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STUDIES ON METHODS OF SOIL MOISTURE DETERMINATION

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STUDIES ON METHODS OF SOIL MOISTURE DETERMINATION

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BIOGRAPHICAL SKETCH OF THE AUTHOR

Howard Eugene Hite, Jr. was born in Wendell, Idaho, on August 10, 1945. His interest in soil water began at the South-central Idaho irrigation farm on which he was raised. He attended Jerome, Idaho, High School and received a diploma in May, 1963. The following September he enrolled in the University of Idaho and began work on a Bachelor of Science degree in Electrical Engineering. Insight on the problems of irrigation water distribution and utilization was gained while working as a hydrographer for the North Side Canal Co. of Jerome, Idaho, during the summer of 1964. The next summer he became familiar with chemical and gravimetric methods of measuring soil moisture while doing quality control work on road construction for the U.S. Forest Service. Work for the Department of Physics at the University of Idaho under National Defense Education Act and National Science Foundation funding during the summer of 1966 and the succeeding year was reported in a paper "Physical Constants of CaO" published in the Journal of Applied Physics in December, 1967. He received his baccalaureate degree in June, 1967, having spent the last semester in partial enrollment in the University of Idaho Graduate School. In June, 1968, he completed the requirements for the Master of Science degree, of which this thesis is a part.

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ABSTRACT

Though the need for instrumentation capable of determining soil moisture quickly and accurately has long been recognized, no dependable means suitable for automatic and remote soil moisture measurement has yet been developed. Presently, the only reliable method for measuring soil moisture is a time consuming process which requires human attention. Water is removed from a soil sample by heating, and the resultant weight loss is determined. Considerable work has been reported on a device which measures the electrical conductivity of a gypsum block imbedded in the soil. Water causes the electrical resistance of the block to decrease. These blocks are alleged to be unreliable under many field conditions. The work reported in this thesis was undertaken with the intent to develop a more reliable instrument for remote site operation. An extensive survey of the literature led to the selection of three fields of study: streaming potential, thermal conductivity and specific heat, and absorption of infrared radiation by moist soil.

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 the unit could be successfully and reliably used in certain ambient temperature ranges. The data also revealed that, when soil is partially frozen at 32^oF, the device could indicate what percentage of the soil water was in the frozen state, provided the soil moisture content were known. Field testing of a similar unit is recommended.

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 great promise and warrants further development.

PART I

A DISCUSSION OF THE PROBLEM
SOIL MOISTURE INSTRUMENTATION

INTRODUCTION

For 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 efforts 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 reported in this thesis was to attempt to improve upon present soil moisture instrumentation, by perfecting present methods or by introducing new ones.

In the course of this thesis, the basic soil fundamentals which pertain to measurement of moisture content will be discussed, and desirable qualities of a general soil moisture measuring device will be listed. Previous work on this subject will be summarized from a historical and technical viewpoint.

Following a decision of which techniques warrant further study, this report will deal with the theoretical and practical problems encountered by the author in his search for a better device for the measurement of soil moisture. Methods and results of experimental testing will be related, and conclusions drawn from the experimentation will be discussed.

STATEMENT OF THE PROBLEM

Soil moisture is simply the water within the ground. Water reaches the soil through precipitation, irrigation, or percolation (travel of water from one point in the soil to another). It is removed by evaporation, plant usage, and, again, by percolation.

The problem at hand was to develop a dependable and accurate method for determining the amount of water in the soil at a given location and a given time.

Desirable characteristics of a soil moisture measuring device will be considered later.

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 this thesis 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 thesis. For that reason the author has chosen to abbreviate the quantity "per cent soil moisture" as "PCM".

FUNDAMENTALS OF SOIL STRUCTURE

PERTAINING TO SOIL MOISTURE

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 influences the physical and chemical properties of the soil,

especially in clay soils. 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. Then the remainder of the void spaces is filled. Generally, moisture tends to make a soil more plastic.

The porosity is the ratio of the volume of the voids to the total volume of the soil mass. Porosity substantially determines the amount of water a given soil can hold. 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 is held by very strong tensile forces to the soil particles, and will move from particle to particle only very slowly. These films are in the order of a few molecules thick. The remainder of the water in soil moves much 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, known as capillary potential. Capillary potential 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.

To summarize, soil is a heterogeneous and changing medium composed of tiny particles and void spaces in which water may be held. Individual soil characteristics determine how well the water is held, and the water changes many physical properties of the soil. (58)

DESIRABLE CHARACTERISTICS OF A
SOIL MOISTURE MEASURING DEVICE

After a basic understanding of the manner in which water is held in the soil is achieved, possible ways to measure this water become apparent. Before beginning to explore these possibilities, general requirements for a practical instrument should be stated.

First and foremost, the device must be accurate and dependable, and must give reproducible results. For most applications an accuracy of $\pm 1\%$ soil moisture is acceptable.

Soil moisture 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 the layman to operate.

Many times it is desired to monitor the moisture at a given point continuously throughout a long period of time. Runoff predictions necessitate this type of monitoring at remote sites where human operation is unfeasible. Automatic irrigation systems also should require no human attention. A device or method for these applications must not disturb the soil while measuring, 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, because 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.

A general device 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.

A SURVEY OF PRESENT METHODS OF
SOIL MOISTURE DETERMINATION

THE GRAVIMETRIC METHOD

The gravimetric method is the most widely accepted method for measurement of soil moisture. A soil sample is weighed, then oven-dried and weighed again. The ensuing weight loss is attributed to the water driven off by heat, and the PCM is given by the change in weight divided by the final weight, multiplied by 100. This method is generally held to be very accurate, but is time-consuming. The soil temperature during drying must not rise over 130°C , or any organic material in the soil may oxidize, and thermal decomposition of the soil may begin; giving erroneously high PCM readings. A drying temperature of about 105°C seems to be optimum. This temperature dries the soil very slowly, and a drying period of at least 24 hours is recommended. In many applications, such as checking for the proper PCM for good compaction on roadbeds which are about to be paved, the 24 hour delay makes this method impractical if not useless.

Techniques to help overcome the time-lag between sampling and useful data have been developed with some success. Methyl or ethyl alcohol, when mixed with a soil sample after preliminary weighing, will dehydrate the soil, and the alcohol may then be burned off, driving

off all moisture as steam. This method also burns off organic matter and is not suited to mucks, peats, or other soils containing undecomposed organic matter. Bouyoucos reports that PCM may be measured in sands in 5 to 10 minutes and in clays in 10 to 35 minutes depending on water content and soil permeability to alcohol (14). Bonar (11) reports that the burning alcohol method agrees with the oven-drying method to within $\pm 0.1\%$ soil moisture content for some purely inorganic soils.

Other methods of rapid drying suggested in the literature include infrared radiation (heat lamps) (64) and heating at reduced pressure. (It should be noted that any vacuum pump used for the purpose of lowering the pressure requires protection from the moisture driven from the soil sample.) Sweeping vapor from the drying oven with desiccated air is also effective, and, for soils having high hygroscopicity, such as fine clay, the combination of a powerful desiccant and heating under reduced pressure is reported by Davisson and Sivaslian to be much superior to even the standard 24 hour oven-dry procedure (32).

No reference to drying soil samples with microwave ovens was found in the literature, and work in this direction may be warranted in the future, at least for applications where organic constituents do not create a problem.

All the various forms of the gravimetric method of PCM determination are destructive in that a given sample may be used only once. Further, the processes involved do not lend themselves to automatic measurements at remote stations.

CHEMICAL METHODS

Two chemical methods of measuring PCM, the alcohol method and the carbide method, are widely accepted; several other chemical methods have been suggested.

The alcohol method consists of shaking a known amount of soil in absolute ethyl or methyl alcohol. All water present in the soil sample is stripped away by the alcohol. The soil is filtered out, and the specific gravity of the alcohol-water mixture is determined. The amount of water present in the original soil sample may then be calculated. Bouyoucos (22) shows that the alcohol method is both sound in principle and reliable. The entire procedure takes less than half an hour, and is well suited to field testing. Like the gravimetric method, the alcohol method is destructive, and is not suited for automatic, remote-site testing. The method cannot be used in alcohol soluble soils, such as those containing much organic matter.

The carbide method employs a gastight bomb in which a known amount of moist soil is mixed with an excess of CaC_2 . Acetylene gas, C_2H_2 , is produced by

the soil water's reaction with CaC_2 , and the PCM is determined from pressure and/or temperature readings, or by measuring the volume of the gas produced.

Niolson (50) reports 610 ml of C_2H_2 at 0°C and 760 mm pressure is evolved for each gram of water present.

Masson (48) computes a theoretical yield of 622 ml per gram of water present, but due to the phosphorus and sulfur present in technical CaC_2 (56), Masson reports a yield of 583 ml per gram of water.

The author of this thesis has used a commercially available device known as the "Speedy Moisture Tester", which employs two steel balls inside the gastight bomb to ensure complete mixing of the soil and CaC_2 when the mixture is shaken. Results generally agreed with the oven-dry method to within 1% of soil moisture.

Emmert (35) suggests mixing known amounts of moist soil and 95% H_2SO_4 , mixing thoroughly with a thermometer, and measuring the temperature rise. After compensating for temperature increase due to the reaction of the soil with the acid, the PCM may be determined. Usually a temperature rise-vs-moisture curve is prepared for each type of soil to be tested. Shaw and Arble (54) report work by Nikolaev (49) stating K_2SO_4 may be used in place of H_2SO_4 .

Distillation after stripping water from the soil with xylene is suggested by Begemann (7).

All of the chemical methods found in the literature are destructive, and none are suited to remote-site, automatic PCM measurement.

TENSION METHODS (Also called "Suction" method)

The capillary tension with which moisture is held to soil particles decreases with increasing PCM. Richards (51) defines capillary potential as "the work done against the 'capillary field force' in transferring a unit mass of water from the flat water surface (of a soil particle) to a point in question." The drier the soil, the more negative the capillary potential will be, and therefore the greater the affinity of the soil for water. This capillary potential is a function not only of PCM, but also of state of soil packing and size of soil particles. For example, a fine sand will have a lower potential than a coarse soil even though their PCM's are the same, and a wet clay will absorb moisture from a sand comparatively dryer. Further, if a comparatively dry soil is sufficiently compressed, water will run out under the force of gravity.

The tensiometer is a device which measures capillary potential either absolutely, or, more often, relatively. It consists of a closed porous cup filled with water inserted in the soil. Some means of determining the pressure inside the cup is provided. The capillary attraction of the soil particles outside the cup causes water to flow out through the pores of the cup,

creating a relative vacuum within. This process continues until the negative potential (vacuum) inside the cup just equals the negative capillary potential outside the cup. After calibration for a given soil type and compaction, relative vacuum may be converted to PCM.

This method has gained wide acceptance in soil water measurements for irrigation purposes, since the availability of water to plant roots is determined not by PCM, but by the capillary potential of the water in the surrounding soil. No calibration is therefore required for measurement of available water to plants. Tensiometers may be located remotely, and require little or no maintenance if properly designed. If relative vacuum is measured by commercially available transducers, the soil moisture data may be easily telemetered automatically. This is a non-destructive method. Walliham (62) reports that reading two adjacent tensiometers gives a measurement of the direction and the magnitude of the capillary gradient.

The tensiometer has one basic fault. It cannot follow rapid changes in PCM, such as those changes accompanying a heavy rainstorm or irrigation--or even a hot, windy day. For an instant change to register accurately on a tensiometer, a waiting period of from 24 to 100 hours must be allowed for the potentials inside and outside the porous cup to reach equilibrium. Also, tensiometers are not readily portable, since

after installation a period must be allowed for the soil in the immediate vicinity of the tensiometer to attain the same compaction as the surrounding area, or large errors will occur.

THE PENETROMETER METHOD

The penetrometer is highly portable, but not accurate. A probe is forced into the soil in question, and the soil's resistance to penetration by the probe is measured. An alternate method consists of a flat blade driven into the ground. The torque required to twist the blade is measured. Heavy soils become more plastic with the addition of water, and the force or torque required to manipulate the penetrometer decreases. This method cannot be used in rocky or sandy soils, but gives some indication of the available moisture present in other soil types. Allyn (3, 4, 5) gives this type device the aliases "availameter" and "stabilimeter". Since the "penetrability" of the soil depends on its compaction, the penetrometer must be recalibrated each time the soil is disturbed, as in agricultural tilling. Further, use of this device assumes homogeneous compaction for a given area. Sampling for this method is destructive, and the penetrometer does not lend itself to automatic, remote-site measurements; and, again, its accuracy is highly questionable.

THE LYSIMETER METHOD

A lysimeter is a large (up to 1/5 acre) tank of enclosed soil which has been isolated from the surrounding soil by means of concrete, metal, and other walls, and may be floored artificially or with natural bedrock. This isolation facilitates studies of percolation, leaching (removal of dissolved minerals by water or percolation), and of accretion, depletion, and storage of soil water. Plants may or may not be grown within the lysimeter.

Smaller lysimeters may employ direct weighing of the entire soil mass by a suitable permanently installed apparatus to indicate PCM. This method may not be used in large-scale PCM determinations of wide areas because of the cost involved in setting up the expensive equipment necessary.

NUCLEAR METHODS

The nuclear methods are superior to all other methods found in the literature. They are accurate, non-destructive, give instantaneous readings, and are well-suited to automatic, remote-site measurements.

The most common form of nuclear PCM measurements employs a unique property of hydrogen - it is the most effective element for slowing down fast neutrons. This property arises from the approximate equality of atomic weights of a neutron and a hydrogen nucleus,

or proton. When a fast neutron collides with a heavy nucleus, it bounces off, retaining nearly all of its energy. A fast-neutron collision with a proton, however, causes a transfer of about one-half the fast neutron's energy to the proton, and the fast neutron is slowed considerably. Fortunately, nearly all hydrogen found in the soil is present as water.

Necessary equipment for PCM determination includes a fast-neutron source (possibly a mixture of Polonium and Beryllium), and a slow-neutron counter (usually a Beryllium Fluoride (BF_3) tube, since no shielding from fast neutrons is required with this detector). The source and detector are usually located about a foot apart and tend to measure a bulb of soil having a vertical diameter of 8 to 10 inches (29) and a horizontal diameter equal to the distance between them. Hood (43) reports successfully controlling the vertical size of the sample with cadmium shielding. Since the fast neutron output of the source is constant, the production of slow neutrons is proportional only to the amount of hydrogen (mostly as water) present in the soil.

Source-detector pairs may be stacked to report the PCM of various levels at a given site.

The gamma ray absorption of the soil is proportional to the soil density, and since the Po-Be neutron source also emits gamma rays, soil density may be measured simultaneously with PCM provided a gamma counter is installed

with the slow-neutron detector. Density may also be measured by x-ray absorption. Further, a single source may be used with multiple detectors placed around it to measure moisture or density gradient.

The source and detector may be placed in the same probe if the slightly reduced accuracy of measuring only reflected slow neutrons is satisfactory. A device of this type has been designed for surface use by Van Bavel et. al. (61), with a reported error of $\pm 1\%$.

For on-the-site measurements, a film of indium foil is used. Slow neutrons are absorbed by stable In^{115} yielding radioactive In^{116} . After a definite exposure period, the film's radioactivity is measured by wrapping the film around the Geiger tube of a portable beta-gamma voltmeter.

Following a study of nuclear methods, Carlton (29) made the following observations, as quoted from Shaw and Arble (55).

"Present models of nuclear soil meters have the following operational characteristics. (a) Moisture contents may be determined within an average accuracy of $\pm 2/3$ lb $\text{H}_2\text{O}/\text{ft}^3$, (b) Densities may be determined within an average accuracy of ± 2.0 lb/ ft^3 , (c) Individual calibration for changes in soil type is not required, (d) Moisture contents and densities

are average values measured over a bulb of soil having a horizontal diameter of 12 to 15 in. and a vertical diameter of 8 to 10 in. (e) Observations spaced at vertical intervals as small as 6 in. show significant changes in moisture content and density, (f) Observations may be made at any desired depth with the exception of the top 4 to 6 in. (g) Observations may be repeated at a given location any number of times without disturbing the natural soil structure, (h) Access tubes may be left in place indefinitely, (i) The apparatus is portable and can be operated by either a one- or two-man crew."

The United States Forest Service, however, has not accepted this type of device. Tests conducted by the Corps of Engineers reveal factors of unreliability, frequent malfunctioning requiring expert repairmen, too much time required for readings, unsuitability for surface measurements, too thick a vertical sampling required, high cost per unit and difficult procurement (52).

Stolzy (57) also reports high cost per unit, and suggests possible radiation hazards involved if the devices are used by laymen. He also points out that irrigation men would rather know capillary potential than PCM. Van Bavel (60) states that with a few simple precautions, the

health hazard due to radiation is quite small. No mention was found in the literature of the possible radiation damage to plants in the area of a permanently installed probe. (Radiation use may require government licensing.)

In summary, the radiation methods are excellent, but costly when compared to other methods of PCM determination.

ELECTRICAL METHODS

The primary electrical method for PCM determination is based on the fact that dry soil is a poor electrical conductor, whereas wet soil is a very good conductor. Intuitively, it would seem that one could find the PCM by simply measuring the conductivity of the soil. This technique, with refinements, is used extensively, especially in automatic irrigation systems. The historical development of this technique provides such insight into the associated problems that it will be summarized here.

As early as the 1890's, men were placing electrodes in the soil for conductivity measurements, and attempting to correlate electrical conductivity to soil moisture. Early in 1897, Whitney, Gardner, Briggs and Means, employees of the U. S. Department of Agriculture, published a bulletin on their experimental work with a Wheatstone bridge. They reported three important variables. (1) The concentration of weekly soluble salts depends on temperature. (2) Highly soluble salts

will form more dilute solutions when the PCM is high.

(3) The amount of salts dissolved in the soil water is a function of the amount of soluble material present in the soil. Of course, the increase in the conductivity of the soil with the addition of water is grossly affected by any change in the total ionic concentration of the soil solution. (This problem still haunts experimenters, 70 years later.) The early engineers solved the variable temperature problem by using a temperature sensitive cell as the power supply for one arm of the Wheatstone bridge (63). Gardner published again in November, 1897, reporting field trials and modifications. Lead-covered underground wires were used to connect the probes. Calibration procedures are explained in this article (38).

By 1899, Briggs had named the apparatus the "soil hygrometer". The electrodes had evolved from 2 cm² parallel plates placed 1 cm apart to much larger metal and carbon electrodes placed 2 ft apart. According to Briggs, PCM, soil temperature, and soluble salt content of the soil could be determined by various adjustments. A schematic diagram, construction, drawings, and installation instructions are included (25).

Apparently, twenty years passed without any more work on the subject. In 1922 and 1923 Deighton worked with the method, but was unable to substantially improve it. Deighton's work did seem to concur with Brigg's

earlier belief that salinity of normal soils is not altered appreciably by every passing shower and that seasonal fluctuations in soil's ionic concentration are non-existent (33, 34).

A German scientist (Gorz) extended the hygrometer theory and state of the art in a paper presented at an international conference in 1926. (40) This method was still considered only as a means of approximation. In 1937 a Russian scientist (Vadyunina) disputed the hygrometer's usefulness even as a means of approximation (59). Nizenkov, another Russian scientist, publicly challenged Vadyunina's statements in 1939 (54), p. 42. Before an academic feud could develop, Bouyoucos and Mick, whose names were to become synonymous with soil moisture determinations, published the first reports of a breakthrough in conductivity measurements. They eliminated most of the problem of changing electrolyte concentrations by placing the hygrometer probes in a block of CaSO_4 , commonly known as gypsum, or plaster of paris. Gypsum is an excellent buffer. Changes in the ionic concentration of the surrounding water affect gypsum's conductivity very little. However, since the dielectric constant of gypsum is proportional to its moisture content, the conductivity is a measure of the moisture contained. Since gypsum is porous, when buried it will take on or give up water readily to the surrounding soil until a capillary equilibrium is reached. The electrical

conductivity is then proportional to the contained moisture which in turn can be related to the capillary potential of the surrounding soil. The soil's capillary potential is used directly in irrigation work, and may be converted to PCM if the soil's characteristics are known.

With the exception of the period during World War II, Bouyoucos and his associates were prolific with reports on improvements and applications of the gypsum block, now known as the Bouyoucos block or Bouyoucos sorption block. Nylon resins were added to the gypsum for strength and durability (17). Various electrode materials were tried, including stainless steel screens (20). For high PCM readings, a nylon block, either encased in gypsum or not was employed (21, 13, 18). Fiberglass was also tested successfully as a block material (23). Automatic irrigation systems were designed (15, 19), and gained popularity in the cane fields of Hawaii (36).

Today the Bouyoucos sorption block rivals the tensiometer in total use. However, the method still has certain faults. Even though gypsum's ionic concentration makes it an excellent buffer, permanently installed systems must be recalibrated at intervals. Laboratory calibrations generally do not agree with field results (8, 28). Gypsum blocks are not reliable at high PCM's: nylon or fiberglass blocks are employed with a loss of the gypsum's buffer action. These must therefore be

recalibrated even more frequently. Wetting and drying cycle hysteresis is common and sometimes pronounced (27). This method is non-destructive and is well-suited to automatic, remote-site measurements.

Capacitance measurements to determine PCM have been attempted since the 1930's with little success. Brown found it possible to measure the humidity of a closed underground pocket with capacitance, dissipation of a capacitor, or commercial humidity detectors, but he was unable to correlate the humidity of the underground pocket to the PCM of the surrounding soil (26).

Radio frequency absorption as an indicator of moisture content has been successfully demonstrated in homogeneous powders such as flour, but has proven unsuccessful in heterogeneous materials such as soil (6).

INFRARED METHODS

While investigating the factors influencing the absorption of radiant energy by soils, Bowers and Hanks discovered that moisture greatly reduces the amount of radiant energy reflected by soils, especially in the infrared region. By use of spectrophotometers, it was shown that nearly 60% of 1.9 μ radiation incident on "Newtonia silt loam" at 1% moisture content is reflected; only 13% is reflected at 20% moisture content (24).

No other literature on this subject was found, but it should be noted that an instrument for the measurement of moisture in potato leaves has been devised at the

U.S.D.A. Snake River Conservation Research Laboratory
at Kimberly, Idaho.

THERMAL METHODS

Both the thermal conductivity and the heat capacity of the soil increase with the addition of water. It may therefore be possible to measure soil water indirectly by the absolute or relative determination of the soil's thermal characteristics.

Shaw and Baver published the first reports of research into thermal methods of PCM determination in 1939. Their apparatus was basically a Wheatstone bridge, two arms of which were coils of No. 40 enameled copper wire wound on glass tubes and buried in soil samples: one in an oven dry sample, the other in a moist sample whose PCM was known. After much experimentation, it was concluded that "heat conductivity gives a reliable index of the moisture content of the soil." Even more important, Shaw and Baver stated, "it has been shown that changes in salt concentration of the soil solution do not materially affect the heat conductivity of the soil." (53) The necessary contact between the heating element and the soil in Shaw and Baver's work was difficult to maintain. Johnson attempted to overcome this problem by placing the elements in Bouyoucos-type gypsum blocks. This jacket theoretically would have its own moisture holding characteristics, and constant contact with the elements

would be ensured (46). Aldous and others, while testing more than fifty moisture cells of different construction, concluded that the porous block form of cell (of the Johnson-Bouyoucos type) is unsuitable because block moisture is not proportional to soil moisture, and small variations of construction changed calibration.

In the same study a direct contact form of cell, in which the electrical heater and temperature sensor were cast in Wood's metal, was devised. The entire unit was placed in direct contact with the soil. This unit proved satisfactory only at low PCM's.

The most effective method tested was a direct conduction method in which the heating and temperature measuring elements were separated by soil. Shrinkage of the soil away from this probe was especially bothersome because of the geometry of the cell. This cell was extremely fragile.

More work on both the Wood's metal and direct conduction methods was recommended (1).

Bloodworth and Page introduced the thermistor, or temperature sensitive resistor, as a combination heat source and temperature indicator. (Aldous had used thermistors, but only as temperature sensing devices.) Bloodworth placed the devices in gypsum and Castone (dental stone powder) blocks. He concluded that, while a lag between soil moisture and block moisture existed,

especially at low soil moisture levels, "By growing actively transpiring plants in the soil containers in which the blocks were imbedded, the lag in response of the blocks to changes in soil moisture was greatly minimized. This condition was attributed to the development of a steeper soil moisture gradient in the boundary layer surrounding the resistance blocks." (9)

Bloodworth held the thermistor block to be definitely superior to the Bouyoucos resistance block under both saline and non-saline conditions (10).

Other suggested methods of this general type include the wrapping of a mercury thermometer with electrically heated wire (47).

PART II

EXPERIMENTAL WORK

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.

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.

While nuclear methods may be the most promising, they have been eliminated 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.

So much has been published already on electrical conduction methods that redundancy has occurred. Unless a significant breakthrough occurs in electrical conductivity, further work is unwarranted. Capacitance measurements and humidity detection in buried air pockets were studied by Brown (26) with no success. Radio frequency absorption and acoustical attenuation warrant further study, 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 warranted.

Several authors have recommended further work on the thermal conductivity method. A comparatively small amount of literature is 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 field has therefore been chosen for developmental research.

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 was held desirable, and is reported in this thesis.

The phenomenon of nuclear magnetic resonance has been successfully utilized to measure moisture content of some homogeneous substances. In a companion thesis by Mr. N. S. Haraprasad it was concluded that the multitude of different ions present in any given soil render this method unfeasible for general soil moisture measurements (41). The topic will therefore not be covered in this thesis.

STREAMING AND ZETA POTENTIALS

THEORETICAL CONSIDERATIONS

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 the 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.

If the zeta potential could be precisely determined at the boundary of a given soil particle,

soil moisture content information might be inferred. This is especially true at low moisture levels at which most moisture is in the form of thin films surrounding the soil particles.

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.

EXPERIMENTATION

Test cells were fabricated from cylindrical porous cups whose diameter was 2.0 inches. Wire mesh electrodes were placed against the inside and 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 connection 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 filling 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 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. A typical data plot is shown in figure 1. 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

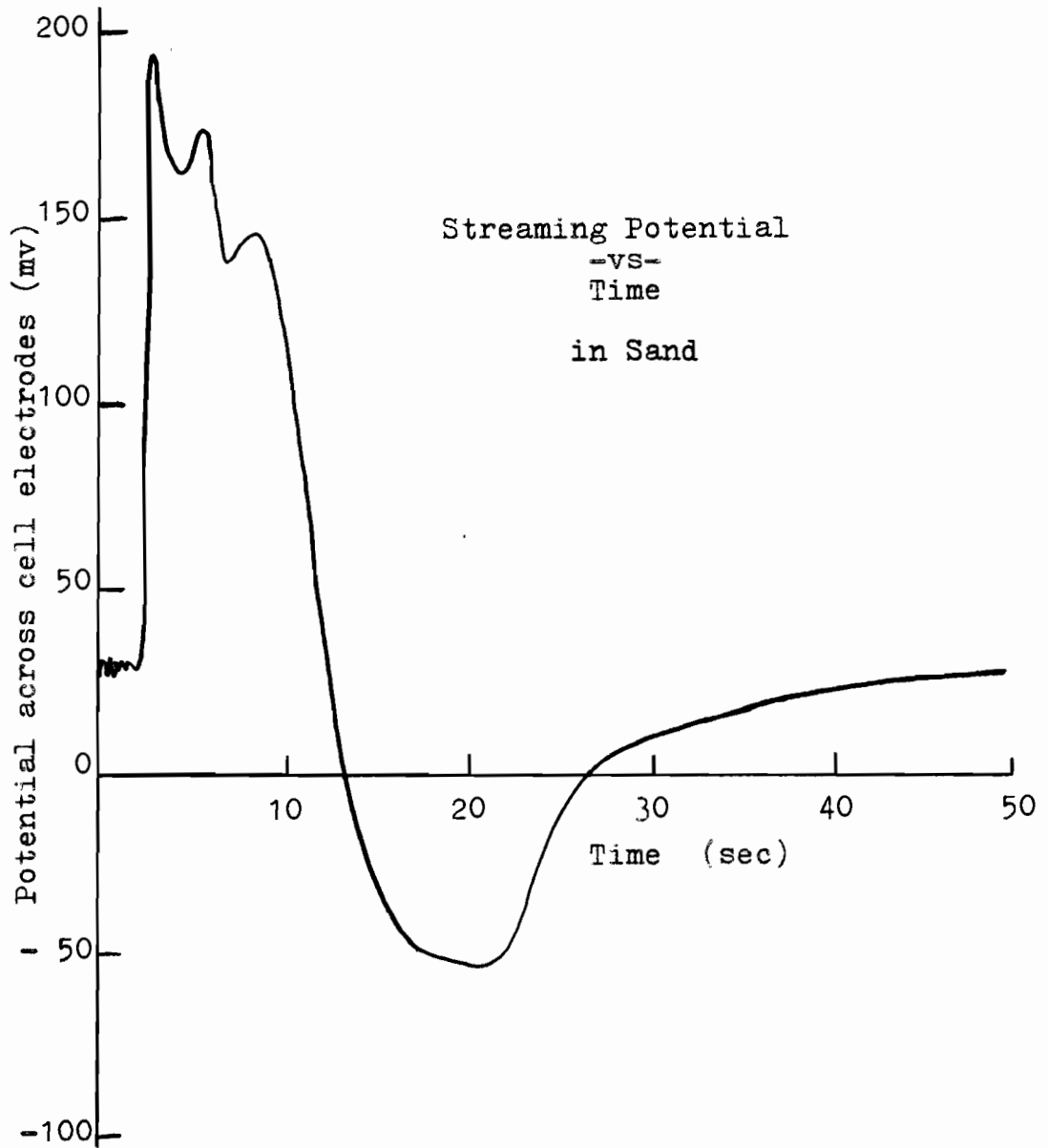


Figure 1. Typical plot of streaming potential-vs-time in the experimental cells with the addition of water.

highly sophisticated equipment.

CONCLUSIONS

Measurement of streaming potentials for determination of soil moisture does not appear feasible for field applications. Further investigation of streaming potential for soil moisture measurement is not recommended.

DEVELOPMENT OF A SYSTEM FOR
INFRARED MEASUREMENT OF SOIL MOISTURE

THEORETICAL CONSIDERATIONS

Whenever electromagnetic waves, such as light, strike a substance, the energy contained in the wave is divided into three parts: some energy is transmitted, or passes through the substance; some energy is reflected back in the general direction from which it came; and some energy is absorbed, or remains in the substance as heat. Many substances tend to readily absorb electromagnetic energy at certain wavelengths. Water, for example, readily absorbs energy in several frequency bands of the infrared region. The infrared region is that part of the electromagnetic spectrum whose frequencies are just below those of visible light. Infrared radiation is often abbreviated IR, and consists of all electromagnetic wavelengths between 0.7 and 400 μ .

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 1.9μ . Results of studies on the energy reflected from "Newtonia silt loam" as reported by Bowers (24) are summarized in figures 2 and 3.

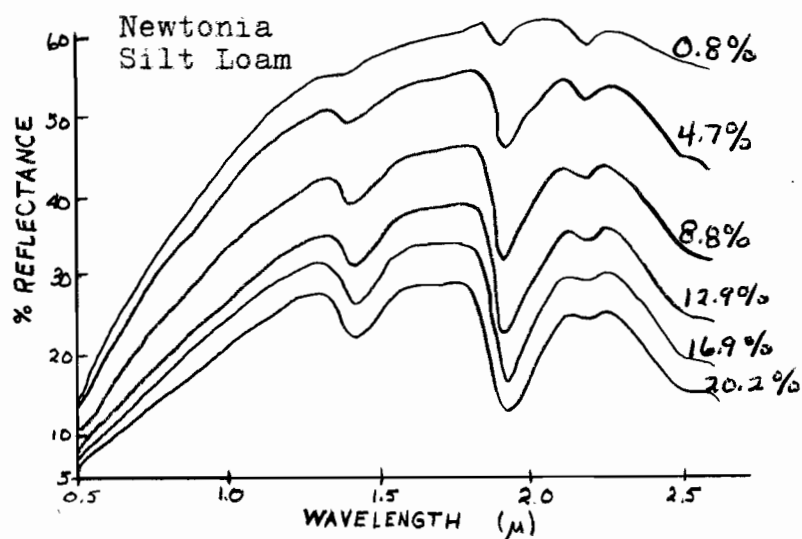


Figure 2. Per cent reflectance-vs-wavelength of incident radiation at various moisture contents (moisture contents indicated directly above each curve). (24)

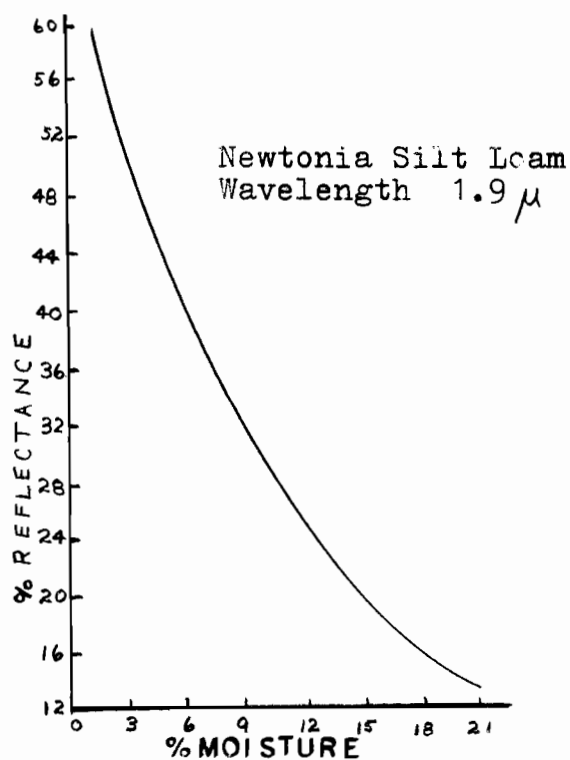


Figure 3. Per cent reflectance-vs-surface moisture content for incident radiant energy of 1.9μ . (24)

PROCEDURE OF DEVELOPMENT

As a result of the literature search and evaluation of the materials available for experimentation, the 1.9μ absorption band of water was chosen for use in an experimental soil moisture measuring device. Ordinary glass is opaque to wavelengths greater than 2.2μ , 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.

FILTERING

In order to isolate the desired 1.9μ energy, it was necessary to filter out other wavelengths. Figure 2 indicates that for highest sensitivity, a very narrow bandwidth centered at 1.9μ would be desirable. Spike filters having a bandwidth of less than 0.1μ 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 from Corning Laboratory Products, the type 7-56 IR Bandpass filter transmits wavelengths from 1.0 to 2.75μ . Longer wavelengths are further filtered by a crown glass window and by the glass bulb which protects the filament IR source.

Glass does not transmit wavelengths above 2.2μ . The transmitted wavelengths of the glass-filter combination are therefore in the range 1.0 to 2.2μ .

SELECTION OF THE IR SOURCE

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.

SELECTION OF A DETECTOR

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. Thermoelectric devices are available for this purpose, but their power requirement was considered prohibitive for battery operation at remote stations. Photomultiplier tubes would require a

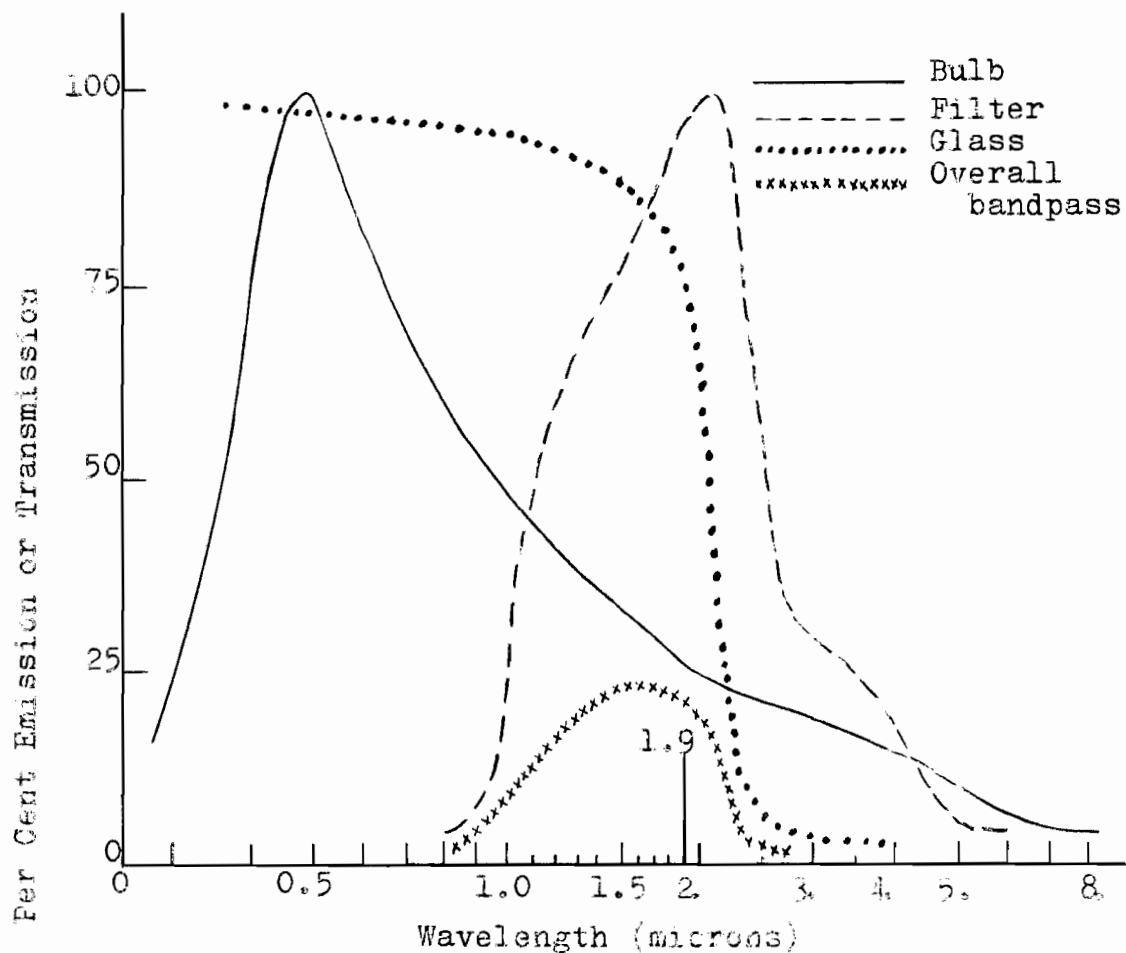


Figure 4. Spectral emission characteristics of the GE-27 incandescent bulb operated at 5.5v, and transmission characteristics of crown glass and the Corning type 7-56 IR filter, showing the resultant overall bandpass of the IR source system.

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 operation of this device 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 of this device was a function of the IR energy falling upon its sensitive window. The drain current varied from much less than 1.0 microamp in dark conditions to 20 microamps under bright incandescent lights. It was decided to attempt to utilize this device in a soil moisture measuring system.

CIRCUITRY

Once the detector had been chosen, a means was required for converting the extremely small detector currents into a more useful quantity. Mechanical devices which chop the detected light beam have been used to create an a-c signal at the output of photodiode detectors.

This signal is then amplified by conventional means to a usable level. In order to eliminate the power and space required by a chopper system, a purely electronic means for accomplishing the same purpose was considered.

A bridge configuration, with the detector forming one arm, was tried. The very high impedance level of the detector was associated with too much noise. Often noise voltages greatly exceeded the signal voltages.

To improve the signal to noise ratio, the detector was placed in parallel with the load resistance of a difference amplifier. An R-C coupled oscillator fed a sine wave to both difference inputs, and the system was balanced under dark conditions so that the difference between the two output voltages was zero. Exposing the detector to IR unbalanced the amplifier and a difference between output voltages was observed. This difference was shown to be a function of the amount of IR energy incident on the detector. However, the extreme difficulty encountered in keeping the amplifier properly balanced over a wide range of ambient temperatures, and the fact that the system was effective only over a narrow range of input intensities, caused this approach to finally be abandoned.

An astable multivibrator configuration, in which one time period is determined by the photodiode current, was more successful. A schematic diagram of the

circuit is shown in figure 5. Transistors Q_1 and Q_2 are the standard multivibrator switching transistors. Capacitor C_1 is charged by the collector current of Q_5 during "OFF" time. This current is controlled by the much smaller current through the base of Q_5 and the photodiode. A constant voltage of 5.5v remains across the photodiode regardless of the current through it. Diode D_1 was added to protect Q_5 from positive-going noise signals which might destroy the fragile base-emitter junction.

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 the temperature compensating network, C , is small.

The temperature compensating network has not yet been designed. Its function will be to adjust the "ON" time with temperature so that sensitivity variations of the detector will be cancelled. Thermistors will be used as temperature sensors in the network. Since temperature response curves are not available for the detector the desired function of the compensating network must be determined experimentally.

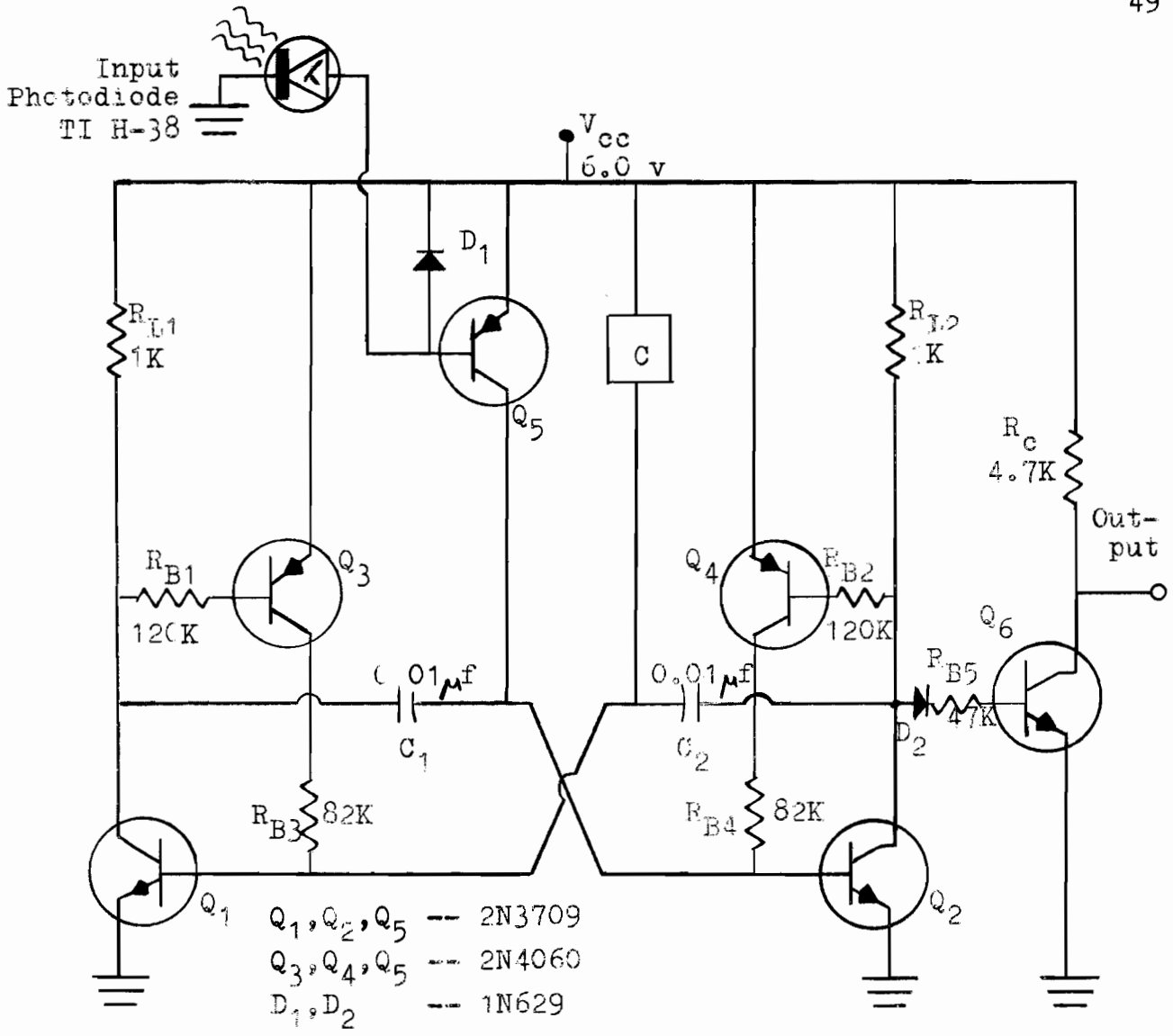


Figure 5. Astable multivibrator used with Photodiode in the IR moisture detector.

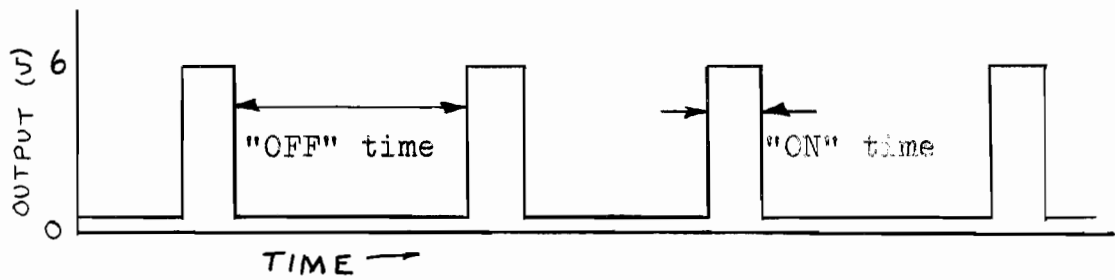


Figure 5a. Multivibrator output waveform.

Until this can be accomplished, a 200 K resistor will be used for C. Transistor Q₆ operates as a buffer amplifier to prevent output circuitry from loading the astable.

PROBE DESIGN AND TESTING

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 appearing adequate, construction of a device capable of measuring soil moisture was undertaken.

A 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 $\frac{1}{4}$ in. plexiglas. A brass shield prevented direct transmission from source to detector. The reflector assembly is illustrated in figure 6.



Figure 6. Reflector assembly of the IR moisture detector, showing source, detector, and reflector.

The astable multivibrator circuit was fabricated on a semicircular vector-board (figure 7) 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. Figure 8 illustrates the completed instrumentation package.

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 Tektronix 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 9.

To protect the instrument during field testing, a brass canister was fabricated to enclose the instrument package and battery power source. This is illustrated in figures 10 and 11. 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 is placed in direct contact with the soil sample, is necessary since an air space in contact

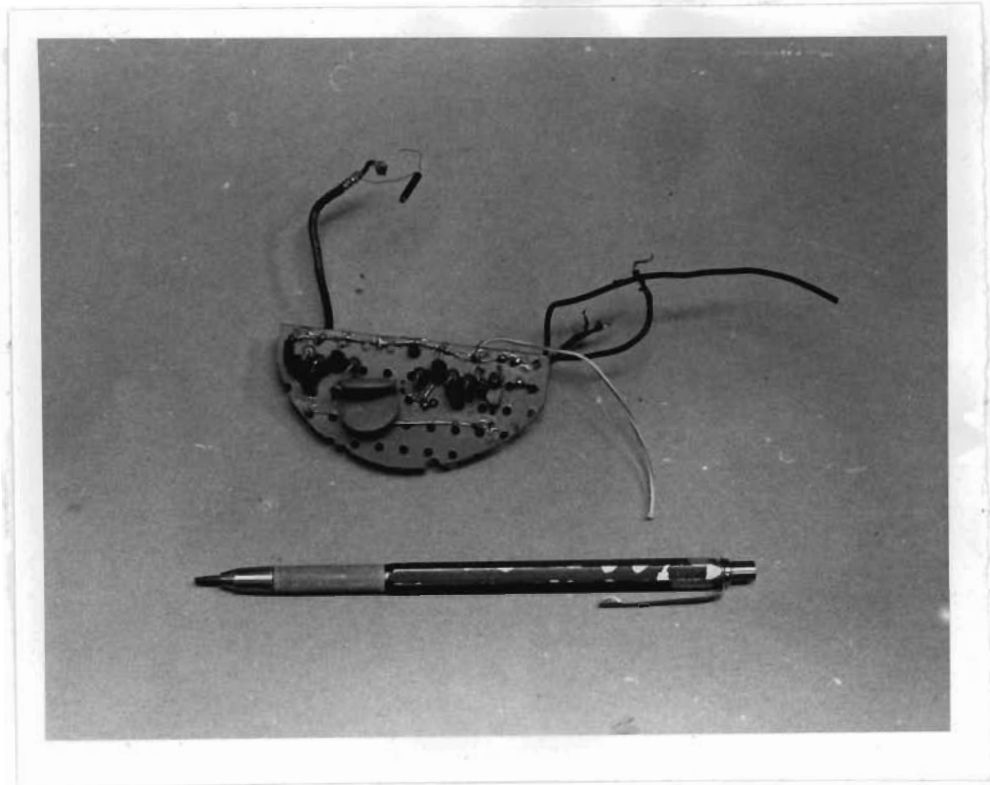


Figure 7. Semi-circular vector board base used to mount the astable multivibrator in the IR moisture detector.

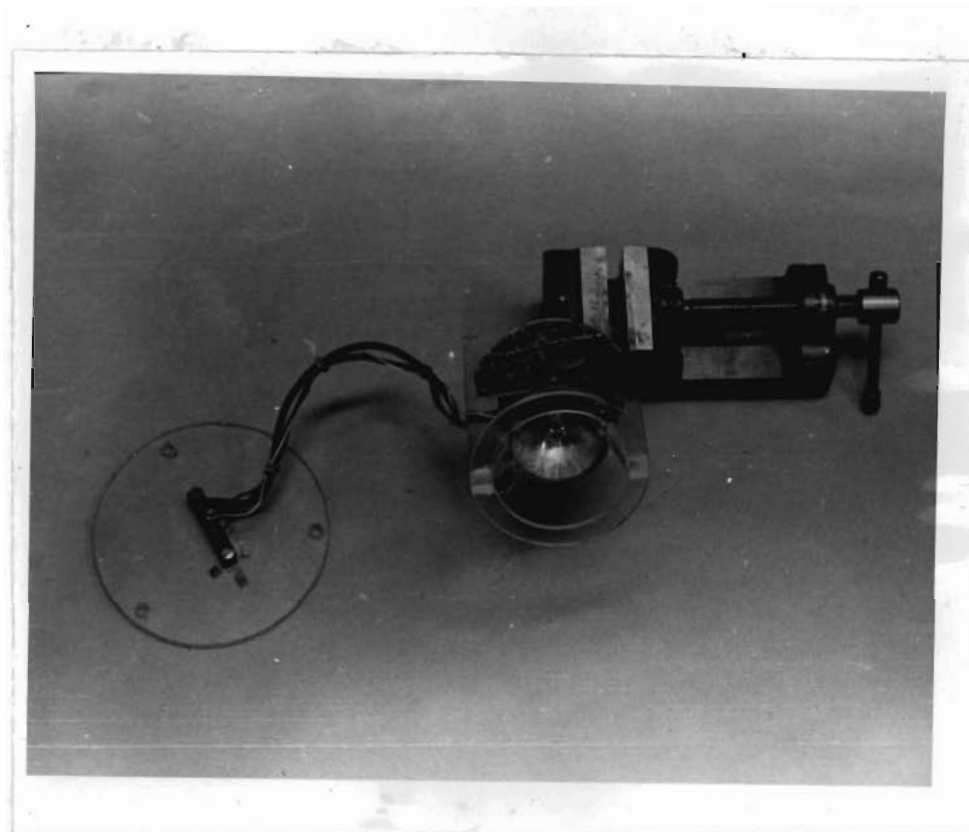
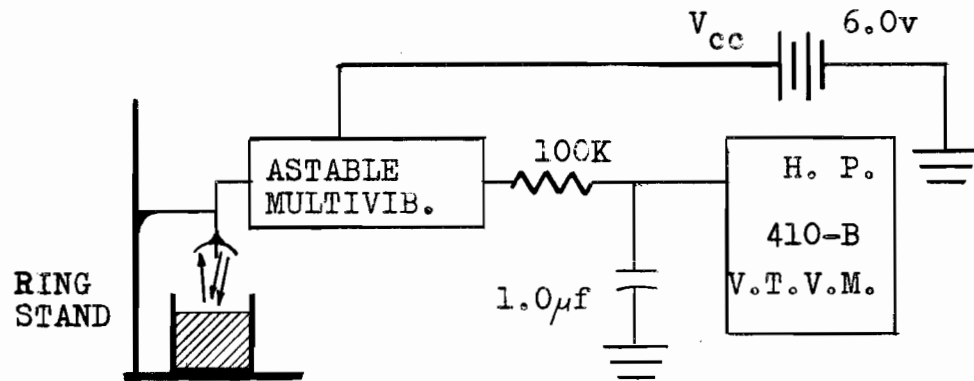


Figure 8. Completed instrument package
for the IR moisture detector.

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 measuring circuit is shown in figure 9 on page 56.



EQUIPMENT SET-UP
FOR TESTING
IR MOISTURE METER

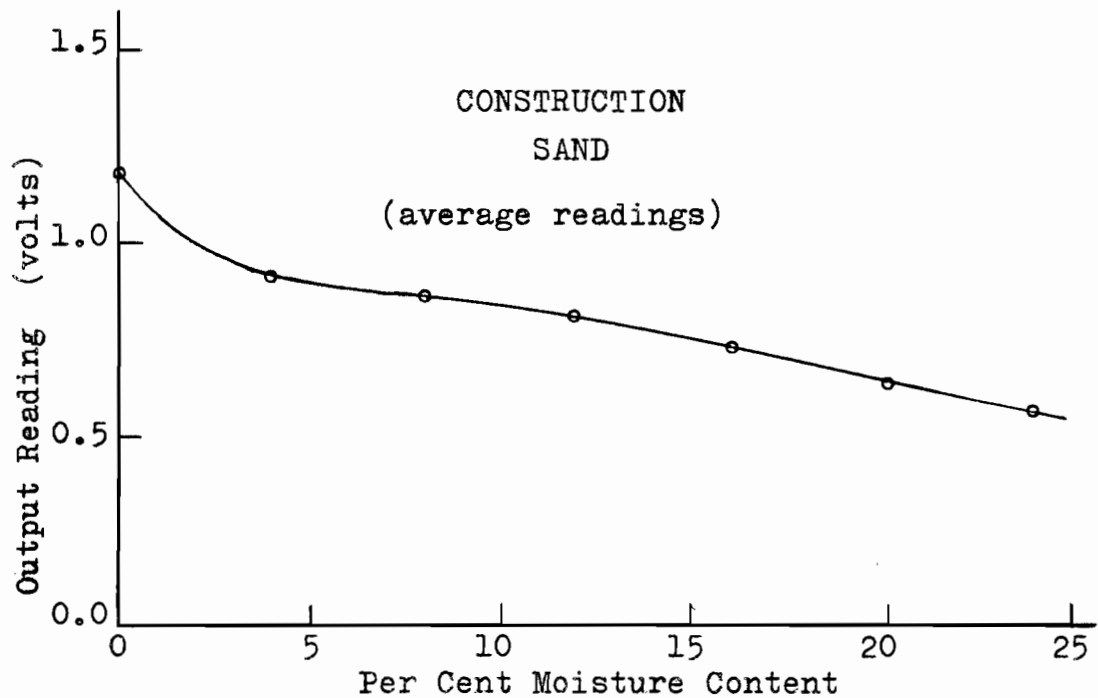


Figure 9. Output direct current voltage-vs-moisture content for IR moisture detector in construction sand.



Figure 10. Assembled IR moisture detector, bottom view, showing window through which measurements are taken.

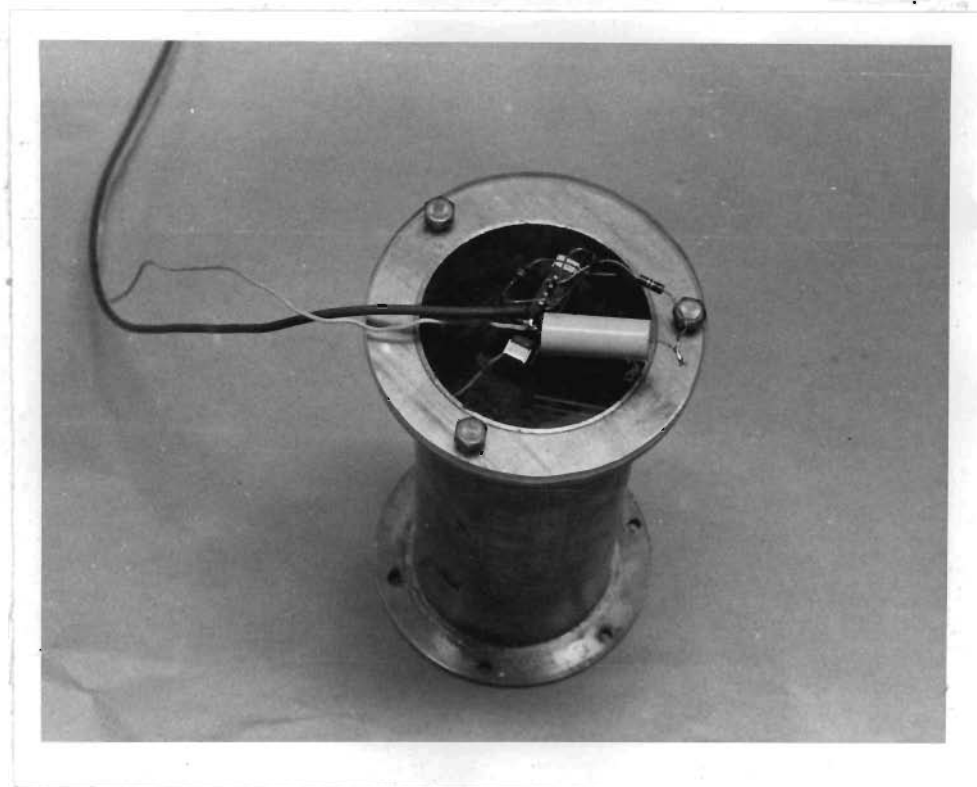


Figure 11. Assembled IR moisture detector, top view, showing external leads for power input and signal output.

with the soil would seriously alter the moisture content of the soil surface. 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. Utilization of a fiber optic transmission paths might eliminate the window entirely.

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

1.9 μ . 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 thesis, the IR experimentation was placed before the thermal probe development for sake of continuity. Chronologically, the IR studies occurred last, and the time available for research was limited. At the time of this writing, efforts to improve the IR **soil moisture** device are in progress. Further results will be published in the final report of the University of Idaho Water Resources Engineering project, "Studies on Methods of Soil Water Determination."

DEVELOPMENT OF A THERMAL DEVICE FOR MEASURING
SOIL MOISTURE CONTENT

THEORETICAL CONSIDERATIONS

GENERAL

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 defined loosely as the amount of heat energy required to raise a unit volume of soil mass one temperature degree - the units are therefore $\text{cal}/(\text{cc})(^{\circ}\text{C})$. This parameter is introduced here to prevent confusion with the quantity "specific heat", which is the amount of heat energy required to raise a unit mass one temperature degree. Heat capacity is equal to the specific heat times the density. The reader will note that for liquid water both the specific heat and the heat capacity of water are very nearly 1.0, however the quantities will not be equal in substances having a density other than 1.0 gm/cc .

*While "heat capacity" is not considered technically correct in thermodynamic circles, it provides an excellent aid to the discussion to follow, and is introduced here for the convenience of the author and reader.

Before attempting to realize a PCM measuring device using the phenomenon of increasing heat capacity and thermal conductivity, an insight into how water causes these changes is desirable.

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, of course, are not empty. They may be filled with air or water, 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 unaffected by the water's presence.

For illustration, consider a rather non-general soil type, construction sand. Construction sand is a coarse-textured soil composed almost entirely of silicon dioxide, and is sometimes called "quartz sand" even though other allotropic forms of SiO_2 are present.

Construction sand was chosen for experimental work in this project because a similar type may be found near any laboratory should verification of the

results presented in this thesis be contemplated. Further, the coarse texture allows water to pass freely and minimizes the time required for a capillary equilibrium to be reached after the addition of water.

The construction 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 total volume occupied by one gram of dry sand is found by taking the reciprocal of the bulk density.

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

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:

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

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.

$$\begin{aligned} \text{H.C.} &= (1-\eta) (\rho_p) (c_{p-p}) \\ &= (0.538) (2.56) (0.188) \\ &= 0.279 \text{ cal/(cc)}(^{\circ}\text{C}) \end{aligned}$$

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 given below.

$$\begin{aligned}
 \text{H.C.} &= (1-\eta) (\rho_p) (c_{p-p}) + (\eta) (\rho_w) (c_{p-w}) \\
 &= (0.1538) (2.56) (0.188) + \\
 &\quad (.417) (1.0) (1.0) \\
 &= 0.279 + 0.417 \\
 &= 0.696 \text{ cal/(cc)}(^{\circ}\text{C})
 \end{aligned}$$

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.

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

Another soil used for testing was Roberts Fine Ash, a volcanic ash soil from the fertile potato lands of Southeastern Idaho. 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. This value was checked using Archimedes' Principle. The porosity is 53.8%. Using calculations similar to those above, the heat capacity is computed as:

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

THERMAL CONDUCTIVITY

A casual observer might expect a sand of about 50% porosity (therefore 50% solids) to possess a thermal conductivity of about one half that of a fused mass of the solid material. This logic is true for heat capacity, but is grossly in error for thermal conductivity. The thermal conductivity of dry quartz sand is less than 5% that of fused quartz.

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 12).

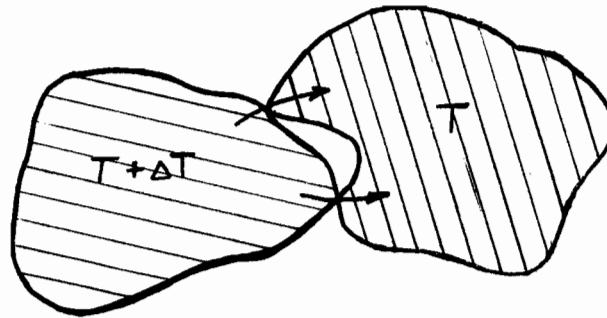


Figure 12. Adjacent sand particles, showing heat conduction paths.

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

If a small amount of water is added to the sand, a film forms around the particles (figure 13). The thermal conductivity of water is only one tenth that

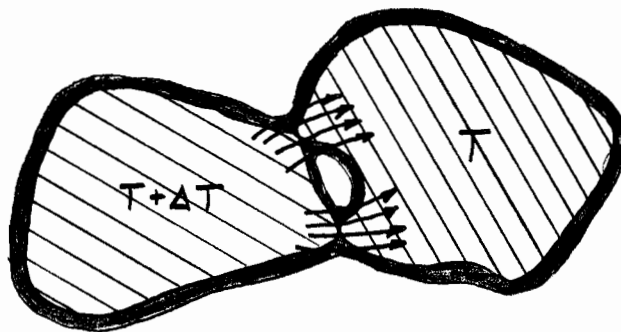


Figure 13. Adjacent sand particles with film water, showing increased heat conduction paths.

of quartz particles. Nevertheless, the heat 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 enhanced.

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 the thermal conductivity-vs-soil moisture curves to be almost exponential for quartz sand and more linear for clay (figure 14).

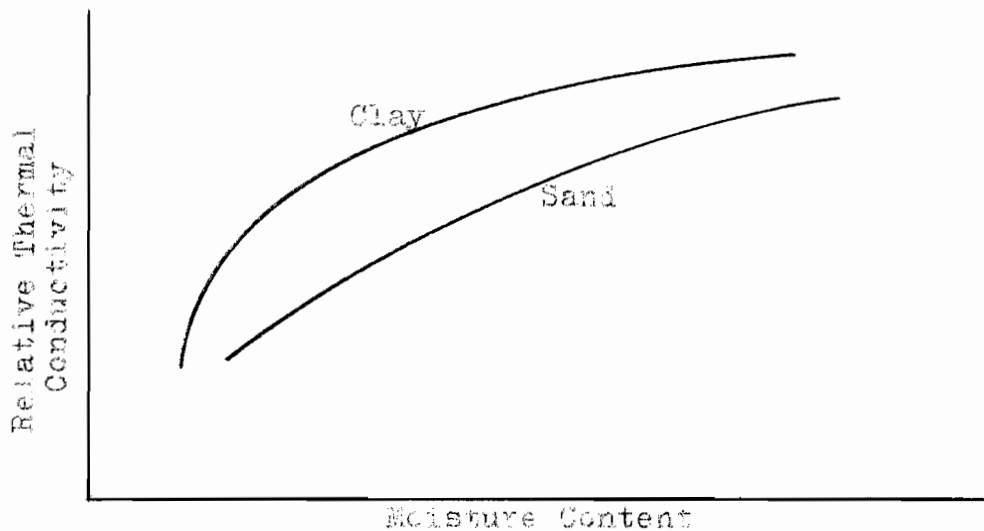


Figure 14. Shape of Conductivity-vs-soil moisture curve

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, the rate of increase decreases at high moisture contents.

DIFFUSIVITY

If a heat source is imbedded in an infinite, homogeneous substance initially at uniform temperature, a heat wave will propagate radially from the source,

and 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.

From a comparison of the previously given thermal conductivity and heat capacity functions, 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 in 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 contains many attempts at imbedding thermal devices in gypsum, nylon, or fiberglass blocks of the general type used in electrical conductivity soil moisture measuring 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 compares the thermal characteristics of a constant, specified material with those of the surrounding medium (soil) will be developed. 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 will be measured indirectly by observing the temperature rise of the material some distance from the point of application of heat energy.

PROCEDURE OF DEVELOPMENT

INTRODUCTION

From its initial conception, the thermal probe was developed in a logical sequence of steps. Problems were encountered and overcome or sidestepped. Various testing methods were explored, either to be discarded or perfected. Were this thesis to cover only the final product, many of the considerations which led to this product might be overlooked. In order that experience gained through trial and error might be shared, that similar mistakes might in the future be avoided, and that any misconceptions might be cleared, the author has chosen to follow the chronological development of his device in this thesis.

CONCEPTION

The original idea was stated concisely in the project log:

"...water has a heat conductivity and a specific heat about five times greater than that of soil. A thermistor may be used to heat a strip of copper ...at one end. Another thermistor at the other end of the copper strip, measuring the temperature rise there, should be sensitive to ground moisture, since the wetter the soil, the faster

heat will be carried away from the strip, and hence the lower the temperature of the measuring thermistor." (42)

MODEL NO. 1

Any thermal device for measuring water content must be large enough to sample a representative block of soil, yet small enough that the power required to heat it does not rule out long-term battery operation.

The first device tested consisted of a copper strip 2 x 1/8 x 1/16 in. with a thermistor securely fastened at each end by wrappings of fine, heat-conducting copper wire. The heater thermistor was a Fenwal type RB33L1 (rod-shaped), the temperature sensor a Fenwal GB32P8 glass probe type thermistor. Resistance-vs-temperature plots for these thermistors are given in Appendix A. The entire device was water-proofed by dipping twice in a 1:1 solution of Duco Cement thinned with acetone, and oven curing. (In thicker solutions, bubbles will form during curing.)

A clay-type soil was obtained from the immediate area of Kirtley Laboratory on the University of Idaho campus. The soil was oven-dried and placed in a glass container with a plastic cover so that moisture could not reach the soil from the air. The thermal unit was imbedded in the soil, and the sample was vibrated by tapping on

the glass container with a hard rubber rod for five minutes.

The instrument was tested in the configuration shown in figure 15. The power supply voltage was set

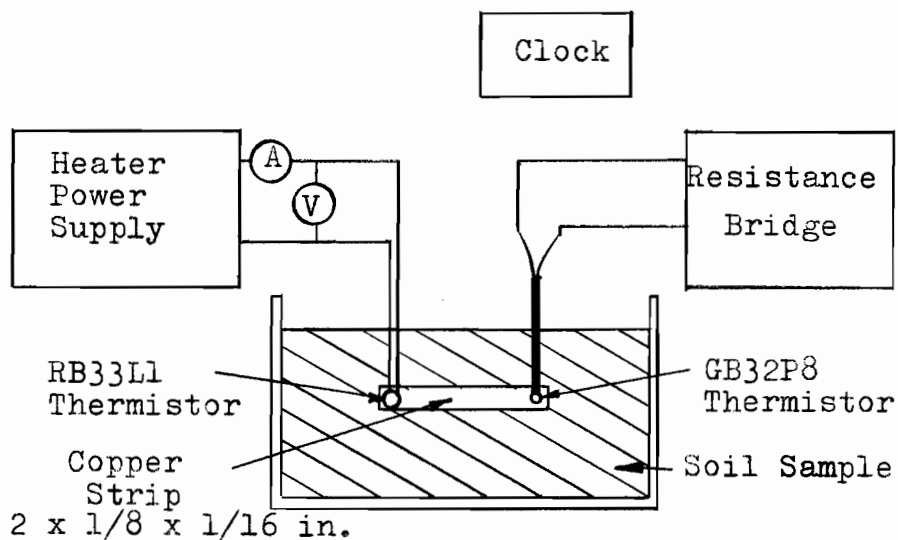


Figure 15. Apparatus used to test Model No. 1.

at 30v, but the heater current was limited by the supply to 92 ma. The heater was turned on for a period of ten minutes and the temperature rise was noted using the bridge and calibration curves. Several runs were made on dry soil to determine whether the results would be consistent. The results are tabulated in table 2.

Ambient Temperature (°F)	Temperature Rise °F			
	2 Min	5 Min	7 Min	10 Min
77	15	23	25	27
78	13	23	25	29
80	13	23	24	27
71	14	24	26	28
71	15	24	26	28

Table 2. Data obtained from Model No. 1 in dry clay.

A nine degree change in ambient temperature does not affect the temperature rise, which is $28 \pm 1^\circ\text{F}$ in ten minutes. These results appeared encouraging, and enough water was added to the soil sample to make 2.5 PCM. When the water had not distributed itself evenly through the soil sample in three days, water was added to 5.0 PCM. Three days later, the water was observed to be in the top layer of the soil only.

In order to minimize the time required for the water to distribute itself throughout the soil sample, it was decided to use construction sand as a test soil. A sample of sand was oven dried, and readings were taken as before.

To discover whether a large difference in ambient temperature would affect the readings, the sample was placed in a refrigerator during the last two trials

tabulated in table 3. From the data shown it would appear that lower ambient temperatures result in smaller temperature rises. This effect was caused by the very high resistance of the heater thermistor at low temperatures. Until the heater thermistor raised its own temperature, the power input was limited by the high heater resistance. For this reason it was decided to abandon heating with a thermistor, and to heat the copper strip with a constant power input to a resistor of known and constant value.

MODEL NO. 2

Model No. 2, shown in figure 16, was constructed using a 2 x 0.1 x 0.03 in. copper strip. A 330 ohm, half-watt resistor (measured resistance 342 ohms) was thermally connected to one end of the strip by wrapping with many turns of fine, enameled copper wire. The other end of the strip was gently bent around a Fenwal GB32P8 glass probe thermistor. This connection was also secured with fine wire. The device was electrically sealed by twice dipping in a 1:1 solution of Duco Cement and acetone. Additional coats of the solution were painted on the ends. The waterproofing was oven cured at 100°F after each coating.

Data taking with the first model had been very

Trial Number	Ambient Temperature (°F)	Temperature Rise °F	
		5 Min	10 Min
1	77	20	24
2	78	20	24
3	80	20	23
4	81	20	23
5	81	20	23
6	73	20	24
7	76	19	23
8	49	18	21
9	45	18	21

Table 3. Results of tests on Model No. 1 in dry sand.

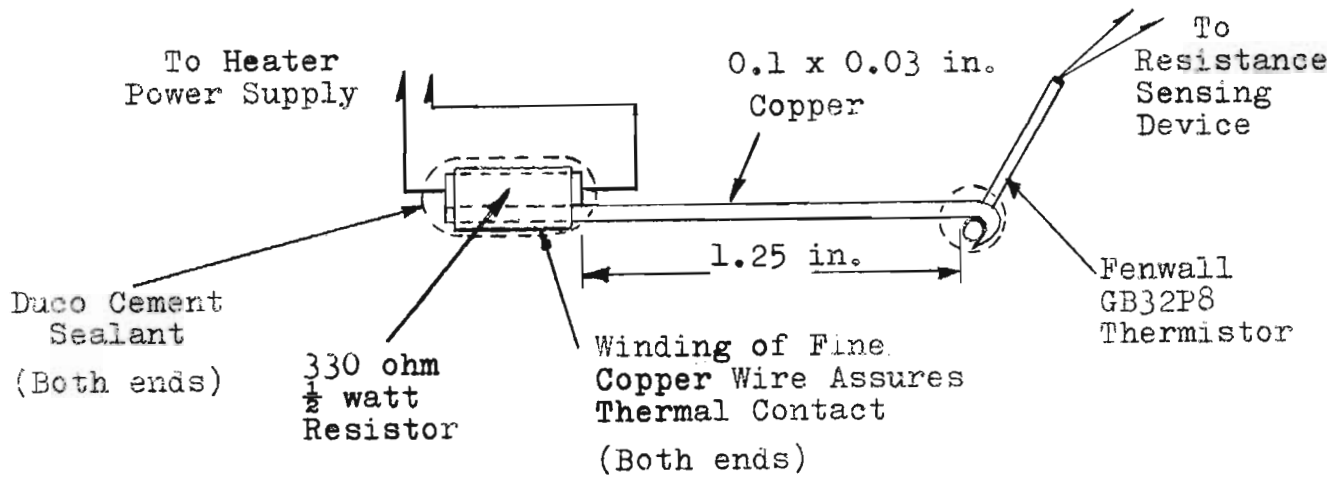


Figure 16-a. Construction drawing of the improved thermal moisture detector, Model No. 2.

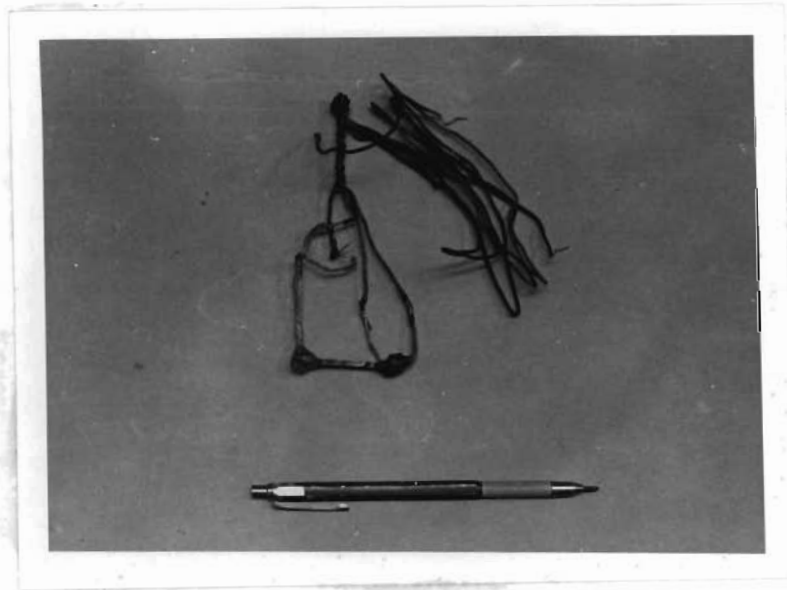


Figure 16-b. Thermal moisture detector, Model No. 2.

time consuming, since an operator was necessary to read the bridge. While the waterproofing of Model No. 2 was being cured, an automatic data taking system was constructed, using a Honeywell x-y recorder. A relatively constant current of 300 microamps was obtained by placing a 100K resistor in series with the heater supply voltage of 30v. When this current was routed through thermistor of Model No. 2 a voltage nearly proportional to the thermistor's resistance appeared between its terminals. The input impedance of the vertical amplifier on the Honeywell x-y recorder was not large enough to prevent loading if connected directly across the thermistor. It was therefore necessary to use an emitter follower configuration to drive the recorder. A circuit diagram is given in figure 17. The 10K resistor biases the transistor into its linear region. The slowest time base on the x-y recorder was too fast for this application, so an external time base was generated using a 10K precision ten-turn potentiometer and a small synchronous motor of the type used in electric clocks. Some loading occurred, due to the low input impedance of the x-y recorder's horizontal drive amplifier, but this effect was within acceptable limits. A photographic exposure timer was used to turn off the heater current after

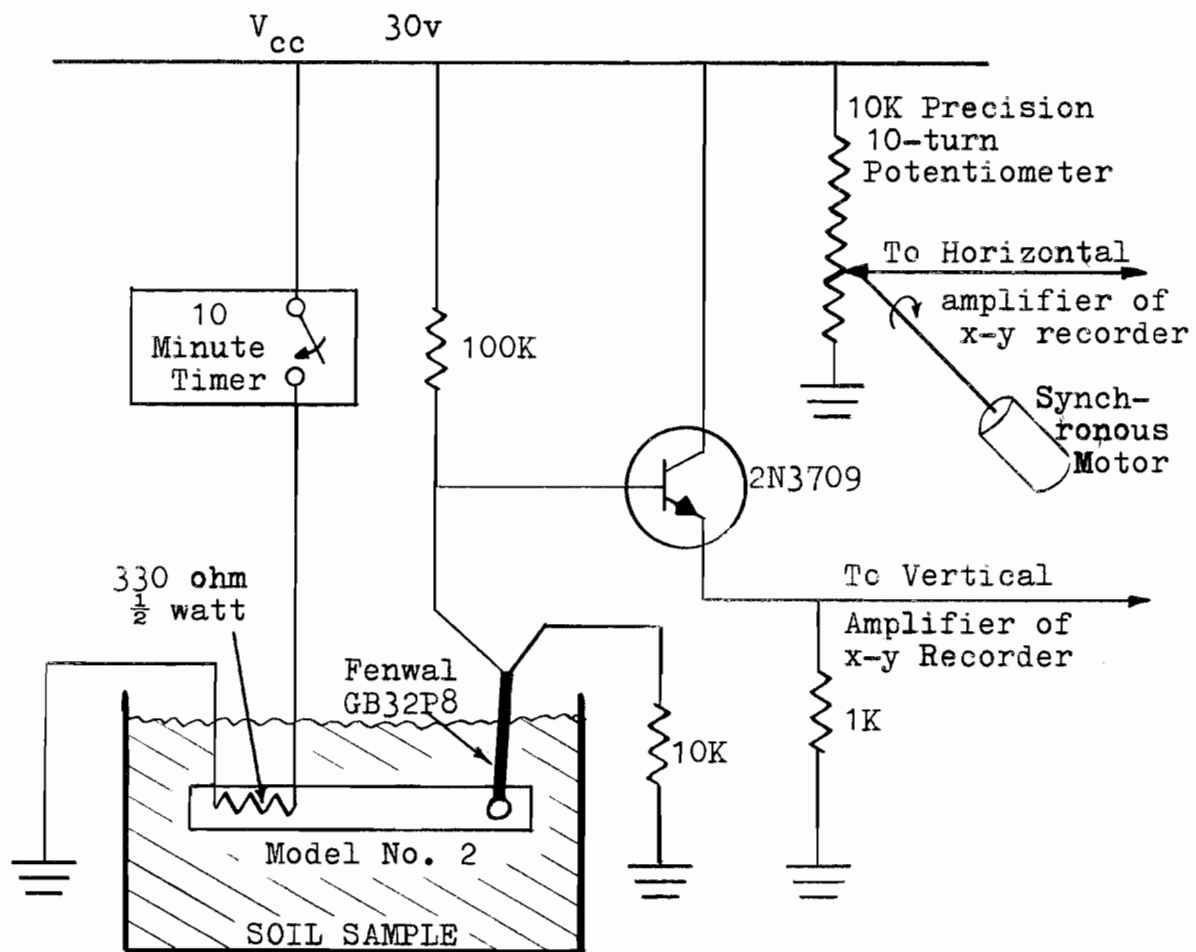


Figure 17. Automatic Data System used with Model No. 2.

10 minutes. Human attention was necessary only to start and stop a data run. The vertical deflection was calibrated by substituting a decade resistance box for the thermistor.

Model No. 2 was tested in sand at 0.0, 5.0, 7.5 and 10.0 PCM. Results are given in table 4 and shown in figure 18. Model No. 2 was accurate at low moisture levels, but became much less accurate near 30% of saturation.

PROTOTYPE I

In order to move the low moisture level lines together on figure 18, and to spread the higher moisture lines apart, the geometric configuration of the device must be modified. A greater amount of the heat generated in the resistor must reach the thermistor. The conducting area of the metal strip must be increased without substantially increasing the surface area exposed to the soil.

Models 1 and 2 were not suited for field use for several reasons. Four separate leads were attached to the devices and each lead had to be waterproofed. The glass probe thermistors used were very fragile and required extreme care in handling. The devices could be placed in the soil only by digging a hole and burying them, thus disturbing the compaction of the critical area which the units sample.

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

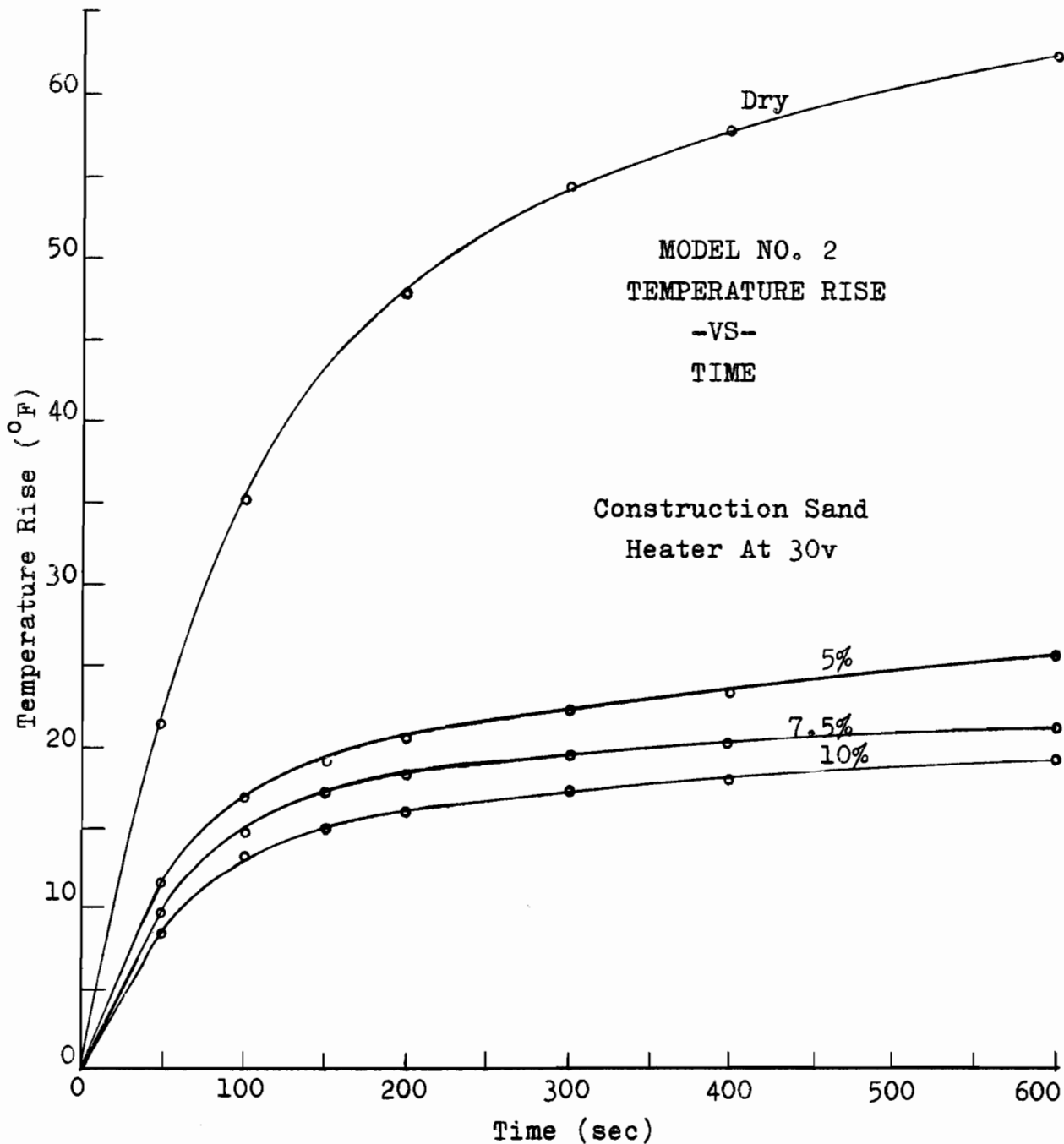


Figure 18. Temperature rise-vs-time plots for different moisture levels using Model No. 2 in construction sand.

Prototype I was designed to overcome these shortcomings. 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 in. diameter and 1/8 in. 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 flange by a silicon rubber washer in slight compression. As shown in figure 19, 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. A tubular plexiglas collar, also shown in

figure 19, was then successfully used to hold the heat conductor firmly to the base. A retaining pin held the collar in place on the base. Thin silicon rubber washers, with holes cut in appropriate places for the thermistor, sealed the space between heat conductor and base. Thin seals of silicon rubber also were used to prevent water seepage between the collar and the heat conductor flange.*

The data system was improved before testing Prototype I by replacing the x-y recorder with a Brown self balancing potentiometer. Since the maximum input voltage allowed was 20mv the emitter resistor was divided as shown in figure 20. Gain adjustments with the x-y recorder were facilitated by the instrument's own controls. The Brown instrument was not equipped with this feature, so an analog computer was programmed to supply an adjustable constant current to the thermistor. The biasing resistor was made adjustable for zero-setting. The chart drive of the Brown instrument was altered to produce a chart speed of 0.02 in./sec.

*Silicon rubber is a very useful sealant. It resists organic and carbon-based solvents. Concentrated acetic acid dissolves it very slowly. It is available in plastic form, and cures to a solid flexible mass in 24 hours. Dow Chemical Co. manufactures it under the trade name Silastic.

PROTOTYPE I

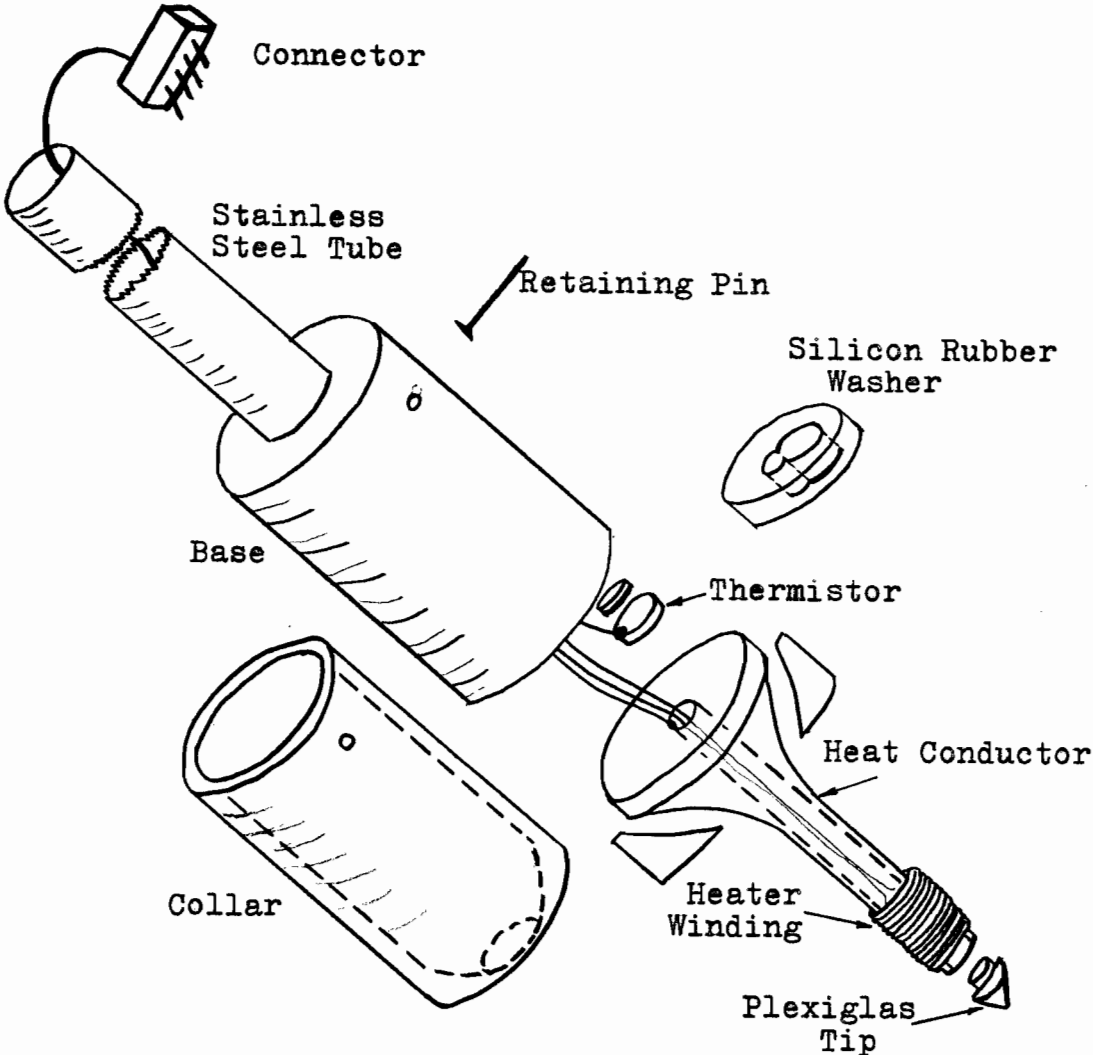


Figure 19. Construction drawing of the thermal soil moisture detector, Prototype I.

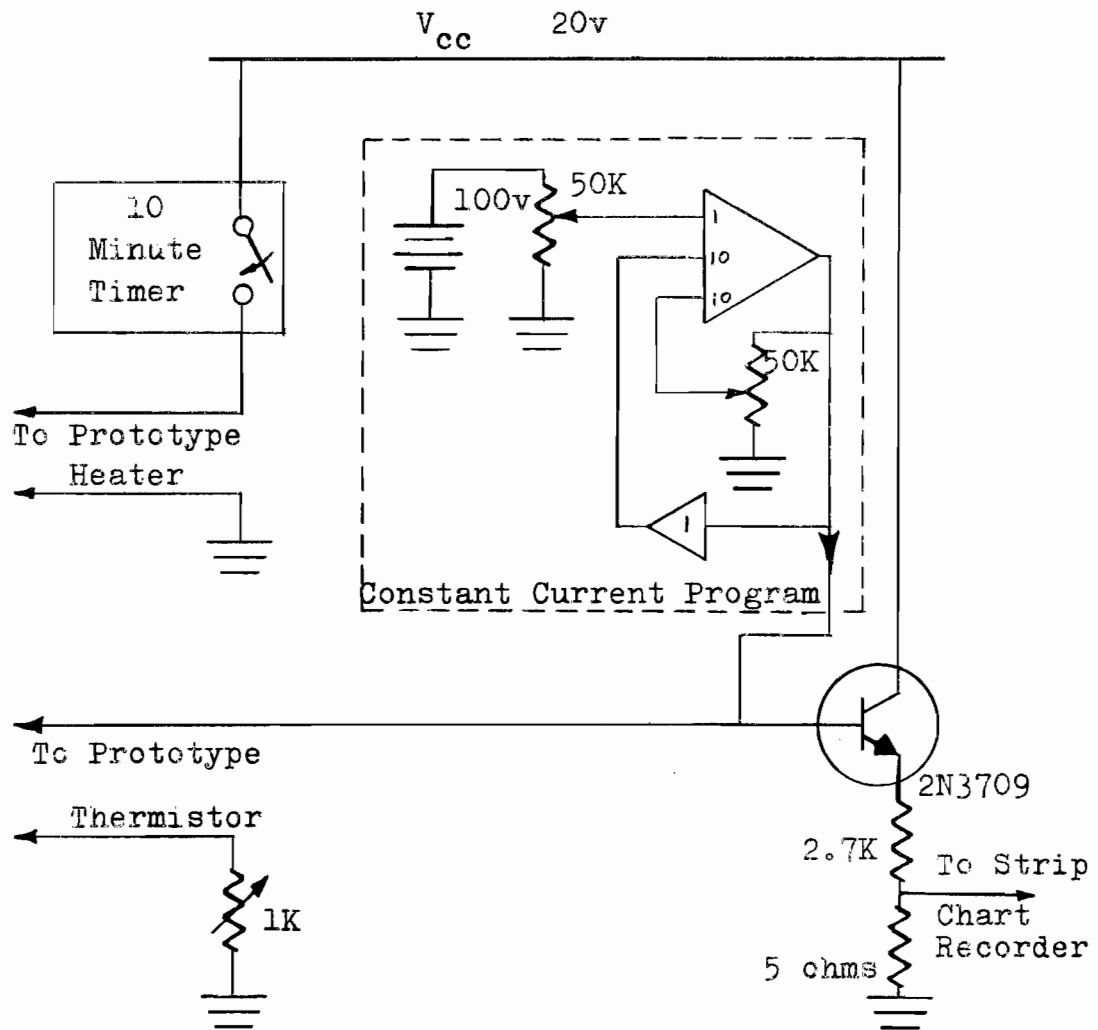


Figure 20. Schematic diagram of the data system used with Prototype I.

The resistance of the prototype was now automatically recorded and could be read directly from the Brown instrument at any desired moment.

The analog computer used in this project was a gift to the University of Idaho from Boeing, Inc. Some repairs were necessary to put the machine in working order, but it then functioned perfectly and was very useful.

To provide better control of temperature in soil samples, to be able to subject the samples to both wetting and controlled drying cycles, and to more closely duplicate field conditions, a large sample holder was designed and fabricated from a 45 in. length of 6 in. plexiglas cylinder. Two 1/4 in. plexiglas disks were cut to seal the cylinder's ends. The bottom plate was drilled and tapped for a pipe fitting, then permanently glued into place with plexiglas cement. Care was taken to achieve an airtight seal. Inside the cylinder a small tube carried thermistors at 6 in. vertical intervals to facilitate temperature monitoring inside a soil sample. Copper tubing was coiled loosely up the inside wall of the cylinder to carry heating or cooling water. The sample holder is illustrated in figure 21.

Several methods of adding water to a soil sample were tried. The best method found was in-

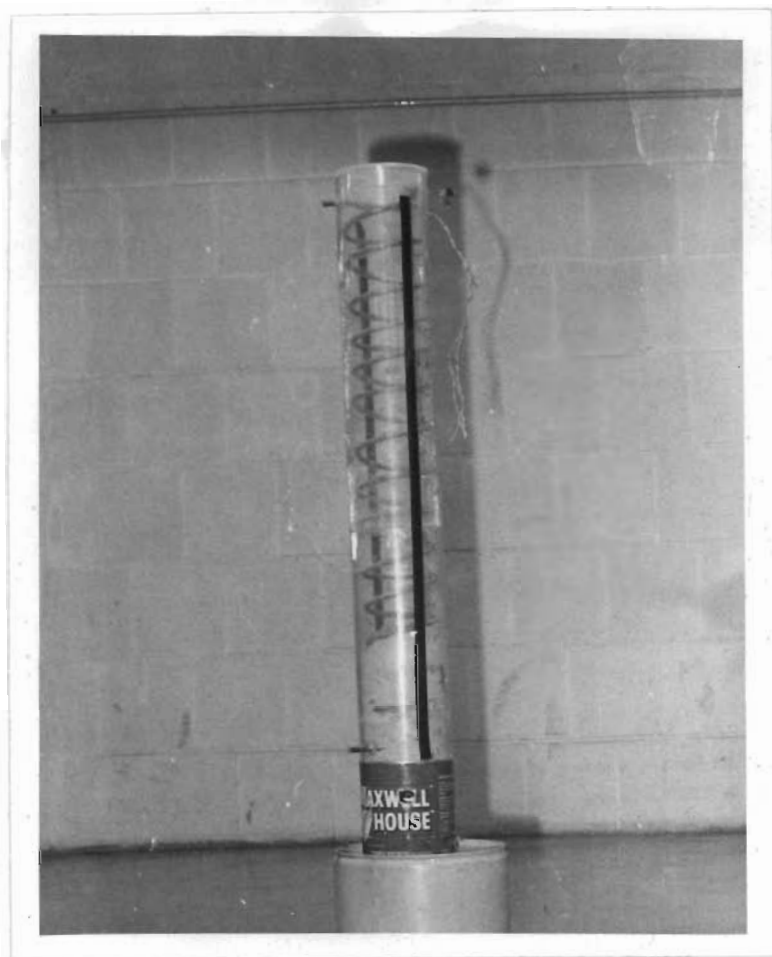


Figure 21. Sample holder used for testing Prototype I.

jecting water with a hypodermic syringe through tiny holes bored at 2 in. intervals in the cylinder wall. These holes were normally covered with black electrical tape.

For drying the soil without disturbing it, air could be gently forced into the pipe fitting at the cylinder bottom, or the top could be sealed and a vacuum drawn for fast evaporation. The vacuum pump used was protected from the moisture by a dehydrator consisting of a 30 in. column of silica gel. The gel was rejuvenated when necessary by heating.

Unfortunately, drying under reduced pressure was not uniform and required up to two weeks, even though the sample temperature was raised to 130°F by running hot water through the copper coils. Drying tended to be quicker near the bottom of the sample where the vapor was drawn off by the pump. It was therefore impossible to determine the PCM of the sample by gravimetric means without disturbing the sample unless at least a week was allowed for capillary equilibrium to be reached. The moisture content at the top of the sample, where gravimetric samples were taken, was much different than the moisture content at lower levels.

The fastest drying time was obtained by alternating gentle upward air flow with pressure reduction.

all the while heating by means of the coils. It was noted that when large droplets of water formed on the top plate while under vacuum, it was time to apply forced air. Drying occurred first in the immediate vicinity of the heating coils.

Forty-five pounds of dry sand were poured into the sample holder around the prototype. The sand was vibrated by tapping the sides of the sample holder with a hammer for 15 minutes. No settling was observable after 10 minutes.

To indicate how much power should be applied to the prototype, data runs on dry sand were taken at 5, 10, 12, 15, and 20 volts heater potential. A 4 watt input power (heater voltage = 20v.) was chosen because sensitivity increases with input power, but it was feared more power might burn out the heater windings. The result of using different heater voltages in dry sand is shown in figure 22.

Data obtained with Prototype I in sand during incremental water addition is tabulated in table 5 and further presented in figures 23 and 24. 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.

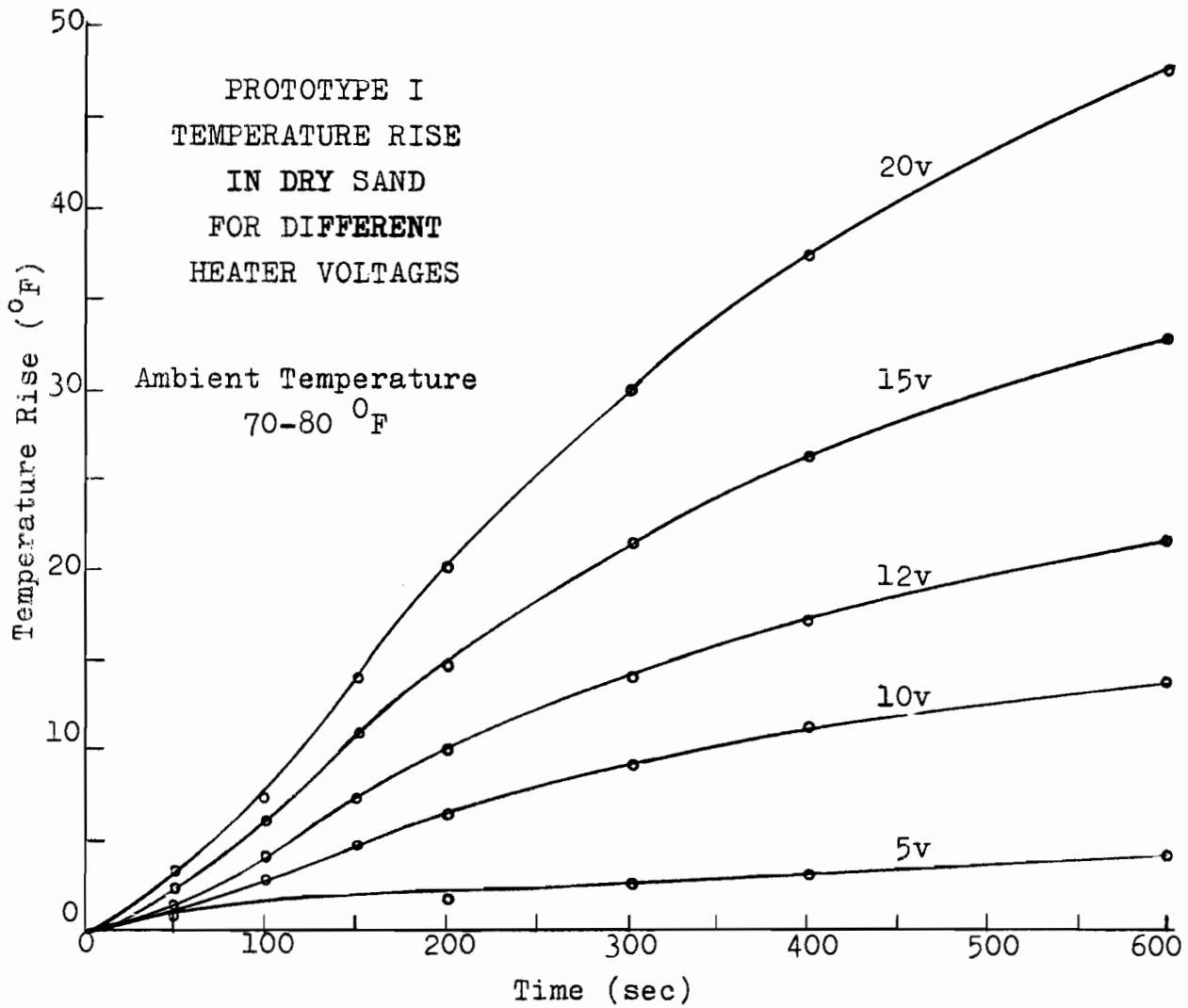


Figure 22. The effect of different heater voltage on Prototype I readings in dry construction sand.

PCM	No. Runs	Reading	Temperature Rise at Various Times (°F)						
			50 Sec	100 Sec	150 Sec	200 Sec	300 Sec	400 Sec	600 Sec
0%	3	Hi	2.5	8.5	15.0	20.0	29.5	37.0	47.0
		Ave	2.2	8.2	14.5	20.7	30.2	37.5	47.8
		Low	2.0	8.0	14.0	21.5	31.0	38.5	49.5
3%	5	Hi	1.0	6.0	11.5	17.0	25.0	31.0	41.0
		Ave	1.5	6.5	12.2	17.6	26.2	32.8	42.1
		Low	2.0	7.0	13.0	18.0	27.0	33.5	43.0
5%	9	Hi	2.0	4.5	12.5	17.5	25.0	30.0	36.5
		Ave	1.7	6.3	11.5	15.8	22.7	27.6	33.8
		Low	1.5	7.0	8.0	11.5	17.0	21.0	27.0
7%	6	Hi	1.0	3.0	5.5	7.5	10.5	12.5	15.0
		Ave	1.0	3.5	6.0	7.9	10.9	13.0	15.7
		Low	1.0	4.0	6.5	8.0	11.0	13.0	16.5
9%	12	Hi	1.5	2.5	5.0	6.5	9.0	11.0	13.5
		Ave	1.0	3.3	5.4	7.1	9.8	11.5	13.9
		Low	1.0	4.0	6.0	8.0	10.5	12.0	14.5
11%	6	Hi	1.0	2.5	4.5	6.0	8.5	10.0	12.0
		Ave	1.0	2.8	4.8	6.3	8.5	10.3	12.4
		Low	1.0	3.0	5.0	6.5	8.5	10.5	13.0

Table 5. Prototype I Temperature Rise in Construction Sand.

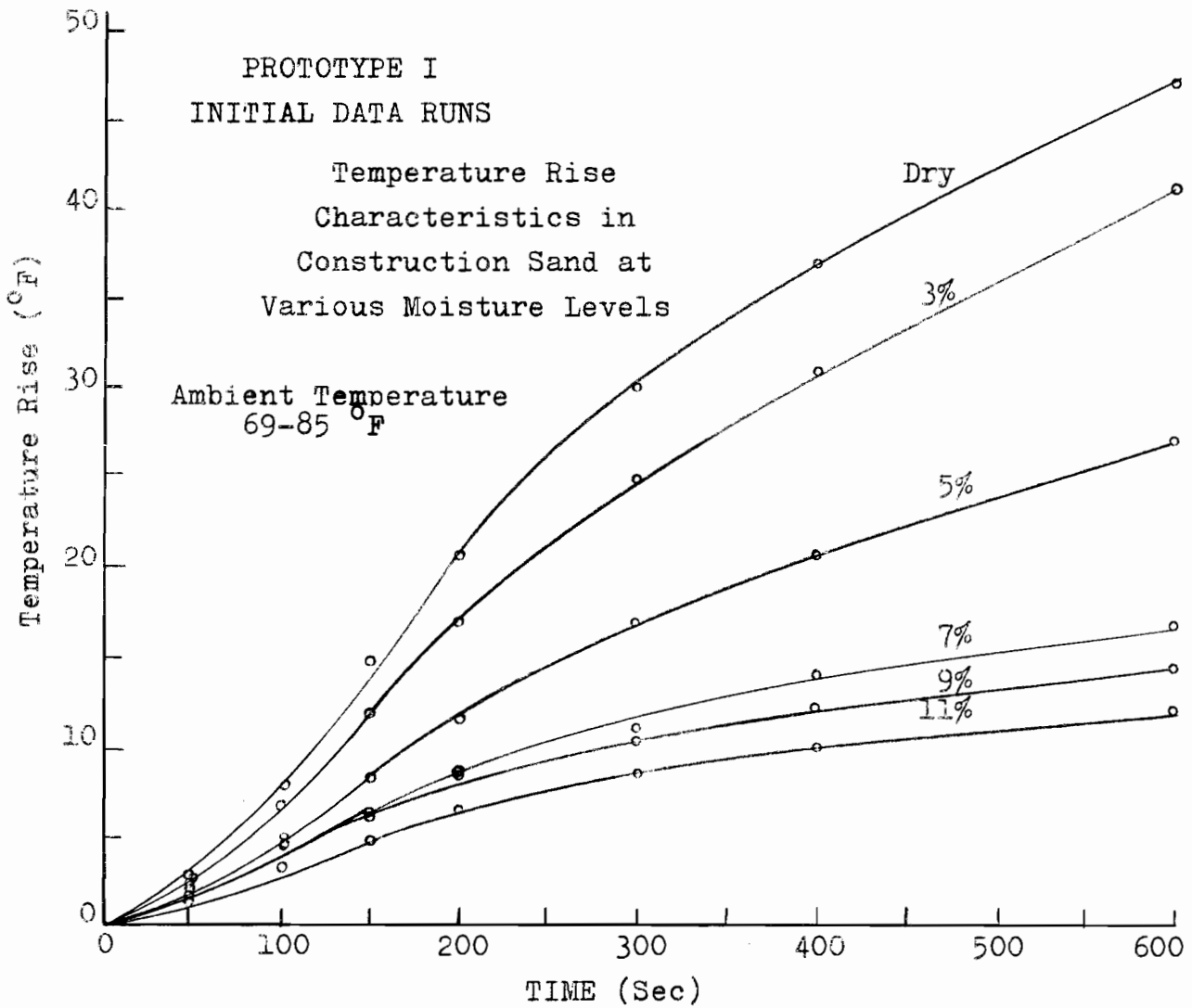


Figure 23. Temperature rise-vs-time plots for different moisture levels using Prototype I in construction sand, showing the results of the first data run at each moisture level.

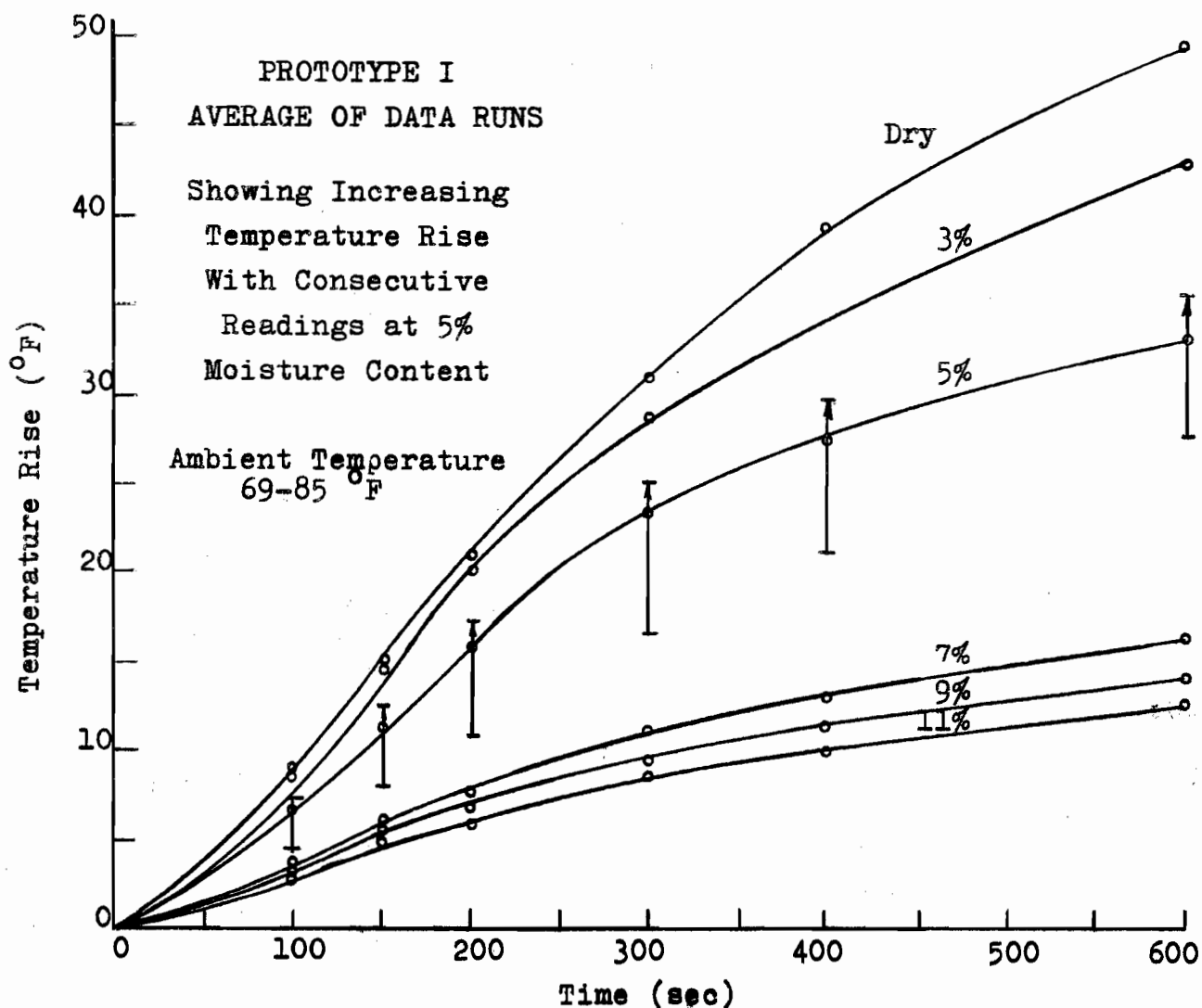


Figure 24. Temperature rise-vs-time plots for different moisture levels using Prototype I in construction sand, illustrating the increase in temperature rise as the soil surrounding the thermal probe was dried by the heat produced during successive trials.

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 layers of soil had a higher water content than the top layers in this sample holder, too, 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.

The heater leads of Prototype I tended to short against the heat conductor, which was used as one connector to the thermistor. The data system would not operate under these conditions, so in each case dismantling the sample and probe was required.

A probe for soil moisture measurement might conceivably be required to operate anywhere in the temperature range from about -20°F to $+100^{\circ}\text{F}$. To investigate the behavior of the prototype at low temperatures a large upright Amana freezer was obtained. The freezer was modified to make room for the sample holder and probe by removing the shelves and placing the cooling coils on the back wall.

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.

PROTOTYPE II

Prototype II was simply a refined Prototype I. It is illustrated in figures 25 and 26. 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

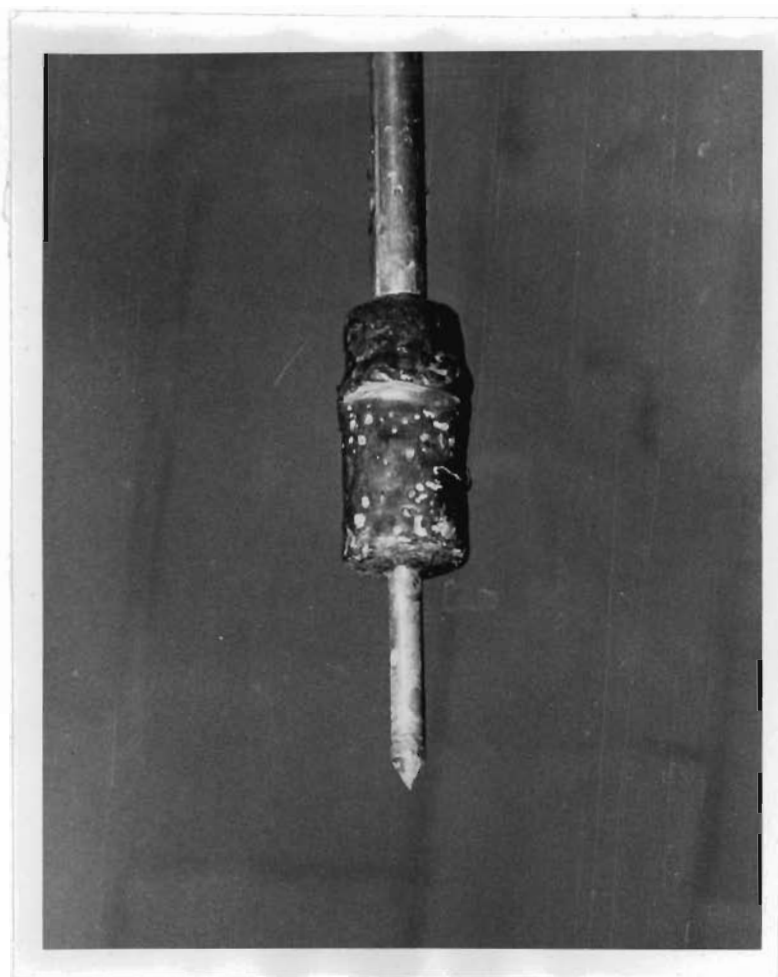


Figure 25. Prototype II, an improved thermal moisture detector for soils.

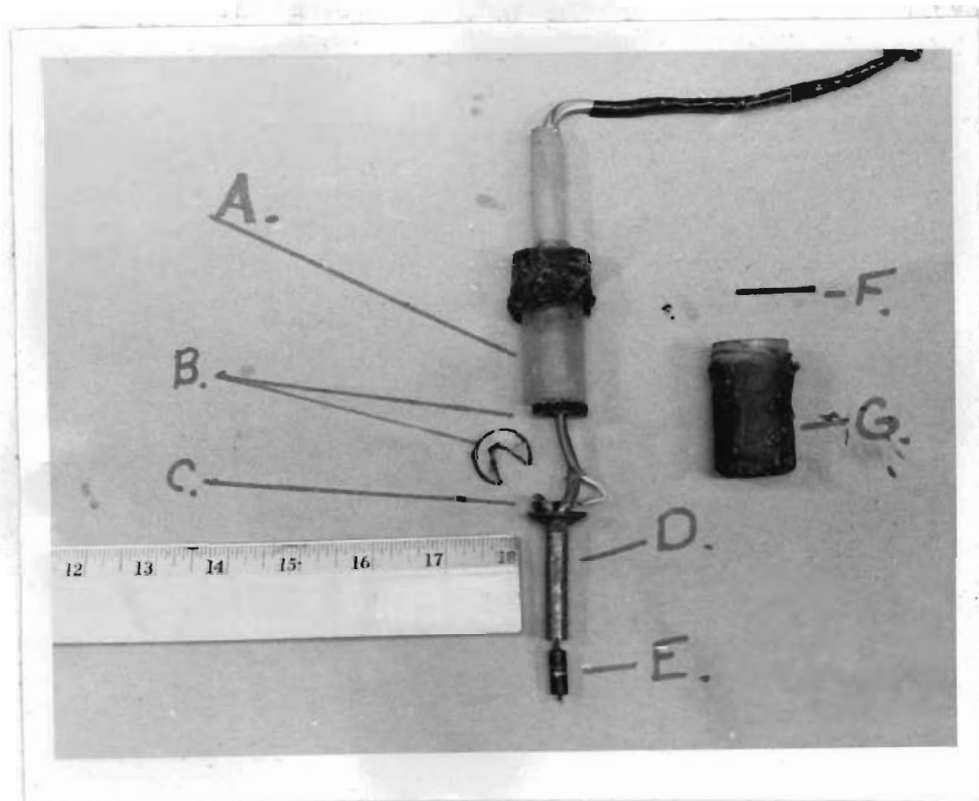


Figure 26. Construction details of Prototype II. Key: A. Base; B. Silicon Rubber Washers; C. Thermistor; D. Heat Conductor; E. Heater Resistor; F. Retaining Pin; G. Collar. Plexiglas Tip not shown.

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. This operation was hindered by the fact that the "silvering" on Fenwal type LA31J1 thermistors was actually done with aluminum. After many failures 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 water-proofing 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

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

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 shut off for one second each minute during its "on" time. If moisture was present, pulses appeared on the otherwise smooth temperature tracing. A schematic diagram and photographs of the system are given in figures 27, 28, 29, 30, 31, and 32.

The only physical problem with Prototype II, other than water entering the probe, was traced to a faulty connector in the wiring leading from the instrumentation to the freezer containing the sample and probe.

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.

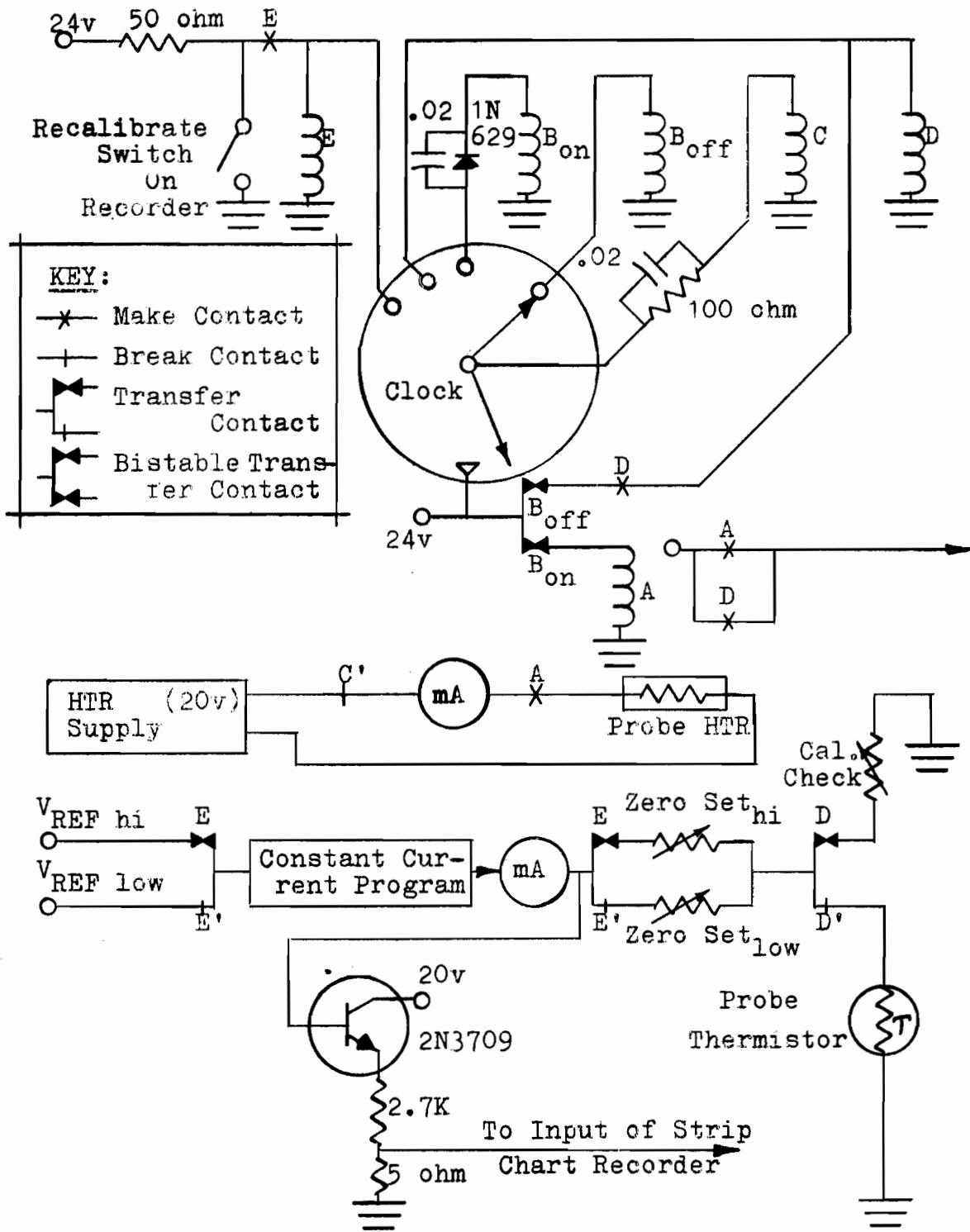


Figure 27. Schematic diagram of the automatic data system used with Prototype II

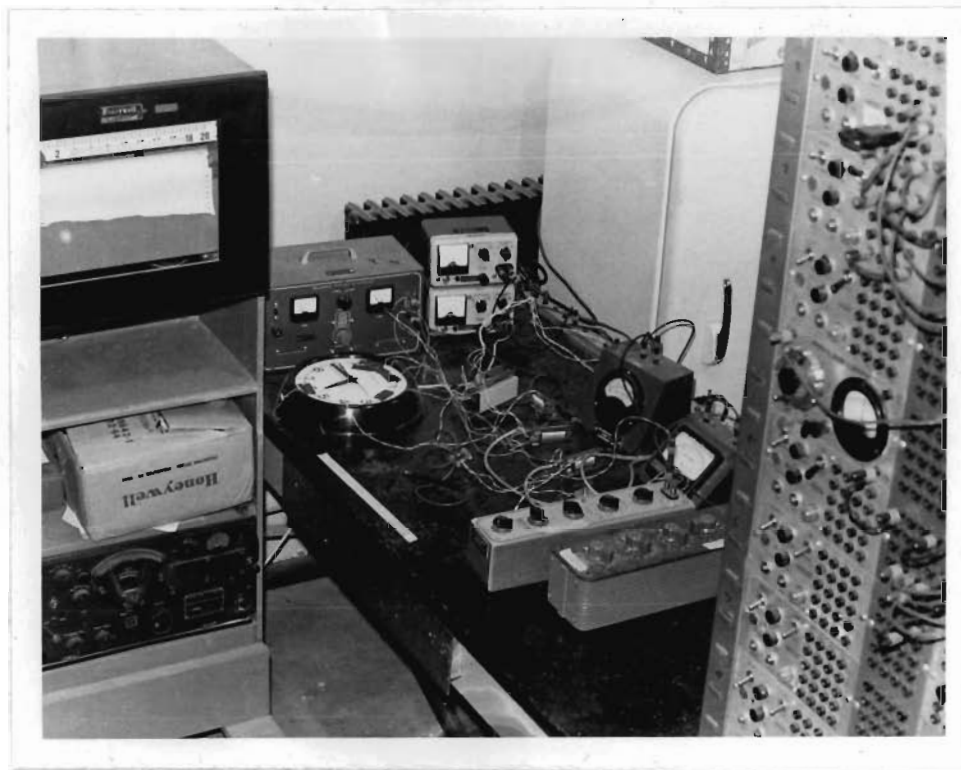


Figure 28. Data system used with Prototype II, showing the relay logic which automatically recalibrated itself for low temperature readings.

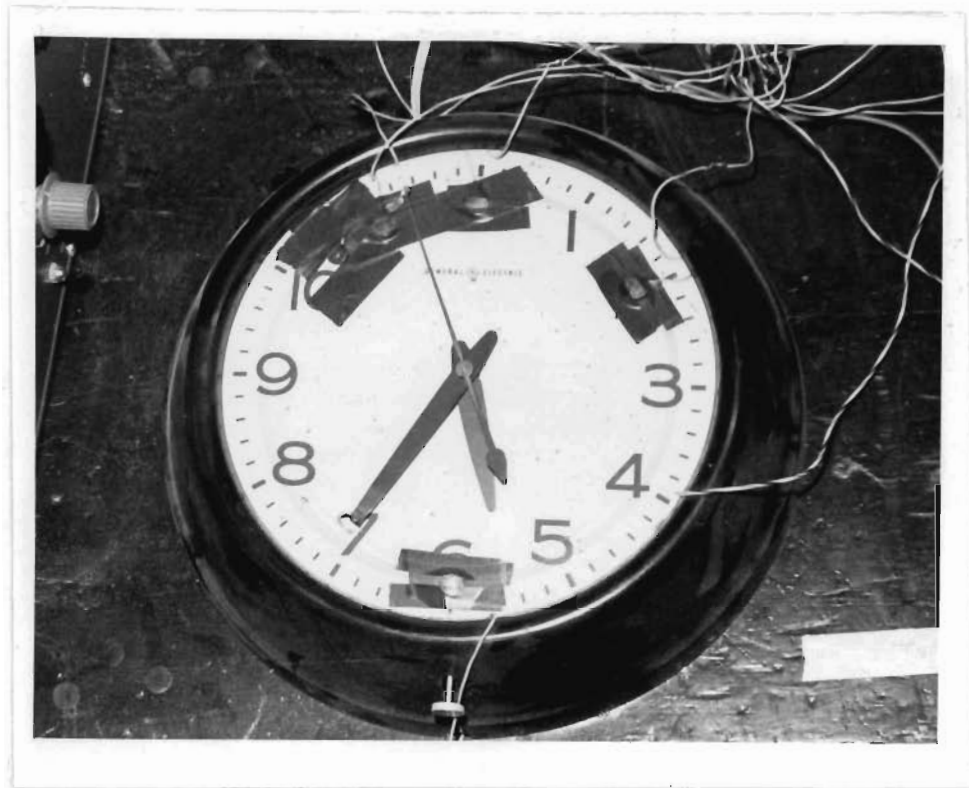


Figure 29. Data system used with Prototype II was controlled by this electric clock. The hands act as contacts, allowing timing accuracies within one second in one hour.

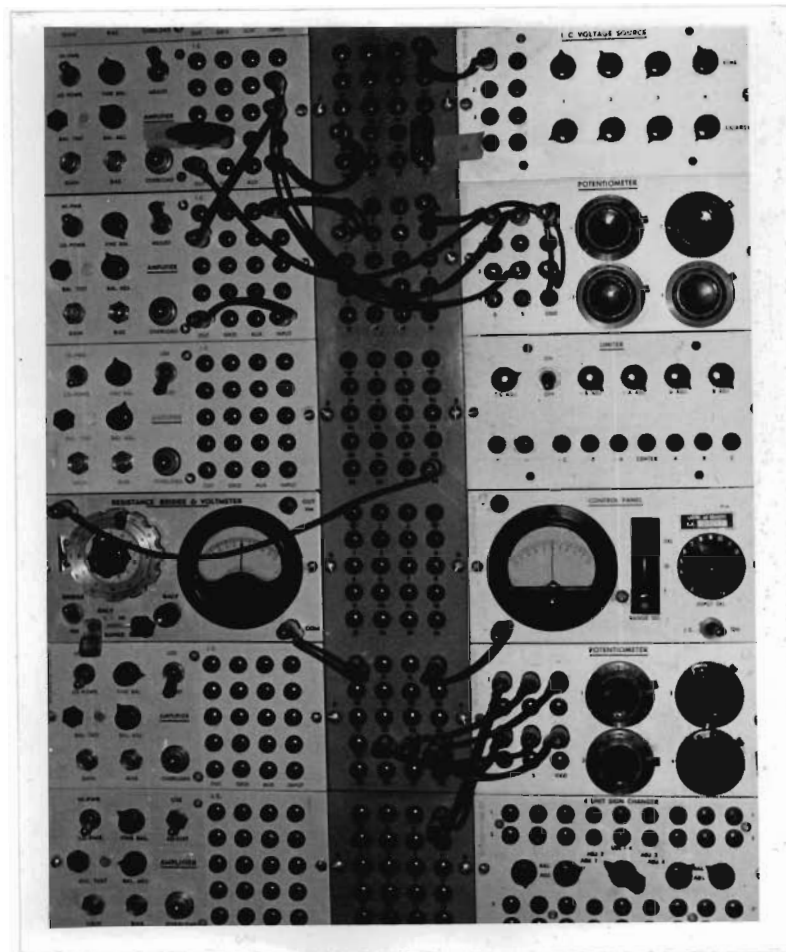


Figure 30. Constant current program on a Boeing Analog Computer. A constant current was passed through the thermistor of Prototype II, so that the voltage across the thermistor was proportional to the resistance of the unit.

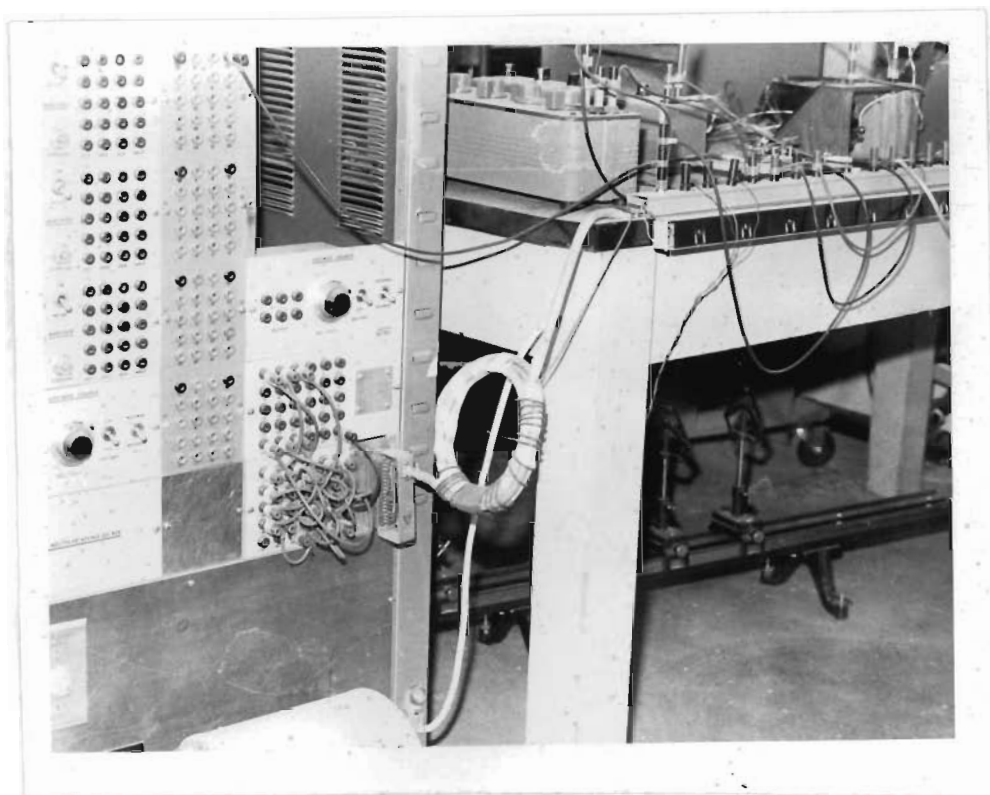


Figure 31. Most data system circuitry passed through this specially built table-patch network at the rear of the analog computer.



Figure 32. For testing of Prototype II, the soil sample occupied a 3-pound coffee can whose lid was sealed with the exception of the funnel tube through which water was added. The sample temperature was varied to sub-zero by a large upright Amana freezer. The freezer shelves were removed and the cooling coils were moved to the freezer's back wall.

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 tables 6 and 7, and illustrated in figures 33, 34, and 35.

Temperature Rise (°F) with Prototype II in Construction Sand

Ambient Temp. °F	PER CENT SOIL MOISTURE													
	10		12		14		16		18		20		22	
	# ¹	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.
-5-10	5	26.4	9	21.3	8	18.0	6	13.2	4	7.0	3	4.0	0	---
11-20	1	22.0	1	20.0	1	16.0	2	12.0	2	7.5	1	3.0	2	4.5
21-30	1	15.0	3	13.0	2	12.5	2	10.0	2	7.0	1	7.0	1	8.0
31-40 ²	11	20.4	4	17.2	4	14.2	5	10.4	6	8.0	6	7.8	4	8.0
31-40 ³	0	---	3	14.3	6	13.2	4	9.5	4	8.3	3	4.6	0	---
41-50	3	18.3	2	15.5	1	16.0	1	14.0	0	---	2	9.5	1	6.0
51-60	4	15.7	4	15.0	3	13.6	3	11.6	4	10.5	2	10.0	1	7.0
61-70	18	16.1	12	14.8	4	13.3	0	---	2	9.5	5	9.4	1	6.0
71-80	0	---	0	---	0	---	2	10.0	1	10.0	1	8.0	0	---
TOTAL MEAN	43	18.7	38	16.1	29	14.8	25	11.6	25	9.1	24	7.4	10	6.8

Total Sampling Size = 194

Table 6: Prototype II Data on Construction Sand

- ¹Number of data runs
- ²Cooling Cycle
- ³Warming Cycle

Temperature Rise (°F) with Prototype II in Roberts Fine Ash

Ambient Temp. °F	PER CENT SOIL MOISTURE													
	Dry		4		7		10		13		16		19	
	# ¹	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.
-5-10	5	58.4	6	59.1	7	56.3	6	39.6	5	29.6	2	26.0	7	24.2
11-20	2	55.0	3	54.3	2	53.0	2	38.5	3	24.7	1	22.0	1	19.0
21-30	0	---	2	51.5	2	48.5	2	38.5	2	22.5	2	21.0	1	20.0
31-40 ²	1	51.0	2	46.5	3	46.3	3	34.6	3	25.0	3	22.3	4	19.0
31-40 ³	0	---	0	---	0	---	2	36.0	5	30.4	2	24.0	2	22.5
41-50	0	---	0	---	2	43.0	1	35.0	1	27.0	2	21.0	1	17.0
51-60	0	---	2	54.5	1	55.0	1	39.0	4	25.7	1	23.0	1	23.0
61-70	3	54.6	0	---	1	49.0	3	35.7	1	22.0	2	20.5	4	20.8
71-80	0	---	2	53.5	1	53.0	2	37.0	1	24.0	1	21.0	4	19.2
TOTAL MEAN	11	56.1	17	54.5	19	51.5	22	37.4	25	26.8	16	22.4	25	21.2

Table 7. Data obtained with Prototype II in Roberts Fine Ash.

- ¹Number of data runs
- ²Cooling Cycle
- ³Warming Cycle

Temperature Rise (°F) with Prototype II in Roberts Fine Ash

Ambient Temp. °F	PER CENT SOIL MOISTURE													
	22		25		28		31		34		37		40	
	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.	#	Aver.
5-30	4	22.8	4	21.5	4	19.0	3	15.6	2	11.5	2	13.2	0	---
11-20	1	19.0	1	19.0	2	19.0	1	14.0	1	11.0	2	12.0	0	---
21-30	2	18.0	2	16.5	3	14.3	2	12.5	1	11.0	3	11.0	0	---
31-40 ²	4	18.8	4	16.8	5	15.6	5	14.0	6	12.8	6	12.2	0	---
31-40 ³	3	20.0	3	17.0	4	17.2	1	20.0	4	14.5	5	16.2	6	11.5
41-50	0	---	2	20.0	1	17.0	2	17.0	1	27.0	2	14.0	0	---
51-60	2	19.0	2	18.0	1	17.0	4	17.3	2	20.5	16	13.8	1	12.0
61-70	3	18.3	3	17.3	4	16.0	2	18.5	3	17.6	1	13.0	1	12.0
71-80	1	18.0	1	16.0	0	---	1	17.0	4	16.2	2	12.0	2	13.5
TOTAL MEAN	20	19.6	22	18.1	24	16.8	21	15.9	24	15.1	39	13.4	10	12.0

Table 7 (cont). Data obtained with Prototype II in Roberts Fine Ash

¹Number of data runs
²Cooling Cycle
³Warming Cycle

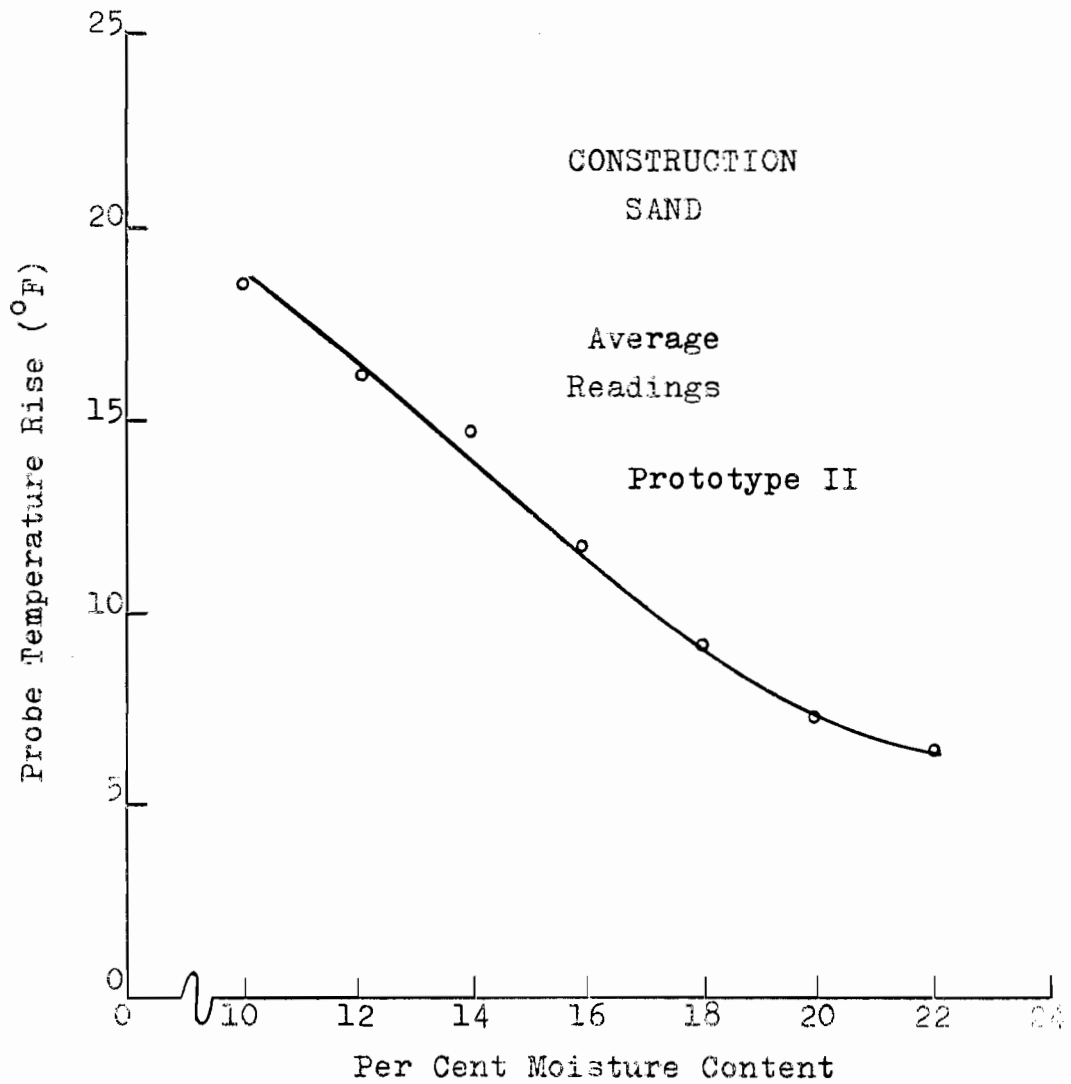


Figure 33. Average temperature rise-vs-soil moisture content using Prototype II in construction sand in the ambient temperature range 33 to 80° F.

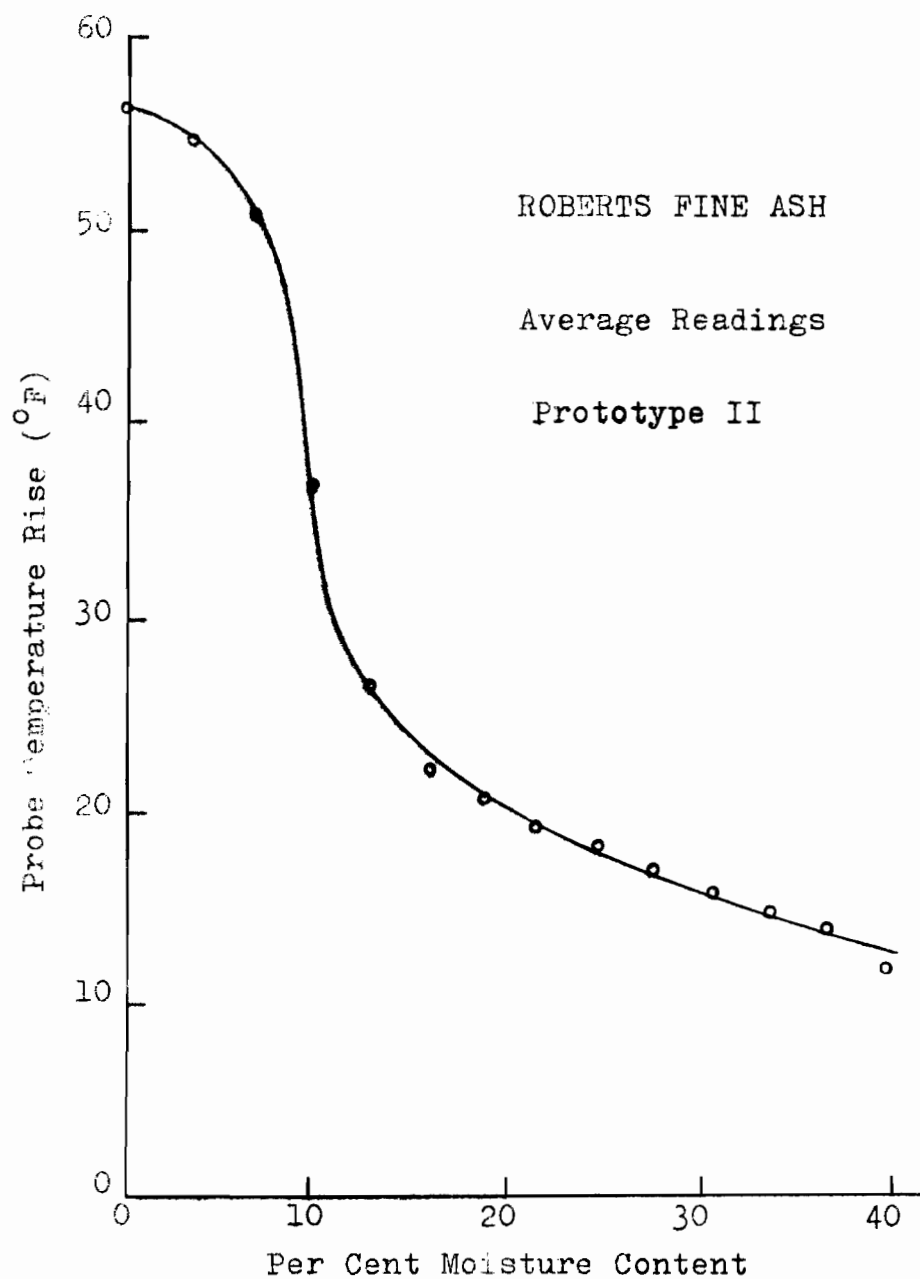


Figure 34. Average temperature rise-vs-soil moisture content using Prototype II in Roberts Fine Ash in the ambient temperature range 33 to 80°F.

PROTOTYPE II
Calibration Scales

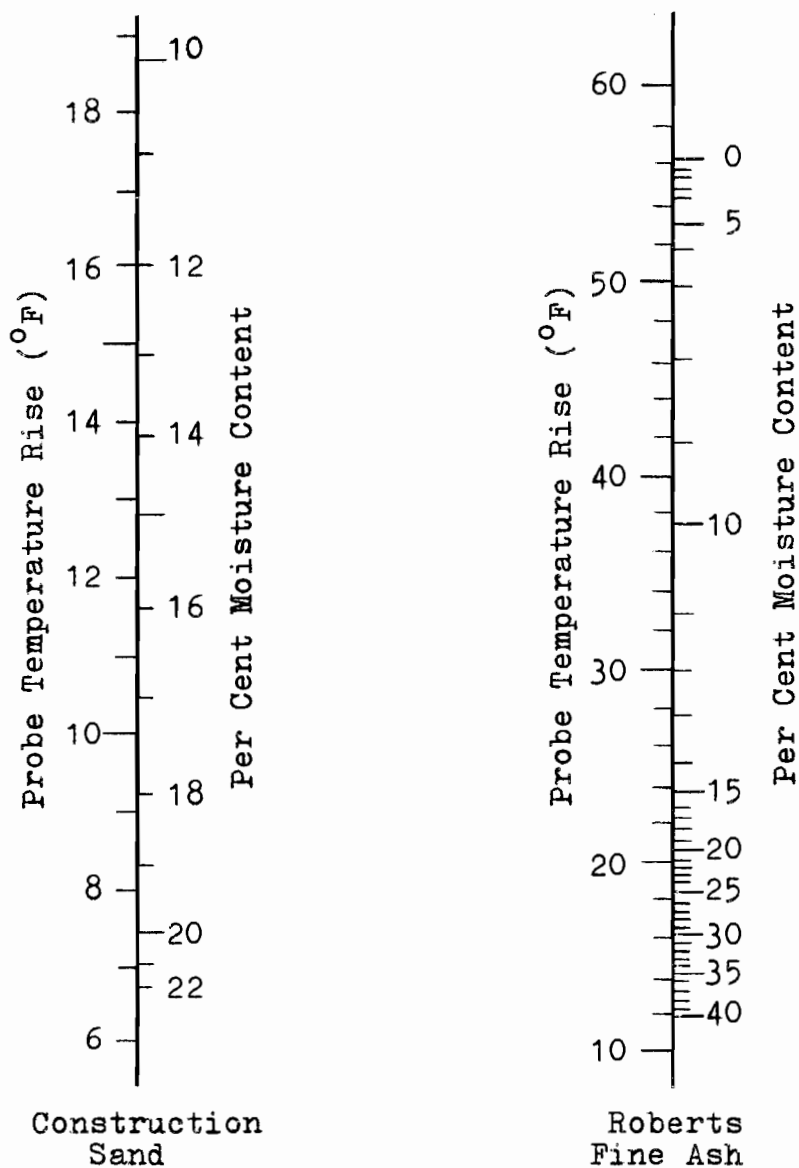


Figure 35. Scales which relate Prototype II temperature rise readings with soil moisture content in construction sand and Roberts Fine Ash. These scales apply in the temperature range 33 to 80°F.

RESULTS AND OBSERVATIONS

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 10 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. The probe temperature is therefore not equal to the average 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 all 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.

CONCLUSIONS AND RECOMMENDATIONS

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 at 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 non-destructive, 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.

Large-scale field testing and production of this device are recommended by the author.

SUMMARY

SUMMARY

It is frequently desirable and necessary to know the moisture content of the soil, but this parameter is often difficult to measure. As water is added to a dry soil, it first forms a film around the soil particles. Then the remainder of the void spaces is filled. Addition of water will change many properties of the soil, however these properties usually vary with location, and may vary with time. The literature contains many proposed methods for soil moisture determination, including chemical, electrical gravimetric, lysimetric, nuclear, penetrometer, tension (capillary potential), and thermal methods. Each method has certain faults. The only generally accepted method is the gravimetric process: a soil sample is weighed, dried, and weighed again to determine the amount of water originally contained. This procedure is time consuming and requires human attention. An electrical device consisting of a gypsum block containing two electrodes has been the subject of many articles. Moisture from the damp soil in which the block is imbedded decreases the electrical resistance of the block. This device is reported to be inaccurate and unreliable in changing soils and may require frequent calibration in field applications.

Experimental testing in three fields of study was proposed and accomplished in an attempt to discover a better method for soil moisture determination, especially for quick, remote, field applications. Subjects chosen for study were the streaming potential, thermal conductivity and heat capacity, and the infrared absorption by a moist soil.

Results of over 100 experiments with specially developed porous cup cells showed no correlation between magnitude of streaming potential and the moisture content of the surrounding soil. Neither did the streaming potential vary with the rate of flow through the cup, or the pressure forcing the flow through the cup in a systematic or reproducible manner. It was concluded that the variables influencing the streaming potential could not be isolated without elaborate equipment. Since the field utilization of this equipment does not appear practical, research on streaming potential was discontinued.

The water in moist soil readily absorbs electromagnetic energy at certain wavelengths in the infrared (IR) spectrum. The literature assures that it is possible to determine the moisture content of a soil by measuring the amount of IR reflection from the soil at 1.9μ . (24) Work was initiated

to determine whether this technique could be adapted to remote site field use. An appropriate detector was mounted at the focal point of a parabolic reflector assembly which also contained a source of 1.9μ energy. The detector was properly shielded so that only energy from the direction of a glass window would be accepted. The unit was placed in the soil so that damp soil was in direct contact with the window. The source, which consisted of a small incandescent lamp operated at slightly reduced voltage, illuminated the soil with the proper wavelength. The reflected energy was integrated and focused upon the detector by the reflector assembly. A specially designed astable multivibrator converted the weak detector signals to a more usable form. Unfortunately, the sensitivity of the instrument was greatly reduced by the reflection of energy from the inside face of the glass window. Efforts to correct this condition are in progress at this writing. Data were taken with the window removed and the soil directly exposed to the reflector assembly. The IR reflection decreased almost linearly to a value at saturation approximately one half the reflection from dry soil. More developmental research on this technique seems warranted.

An original design for thermal testing of soil in situ was considered. Heat was applied to a

metal strip in contact with the soil. The temperature rise at a point on the strip somewhat removed from the point of heat application was observed to decrease with the addition of water to the surrounding soil. The heat energy loss from the strip to the soil was seen to be a function of the thermal conductivity and heat capacity* of the soil. Both of these parameters increased with the addition of water. Experiments at room temperature on a heated thin copper strip in soil whose moisture content was incrementally varied from dry to 10% soil moisture gave consistent results. Readings became less readily determinable at higher moisture levels, but the instrument proved to be an accurate indicator of soil moisture. A more sophisticated prototype operating on the same principle was fabricated, then improved. Experimental data taken with the prototype indicated it could be used as a reliable and accurate indicator of soil moisture in the temperature range from 33° to 80°F, especially at relatively low moisture levels. Rapidly changing soil temperatures caused erroneous readings since these changes were not uniform throughout the measured soil. The prototype could not be

*Specific heat on a volume basis; equal to the specific heat at constant pressure times the mass density.

used in the ambient soil temperature range 20° to 32°F , since the heat of fusion required to melt the frozen soil moisture caused the probe temperature rise to be reduced. However, the experiments revealed that if soil moisture content were known, the prototype could be used to indicate what portion of the soil water was frozen at 32°F ambient temperature. At ambient temperature much below freezing, the probe temperature rise may not be sufficient to melt the surrounding soil water. The probe can therefore be used to measure soil moisture at ambient temperatures from -5° to 20°F , but a separate calibration may be required for this range. Probe readings were independent of ambient temperature in the range 33° to 80°F , but the probe temperature rise appeared to be slightly higher for a given soil moisture content at sub-zero temperatures. Since many applications require soil moisture determination within the ambient temperature limitations of this device, it could be useful. Field testing will be required to determine whether any flaws exist which did not appear in the laboratory testing. A different calibration curve will be required for each soil type, but once calibration has been established it should remain correct, since the thermal properties of the soil are only slightly influenced by changes in the ionic concen-

tration of the soil. Performance of the probe was superior in fine-grained soils because of better thermal contact between the probe and the surrounding soil. Field testing is recommended by the author.

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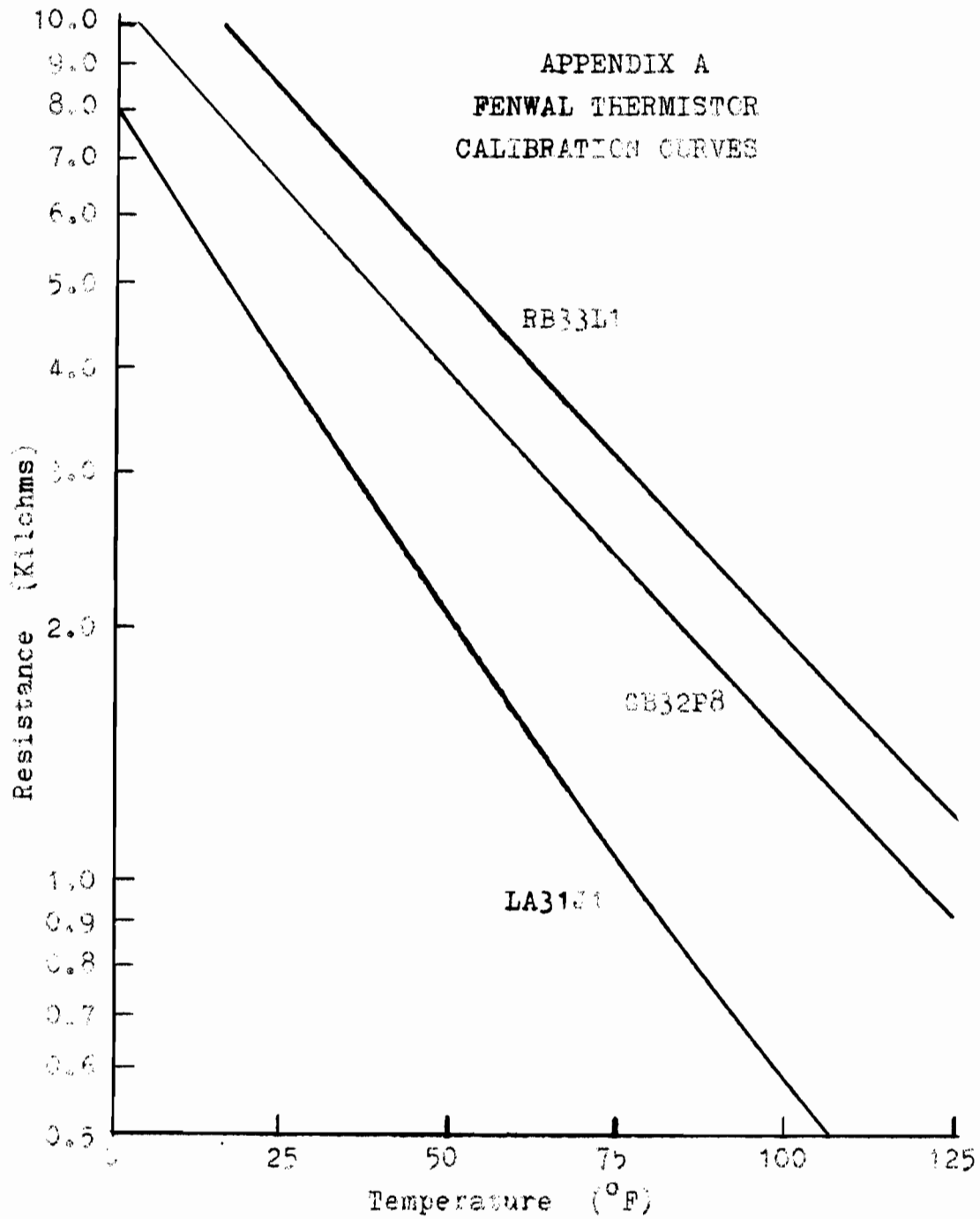
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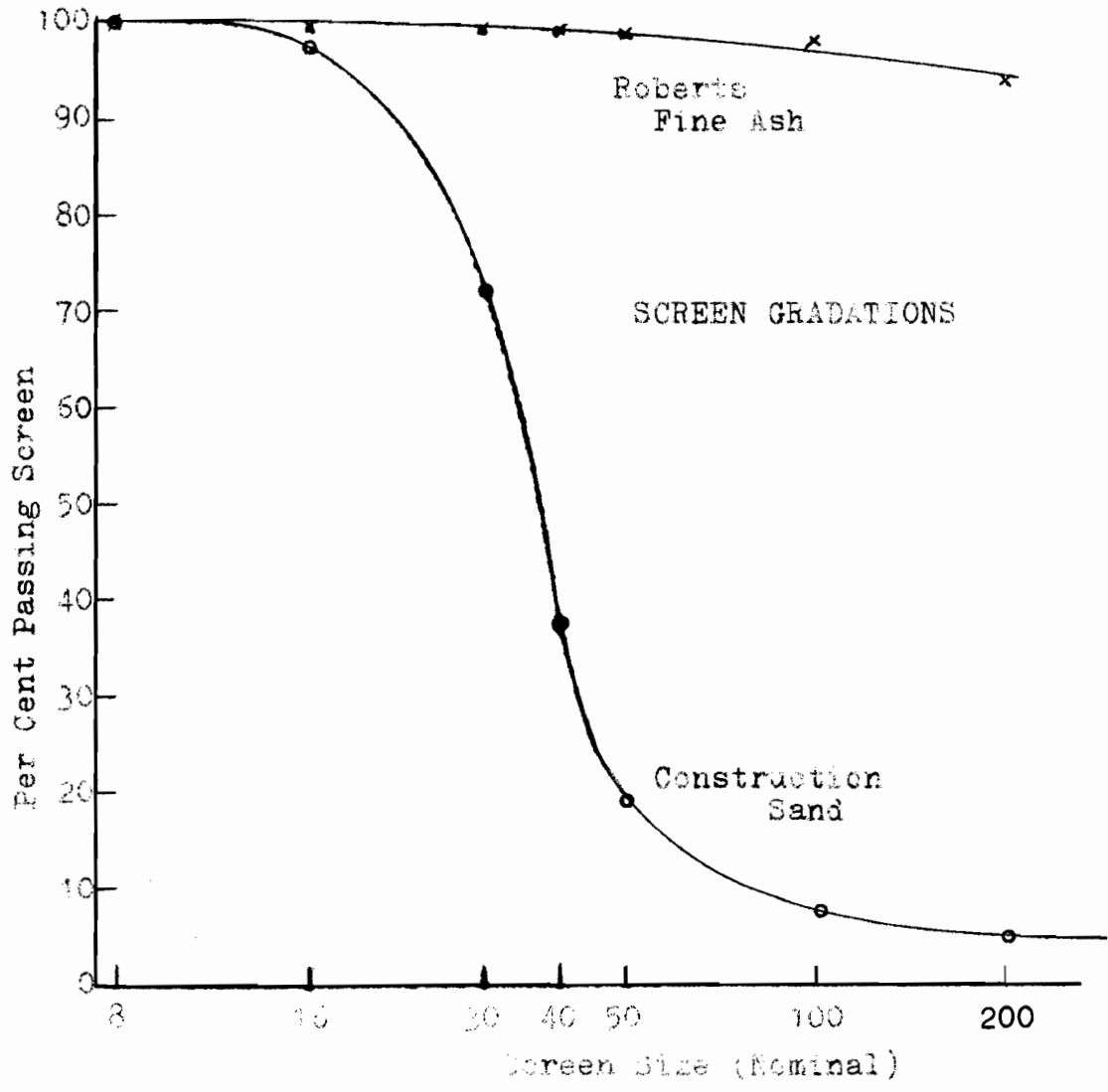
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Appendix A. Resistance -vs- temperature curves for several Penwal thermistors. These values are typical, tolerance is $\pm 5\%$.



Appendix B. Screen gradations of the two soil types in which the soil moisture detectors were tested.