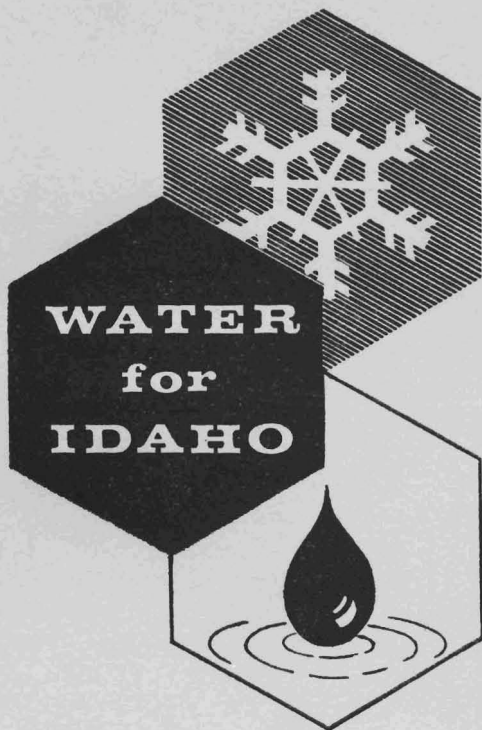


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**Research Technical Completion Report
Project A-019-IDA**



**Studies of
Methods of
Soil Water Determination**

Project Investigator J. I. Hagen

Water Resources Research Institute
University of Idaho
Moscow, Idaho
June, 1968

RESEARCH TECHNICAL COMPLETION REPORT

PROJECT A-019-IDA

Studies on Methods of
Soil Water Determination

Principal Investigator - J. I. Hagen
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Moscow, Idaho

Period of Project - July, 1966 to June, 1968

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ABSTRACT

The work reported was undertaken with the intent to develop a more reliable instrument initially for remote site operation. A survey of the literature led to the selection of four fields of study: streaming potential, thermal conductivity and specific heat, absorption of infrared radiation by moist soil, and some adaptation of the principle of nuclear magnetic resonance.

Experimentation revealed that the factors controlling streaming potential were so diverse that isolation of soil moisture or moisture flow variables was not feasible in field applications.

Extensive laboratory testing of an original thermal measuring device showed that this principle could be successfully and reliably used in certain ambient temperature ranges. The data also revealed that, when soil is partially frozen at 32°F, information could be derived on the percentage of the soil water in the frozen state, provided the soil moisture content was known.

Certain wavelengths in the infrared spectrum are readily absorbed by moisture in the soil. A prototype instrument which utilizes this phenomenon was fabricated. Certain problems in packaging the unit were encountered, but preliminary experimentation assured that this measuring technique shows promise and could be further developed.

Nuclear magnetic resonance may be discounted as a means of measuring soil moisture content because of fundamental difficulties.

PART IBACKGROUND DISCUSSIONA. INTRODUCTION

In many practical situations, it is desirable to know something about the water content of soils. Agriculturists wish to know when and how much to irrigate, how much runoff they can expect, and the depth of the water table. Foresters and conservationists need soil moisture information to be able to predict erosional runoff, flooding conditions, and water storage. When soil is used as a construction material, the moisture content affects its compaction, bearing value, shear strength, and other structural properties. Rational design, therefore, requires knowledge of soil moisture content. Water seepage beneath roadbeds causes stripping of asphalt surfaces. This phenomenon is not fully understood because of a lack of knowledge of the movement of water beneath the earth's surface.

The lack of knowledge in the field of soil moisture can be attributed to a lack of adequate means of measurement rather than a lack of interest. Need for a reliable and practical instrument for measuring soil water has existed for the better part of the past century. Almost all obvious forms of physical phenomena pertaining to soil moisture have been investigated in an attempt to realize this instrumentation. These effects have met questionable success. Devices fulfilling the requirements of some specific applications have been designed. Soil scientists generally agree, however, that improved instrumentation is needed.

The purpose of the research herein reported was to attempt to improve upon present soil moisture instrumentation, by perfecting present methods or by introducing new ones. The basic soil fundamentals which pertain to measurement of moisture content are discussed, and desirable qualities of a general soil moisture measuring device are listed.

The theoretical and practical problems encountered in this work together with the methods and results of experimental testing are discussed and conclusions are drawn.

In addition to the Principal Investigator three other people were technically associated with this project:

1. Mr. Howard Eugene Hite, graduate research assistant (spring 1967 - spring 1968), and candidate for the M.S. degree in Electrical Engineering.
2. Mr. N.S. Harasprasad, candidate for the M.S. in Electrical Engineering (summer 1967 - spring 1968).
3. Mr. Roger Lackey, Senior in Electrical Engineering.

FUNDAMENTAL CONSIDERATIONS

Soil is defined as the loose surface material of the earth in which plants grow. It has been formed from the disintegration of the lithosphere and the decomposition of plant life. It is composed mostly of silicon and oxygen, but contains aluminum, calcium, carbon, iron, sodium, and other elements in small proportions. Soil is extremely heterogeneous, since the factors which formed the soil differ from place to place. Therefore, any generalizations from a study of the characteristics of a certain soil type may not be valid for another type.

As might be expected, the chemical makeup of soils also varies from one location to another. Alkali metals found in some locations tend to form relatively water-soluble carbonates, which may be leached (washed from the soil) by heavy rains. The composition of a soil therefore may vary with time at a given location.

Close observation of any sample of soil demonstrates that it is not a connected mass, but that it is composed of millions of tiny particles. More difficult to observe are the tiny spaces, or voids, between the particles. The size of the individual particles also influences the physical and chemical properties of the soil. Physical and chemical activities usually take place on the surfaces of the particles, and the total particle surface area of a given volume of soil increases as the particle size decreases. Since the texture, or proportions of different sized particles, also influences the total volume of the voids, it is one of the most important soil parameters.

As water is added to a dry soil, it first forms a film around the soil particles. The remainder of the void spaces are then filled.

The ratio of the void volume to the total volume of the soil mass is the porosity. The degree of saturation, S , is the ratio of the volume of voids filled with water to the total volume of the voids. Like the porosity, the degree of saturation is usually stated as a per cent.

The ability of water to travel through soil is determined by the size of the individual particles and voids, rather than by the porosity. Film water, in the order of a few molecules thick, is held by very strong tensile forces to the soil particles, and will move from particle to particle only very slowly. The remainder of the water in soil moves more freely. The further a given water molecule is from a soil particle, the more easily it can move to an adjacent void. It follows that water moves more freely in coarse-textured soils such as sands than in fine-textured clays.

Water is held to the soil particles by a definite and measurable potential and is usually taken to be negative. Moisture can be removed from the soil by any device which exerts a more negative potential, or vacuum, on the water.

Soil moisture may also be removed from the soil by any powerful chemical dehydrating agent, or by raising the temperature above 105°C for a few hours. Care must be taken not to burn off or oxidize organic constituents of the soil during dehydration. Chemical decomposition of the soil must also be avoided under most applications which necessitate drying the soil.

Dry soil is a poor electrical conductor. Water in the soil readily dissolves enough mineral matter to become an electrolyte, thereby increasing the conductivity of the soil. This conductivity is related to the ionic content of the soil moisture as well as to the amount of water present.

The specific heat of mineral soils is about 0.2, hence any addition of water tends to increase the specific heat of the soil mass measurably. Thermal conductivity of the mass also increases, since the water creates larger contact areas between particles and fills in the insulating voids.

There are several methods of expressing soil moisture, each with a different application. The most common are:

1. the energy condition of the soil water.
2. the amount of water in a given volume of soil.
3. the amount of water in a given mass of soil.

For the present purpose the third method will be used, and the per cent soil moisture will be defined as

$$\text{per cent soil moisture} = \frac{\text{weight of water in soil}}{\text{weight of dry soil}} \times 100.$$

The quantity "per cent soil moisture" is used many times in the text of this report and will be designated "PCM".

DESIRABLE CHARACTERISTICS OF ASOIL MOISTURE SENSOR

It is desirable that the instrument be accurate and dependable, and must give reproducible results. For most applications an accuracy of $\pm 1\%$ soil moisture is acceptable. Determinations should require no longer than about 15 minutes to be most useful in construction applications. A portable instrument would be best here, and it should be simple enough for a layman to operate.

Many times it is desired to monitor the moisture at a given point continuously and automatically throughout a long period of time, i.e. runoff predictions at remote sites, and automatic irrigation systems. A sensor for such applications should not disturb the soil while operating, and must be able to measure the same position many times without changing the surrounding area. It must be durable and not subject to corrosion or weathering. Power consumption, if any, must be kept at a minimum, since batteries may be the only source of power. Output data should be in a form that can easily be telemetered or used to control electrical or mechanical systems.

The instrument should work in any soil type without frequent recalibration. It should sample a large enough volume of soil to give readings representative of the surrounding area. Of course, such a device should be inexpensive and simple to construct, but for some permanent applications these may be secondary requirements.

A method for measuring soil moisture need not possess every quality listed here to be useful. Rather, these qualities should be used as guides when evaluating a proposed measuring method.

B. CHOICE OF FIELDS OF STUDY

After a lengthy and detailed study of the available literature on soil moisture instrumentation, a decision was required as to which methods seemed to warrant more developmental research. The reasons for the elimination of many methods and the final acceptance for study of others will now be stated. A complete listing of all references consulted is given at the end of this report.

Gravimetric methods are generally time-consuming and are destructive in that a given sample may be used only once. Human presence is required and the method is not suited to automatic or remote-controlled operation. This method is generally accepted, and much literature is available on the subject. Although this method will be used for calibration and/or checking accuracy, it warrants no further study here.

Chemical methods are destructive, usually necessitate delicate or expensive equipment, require human presence, and are not suited to remote-site automatic operation. While this field is so broad that further study may be desirable, other methods presently show more promise.

Tension methods have an inherent delay in response to quick changes of moisture content which render them unsuitable to many applications. They are undependable for low moisture contents.

Penetrometers will probably never be accurate because of variable soil densities encountered in the field.

Lysimeter weighing methods are generally acceptable in experiments on soil masses, but do not apply here.

Nuclear methods may be the most promising, but they have been eliminated here because excellent measuring units are already on the market. These units are too costly to procure for purely observational purposes, and a substantial understanding of the inherent dangers of radiation usage would be required by a potential user.

Much has been published on electrical conduction methods and it would appear that little remains to be said. Capacitance measurements and humidity detection in buried air pockets were studied by Brown (26) with no success. Radio frequency absorption and acoustical attenuation suggest further examination, but are not included here because of the limited time available for this study.

With the recent availability of suitable, inexpensive detectors, infrared reflection measurements have become feasible. While it has been demonstrated that infrared reflection from soil is related to soil moisture content, no efforts to implement this phenomenon have been found in the literature. Research in this direction is therefore suggested.

Several authors have recommended further work on the thermal conductivity method. A comparatively small amount of literature is, however, available on this subject. This method is easily adaptable to automatic, remote operation, since it is non-destructive and can easily be used with electronic telemetering equipment. This method has therefore been chosen for particular emphasis.

Whenever a liquid is drawn through a substance by osmotic (or other) pressure, an electrical potential is induced at the boundaries of the barrier substance. This potential is called streaming potential. A study of the feasibility of utilizing this potential in soil moisture measurements is discussed in this report.

Nuclear magnetic resonance apparatus is being used regularly for moisture measurements in organic materials. While this method would require some elaborate apparatus, it would seem, other factors equal, that at least an auger boring could be simply and quickly measured. Mr. Harasprasad investigated this possibility and the findings are examined in a later section.

PART IISTUDIES AND EXPERIMENTAL
WORK PERFORMEDA. STREAMING AND ZETA POTENTIALS

Whenever a liquid is forced through a porous material, such as a clay diaphragm or capillary tube, a difference in electrical potential can be observed between the two ends of each conducting pore. This potential, known as the streaming potential, is proportional to the pressure forcing the movement of the liquid, but is independent of the surface area on which the pressure acts. Forcing an electric current to flow through a clay diaphragm causes a liquid mass to be transported through the diaphragm, and flow can be reversed simply by reversing the polarization of impressed voltage.

The potential involved in electro-osmosis and allied phenomena between the fixed and freely mobile portions is called zeta potential. Zeta potential is a function of the fixed surface and of the ionic content of the mobile substance (39). In any measurement of streaming potential, care must be taken to avoid the interaction of the zeta potential with the streaming potential.

Since the streaming potential is a function of the mass of liquid flowing through a porous substance, such as clay, it may be possible to determine the quantity of water flow in a porous solid by measuring the streaming potential. A variant of this might conceivably be where the potential is measured by distilled water being drawn through a separate porous media somewhat in a manner analogous to the tensiometer.

Test cells were fabricated from small cylindrical porous cups. Wire mesh electrodes were placed against the inside the outside of the cups. Electrodes of brass, bronze, and stainless steel were tried. Copper wire, soldered to the electrodes with lead-tin solder, connected the cells to measuring equipment.

A General Radio D-C Amplifier and Electrometer, Type 1230-A, was used to measure potentials between the electrodes. This instrument was equipped with variable input impedances ranging to infinity and with output terminals for connections to recording equipment.

A dry test cell was suspended in a large, empty beaker. Tap water was poured into the cell, and a voltage immediately appeared between electrodes. This voltage decreased as the porous cup was saturated. In most cases the polarity of the induced voltage actually reversed for a short period. This phenomenon has not yet been explained. In all cases the voltage between the electrodes decayed to a value very nearly the same as the potential before the addition of water.

The experiment was repeated with dry sand within the beaker outside the test cell. The potential varied in much the same manner, except the time required for the potential to reach its initial (dry) value was much longer, probably due to the time required for the flow of water from the cell to saturate the surrounding sand. Both experiments were repeated with the water added to the outside of the cup, resulting in similar potentials but with the opposite polarities.

In all experimentation, plots of potential as a function of time were obtained using a Honeywell 500 x-y recorder. The shape of the curves obtained were similar, but the magnitude varied from trial to trial. The potentials were very sensitive to vibration and shock. After over one hundred tests, no correlation could be observed between rate of flow of water through the walls of the cup and the potential magnitude. Apparently, so many uncontrollable variables exist that it is impossible to isolate one, such as liquid flow, for study without highly sophisticated equipment.

It appears safe to conclude that measurement of streaming potentials for determination of soil moisture does not appear feasible for field applications.

B. DEVELOPMENT OF A SYSTEM FOR INFRARED MEASUREMENT OF SOIL MOISTURE

Water specifically absorbs energy at 1.38, 1.9, 2.7, 3.2, and 6.2 μ . (45) The absorption bands at 1.38 and 1.9 μ have been shown to represent overtones of the fundamental frequencies at which water molecules vibrate. The other absorption bands have not yet been identified (24). Soil is opaque to frequencies in the vicinity of visible light, that is, little or no transmission will occur. All electromagnetic energy in this range falling upon a sample of soil is either reflected or absorbed. Water in the soil causes increased absorption, as evidenced by the soil becoming dark in color. This effect is especially pronounced at 1.9 μ . Results of studies on the energy reflected from "Newtonia silt loam" as reported by Bowers (24) are summarized in figures 2 and 3.

As a result of the literature search and evaluation of the materials available for experimentation, the 1.9 μ absorption band of water was chosen for use in an experimental soil moisture measuring device. Ordinary glass is opaque to wavelengths greater than 2.2 μ , and since the special optics required for this range were not readily available, experimentation was necessarily limited to the very near infrared, that is, wavelengths very near visible light.

In order to isolate the desired 1.9 μ energy, it was necessary to filter out other wavelengths. Figure 2 indicates that for highest sensitivity, a very narrow bandwidth centered at 1.9 μ would be desirable. Spike filters having a bandwidth of less than 0.1 are available in the near IR region, but their cost (\$500 to \$2000 per unit) was considered prohibitive in this study. A relatively inexpensive (\$6.00 per unit) wide band filter was chosen. Available

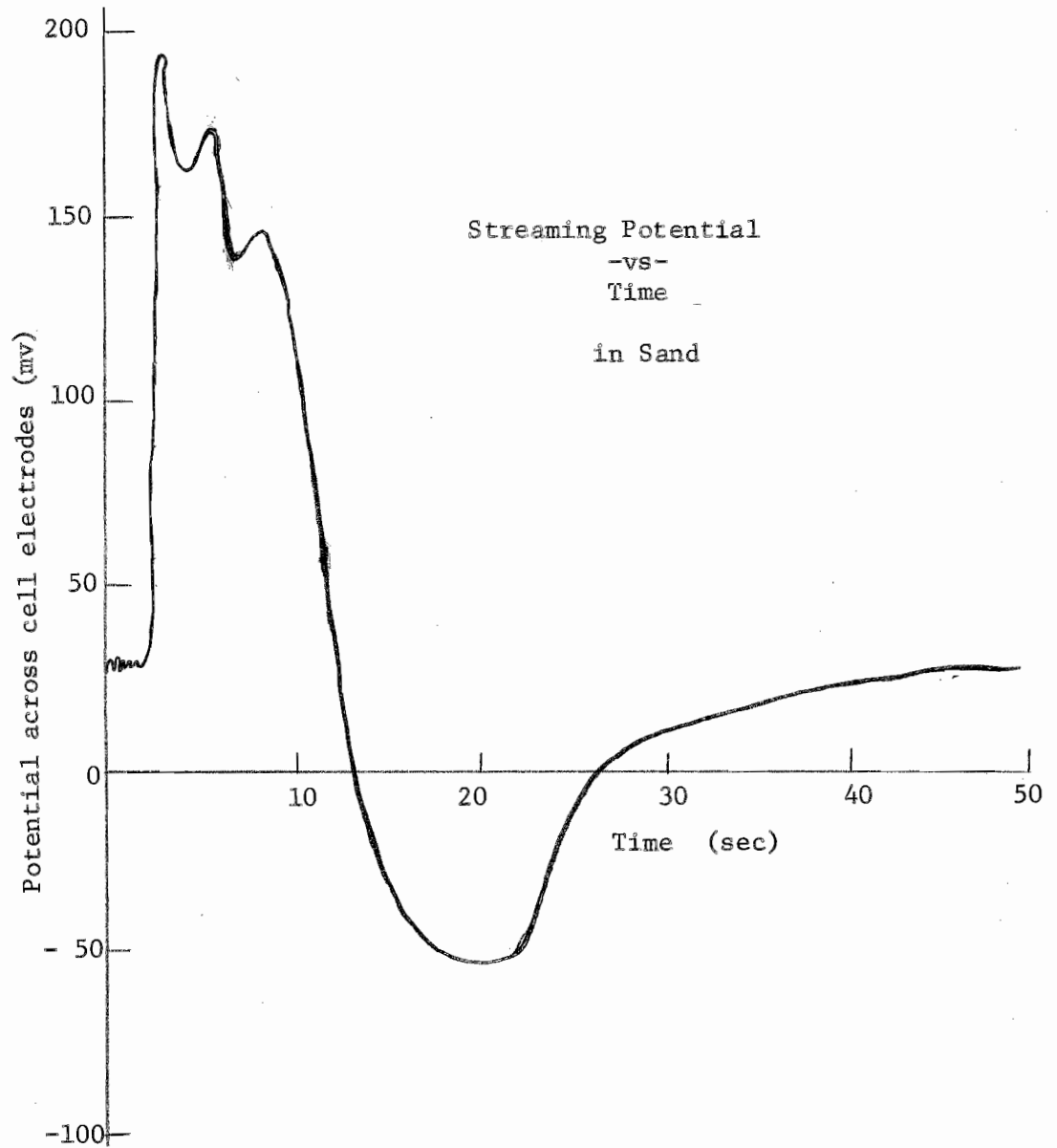


Figure 1. Typical plot of streaming potential-vs-time in the experimental cells with the addition of water.

from Corning Laboratory Products, the type 7-56 IR Bandpass filter transmits wavelengths from 1.0 to 2.75 μ . Longer wavelengths were further filtered by a crown glass window and by the glass bulb which protects the filament IR source. Glass does not transmit wavelengths above 2.2 μ . The transmitted wavelengths of the glass-filter combination are therefore in the range 1.0 to 2.2 μ .

Spectrophotometry studies indicated a 6.0v flashlight bulb, type GE-27 could be used as a source of IR energy in the desired range, especially if it were operated at a slightly reduced voltage. The spectral emission of this bulb at 5.5v is shown in figure 4.

Parameters considered in the selection of a detector were frequency response, temperature characteristics, power requirements, physical size, and the associated equipment and circuitry required. Available detectors with the necessary frequency response included: lead sulfide, indium arsenide, indium antimonide, and doped germanium photoconductive detectors; thermopiles; thermocouples; photomultipliers; and photodiodes. Photoconductive detectors require cooling for adequate sensitivity. Systems using these detectors usually include some means for holding the detector temperature near that of liquid nitrogen. Thermo-electric devices are available for this purpose, but their power requirements was considered prohibitive for battery operation at remote stations. Photomultiplier tubes would require a high voltage supply. These are inefficient and would result in excessive battery drain. Solid-state photodiode devices possess the desired frequency, power and size characteristics and are readily compatible with transistorized circuitry.

The Texas Instruments type H-38 photodiode is very sensitive in the desired IR region. The operational principle is similar to that of a transistor whose base current results from the bombardment of an exposed base region by electromagnetic waves. This device was available from the Department of Electrical Engineering as part of Texas Instruments' Educational Gift Plan. Testing with a bias potential of 6.0v impressed from source to drain indicated that the drain current was a function of the IR energy falling upon its sensitive window. The drain current varied from much less than 1.0 microamps in dark conditions to 20 microamps under bright incandescent lights.

Once the detector had been chosen, a means was required for converting the extremely small detector currents into a more useful quantity. After some considerable examination of conventional means of doing this, it was found that a satisfactory approach was to use an astable multivibrator configuration in which one time period would be determined by the photodiode current. The circuit is shown in figure 5. Transistors Q₁ and Q₂ are the standard multivibrator switching transistors. Capacitor C₁ is charged by the collector current of Q₅ during "OFF" time. This current is controlled by the much smaller current through the base of Q₅ and the photodiode. A constant voltage of 5.5v remains across the photodiode regardless of the current through it. Diode D₁ was added to protect Q₅ from positive-going noise signals which might destroy the fragile base-emitter junction.

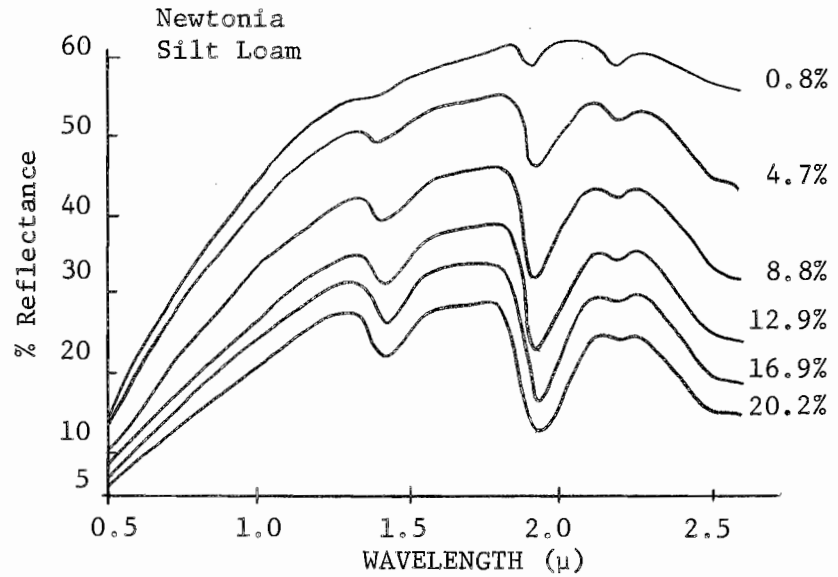


Figure 2. Per cent reflectance-vs-wavelength of incident radiation at various moisture contents (moisture contents indicated directly above each curve). (24)

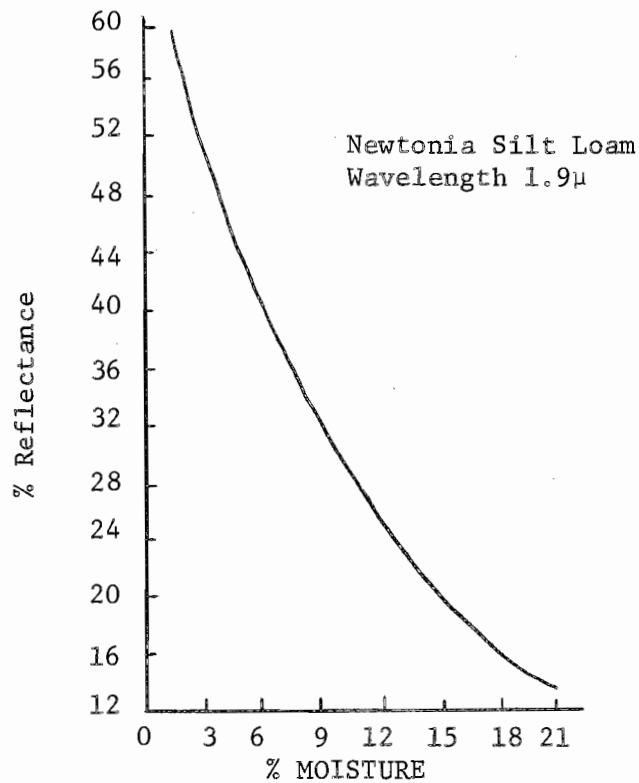


Figure 3. Per cent reflectance-vs-surface moisture content for incident radiant energy of 1.9 μ . (24)

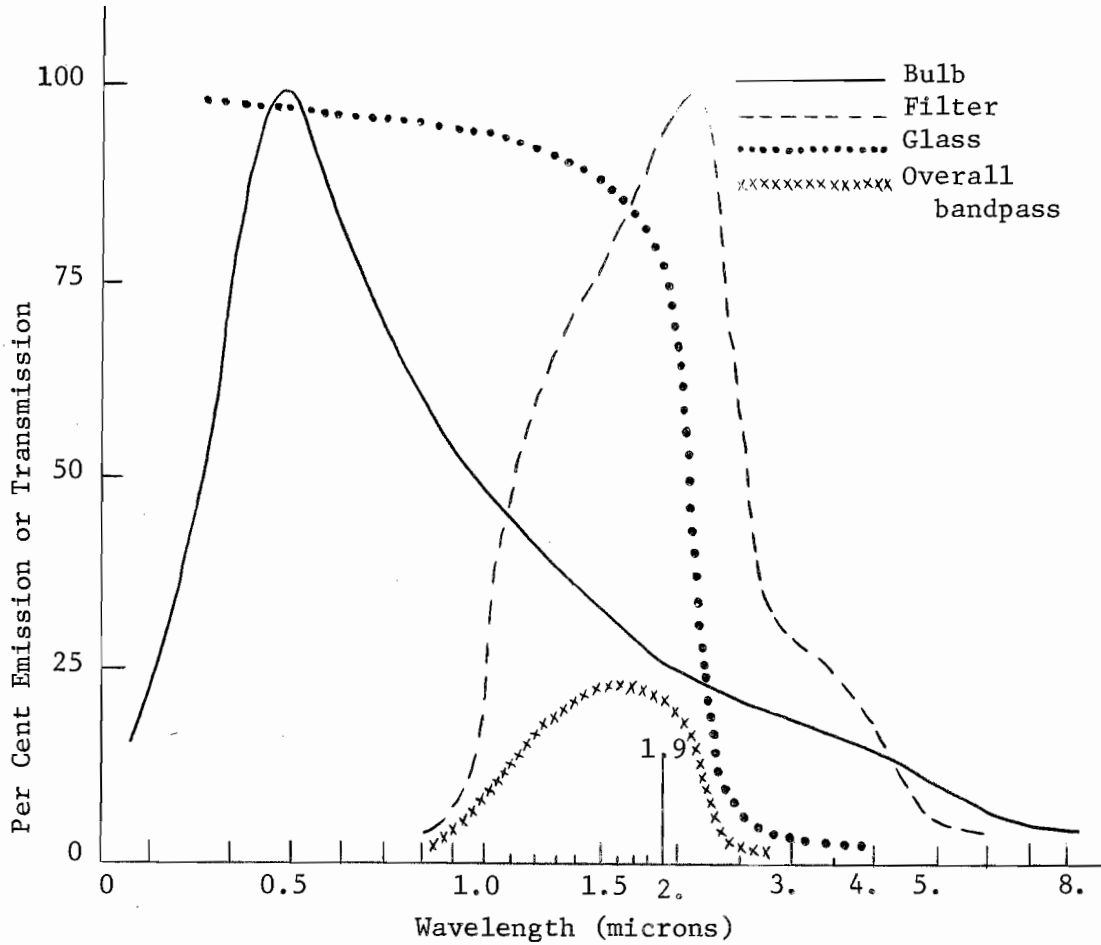


Figure 4. Spectral emission characteristics of the GE-27 incandescent bulb operated at 5.5v, and transmission characteristics of crown glass and the Corning Type 7-56 IR filter, showing the resultant overall bandpass of the IR source system.

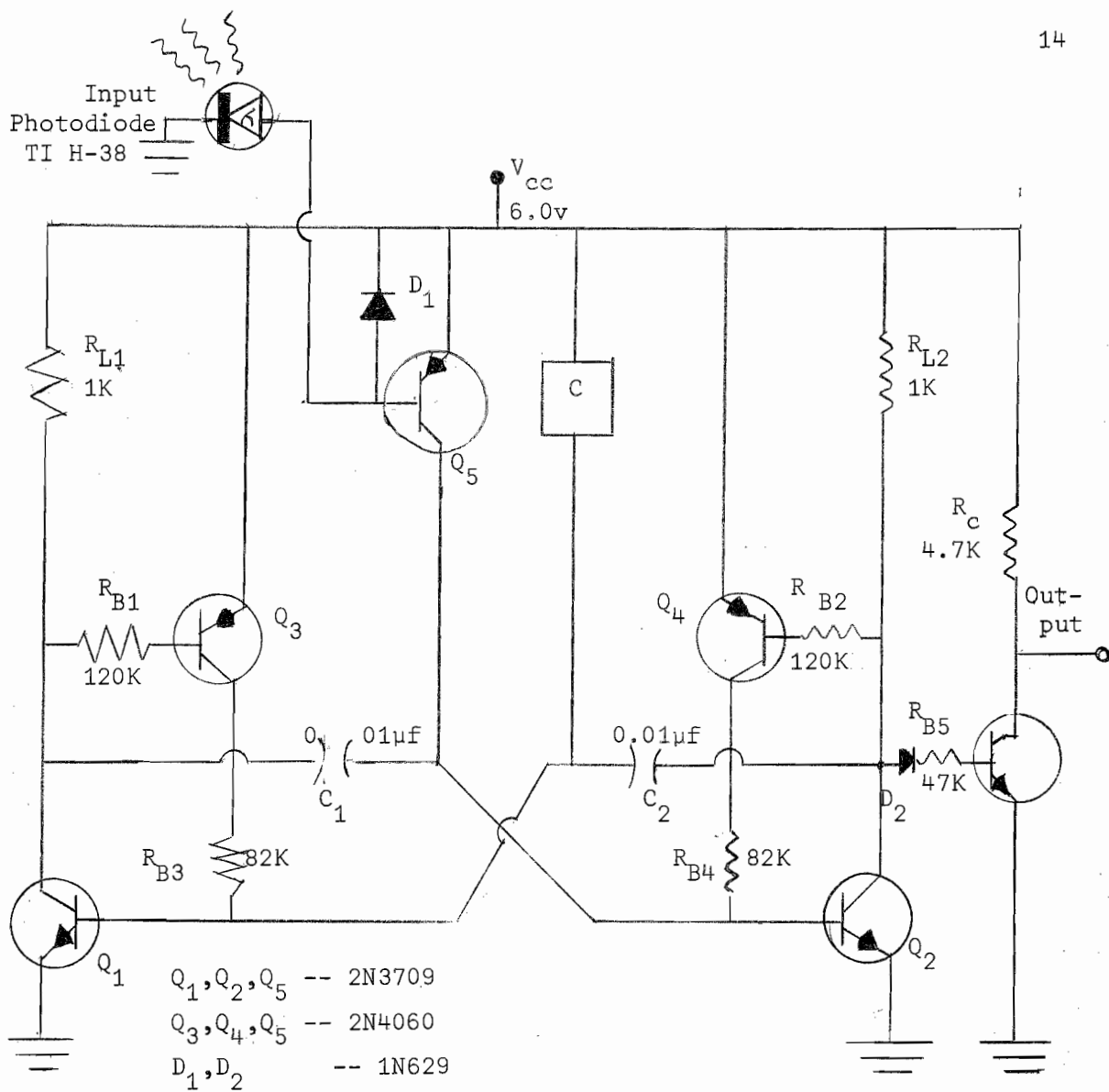


Figure 5. Astable Multivibrator used with Photodiode in the IR moisture detector.

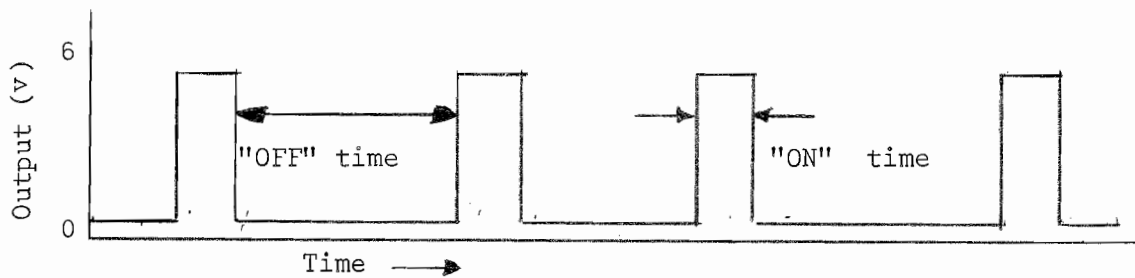


Figure 5a. Multivibrator output waveform.

If the input level of the IR to the detector is small, the collector current of Q_5 may not be sufficient to hold Q_2 on while C_2 is charging. Transistor Q_4 was added to provide sufficient base current to Q_2 to hold it saturated even under dark conditions. Transistor Q_3 similarly holds Q_1 saturated properly if the current through a temperature compensating network, C, is small.

The temperature compensating network was not worked out. Its function would be to adjust the "ON" time with temperature so that sensitivity variations of the detector would be cancelled. Thermistors can be used as temperature sensors in the network. Since temperature response curves were not available for the detector, the desired function of the compensating network would need to be determined experimentally. Lacking this, a 200 K resistor was used for C. Transistor Q_6 operates as a buffer amplifier to prevent output circuitry from loading the astable.

The multivibrator circuitry was first evaluated by placing the detector and a point source on an optical bench. The period of the multivibrator was shown to vary with the intensity of light incident on the detector and was sensitive to intensities as small as 1% of the maximum intensity measurable. This range appeared adequate.

A simple parabolic reflector of the type commonly found in flashlights was bisected symmetrically through its focal axis. One section served to concentrate radiation from the bulb source positioned at its focal point onto a soil sample. The IR bandpass filter was placed directly in front of the source reflector to eliminate unwanted wavelengths. Reflected energy was integrated and focused on the detector by the other half of the reflector. The two sections were separated by a small sheet of 1/4 in. plexiglas. A brass shield prevented direct transmission from source to detector.

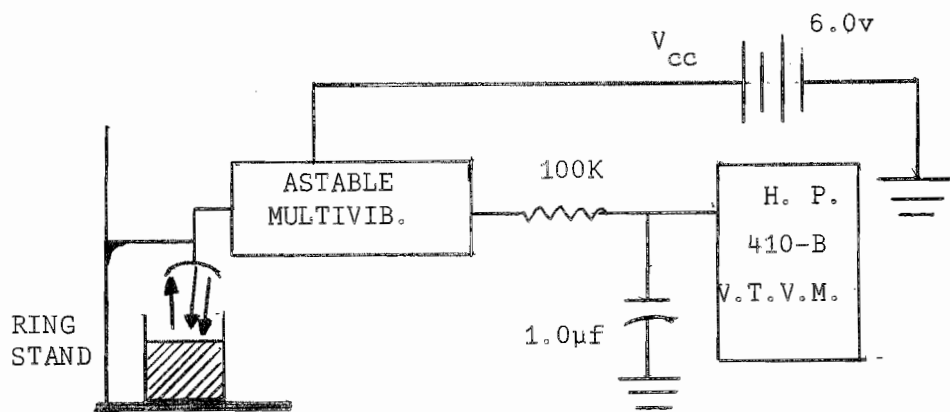
The astable multivibrator circuit was fabricated on a semi-circular vector-board and mounted directly behind the reflector assembly. The detector, which is situated at the focal point of one section of the reflector, was connected to the multivibrator circuit by a short length of 0.07 in. diameter coaxial cable.

For experimentation the system was mounted on a ring stand with a burette clamp and positioned 1.5 in. above prepared sand samples of known moisture content. The output wave form was monitored on a Tektronic type 545 oscilloscope, while average value of the output voltage was read on an H.P. 410-B vacuum tube voltmeter. Results of testing are summarized in table 1 and illustrated in figure 6.

To protect the instrument during field testing, a brass canister was fabricated to enclose the instrument package and battery power source. The canister was hermetically sealed using silicon rubber. A connector at the top of the canister allowed external monitoring of the enclosed circuitry. Soil samples were observed through a crown glass window at the bottom of the unit. This window, which was placed in direct contact with the soil sample, is necessary since an air space in contact with the soil would seriously alter the moisture

Per Cent Moisture	Random Initial Position	Sample Rotated 90°	Sample Rotated 180°	Sample Rotated 270°	Average
0	1.16	1.17	1.18	1.17	1.170
4	0.91	0.90	0.89	0.93	0.908
8	0.86	0.87	0.89	0.86	0.870
12 (1)	0.81	0.83	0.81	0.80	0.813
12 (2)	0.77	0.79	0.80	0.79	0.788
16	0.72	0.70	0.72	0.73	0.718
20	0.63	0.64	0.64	0.63	0.635
24	0.59	0.58	0.58	0.59	0.585

Table 1. Results of ring stand test on IR moisture detector. Readings are in volts. The circuit is shown in figure 6.



EQUIPMENT SET-UP
FOR TESTING
IR MOISTURE METER

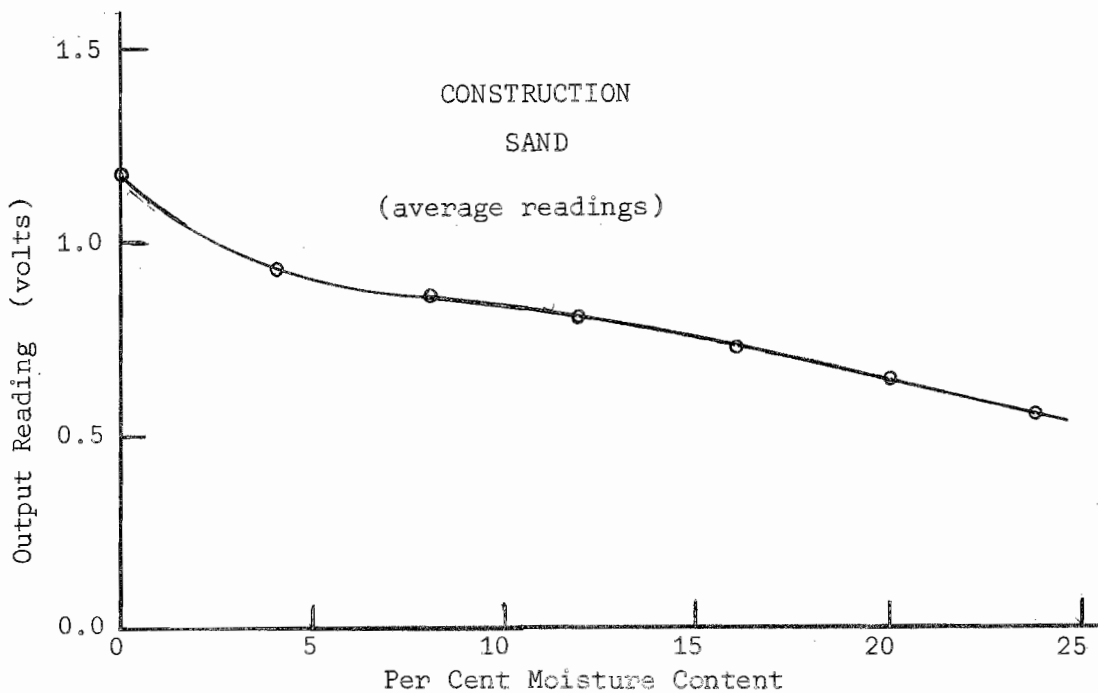


Figure 6. Output direct current voltage-vs-moisture content for IR moisture detector in construction sand.

content reading of the soil surface because of evaporation into the space introduced. The window also prevents moisture from reaching the electronics package.

Considerable reflection from the inner face of the window greatly reduced sensitivity. Efforts to alleviate this condition by tilting the window so that the reflection from the glass was directed away from the detector, were somewhat successful. Magnesium fluoride non-reflective coatings on the inner face of the window have been suggested as a means of minimizing unwanted reflections. Filter optics might be used instead of a window with some advantage.

CONCLUSIONS AND RECOMMENDATIONS

The absorption of IR energy by moist soil is an indication of its moisture content. Data taken with inexpensive equipment have shown that a soil moisture measuring device which measures energy at certain wavelengths reflected from the soil is feasible. This type device would be especially valuable for measurement at remote sites. Special astable multivibrators controlled by photodiodes have been successfully designed to provide soil moisture information in a form which may be telemetered.

Further investigation of an IR moisture meter is warranted. The wavelength best suited for use is 1.9μ . Magnesium fluoride or similar coatings on glass should be studied as a possible means of filtering, since the transmission characteristics of the coatings are a function of coating thickness. Recently available solid state detectors should be investigated to determine whether these inexpensive devices will stand up under field use. The effect of the soil's texture, color, mineral content, ionic concentration, etc. on IR absorption must also be studied. Calibration curves will probably need to be prepared for different soil types.

In this report, the IR experimentation is discussed before the thermal probe development for sake of continuity. Chronologically, the IR studies occurred last, and the time available for research was limited.

C. USING THERMAL PRINCIPLES
FOR MEASURING SOIL MOISTURE CONTENT

1. Discussion

It is well known that the addition of water to a soil mass increases both the heat capacity* and the thermal conductivity. Here heat capacity is considered to be the amount of heat energy required to raise a unit volume of soil mass one temperature degree - the units are therefore cal/(cc)(°C). Heat capacity is equal to the specific heat times the density. For liquid water both the quantities are very nearly 1.0.

Before attempting to realize a PCM measuring device using the phenomenon of increasing heat capacity and thermal conductivity, a brief look at fundamentals will be instructive.

HEAT CAPACITY - Soil is composed of tiny particles and voids. The particles are often some combination of silicon and oxygen, which together make up 75% of the mass of the lithosphere (58). The voids may be filled with water or air, or occasionally some other fluid. Addition of water to a soil mass causes air to be driven out of the voids. Since the heat capacity of water is very much greater than that of air, the heat capacity of the soil mass increases measurably whenever the water content increases. The heat capacity of the solid particles in the soil is virtually unaffected by the presence of water.

Masonry (construction) sand was extensively used as a laboratory sample because the coarse texture allowed water to pass freely and minimized the time required for a capillary equilibrium to be reached after the addition of water. The sand available had a bulk density of 1.49 g/cc when vibrated for two minutes after drying for 24 hours at 105°C. At this compaction, the sand saturated at 28 PCM.

The specific volume of the dry sand is:

$$V_T = \frac{1}{1.49} = 0.671 \text{ cc/g.}$$

For each gram of dry sand, 0.28 g of water is required to fill the voids. If the density of water is assumed to be unity, then the volume of the voids is 0.28 cc for each gram of dry sand. The volume occupied by the particles is:

$$V_p = V_T - V_v = 0.671 - 0.280 = 0.391.$$

* As distinct from specific heat - a convenience for the present purpose.

The particle density is therefore $1.0/0.391 = 2.56$ g/cc. A check using Archimedes' Principle indicated a particle density of 2.57 g/cc. The density of pure quartz sand is known to be 2.59 - 2.66 g/cc. (30)

The porosity is given by:

$$\eta = \frac{V_v}{V_T} = \frac{0.280}{0.2671} = 41.7\%.$$

The volume occupied by the particles is $(1-\eta)$ or 58.3% of the total volume.

For simplicity, assume the particles to be similar to quartz in thermal properties. The specific heat of quartz is known to be 0.188 cal/g (31). In dry sand, the heat capacity of the air in the voids can be shown to be negligible. The heat capacity of dry sand may now be calculated.

$$\begin{aligned} \text{H.C.} &= (1-\eta) (\rho_p) (c_{p-p}) \\ &= (0.583) (2.56) (0.188) \\ &= 0.279 \text{ cal/(cc) } (^{\circ}\text{C}). \end{aligned}$$

Here H.C. is the heat capacity, η is the porosity, ρ_p is the particle density, and c_{p-p} is the specific heat of the particles.

For saturated sand, the heat content is:

$$\begin{aligned} \text{H.C.} &= (1-\eta) (\rho_p) (c_{p-p}) + (\eta) (\rho_w) (c_{p-w}) \\ &= (0.583) (2.56) (0.188) + (.417) (1.0) (1.0) \\ &= 0.279 + 0.417 \\ &= 0.696 \text{ cal/ (cc) } (^{\circ}\text{C}). \end{aligned}$$

The degree of saturation, S , is defined as the ratio of the volume of water present in a given soil mass to the volume of the voids. From the previous considerations, we note that heat capacity is a linear function of degree of saturation.

$$\begin{aligned} \text{H.C.} &= (1-\eta) (\rho_p) (c_{p-p}) + S (\eta) (\rho_w) (c_{p-w}) \\ &= 0.279 + (0.417) S \text{ cal/(cc) } (^{\circ}\text{C}). \end{aligned}$$

Samples of Roberts Fine Ash, a volcanic ash soil from the fertile potato lands of Southeastern Idaho, was also used for testing. This soil has a bulk density of 1.25 g/cc, and saturates at 43 PCM. Particle density was calculated to be 2.70 g/cc and the porosity, 53.8%. Using calculations similar to those above, the heat capacity becomes:

$$\text{H.C.} = 0.234 + (0.538) S \text{ cal/(cc) } (^{\circ}\text{C}).$$

THERMAL CONDUCTIVITY - Total thermal conduction is proportional to the area available for the transportation of heat energy. Consider two adjacent dry sand particles, one at a higher temperature than the other (figure 7).

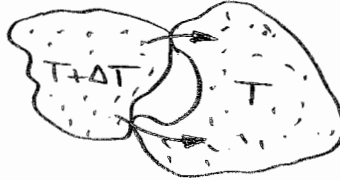


Figure 7. Adjacent sand particles showing heat conduction paths.

The contact area, through which heat energy is transmitted, is very small. The voids thus act as insulation.

If a small amount of water is added to the sand, a film forms around the particles (figure 8). The thermal conductivity of water is only one tenth that of quartz particles. Nevertheless, the heat

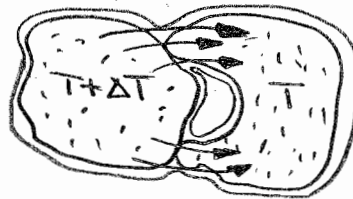


Figure 8. Adjacent sand particles with film water, showing increased heat conduction paths.

conducting area between the particles increases so drastically with the formation of interconnecting water films that the thermal conductivity of the whole soil mass is greatly increased.

Once good contact area between adjacent particles is established, further addition of water increases the thermal conductivity of the mass only by providing additional conducting paths of the relatively poor conductor, water. Shaw and Baver (53) found that the thermal conductivity-vs-soil moisture curves to be almost exponential for quartz sand and more linear for clay (figure 9).

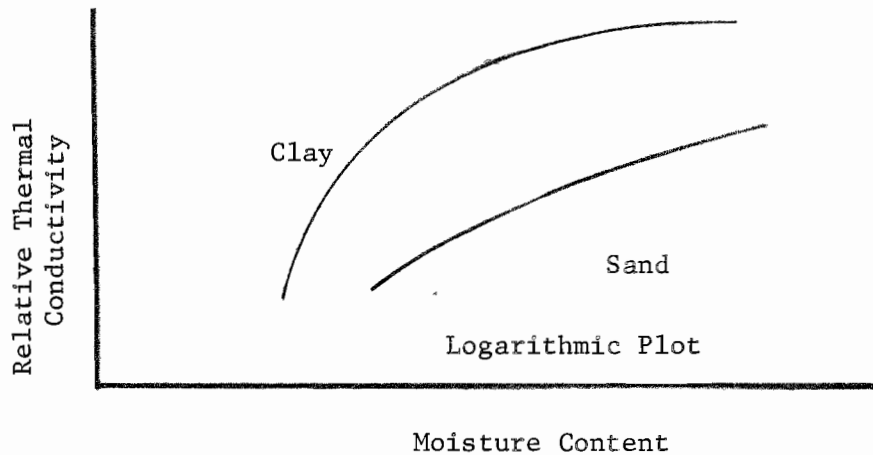


Figure 9. Shape of Conductivity-vs-soil moisture curve

The relationship between thermal conductivity and soil moisture is complicated by particle shape as well as texture, and must be determined experimentally for any given soil. The curve shape is general. Thermal conductivity increases with soil moisture while the rate of increase decreases at high moisture contents.

If a heat source is imbedded in an infinite, homogeneous substance initially at uniform temperature, and, after a time, the temperature at any point in the substance will be a function of the radial distance from the heat source, the thermal diffusivity, a , of the substance, and the time, measured from the moment when the heat source is turned on (44). The temperature will, in fact, be directly proportional to the diffusivity, which is given by

$$a = \frac{k}{\rho c_p} = \frac{k}{H.C.}$$

where k is the thermal conductivity, ρ is the density, c_p is the specific heat at constant pressure, and H.C. is the heat capacity as previously defined. The diffusivity can be expected to increase with additions of water at low moisture levels, and to become constant or even decrease at high moisture levels, where the slope of the thermal conductivity decreases.

Strangely, Aldous et.al. (1) reported that in a study of over fifty configurations, best results were obtained using instruments which measure relative diffusivity. These instruments, however, become less accurate at high soil moisture contents. A configuration which utilizes the constructive addition of the increase in heat capacity and the increase in thermal conductivity would seem intuitively more desirable.

SORPTION BLOCKS - The literature describes many attempts at imbedding thermal devices in gypsum, nylon, or fiberglass blocks of the general type used in electrical conductivity soil moisture measure devices. Aldous et.al. (2) considered the porous block type thermal device unsuitable because block moisture was not always representative of soil moisture. (A porous block will be nearly completely dehydrated in clay soils while moisture still exists in the clay.) A direct contact thermal device would seem superior to a device imbedded in a sorption block, provided constant contact could be maintained between the device and the surrounding soil.

Devices which provide a constant power to a heater, then measure the heat loss to the surrounding medium indirectly by observing the temperature rise of the heater, utilize changes in heat capacity and thermal conductivity in a constructive manner. Heat loss to the surrounding medium increases with any increase in the medium's heat capacity or its thermal conductivity.

A device which would compare the thermal characteristics of a constant, specified material with those of the surrounding medium (soil) was favored. The heated known material is placed in intimate contact with the soil, so that a relatively high soil thermal conductivity combined with a high heat capacity will cause much energy loss from the known material to occur. This energy loss can be measured indirectly by observing the temperature rise of the material some distance from the point of application of heat energy.

2. EXPERIMENTAL - While many problems and fine points were encountered in laboratory work, they are not all recorded in detail here. Rather, reference may be made to H.E. Hite's original thesis (42) from which most of this section is taken.

Data taking was extensively automated as indicated in the illustrations following. Environmental conditions were simulated and some considerable effort extended in order to have some ready control over variables such as moisture and temperature.

For much of the work, a 6 inch diameter by 45 inch long Plexiglass cylinder, fitted with ends, served as a sample chamber. This was mounted in a reconstructed upright freezer. A copper tubing helix for circulating hot or cold water ran through the chamber and connection to a vacuum pump was made through a 30 inch column of silica gel. Moisture was added through small holes with a hypodermic syringe, the holes then covered with tape. Most successful drying occurred by alternating vacuum with upward flow of air while circulating hot water in the coil. Nevertheless, gravity gradients of moisture concentration were troublesome.

In fine soils and clays, equilibrium conditions could not be established for several days.

Figure 10 illustrates a variant of one of the first experimental models. Representative data is given in the table and figure 12. A relatively constant heater current of 300 microamperes was supplied by placing a 100 K resistor in series with a 30v. supply. Connection to a chart recorder was made through an emitter follower (figure 11).

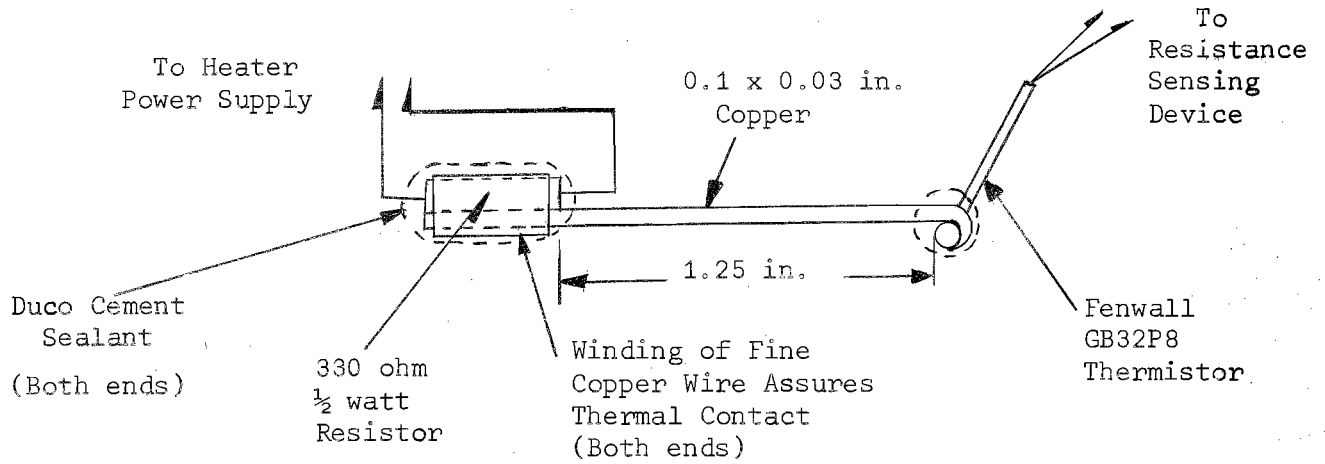


Figure 10. Construction drawing of the improved thermal moisture detector, Model No. 2.

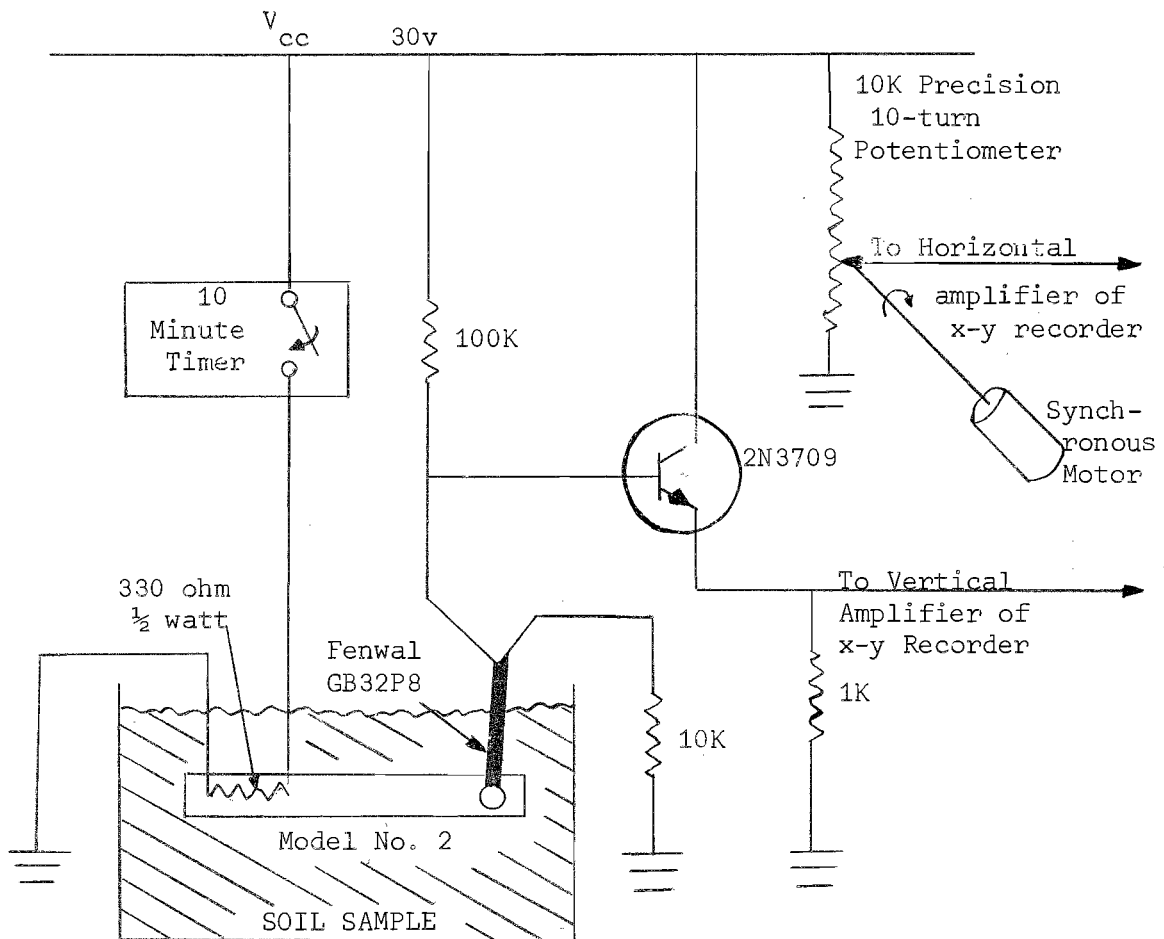


Figure 11. Automatic Data System used with Model No. 2.

PCM	#*	Temperature Rise (°F)							
		50 Sec	100 Sec	150 Sec	200 Sec	300 Sec	400 Sec	600 Sec	
0 %	8	Max	23	36	44	49	55	59	63
		Mean	20.8	35.4	43.0	47.4	53.7	57.8	62.1
		Min	19	34	41	45	52	55	60
5 %	5	Max	12	18	19	20	22	24	26
		Mean	11.6	17.0	19.0	20.0	21.8	23.0	25.4
		Min	10	16	19	20	21	22	24
7.5%	8	Max	11	15	17	19	20	21	22
		Mean	10.0	14.9	16.6	17.9	19.1	20.0	21.0
		Min	9	14	16	17	18	19	20
10.0%	7	Max	10	13	15	16	17	18	19
		Mean	9.0	12.9	14.6	15.9	17.0	17.9	18.9
		Min	8	12	14	15	17	17	18

Ambient Temperature: 35° - 40°F

*Number of data runs made at each PCM level.

Table 2. Data obtained with Model No. 2 in construction sand.

In order to move the low moisture level lines together on figure 12, and to spread the higher moisture lines apart, the geometric configuration of the device was altered so that more of the heat generated in the resistor would reach the thermistor. The conducting area of the metal strip was increased without substantially increasing the surface area exposed to the soil. For this purpose and in order to arrange things in a geometry amenable to soil penetration, a "Prototype I" was constructed. This is illustrated in figure 13 and the circuit diagram in figure 14.

The heat conductor was brass and hollow, and flanged smoothly outward at the top to provide contact area for the inexpensive Fenwal type LA31J1 disk thermistor. This thermistor is a sintered disk of 1/4 inch diameter and 1/8 inch thick. Both faces are silvered, and leads are soldered to the silvering. For use in Prototype I, the lead and solder were filed off one face, and the flat silvering was held against the heat conductor

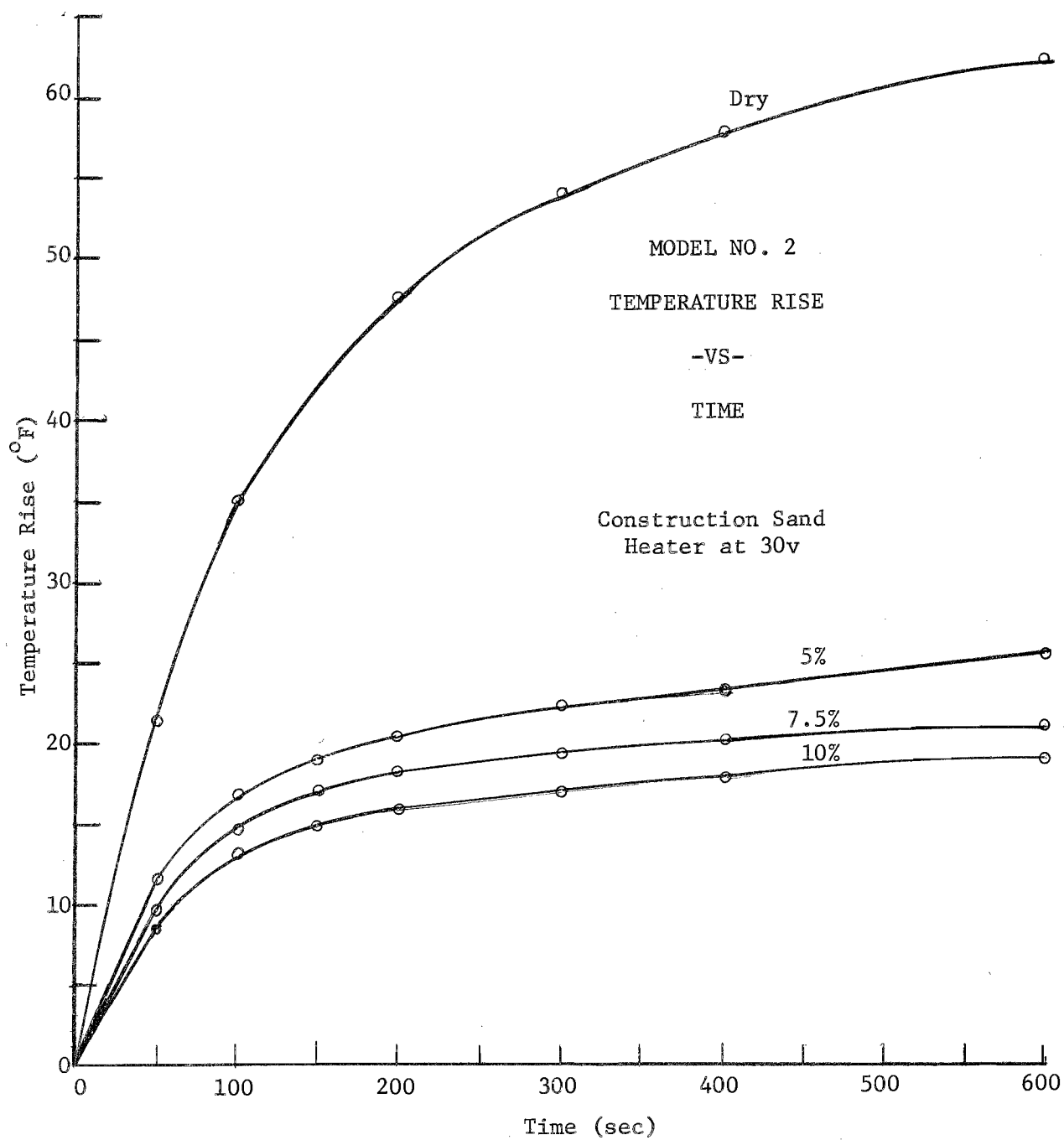


Figure 12. Temperature rise-vs-time plots for different moisture levels using Model No. 2 in construction sand.

PROTOTYPE I

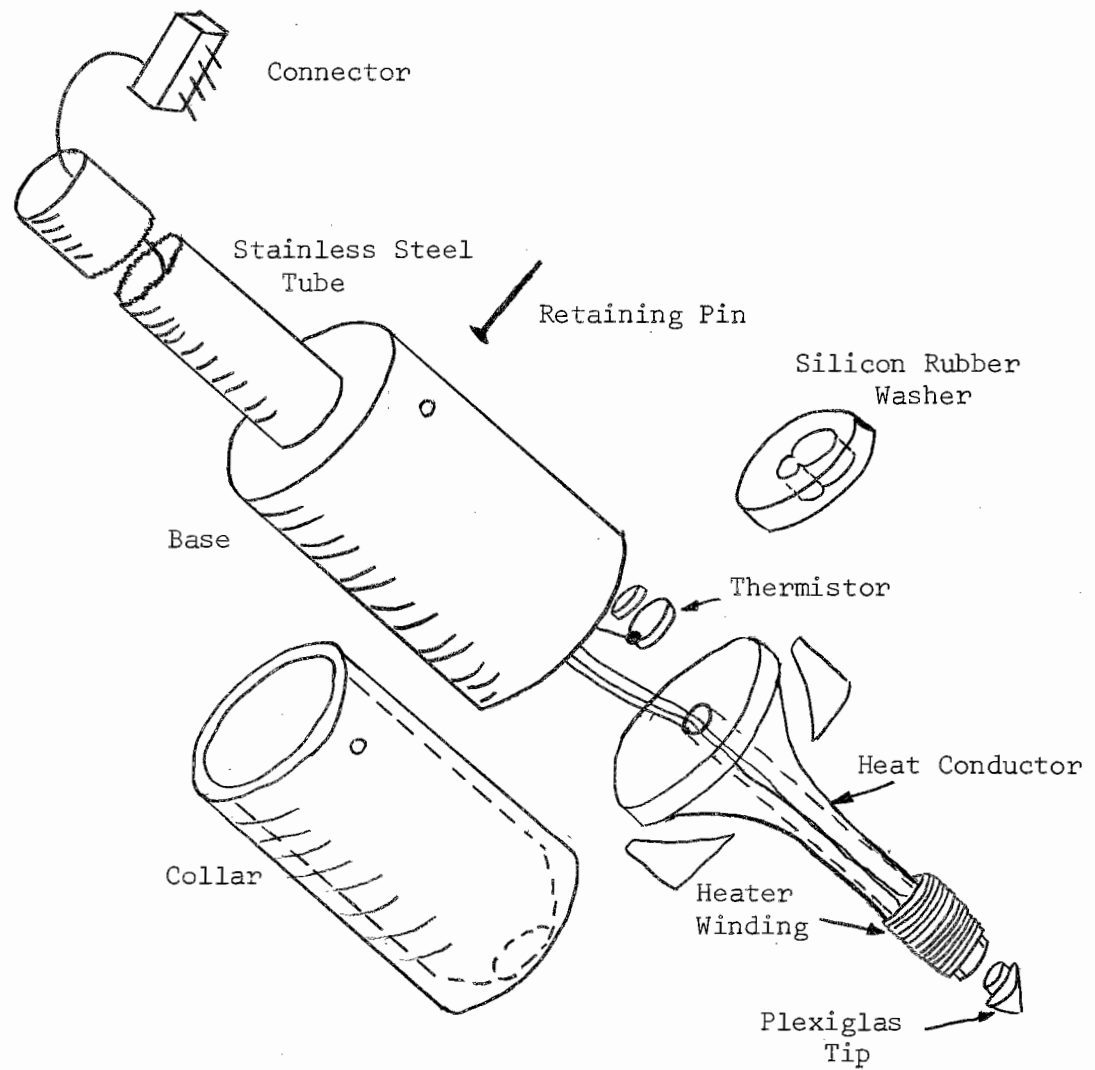


Figure 13. Construction drawing of the thermal soil moisture detector, Prototype I.

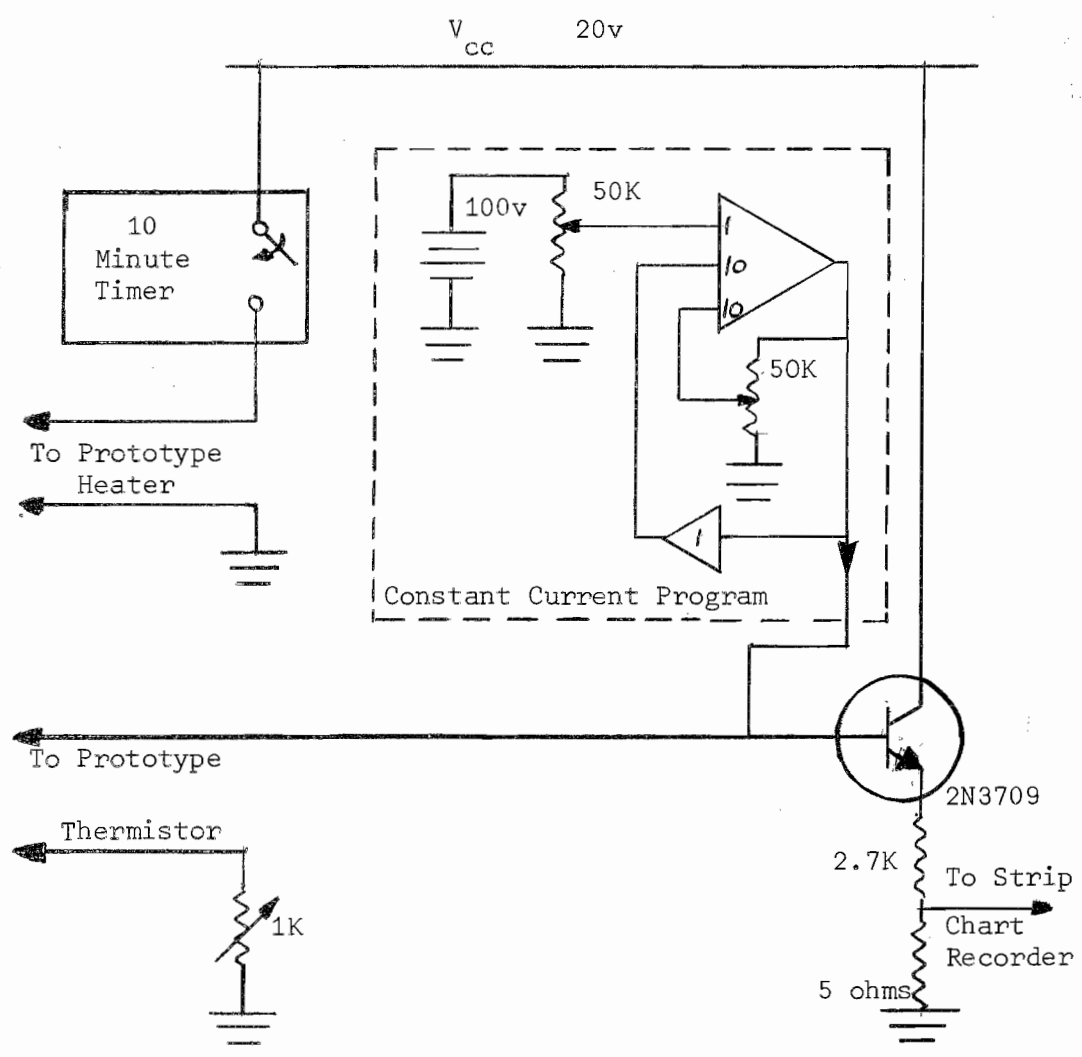


Figure 14. Schematic diagram of the data system used with Prototype I.

flange by a silicon rubber washer in slight compression. The heater consisted of 100 ohms of fine insulated nichrome wire wrapped tightly around the heat conductor, and protected by dipping in the 1:1 mixture of Duco Cement and acetone. A substantial plexiglas base was machined to connect the prototype with a 30 in. length of 1/2 in. stainless steel tubing, which served to bring leads out of the ground when the instrument was in place. The original design called for a hollow plexiglas screw to hold the heat conductor firmly against the base. The high temperatures encountered directly beneath the heater winding weakened the plexiglas screw so that it held for only three data runs. The screw was discarded, and a pointed plug machined for the lower end of the heat conductor.

Data obtained with Prototype I in sand during incremental water addition is shown in figure 15. At 5 PCM consecutive readings indicated less and less moisture present, apparently because water was driven out of the immediate vicinity of the probe by the heat produced and sufficient time to return to equilibrium was not allowed.

At 13 PCM water ran out of the bottom of the sample holder, indicating saturation at the bottom level. The sand actually saturates at 28 PCM. It was concluded that the force of gravity was creating a vertical moisture gradient in the sample holder. The data presented for Prototype II can therefore be used only to show the trend of the effect of moisture on probe readings. The graphs cannot be used as calibration charts since the moisture levels given are only average moisture content of the entire sample, and may be quite different than the moisture level in the immediate vicinity of the prototype.

The sample holder was no longer used in this project because of the observed moisture gradient. It could be used in soils possessing capillary potentials great enough to resist the gravitational forces. Perhaps other uses for such a sample holder exist in soil studies.

During the remainder of the experimental work, a three pound coffee can was used as a sample holder. Probably the lower layer of soil had a higher water content than the top layer in this sample holder, as well, but the volume of the sample which actually affected the probe was a large proportion of the total volume of the sample. Errors introduced by using the average moisture content were thereby reduced.

A probe for soil moisture measurement might conceivably be required to operate anywhere in the temperature range from about -20°F to $+100^{\circ}\text{F}$. Each time the probe temperature was lowered below freezing, the thermistor circuit opened. Moisture had entered the probe, and tiny ice crystals forced the thermistor away from the heat conductor flange. It became necessary to improve the probe design, and Prototype II was developed, this being simply a refined Prototype I. The heater was a 100 ohm, one-watt resistor placed inside the heat conductor. Shim brass assured a tight, heat conducting fit between heater and heat conductor. Prototype II could be pushed into a sample more easily than Prototype I since the external heater winding was not used.

To prevent loss of contact at freezing temperatures, the thermistor was soldered directly onto the heat conductor flange. After many failures

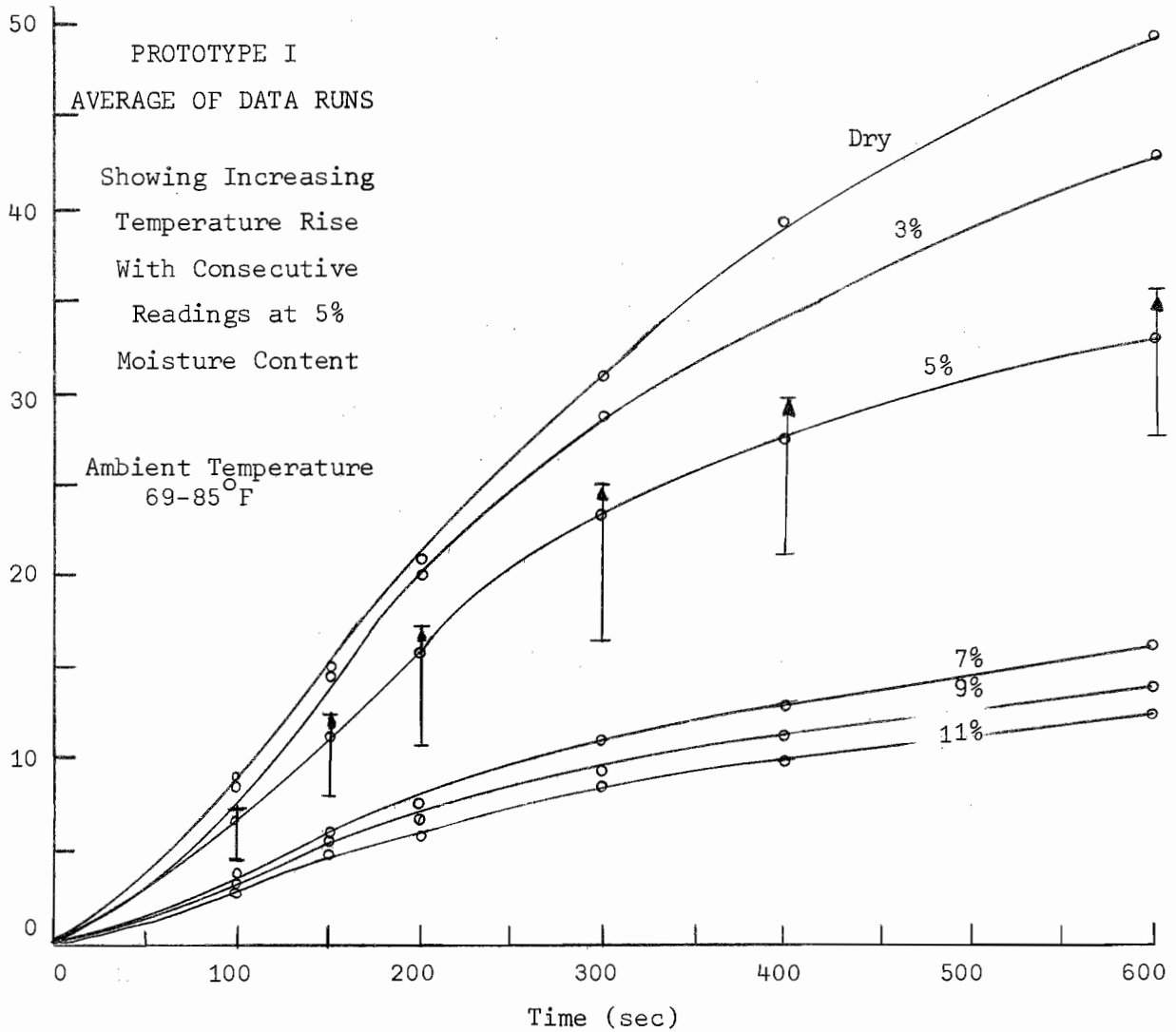


Figure 15. Temperature rise-vs-time plots for different moisture levels using Prototype I in construction sand, illustrating the increase in temperature rise as the soil surrounding the thermal probe was dried by the heat produced during successive trials.

a good solder joint was achieved using Alpha 0.062 in. diameter 50/50 alloy solder, and Salment non-corrosive flux.*

Attempts to seal out moisture by coating seams with wax were partially successful, but the waterproofing failed at moisture contents near saturation. When moisture entered the probe, application of heater voltage changed the thermistor reading.

The data-taking system was made completely automatic by the addition of a system of relays and an electric clock, whose hands were used as electrical contacts. The operator simply added water to the desired level and started the system. A potential of 20v was applied to the heater for a ten minute period each hour, and the chart drive operated only during this period and a five minute calibration check period immediately preceding heating time. Sample temperature was lowered to about 0°F in twelve hours, then slowly warmed to room temperature. Since the thermistor resistance was many times higher at the low temperatures, the Brown potentiometer tended to run off the upper end of the scale. The data system automatically reduced the system gain to a new value suitable for low temperature runs. During the warming cycle, the gain was reset to its original value. To check for moisture in the probe, the heater was turned off for one second each minute during its "on" time. If moisture were present, pulses appeared on the otherwise smooth temperature tracing. A schematic diagram of the system is given in figure 16.

Over 400 individual data runs were made. The sample soils used were Roberts Fine Ash and Construction Sand. Efforts to test the probe in a clay-type soil from the area south of Moscow, Idaho, were unsuccessful due to the time required for moisture to reach a capillary equilibrium in this soil type. Preliminary wetting experiments indicated at least one week must be allowed for equilibrium to be reached after the addition of water to a sample at soil moisture levels below about 15% in the clay-type soil.

A summary of the data obtained with Prototype II is given in figures 17, 18, and 19.

*Salment non-corrosive flux is available from Hascol Enterprises, Sharon, Pennsylvania.

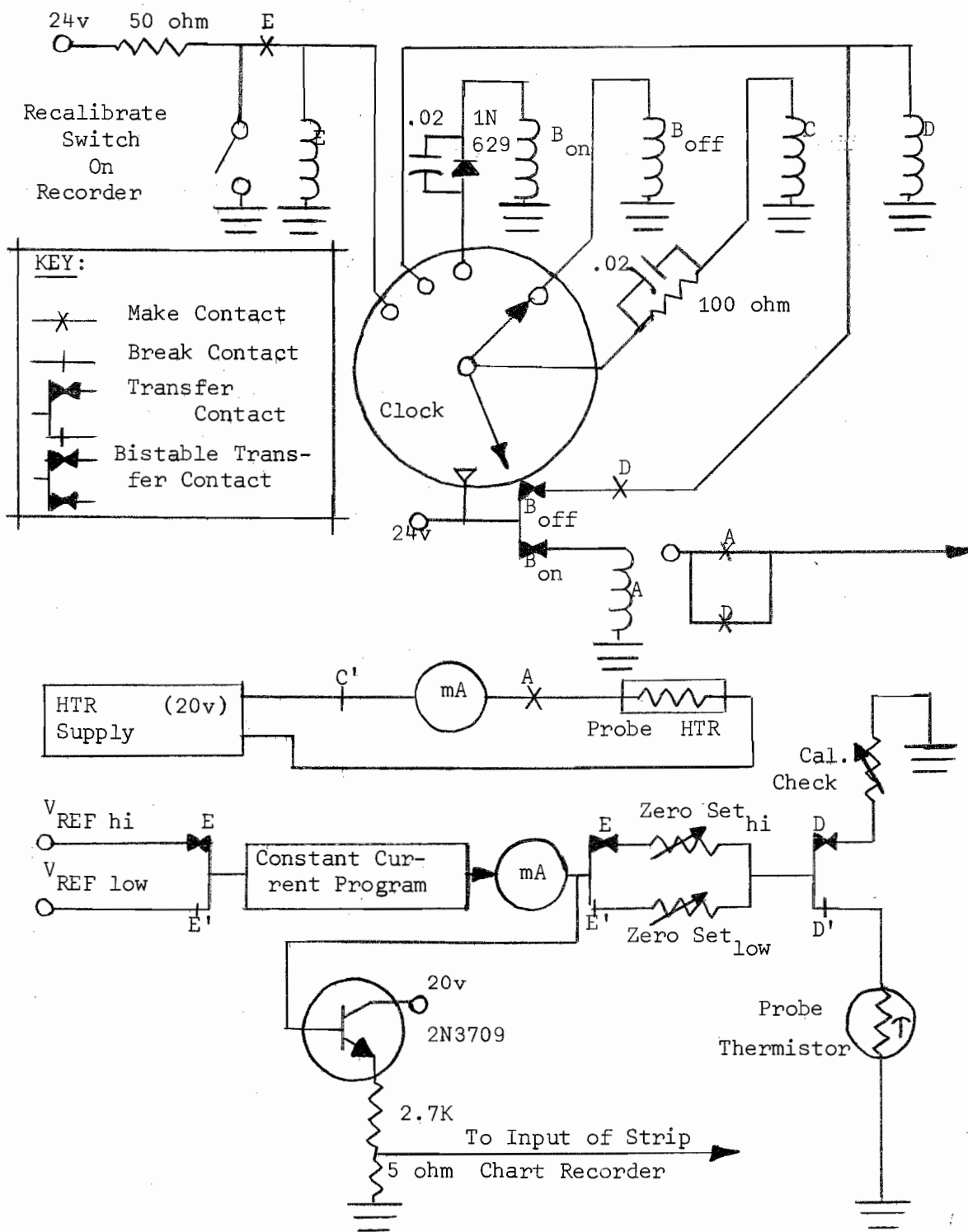


Figure 16. Schematic diagram of the automatic data system used with Prototype II

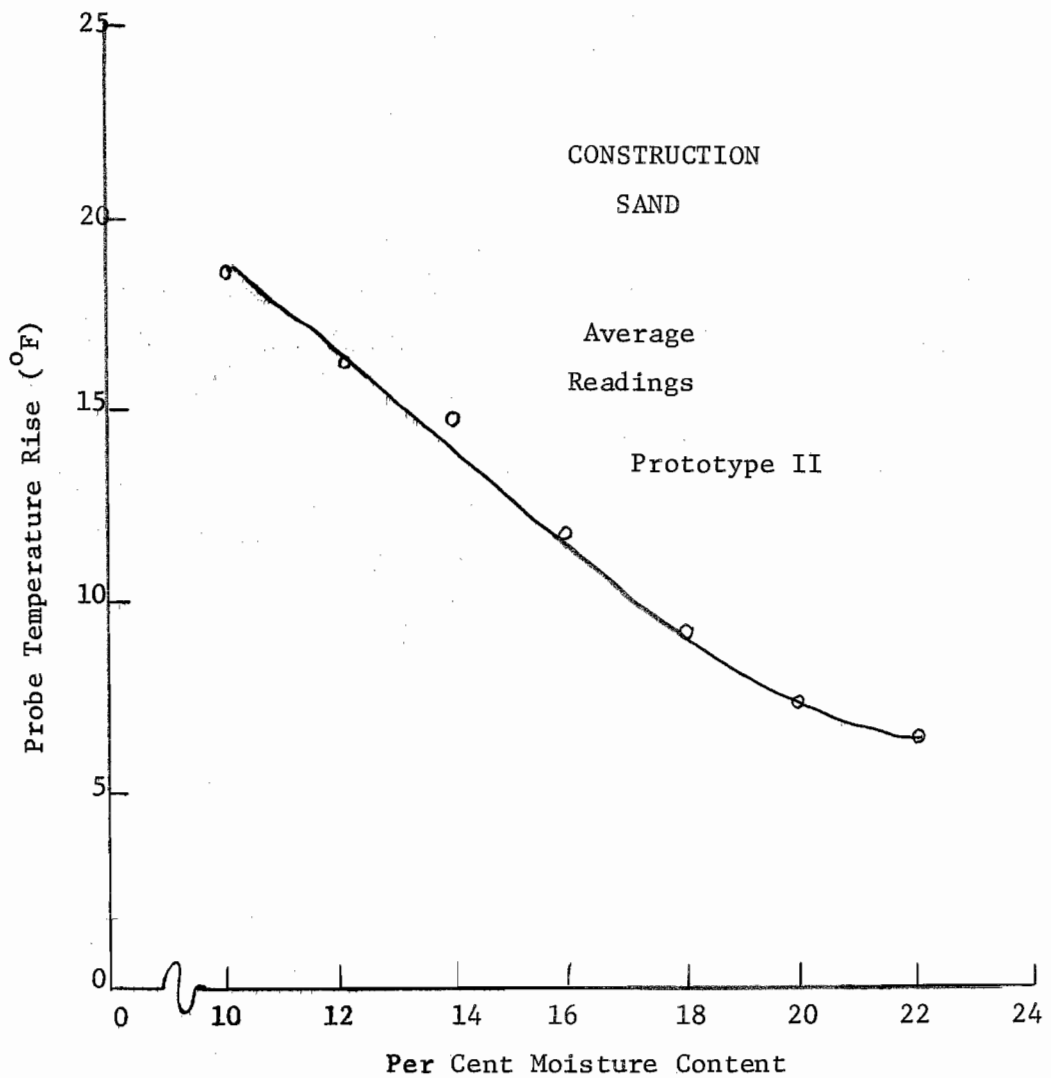


Figure 17. Average temperature rise-vs-soil moisture content using Prototype II in construction sand in the ambient temperature range 33 to 80°F.

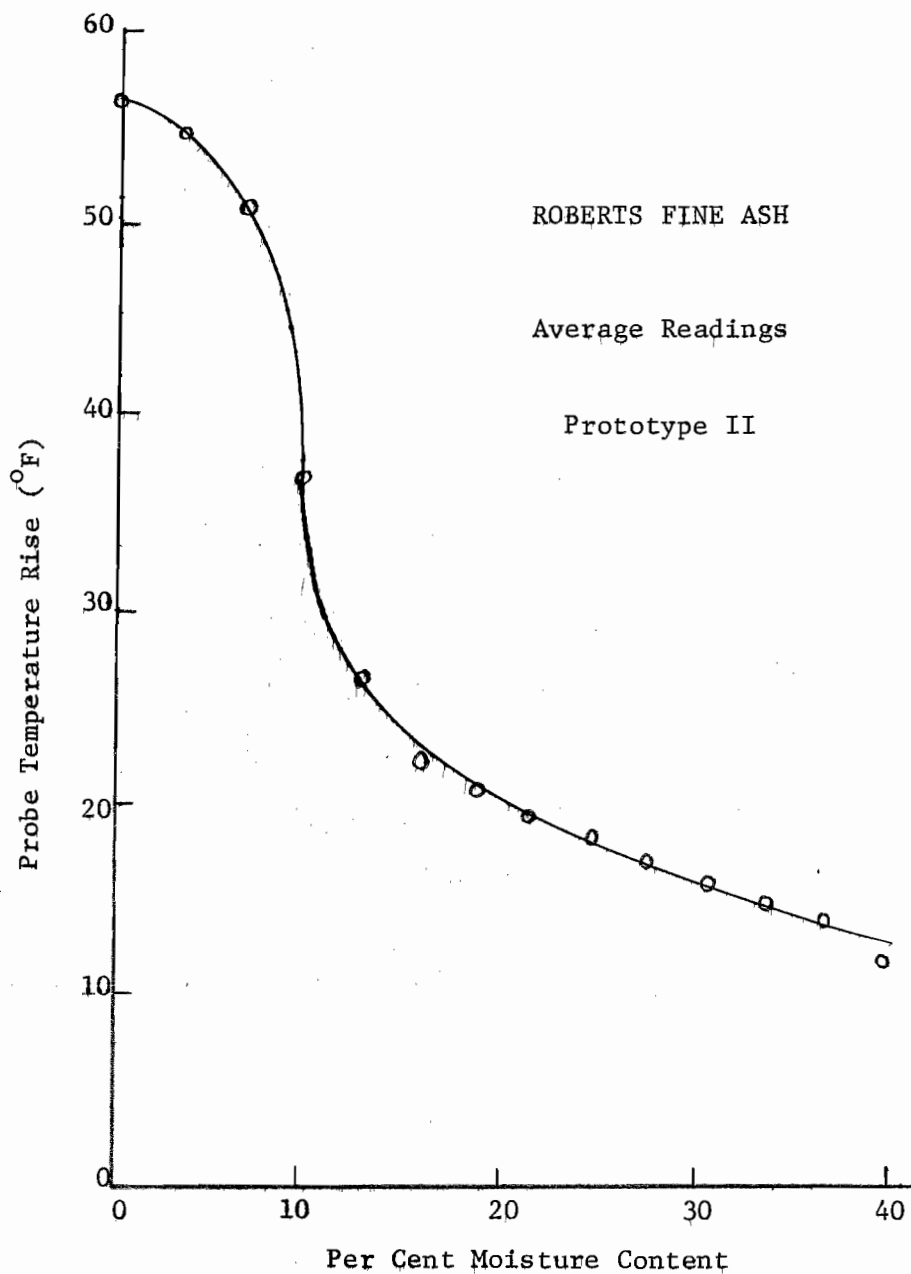


Figure 18. Average temperature rise-vs-soil moisture content using Prototype II in Roberts Fine Ash in the ambient temperature range 33 to 80°F.

PROTOTYPE II

Calibration Scales

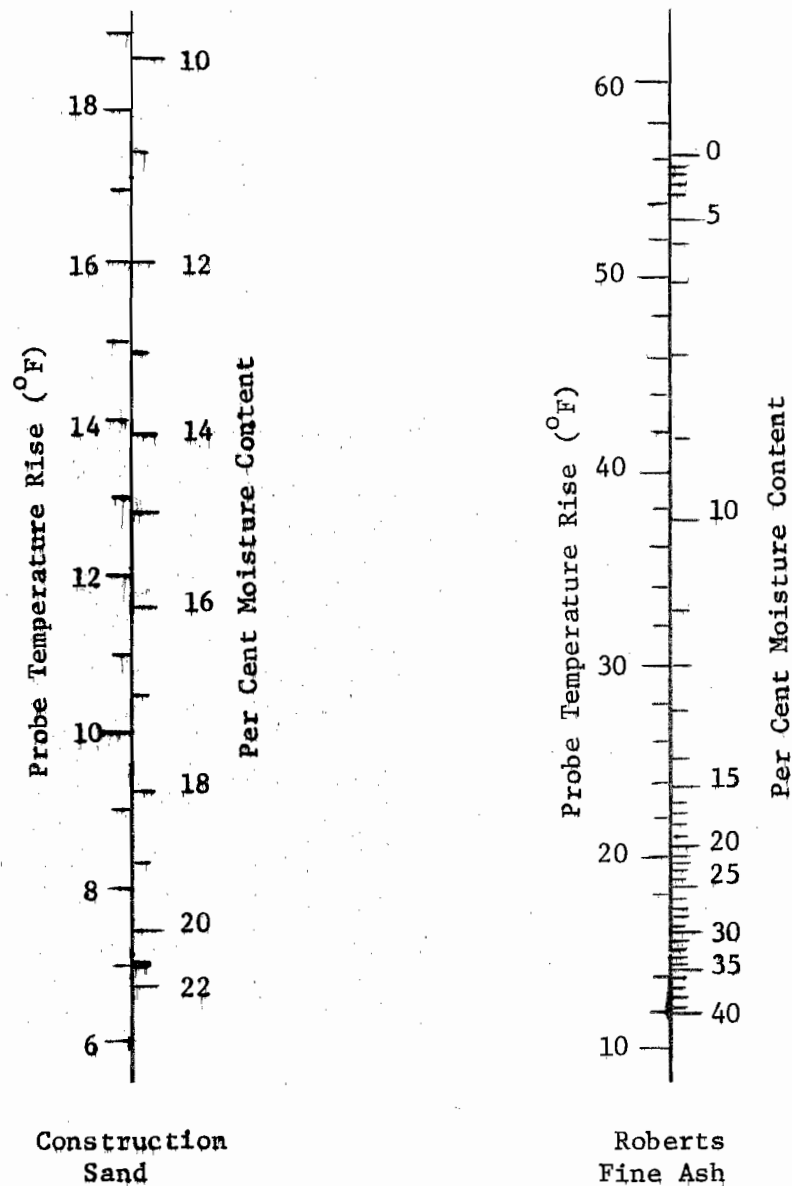


Figure 19, Scales which relate Prototype II temperature rise readings with soil moisture content in construction sand and Roberts Fine Ash, These scales apply in the temperature range 33 to 80°F,

RESULTS, OBSERVATIONS, AND RECOMMENDATIONS

The prototypes were designed to be less accurate at lower moisture levels and more accurate at the higher levels, as compared to Model No. 2. The conduction area was therefore enlarged with respect to the soil contact area. The data indicates that, while the prototypes are better than the earlier models in this respect, a still greater enlargement of the heat conducting area without increasing the soil contact area is required. This could be accomplished simply by increasing the thickness of the heat conductor cylinder walls.

Soldering the thermistor directly to the heat conductor flange eliminated open circuits at low temperatures. However, a better waterproofing is required before the prototype can be used in the field.

A wide variation in temperature rise readings occurred for a given moisture content even when measurements were made with identical initial temperature readings. At first this variation seemed to indicate the reliability of the probe was in question. An additional series of data runs was taken in which the ambient soil temperature was held constant at 65°F in Roberts Fine Ash at 23% soil moisture. Thirty-nine consecutive runs spaced one hour apart gave identical temperature rises of 19°F for a ten minute heating period at 20v heater potential. Water was added to 31% and two days were allowed for the moisture to reach capillary equilibrium. Twenty-six consecutive runs gave temperature rises of exactly 16°F. The prototype was therefore considered to be consistent under constant temperature and water conditions. At 31% moisture content, the temperature was lowered to 47°F and allowed to stabilize. Twenty-two consecutive runs again gave 16°F. The temperature was lowered to 4°F and again allowed to stabilize. Twenty-five consecutive readings fell between 15 and 16°F with a mean reading of 15.7, which should correspond to 32% soil moisture.

To determine the cause of the variable readings found in the data, the sample temperature was warmed to 75°F and allowed to stabilize. Again, readings of 16°F rise were taken at the 32% moisture level. The freezer was turned on to begin lowering the sample temperature. One half hour later, the probe temperature had dropped to 72°F and a data run resulted in a temperature rise of 13.5°F. The sample temperature was lowered to 45°F and allowed to stabilize. The freezer was then turned off and the door was opened allowing warm air (76°F) to raise the sample temperature. One half hour later the probe temperature read 47° and a data run produced a temperature rise of 18°F.

A study of the previously acquired data affirmed that temperature rises were consistently low during cooling and consistently high during warmup. This phenomenon can be attributed to the temperature gradients in the soil sample during warming or cooling cycles. The central area of the sample, which the probe measures, is the last to be affected by a changing ambient temperature of the surrounding soil volume, and erroneous readings occur. Since temperature fluctuations occur much more slowly deep in the ground, the erroneous readings would probably not be encountered in field use.

The probe cannot be used for moisture determination if the probe temperature must pass through the freezing point during its temperature rise. Considerable heat is required (heat of fusion) to convert the soil moisture from a solid to liquid form. Very low temperature rises therefore occur when runs are made with ambient temperature at or just below the freezing point. From observation of the data, however, it appears possible to calculate how much of the soil water is in the frozen state at 32°F ambient temperature if the moisture level is known. (Below 32°F most of the soil water is probably ice, above 32°F, it is all liquid). If the frozen portion of the soil water is large, very low temperature rises occur in data runs.

Comparison of data on sand and on Roberts Fine Ash assures that a calibration curve is required for each soil type. A field calibration at the site to be monitored would be preferable to a laboratory calibration, since it is doubtful that the state of compaction in the field could be duplicated in the laboratory. A field calibration could be obtained by correlating thermal probe readings with gravimetric measurements at the same site for several different PCM levels. The sampling for gravimetric moisture determination should not disturb the soil surrounding the thermal probe, but the sample should be taken at the same depth and in the immediate vicinity of the thermal probe.

The PCM level at the probe site would be determined by observing the ambient soil temperature, applying a specified power input to the probe heater for a given length of time, and observing the temperature rise. Previously acquired calibration tables would then relate temperature rise to soil moisture content.

The thermal probe gave acceptable results in the temperature range 34° to 80°F. Probe temperature rise is independent of ambient temperature in this range. The probe is very accurate at low moisture contents but becomes less accurate near saturation. Moisture levels can consistently be determined to within 1% soil moisture near 25% saturation, within 2% soil moisture near 50% saturation, and within 3% soil moisture above 75% saturation in Roberts Fine Ash, which saturates at 43% moisture content.

The thermal probe may not be used in the temperature range 20° to 33°F because the heat of fusion required to melt the frozen soil will result in very low temperature rises in the probe. At 32° ambient temperature, this depression of probe temperature rise indicated what portion of soil moisture is in the frozen state. Moisture content must be known to use this phenomenon.

The probe was usable at temperatures from -5° to 20°F, but temperature rise readings were slightly less than those above 35°F at the same moisture content. This effect was most pronounced at below-zero temperatures.

The probe readings were influenced by rapid temperature changes in the soil. Fine soils were more suitable for this probe because they provide better thermal contact with it.

An accurate and dependable thermal probe for measuring soil moisture appears feasible using the general design of Prototype II. Necessary modifications include better waterproofing and increasing the heat conductance between heater and thermistor to provide better accuracy at high moisture contents. Calibration for each location will be necessary because the thermal characteristics of the soil vary slightly with soil type. Once calibration has been established, however, it should remain correct unless the probe is physically disturbed.

A probe of this type would be inexpensive and could be installed by technicians with little technical background. Systems for remote use could be easily built around this probe. Testing is nondestructive, except that time must be allowed after each reading for the soil to reattain energy equilibrium. Since this probe is insensitive to changes in ionic concentrations of the soil, it is superior to the resistance block technique.

D. NUCLEAR MAGNETIC RESONANCE

Noting some published material on the use of NMR for moisture determination in the food industry (65), the possible use for soil water determination appeared worth exploring. N.S. Harasprasad, for his M.S. thesis project, undertook the construction of a simplified version of an NMR apparatus (67). Improved electronics were subsequently built (73) in an attempt to improve the first version. A magnetron magnet with added pole force was used, although it was clear that the field homogeneity fell quite short of the desired value for sharp resonance (71).

While a small indication was obtained for distilled water, any attempt to observe resonance with soil present met with complete failure.

Samples were then prepared and run on a highly sophisticated instrument available in the Physical Sciences Department (Varian-A60). A sharp peak, obtained with distilled water, was compared with a shifted, smaller and broader peak obtained with 10% soil present. With 90% soil present, the resonance indication was wiped out. A number of other tests were made. All samples were kept spinning during analysis since this improves the effective field homogeneity (73).

The phenomena known as "paramagnetic broadening" (75, 76) is obviously responsible because paramagnetic metals and salts are in abundance in almost all soils. The hydrogen bonding existing between the particulate surface and first layer of interfacial water has also been variously discussed and no doubt has effects which were not foreseen at the outset.

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