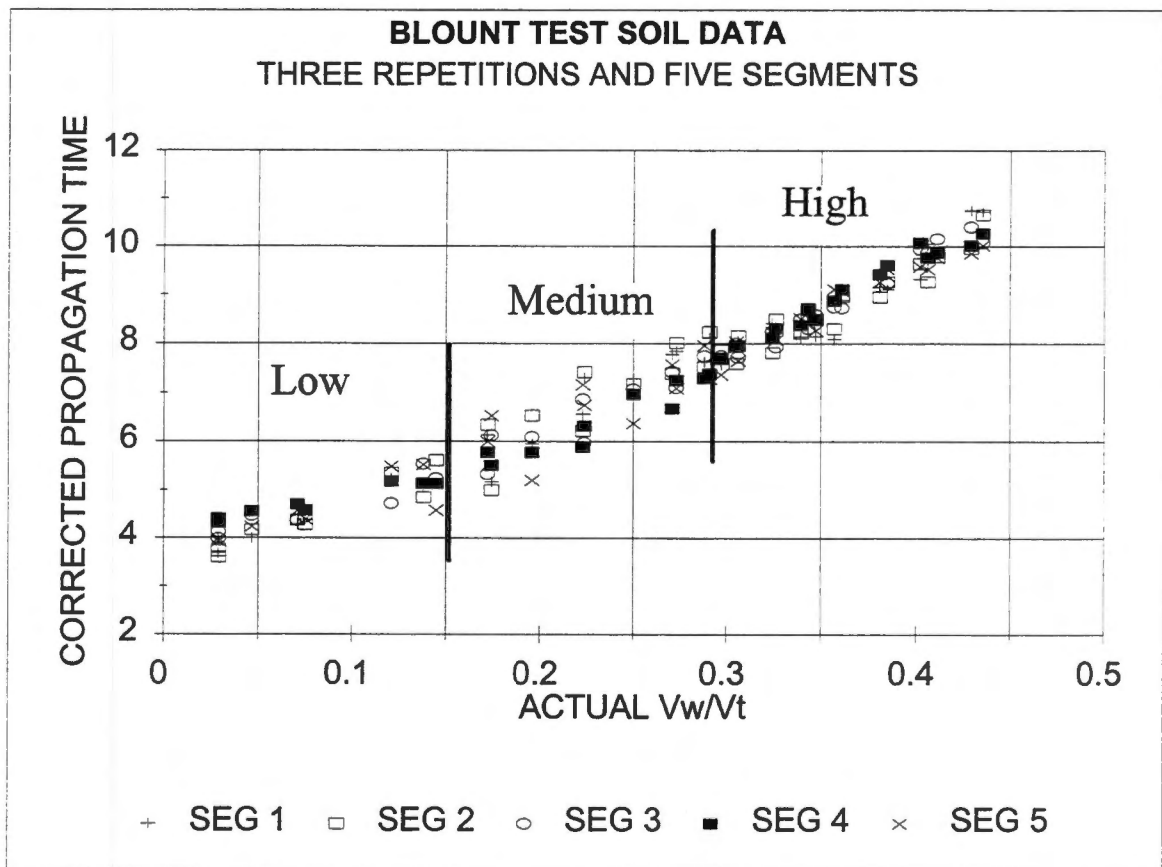
Table B-4. Water Delivery Apparatus #2 water delivery distribution.

Cup #	Test 1	Test 2	Test 3
1	16.64	17.91	17.07
2	19.46	21.58	19.65
3	18.46	22.15	18.96
4	22.42	21.24	21.3
5	24	23.86	23.91
6	23.52	22.96	24.66
7	24.58	22.98	24.14
8	26.4	25.55	26.28
9	24.1	24.9	19.48
10	19.86	27.04	22.79
11	22.46	20.74	19.71
12	17.51	17.66	18.98
13	17.67	19.49	19.98
14	26.14	17.03	18.45
15	18.29	18.68	19.15
Std. Dev.	3.32	3.03	2.72

Note: Results are in grams of water flowing out of the reservoir into a cup under each needle.

APPENDIX C

OTHER CALIBRATION RESULTS



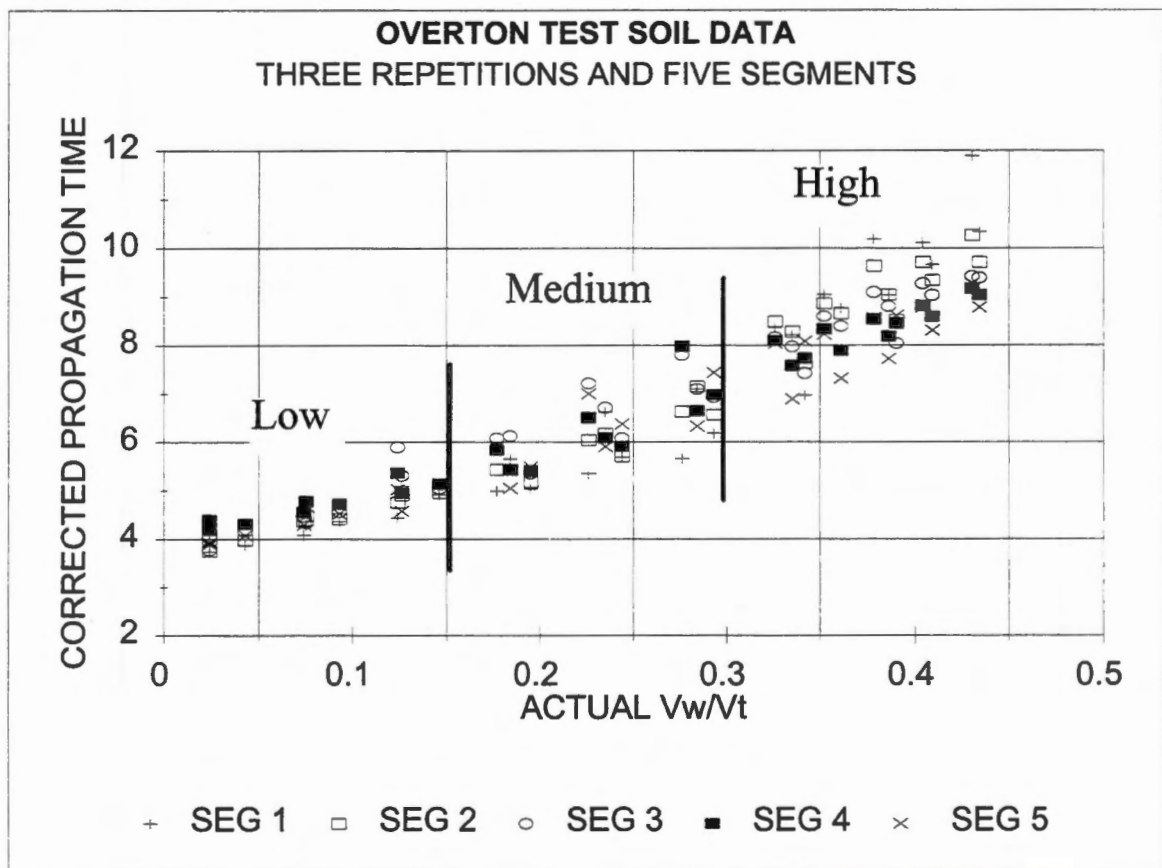


Figure C-1-2. Calibration data for Overton test site soil for all repetitions and probe segments.

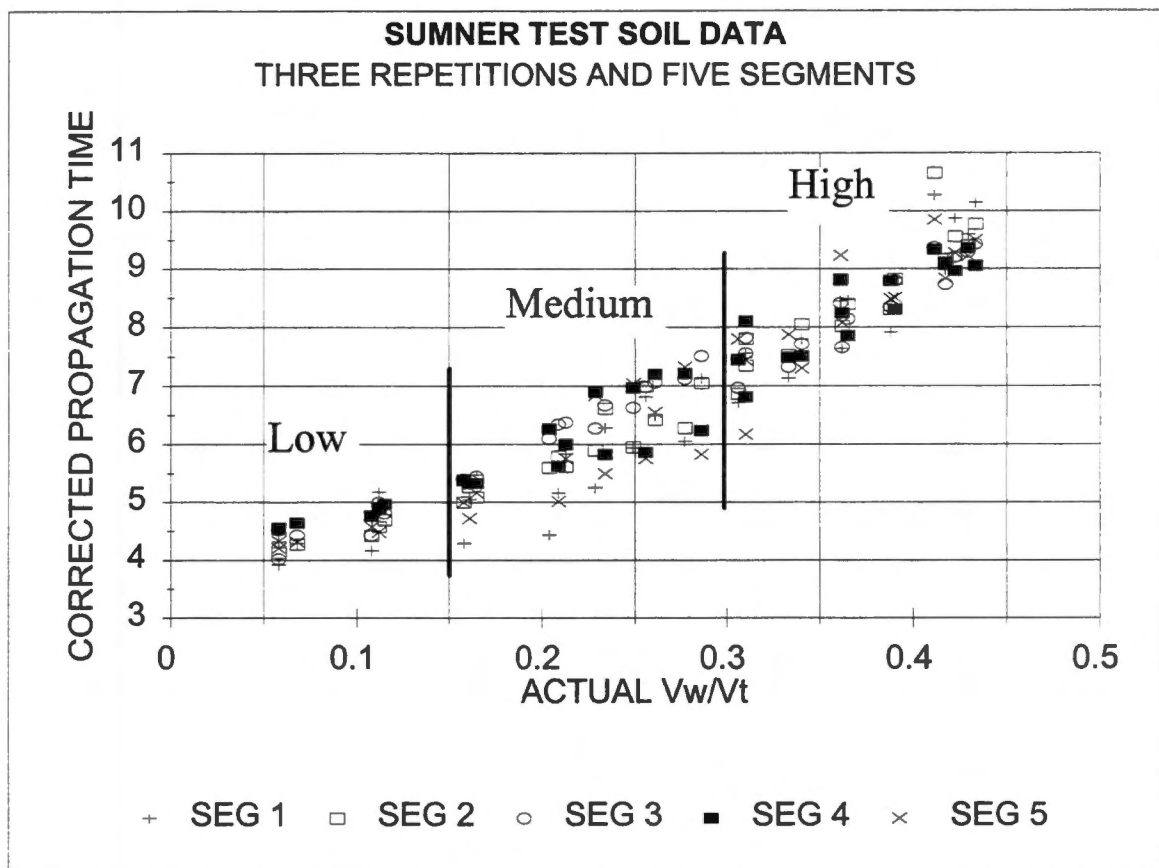


Figure C-1-3. Calibration data for Sumner test site soil for all repetitions and probe segments.

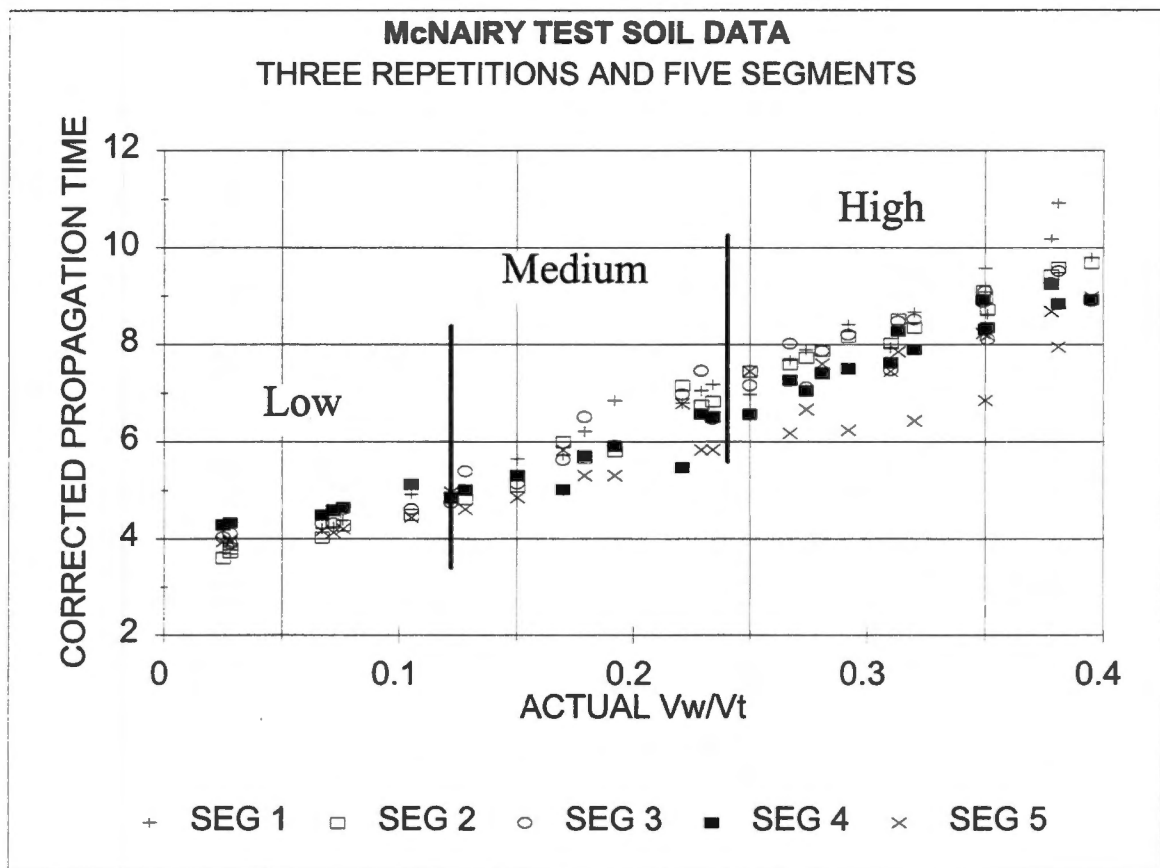


Figure C-1-4. Calibration data for McNairy test site soil for all repetitions and probe segments.

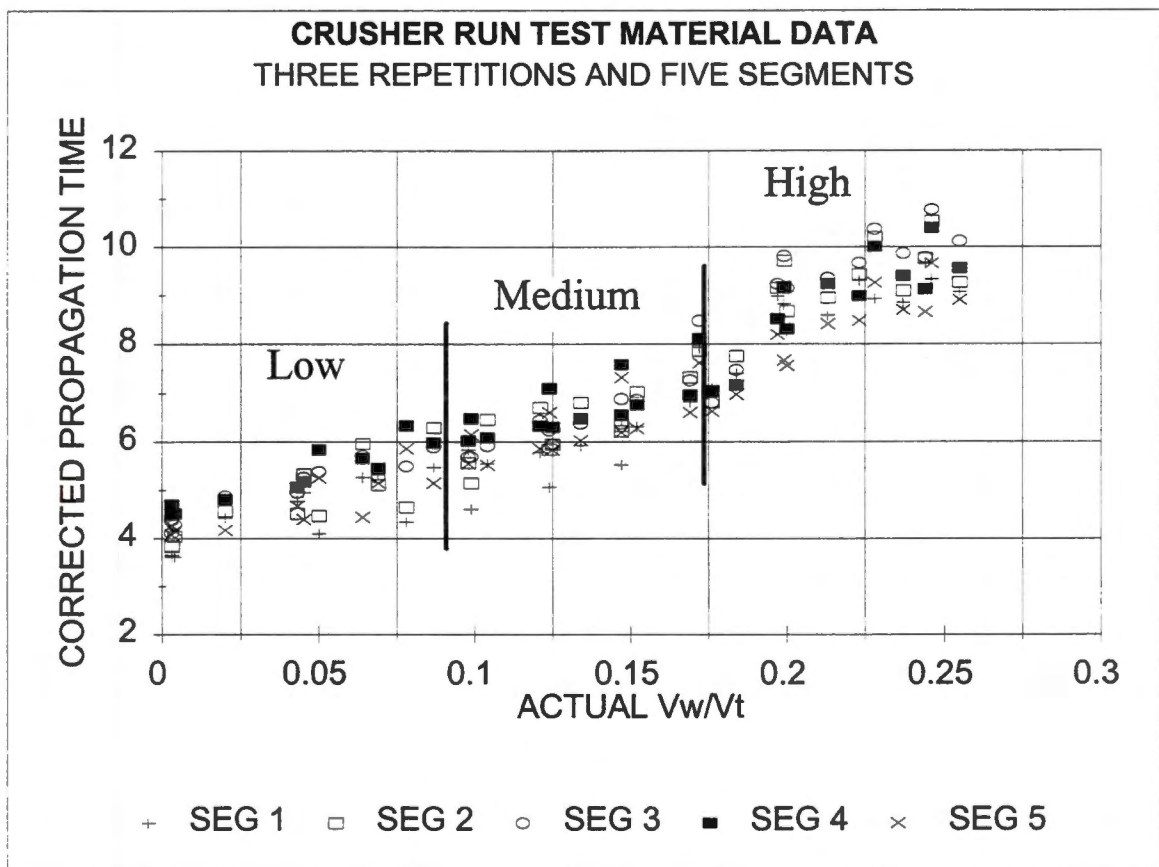


Figure C-1-5. Calibration data for crusher run gravel for all repetitions and probe segments.

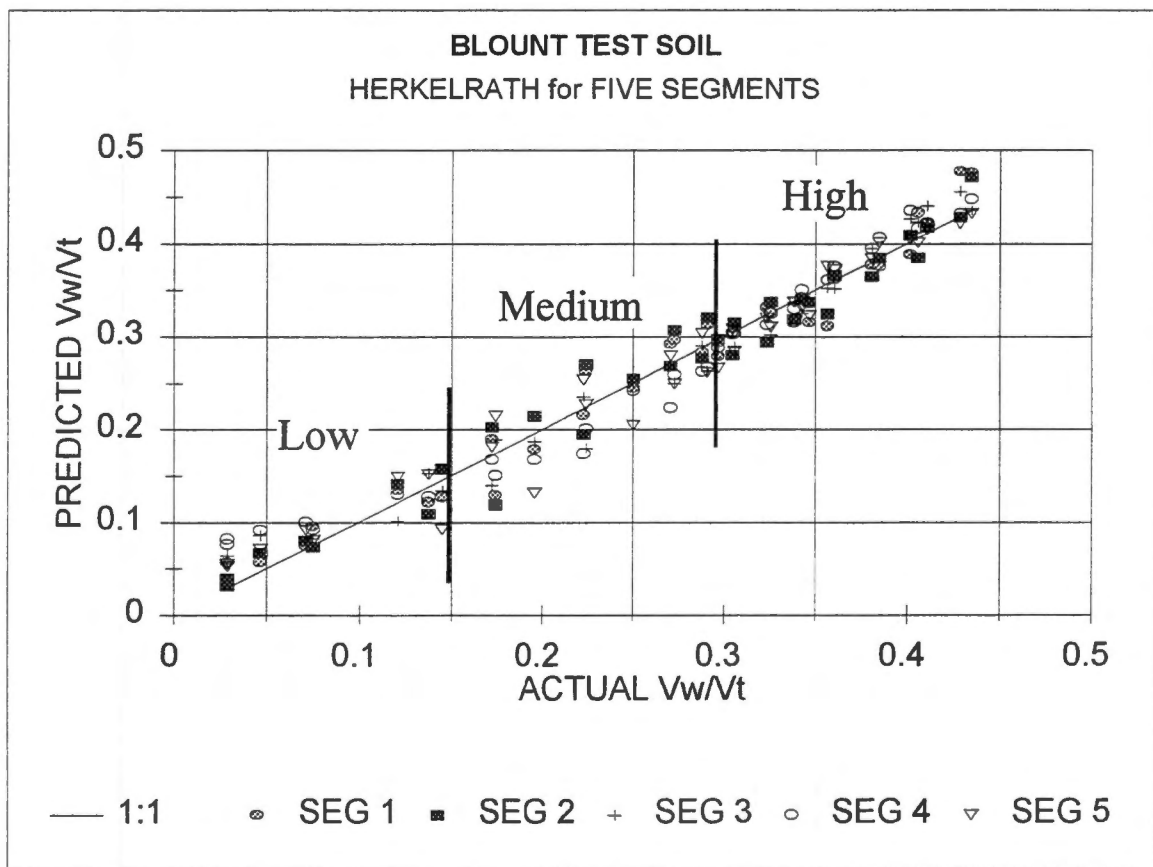


Figure C-2-1. Predicted volumetric water contents calculated with the Herkelrath equation for Blount test site soil calibration data.

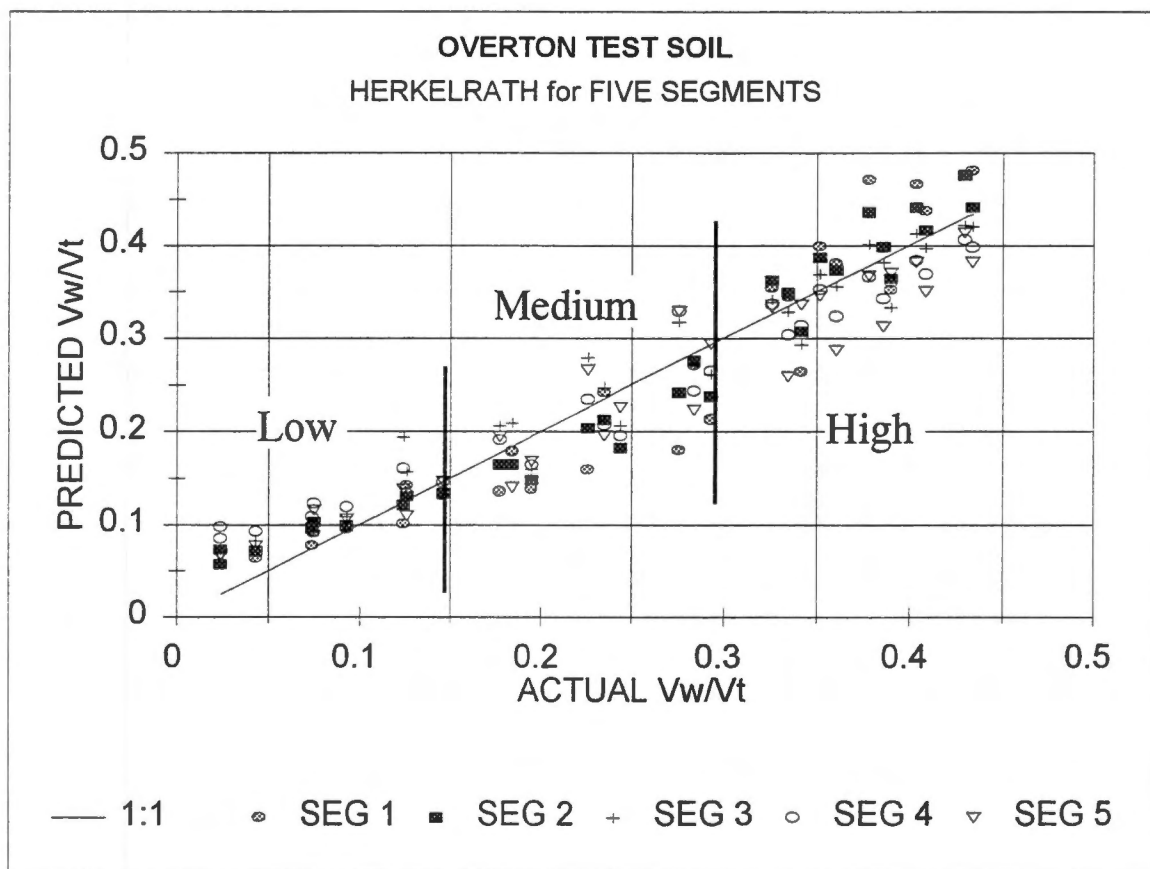


Figure C-2-2. Predicted volumetric water contents calculated with the Herkelrath equation for Overton test site soil calibration data.

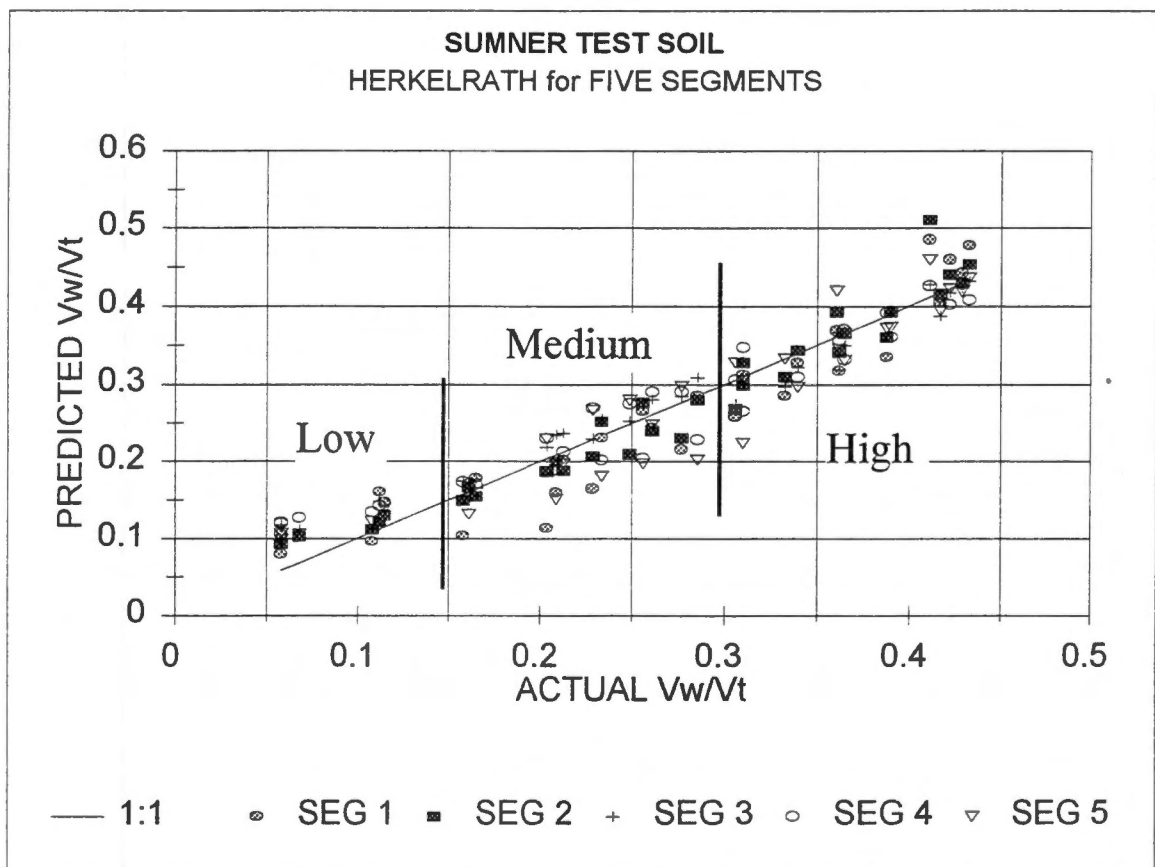


Figure C-2-3. Predicted volumetric water contents calculated with the Herkelrath equation for Sumner test site soil calibration data.

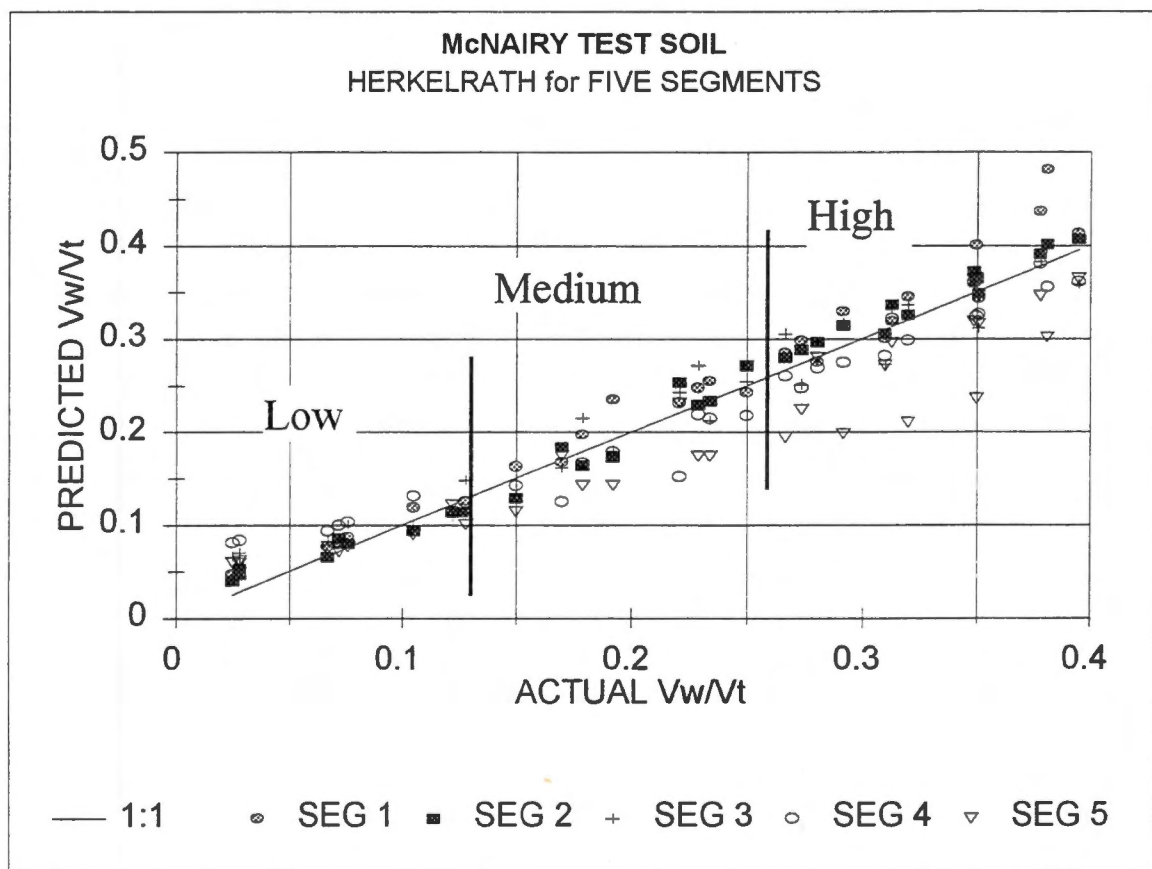


Figure C-2-4. Predicted volumetric water contents calculated with the Herkelrath equation for McNairy test site soil calibration data.

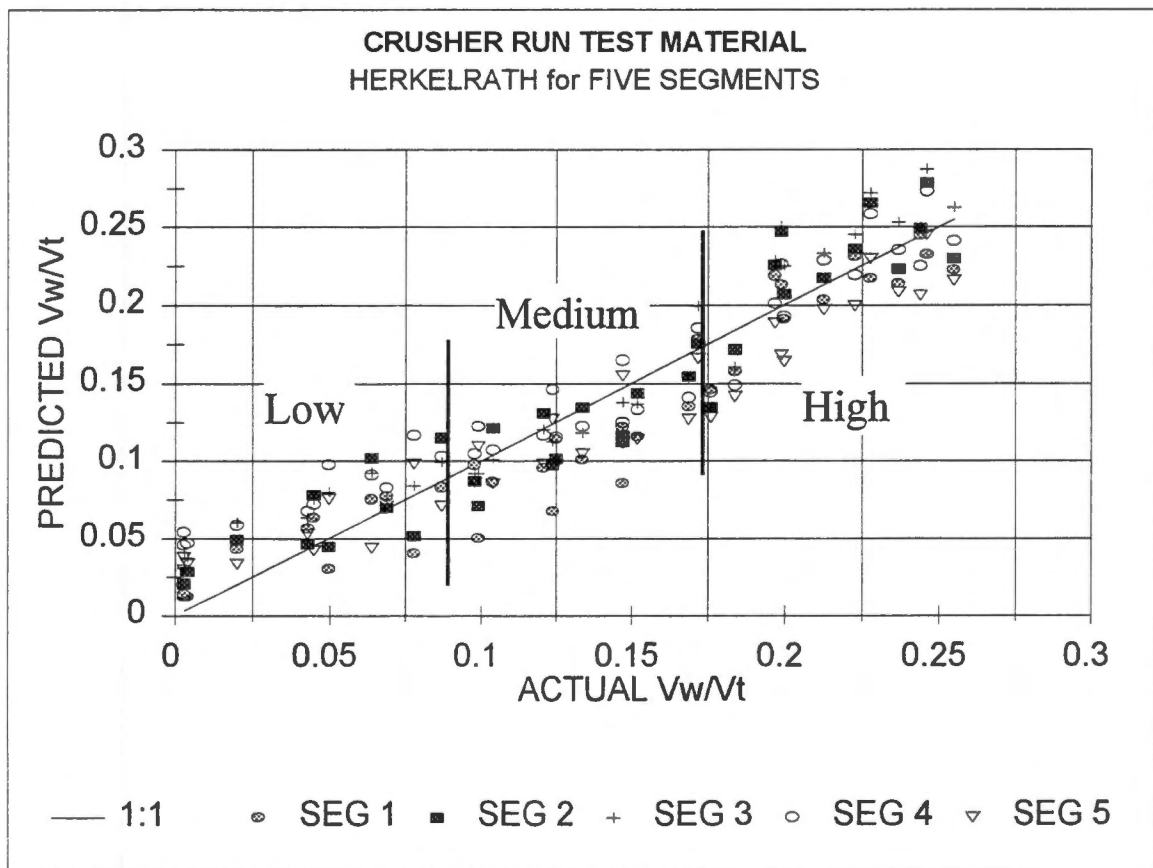


Figure C-2-5. Predicted volumetric water contents calculated with the Herkelrath equation for crusher run gravel calibration data.

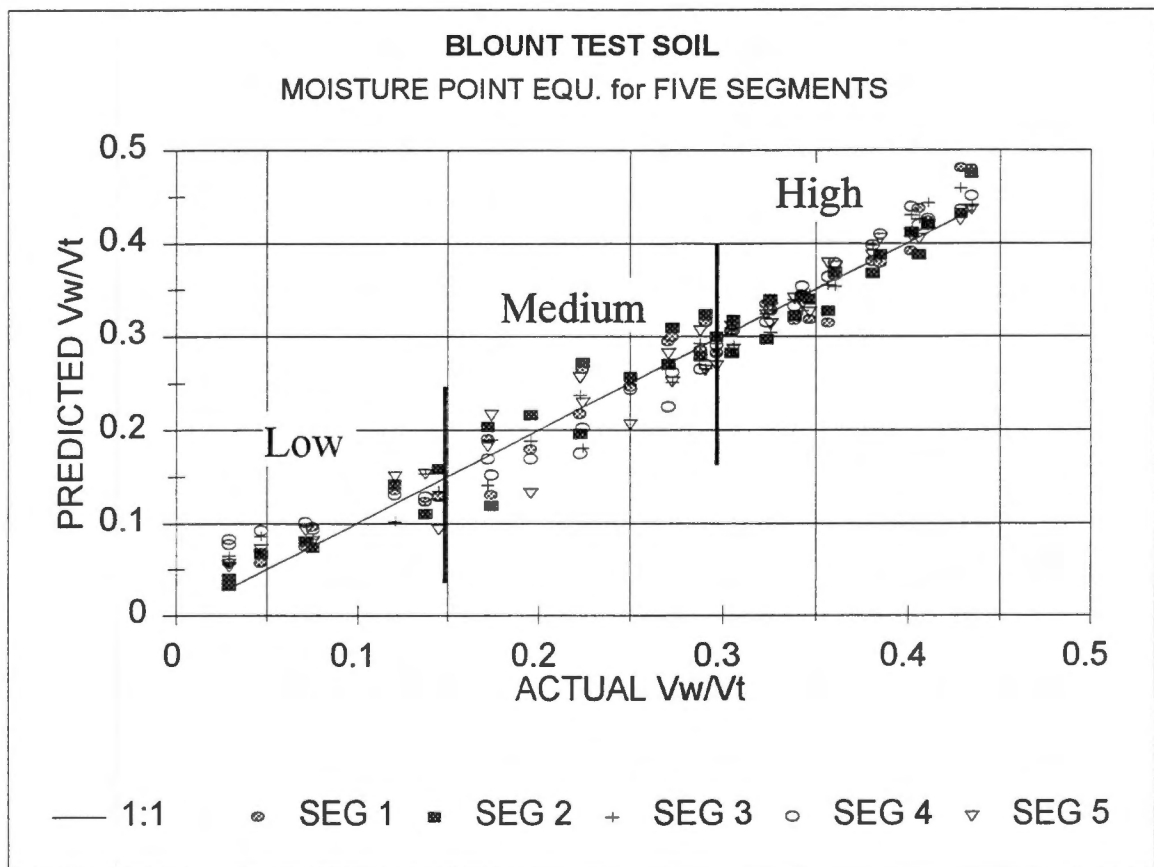


Figure C-3-1. Predicted volumetric water contents calculated with the *Moisture Point* equation for Blount test site soil calibration data.

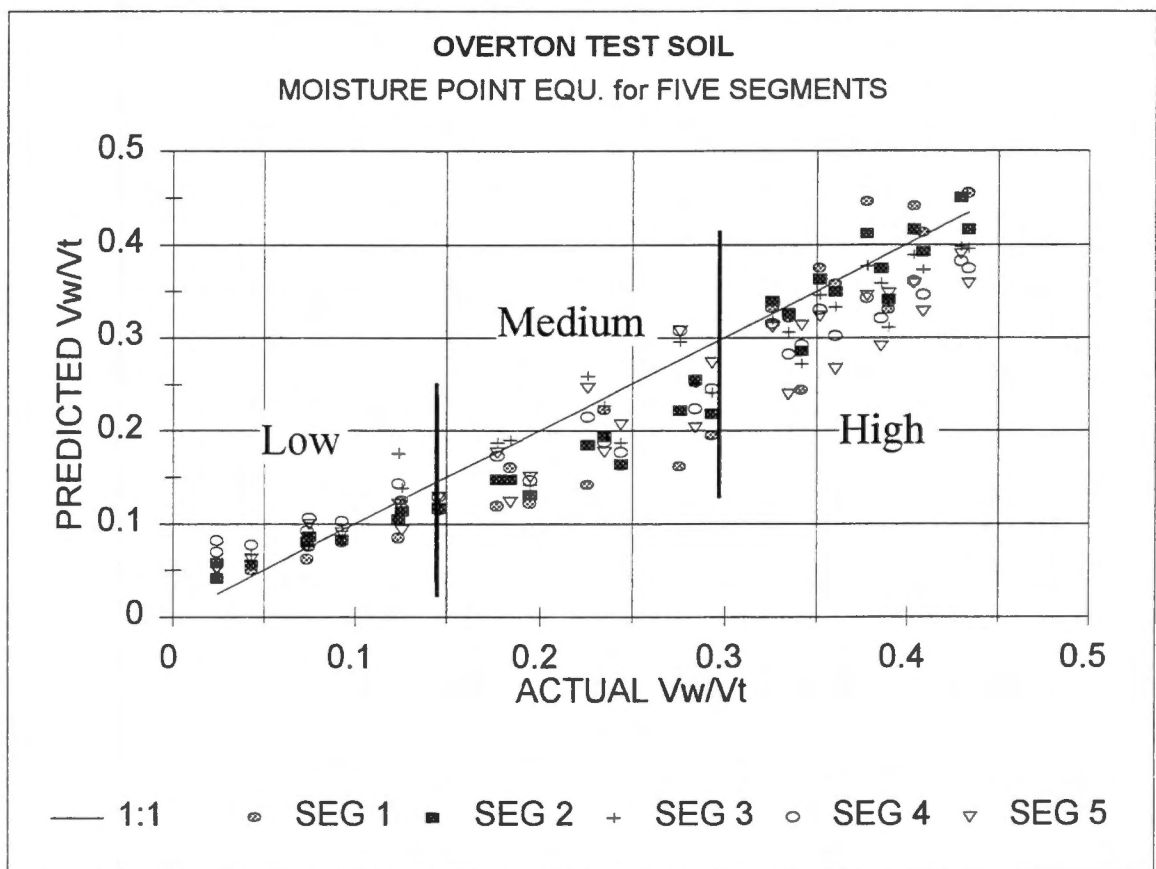


Figure C-3-2. Predicted volumetric water contents calculated with the *Moisture Point* equation for Overton test site soil calibration data.

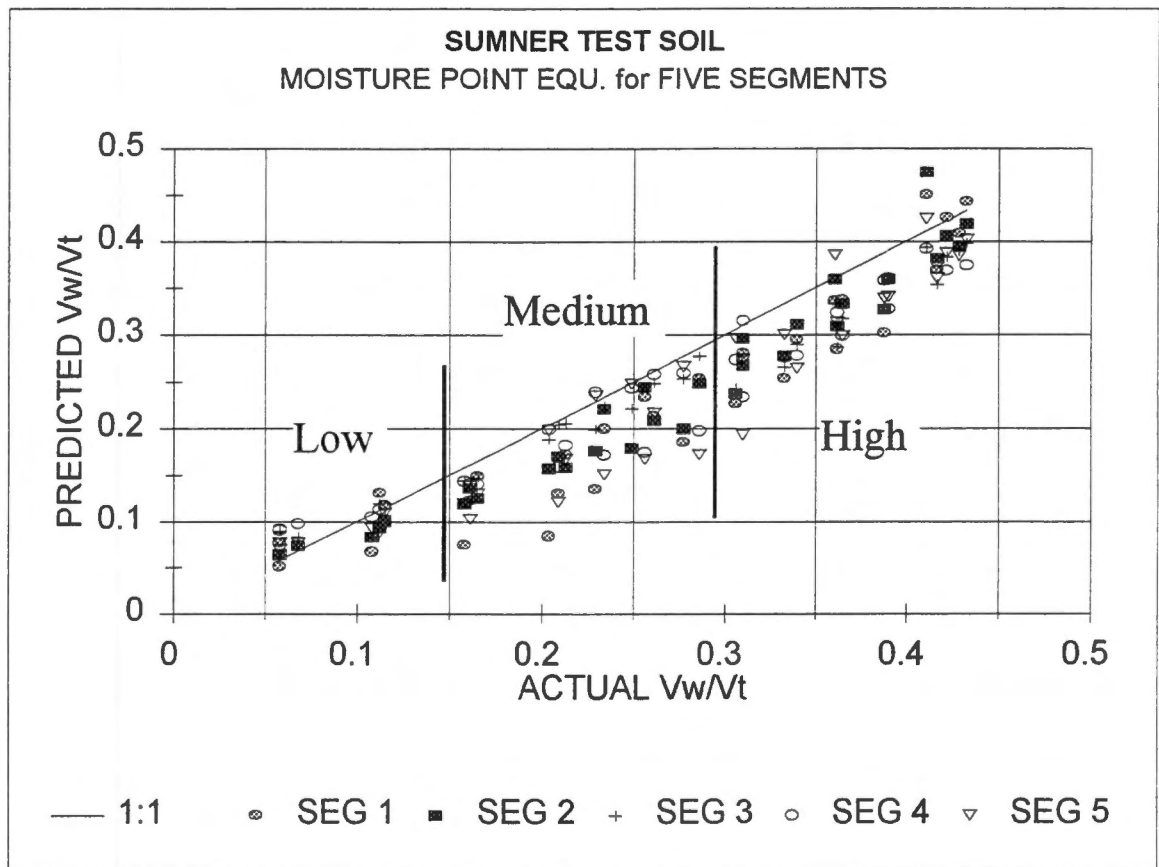


Figure C-3-3. Predicted volumetric water contents calculated with the *Moisture Point* equation for Sumner test site soil calibration data.

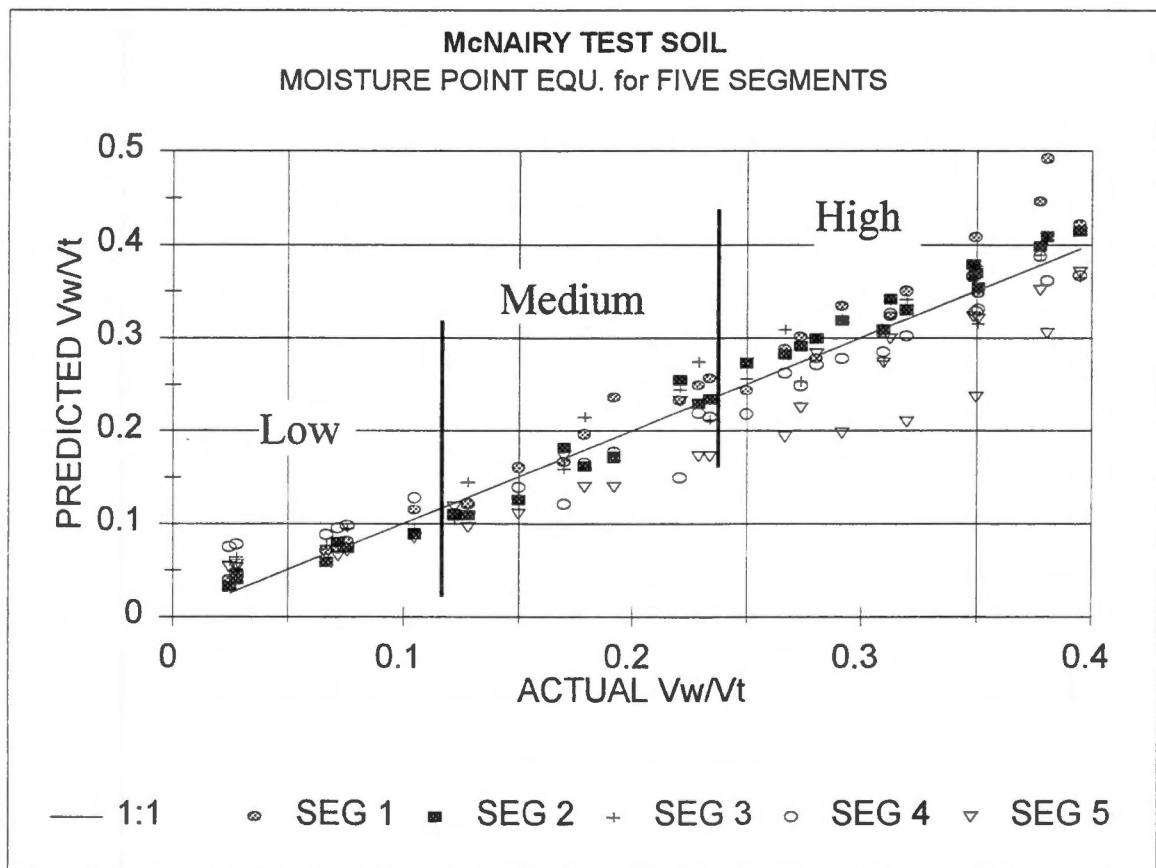


Figure C-3-4. Predicted volumetric water contents calculated with the *Moisture Point* equation for McNairy test site soil calibration data.

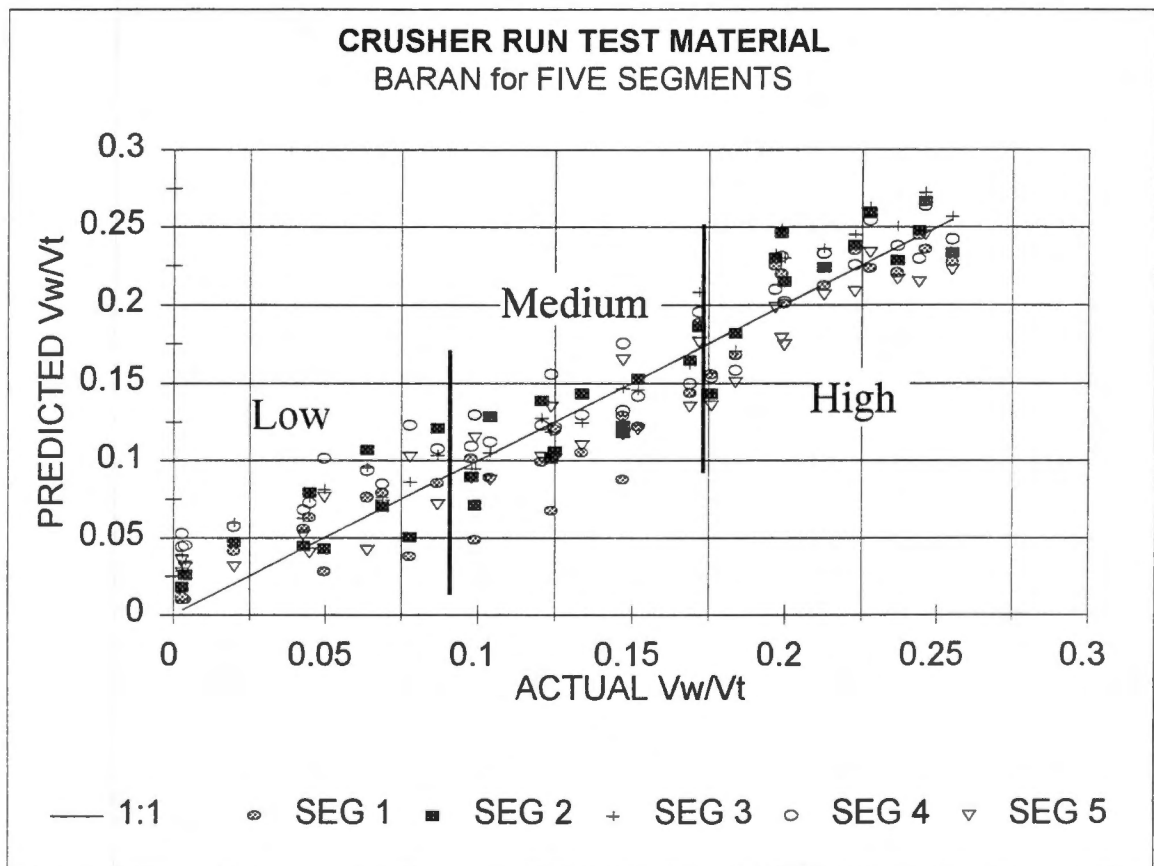


Figure C-3-5. Predicted volumetric water contents calculated with the Baran equation for crusher run gravel calibration data.

APPENDIX D

TEST SITE TIME LINES

Table D-1. Blount County test site time line.

Blount Test Site	Contractor: <i>Renfro</i>
9-16-96	crusher run gravel probes installed using road grader
"	AS Base probe placed (asphalt not cooled with water)
9-17-96	installed subgrade probes and concrete vault
9-18-96	installed one single segment probe in Asphaltic Concrete
10-26-96	system brought online and allowed to scan
11-25-96	started collecting data
2-3-97	installed weather station
4-16-97	installed pavement thermistors with 30 ft lead extensions
7-21-97	subsurface investigation
30 ft coaxial cables for TDR and a 53.5 ft delay compensation cable	

Table D-2. Overton County test site time line.

Overton Test Site	Contractor: <i>Highway Inc.</i>
9-23-96	installed subgrade and crusher run gravel probes and pans
10-9-96	installed concrete vault
1-24-97	system brought online
2-12-97	installed weather station
3-7-97	installed rain gage and pan lysimeter tipping buckets
4-30-97	installed pavement thermistors with 30 ft lead extensions
7-22-97	subsurface investigation and piezometer installation
30 ft coaxial cables for TDR and a 53.5 ft delay compensation cable	

Table D-3. Sumner County test site time line.

Sumner Test Site	Contractor: <i>Thomas Group</i>
7-(28-30)-97	installed subgrade and crusher run gravel probes and pans and concrete vault
8-20-97	AS Base probe placed (asphalt cooled with water)
8-22-97	installed Asphaltic Concrete probes (two single-segment probes)
9-9-97	installed weather station, pavement thermistors, and pan lysimeter tipping buckets
10-28-97	system brought online
60 ft coaxial cables for TDR and a 113.44 ft delay compensation cable	

Table D-4. McNairy County test site time line.

McNairy Test Site	Contractor: <i>Jones Bros. Construction</i>
10-14-96	installed subgrade and crusher run gravel probes and pans and installed concrete vault
3-24-97	system brought online and installed pan lysimeter tipping buckets
4-1-97	installed asphalt layer probes
7-23-97	subsurface investigation and piezometer installation
9-10-97	installed weather station and pavement thermistors with 30 ft lead extensions
30 ft coaxial cables for TDR and a 53.5 ft delay compensation cable	

APPENDIX E

PROCEDURES

Procedures were developed by
Nathan Randy Rainwater, Research Associate; P.E.
The University of Tennessee, Knoxville
Department of Agricultural and Biosystems Engineering

E-1. Procedure for bringing TDR/MP-917 Multiplexed System online.

- Power up system and download program to CR10X (blountc.dld, overtonc.dld, mcnairec.dld, or sumnerc.dld).
- Set the MP-917 to mode 0 by turning it on with the instrument switch while holding the mode button down. The mode will be displayed in the window. Push the mode button until 0 is in the window. Push the measure/display button to accept the displayed mode. The instrument then displays the probe type. The probe type should be on three. Push the mode button to change the type number. Push the measure/display button to accept the type displayed. Turn the instrument off.
- Connect a CR10KD to the CR10X and a notebook computer to the MP-917 through the interface module card. Enter the manual mode by setting flag 1 high (*6, see p.1-5 of CR10X manual). Set flag 4 high to turn the MP-917 on.
- Open the view Point software (C:\vpnt96\vp). Check probe scans using view point. When singlediode probes are scanned, the instrument default will have to be changed to probe type 9 before scanning. This may be done in view point or by turning the instrument off before advancing to the single diode probe. Advancing to the next probe is done by toggling flag 3.
- ☛After checking scans, reset the MP-917 for multiplexed operation as follows.
 - Advance to probe 1.
 - Adjust instrument defaults in view point (F9).
 - Set baud rate to 3 (1200)
 - Change probe type selection parameter to PLUG (type plug the push enter while that parameter is highlighted)
 - After saving changes exit view point using shift F10, this should automatically change message level to 3 but it doesn't always work, thus follow the next step to check message level
 - Open windows terminal, open the TDR. file, push enter, type "msgl" and push enter. The message level should be displayed, if it is not 3, type "msgl 3" and push enter, exit windows terminal.
 - Set flags 1 and 4 low.
 - Set the mode to 6 following the procedure above. Turn the MP-917 switch off. Changing the mode back to 6 may be accomplished in a instrument default setting?
 - The system is now ready for operation. Use PC208W to monitor inputs.

(SET DATA LOGGERS TO LOCAL STANDARD TIME)

E-2. Procedure for bringing *CSI* CR500 telephone transceiver data logger online.

(Blount, Overton, McNairy)

- Download the program to the CR500 (phon_etc.dld).
- If the control port in the CR500 is not high, move the wire to the 5V port temporarily.
- Disconnect the phone line from the DC112 modem. Plug the line into the connector on the telephone line.
- Afterwards, plug line back into DC112, move transceiver control wire back to C1 or leave disconnected

E-3. Procedure for downloading and processing CR500 data logger data.

- CR500 data is processed each month. Download on site early each month. The portion of the file that is processed should be from the beginning of the month to the end of the month. Copy the file to the DATAPROC directory. Rename with the site letter, cr, month, yr, and .dat (Bcrapr97.dat for example). Erase all data after the end of the month in the renamed file. In the PC2O8W .dat file erase to the beginning of the next month.
- Import the file into the "Hrly" spreadsheet, block R6, using the procedures described in Appendix E-4. Check if the data time matches with the data already in the spreadsheet. Adjust as necessary. When data matches, highlight all but the last 2 columns of the CR500 data and delete using the EDIT - DELETE function, select PARTIAL delete in the dialogue box.

E-4. Procedures for processing data.

- I. PC208W will be programmed to download automatically between 11:00 p.m. and 1:00 a.m., after the last TDR scan of the day. Check success of download by going to STATUS in PC208W. Check the data by selecting VIEW and opening the .dat files.
- II. Go to WINDOWS EXPLORER. Copy .DAT file from PC208W to DATAPROC subdirectory using right button drag (select "copy" not "move"). Rename the .DAT file in the Dataproc subdirectory to Bmmddy.dat (use first initial of site B, O, S, or M). Use the date you are processing or the last day of the month if you are processing the end of the month files. If the data is from a manual download, Manual Download Procedures.
- III. Exit, go to the DOS prompt. Go to the dataproc subdirectory (CD\DATAPROC). Type "New Bmmddy" or whatever file name is appropriate. The extension is not required. This step divides the 3 types of data using a C program into 3 files: Bmmddy.tdr, Bmmddy.dly, Bmmddy.hr. You can quickly check this by typing DIR B*.TDR for example and see if the division was successful.
- IV. Go to QBASIC (CD\QBASIC, then QBASIC). Open DPROCTMC.BAS for all data except Sumner Co., open SUMNERDP.BAS for Sumner Co. Type in correct file in the line NAME\$=" ". Use the same format as above without an extension (Bmmddy). Press F5 to run. Progress will be printed on screen.
- V. Go to the appropriate Quattro Pro file. Data is filed by the month under four folders in the QPROFILE folder. There are Windows Shortcuts to each. Go to DATA - QUICK COLUMNS. Click on the open folder symbol. In the "Look In" line of the dialogue box, go to the DATAPROC folder. In the "name" line type the location letter, *, and appropriate file extension (B*.PRB for example). The correct file extension to import is shown in the title of each page. Quickly examine the data to check for obvious problems. The first line of the .hr file will be identical the last line already on the spreadsheet. Erase the doubled line of data. Save!
- VI. After the data is processed, go to NOTEPAD (or WORDPAD). Open the PC208W .DAT file you have successfully processed; erase all but last line. Make sure there is not a blank line at the top of the file. Save.
- VII. PC208W must be left open at end of work day for automatic dial up and download.

E-5. Record of bad TDR probes and segments as of 11/10/97.

→ Blount Co.

Probe 1 segment 1 as of mid-April, Segment 2 as of Feb '98

Probe 2 segments 2, 3, 4, as of mid-August

Probe 4 segments 1, 2 as of mid-April

Probe 6 all segments since installation

Probe 7 as of Nov '97

No probe 8

→ McNairy Co.

Probe 3 segments 1, 2 occasionally will malfunction

Probes 4 and 5 are occasionally erratic since early June

Probe 5 defective since Dec '97

→ Overton Co.

Probe 2 segments 2, 3, 4 as of early May '97

Probe 4 all segments since installation

Probe 7 as of late October

Probe 3 as of Jan '98

→ Sumner Co.

Probes 5 and 6 give occasional bad numbers in one or two segments at a time.

APPENDIX F

PROGRAMS

Data logger and QBASIC programs were primarily developed by
Nathan Randy Rainwater, Research Associate; P.E.
The University of Tennessee, Knoxville
Department of Agricultural and Biosystems Engineering

F1. CR10X PROGRAM FOR BLOUNT, OVERTON, and McNAIRY COUNTY SITES.

{CR10X}

*Program function: hourly averages of battery V, air temp/RH, 8 thermistors;
hourly totals of tipping buckets (mm);
24 hr. total of solar radiation (MJ/m²)
3 consecutive TDR scans 4 times daily (nanasec)*

*Flag usage: 1 - enter manual TDR scan mode
3 - (in manual mode) advance channel
4 - (in manual mode) MP-917 power toggle*

*Excitation channel usage: 1 - 108B thermistors (high temp range)
2 - RH
3 - 107B thermistors and air temp*

*Control Port usage: C1..C3 SDMX50
C4, C5 AM416
C6..C8 Interface Module card*

*Pulse Input channel usage: P1 - pan lysimeter tipping bucket
P2 - rainfall tipping bucket*

Note: SDMX50 address is set to 00 for this program, see SDMX50 manual.

***Table 1 Program ;meteorologic and non TDR sensors**

01: 60.0 Execution Interval (seconds)

1: Batt Voltage (P10)

1: 7 Loc [Volts]

2: Temp (107) (P11)

1: 3 Reps

2: 3 SE Channel

3: 3 Excite all reps w/Exchan 3

4: 8 Loc [soilsub_1]

5: 1.0 Mult

6: 0.0 Offset

3: Temp (107) (P11)

- 1: 2 Reps
- 2: 6 SE Channel
- 3: 3 Excite all reps w/Exchan 3
- 4: 11 Loc [stoneba_1]
- 5: 1.0 Mult
- 6: 0.0 Offset

4: AC Half Bridge (P5)

- 1: 3 Reps
- 2: 3 ± 25 mV Slow Range
- 3: 8 SE Channel
- 4: 1 Ex Channel Option
- 5: 1000 mV Excitation
- 6: 13 Loc [AC_1]
- 7: 200 Mult
- 8: 0.0 Offset

5: Polynomial (P55)

- 1: 3 Reps
- 2: 13 X Loc [AC_1]
- 3: 13 F(X) Loc [AC_1]
- 4: -26.97 C0
- 5: 69.635 C1
- 6: -40.66 C2
- 7: 16.573 C3
- 8: -3.455 C4
- 9: .301 C5

6: Pulse (P3)

- 1: 1 Reps
- 2: 1 Pulse Input Channel
- 3: 2 Switch Closure
- 4: 16 Loc [pan]
- 5: .004732 Mult ;*mult for 1m x 1m pan lys*
- 6: 0.0 Offset

7: Pulse (P3)

- 1: 1 Reps
- 2: 2 Pulse Input Channel
- 3: 2 Switch Closure
- 4: 17 Loc [precip]
- 5: .1 Mult
- 6: 0.0 Offset

8: Temp (107) (P11)

1: 1 Reps
2: 1 SE Channel
3: 3 Excite all reps w/Exchan 3
4: 18 Loc [airtemp]
5: 1.0 Mult
6: 0.0 Offset

9: Excite-Delay (SE) (P4)

1: 1 Reps
2: 5 ± 2500 mV Slow Range
3: 2 SE Channel
4: 2 Excite all reps w/Exchan 2
5: 15 Delay (units 0.01 sec)
6: 2500 mV Excitation
7: 19 Loc [RH]
8: .1 Mult
9: 0.0 Offset

10: Volt (Diff) (P2)

1: 1 Reps
2: 22 ± 7.5 mV 60 Hz Rejection Range
3: 6 DIFF Channel
4: 20 Loc [MJpsm]
5: .012 Mult
6: 0 Offset

11: IF (X<=>F) (P89)

1: 20 X Loc [MJpsm]
2: 4 <
3: 0.0 F
4: 30 Then Do

12: Z=F (P30)

1: 0.0 F
2: 00 Exponent of 10
3: 20 Z Loc [MJpsm]

13: End (P95)

14: If time is (P92)

1: 0000 Minutes (Seconds --) into a
2: 1440 Interval (same units as above)
3: 10 Set Output Flag High

15: Real Time (P77)

1: 1220 Year,Day,Hour/Minute (prev day at midnight, 2400 at midnight)

16: Totalize (P72)

1: 1 Reps

2: 20 Loc [MJpsm]

17: If time is (P92)

1: 0000 Minutes (Seconds --) into a

2: 60 Interval (same units as above)

3: 10 Set Output Flag High

18: Real Time (P77)

1: 110 Day,Hour/Minute

19: Average (P71)

1: 9 Reps

2: 7 Loc [Volts]

20: Average (P71)

1: 2 Reps

2: 18 Loc [airtemp]

21: Totalize (P72)

1: 2 Reps

2: 16 Loc [pan]

22: Totalize (P72)

1: 1 Reps

2: 20 Loc [MJpsm]

***Table 2 Program ;TDR scans**

01: 1.0 Execution Interval (seconds)

1: If Flag/Port (P91) ;*checks flag 1 for manual mode*

1: 11 Do if Flag 1 is High

2: 2 Call Subroutine 2 ;*for manual operation*

2: If time is (P92)

1: 0 Minutes (Seconds --) into a

2: 360 Interval (same units as above)

3: 30 Then Do

3: Beginning of Loop (P87) ;3 reps of TDR scans
1: 2 Delay
2: 3 Loop Count

4: Z=F (P30) ;zeros probe number counter
1: 0.0000 F
2: 0 Exponent of 10
3: 1 Z Loc [probe]

5: Do (P86)
1: 54 Set Port 4 Low

6: Do (P86) ;enable AM416
1: 44 Set Port 4 High

7: Beginning of Loop (P87) ;1 loop for each probe
1: 0 Delay
2: 8 Count(s)

8: Z=Z+1 (P32)
1: 1 Z Loc [probe]

9: Do (P86) ;clock pulse triggers channel advance in AM416
1: 75 Pulse Port 5

10: SDMX50 Channel Select (P109)
1: 0 ADDRESS
2: 1 SDMX50 Channel

11: Do (P86)
1: 1 Call Subroutine 1 ;MP-917 operation

12: End (P95) ;end loop over each probe

13: Do (P86)
1: 54 Set Port 4 Low ;low power state for AM416

14: End (P95) ;end loop over 3 reps

15: End (P95) ;end loop for then do of p92

***Table 3 Subroutines**

1: Beginning of Subroutine (P85)

1: 1 Subroutine 1 ;*operates MP-917, records segment data*

2: Beginning of Loop (P87) ;*zero input locations for the 5 segments*

1: 0 Delay

2: 5 Loop Count

3: Z=F (P30)

1: 0.0000 F

2: 0 Exponent of 10

3: 2 -- Z Loc [seg_1]

4: End (P95)

5: Do (P86)

1: 48 Set Port 8 High ;*Turn on MP-917*

wait (20 seconds) until ID's are sent, measurement is complete.

6: Beginning of Loop (P87)

1: 1 Delay

2: 20 Loop Count

7: End (P95)

8: Port Serial I/O (Special) (P15) ;*read serial data from MP-917*

1: 1 Reps

2: 1 ASCII/RS-232, 1200 Baud

3: 0 Wait for Clear to Send

4: 6 First Control Port

5: 2 Output Loc [seg_1]

6: 0 No. of Locs to Send

7: 13 Termination Character

8: 100 Maximum Characters

9: 9500 CTS/Input Wait

10: 2 Loc [seg_1]

11: 1 Mult

12: 0.0000 Offset

9: Do (P86)

1: 58 Set Port 8 Low

10: Beginning of Loop (P87) ;2 second delay

1: 1 Delay

2: 2 Loop Count

11: End (P95)

12: Do (P86) ;record data to final storage

1: 10 Set Output Flag High

13: Real Time (P77)

1: 110 Day,Hour/Minute

14: Sample (P70)

1: 1 Reps

2: 1 Loc [probe]

15: Sample (P70)

1: 5 Reps

2: 2 Loc [seg_1]

16: End (P95)

Subroutine 2 is manual operation mode. It operates the multiplexers, allows on/off control of MP-917, does not record any data. Use for system checkout probe by probe with MP-917 being monitored with Viewpoint.

17: Beginning of Subroutine (P85) ;

1: 2 Subroutine 2

18: Z=F (P30)

1: 0.0000 F

2: 0 Exponent of 10

3: 1 Z Loc [probe]

19: Do (P86)

1: 54 Set Port 4 Low

20: Do (P86)

1: 44 Set Port 4 High

21: Beginning of Loop (P87)

1: 0 Delay

2: 8 Count(s)

22: Z=Z+1 (P32)

1: 1 Z Loc [probe]

23: Do (P86)
1: 75 Pulse Port 5

24: SDMX50 Channel Select (P109)
1: 0 ADDRESS
2: 1 SDMX50 Channel

25: Do (P86)
1: 3 Call Subroutine 3

26: If Flag/Port (P91)
1: 21 Do if Flag 1 is Low
2: 31 Exit Loop if True

27: End (P95)

28: Do (P86)
1: 24 Set Flag 4 Low

29: Do (P86)
1: 58 Set Port 8 Low

30: End (P95) ;*end of subroutine 2*

*Subroutine 3 waits for either flag 1 to clear (end) or
for flag 3 to set (advance).*

31: Beginning of Subroutine (P85)
1: 3 Subroutine 3

32: Beginning of Loop (P87)
1: 1 Delay
2: 0 Loop Count

33: If Flag/Port (P91)
1: 13 Do if Flag 3 is High
2: 31 Exit Loop if True

34: If Flag/Port (P91)
1: 21 Do if Flag 1 is Low
2: 31 Exit Loop if True

35: If Flag/Port (P91)
1: 14 Do if Flag 4 is High
2: 48 Set Port 8 High

36: If Flag/Port (P91)

1: 24 Do if Flag 4 is Low
2: 58 Set Port 8 Low

37: End (P95) ;*end wait for flags*

38: Do (P86)

1: 23 Set Flag 3 Low

39: End (P95) ;*end of subroutine 3*

End Program

-Input Locations-

1 probe 1 1 2
2 seg_1 1 2 2
3 seg_2 1 1 0
4 seg_3 1 1 0
5 seg_4 1 1 0
6 seg_5 1 1 0
7 Volts 0 1 1
8 soilsub_1 4 2 1
9 soilsub_2 8 2 1
10 soilsub_3 16 2 1
11 stoneba_1 4 2 2
12 stoneba_2 16 2 2
13 AC_1 4 4 3
14 AC_2 8 4 3
15 AC_3 16 4 3
16 pan 0 1 1
17 precip 0 2 1
18 airtemp 0 2 1
19 RH 0 1 1
20 MJpsm 1 3 2

-Program Security-

0000

0000

0000

-Mode 4-

-Final Storage Area 2-

0

-CR10X ID-

0

-CR10X Power Up-

3

F2. CR10X Program for Sumner Test Site.

{CR10X}

*THIS PROGRAM IS FOR 8 5-SEGMENT PROBES AND 2 1-SEGMENT PROBES
PROBES 1 - 6 & 9, 10 ARE 5-SEG, PROBES 7, 8 ARE SINGLE SEG.*

TABLE 1 IS THE SAME AS OTHER SITES CR10X PROGRAM

***Table 2 Program ;TDR scans**

01: 1.0 Execution Interval (seconds)

1: If Flag/Port (P91) ;*checks flag 1 for manual mode*

1: 11 Do if Flag 1 is High

2: 2 Call Subroutine 2 ;*for manual operation*

2: If time is (P92)

1: 0 Minutes (Seconds --) into a

2: 360 Interval (same units as above)

3: 30 Then Do

*THE REST OF THE PROGRAM SCANS WITH 3 REPS, THE SECOND SDMX50
PREVENTS USING*

*THE LOOP COMMAND. THE CHANNEL IN THE P109 COMMAND IS
AUTOMATICALLY INCREMENTED*

*WITH THE PASSING OF EACH LOOP, THE P109 COMMAND THAT ACTIVATES
THE SECOND*

*SDMX50 FROM CH 8 OF SDMX50 #1 MUST REMAIN ON CH 8 FOR EACH REP.
THUS, THE COMMANDS ARE REPEATED 3 TIMES INSTEAD OF LOOPING.*

REP 1

3: Z=F (P30) ;*zeros probe number counter*

1: 0.0000 F

2: 0 Exponent of 10

3: 1 Z Loc [probe]

4: Do (P86)

1: 54 Set Port 4 Low

5: Do (P86) ;*enable AM416*

1: 44 Set Port 4 High

6: Beginning of Loop (P87) ;1 loop for each probe 1-7

1: 0 Delay

2: 7 Count(s)

7: Z=Z+1 (P32)

1: 1 Z Loc [probe]

8: Do (P86) ;clock pulse triggers channel advance in AM416

1: 75 Pulse Port 5

9: SDMX50 Channel Select (P109)

1: 0 ADDRESS

2: 1 SDMX50 Channel

10: Do (P86)

1: 1 Call Subroutine 1 ;MP-917 operation

11: End (P95) ;end loop for probe 1-7

THE FOLLOWING NESTED LOOP IS FOR THE 2 5-SEG PROBES ADDED AT THE SUMNER CO

SITE and PROBE 8, IT TREATS THE PROBES AS PROBES 8-10 (I HOPE IT WORKS!)

12: SDMX50 Channel Select (P109)

1: 00 SDMX50 Address

2: 8 SDMX50 Channel

13: Beginning of Loop (P87) ;loop for probe 8-10

1: 0000 Delay

2: 3 Loop Count

14: Z=Z+1 (P32)

1: 1 Z Loc [probe]

15: Do (P86)

1: 75 Pulse Port 5

16: SDMX50 Channel Select (P109)

1: 01 ADDRESS

2: 1 SDMX50 Channel

17: Do (P86)

1: 1 Call Subroutine 1

18: End (P95) ;THIS ENDS THE NESTED LOOP FOR PROBES 8-10

19: Do (P86)
 1: 54 Set Port 4 Low ;*low power state for AM416*

20: Beginning of Loop (P87) ;*2 second delay*
 1: 1 Delay
 2: 2 Loop Count

21: End (P95)

REP 2

22: Z=F (P30) ;*zeros probe number counter*
 1: 0.0000 F
 2: 0 Exponent of 10
 3: 1 Z Loc [probe]

23: Do (P86)
 1: 54 Set Port 4 Low

24: Do (P86) ;*enable AM416*
 1: 44 Set Port 4 High

25: Beginning of Loop (P87) ;*1 loop for each probe 1-7*
 1: 0 Delay
 2: 7 Count(s)

26: Z=Z+1 (P32)
 1: 1 Z Loc [probe]

27: Do (P86) ;*clock pulse triggers channel advance in AM416*
 1: 75 Pulse Port 5

28: SDMX50 Channel Select (P109)
 1: 0 ADDRESS
 2: 1 SDMX50 Channel

29: Do (P86)
 1: 1 Call Subroutine 1 ;*MP-917 operation*

30: End (P95) ;*end loop over each probe 1-7*

THE FOLLOWING NESTED LOOP IS FOR THE 2 5-SEG PROBES ADDED AT THE SUMNER CO SITE and PROBE 8, IT TREATS THE PROBES AS PROBES 8-10 (I HOPE IT WORKS!)

31: SDMX50 Channel Select (P109)

1: 00 SDMX50 Address

2: 8 SDMX50 Channel

32: Beginning of Loop (P87)

1: 0 Delay

2: 3 Loop Count

33: Z=Z+1 (P32)

1: 1 Z Loc [probe]

34: Do (P86)

1: 75 Pulse Port 5

35: SDMX50 Channel Select (P109)

1: 01 ADDRESS

2: 1 SDMX50 Channel

36: Do (P86)

1: 1 Call Subroutine 1

37: End (P95) ;*THIS ENDS THE NESTED LOOP FOR PROBES 8-10*

38: Do (P86)

1: 54 Set Port 4 Low ;*low power state for AM416*

39: Beginning of Loop (P87)

1: 1 Delay

2: 2 Loop Count

40: End (P95)

REP 3

41: Z=F (P30) ;*zeros probe number counter*

1: 0.0000 F

2: 0 Exponent of 10

3: 1 Z Loc [probe]

42: Do (P86)

1: 54 Set Port 4 Low

43: Do (P86) ;*enable AM416*

1: 44 Set Port 4 High

44: Beginning of Loop (P87) ;*1 loop for each probe 1-7*

1: 0 Delay

2: 7 Count(s)

45: Z=Z+1 (P32)

1: 1 Z Loc [probe]

46: Do (P86) ;*clock pulse triggers channel advance in AM416*

1: 75 Pulse Port 5

47: SDMX50 Channel Select (P109)

1: 0 ADDRESS

2: 1 SDMX50 Channel

48: Do (P86)

1: 1 Call Subroutine 1 ;*MP-917 operation*

49: End (P95) ;*end loop over each probe 1-7*

THE FOLLOWING NESTED LOOP IS FOR THE 2 5-SEG PROBES ADDED AT THE SUMNER CO

SITE and PROBE 8, IT TREATS THE PROBES AS PROBES 8-10 (I HOPE IT WORKS!)

50: SDMX50 Channel Select (P109)

1: 00 SDMX50 Address

2: 8 SDMX50 Channel

51: Beginning of Loop (P87)

1: 0 Delay

2: 3 Loop Count

52: Z=Z+1 (P32)

1: 1 Z Loc [probe]

53: Do (P86)

1: 75 Pulse Port 5

54: SDMX50 Channel Select (P109)

1: 01 ADDRESS

2: 1 SDMX50 Channel

55: Do (P86)

1: 1 Call Subroutine 1

56: End (P95) ;*THIS ENDS THE NESTED LOOP FOR PROBES 8-10*

57: Do (P86)

1: 54 Set Port 4 Low ;*low power state for AM416*

58: End (P95) ;*end for P92*

***Table 3 Subroutines**

1: Beginning of Subroutine (P85)

1: 1 Subroutine 1 ;*operates MP-917, records segment data*

2: Beginning of Loop (P87) ;*zero input locations for the 5 segments*

1: 0 Delay

2: 5 Loop Count

3: Z=F (P30)

1: 0.0000 F

2: 0 Exponent of 10

3: 2 -- Z Loc [seg_1]

4: End (P95)

5: Do (P86)

1: 48 Set Port 8 High ;*Turn on MP-917*

wait (20 seconds) until ID's are sent, measurement is complete.

6: Beginning of Loop (P87)

1: 1 Delay

2: 20 Loop Count

7: End (P95)

8: Port Serial I/O (Special) (P15) ;*read serial data from MP-917*

1: 1 Reps

2: 1 ASCII/RS-232, 1200 Baud

3: 0 Wait for Clear to Send

4: 6 First Control Port

5: 2 Output Loc [seg_1]

6: 0 No. of Locs to Send

7: 13 Termination Character

8: 100 Maximum Characters

9: 9500 CTS/Input Wait

10: 2 Loc [seg_1]

11: 1 Mult

12: 0.0000 Offset

9: Do (P86)

1: 58 Set Port 8 Low

10: Beginning of Loop (P87) ;2 second delay

1: 1 Delay

2: 2 Loop Count

11: End (P95)

12: Do (P86) ;record data to final storage

1: 10 Set Output Flag High

13: Real Time (P77)

1: 110 Day,Hour/Minute

14: Sample (P70)

1: 1 Reps

2: 1 Loc [probe]

15: Sample (P70)

1: 5 Reps

2: 2 Loc [seg_1]

16: End (P95)

Subroutine 2 is manual operation mode. It operates the multiplexers, allows on/off control of MP-917, does not record any data. Use for system checkout probe by probe with MP-917 being monitored with Viewpoint.

17: Beginning of Subroutine (P85) ;

1: 2 Subroutine 2

18: Z=F (P30)

1: 0.0000 F

2: 0 Exponent of 10

3: 1 Z Loc [probe]

19: Do (P86)

1: 54 Set Port 4 Low

20: Do (P86)

1: 44 Set Port 4 High

```

21: Beginning of Loop (P87)
    1: 0    Delay
    2: 8    Count(s)

22: Z=Z+1 (P32)
    1: 1    Z Loc [ probe  ]

23: Do (P86)
    1: 75    Pulse Port 5

24: SDMX50 Channel Select (P109)
    1: 0    ADDRESS
    2: 1    SDMX50 Channel

25: Do (P86)
    1: 3    Call Subroutine 3

26: If Flag/Port (P91)
    1: 21    Do if Flag 1 is Low
    2: 31    Exit Loop if True

27: End (P95)

```

The following loop is added for probes 9 and 10 and SDMX50 #2

```

28: Beginning of Loop (P87)
    1: 0000    Delay
    2: 2    Loop Count

29: Z=Z+1 (P32)
    1: 1    Z Loc [ probe  ]

30: Do (P86)
    1: 75    Pulse Port 5

31: SDMX50 Channel Select (P109)
    1: 01    ADDRESS
    2: 1    SDMX50 Channel

32: Do (P86)
    1: 3    Call Subroutine 3

33: If Flag/Port (P91)
    1: 21    Do if Flag 1 is Low
    2: 31    Exit Loop if True

34: End (P95)

```

end of loop for probes 9 and 10

35: Do (P86)

1: 24 Set Flag 4 Low

36: Do (P86)

1: 58 Set Port 8 Low

37: End (P95) ;*end of subroutine 2*

Subroutine 3 waits for either flag 1 to clear (end) or for flag 3 to set (advance).

38: Beginning of Subroutine (P85)

1: 3 Subroutine 3

39: Beginning of Loop (P87)

1: 1 Delay

2: 0 Loop Count

40: If Flag/Port (P91)

1: 13 Do if Flag 3 is High

2: 31 Exit Loop if True

41: If Flag/Port (P91)

1: 21 Do if Flag 1 is Low

2: 31 Exit Loop if True

42: If Flag/Port (P91)

1: 14 Do if Flag 4 is High

2: 48 Set Port 8 High

43: If Flag/Port (P91)

1: 24 Do if Flag 4 is Low

2: 58 Set Port 8 Low

44: End (P95)

end wait for flags

45: Do (P86)

1: 23 Set Flag 3 Low

46: End (P95) ;*end of subroutine 3*

End Program

-Input Locations-

1 probe 1 1 10
2 seg_1 1 2 2
3 seg_2 1 1 0
4 seg_3 1 1 0
5 seg_4 1 1 0
6 seg_5 1 1 0
7 Volts 0 1 1
8 soilsub_1 4 2 1
9 soilsub_2 8 2 1
10 soilsub_3 16 2 1
11 stoneba_1 4 2 2
12 stoneba_2 16 2 2
13 AC_1 4 4 3
14 AC_2 8 4 3
15 AC_3 16 4 3
16 pan 0 1 1
17 precip 0 2 1
18 airtemp 0 2 1
19 RH 0 1 1
20 MJpsm 1 3 2

-Program Security-

0000
0000
0000

-Mode 4-

-Final Storage Area 2-

0

-CR10X ID-

0

-CR10X Power Up-

3

F-3. CR500 data logger program for Blount, Overton, and McNairy Test Sites.

{CR500}

***Table 1 Program**

01: 60.0 Execution Interval (seconds)

1: If time is (P92)
1: 0 Minutes (Seconds --) into a
2: 600 Interval (same units as above) ; *10:00 am*
3: 41 Set Port 1 High ; *cell phone on*

2: If time is (P92)
1: 00 Minutes (Seconds --) into a
2: 780 Interval (same units as above) ; *1:00 pm*
3: 51 Set Port 1 Low ; *cell phone off*

3: If time is (P92)
1: 0000 Minutes (Seconds --) into a
2: 1380 Interval (same units as above) ; *11:00 am*
3: 41 Set Port 1 High ; *cell phone on*

4: If time is (P92)
1: 0000 Minutes (Seconds --) into a
2: 1435 Interval (same units as above) ; *11:55 pm*
3: 51 Set Port 1 Low ; *cell phone off*

5: Pulse (P3)
1: 1 Reps
2: 2 Pulse Input Channel
3: 2 Switch Closure
4: 1 Loc [pan2]
5: .00473 Mult
6: 0.0 Offset

6: Pulse (P3)
1: 1 Reps
2: 1 Pulse Input Channel
3: 21 Low Level AC, Output Hz
4: 2 Loc [WS_mps]
5: .75 Mult
6: .2 Offset

```

7: IF (X<=>F) (P89)
  1: 2    X Loc [ WS_mps  ]
  2: 4    <
  3: .20001 F
  4: 30   Then Do

8: Z=F (P30)
  1: 0.0   F
  2: 00    Exponent of 10
  3: 2     Z Loc [ WS_mps  ]

9: End (P95)

10: If time is (P92)
  1: 0000   Minutes (Seconds --) into a
  2: 60     Interval (same units as above)
  3: 10     Set Output Flag High

11: Real Time (P77)
  1: 110    Day,Hour/Minute

12: Average (P71)
  1: 1      Reps
  2: 2      Loc [ WS_mps  ]

13: Totalize (P72)
  1: 1      Reps
  2: 1      Loc [ pan2    ]

*Table 2 Program
  02: 0.0   Execution Interval (seconds)

*Table 3 Subroutines

End Program

```

-Input Locations-

```

1 pan2    0 1 1
2 WS_mps  0 2 2

```

-Program Security-

```

0000
0000
0000

```

-Mode 4-

```

-Final Storage Area 2-
0

```

F-4. Second CR10X Program for Sumner Test Site.

{CR10X}

*SMNRPHONE.CSI, THIS PROGRAM OPERATES THE CULLULAR PHONE,
RECORDS WIND SPEED,
RECORDS TIPPING BUCKET DATA FOR 3 PAN LYS. PANS 3 & 4 ARE IN THE
CENTER LINE
OF THE ROADWAY AND USE C7 AND C8 AS PULSE INPUT CHANNELS.*

***Table 1 Program**

01: 60 Execution Interval (seconds)

1: If time is (P92)

1: 0 Minutes (Seconds --) into a

2: 600 Interval (same units as above) ;10:00 AM

3: 41 Set Port 1 High ;*cell phone on*

2: If time is (P92)

1: 0 Minutes (Seconds --) into a

2: 780 Interval (same units as above) ;1:00 PM

3: 51 Set Port 1 Low ;*cell phone off*

3: If time is (P92)

1: 0000 Minutes (Seconds --) into a

2: 1380 Interval (same units as above) ;11:00 PM

3: 41 Set Port 1 High ;*cell phone on*

4: If time is (P92)

1: 0000 Minutes (Seconds --) into a

2: 1435 Interval (same units as above) ;11:55 PM

3: 51 Set Port 1 Low ;*cell phone off*

5: Pulse (P3)

1: 1 Reps

2: 2 Pulse Channel 2

3: 2 Switch Closure, All Counts

4: 1 Loc [pan2]

5: .004732 Mult

6: 0.0 Offset

```

6: Pulse (P3)
  1: 1    Reps
  2: 1    Pulse Channel 1
  3: 21   Low Level AC, Output Hz
  4: 2    Loc [ WS_mps  ]
  5: .75  Mult
  6: .2   Offset

7: IF (X<=>F) (P89)
  1: 2    X Loc [ WS_mps  ]
  2: 4    <
  3: .20001 F
  4: 30   Then Do

8: Z=F (P30)
  1: 0.0  F
  2: 00   Exponent of 10
  3: 2    Z Loc [ WS_mps  ]

9: End (P95)

10: Pulse (P3)
  1: 1    Reps
  2: 8    Control Port 8
  3: 2    Switch Closure, All Counts
  4: 3    Loc [ Pan_3  ]
  5: .004732 Mult
  6: 0.0  Offset

11: Pulse (P3)
  1: 1    Reps
  2: 7    Control Port 7
  3: 2    Switch Closure, All Counts
  4: 4    Loc [ Pan_4  ]
  5: .004732 Mult
  6: 0.0  Offset

12: If time is (P92)
  1: 0000  Minutes (Seconds --) into a
  2: 60    Interval (same units as above)
  3: 10    Set Output Flag High (Flag 0)

13: Real Time (P77)
  1: 110   Day,Hour/Minute (midnight = 0000)

```

14: Average (P71)

1: 1 Reps

2: 2 Loc [WS_mps]

15: Totalize (P72)

1: 1 Reps

2: 1 Loc [pan2]

16: Totalize (P72)

1: 2 Reps

2: 3 Loc [Pan_3]

*Table 2 Program

02: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-

1 pan2 1 1 1

2 WS_mps 1 2 2

3 Pan_3 1 1 1

4 Pan_4 1 1 1

-Program Security-

0000

0000

0000

-Mode 4-

-Final Storage Area 2-

0

-CR10X ID-

0

-CR10X Power Up-

3

F-5. *QBASIC* program to process Blount, Overton, McNairy Test Site data.

*REM This program processes the TDR data as outlined in the steps. It assumes
REM that the first 24 lines of the data file are 3 complete reps of 8 probes.
REM This should always be the case unless data is downloaded during a scan,
REM which should be avoided. Downloads will be scheduled around scans.
REM It also assumes the initial download has been divided into 3 files separating
REM the 3 types of data (.TDR, .HR, .DLY) the C program "NEW" or PC208W Split.
REM Appropriate file names should be filled in each time the program is run.*

```
REM This step writes each line with outlier propagation times to a separate
REM file .bad
CLS
REM Put the correct date and location letter (B, O, M) in the file name
NAME$ = "b021198"
D = 1.75
PRINT "Good Morning! Get ready for another great day"
OPEN "C:\DATAPROC\" + NAME$ + ".TDR" FOR INPUT AS 10
OPEN "C:\DATAPROC\" + NAME$ + ".bad" FOR OUTPUT AS 1
DO UNTIL EOF(10)
    INPUT #10, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!

    SELECT CASE S1!
        CASE IS < 2.5, IS > 15
            WRITE #1, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
            GOTO NEXTPROBE
        END SELECT
    SELECT CASE PROBE%
        CASE 7 TO 8
            GOTO NEXTPROBE
        END SELECT
    SELECT CASE S2!
        CASE IS < 2.5, IS > 15
            WRITE #1, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
            GOTO NEXTPROBE
        END SELECT
    SELECT CASE S3!
        CASE IS < 2.5, IS > 15
            WRITE #1, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
            GOTO NEXTPROBE
        END SELECT
    SELECT CASE S4!
        CASE IS < 2.5, IS > 15
            WRITE #1, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
            GOTO NEXTPROBE
        END SELECT
    SELECT CASE S5!
```

```

        CASE IS < 2.5, IS > 15
        WRITE #1, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
        GOTO NEXTPROBE
    END SELECT
NEXTPROBE:
LOOP
CLOSE 10, 1
PRINT "Bad time values written to seperate file, going to next step"
SLEEP 5

REM This step replaces outlier propagation times with 0 and writes to a new file.
OPEN "C:\DATAPROC\" + NAMES$ + ".TDR" FOR INPUT AS 10
OPEN "C:\DATAPROC\" + NAMES$ + ".TMP" FOR OUTPUT AS 2
DO UNTIL EOF(10)
    INPUT #10, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
    SELECT CASE S1!
        CASE IS < 2.5, IS > 15
            S1! = 0
    END SELECT
    SELECT CASE S2!
        CASE IS < 2.5, IS > 15
            S2! = 0
    END SELECT
    SELECT CASE S3!
        CASE IS < 2.5, IS > 15
            S3! = 0
    END SELECT
    SELECT CASE S3!
        CASE IS < 2.5, IS > 15
            S3! = 0
    END SELECT
    SELECT CASE S4!
        CASE IS < 2.5, IS > 15
            S4! = 0
    END SELECT
    SELECT CASE S5!
        CASE IS < 2.5, IS > 15
            S5! = 0
    END SELECT

    WRITE #2, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!
LOOP
CLOSE 10, 2
PRINT "Bad numbers replaced with 0 and written to new file, going to next step"
SLEEP 5

REM This step arranges the reps by probe number.
OPEN "C:\DATAPROC\" + NAMES$ + ".TMP" FOR INPUT AS 10
OPEN "C:\DATAPROC\" + NAMES$ + ".PRB" FOR OUTPUT AS 3
DO UNTIL EOF(10)
    DIM REP!(24, 9)

```



```

FOR R% = 1 TO 24
  FOR C% = 1 TO 9: INPUT #10, REP!(R%, C%): NEXT C%
NEXT R%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 1 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 2 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 3 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 4 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 5 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 6 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 7 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
FOR Y% = 1 TO 24
  IF REP!(Y%, 4) = 8 THEN WRITE #3, REP!(Y%, 1), REP!(Y%, 2), REP!(Y%, 3), REP!(Y%, 4),
  REP!(Y%, 5), REP!(Y%, 6), REP!(Y%, 7), REP!(Y%, 8), REP!(Y%, 9)
NEXT Y%
LOOP
CLOSE 10, 3
PRINT "TDR data arranged by probes and written to new file, going to next step"
KILL "C:\DATAPROC\" + NAMES$ + ".TMP"
SLEEP 5

```

REM This step calculates the average propagation time of the 3 reps for each probe and
 REM writes the data to a new file. Numbers outside of reasonable range are not averaged.
 REM This step calculates the corrected measured time from the rep averages of measured time.

```

OPEN "C:\DATAPROC\" + NAMES$ + ".PRB" FOR INPUT AS 10
OPEN "C:\DATAPROC\" + NAMES$ + ".TMC" FOR OUTPUT AS 4
A1 = 2.336
B1 = .629
A2 = 1.879
B2 = .667
A3 = 1.224

```

```

B3 = .653
A4 = 1.346
B4 = .7
A5 = 1.622
B5 = .678
DO UNTIL EOF(10)
FOR PROBE = 1 TO 6
DIM FS!(3, 9)
FOR R = 1 TO 3
    FOR C = 1 TO 9: INPUT #10, FS!(R, C): NEXT C
NEXT R
10  IF FS!(1, 5) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF FS!(2, 5) = 0 THEN R2ND = 1 ELSE R2ND = 0
    IF FS!(3, 5) = 0 THEN R3ND = 1 ELSE R3ND = 0
    N = 3 - (R1ND + R2ND + R3ND)
    IF N = 0 THEN S1! = 0 ELSE S1! = (FS!(1, 5) + FS!(2, 5) + FS!(3, 5)) / N
    IF S1! = 0 THEN Tc1! = 0 ELSE Tc1! = S1! / B1 - A1
20  IF FS!(1, 6) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF FS!(2, 6) = 0 THEN R2ND = 1 ELSE R2ND = 0
    IF FS!(3, 6) = 0 THEN R3ND = 1 ELSE R3ND = 0
    N = 3 - (R1ND + R2ND + R3ND)
    IF N = 0 THEN S2! = 0 ELSE S2! = (FS!(1, 6) + FS!(2, 6) + FS!(3, 6)) / N
    IF S2! = 0 THEN Tc2! = 0 ELSE Tc2! = S2! / B2 - A2
30  IF FS!(1, 7) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF FS!(2, 7) = 0 THEN R2ND = 1 ELSE R2ND = 0
    IF FS!(3, 7) = 0 THEN R3ND = 1 ELSE R3ND = 0
    N = 3 - (R1ND + R2ND + R3ND)
    IF N = 0 THEN S3! = 0 ELSE S3! = (FS!(1, 7) + FS!(2, 7) + FS!(3, 7)) / N
    IF S3! = 0 THEN Tc3! = 0 ELSE Tc3! = S3! / B3 - A3
40  IF FS!(1, 8) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF FS!(2, 8) = 0 THEN R2ND = 1 ELSE R2ND = 0
    IF FS!(3, 8) = 0 THEN R3ND = 1 ELSE R3ND = 0
    N = 3 - (R1ND + R2ND + R3ND)
    IF N = 0 THEN S4! = 0 ELSE S4! = (FS!(1, 8) + FS!(2, 8) + FS!(3, 8)) / N
    IF S4! = 0 THEN Tc4! = 0 ELSE Tc4! = S4! / B4 - A4
50  IF FS!(1, 9) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF FS!(2, 9) = 0 THEN R2ND = 1 ELSE R2ND = 0
    IF FS!(3, 9) = 0 THEN R3ND = 1 ELSE R3ND = 0
    N = 3 - (R1ND + R2ND + R3ND)
    IF N = 0 THEN S5! = 0 ELSE S5! = (FS!(1, 9) + FS!(2, 9) + FS!(3, 9)) / N
    IF S5! = 0 THEN Tc5! = 0 ELSE Tc5! = S5! / B5 - A5
    WRITE #4, FS!(1, 1), FS!(1, 2), FS!(1, 3), FS!(1, 4), S1!, S2!, S3!, S4!, S5!, Tc1!, Tc2!, Tc3!, Tc4!,
Tc5!
NEXT PROBE
FOR PROBE = 7 TO 8
DIM SS!(3, 9)
FOR R = 1 TO 3
    FOR C = 1 TO 9: INPUT #10, SS!(R, C): NEXT C
NEXT R
    IF SS!(1, 5) = 0 THEN R1ND = 1 ELSE R1ND = 0
    IF SS!(2, 5) = 0 THEN R2ND = 1 ELSE R2ND = 0

```

```

      IF SS!(3, 5) = 0 THEN R3ND = 1 ELSE R3ND = 0
      N = 3 - (R1ND + R2ND + R3ND)
      IF N = 0 THEN S1! = 0 ELSE S1! = (SS!(1, 5) + SS!(2, 5) + SS!(3, 5)) / N
      WRITE #4, SS!(1, 1), SS!(1, 2), SS!(1, 3), SS!(1, 4), S1!
NEXT PROBE
LOOP
PRINT "Reps averaged and data written to new file, going to next step"
CLOSE 10, 4
SLEEP 5

REM This step calculates volumetric water content using Topp's Equation, and converts
REM to Ww/Ws using VMC/D and writes data to a new file.
OPEN "C:\DATAPROC\" + NAME$ + ".TMC" FOR INPUT AS 10
OPEN "C:\DATAPROC\" + NAME$ + ".TOP" FOR OUTPUT AS 5
DO UNTIL EOF(10)
FOR PROBE = 1 TO 6
  INPUT #10, ID%, DAY%, HRMIN%, PROBE%, S1!, S2!, S3!, S4!, S5!, Tc1!, Tc2!, Tc3!, Tc4!,
  Tc5!
  V1! = -.053 + .029 * ((3 * 10 ^ 8 * Tc1! * 10 ^ -9) / (2 * .3)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * Tc1! *
  10 ^ -9) / (2 * .3)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * Tc1! * 10 ^ -9) / (2 * .3)) ^ 6
  IF V1! = -.053 THEN V1! = 0
  IF V1! = 0 THEN ND1 = 1 ELSE ND1 = 0
  W1! = V1! / D
  V2! = -.053 + .029 * ((3 * 10 ^ 8 * Tc2! * 10 ^ -9) / (2 * .3)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * Tc2! *
  10 ^ -9) / (2 * .3)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * Tc2! * 10 ^ -9) / (2 * .3)) ^ 6
  IF V2! = -.053 THEN V2! = 0
  IF V2! = 0 THEN ND2 = 1 ELSE ND2 = 0
  W2! = V2! / D
  V3! = -.053 + .029 * ((3 * 10 ^ 8 * Tc3! * 10 ^ -9) / (2 * .3)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * Tc3! *
  10 ^ -9) / (2 * .3)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * Tc3! * 10 ^ -9) / (2 * .3)) ^ 6
  IF V3! = -.053 THEN V3! = 0
  IF V3! = 0 THEN ND3 = 1 ELSE ND3 = 0
  W3! = V3! / D
  V4! = -.053 + .029 * ((3 * 10 ^ 8 * Tc4! * 10 ^ -9) / (2 * .3)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * Tc4! *
  10 ^ -9) / (2 * .3)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * Tc4! * 10 ^ -9) / (2 * .3)) ^ 6
  IF V4! = -.053 THEN V4! = 0
  IF V4! = 0 THEN ND4 = 1 ELSE ND4 = 0
  W4! = V4! / D
  V5! = -.053 + .029 * ((3 * 10 ^ 8 * Tc5! * 10 ^ -9) / (2 * .3)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * Tc5! *
  10 ^ -9) / (2 * .3)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * Tc5! * 10 ^ -9) / (2 * .3)) ^ 6
  IF V5! = -.053 THEN V5! = 0
  IF V5! = 0 THEN ND5 = 1 ELSE ND5 = 0
  W5! = V5! / D
  N = 5 - (ND1 + ND2 + ND3 + ND4 + ND5)
  IF N = 0 THEN PA! = 0 ELSE PA! = (V1! + V2! + V3! + V4! + V5!) / N
  AW! = PA! / D
  WRITE #5, ID%, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
  W4!, W5!, AW!
NEXT PROBE
FOR PROBE = 7 TO 8
  INPUT #10, ID%, DAY%, HRMIN%, PROBE%, S1!

```

```

V1! = -.053 + .029 * ((3 * 10 ^ 8 * S1! * 10 ^ -9) / (2 * .4)) ^ 2 - 5.5 * 10 ^ -4 * ((3 * 10 ^ 8 * S1! *
10 ^ -9) / (2 * .4)) ^ 4 + 4.3 * 10 ^ -6 * ((3 * 10 ^ 8 * S1! * 10 ^ -9) / (2 * .4)) ^ 6
IF V1! = -.053 THEN V1! = 0
W1! = V1! / D
WRITE #5, ID%, DAY%, HRMIN%, PROBE%, V1!, "NA", "NA", "NA", "NA", V1!, W1!, "NA",
"NA", "NA", "NA", W1!
NEXT PROBE
LOOP
PRINT "Water content calculated and all data written to new file, going to next step"
CLOSE 10, 5
SLEEP 5

REM This step writes individual probe data to seperate files
OPEN "C:\DATAPROC\" + NAME$ + ".TOP" FOR INPUT AS 100
OPEN "C:\DATAPROC\" + NAME$ + ".PR1" FOR OUTPUT AS 6
OPEN "C:\DATAPROC\" + NAME$ + ".PR2" FOR OUTPUT AS 7
OPEN "C:\DATAPROC\" + NAME$ + ".PR3" FOR OUTPUT AS 8
OPEN "C:\DATAPROC\" + NAME$ + ".PR4" FOR OUTPUT AS 9
OPEN "C:\DATAPROC\" + NAME$ + ".PR5" FOR OUTPUT AS 10
OPEN "C:\DATAPROC\" + NAME$ + ".PR6" FOR OUTPUT AS 11
OPEN "C:\DATAPROC\" + NAME$ + ".PR7" FOR OUTPUT AS 12
OPEN "C:\DATAPROC\" + NAME$ + ".PR8" FOR OUTPUT AS 13

DO UNTIL EOF(100)
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #6, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!, W4!,
W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #7, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!, W4!,
W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #8, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!, W4!,
W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #9, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!, W4!,
W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #10, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #11, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
    WRITE #12, ID$, DAY%, HRMIN%, PROBE%, V1!, W1!

```



```

INPUT #100, ID$, DAY%, HRMIN%, PROBE%, V1!, V2!, V3!, V4!, V5!, PA!, W1!, W2!, W3!,
W4!, W5!, AW!
WRITE #13, ID$, DAY%, HRMIN%, PROBE%, V1!, W1!
LOOP
CLOSE 100, 6, 7, 8, 9, 10, 11, 12, 13
PRINT "Individual probe data written to seperate files, go to next step"

REM This step calculates daily averages using .TOP file as input
REM This step also checks the order of the data to assure that it begins
REM with the first scan of the day and ends with the last
OPEN "C:\DATAPROC\" + NAMES$ + ".TOP" FOR INPUT AS 100
OPEN "C:\DATAPROC\" + NAMES$ + ".DAV" FOR OUTPUT AS 14
DO UNTIL EOF(100)
DIM DLY!(32, 16)
FOR R = 1 TO 32
FOR C = 1 TO 16: INPUT #100, DLY!(R, C): NEXT C
NEXT R

PRINT "Checking order of data"
IF DLY!(1, 3) > 2 THEN GOTO BADSTART
IF DLY!(32, 3) < 1805 THEN GOTO BADEND
IF DLY!(32, 3) > 1830 THEN GOTO BADEND
IF DLY!(1, 4) <> 1 THEN GOTO BADORDER
IF DLY!(32, 4) <> 8 THEN GOTO BADORDER
PRINT "Order is within acceptable parameters, calculate daily averages"
CALCULATE:
REM Calculate the daily average of each segment of probe 1
IF DLY!(1, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(9, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(17, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(25, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(1, 5) + DLY!(9, 5) + DLY!(17, 5) + DLY!(25, 5)) / N
AW1! = AV1! / D
IF DLY!(1, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(9, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(17, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(25, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(1, 6) + DLY!(9, 6) + DLY!(17, 6) + DLY!(25, 6)) / N
AW2! = AV2! / D
IF DLY!(1, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(9, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(17, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(25, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(1, 7) + DLY!(9, 7) + DLY!(17, 7) + DLY!(25, 7)) / N
AW3! = AV3! / D
IF DLY!(1, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(9, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(17, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0

```

```

IF DLY!(25, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(1, 8) + DLY!(9, 8) + DLY!(17, 8) + DLY!(25, 8)) / N
AW4! = AV4! / D
IF DLY!(1, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(9, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(17, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(25, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(1, 9) + DLY!(9, 9) + DLY!(17, 9) + DLY!(25, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0
IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0
S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA1! = 0 ELSE DPA1! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW1! = DPA1! / D
WRITE #14, DLY!(25, 1), DLY!(25, 2), DLY!(25, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA1!, AW1!,
AW2!, AW3!, AW4!, AW5!, DPW1!

```

REM Calculate the daily average of each segment of probe 2

```

IF DLY!(2, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(10, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(18, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(26, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(2, 5) + DLY!(10, 5) + DLY!(18, 5) + DLY!(26, 5)) / N
AW1! = AV1! / D
IF DLY!(2, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(10, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(18, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(26, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(2, 6) + DLY!(10, 6) + DLY!(18, 6) + DLY!(26, 6)) / N
AW2! = AV2! / D
IF DLY!(2, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(10, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(18, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(26, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(2, 7) + DLY!(10, 7) + DLY!(18, 7) + DLY!(26, 7)) / N
AW3! = AV3! / D
IF DLY!(2, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(10, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(18, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(26, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(2, 8) + DLY!(10, 8) + DLY!(18, 8) + DLY!(26, 8)) / N
AW4! = AV4! / D

```

```

IF DLY!(2, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(10, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(18, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(26, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(2, 9) + DLY!(10, 9) + DLY!(18, 9) + DLY!(26, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0
IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0
S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA2! = 0 ELSE DPA2! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW2! = DPA2! / D
WRITE #14, DLY!(26, 1), DLY!(26, 2), DLY!(26, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA2!, AW1!,
AW2!, AW3!, AW4!, AW5!, DPW2!

```

REM Calculate the daily average of each segment of probe 3

```

IF DLY!(3, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(11, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(19, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(27, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(3, 5) + DLY!(11, 5) + DLY!(19, 5) + DLY!(27, 5)) / N
AW1! = AV1! / D
IF DLY!(3, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(11, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(19, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(27, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(3, 6) + DLY!(11, 6) + DLY!(19, 6) + DLY!(27, 6)) / N
AW2! = AV2! / D
IF DLY!(3, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(11, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(19, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(27, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(3, 7) + DLY!(11, 7) + DLY!(19, 7) + DLY!(27, 7)) / N
AW3! = AV3! / D
IF DLY!(3, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(11, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(19, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(27, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(3, 8) + DLY!(11, 8) + DLY!(19, 8) + DLY!(27, 8)) / N
AW4! = AV4! / D
IF DLY!(3, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(11, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(19, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(27, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0

```

```

N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(3, 9) + DLY!(11, 9) + DLY!(19, 9) + DLY!(27, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0
IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0
S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA3! = 0 ELSE DPA3! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW3! = DPA3! / D
WRITE #14, DLY!(27, 1), DLY!(27, 2), DLY!(27, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA3!, AW1!,
AW2!, AW3!, AW4!, AW5!, DPW3!

```

REM Calculate the daily average of each segment of probe 4

```

IF DLY!(4, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(12, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(20, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(28, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(4, 5) + DLY!(12, 5) + DLY!(20, 5) + DLY!(28, 5)) / N
AW1! = AV1! / D
IF DLY!(4, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(12, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(20, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(28, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(4, 6) + DLY!(12, 6) + DLY!(20, 6) + DLY!(28, 6)) / N
AW2! = AV2! / D
IF DLY!(4, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(12, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(20, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(28, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(4, 7) + DLY!(12, 7) + DLY!(20, 7) + DLY!(28, 7)) / N
AW3! = AV3! / D
IF DLY!(4, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(12, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(20, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(28, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(4, 8) + DLY!(12, 8) + DLY!(20, 8) + DLY!(28, 8)) / N
AW4! = AV4! / D
IF DLY!(4, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(12, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(20, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(28, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(4, 9) + DLY!(12, 9) + DLY!(20, 9) + DLY!(28, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0

```



```

IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0
S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA4! = 0 ELSE DPA4! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW4! = DPA4! / D
WRITE #14, DLY!(28, 1), DLY!(28, 2), DLY!(28, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA4!, AW1!,
AW2!, AW3!, AW4!, AW5!, DPW4!

```

REM Calculate the daily average of each segment of probe 5

```

IF DLY!(5, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(13, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(21, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(29, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(5, 5) + DLY!(13, 5) + DLY!(21, 5) + DLY!(29, 5)) / N
AW1! = AV1! / D
IF DLY!(5, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(13, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(21, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(29, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(5, 6) + DLY!(13, 6) + DLY!(21, 6) + DLY!(29, 6)) / N
AW2! = AV2! / D
IF DLY!(5, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(13, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(21, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(29, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(5, 7) + DLY!(13, 7) + DLY!(21, 7) + DLY!(29, 7)) / N
AW3! = AV3! / D
IF DLY!(5, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(13, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(21, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(29, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(5, 8) + DLY!(13, 8) + DLY!(21, 8) + DLY!(29, 8)) / N
AW4! = AV4! / D
IF DLY!(5, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(13, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(21, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(29, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(5, 9) + DLY!(13, 9) + DLY!(21, 9) + DLY!(29, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0
IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0

```

```

S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA5! = 0 ELSE DPA5! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW5! = DPA5! / D
WRITE #14, DLY!(29, 1), DLY!(29, 2), DLY!(29, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA5!, AW1!,
AW2!, AW3!, AW4!, AW5!, DPW5!

```

REM Calculate the daily average of each segment of probe 6

```

IF DLY!(6, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(14, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(22, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(30, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(6, 5) + DLY!(14, 5) + DLY!(22, 5) + DLY!(30, 5)) / N
AW1! = AV1! / D
IF DLY!(6, 6) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(14, 6) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(22, 6) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(30, 6) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV2! = 0 ELSE AV2! = (DLY!(6, 6) + DLY!(14, 6) + DLY!(22, 6) + DLY!(30, 6)) / N
AW2! = AV2! / D
IF DLY!(6, 7) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(14, 7) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(22, 7) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(30, 7) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV3! = 0 ELSE AV3! = (DLY!(6, 7) + DLY!(14, 7) + DLY!(22, 7) + DLY!(30, 7)) / N
AW3! = AV3! / D
IF DLY!(6, 8) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(14, 8) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(22, 8) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(30, 8) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV4! = 0 ELSE AV4! = (DLY!(6, 8) + DLY!(14, 8) + DLY!(22, 8) + DLY!(30, 8)) / N
AW4! = AV4! / D
IF DLY!(6, 9) = 0 THEN ND1 = 1 ELSE ND1 = 0
IF DLY!(14, 9) = 0 THEN ND2 = 1 ELSE ND2 = 0
IF DLY!(22, 9) = 0 THEN ND3 = 1 ELSE ND3 = 0
IF DLY!(30, 9) = 0 THEN ND4 = 1 ELSE ND4 = 0
N = 4 - (ND1 + ND2 + ND3 + ND4)
IF N = 0 THEN AV5! = 0 ELSE AV5! = (DLY!(6, 9) + DLY!(14, 9) + DLY!(22, 9) + DLY!(30, 9)) / N
AW5! = AV5! / D
IF AV1! = 0 THEN NS1 = 1 ELSE NS1 = 0
IF AV2! = 0 THEN NS2 = 1 ELSE NS2 = 0
IF AV3! = 0 THEN NS3 = 1 ELSE NS3 = 0
IF AV4! = 0 THEN NS4 = 1 ELSE NS4 = 0
IF AV5! = 0 THEN NS5 = 1 ELSE NS5 = 0
S = 5 - (NS1 + NS2 + NS3 + NS4 + NS5)
IF S = 0 THEN DPA6! = 0 ELSE DPA6! = (AV1! + AV2! + AV3! + AV4! + AV5!) / S
DPW6! = DPA6! / D
WRITE #14, DLY!(30, 1), DLY!(30, 2), DLY!(30, 4), AV1!, AV2!, AV3!, AV4!, AV5!, DPA6!, AW1!,

```

AW2!, AW3!, AW4!, AW5!, DPW6!

REM Calculate the daily average of each segment of probe 7

IF DLY!(7, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0

IF DLY!(15, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0

IF DLY!(23, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0

IF DLY!(31, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0

N = 4 - (ND1 + ND2 + ND3 + ND4)

IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(7, 5) + DLY!(15, 5) + DLY!(23, 5) + DLY!(31, 5)) / N

AW1! = AV1! / D

DPA7! = AV1!

DPW7! = DPA7! / D

WRITE #14, DLY!(31, 1), DLY!(31, 2), DLY!(31, 4), AV1!, "NA", "NA", "NA", "NA", DPA7!, AW1!,
"NA", "NA", "NA", "NA", DPW7!

REM Calculate the daily average of each segment of probe 8

IF DLY!(8, 5) = 0 THEN ND1 = 1 ELSE ND1 = 0

IF DLY!(16, 5) = 0 THEN ND2 = 1 ELSE ND2 = 0

IF DLY!(24, 5) = 0 THEN ND3 = 1 ELSE ND3 = 0

IF DLY!(32, 5) = 0 THEN ND4 = 1 ELSE ND4 = 0

N = 4 - (ND1 + ND2 + ND3 + ND4)

IF N = 0 THEN AV1! = 0 ELSE AV1! = (DLY!(8, 5) + DLY!(16, 5) + DLY!(24, 5) + DLY!(32, 5)) / N

AW1! = AV1! / D

DPA8! = AV1!

DPW8! = DPA8! / D

WRITE #14, DLY!(32, 1), DLY!(32, 2), DLY!(32, 4), AV1!, "NA", "NA", "NA", "NA", DPA8!, AW1!,
"NA", "NA", "NA", "NA", DPW8!

LOOP

GOTO FINISH

BADSTART:

PRINT "Data does not begin at 12:01, stopping this procedure"

GOTO FINISH

BADEND:

PRINT "Data may not end at the fourth scan of the day, stopping this step"

GOTO FINISH

BADORDER:

PRINT "Data is not in proper order, stopping this procedure"

GOTO FINISH

FINISH:

PRINT "Daily averages are calculated, go to next step"

CLOSE 100, 14

SLEEP 5

REM This step writes daily averages to individual probe files

OPEN "C:\DATAPROC\" + NAMES\$ + ".DAV" FOR INPUT AS 100

OPEN "C:\DATAPROC\" + NAMES\$ + ".PA1" FOR OUTPUT AS 15

OPEN "C:\DATAPROC\" + NAMES\$ + ".PA2" FOR OUTPUT AS 16

OPEN "C:\DATAPROC\" + NAMES\$ + ".PA3" FOR OUTPUT AS 17

OPEN "C:\DATAPROC\" + NAMES\$ + ".PA4" FOR OUTPUT AS 18

```

OPEN "C:\DATAPROC\" + NAMES$ + ".PA5" FOR OUTPUT AS 19
OPEN "C:\DATAPROC\" + NAMES$ + ".PA6" FOR OUTPUT AS 20
OPEN "C:\DATAPROC\" + NAMES$ + ".PA7" FOR OUTPUT AS 21
OPEN "C:\DATAPROC\" + NAMES$ + ".PA8" FOR OUTPUT AS 22

DO UNTIL EOF(100)
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #15, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #16, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #17, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #18, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #19, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #20, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #21, ID$, DAY%, PROBE%, DPA!, DPW!
    INPUT #100, ID$, DAY%, PROBE%, V1!, V2!, V3!, V4!, V5!, DPA!, W1!, W2!, W3!, W4!, W5!,
    DPW!
    WRITE #22, ID$, DAY%, PROBE%, DPA!, DPW!
LOOP
CLOSE 100, 15, 16, 17, 18, 19, 20, 21, 22
PRINT "Daily averages written to individual probe files, ready for import"
PRINT "Beam me up Scotty"
END

```

F-6. SAS program used to analyze test site soils calibration data.

```
*ptions ls=72 ps=60 nodate;
data calibrat;
infile 'a:\soil.txt';
input soil seg range$ rep act mp topp herk baran led mal jac ph3 ph4 max ;

diffmp = mp - act;
adiffmp = abs(diffmp);

difftp = topp - act;
adifftp = abs(difftp);

diffh = herk - act;
adiffh = abs(diffh);

diffb = baran - act;
adiffb = abs(diffb);

diffl = led - act;
adiffl = abs(diffl);

diffm = mal - act;
adiffm = abs(diffm);

diffj = jac - act;
adiffj = abs(diffj);

diff3 = ph3 - act;
adiff3 = abs(diff3);

diff4 = ph4 - act;
adiff4 = abs(diff4);

diffx = max - act;
adiffx = abs(diffx);

run;

proc means;
var adiffmp adifftp adiffh adiffb adiffl adiffm adiffj adiff3 adiff4 adiffx ;
run;
```

```

data long; set calibrat;
  length mod1 - mod10 $ 5;
array ooo mp -- max;
array aaa adiffmp adifftp adiffh adiffb adiffi adiffm adiffj adiff3 adiff4 adiffx ;
array mmm mod1-mod10;
  mod1='mp' ;
  mod2='topp' ;
  mod3='herk' ;
  mod4='baran' ;
  mod5='led' ;
  mod6='mal' ;
  mod7='jac' ;
  mod8='ph3' ;
  mod9='ph4' ;
  mod10='max' ;
drop mod1-mod10 adiffmp--adiffx mp--max;

do over aaa;
orig=ooo; adiff=aaa; model=mmm; output;
end;
run;

%macro domix(var);
proc mixed data=calibrat;
title2 "Mixed analysis of variable &var";
class soil seg range rep ;
model &var = soil|seg|range      rep(soil) /predicted;
lsmeans soil|seg|range      rep(soil) /pdiff;
make 'predicted' out=rrr noprint;
make 'lsmeans' out=mmm noprint;
make 'diffs' out=ppp noprint;
run;
%include 'a:pdmix612.sas';
%pdmix612(ppp,mmm);
proc univariate normal data=rrr;
var _resid_;
run;

```

```

%mend;

%domix(adiffmp);
%domix(adifftp);
%domix(adiffh );
%domix(adiffb );
%domix(adiff1 );
%domix(adiffm );
%domix(adiffj );
%domix(adiff3 );
%domix(adiff4 );
%domix(adiffx );

proc glm data=long;
class model ;
model orig= model act(model)/solution;
run;

proc mixed data=long;
title2 "MODEL COMPARISON ";
class soil seg range rep model;
model adiff = model|soil|seg|range@2 model*soil*range rep(soil) /predicted;
lsmeans model|soil|seg|range@2 model*soil*range rep(soil) /pdiff;
make 'predicted' out=rrr noprint;
make 'lsmeans' out=mmm noprint;
make 'diffs' out=ppp noprint;
run;
%include 'a:pdmix612.sas';
%pdmix612(ppp,mmm);
proc univariate normal data=rrr;
var _resid_;
run;

```


F-7. SAS program used to analyze crusher run calibration data.

```
*ptions ls=72 ps=60 nodate;
data calibrat;
infile 'a:\crusher.txt';
input seg range$ rep act mp topp herk baran led mal jac ph3 ph4 max;

diffmp = mp - act;
adiffmp = abs(diffmp);

difftp = topp - act;
adifftp = abs(difftp);

diffh = herk - act;
adiffh = abs(diffh);

diffb = baran - act;
adiffb = abs(diffb);

diffl = led - act;
adiffl = abs(diffl);

diffm = mal - act;
adiffm = abs(diffm);

diffj = jac - act;
adiffj = abs(diffj);

diff3 = ph3 - act;
adiff3 = abs(diff3);

diff4 = ph4 - act;
adiff4 = abs(diff4);

diffx = max - act;
adiffx = abs(diffx);

run;

proc means;
var adiffmp adifftp adiffh adiffb adiffl adiffm adiffj adiff3 adiff4 adiffx;
run;
```

```

data long; set calibrat;
  length mod1 - mod10 $ 5;
array ooo mp -- max;
array aaa adiffmp adifftp adiffh adiffb adiffi adiffm adiffj adiff3 adiff4 adiffx ;
array mmm mod1-mod10;
  mod1='mp ' ;
  mod2='topp ' ;
  mod3='herk ' ;
  mod4='baran' ;
  mod5='led' ;
  mod6='mal' ;
  mod7='jac' ;
  mod8='ph3' ;
  mod9='ph4' ;
  mod10='max' ;

drop mod1-mod10 adiffmp--adiffx mp--max;

do over aaa;
orig=ooo; adiff=aaa; model=mmm; output;
end;
run;

%macro domix(var);
proc mixed data=calibrat;
title2 "Mixed analysis of variable &var";
class seg range rep ;
model &var = seg|range      rep /predicted;
lsmeans seg|range      rep /pdiff;
make 'predicted' out=rrr noprint;
make 'lsmeans' out=mmm noprint;
make 'diffs' out=ppp noprint;
run;
%include 'a:pdmix612.sas';
%pdmix612(ppp,mmm);
proc univariate normal data=rrr;
var _resid_;
run;

```

```

%mend;
%domix(adiffmp);
%domix(adifftp);
%domix(adiffh );
%domix(adiffb );
%domix(adiff1 );
%domix(adiffm );
%domix(adiffj );
%domix(adiff3 );
%domix(adiff4 );
%domix(adiffx );

proc glm data=long;
class model ;
model orig= model act(model)/solution;
run;

proc mixed data=long;
title2 "MODEL COMPARISON ";
class seg range rep model;
model adiff = model|seg|range@2 model*range rep /predicted;
lsmeans model|seg|range@2 model*range rep /pdiff;
make 'predicted' out=rrr noprint;
make 'lsmeans' out=mmm noprint;
make 'diffs' out=ppp noprint;
run;
%include 'a:pdmix612.sas';
%pdmix612(ppp,mmm);
proc univariate normal data=rrr;
var _resid_;
run;

```

APPENDIX G

TEST SITE EQUIPMENT

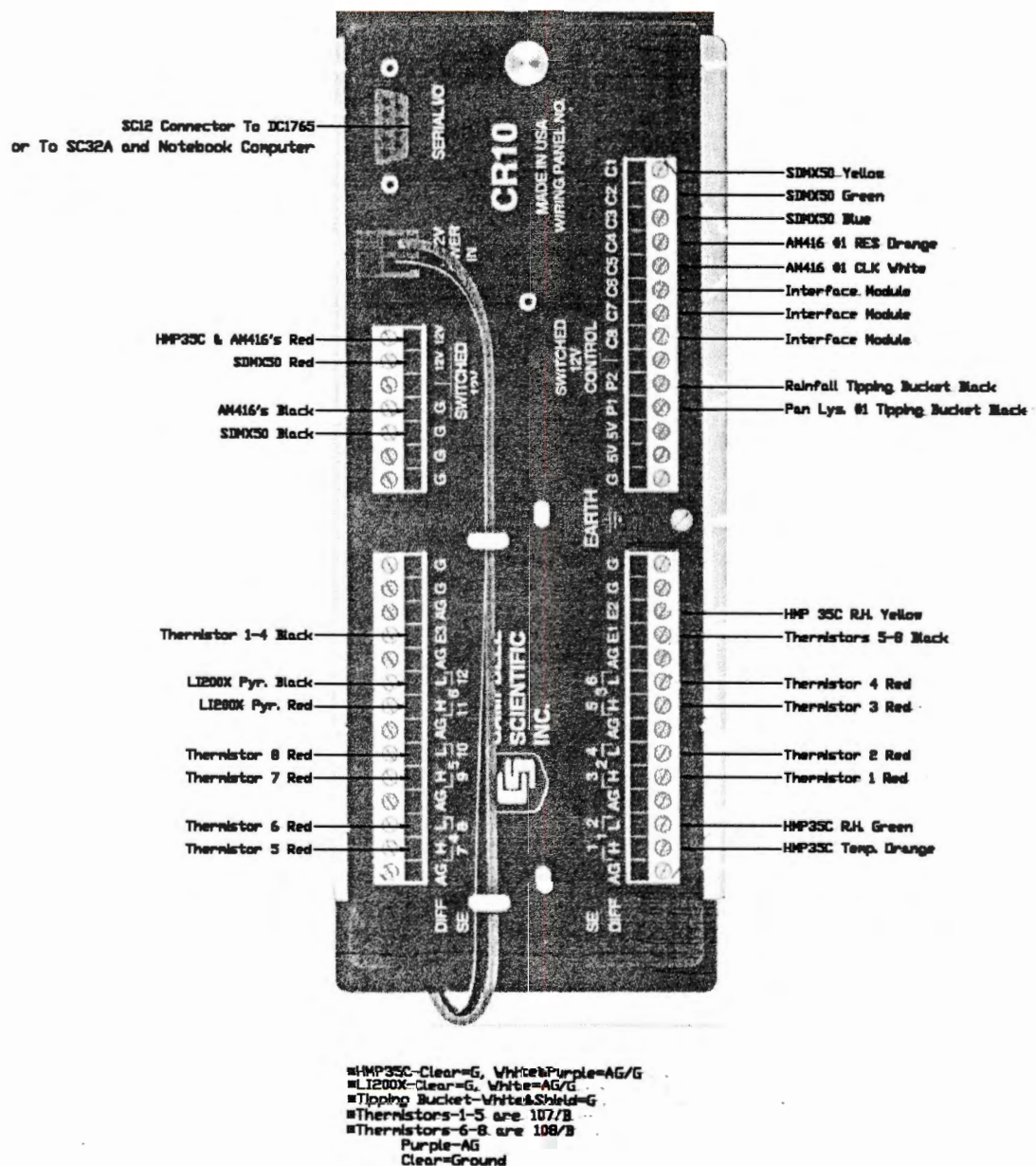


Figure G-1. CR10X wiring.

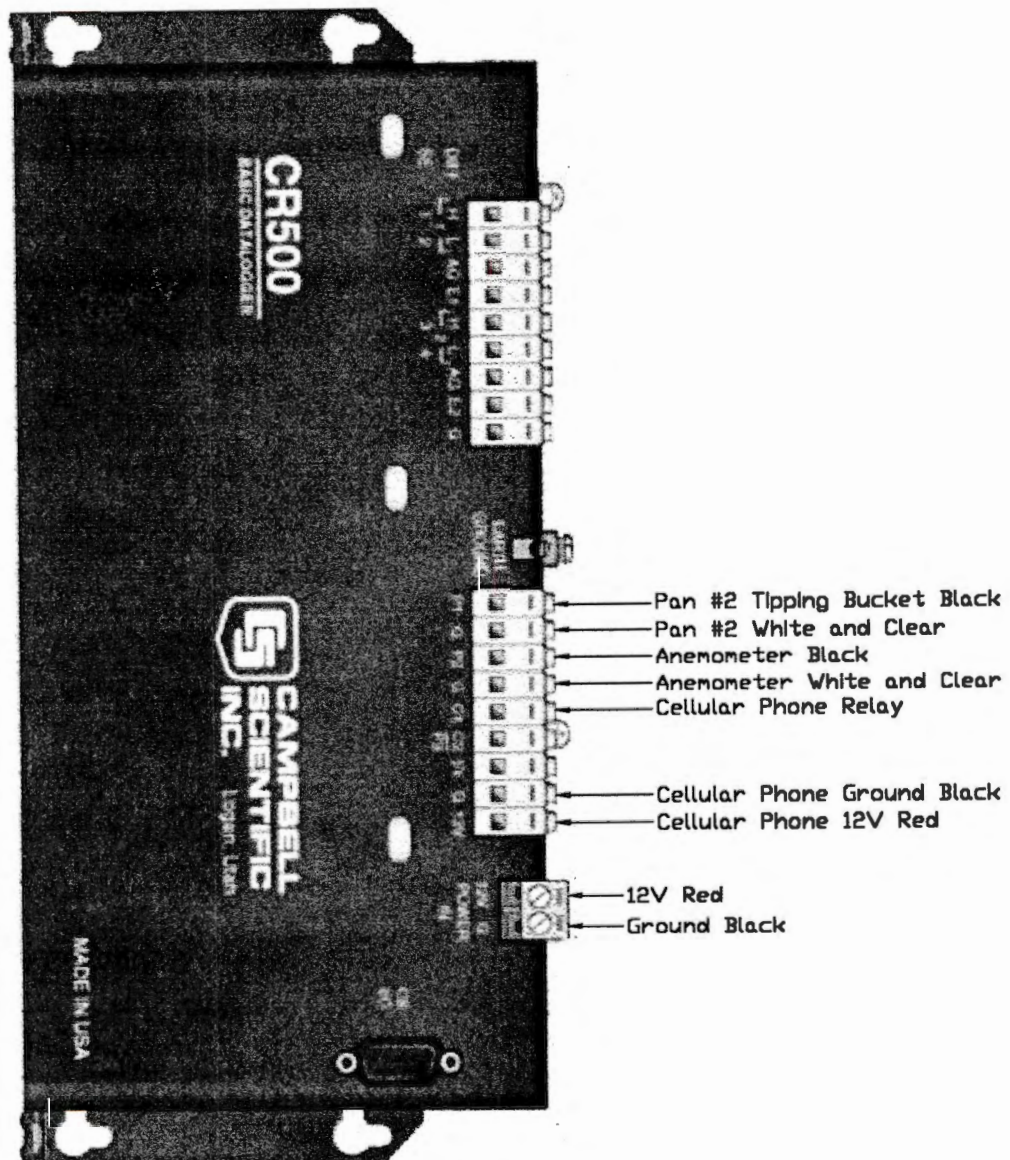


Figure G-2. CR500 wiring.

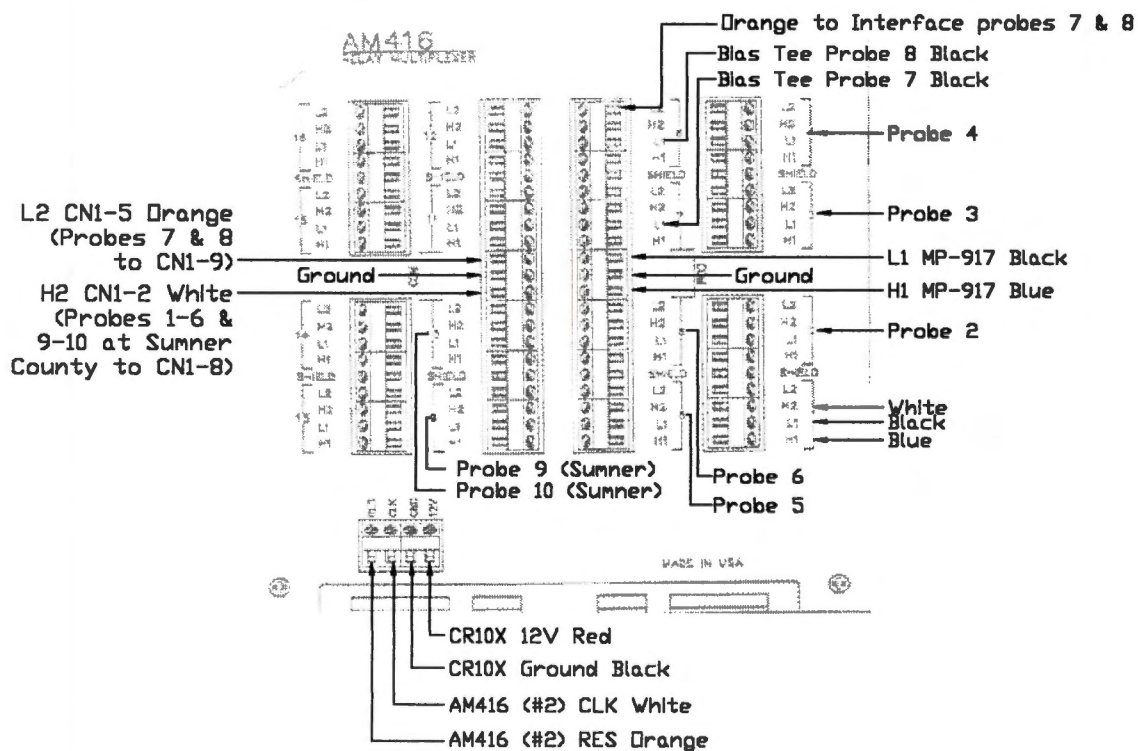


Figure G-4. AM-416 multiplexer number 1 wiring.

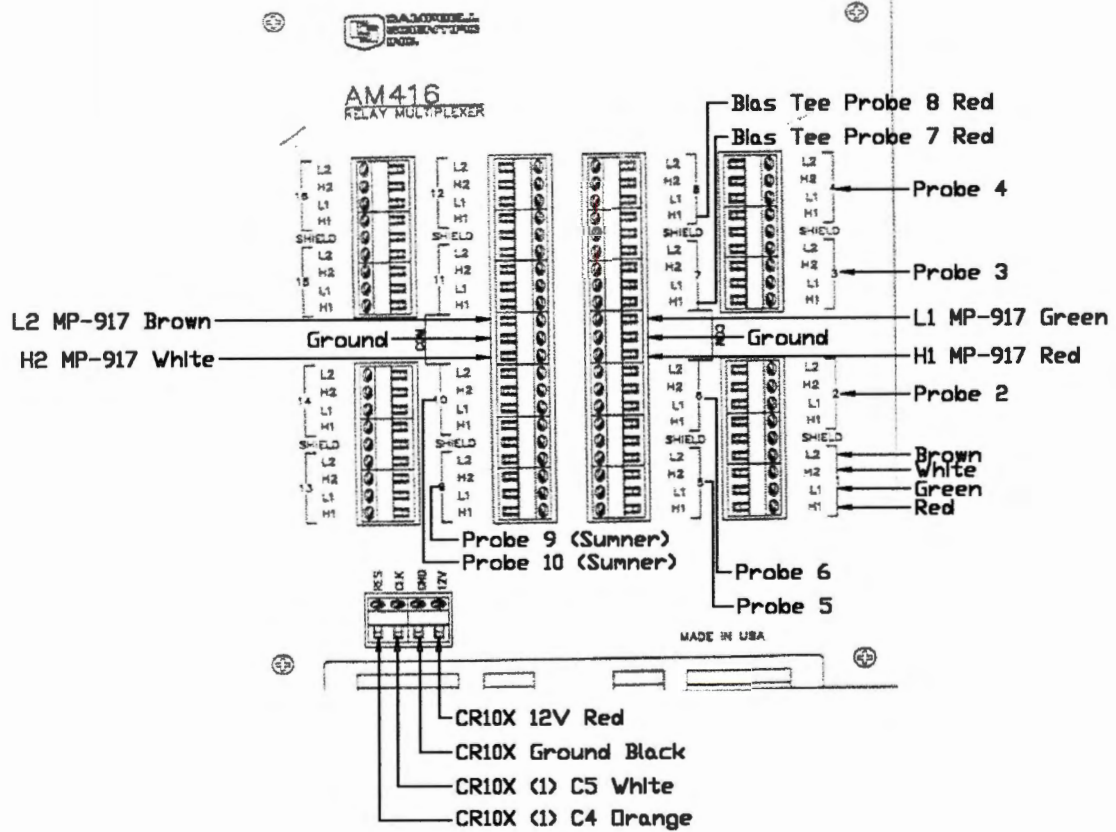


Figure G-5. AM-416 multiplexer number 2 wiring.

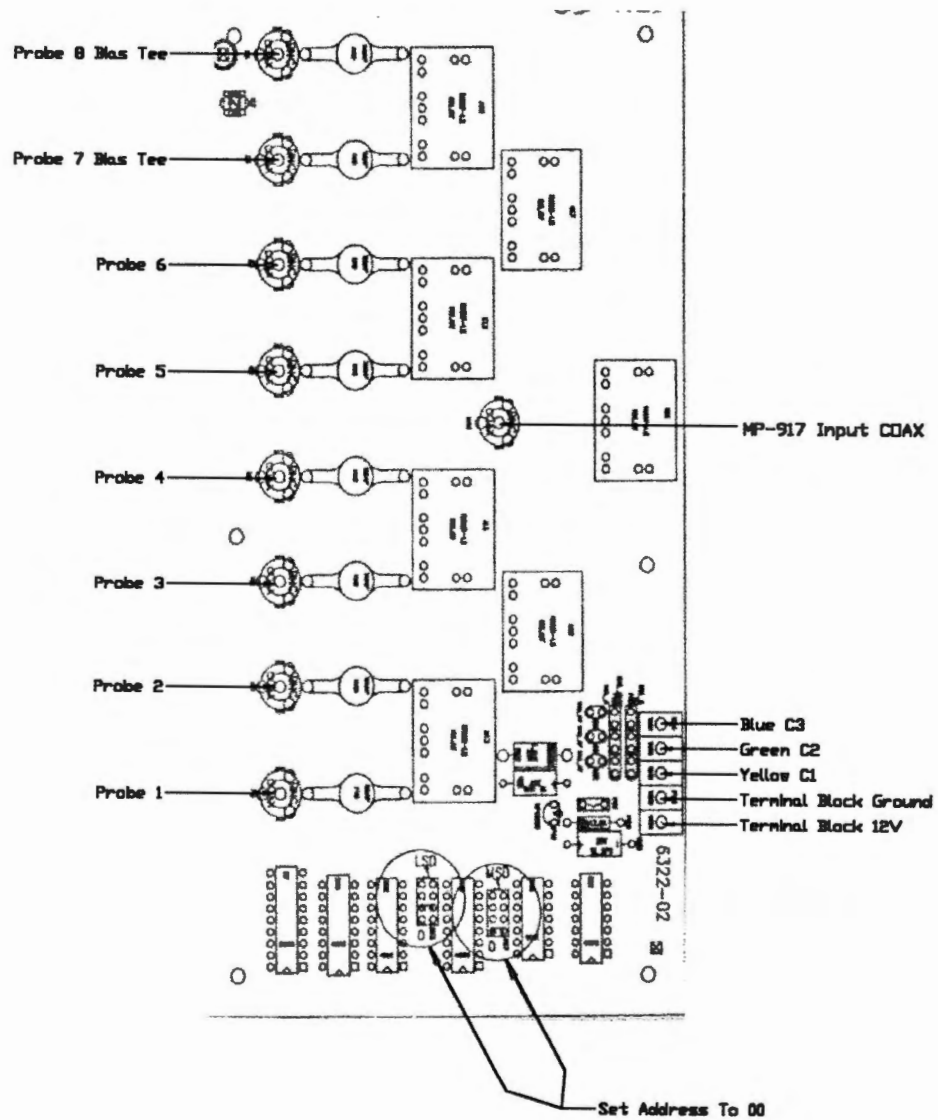


Figure G-6. SDM50 coaxial multiplexer wiring.

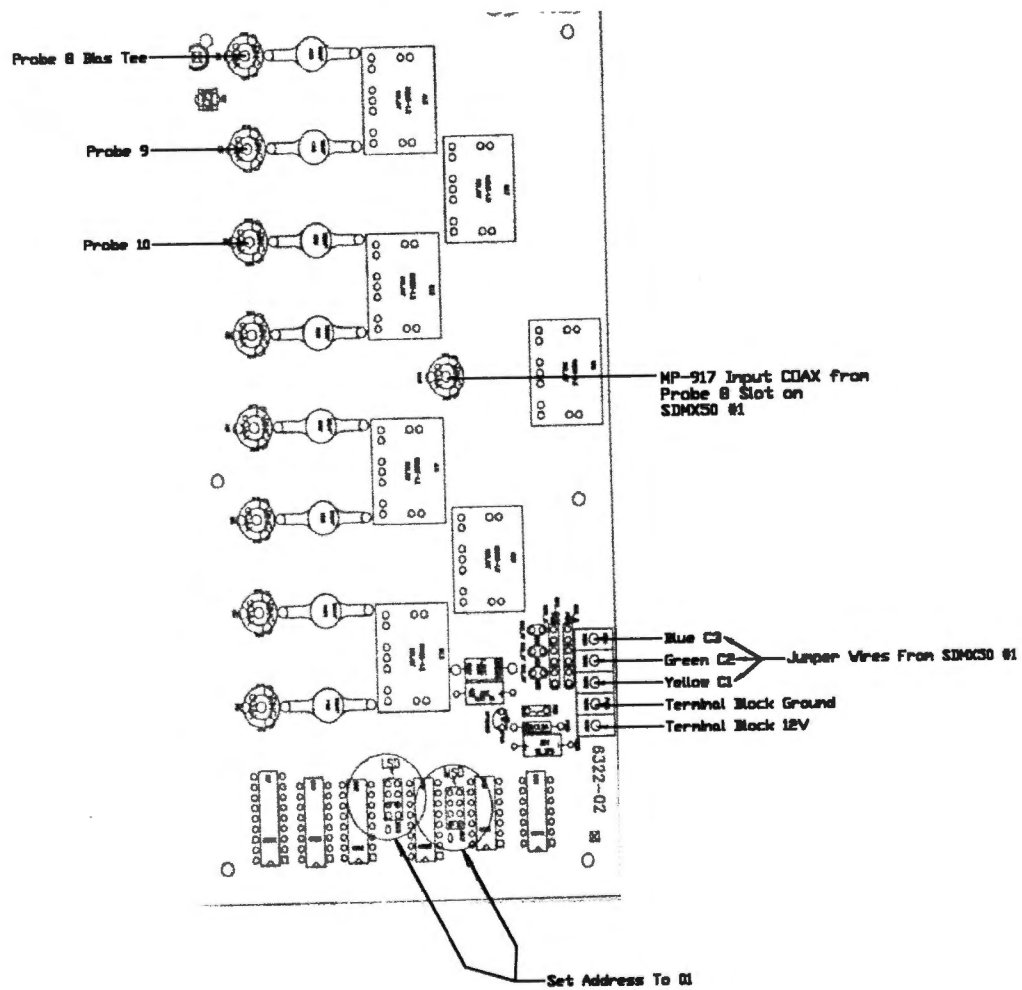


Figure G-7. SDMXX50 coaxial multiplexer number 2 wiring for Sumner Test Site.

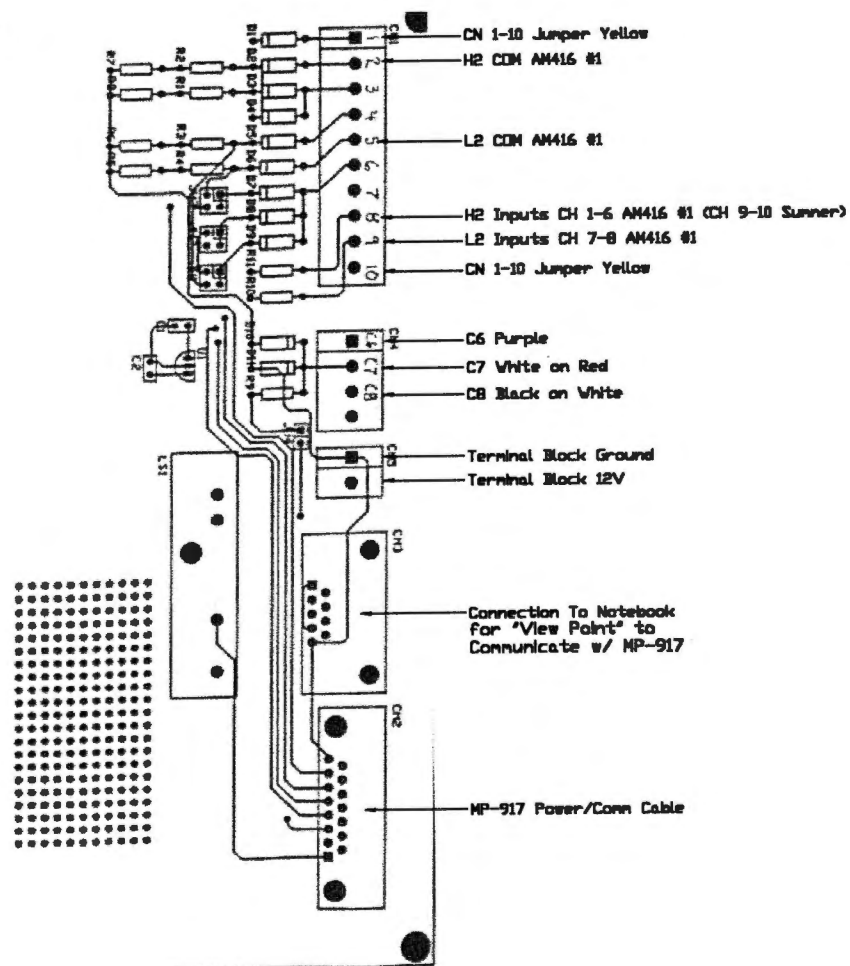


Figure G-8. *Moisture Point* to *CSI* data logger interface card wiring.

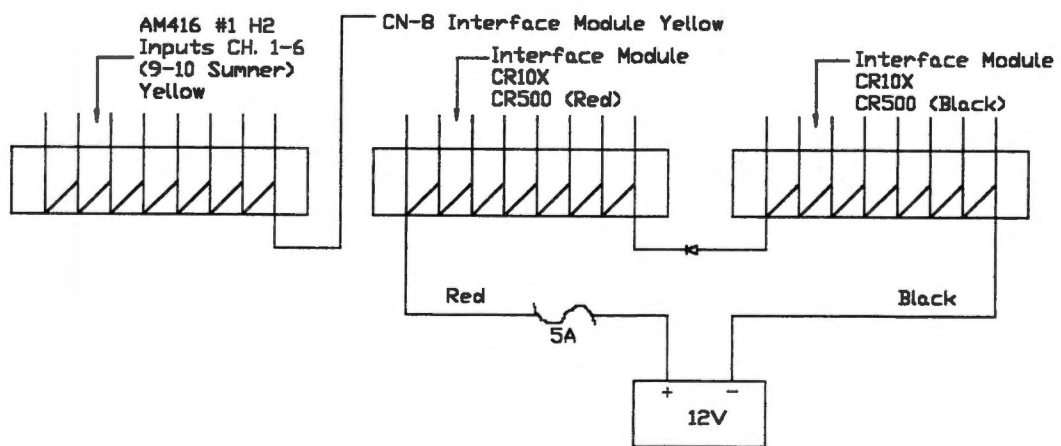


Figure G-9. Terminal block wiring.

Table G-10. CS/ 108/B pavement thermistor locations.

Test Site	Pavement Thermistor 1	Pavement Thermistor 2	Pavement Thermistor 3
Blount	2.54	7.62	12.7
Overton	5.08	12.7	17.78
Sumner	5.08	12.7	17.78
McNairy	2.54	7.62	12.7

Note: Thermistor positions are centimeters below pavement surface.

Table G-11. Soil subgrade five-segment TDR probe positions.

Test Site	TDR Probe 1	TDR Probe 2	TDR Probe 3
Blount	15.24	48.26	83.82
Overton	15.24	45.72	106.68
Sumner	20.32	45.72	106.68
McNairy	15.24	45.72	106.68

Note: Depths are in centimeters below soil subgrade surface.

APPENDIX H

SOIL AND ASPHALT PROPERTIES

Table H-1. Asphalt layer thicknesses for test sites.

Asphalt Layer	Asphalt Layer Thicknesses (cm)			
	Blount	Overton	Sumner	McNairy
AS Base	6.35	7.62	6.99	7.62
AC-Base	7.62	8.89	7.62	10.16
Binder	4.45	6.99	3.18	Future
Surface	3.18	3.18	2.54	Future
Primecoat	not applied	removed over pans and probes	omitted over pans and probes	removed over pans and probes
Lime Stabilized Base (Soil Subgrade)	not applied	not applied	top 15.25 cm of soil subgrade	not applied

Note: Primecoat is an asphalt mixture 0.75 cm thick that is sprayed on the crusher run gravel.

Note: Lime Stabilized Base refers to subgrade soil that has been mixed with lime to increase soil strength.

Table H-2. Soil properties for individual test sites.

Test Site	Soil Property						
	% Clay	% Silt	% Sand	ρ_b at Probe Locations			Mean ρ_b
				Probe 1	Probe 2	Probe 3	
Blount	48.3	41.7	10	1.59	1.49	1.54	1.54
Overton	37.8	47.2	15	1.73	1.65	1.34	1.57
Sumner	31.6	51.54	16.86	N/A	1.52	N/A	1.52
McNairy	18.4	33.3	48.3	1.95	1.84	1.83	1.87

Note: ρ_b is dry bulk density of the soil in units of Mg m^{-3} .

Note: Particle sizes were based on AASHTO particle sizes.

Table H-3. Calibration test material densities.

Test Material Dry Bulk Density					
	Blount	Overton	Sumner	McNairy	Crusher Run Gravel
Target Density	1.54	1.61	1.52	1.87	N/A*
Repetition 1	1.54	1.57	1.52	1.65	1.95
Repetition 2	1.54	1.57	1.52	1.65	1.95
Repetition 3	1.54	1.57	1.52	1.65	1.95

Note: Target density is mean bulk density from field data Table H-2.

Note: Dry bulk density is in units of Mg m^{-3} .

*No dry bulk density was taken from field.

Table H-4. Blount County test site subsurface investigation results.

Sample	Laboratory W_w/W_s	Laboratory V_w/V_t	Probe* W_w/W_s	Probe† V_w/V_t	ρ_b $Mg\ m^{-3}$
Top of Soil Subgrade	0.158	0.24	NA	NA	1.52
Crusher Run Gravel	0.019	NA	0.14	0.29	NA
6 in. (Probe 3)	0.183	0.292	0.24	0.43	1.59
19 in. (Probe 2)	0.293	0.436	0.25	0.45	1.49
33 in. (Probe 1)	0.285	0.439	0.24	0.42	1.54

† TDR daily average volumetric water contents calculated by Topp's equation in units of $m^3\ m^{-3}$ for corresponding day of subsurface investigation.

* Back-calculated using bulk density corresponding to probe.

Table H-5. Overton County test site subsurface investigation results.

Sample	Laboratory W_w/W_s	Laboratory V_w/V_t	Probe* W_w/W_s	Probe† V_w/V_t	ρ_b $Mg\ m^{-3}$
Crusher Run Gravel	0.013	NA	Bad Probe	Bad Probe	NA
6 in. (Probe 3)	0.167	0.289	0.21	0.37	1.73
18 in. (Probe 2)	0.173	0.286	0.235	0.415	1.65
42 in. (Probe 1)	0.248	0.332	0.24	0.41	1.34

† TDR daily average volumetric water contents calculated by Topp's equation in units of $m^3\ m^{-3}$ for corresponding day of subsurface investigation.

* Back-calculated using bulk density corresponding to probe.

Table H-6. Sumner County test site subsurface investigation results.

Sample	Laboratory W_w/W_s	Laboratory V_w/V_t	Probe* W_w/W_s	Probe† V_w/V_t	ρ_b $Mg\ m^{-3}$
6 in. (Probe 3)	0.236	NA	NA	0.48	NA
18 in. (Probe 2)	0.229	0.349	0.355	0.54	1.52
42 in. (Probe 1)	0.355	NA	NA	0.37	NA

† TDR daily average calculated by Topp's equation in units of $m^3\ m^{-3}$ from samples taken at time of equipment installation.

* Back-calculated using bulk density corresponding to probe.

Note: Subsurface investigation has not been performed at time of publication.

Table H-7. McNairy County test site subsurface investigation results.

Sample	Laboratory W_w/W_s	Laboratory V_w/V_t	Probe* W_w/W_s	Probe† V_w/V_t	ρ_b $Mg\ m^{-3}$
6 in. (Probe 3)	0.12	0.234	0.18	0.31	1.95
18 in. (Probe 2)	0.159	0.295	0.19	0.33	1.84
42 in. (Probe 1)	0.155	0.283	0.19	0.32	1.83

† TDR daily average volumetric water content calculated by Topp's equation in units of $m^3\ m^{-3}$ for the corresponding day of subsurface investigation.

* Back-calculated using bulk density corresponding to probe.

APPENDIX I

PRELIMINARY FIELD DATA

Table I-1. Monthly mean volumetric water contents from Blount County test site data 1997.

Month	Soil Subgrade Probes			Stone Base Probes	
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Jan.	0.41	0.43	0.40	0.23	0.16
Feb.	0.41	0.44	0.40	0.25	0.16
March	0.41	0.44	0.41	0.27	0.17
April	0.41	0.44	0.41	0.25	0.16
May	0.42	0.45	0.42	0.25	0.16
June	0.41	0.45	0.42	0.26	0.16
July	0.41	0.45	0.43	0.25	0.17
Aug.	0.41	0.47	0.43	0.21	0.16
Sep.	0.40	0.46	0.42	0.20	0.16
Oct.	0.40	0.45	0.42	0.18	0.15
Nov.	0.40	0.46	0.42	0.19	0.15
Dec.	0.40	0.46	0.42	0.23	0.16

Note: Currently field data volumetric water contents are computed with Topp's Equation
in units of $\text{m}^3 \text{ m}^{-3}$.

Note: Soil subgrade probe depths can be reviewed in Table G-11. Probe 4 is in the
bottom of the stone base layer, and probe 5 is in the top.

Table I-2. Monthly mean volumetric water contents from Overton County test site data 1997.

Month	Soil Subgrade Probes			Stone Base Probes	
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Jan.	N/A	N/A	N/A	N/A	N/A
Feb.	N/A	N/A	N/A	N/A	N/A
March	0.40	0.39	0.35	N/A	0.21
April	0.40	0.39	0.35	N/A	0.21
May	0.41	0.40	0.35	N/A	0.21
June	0.41	0.41	0.36	N/A	0.21
July	0.41	0.42	0.36	N/A	0.21
Aug.	0.40	0.41	0.36	N/A	0.21
Sep.	0.40	0.41	0.35	N/A	0.20
Oct.	0.38	0.41	0.36	N/A	0.20
Nov.	0.40	0.41	0.36	N/A	0.21
Dec.	0.40	0.40	0.34	N/A	0.21

Note: Currently field data volumetric water contents are computed with Topp's Equation
in units of $\text{m}^3 \text{ m}^{-3}$.

Note: Soil subgrade probe depths can be reviewed in Table G-11. Probe 4 is in the
bottom of the crusher run layer but is not functional, and probe 5 is in the top.

Note: The Overton County test site was brought online in March.

Table I-3. Monthly mean volumetric water contents from Sumner County test site data 1997.

Month	Soil Subgrade Probes			Stone Base Probes			
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 9	Probe 10
Jan.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Feb.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
March	N/A	N/A	N/A	N/A	N/A	N/A	N/A
April	N/A	N/A	N/A	N/A	N/A	N/A	N/A
May	N/A	N/A	N/A	N/A	N/A	N/A	N/A
June	N/A	N/A	N/A	N/A	N/A	N/A	N/A
July	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Aug.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sep.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Oct.	0.39	0.46	0.48	0.20	0.24	0.20	0.18
Nov.	0.36	0.43	0.45	0.19	0.19	0.20	0.18
Dec.	0.34	0.42	0.44	0.19	0.19	0.19	0.18

Note: Currently field data volumetric water contents are computed with Topp's Equation in units of $\text{m}^3 \text{ m}^{-3}$.

Note: Soil subgrade probe depths can be reviewed in Table G-11. Probe 4 is in the bottom of the crusher run layer, and probe 5 is in the top. Probes 9 and 10 are respectively at the same depths but located under the longitudinal joint of the travel lanes .

Note: Sumner County test site was brought online in October.

Table I-4. Monthly mean volumetric water contents from McNairy County test site data 1997.

Month	Soil Subgrade Probes			Stone Base Probes	
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Jan.	N/A	N/A	N/A	N/A	N/A
Feb.	N/A	N/A	N/A	N/A	N/A
March	0.30	0.31	0.30	0.26	0.20
April	0.31	0.31	0.31	0.26	0.22
May	0.32	0.32	0.30	0.26	0.23
June	0.32	0.32	0.30	0.26	0.23
July	0.32	0.32	0.30	0.26	0.24
Aug.	0.32	0.32	0.30	0.26	0.23
Sep.	0.32	0.32	0.30	0.26	0.23
Oct.	0.32	0.32	0.30	0.27	0.23
Nov.	0.32	0.32	0.30	0.25	0.23
Dec.	0.32	0.32	0.30	0.27	N/A

Note: Currently field data volumetric water contents are computed with Topp's Equation in units of $\text{m}^3 \text{ m}^{-3}$.

Note: Soil subgrade probe depths can be reviewed in Table G-11. Probe 4 is in the bottom of the crusher run layer, and probe 5 is in the top.

Note: The McNairy County test site was brought online in March.

VITA

Wesley Carl Wright was born in Jefferson City, Tennessee on May 13, 1972. He attended schools in the public system of Jefferson County, Tennessee, where he graduated from Jefferson County High School in May 1990. He entered The University of Tennessee, Knoxville during August 1990 where in December, 1995 he received the Bachelor of Science degree in Soil Science with emphasis in Environmental Science. In January, 1996 he was employed as a graduate research assistant by the Tennessee Institute of Agriculture, Knoxville Experiment Station and began study toward a Master of Science degree in Biosystems Engineering Technology at The University of Tennessee, Knoxville where he received the Master's degree in May, 1998. He is currently employed by the Agricultural and Biosystems Engineering Department, at the University of Tennessee, as a research assistant.

3423 2481
10/15/98 MAB 3
INFORMATION
SERIALS
SECTION