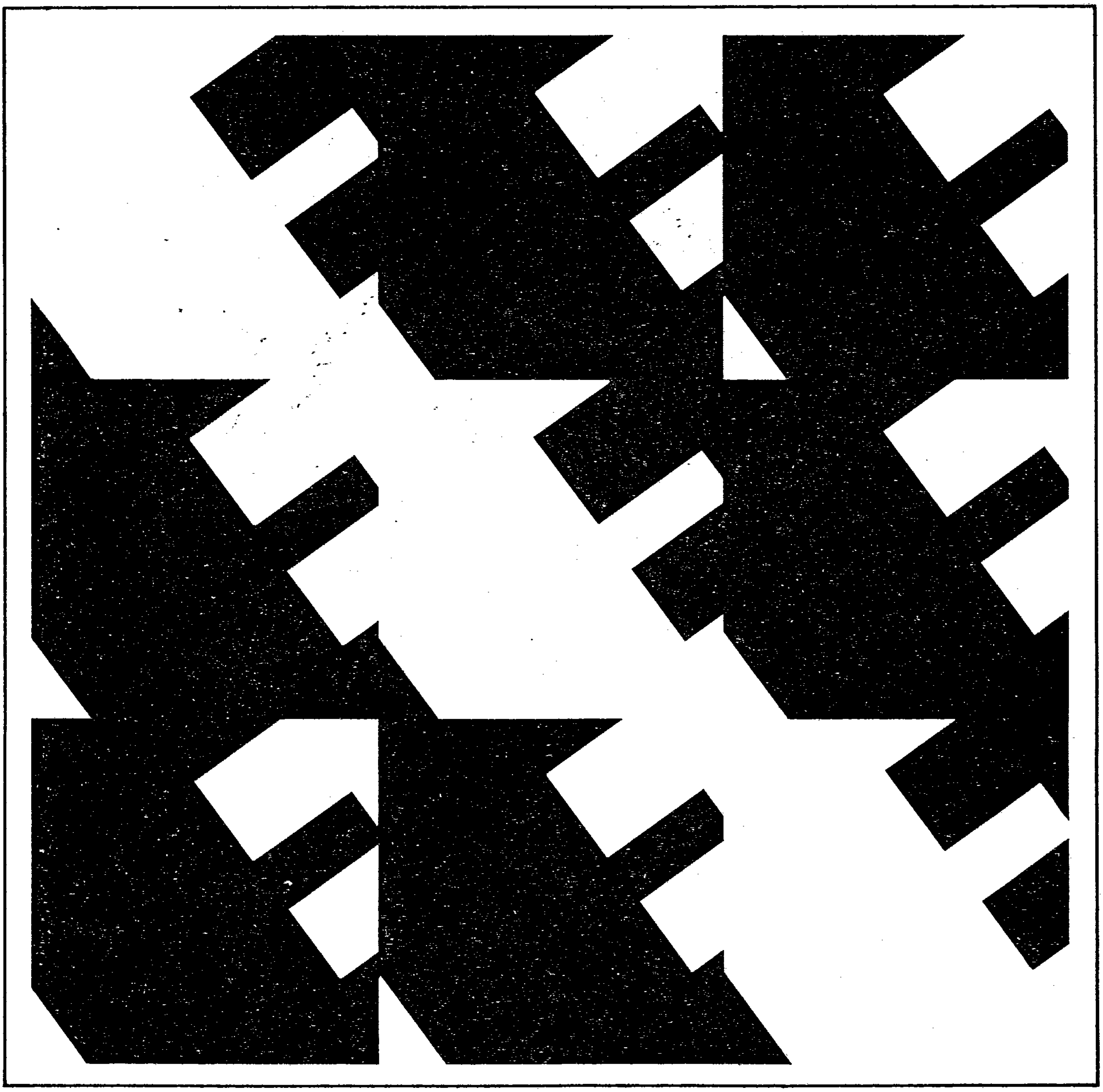
IEEE Std 442-1981

C-86-13

IEEE Guide for Soil Thermal Resistivity Measurements



IEEE Std 442-1981

Published by The Institute of Electrical and Electronics Engineers, Inc. 345 East 47th Street, New York, New York 10017

November 24, 1981

SH08409

IEEE
Std 442-1981

IEEE Guide for Soil Thermal Resistivity Measurements

Sponsor

Insulated Conductors Committee of the
IEEE Power Engineering Society

The Institute of Electrical and Electronics Engineers, Inc
345 East 47th Street, New York, NY 10017

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

COPYRIGHT Institute of Electrical and Electronics Engineers, Inc
Licensed by Information Handling Services

Foreword

(This Foreword is not a part of IEEE Std 442-1981, IEEE Guide for Soil Thermal Resistivity Measurements.)

Throughout the years, many utilities, consultants, and testing firms have measured soil thermal resistivity both in situ and in the laboratory on selected soil samples. Such measurements have utilized various types of equipment and measurement techniques. In many cases, these testing methods have yielded inaccurate or inconsistent measurements of soil thermal resistivity. This has been attributed to the unavailability of commercial testing equipment and the lack of standardization associated with the measurements.

The Insulated Conductors Committee, recognizing the need for industry guidelines for the measurement of soil thermal resistivity, organized a working group of Subcommittee 12, Tests and Measurements, to write this needed guide. During the preparation of this guide, members of the working group made many round-robin tests and measurements on selected soil samples. The expertise developed during these tests is reflected in many parts of this guide.

The IEEE will maintain this guide current with changes in the state of technology. However, comments or suggestions for additions are invited on this guide. These should be addressed to:

Secretary
IEEE Standards Committee
Institute of Electrical and Electronics Engineers, Inc
345 East 47th Street
New York, New York 10017

The membership and individuals contributing to the writing of this guide and the performance of the round-robin tests consisted of the following:

M. A. Martin, Jr, *Chairman*

Mr. A. F. Baljet
Mr. R. A. Bush
Mr. D. Clarke
Mr. J. R. Easterling
Dr. W. W. Welna
Mr. M. L. Fenger
Mr. S. W. Margolin
Mr. J. J. Rueckert
Mr. J. Stolpe

At the time this guide was approved the members of the Test and Measurements Subcommittee were:

T. A. Balaska, *Chairman*

C. F. Ackerman
E. M. Allam
A. M. Aubrey
A. T. Baker
A. F. Baljet
R. Bartnikas
E. W. Bennett
C. W. Baldes
L. A. Bondon
J. A. Bradley
R. A. Burkhardt
M. D. Calcumuggio
P. Chowdhuri
W. Cole
J. E. Conley
W. F. Constantine
J. N. Cooper
F. V. Cunningham
J. Densley
E. K. Duffy
G. S. Eager
N. W. Edgerton
R. M. Eichorn
A. Fitspatrick
E. O. Forster
R. W. Foster
R. D. Fulcomer
J. B. Gardner
J. Garland
A. Garschick
D. W. Gasda
S. Gerhard
W. R. Goldbach
O. K. Gratzol
R. A. Guba
L. F. Hamilton
C. A. Hatstat
J. G. C. Henderson
W. J. Herbert
V. Herter
H. C. Hervig, Jr
R. R. Howard
H. I. Jehan
C. V. Johnson
R. J. Kasper
L. J. Kelly
W. B. Kenyon
F. Kimsey
M. Kopchik, Jr
J. R. Kushner
F. E. LaFetra
A. F. LaScala
J. S. Lasky
R. H. Lee
R. E. Leuch
T. H. Ling
R. Lukac
G. E. Lusk
R. Luther
E. A. MacKenzie
M. A. Martin, Jr
I. J. Marwick
E. J. McGowan
A. L. McKean
M. I. F. Monzon
C. E. Muhleman
J. H. Nicholas
M. G. Noble
H. Orton

J. J. Pachot
A. S. Paniri
W. M. Pate
J. R. Perkins
K. A. Petty
C. A. Pieroni
J. S. Pirrong
J. O. Punderson
J. G. Quin
P. H. Reynolds
N. M. Sacks
C. Saldivar
D. Sandwick
E. L. Sankey
A. Sansores
G. W. Seman
J. J. Shortall
N. Singh
H. B. Slade
D. E. Soffrin
N. Srinivas
W. T. Starr
J. L. Steiner
R. Thayer
K. Tomori
R. T. Traut
P. D. Tuttle
J. R. Tuzinski
C. F. von Hermann
J. F. Wagner
E. M. Walton
R. H. W. Watkins
W. D. Wilkens
O. L. Willis
P. J. Wilson
R. T. Zukowski

When the IEEE Standards Board approved this standard on March 5, 1981, it had the following membership:

I. N. Howell, Jr, *Chairman*

Irving Kolodny, *Vice Chairman*

Sava I. Sherr, *Secretary*

G. Y. R. Allen
J. H. Beall
J. T. Boettger
Edward Chelotti
Edward J. Cohen
Warren H. Cook
Len S. Corey
Jay Forster
Kurt Greene
Loering M. Johnson
Joseph L. Koepfinger
J. E. May
Donald T. Michael*
F. Rosa
R. W. Seelbach
J. S. Stewart
W. E. Vannah
Virginius N. Vaughan, Jr
Art Wall
Robert E. Weiler

*Member emeritus

Contents

SECTION PAGE

FIGURES

APPENDIXES

IEEE Guide for Soil Thermal Resistivity Measurements

1. Scope

This guide covers the measurement of soil thermal resistivity. A thorough knowledge of the thermal properties of a soil will enable the user to properly install and load underground cables. The method used is based on the theory that the rate of temperature rise of a line heat source is dependent upon the thermal constants of the medium in which it is placed. The designs for both laboratory and field thermal needles are also described in this guide.

2. Purpose

The purpose of this guide is to provide sufficient information to enable the user to select useful commercial test equipment, or to manufacture equipment which is not readily available on the market, and to make meaningful resistivity measurements with this equipment. Measurements may be made in the field or in the laboratory on soil samples or both.

If the native soil is to be tamped back into the trench at the same density at which it was removed, it may be desirable to make in-situ resistivity measurements along the route of the cable.

If the native soil is to be placed in the trench at a density different than undisturbed soil in the same vicinity, laboratory measurements are required on soil samples recompacted to the desired density.

In order to draw meaningful comparisons on selected foreign backfill materials, thermal resistivity measurements should be made in the laboratory on soils which are compacted so as to provide maximum dry densities.

3. References

[1] ANSI/ASTM D 698-78, Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5 lb (2.49 kg) Rammer and 12 in (305 mm) Drop[1]

[2] ANSI/ASTM D 1557-78, Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10 lb (4.54 kg) Rammer and 18 in (457 mm) Drop

[3] ANSI/ASTM D 2049-69, Standard Test Method for Relative Density of Cohesionless Soils

[4] MANTEL, C. L. Engineering Materials Handbook, First ed. McGraw-Hill, 1958

4. Factors Influencing Soil Thermal Resistivity

The thermal resistivity of soil depends on the type of soil encountered as well as the physical conditions of the soil. The conditions which most influence the resistivity of a specific soil are the moisture content and dry density. As the moisture content or dry density or both of a soil increases, the resistivity decreases. The structural composition of the soil also affects the resistivity. The shape of the soil particles determines the surface contact area between particles which affects the ability of the soil to conduct heat.

The thermal resistivity (ρ) of various soil materials are listed below:

Soil Material	(ρ) (°C — cm/W)
Quartz Grains	11
Granite Grains	26
Limestone Grains	45
Sandstone Grains	58
Mica Grains	170
Water	165
Organic	400 Wet — 700 Dry
Air	4000

---

[1] ANSI documents are available from The American National Standards Institute, 1430 Broadway, New York, NY 10018.

From the above list, one can generally conclude that the soil with the lowest thermal resistivity has a maximum amount of soil grains and water. It also has a minimum amount of air.

4.1 Factors Influencing Measurements. During the measurement of soil thermal resistivity, the following factors may adversely affect the accuracy of the test measurement.

Migration of the soil moisture away from the needle during the test can result in higher or lower resistivity measurements. This migration may be significant, and normally takes place when the input power per unit area of the needle is too high. Moisture migration associated with preliminary mass transfer may lower resistivity measurements when initial soil moisture content is less than 5% in some soils, particularly sands. Moisture migration can take place toward the end of the test resulting in increasing the apparent soil thermal resistivity.

Laboratory measurements of soil thermal resistivity may be affected by the redistribution of moisture due to gravity. If gravity induced moisture redistribution takes place during the measurement, the resistivity measurement normally goes up. The error can be significant if the resistivity is sensitive to the change in moisture content at the dry soil density selected for the test.

Power supply stability must be maintained throughout the test. The power dissipated in the needle must be controlled so that variation in the magnitude of heat flux is kept within ±1%.

Under certain circumstances the in-situ resistivity measured using the field needle may vary from one soil depth to the next. If the surface contact area between the needle and the soil is decreased due to improper installation of the needle, the measured resistivity would be high. When a local nonhomogeneous material, such as a large rock, is present in the vicinity of any of the thermocouples located in the field needle, a misleading resistivity will be measured. Also, if soil layers are present which have different soil thermal resistivities, the field needle should be inserted so that the thermocouples are located at a distance 25 times the diameter of the needle away from the boundary layer of the soil. The location of different soil layers can be physically determined by taking core samples at various depths.

4.2 Factors Influencing Application of Measured Soil Thermal Resistivity. The temperature rise of buried cables is directly dependent on the resistivity of the adjacent soil. The soil resistivity value that is used for temperature rise calculations is normally derived from soil thermal resistivity measurements. The in-situ resistivity of a soil changes from season to season, due to changes in the moisture content of the soil or due to the relocation of the water table. It is important to consider these factors when determining a resistivity value for ampacity calculations.

Another major factor that must be considered while utilizing measured resistivity values is the phenomenon of moisture migration and possible soil thermal runaway, therefore, soil thermal stability must be considered.

The moisture migration process begins when a temperature gradient is imposed across the soil. This temperature gradient will cause a water vapor pressure gradient to develop, resulting in moisture migration away from the heat source. If the soil is stable, equilibrium is maintained by moisture moving back toward the cable due to capillary action. If unstable conditions exist, the moisture movement due to the vapor pressure gradient predominates, causing local drying of the soil near the cable. As the soil dries, the thermal resistivity of the soil increases resulting in an increased temperature gradient across the soil. This condition causes the vapor pressure gradient to increase resulting in more moisture migration away from the cable. This leads to thermal runaway conditions which may result in the destruction of the cable due to excessively high temperatures.

In the past, cables have been rated based on maximum cable-earth interface temperature limits to minimize the risk of excessive soil moisture migration. Research work recently reported in the literature indicates that maximum interface temperature should not be employed in rating buried cables, as heat generated is the controlling factor associated with inducing soil moisture migration.

5. Test Equipment

Figure 1 is a schematic of the system required to measure thermal resistivity in the laboratory or in the field. The equipment for the two techniques differs primarily in the size of the needle and the portability requirements of the devices used in the field as shown in Appendixes A and B.

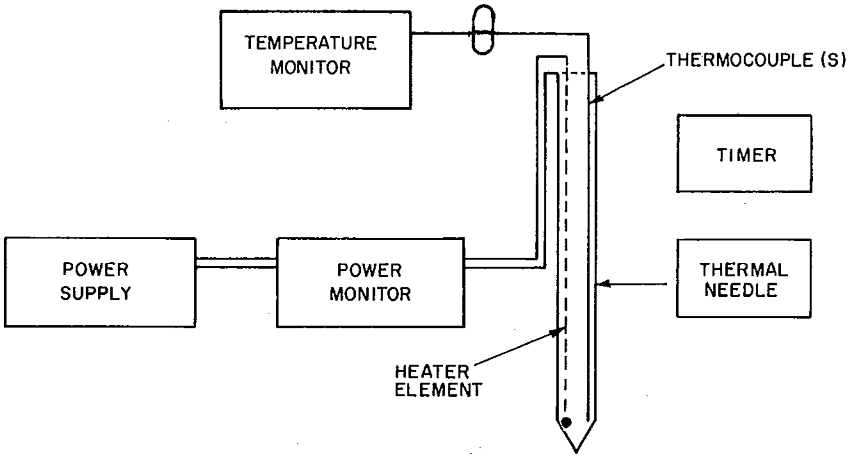


Fig 1
General Schematic Diagram for Test Equipment

5.1 Equipment Required for Field Measurements

5.1.1 Field Thermal Needle. The field thermal needle is fabricated from a stainless steel tubing which is approximately 200 cm long and 8 mm in diameter. The tubing contains a single heater wire occupying the bottom 120 cm of the seamless stainless steel tubing. The tubing functions as the return conductor. Three copper constantan thermocouple junctions, isolated electrically from the tubing and having a common constantan lead, are generally installed in the needle as shown in Appendix A. The thermocouples are positioned at intervals of 30 cm from the needle tip, with suitable means at the top of the needle for making electrical connections. In order to eliminate moisture in the needle and to reduce the initial thermal transient, the needle may be filled with an epoxy resin.

5.1.2 Power Supply. An adjustable, regulated electric power supply is preferred if a fixed power source is available. The unit should be capable of providing up to 10 A at 15 V.

Where a power source is not available in the field, a 12 V automotive type storage battery or other suitable source may be used to energize the heater of the needle. An ammeter and variable resistors will be required to adjust the heater current in the range of 1 A to 10 A.

5.1.3 Power Monitor. A 100 W analog wattmeter can be used to measure the power dissipated in the needle. Experience has indicated that the analog wattmeter is a reliable and efficient device for measuring needle power during field measurements. If a wattmeter is not available, a voltmeter/ammeter combination may be used to measure the power dissipation in the needle.

5.1.4 Temperature Monitor. A multipoint portable digital instrument designed to indicate the thermocouple output to 0.1°C is preferred for field use, although manual balance potentiometers with reference junctions and single or double pole selector switches have been used successfully.

5.2 Equipment Required for Laboratory Measurements

5.2.1 Laboratory Thermal Needle. Laboratory measurements typically employ a 100 mm long, 2.4 mm diameter stainless steel thermal needle. The internal parts of the needle include a Manganin heater element [4][2] and a 0.25 mm metal sheath thermocouple, which are both electrically isolated from the stainless steel needle. These parts should be electrically isolated from the needle wall by employing

---

[2] Numbers in brackets correspond to those in the References, Section 3 of this guide.

appropriate insulating materials or with internal ceramic tubing as shown in Appendix B.

5.2.2 Power Supply. An adjustable regulated ac or dc power supply is required with the capability of providing up to at least 5 V and 3 A.

5.2.3 Power Monitor. A 20 W ac or dc wattmeter is preferred to monitor the heat dissipation in the needle. If a dc power supply is used or an ac power supply is used in conjunction with low-inductance resistance heaters in the needle, then a voltmeter and an ammeter can be used to determine the heat generated in the needle.

5.2.4 Temperature Monitor. A digital thermocouple readout device with readability to 0.1°C is preferred to monitor the temperature of the needle. A manual balance potentiometer with appropriate reference junction compensation is also acceptable.

6. Test Methods

6.1 Methods for Field Measurements

6.1.1 Installation of Field Needle. The thermal needle should be carefully inserted in the earth. The needle should be inserted so that the middle thermocouple is located at the depth that the cable is to be installed. Resistivities could then be determined at the cable depth and 30 cm above and below that depth. If, due to soil conditions, insertion of the needle is difficult, a pilot hole should first be made. Under no conditions should the thermal needle be hammered or inserted with excessive force into the soil. When a pilot hole is needed, a pilot rod of slightly smaller diameter than the thermal needle should be driven into the soil using a slide hammer and guide (Appendix C), or another appropriate device. Similar means should be used to remove the pilot rod. If insertion of the thermal needle is difficult, because of unusual soil conditions, the pilot rod should be reinserted and removed again. This process can be repeated until the hole is enlarged enough to accommodate the needle. If the soil is extremely rocky, an electric drill may be used to facilitate producing a pilot hole.

6.1.2 Test Procedure for Field Needle. After insertion has been completed, the following procedure should be performed:

(1) Make power and temperature monitoring connections.

(2) Allow 10–15 min for the needle to reach thermal equilibrium with the surrounding earth while monitoring the temperature at 2 min intervals. This time will depend on the difference between the air temperature and earth temperature.

(3) Select a power level which will give at least 3°C–4°C temperature rise over approximately one logarithmic cycle of time to allow for easy interpretation of the measured data.

A heat input between 0.3 W/cm and 0.8 W/cm is usually applied to the field thermal needle. The power selected depends on the resistivity of the soil and will have to be based on experience for a given type of soil. If the soil has a very low resistivity, then a high heat flux is required to produce an acceptable temperature change. If the soil has a very high resistivity, then a low heat flux is required to keep from overheating the needle. If the needle temperature reaches 95°C at any time, the test should be terminated immediately, and a lower heat flux should be applied to the needle at the next location.

(4) If automotive type batteries are used to power the needle, the battery operation must be stabilized for a period of at least 5 min. Stabilization should be performed by operating a preheater which matches the heater in the thermal needle at the specified power level. Once stabilized, a well charged battery should give constant power output during the duration of the test run.

(5) Switch on the power to the needle heater.

(6) Record temperatures of each thermocouple junction in turn at 30 s intervals for the first 5 min to establish that the needle will not be overheated. The temperature should not exceed 75°C during the first 5 min under normal conditions.

(7) Continue recording temperatures in turn at 1 min intervals for 30–40 min. At the end of this time, switch off the heater.

6.2 Methods for Laboratory Measurements

6.2.1 Sample Preparation and Installation of Laboratory Needle. The laboratory needle is used primarily to determine the effects of changes in density and moisture content on the resistivity of soil and special backfill materials. It is usually advantageous to test soils that have been recompacted in the laboratory to a density that corresponds to the maximum density that can be achieved in the field. If the soil is to be tested at the maximum density, ANSI/ASTM D 698-78 [1], ANSI/ASTM D 1557-78 [2], or ANSI/ASTM D 2049-69 [3], should be followed to determine the moisture content required at which the maximum density can be obtained. For most soils, the sample is mixed to the desired moisture content and then compacted to the desired density. Silty soils artificially moistened should be allowed to equilibrate for at least 12 h in an airtight container prior to sample preparation and test. The soil should be compacted in one inch intervals so that the density of the soil in the container remains relatively uniform. The sample should be placed in a rigid cylindrical container with a minimum inside diameter of 10 cm. The height of the container would vary depending on the length of the laboratory needle used.

There are some sands which contain chemical deposits which form light bonds between sand particles as the sand dries. These bonds may lower the thermal resistivity of the sand due to the reduction in contact resistance between sand particles. Thus a sand that is compacted at zero percent moisture could have a higher resistivity than a sand that is compacted at a high moisture content and then dried to zero percent moisture. Discretion is required in the selection of the technique to be used to measure the resistivity of sands at low moisture contents.

Care should be taken in inserting the laboratory needle into the sample. If insertion of the needle is difficult, then a probe of slightly smaller diameter may be inserted into the soil to make a pilot hole.

6.2.2 Test Procedure for Laboratory Needle. An input power between 0.2 and 0.5 W/cm is usually applied to the laboratory needle. The heat input selection depends on the resistivity of the soil. If a soil with a high moisture content has been compacted to a high density, a high heat input is needed to produce an acceptable temperature change over the interval of the test. If a soil with a low moisture content has been conpacted in the container to a very low dry density, the resistivity will be high and a low heat input is required. The temperature of the thermocouple is recorded at 15 s intervals for 10 min. If, at any time, the needle temperature reaches 95°C, the test should be terminated.

7. Analysis of Test Results

The analytical model used to calculate thermal resistivity was derived assuming that a line heat source of infinite length dissipates heat in an infinite medium. Under these conditions the following is valid:

$$\rho = 4\pi \frac{(T_2 - T_1)}{2.303\, q \log\left(\frac{t_2}{t_1}\right)} \qquad \text{(Eq 1)}$$

where

ρ = resistivity °C cm/W
T_1 = temperature measured at some arbitrary elapsed time, celsius
T_2 = temperature measured at another arbitrary elapsed time, celsius
q = heat dissipated per unit length W/cm
t_1 = elapsed time at which a temperature measurement was recorded, min
t_2 = elapsed time at which another temperature measurement was recorded, min

Initial transients exist due to the finite diameter of the needle. Boundary effects are possible due to the finite medium of the soil. A convenient way of determining when the initial transients are over and when the finite boundary begins to effect measurements, is to plot temperatures versus the log of time for the duration of the test. On semilog paper the data points located on the linear section of the curve can be used to compute the resistivity of the soil. If the temperatures plotted at the beginning of the test deviate from the straight line, the initial transients have not yet settled out. If the temperatures deviate from the straight line at the end of the test, the finite boundary or moisture migration is affecting the test. In either case these data should not be used in resistivity computations.

To simplify the resistivity calculations, extend the straight line section of the curve to intersect at least one cycle on the semilog paper. By recording the temperature change over one logarithmic cycle, the resistivity computation reduces to:

$$\rho = \frac{4\pi\, \Delta T}{2.303 \cdot q} \qquad \text{(Eq 2)}$$

7.1 Sample Calculation. Data, including times and temperatures, should be tabulated during the test on an appropriate data sheet. Subse-

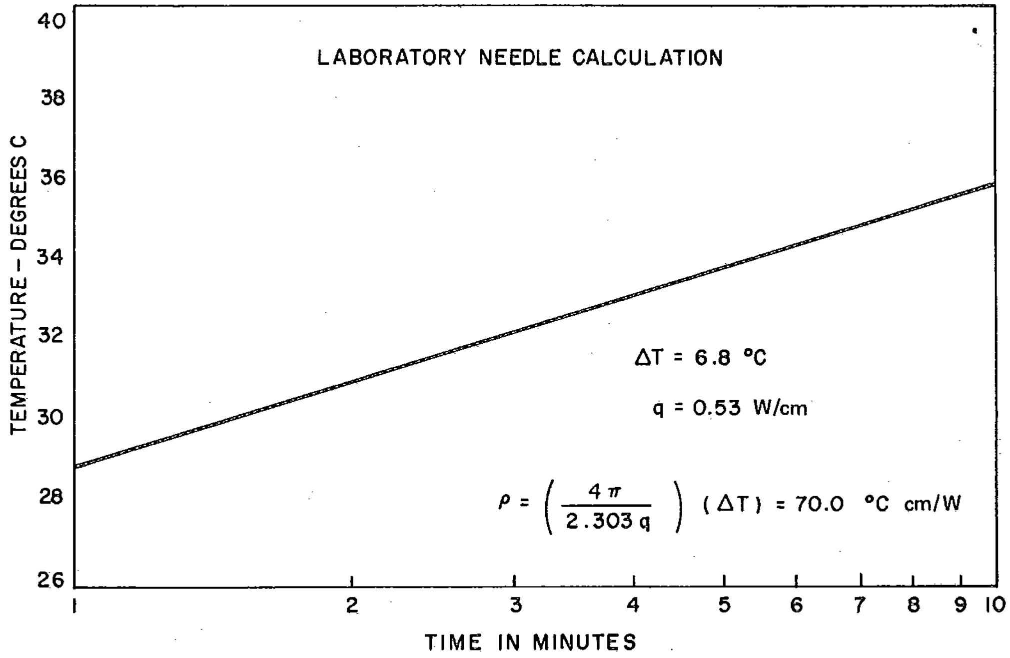


Fig 2
Temperature versus Log of Time

quently, the temperatures versus log time should be plotted for each thermocouple until a straight line can be fitted. A sample calculation follows for a test performed with a laboratory needle. Data from a typical test are shown in Appendix D. The data have been plotted in Fig 2.

A similar procedure is followed when calculating the in situ resistivity of a soil using the field needle. It should be noted that since the time span required to make a field resistivity measurement is greater, the time elapsed shown on the x-axis should be increased to at least 30 min.

7.2 Interpretation of Results. To judge the reliability of the thermal resistivity data gathered in the field or laboratory, one must make comparisons to existing data gathered in previous tests for similar types of soil. Figure 3 shows some characteristic thermal resistivity versus moisture content curves for soils including sands, clays and silts.

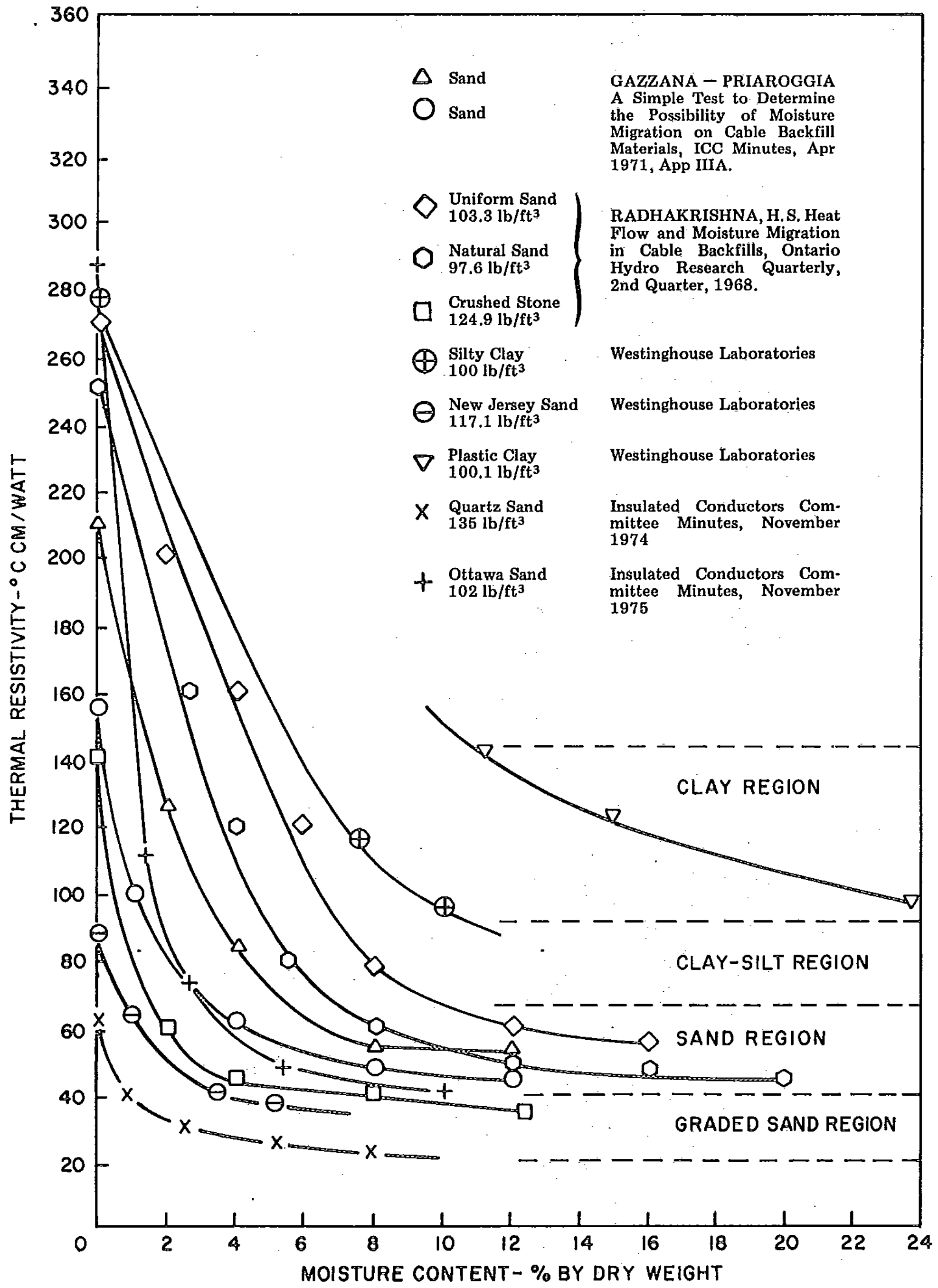
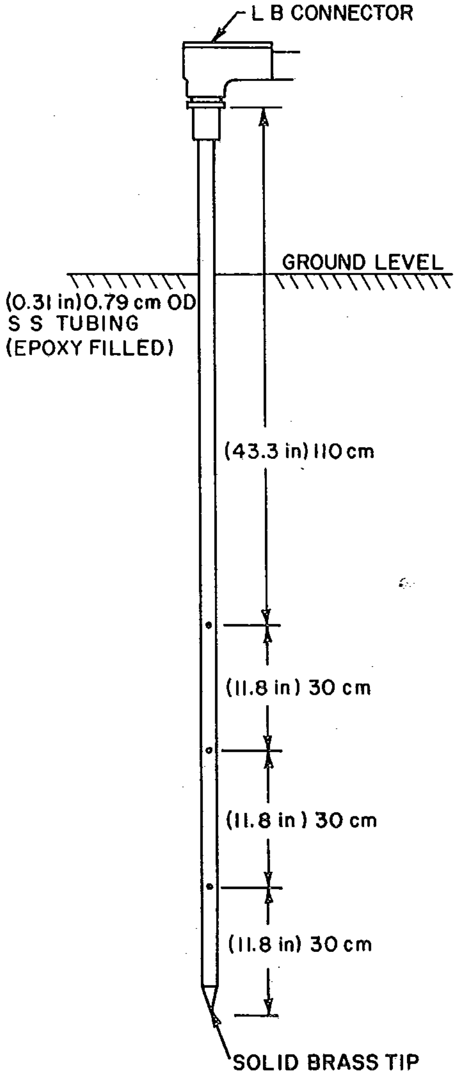


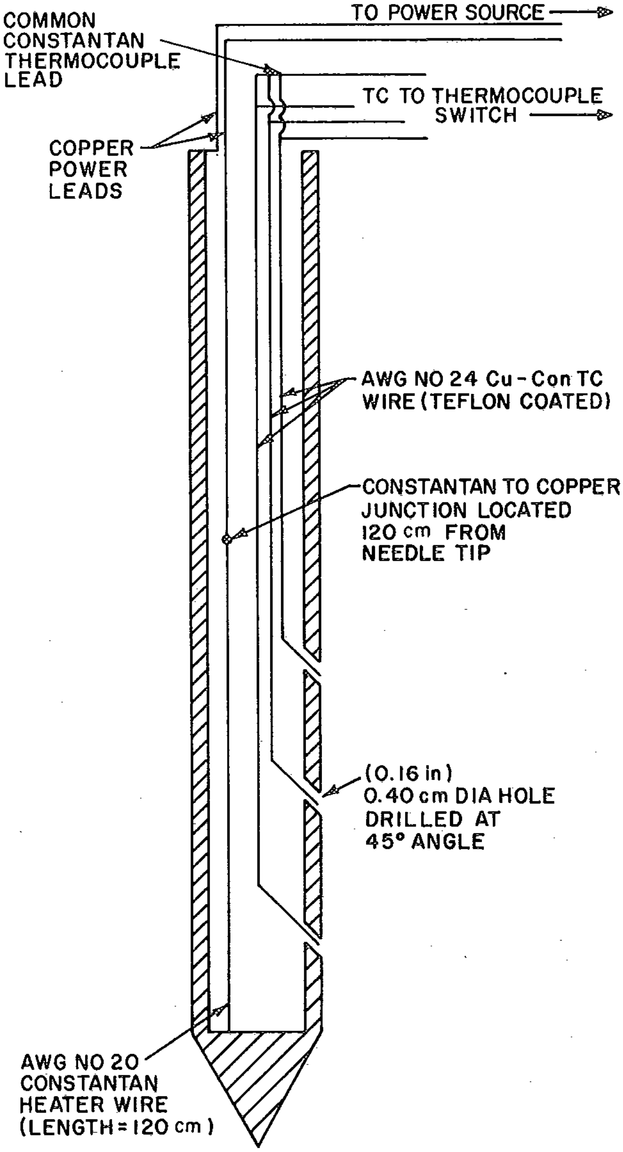
Fig 3
Thermal Property Characteristics of Soils

Appendixes

(These appendixes are not a part of IEEE Std 442-1981, IEEE Guide for Soil Thermal Resistivity Measurements.)

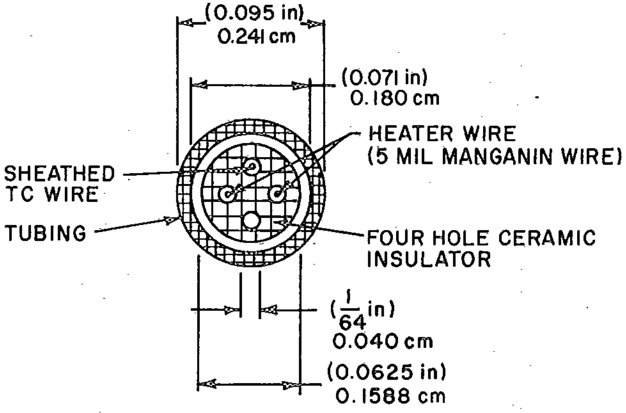
Appendix A
Field Needle

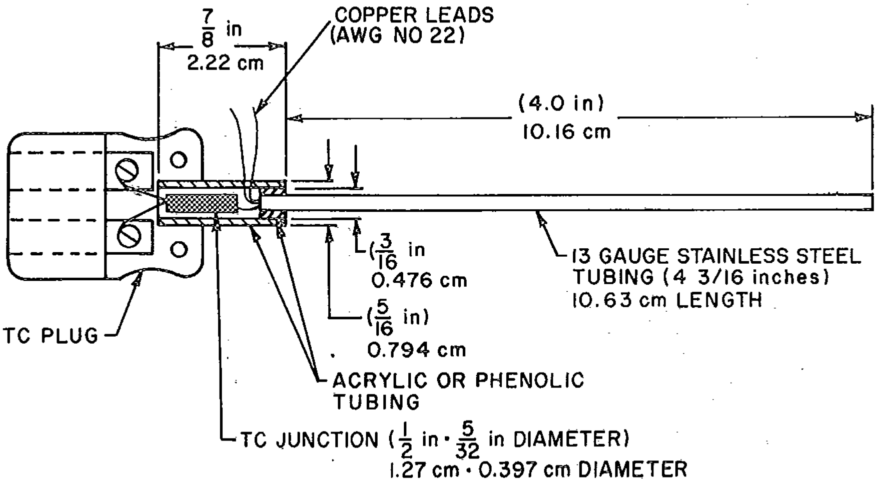




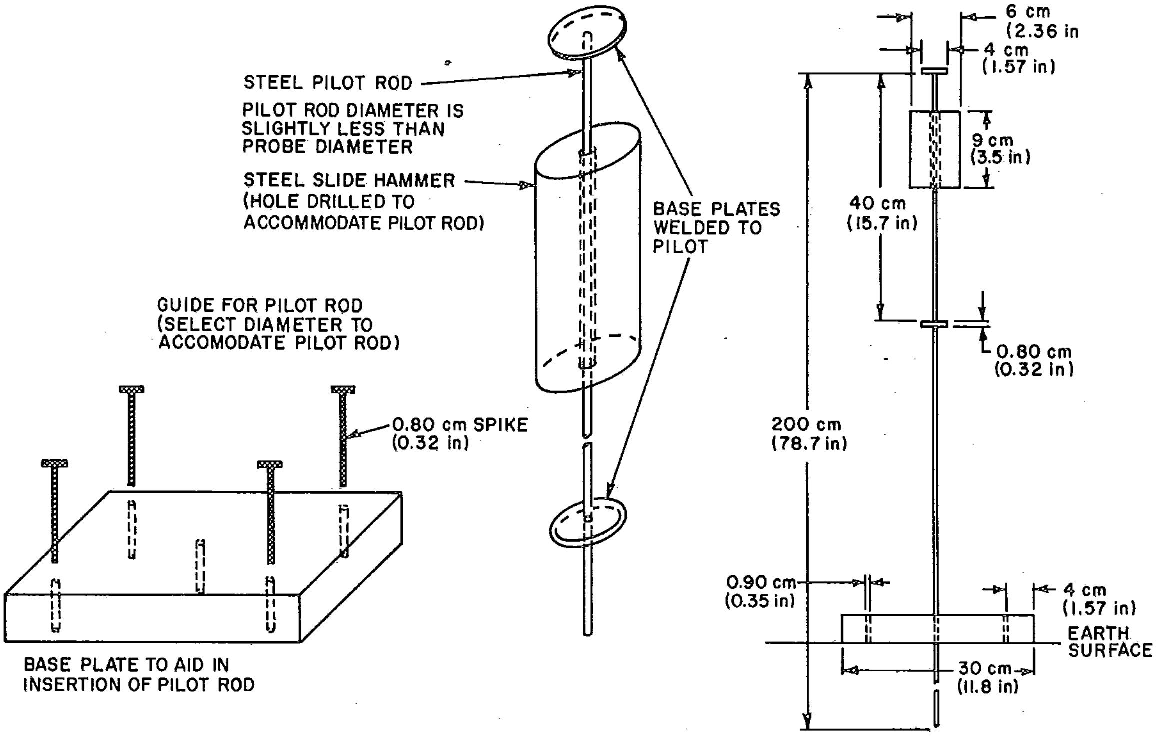
ENLARGED CROSS SECTION

Appendix B
Laboratory Needle





Appendix C
Slide Hammer Assembly



Appendix D
Miniature Needle Data Sheet

Test No. 1

Date March 12, 1978

Moisture Content 24.7 %

Dry Density 77.2 PCF

Needle No. 4

Soil Type Red Clay

Ambient Temperature 20 °C

Watts/CM 0.53

Resistivity 70.0 °C cm/w

Container Volume 1/30 Ft³

Time	Millivolts	Temp °C
1.00	1.184	28.89
1.25	1.210	29.52
1.50	1.233	30.09
1.75	1.251	30.53
2.00	1.265	30.87
2.25	1.280	31.23
2.50	1.294	31.58
2.75	1.306	31.87
3.00	1.317	32.14
3.25	1.325	32.33
3.50	1.334	32.55
3.75	1.343	32.77
4.00	1.351	32.97
4.25	1.359	33.16
4.50	1.365	33.31
4.75	1.372	33.48
5.00	1.378	33.63
5.25	1.385	33.80
5.50	1.390	33.92

Time	Millivolts	Temp °C
5.75	1.395	34.04
6.00	1.400	34.16
6.25	1.405	34.29
6.50	1.410	34.41
6.75	1.412	34.53
7.00	1.419	34.63
7.25	1.422	34.70
7.50	1.427	34.82
7.75	1.431	34.92
8.00	1.435	35.02
8.25	1.439	35.12
8.50	1.442	35.19
8.75	1.446	35.29
9.00	1.449	35.36
9.25	1.453	35.46
9.50	1.456	35.53
9.75	1.460	35.63
10.00	1.462	35.68
10.25	1.465	35.75