THE MEASUREMENT OF SOIL MOISTURE BY HEAT DIFFUSION

By
William M Aldous
Warren L Lawton and Robert C Mainfort
Airport Division

Technical Development Report No 165

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA

April 1952

U S DEPARTMENT OF COMMERCE

Charles Sawyer, Secretary

CIVIL AERONAUTICS ADMINISTRATION

C F Horne, Administrator

D M Stuart, Director, Technical Development and Evaluation Center

This is a technical information report and does not necessarily represent CAA policy in all respects

TABLE OF CONTENTS

Manuscript Received August 1951

THE MEASUREMENT OF SOIL MOISTURE BY HEAT DIFFUSION

SUMMARY

This report describes the development and testing of several experimental forms of moisture measuring cells to be embedded in the ground for the periodic measurement of soil moisture and temperature All of the devices included in this study were of the "heat diffusion" type in which the temperature rise of an electrically activated heat source, surrounded by soil, was measured by a sensitive temperature measuring device The temperature differential was used as an indication of soil moisture content The operation was based upon the principle that the rate of heat transmission through a soil mass varies with the moisture content of the soil

Three general forms of the heat diffusion type cell were developed (1) a porous block cell in which the electrical elements were embedded in a porous medium which was expected to assume a moisture content corresponding to that of the surrounding soil, (2) a direct contact cell in which the electrical elements, properly protected, were placed in direct contact with the soil, and (3) a modified direct contact cell (thermal conductivity cell) in which the heater and the temperature measuring elements were separated by a portion of the soil being tested

An evaluation of the more satisfactory cells indicated that the basic principles were sound and that electrical and mechanical difficulties could be largely overcome However, certain operating difficulties encountered when the cells were used in the soil have not been entirely eliminated The porous block cell proved unsuitable because a simple relationship between soil moisture and block moisture could not be obtained under varying test conditions The calibration curves of individual cells also proved quite sensitive to minor variations in their construction

The best direct contact cell, in which the elements were set in Wood's metal, was satisfactory when used in soils at moisture contents below approximately the shrinkage limit Above this point no change in cell reading was obtained for changes in soil moisture

The thermal conductivity type proved to be the most satisfactory of the cells developed, although with high-shrinkage soils good contact between the soil and cell could not be maintained during laboratory drying cycles It is believed that with modification and under field conditions, which may be less severe as far as soil shrinkage is concerned, this cell may be made to operate successfully

Although the final objective of this project has not yet been reached, the study has contributed measurably to the fund of knowledge on soil moisture measuring equipment More than fifty moisture cells of different construction were tested Some of these, although not suitable over the entire range of moisture contents encountered in civil engineering soil use, may be useful in limited applications or for specific purposes

INTRODUCTION

The effect of soil moisture variation upon the structural properties of soils is a primary consideration in the design and maintenance of highways and airport runways Vertical and lateral movements of moisture in soils are believed to be considerably influenced by temperature gradients throughout the soil, and although not fully understood, the importance of this phenomenon to pavement performance is well recognized Considerable progress in the understanding of the entire soil moisture problem could be made if there were available a simple and reliable measuring device which could provide continuous records of soil moisture and temperature in any desired location

Such information accumulated and studied for various soil types over an extensive period of time would indicate the range of moisture content to be expected for any particular soil and location The determinations of soil bearing value, shearing strength, and other properties required for the rational design of pavements could then be based upon observed or predictable moisture contents Since the supporting power of a subgrade soil directly influences the type, thickness, and character of superimposed pavements provided to support design wheel loads, the importance of authentic soil moisture information in airport paving design cannot be overemphasized

Present methods of obtaining soil moisture data require the removal of soil samples by drilling — through a pavement when necessary — and determining the moisture content of the samples in the laboratory

This method is costly and cumbersome and does not lend itself readily to the accumulation of mass data The removal of samples also destroys the soil structure and prevents successive readings at a specific location

A preliminary study indicated that numerous attempts had been made principally in the agricultural field, to develop a continuous-reading moisture device None of these had been satisfactory Most of these devices, referred to as moisture cells, depended upon measuring the variations in electrical resistance of soil due to changes in moisture content In actual field testing, using the resistance type cell for measuring subgrade moisture, it was found that even slight changes in the chemical composition of soil affected the accuracy of the measuring cell Further, these cells proved to be inefficient at moisture contents above the field moisture equivalent of the soil In no previous moisture cell development was any provision made for obtaining soil temperature readings concurrently with moisture determinations

After a thorough study of the available data concerning soil moisture-measuring equipment and methods, the Technical Development and Evaluation Center undertook the development of a device which (when once embedded in a required location) could, by simple instrumentation, provide long-term records of soil moisture and temperature at any desired time intervals

The moisture cells described in this report have evolved as a result of extensive study and experimentation over the past four years For the purpose of record, and to emphasize the problems encountered during this study, all of the basic cell types and variations will be discussed Other than those used for purely exploratory testing, the cells described fall into three general categories (1) porous block cell, in which the cell elements are set in a porous block designed to indicate the moisture content of the surrounding soil, (2) direct contact cell, in which properly protected elements are placed in direct contact with the soil, and (3) thermal conductivity cell, a modification of the direct contact cell in which the thermal conductivity of the soil is more directly used to indicate its moisture content

BASIC FEATURES OF THE MOISTURE CELL

The moisture cells described in this report are modifications of a design suggested by Shaw and Baver[1] Their operation is based upon the principle that the heat conductivity of soil will vary in a fixed relationship with the moisture content of the soil The thermal conductivity of soils as related to density, moisture content, and temperature has been reported by others[2,3] When dry, soil acts as a heat-insulating medium Consequently, heat applied to a source surrounded by dry soil would not be readily dissipated As a result a considerable temperature rise takes place at the heat source Conversely, with a wet soil the heat would be conducted away from the source more rapidly and result in a smaller temperature rise To utilize this principle it was necessary that three important items be provided (1) a regulated heat source from which the amount of heat diffused into the surrounding soil could be measured, (2) a method for measuring the temperature rise of the heat source, and (3) instrumentation and techniques for supplying, controlling, and recording the input and output values of the system and for converting the output records into soil moisture values

Controlled Heat Source

The heat source, from which diffusion into the surrounding soil was to be studied, varied somewhat with different experimental cells It consisted primarily of a resistance wire heater coil which in most cases surrounded the temperature measuring device The two elements were rigidly fixed in relation to each other During operation the heater coil was electrically energized by battery for fixed periods of time, the amount of current being controlled and measured through special metering devices The heater coil was constructed of copper-nickel

[1] B T Shaw and L D Baver, "Heat Conductivity as an Index of Soil Moisture," American Society of Agronomy Journal, Vol 31, pp 886-891, October 1939

[2] Miles S Kersten, "The Thermal Conductivity of Soils," Proceedings Highway Research Board, Vol 28, pp 391-409, 1948

[3] Harrison E Patten, "Heat Transference in Soils," U S Department of Agriculture, Bureau of Soils, Bulletin No 59, 1909

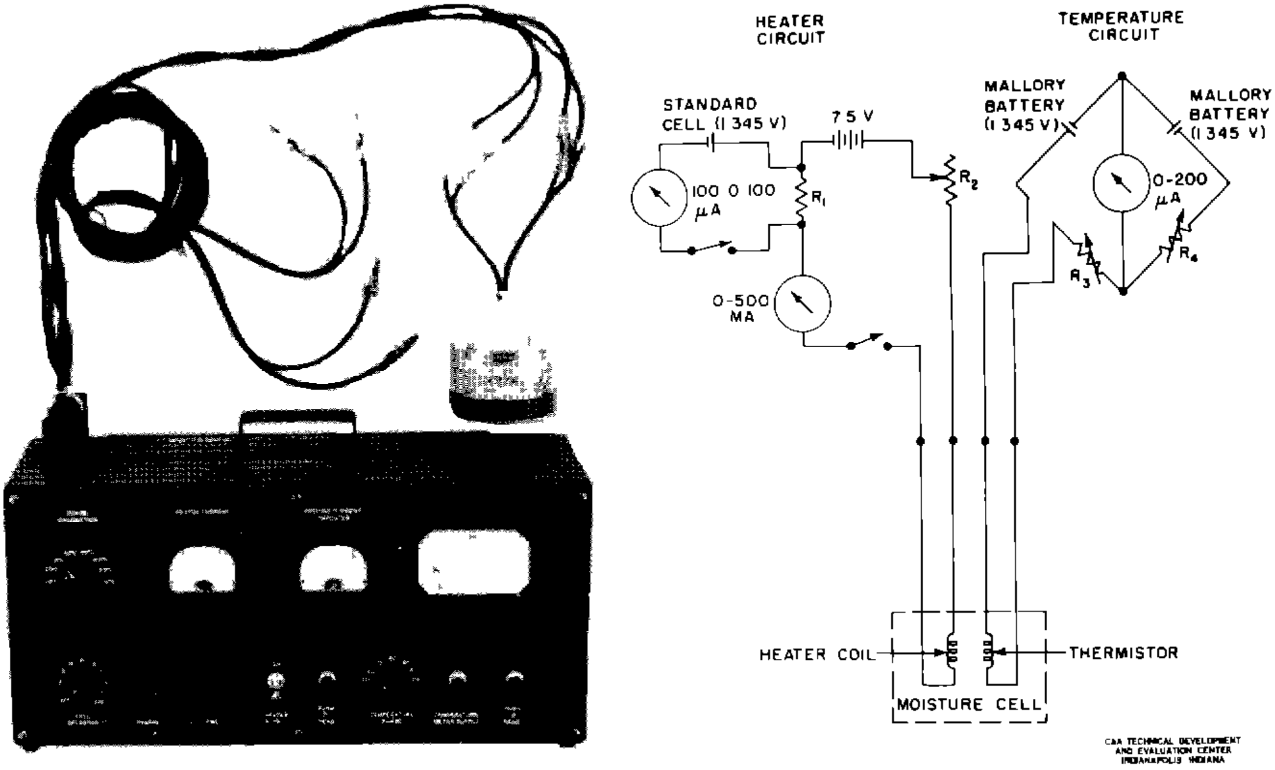


Fig 1 Electrical Control and Indicating Meter

alloy wire, the resistance of which did not change appreciably over the temperature range employed in this study

Temperature Measuring Device

The temperature indicating element used in all but one of the cells was a Western Electric Thermistor[4] properly attached to a current measuring circuit and meter The meter readings, in microamperes, can be converted readily to temperature values by the use of calibration charts The thermistor is a standard product used extensively in commercial and scientific work and is supplied in a variety of sizes and shapes It consists of a selected combination of at least two metallic oxides which, when properly combined and compressed, become a temperature measuring element of extreme sensitivity The thermistors used in this study had the ability to change their electrical resistances from 68 to 3,300 ohms for temperatures ranging from 100 to 0°C This high sensitivity combined with uniformity and reproducibility of performance make this device well suited for indicating the minor temperature variations of the heater coil which would accompany only slight changes in ambient soil moisture content

[4]J A Becker, C B Green, and G L Pearson, "Properties and Uses of Thermistors — Thermally Sensitive Resistors," Electrical Engineering, November 1946

Electrical Control and Indicating Meter.

The indicating meter used with the moisture cells was common to all of the cells tested The system was designed to indicate temperatures of the thermistors to an accuracy of 0 1°C The current flow to the thermistor during activation for reading was limited to an amount that would not change the operating characteristics of the thermistors The entire system was constructed so that it would be easily portable and able to withstand normal field use The meter, together with a schematic wiring diagram of its electrical circuits, is shown in Fig 1. The electrical system of the metering device embodies two separate circuits, a heating circuit and a temperature circuit The heating circuit consisting of a battery, meter, and variable resistors is further divided into two systems one

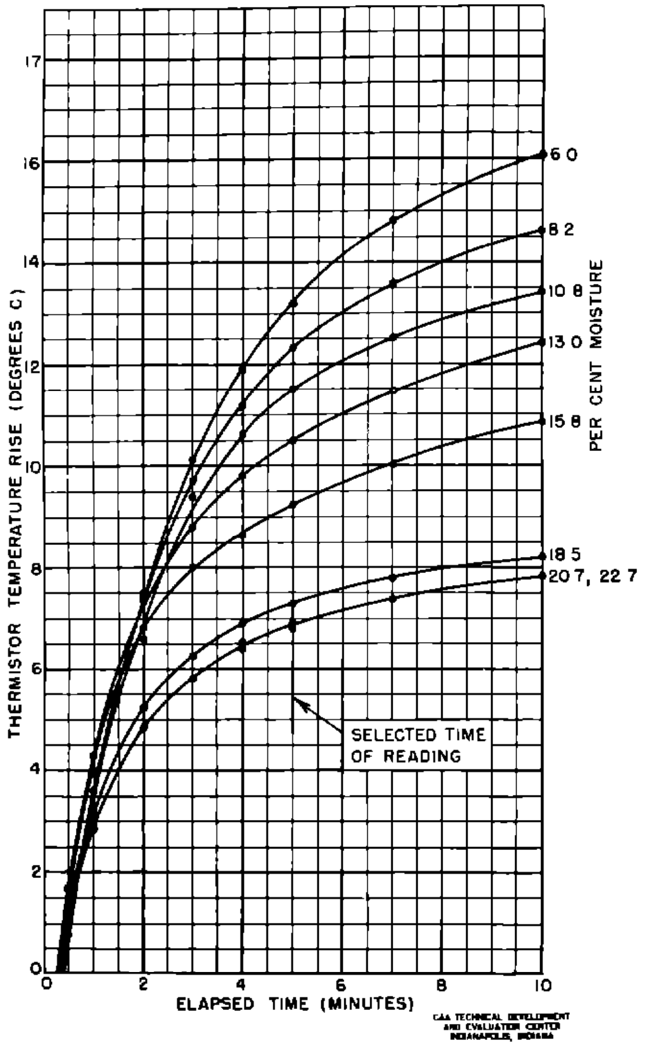


Fig 2 Typical Thermistor Operating Characteristics

providing the input supply to the heating coil, the other providing an extremely sensitive method for controlling the input

When the voltage drop across the resistor R_1 just equals the voltage of the constant voltage cell, the current has a predetermined fixed magnitude of 310 milliamperes (ma) The accuracy of the resistor, the sensitivity of the meter, and the constancy of the voltage cell control the precision by which the heater current can be indicated In effect, one division on the heater current meter scale is expanded over the whole range of the precise heater control indicator, allowing extreme accuracy in the control of the heating current input.

The temperature circuit is an unconventional bridge circuit using two constant voltage batteries with the thermistor as the temperature sensing device This design permits very accurate temperature readings The resistance in the arms R_3 and R_4 is tapped and connected to a control switch permitting the reading of thermistor temperatures over a total range of minus 20° C to plus 101° C Six overlapping full scale increments of 21° C are used over this range

Operation

In operation, the lead wires from the meter are attached to the proper leads of the cell assembly The initial temperature of the cell is determined by measuring the current across the bridge in microamperes and converting to degrees centigrade by means of calibration tables This is the existing temperature of the soil The heater coil is then energized by passing a fixed current of 310 ma through it for a predetermined time (usually two or five minutes) at the end of which period the final temperature is determined The temperature differential thus obtained is utilized as an index of the diffusion of heat from the heating coil

Fig 2 shows typical relationships between soil moisture, time of activating the heater coil, and temperature rise as indicated by the thermistor. From such data, optimum heating time for any cell can be determined

TESTING PROCEDURES

All of the assembled moisture cells and their component parts were tested by using certain general procedures Specific testing required to evaluate certain cells is included with the description of the particular cells

All heating coil and thermistor subassemblies were subjected to resistance measurements before final assembly Resistance values varied with different cell designs, but in all cases the tolerance was limited to a value of ± 0 03 per cent The plastic insulation covering each heater coil, for which a minimum leakage resistance requirement of 100,000 ohms was specified, was tested by partially immersing the subassembly in water and measuring the resistances between the heating circuit and the thermistor circuit and between each of these circuits and the water

The accuracy of the thermistor as a temperature indicating device was checked by immersing the heating coil and thermistor assembly in a water bath, the temperature of which could be accurately controlled Satisfactory agreement was obtained between the electrical measurements and the standard thermometer measurements of the water bath over a range of 0 to 75° C.

The scope of the testing of the assembled moisture cells varied as the development progressed. Cells showing promise were tested more fully than those found to be unsatisfactory in preliminary tests. Eventually a procedure was established by which the possibilities of a cell could be determined by simple controlled exploratory tests. Although some modifications were made for specific tests, the general procedure for testing a new cell was to place it successively in water, loosely compacted soil, soil molded to controlled density, and selected field locations. Periodic readings of the cells were made under different conditions of moisture and temperature.

The basic soil used in these studies is a clay loam obtained from the Weir Cook Airport at Indianapolis. The properties of this soil are:

Gradation — 32 per cent sand, 38 per cent silt, 30 per cent clay
Maximum density (Proctor) — 116 pounds per cubic foot
Optimum moisture — 14.0 per cent
Liquid limit — 30.0
Plasticity index — 14.0
Shrinkage limit — 13.2
pH — 8.0

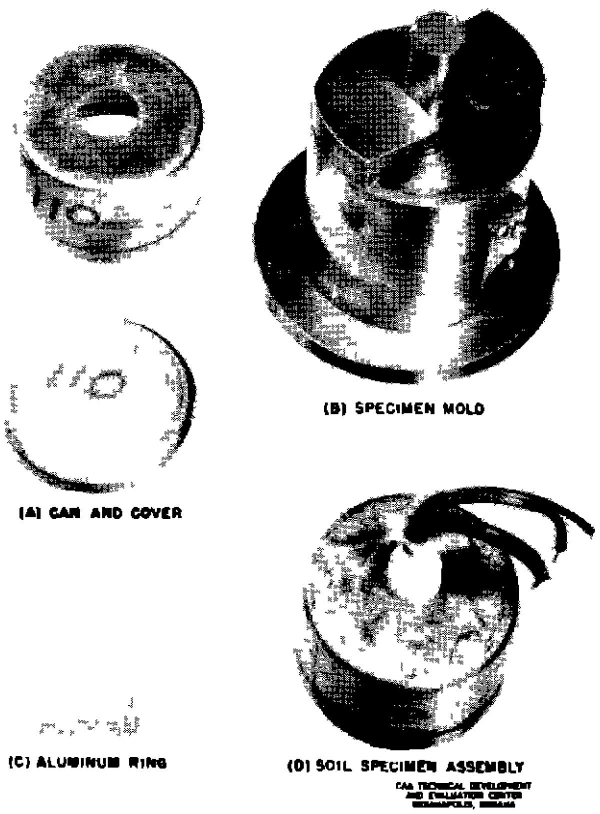


Fig. 3 Equipment Used For Preparing Laboratory Soil Test Samples

Certain of the more promising types of cells also were tested in a sandy loam obtained by blending 70 per cent sand with 30 per cent of the clay loam. The fraction of soil passing the No. 10 sieve was used in all cases.

The equipment used to prepare the laboratory samples in which the cells were tested is shown in Fig. 3. Item A is a can, 3 3/4 inches in diameter and 2 1/2 inches high, used to contain the sample during tests. A hole was cut in the bottom of the can for insertion of the cell to be tested. Item B is a 3 3/4-inch diameter steel mold for containing the can and soil during compaction. Item C is an aluminum ring used to obtain a close fit around the projecting portion of the cell so that the cell and soil can be properly sealed. Item D shows the sealed assembly, using one type of moisture cell, ready for testing.

In preparing the test sample the soil first was combined with the desired amount of water and allowed to slake in sealed cans for approximately two weeks prior to testing in a moist cabinet with temperature controlled. After slaking, the amount of moist soil necessary to produce a sample of required density was placed in the can, the whole inserted in the metal mold, and the soil compacted to a predetermined height by static loading applied through the medium of a hydraulic laboratory press.

After compaction the soil container was removed from the supporting mold, and the top was sealed in place. A hole slightly smaller than the cell to be tested was then bored in the soil through the circular opening in the bottom of the can, and the cell carefully inserted. A slight pressure was required to introduce the cell, indicating intimate contact between the cell and the soil. The aluminum ring was placed over the protruding portion of the cell, and all openings were thoroughly sealed with a mixture of hot beeswax and paraffin. In this manner both the soil and the moisture measuring device were sealed within an impervious container, assuring a constant moisture content during testing.

Meter readings of the embedded cells were begun at fixed periods after molding, depending upon the type cell being tested. Readings usually were made at two temperatures of the sample, 35 and 70° F In more severe tests the moisture content of the sample was read periodically during alternate drying and wetting cycles

For the drying cycle, the sample was uncovered and allowed to dry, for the wetting cycle, moisture was added in increments up to saturation At each point during the moisture variation, the meter was read and the test assembly weighed From this the moisture content indicated by the moisture cell could be checked against the actual moisture content determined from the wet and dry weight of the sample Upon completion of the meter readings of any one soil sample, the sample was carefully dismantled and representative portions selected from which the average moisture content of the soil surrounding the cell was determined by drying to constant weight in an oven at 110° C

POROUS BLOCK MOISTURE CELL

The "porous block" moisture cell, as discussed in this report, refers to the type of cell in which the component parts were enclosed within a porous block It was believed that, when surrounded by moist soil, the moisture content of the block would reach equilibrium with that of the soil and that subsequent fluctuations of soil moisture would be reflected by corresponding changes in the moisture content of the porous block Should it be established that the moisture content of the block and that of its surrounding soil were related to each other directly, the constant and reproducible characteristics of the block would offer a more desirable medium for measuring fluctuations in soil moisture than would the soil itself A desirable feature of this design was the physical protection afforded to the measuring elements by the porous block

Plaster of Paris Block

The first porous medium studied was a special form of plaster of Paris known commercially as Hydrocal The use of this material was considered advantageous because its important properties (particle size, chemical composition, and affinity for water) were constant, readily predictable, and subject to accurate measurement

Unfortunately, laboratory tests showed that the blocks did not follow closely the surrounding soil moisture, there being considerable lag in the response of the block to the soil moisture changes A further serious disadvantage to the use of the plaster of Paris block was its solubility in water When buried in moist soil it would be only a matter of time before the block would be dissolved by ground water, leaving the measuring elements free in a cavity in the soil The plaster of Paris block, therefore, was used only as an expedient to test various cell components until such time as a more suitable porous material could be found For this purpose its use was satisfactory

Using Hydrocal as a bedding material, laboratory tests were performed to determine the most efficient form of moisture cell construction with respect to size and type of temperature measuring elements (Thermistor Nos 1-A, 14-A, 17-A, and a Bendix-Friez Thermogage), method of supporting the heater coil, resistance of the heater coil, location of the electrical elements in relation to each other, and the shape and size of blocks The more important of these designs are shown in Fig. 4

From these tests it was found that the Thermistor Type 17-A was the most satisfactory temperature measuring element and that the nearest approach to temperature equilibrium between the thermistor and the heater coil could be obtained by locating the heater coil symmetrically around the thermistor with a minimum of mass between them Maximum accuracy could be obtained using a self-supported heating coil wound with 16-ohm resistance wire cemented around the thermistor Variations in the dimensions and shapes of the blocks used in these tests were not critical when using a heating period of two minutes or less

Alundum Block

During the testing period in which Hydrocal was used to enclose the cell, investigations were made to determine the availability of other durable, non-soluble, porous materials that might simulate the moisture absorbing properties of soil The most suitable material found was alundum, manufactured by the Norton Company, Worcester, Mass A special mixture was selected which when molded, compressed, and fired closely duplicated the grain size composition of clay loam soil In this manner it was hoped to obtain a stable material having a capillary potential similar to that of an average soil

Initial testing indicated that the alundum block readily absorbed moisture from surrounding soils when the moisture content of such soils was relatively high A considerable lag was evident, however, before the moisture content of the block and surrounding soil reached equilibrium at low or medium moisture contents This condition

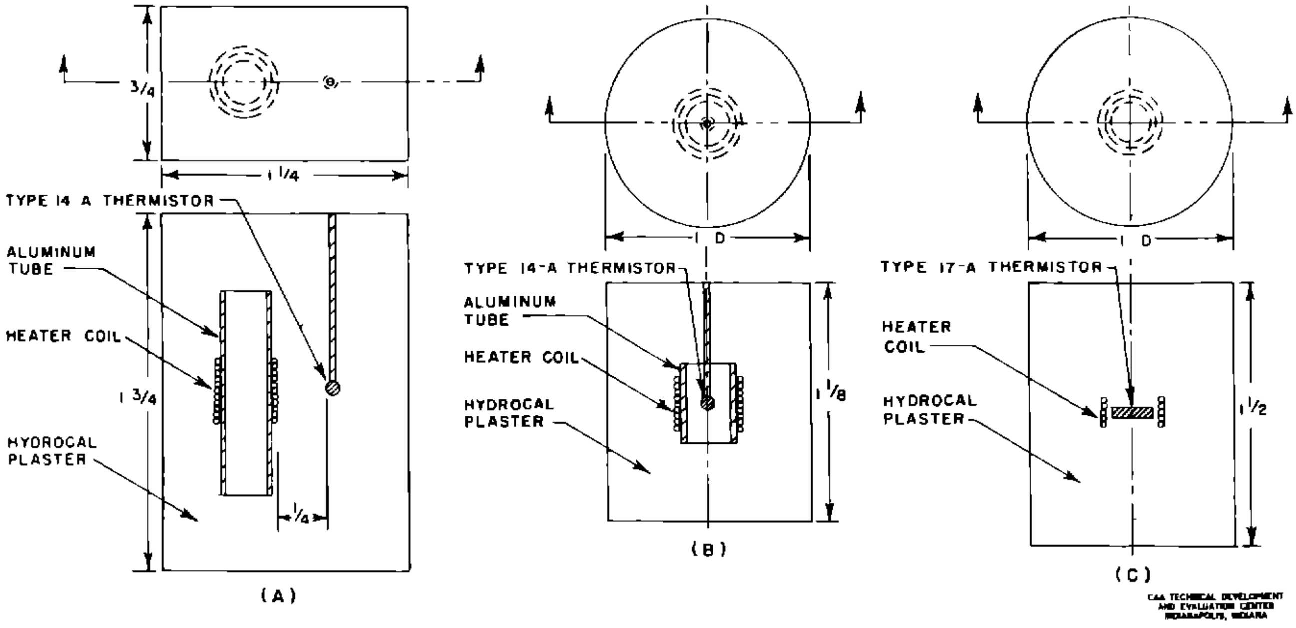


Fig 4 Different Forms of Hydrocal Block Cells

was particularly apparent with fine grained, high capillary soils Moisture equilibrium was more nearly obtained during wetting cycles than during drying cycles with all of the soils tested

Efforts were continued in an attempt to improve the characteristics of the porous blocks Different mixtures of alundum were used in order to study blocks of different densities and corresponding rates of moisture absorption The most satisfactory was a mixture containing 50 to 55 per cent air voids, designated by the manufacturer as Alundum Type RA 1155

The general form of the alundum block cell and the location of its component parts followed the same pattern as developed for the Hydrocal block The coil was wound directly around the thermistor and inserted through a hole into the center of the block at a position equidistant from the sides and bottom of the block The thermistor and heater coil assembly were insulated against moisture penetration by dip treating with a liquid plastic and drying in a low temperature oven before inserting into the block The electrical elements were securely cemented into the block by a commercial nonshrinking bonding agent, X-Pandotite Cement

Laboratory testing revealed several weaknesses in this type of cell The insulation of the electrical elements against moisture was unsatisfactory and the heat transfer properties of the bonding cement were extremely variable, due to the difficulty of obtaining a uniform application within the small area available Further, the cost of winding and insulating the self-supported form of heater coil was excessive These disadvantages combined to cause the abandonment of this particular form of the porous block cell

After considerable study and experimentation, the alundum block cell was modified to the form shown in Fig 5 The added feature of this cell was a melamine plastic mandrel, open at the top, the inside diameter of which closely approximated that of the thermistor unit The thermistor was inserted into the mandrel at a selected location and secured in place by a plastic compound applied in liquid form and hardened by oven heating at a temperature of 125° C The heater was wound around the mandrel tubing and symmetrically located with respect to the thermistor

The portion of the mandrel around which the heater coil was wound had been molded to a wall thickness of 0 015 inch in order to minimize the distance between the heater coil and the thermistor Testing of this fabrication (prior to assembly) indicated that good heat transfer was possible through the plastic mandrel wall and that no trouble should be expected from the heat insulating characteristics of the cementing material, since this application could be kept to a very small thickness

When completely assembled and firmly fixed to the mandrel, the cell unit

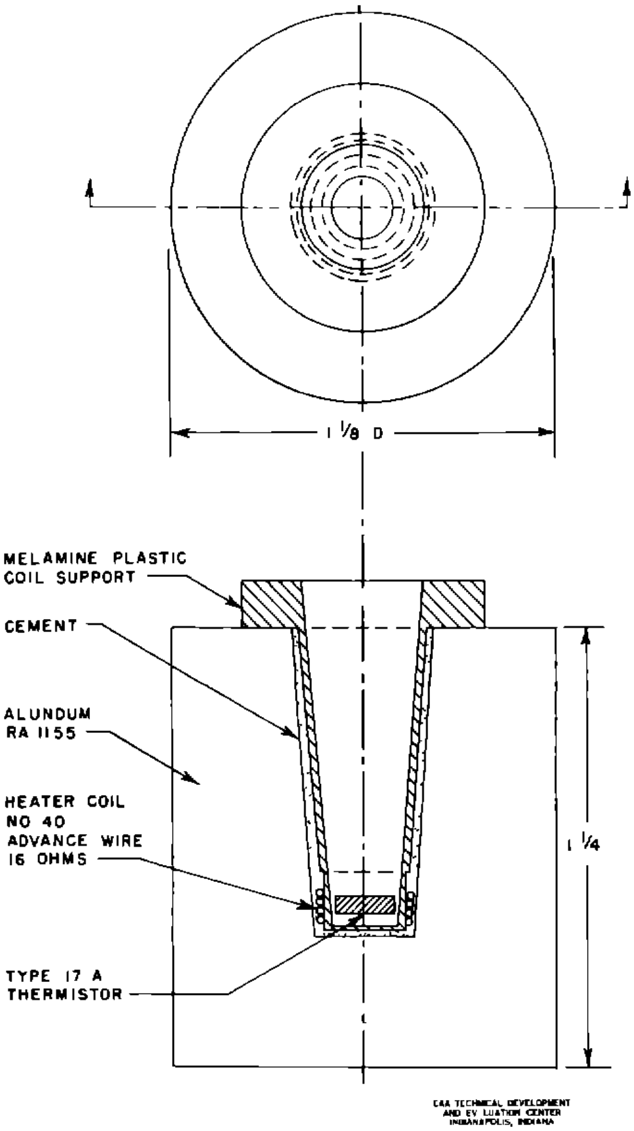


Fig 5 Alundum Block Cell — Coil Wound on Mandrel

was inserted into the alundum block and cemented into place There were used for this purpose several different potting compounds including X-Pandotite, Smooth-On (a powdered iron and graphite mixture), and Silastic (a silicone rubber compound). A snug-fitting bell cap was cemented over the top of the mandrel for the purpose of containing and directing lead wires from the cell to the recording meter The lead wires were thoroughly moistureproofed and placed in Saran tubing. The detailed assembly of this form of cell is illustrated in Fig 6

The Alundum Type RA 1155 block cell was subjected to extensive laboratory testing Sandy loam and clay loam soils were used at ambient temperatures of 35 and 70° F, with different moisture contents A two-minute heating period was used for obtaining the temperature rise of the cell

Under these severe testing conditions several weaknesses in the operation of the porous block cell were revealed In order that a cell of this form operate successfully,

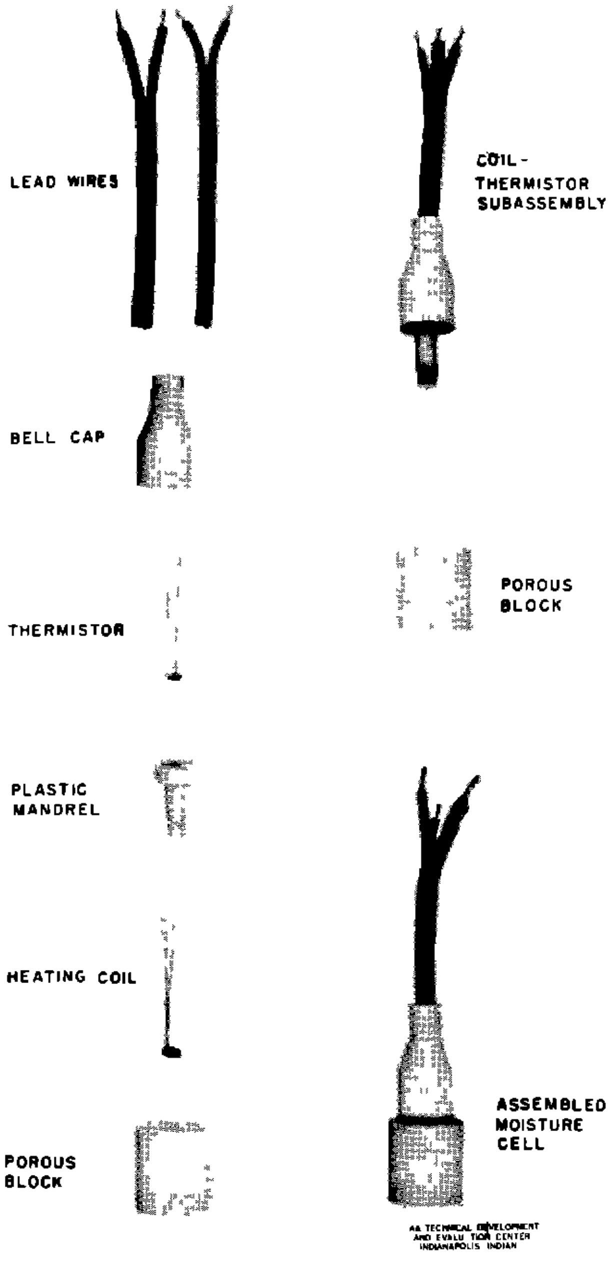
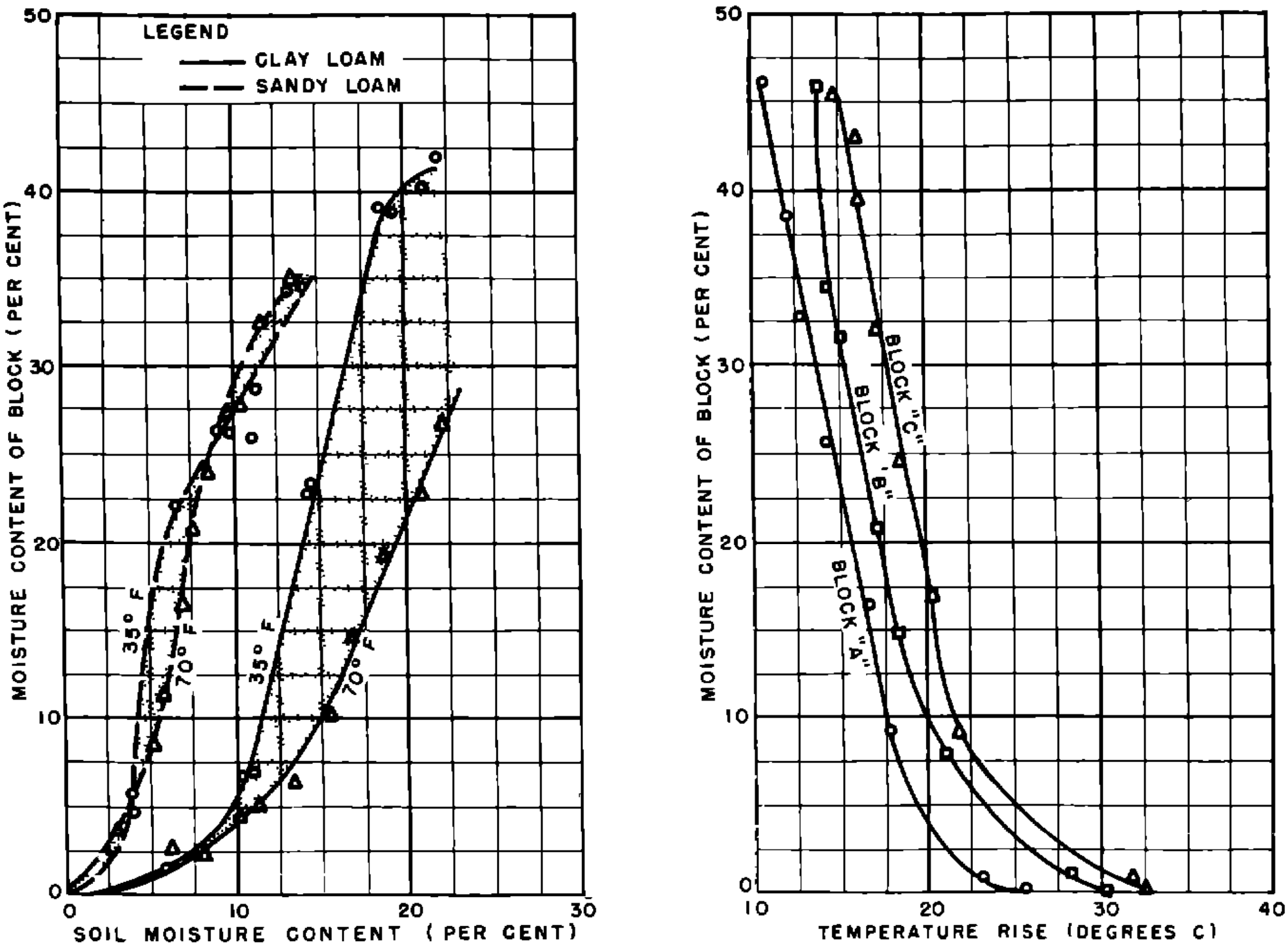


Fig 6 Detail and Assembly Views of the Final Design of Alundum Block Cell



(A) BLOCK VERSUS MOISTURE CONTENT FOR DIFFERENT SOIL CONDITIONS

(B) TEMPERATURE RISE VERSUS BLOCK MOISTURE FOR DIFFERENT CELLS

Fig 7 Operating Characteristics of the Alundum Block Moisture Cell

CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS INDIANA

it is necessary that there be a simple relationship between the moisture content of the porous block and the surrounding soil and between the moisture content of the block and the temperature rise of the heating element

The relationship between the moisture content of the block and that of the surrounding soil proved to be quite complex, being dependent upon soil type, soil condition, and ambient temperature See Fig 7A The relationship between the temperature rise of the heater coil and the moisture content of the block was satisfactory for individual blocks, but because of slight physical differences in the block and cell construction, this relationship varied considerably between different cells (as shown in Fig 7B). As a result of these tests it was apparent that the porous block cell was not generally applicable unless individual cells were calibrated for each soil and temperature condition to be tested Such procedure would be impractical

In an effort to provide a porous medium which would maintain a simple relationship with the soil under different conditions of test, the alundum blocks were replaced by blocks made of soil cement In all other respects the cells were identical to those previously tested The soil used for molding the blocks was the same as that in which the cell was to be tested Blocks of different densities were molded using three degrees of cement treatment, 15, 20, and 25 per cent based on the dry weight of the soil The soil-cement blocks, however, proved to be no more satisfactory than those of alundum and had the added disadvantage of being less durable

In addition to the basic faults of the alundum block cell, several structural weaknesses were revealed during laboratory and limited field testing These were poor electrical insulation which caused the cells to short out when subjected to prolonged moisture attack, poor thermal conductivity of the cementing material, variation in the performance of similar cells due to nonuniformity of density in the cementing materials used to seal the elements in the block, and shrinkage of the cement surrounding the heater coil, which shrinkage adversely affected the reliability and reproducibility of the results.

Although it is possible that some of the structural faults and differences in individual cell construction could be eliminated by improved fabrication methods or by the use of larger cells, the basic difficulties appeared to involve the relationship between the block and the soil For this reason it was decided to explore the possibility of using a direct contact form of cell in which there would be no porous medium between the soil and the cell

DIRECT CONTACT MOISTURE CELL

In the "direct contact" moisture cell no porous intermediate was placed between the soil and the electrical measuring elements Instead, these elements were enclosed by a protective material with high thermal conductivity and designed to provide intimate contact between the soil and the cell and between the electrical elements of the cell in order that detrimental air voids adjacent to the heater coil and thermistor could be eliminated or held to a minimum

The fabrication of the direct contact type of cell entailed a considerable amount of special investigation relative to the dimensions and electrical resistance properties of thermistors, the characteristics of the heater coil, particularly as to type of winding and applicability of different wire sizes, and the thermal conductivity values of available insulating materials In an effort to prevent the occurrence of air bubbles within the assembly, a study was made to determine the adaptability of various inert fillers for this purpose

In order to fulfill the basic requirements of the moisture cell, it was necessary that the heat generated in the heater coil be transmitted rapidly to the surrounding material and that the coil wire be electrically insulated from all elements with which it might come in contact The most efficient type of material for this purpose, therefore, would be one having high electrical insulating properties combined with good heat-conducting characteristics

To determine the suitability of different insulating materials, coils were insulated with different materials and tested with the thermistor for rate of change of temperature when energized for short periods of time During these tests several materials proved to be good heat conductors when tested in air but failed to provide satisfactory electrical insulation when tested in water The most satisfactory insulator was a commercial air drying varnish known as Formvar Best results were obtained with three dippings in the varnish, each application being followed by oven drying This method of treatment gave a coating of about twice the thickness of a single application and was used with most of the direct contact cells tested.

Different metallic materials were considered for enclosing the electrical elements in order to provide rapid heat transfer to the surrounding soil The designs were modified as investigation proceeded. The cells were tested in the same manner as were the porous block type, using the clay loam and sandy loam at ambient temperatures of 70 and 35° F.

In the first form of direct contact cell, the electrical elements were encased and supported by the same type of plastic mandrel as that used in the alundum block cell The protective covering used was Smooth-On No 12, a metallic cement consisting largely of minute iron particles, graphite, and a cementing agent This cement had been used successfully as a heat-conducting material in numerous industrial applications and was generally considered to be a satisfactory waterproofing medium Severe laboratory testing showed, however, that there was considerable water infiltration through the material, which destroyed the effectiveness of the cells

The next form of cell utilized a thin-walled copper cup (0.01 inch thick) to cover and protect the heater coil and thermistor The use of copper provided a superior heat-conducting material as well as a durable medium for making contact with the soil In this design a larger sized thermistor (Type 16-A) was used This thermistor was approximately 0 4 inch in diameter and 0.2 inch thick Bakelite discs, of a diameter equal to the diameter of the thermistor plus twice the thickness of the heater coil wire, were cemented concentrically to the top and bottom of the thermistor This arrangement greatly facilitated the winding of the coil directly on the thermistor and, through the insulation effect of the Bakelite, tended to channel the flow of heat directly from the heater coil to the thermistor The top of the cup was sealed with a circular neoprene rubber plug provided with holes through which the lead wires from the thermistor and heater coil could be passed.

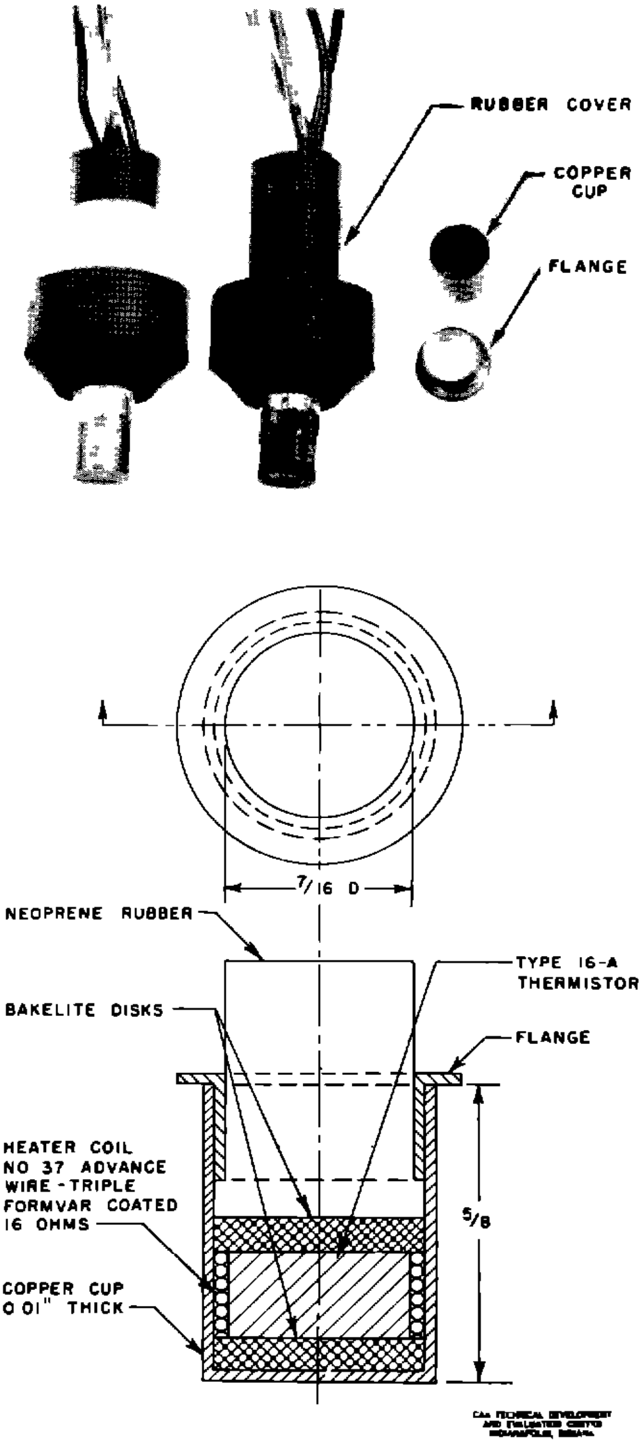


Fig 8 Copper Cup Enclosed Direct Contact Cell

Fig 8 illustrates one form of the copper cup cell In this design the copper cup had an inside diameter just large enough to allow a slip fit over the electrical assembly. The heater coil was cemented to the thermistor with Scotchweld insulation. Detailed testing of this cell indicated that, although moisture infiltration to the heater coil had been minimized, the cell was still unsatisfactory The principal deficiency appeared to be the presence of variable air voids between the electrical elements and the copper cup This defect caused considerable variation in the temperature rise of presumably identical cells under similar test conditions During these tests it was found, due to the larger thermistor and coil and possibly other physical characteristics of this type of assembly, that the optimum time required for attaining temperature equilibrium between the thermistor and heater coil was nearer a five-minute interval than the two-minute interval used with the porous block cells

The copper cup cell was redesigned using a larger diameter cup filled with powdered copper as a heat transfer medium between the cup and the electrical elements This powder (precipitated copper) was well tamped and vibrated into place and appeared to provide a continuous metal phase between the cup and the heater coil Tests showed, however, that very poor thermal conductance was obtained with this system This indicated that an excessive number of air voids were present and that these air voids, even though present in a high heat-conducting material, were sufficient to reduce thermal conductance This same type cell was tested using Smooth-On in place of the powdered copper, but this design also proved to be unsatisfactory

In an effort to eliminate air voids within the cell assembly, electrical transformer fluids were studied for possible use as fillers In this design, a copper tube covered at the top and bottom with Bakelite discs was used to enclose the cells From the top disc a perforated Bakelite thin-walled cylinder projected into the tube to support the heater coil When wound around this circular support the heater coil was located equidistant between the copper tube and the thermistor Two commercial transformer fluids, Inerteen and Aroclor, were selected for their high heat-transmitting characteristics and were tried as fillers Sufficient liquid was used to fill the cell entirely when at room temperature (70° F) Expansion of the liquid when heated during testing was provided for by a very thin rubber diaphragm located in the bottom of the cell Preliminary testing of this type cell showed that the rate of heat transmission through the liquid was low and that the provision for expansion was not satisfactory This model cell was then eliminated from further consideration

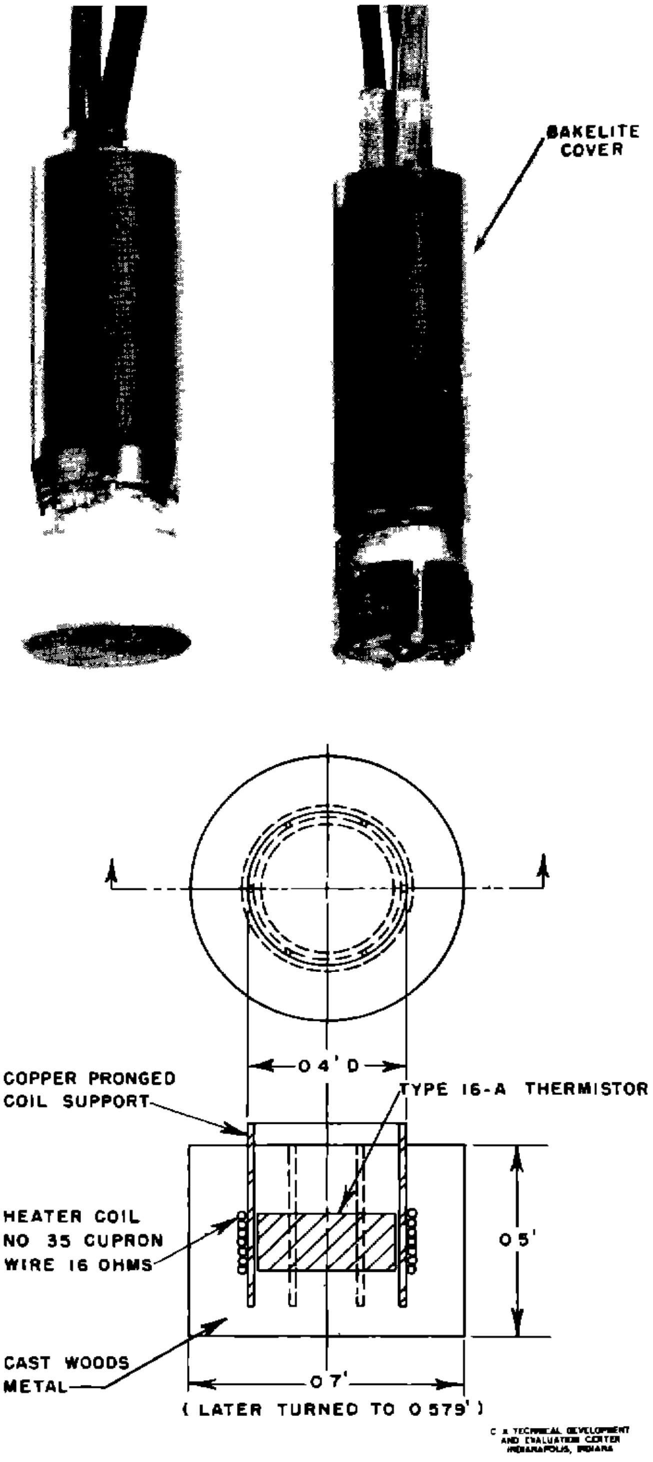


Fig 9 Wood's Metal Enclosed Direct Contact Cell (Design 1)

The next form of cell tested is shown in Fig 9 In this design the electrical elements were enclosed in a fusible alloy known as Wood's metal The heater coil was supported around a Thermistor Type 16-A by a thin-walled copper tube slotted at six places around the circumference to allow easier placement of the sealing material The thermistor was insulated by repeated dipping in Formvar (diluted with a solvent to a solution containing ten per cent solid content) with a baking period following each application The heater coil was insulated with a tetrafluoro ethylene synthetic resin, designated commercially as Teflon After winding, the coil assembly was further treated with Formvar The assembly was then centered in a mold, and liquid Wood's metal, at a temperature of approximately 120° C, was poured around it The lead wires were sealed in a Bakelite cover filled with Biwax potting compound

Initial tests indicated that the thickness of Wood's metal was too great, resulting in cells of an unnecessarily large mass from the standpoint of rapid heat transfer The Wood's metal support was reduced in diameter to 0 579 inch but the mass was still too great The cell was redesigned using a smaller Thermistor Type 17-A (0 200 inch in diameter by 0 03125 inch thick), which allowed an over-all cell diameter of only 0 40 inch. This form of the cell was quite promising, and different variations in its detailed construction were studied in order to obtain optimum operating characteristics

Further experimentation indicated that easier and more uniform application of the Wood's metal could be made if the thermistor was turned on edge A cell of this type was modified by soldering copper fins to the Wood's metal in an attempt to increase the contact area between the cell and the soil No appreciable benefit was derived from this variation The design was later modified by replacing the pronged coil support by an accurately turned copper mandrel. This form is shown in detail and assembly in Fig 10 In the fabrication of this model, the thermistor was thoroughly dip treated with Formvar insulation until it was capable of developing a resistance of from 10 to 30 megohms when tested in water The heater coil was made of No. 33 AWG Cupron wire coated with Teflon insulation followed by an application of Formvar The copper mandrel coil support had an outside diameter of 0 280 inch and an inside diameter of 0 250 inch The assembly was rigidly supported in a mold and the molten Wood's metal poured around it. The pouring of the metal was facilitated by the position of the thermistor which considerably reduced the chances of trapping air bubbles

An exploded view of the principal components of this cell prior to sealing with the

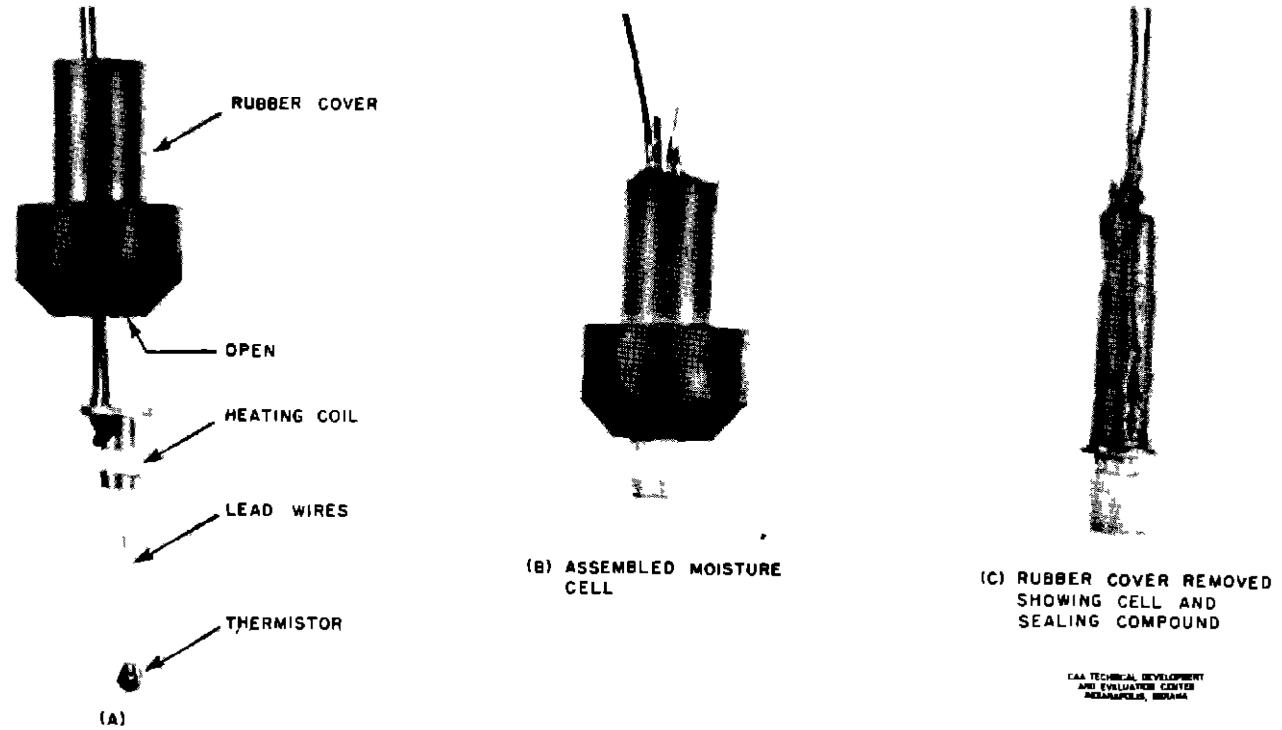


Fig 10 Wood's Metal Enclosed Direct Contact Cell (Design 3)

Wood's metal is shown in Fig 10A In this design a hollow rubber cap was used to enclose the lead wires and provide a seal for the top of the cell When assembled, the rubber cap was filled and sealed with Biwax potting compound. Fig 10B shows the assembled cell after application of the Wood's metal and with the rubber cap sealed in place Fig 10C is a view in which the rubber cap has been cut away exposing the potting compound filler

The performance of this cell was quite erratic When tested in sandy loam and clay loam, at temperatures of 35 and 70° F, the relationship between temperature rise of the cell and soil moisture content was not consistent Instead of a smooth curve relationship there were many points of abnormally high temperature rise, indicating poor contact between the soil and the cell Studies had shown that air gaps of a magnitude of even 0 001 inch would cause high cell temperature rise, particularly at the lower soil moisture contents At moisture contents above the shrinkage limits, the air gaps varied with fluctuating moisture conditions, further reducing the accuracy of the cell readings

It was believed that part of the poor contact between the soil and the cell was attributable to the rubber mounting cap The large overhang at the top of the Wood's metal tended to prevent a tight seating of the bottom of the cell against the soil In addition, the expansion and contraction of the rubber probably caused considerable movement of the cell relative to the soil

The cell was remodeled, reverting back to the Bakelite cover (sealed with Biwax) in place of the rubber cap and using tapered sides for the cell In other respects the cell was identical to those with rubber caps The basic form was further modified by slightly rounding the contact end in an effort to insure more intimate contact with the soil and finally by placing a Bakelite pointed tip on the contact end of the cell This later modification allowed the cell to measure only the moisture characteristics of the soil adjacent to the cell rather than including the soil in contact with the bottom which soil may have been disturbed during insertion of the cell None of these variations significantly affected the operation of the cell

Concurrently with these cells a design was tested in which no direct support for the heater coil was used During fabrication the coil was wound on a mandrel, cemented, and removed from the mandrel The Thermistor Type 17-A was centered in the coil, the assembly held rigid by clamps, and the Wood's metal cast around it In other

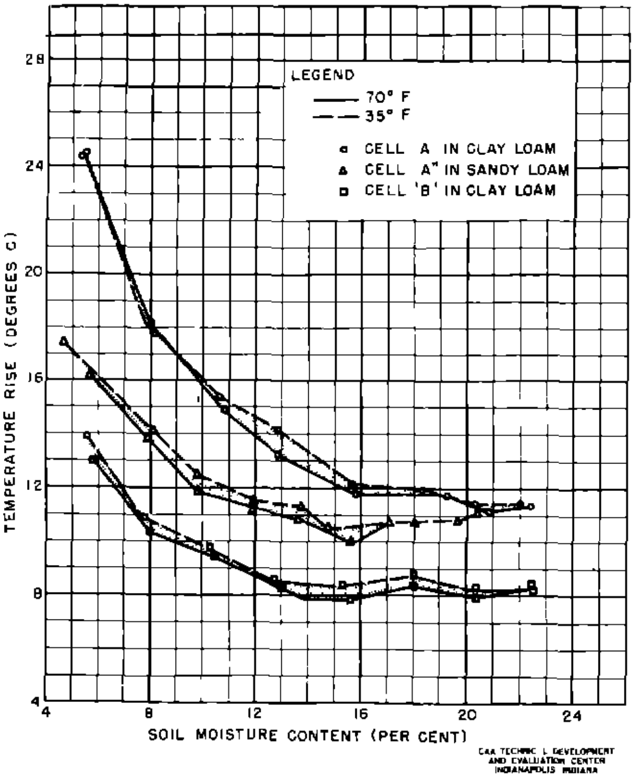


Fig 11 Operating Characteristics of Typical Wood's Metal Direct Contact Cells

respects the cell was constructed the same as that using the copper tube coil support Although the performance of this cell was satisfactory, it did not offer sufficient improvement over other designs to warrant the additional work required for its proper fabrication

Fig 11 presents data which can be considered typical for the Wood's metal direct contact cell The curves show the relationships between the temperature rise of two forms of cells, during an energizing period of five minutes, and the corresponding moisture contents for sandy loam and clay loam soils tested at temperatures of 35 and 70° F Cell A was the form in which no heater coil support was used, and Cell B was the form in which the coil was wound on a copper tube The tests were conducted by inserting the cells into laboratory soil samples prepared at different moisture contents No tests were conducted in which the cells were read during continuous wetting or drying of the samples Each point on the curve represents an average value obtained from three or more individual cell readings

The results of these tests show that the cells performed satisfactorily when the soil moisture content did not exceed about 15 per cent Beyond this point the curves leveled off, the temperature rise showing no change with increasing moisture content This point of leveling off corresponded to that obtained when testing the cell in water

From the data it is further shown that the operation of the cells was not affected by soil temperature Within the limits of experimental error the 35 and 70° F curves compare quite favorably However, the operation of the cells was considerably influenced by the type of soil used The relative positions of the sandy loam and clay loam curves suggest that a family of curves would be obtained from testing a group of different soils and that the moisture cell would have to be calibrated for each type This could be done at the time of burying the cell by obtaining one point on the calibration curves and selecting the nearest established curve to that point

The difference between the positions of the curves for Cells A and B was due to differences in the construction of the cells The temperature rise of a cell during a given heating period varies, among other factors, with the mass of the cell Cell A was less massive than Cell B and had the higher temperature rise for a given moisture content

Although the Wood's metal form of direct contact cell was promising enough to warrant further study, it was not suitable in its present form for use over the range of moisture contents required for civil engineering purposes Therefore, a study was begun to evaluate an entirely new version of direct contact cell in which the thermal conductivity of the soil was utilized in a different way

THERMAL CONDUCTIVITY MOISTURE CELL

This design, which actually is another form of the direct contact cell, has been designated the "thermal conductivity" cell because a direct measurement of heat transmitted through soil is involved in its operation and calibration In the previously described cells, the residual heat remaining at the source after dissipation of applied heat into the surrounding soil was used as a means of moisture measurement With the thermal conductivity cell a portion of the soil to be tested is located between the heat source and the temperature measuring element

The cell is designed to enclose the soil sample within a hemispherical heat source The amount of heat reaching the

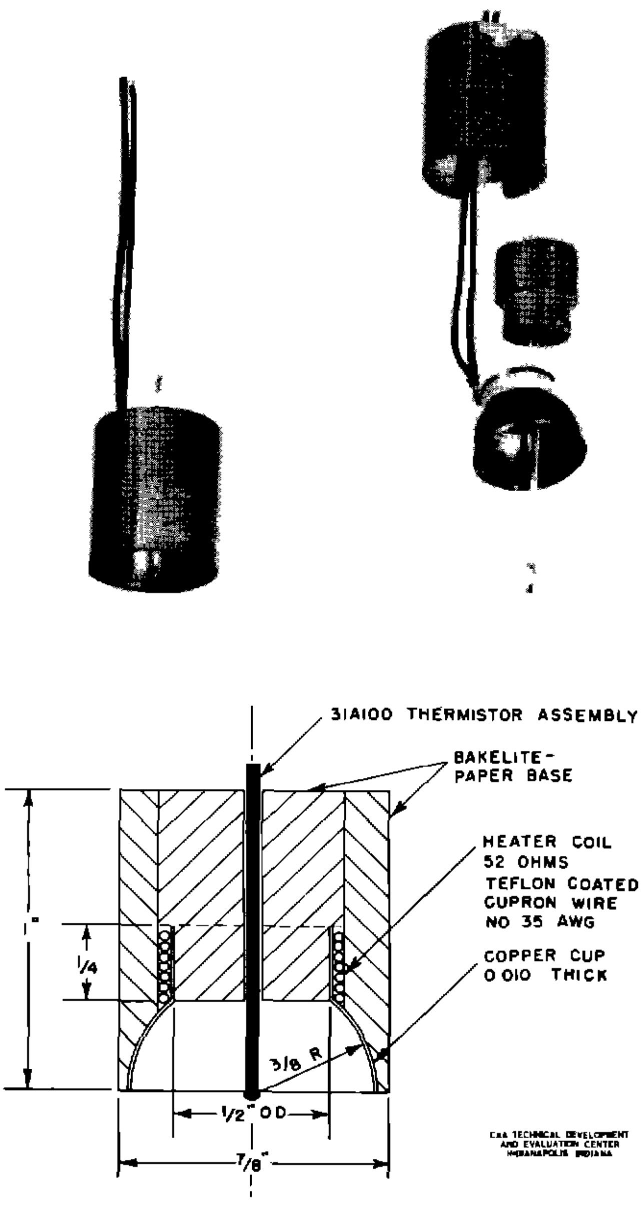


Fig 12 Thermal Conductivity Cells

temperature measuring element through the soil is dependent upon two factors the thermal conductivity of the particular soil lying between the heat source and temperature measuring element, and the amount of heat dissipated through the surrounding soil not enclosed by the cell Both of these factors are dependent upon the moisture content of the soil

Several forms of this cell were tested, all using the same type heater coil and thermistor but with the copper shells varying from 2 1/2 to 5/8 inches in diameter and 1 inch to 3/8 inch in depth

The most efficient design of the thermal conductivity cell was that in which the hemispherical cup was 3/4 inch in diameter and 1 inch high This cell, Fig 12, consisted of a hemispherical cup through the center of which a glass-enclosed Thermistor No. 31A100 projected. The heating coil was wound around an open tube projecting from the top of the cup The entire cell, except the bottom, was enclosed in Bakelite to obtain a high degree of heat insulation. The heater coil was the same as had been used successfully in the Wood's metal cells, Cupron wire coated with Teflon The glass-enclosed thermistor was used in order to eliminate the time-consuming insulating procedures previously required and to provide a more durable insulation for the thermistor, which in this cell is exposed directly to the soil

The usual laboratory tests were conducted with this cell, using the clay loam soil compacted to a density of 100 pounds per cubic foot Testing at 70 and 35° F showed the operation of the cells to be unaffected by temperature change Fig 13A shows an average curve of the temperature rise measured by four cells against corresponding moisture contents of the soil when the cells were tested at room temperature in individual soil samples at different moisture contents A five-minute heating period was used for the heater coil The data indicated that the cells were satisfactory when used in soil at moisture contents ranging from air dry condition to saturation, a range satisfactory for engineering use

A more severe test was next used in which the cells were placed in wet soil and read periodically during air drying and rewetting of the soil The operating characteristics of the cells under these conditions are shown in Fig 13B At the start of drying, the clay loam soil began to shrink away from the edge of the hemispherical cup, forming an air gap between the cell and the soil At moisture contents below the shrinkage limit of the soil the air gap remained constant, and a satisfactory curve was obtained for this portion of the test At the end of the drying cycle a sample was examined, and the air gap between the heater and the soil was clearly visible During rewetting, the calibration curve did not overlap the curve obtained during drying, this was probably due to a partial closing of the air gap by loose soil particles The difference between the curves for the clay loam in Figs 13A and 13B, relative to the heat rise for the same

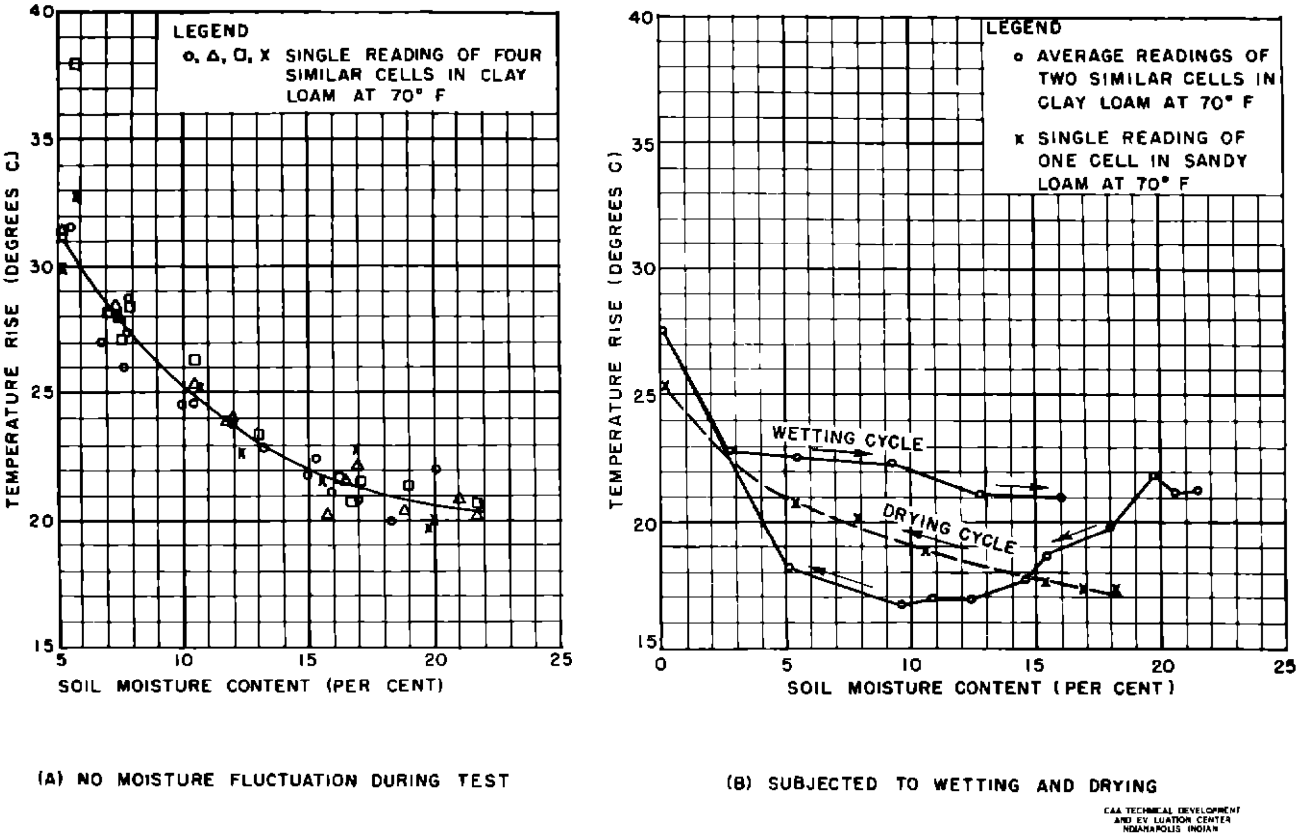


Fig 13 Operating Characteristics of the Thermal Conductivity Cell Under Different Test Conditions

moisture content, can be attributed to the poor contact between the cell and the soil during the drying cycle Where air gaps occur in connection with the thermal conductivity cell, lower than normal temperature rises are obtained

The curve obtained during the drying of the sandy loam was satisfactory Re-wetting tests were not run on this soil As in the case of the Wood's metal cell, the calibration curves for different soils were not the same

Although unsatisfactory under accelerated drying conditions, the thermal conductivity cell was the most satisfactory form of the heat diffusion type cell tested It proved to be sensitive over a higher range of moisture contents than was the Wood's metal cell Its faulty operation during accelerated drying might be due to the small size soil sample used or to the artificial laboratory procedures Under normal field conditions, where moisture differential and rate of change are relatively low and a large volume of soil is involved, it is possible that any soil movement due to moisture change would be too small to affect moisture cell operations

In its present form the thermal conductivity cell is of extremely delicate construction Considerable care in handling would be required were it to be used in field testing

CONCLUSIONS

1 Several soil moisture measuring devices of the heat diffusion type have been developed which, although not entirely satisfactory under all conditions of soil moisture, represent substantial progress toward the ultimate development of a satisfactory moisture cell.

2 The data obtained with the more promising cells proved that the principle of utilizing the heat conductivity of a soil as a measure of its moisture content is sound and that structurally suitable cells can be fabricated The problem of obtaining good thermal relationship between the electrical elements of the cell, and of successfully waterproofing them against soil moisture under the combined action of hydrostatic head and weathering, has been largely

overcome

3 A porous block form of cell, in which a porous medium was placed between the soil and the electrical elements of the cell, was not satisfactory except under specific soil conditions Its operation was considerably affected by soil composition, ambient temperature conditions, and individual cell characteristics, indicating that a separately calibrated block would be required for each soil condition encountered

4 A direct contact form of cell, in which the electrical elements were cast in Wood's metal and the unit placed in direct contact with the soil, performed satisfactorily at soil moisture contents below approximately the shrinkage limit of the soil Above this point the cell did not respond to moisture changes and, in some cases, could not maintain intimate contact with the soil

5 A thermal conductivity form of cell, in which the heating and temperature measuring elements were separated by the soil, was the most satisfactory cell tested However, its performance was erratic, when tested with plastic soils under accelerated laboratory drying conditions, because of shrinkage of the soil away from the cell

6 It is believed that both the Wood's metal direct contact cell and the thermal conductivity cell should be tested more extensively, especially under field conditions and with a large number of different soil types

7 For any cell that might be used, it will be necessary that it be calibrated for different soils and densities The exact procedure for doing this would depend upon the final form and characteristics of the cell but would probably involve the development of a family of curves suited to the particular cells being used At the time of burying the cell, a point on the calibration curve could be determined from which the curve nearest to the calibration point would be selected

8 During this study there has been developed a considerable amount of equipment and information, some of which may be applicable to problems encountered in other than civil engineering fields

GPO 81 104145