THE MEASUREMENT OF SOIL MOISTURE AND DENSITY BY NEUTRON AND GAMMA-RAY SCATTERING

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FOREWORD

For the past several years the Civil Aeronautics Administration has taken a deep interest in the development of equipment and methods for measuring soil moisture in the field, either in an embankment during construction or under a pavement after construction For the latter purpose it is particularly important to have a device which will give continuous readings at the same point without the necessity of removing successive soil samples

Early attempts to develop a suitable device were centered around a heat diffusion type of moisture cell This involves a low-energy constant-rate source of heat, which is placed in the soil, and a means of measuring the temperature rise at the source of heat after a definite heating period This indicates the insulating effect of the soil, which in turn varies with its moisture content Experiments with this type of cell have been conducted at the CAA Technical Development and Evaluation Center, Indianapolis, Indiana, and are still in progress

Discussions with members of the staff of the College of Engineering, Cornell University, indicated a possibility also of developing a practical instrument for measuring both soil moisture and soil density by measuring the influence of these properties on the propagation of neutron and gamma rays The preliminary investigations covered in this report were carried out under contract between Cornell University and the Civil Aeronautics Administration Professor D J Belcher was the project director, with Dr T R Cuykendall and Dr H S Sack as consultants

Although considerable additional development and refinement are needed it seems safe to say that a potentially useful and practical tool for the soil engineer has been provided

SUMMARY

The influence of moisture and the density of materials on the propagation of gamma and neutron rays aroused the interest of those concerned in moisture and density studies A research and development contract between the Civil Aeronautics Administration and Cornell University has resulted in the development of a device for measuring the moisture and density of soils

The apparatus, consisting of a radioactive source and detector, is given access to the soil by being lowered into a one-inch metal tube driven into the ground Fast neutrons emitted by the source are converted by impact with water molecules to slow neutrons The number of slow neutrons is proportional to the water content of the surrounding soil A similar arrangement, utilizing gamma-ray emanation, measures soil density

The method permits measurement of water regardless of state, it is sensitive over wide ranges of moisture content, it successfully measures moisture in layers of stratified soil, and it enables observations to be taken at any desired depth and at short intervals, it lends itself to continuous and automatic recording

Laboratory and field checking of the results of test measurements show that the accuracy of the neutron and gamma-ray methods of determination equals or exceeds that of standard procedures The apparatus is relatively inexpensive, and by observing simple precautions, is without hazard to health

INTRODUCTION

Over a span of approximately 50 years the records and literature on the subject of soils contain descriptions of various types of apparatus that have been developed for the purpose of determining soil moisture 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 Because of the limitations of moisture measuring devices little is known, in a definite sense, of the movement of moisture in soils This is particularly true in unsaturated soils The movement of moisture through soil by percolation, by capillary and by vapor transfer is little known except by analogy and inference When in the frozen state, the soil conditions defy study

An essential to the satisfactory study of values and trends in soil moisture is the need for continuing observations of the same soil throughout its seasonal cyclic changes Destructive sampling with an auger introduces many uncertainties in most soil formations because of their heterogeneous nature This type of an investigation, although simple, is expensive and also lacks continuity, especially over critical periods of rapid rise and fall of the groundwater table To date, the problem of installing measuring devices without materially altering the adjacent soil conditions has been met with but limited success

Most of these early instrument methods have been related to the variations in electrical resistance offered by soils in varying degrees of saturation In general, these have presented overwhelming difficulties, particularly in the calibration of the equipment at its installation site A number of improvements over the direct measurement method have been developed These, in general, substitute for the direct (electrode) contact with the soil, blocks of material that absorb and give up moisture in a way that is related to the changes in the moisture of the surrounding soil The electrodes embedded in these blocks are used to measure the resistance of the material in the block and the variations in the moisture content This arrangement very much simplifies the calibration of the installation and also insures uniform contact between the electrodes and the measured media

In the field installation of this type of moisture recorder it is necessary to select a representative soil column and to install the electrodes or moisture blocks individually at critical points that should be determined by inspection Where the measurements are desired at depths below four feet, the problem of installation becomes difficult because of the need for an adequate excavation and the resultant disturbing of the soil and the consequent change in its drainage properties

The ever-present need for information on soil moisture characteristics has been enlarged by the need for more accurate information in subgrade soil moisture as a means of providing better design information for pavements With the recent availability of radioactive materials, the problem of determining soil moisture was reviewed in the light of the ability of some of these materials to react indirectly, although with great sensitivity, to moisture The interest of the Civil Aeronautics Administration and staff members of the Engineering College of Cornell University combined to study the possibilities of using nuclear materials to measure soil moisture contents In principle, the neutron method of counting hydrogen nuclei seemed to hold considerable promise Among the favorable characteristics was the fact that the neutrons would detect the presence of water regardless of state so that whether the water was in a form of a liquid, vapor or solid meant that it would be possible to make observations at any time of the year Secondly, it appeared that there would be equal sensitivity over the entire range of moisture and, third, that it does not depend upon the installation of electrodes at various depths in the soil column The neutrons that have the ability to count the hydrogen nuclei contained in water particles readily penetrate stainless steel and aluminum metals so that the simplicity of the installation seemed a desirable attribute The fact that the measurements could be made by lowering a small unit into the water-proofed stainless steel tube indicated that a low-cost installation could be made, especially with reference to the infinite variation in the number of levels at which moisture determinations could be made It also largely removed the question of selecting a representative site since the tubes could be installed and withdrawn almost at will and in great numbers, if necessary Finally, measurements can be made in short-time intervals of the order of one-half hour or less, thus recording relatively rapid changes in moisture content

One of the requisites of a soil moisture measuring device is that it be adaptable in all types of soil, ranging from clays through silts, sands and gravels, as well as in stratified and heterogeneous deposits, such as glacial drift containing material sizes ranging from clay to boulders The problem of inhomogeneities is not confined to that of grain sizes but it also includes variations in density of the soil, the presence of organic matter, such as vegetation and inorganic salts of magnesium, potassium and other metals The latter is particularly important in the dry areas west of the Mississippi River The organic materials are often associated with low-level ground that is, at the same time, topographically favorable to airport locations The alkali soils of the west, containing the inorganic salts, are also concentrated in those areas that are predominantly level

Destructive sampling has introduced one of the chief uncertainties into field studies The use of an auger of 2-inch diameter may well change the drainage properties of the surrounding soil throughout a 2-foot radius of influence. Further sampling at a later date must avoid this influence In doing so, variations in the soil may introduce significant errors This problem becomes magnified many times when sampling beneath pavements

Representative sites for sampling are important When an auger boring is made or a resistance unit installed, it is desirable to know what application these observations will have beyond the immediate site In many instances particularly in auger sampling, ignorance of surrounding subsurface inequalities gives false values to the data obtained

Under some conditions it is impossible to obtain satisfactory moisture samples by the auger method Where water can drain freely down the test hole from seepage planes, these difficulties will occur It has also been virtually impossible to obtain samples for studies of water in the form of vapor or ice in soil

The ideal condition for making soil moisture studies exists when nondestructive testing can be used, when moisture in the soil itself can be measured, and when the soil is undisturbed and free from unnatural influences

The advantages of the nuclear method closely parallel the ideal described The simple tube, placed vertically in the soil column, introduces a minimum of change in environment Since the tube is placed in a drilled hole of slightly smaller diameter, the intimate contact between the outer tube wall and soil eliminates any unnatural tendency for vertical drainage downward along the tube wall The tube provides access to the soil at any practical depth to which it is driven and an unlimited opportunity for making measurements of the same soil at any period of the year Inexpensive to install, it can be withdrawn or abandoned without appreciable loss of time or investment

On the basis of the need for a solution to the problem and the promise inherent in the nuclear method, an exploratory contract was arranged between the CAA Technical Development and Evaluation Center and Cornell University This contract contemplated an investigation of the feasibility of this method of measuring soil moisture The report of the development work follows

PHYSICAL BASIS OF THE NEUTRON METHOD

The physical phenomena that form the basis of the new method for the determination of moisture content and density of soils are the scattering of neutrons or gamma rays and the loss in their energy during this process It is well known that the interaction between neutrons and other materials is, with the exception of a few specific substances, very weak These neutrons, therefore, can travel for a long time before they are destroyed However, during their lifetime they collide with the nuclei of the material through which they travel and are scattered in all directions At the same time, in each collision or scattering process they lose some of their energy The scattering is particularly strong and the loss of energy marked if the neutrons collide with hydrogen atoms Thus, if we have a source of fast neutrons, and if these neutrons travel away from the source, they will be scattered by the material surrounding the source and a great number will return to the source or to its immediate vicinity Those neutrons which have been scattered by hydrogen atoms will have lost most of their energy and return as slow neutrons The more hydrogen atoms there are present the more slow neutrons will return to the vicinity of the source A schematic picture of this situation is given in Fig 1, where the scatterings from other than hydrogen nuclei, since they are less important, are left out Thus in counting the number of slow neutrons at, or near to, the source, one will obtain a measure of the number of hydrogen atoms present It is also a fact that this scattering and slowing down process is practically independent of whether or not the hydrogen is bound chemically In particular, it is independent of whether water, which contains two hydrogen atoms per molecule, is in the vapor, liquid, or solid state

Such a device for measuring the moisture content consists then of a source of fast

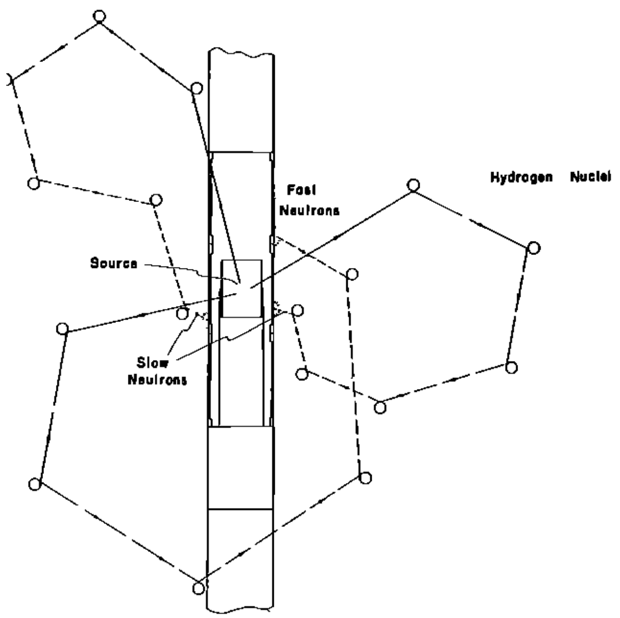

Fig 1 Showing How Neutrons Emitted by the Source are Scattered by Hydrogen Nuclei Within the Soil Mass and Return to the Detector

neutrons, e g , a mixture of radium and beryllium, a detector for slow neutrons, rigidly placed near the source, e g , a rhodium foil or a boron counter, and an electronic device for counting and, if desired, recording the number of slow neutrons reaching the detector per second Such an assembly of source and detector can be lowered into a small diameter (one inch) metal tube placed in the soil, and can be connected by a cable to the counting mechanism which is placed above the soil surface

To measure density of soil the scattering properties of gamma rays can be used If gamma rays emitted by a source, e g , radium, pass through a material, these rays are scattered as a consequence of their interaction with the atoms of the material The scattering is the stronger, the greater the number of electrons that are contained in an atom Since to a good approximation, for the constitution of soil, the number of electrons is proportional to the density of the substance, a heavy substance will scatter more than a light one The method is then again to measure the gamma rays which are scattered back from the material to the vicinity of the source In the case of gamma-ray scattering, the theory of the effect has not been as well studied and the phenomenon is very complex. However, it can be shown that, contrary to the case of neutrons, no effect will be found if detector and source are at the same place, and thus the distance between detector and source is a very essential parameter in the construction of the device

This apparatus for the determination of the density then consists of a gamma-ray source, e g , a weak radium preparation, and a detector for gamma rays, e g , a Geiger counter, mounted at a well-defined distance from the source, and separated from the source by lead, in order to prevent direct gamma rays from the source reaching the detector Again, this assembly can be mounted in such a way that it can be lowered in a metal tube and be connected by a cable to an electronic count rate meter

Since the theoretical consideration of scattering of neutrons and of gamma rays under these conditions presents a difficult problem, counting rates cannot yet be calculated in advance for a specific arrangement Therefore, it is necessary to obtain calibration curves to relate the readings with the actual moisture content or with the density

Most of the laboratory experiments and the field tests have been made with the simple arrangements as previously described It is evident that if this method were to be applied in the field for routine measurements, further developments in instrumentation would be desirable Since the art of detecting and measuring neutrons, gamma rays, etc , is advancing rapidly, developments in this field will also be of help in the future instrumentation of the device here discussed However, it is believed that the results obtained with the equipment, as developed so far, are sufficiently significant to permit a judgment of the usefulness and the possibilities of this new method

EXPERIMENTAL LABORATORY PROCEDURE

A program of laboratory experiments was set up to determine if the number of low energy neutrons scattered back from the soil mass surrounding the neutron source could effectively be used as a measure of soil moisture In order to carry out a series of experiments in a rapid, well-controlled, and simple yet adequate manner, certain procedures were used, as follows

A quantity (about eight to ten cubic feet) of the soil to be used was taken to the laboratory, spread out to air-dry, and then mixed thoroughly with the desired quantity of water The well-mixed soil was then carefully packed into cylindrical drums, in most cases 17 inches in diameter and 23 inches high Particular attention was paid to insure as uniform a density as possible An aluminum or stainless steel (the type of tube makes a slight difference in the calibration curve) tube, 15/16-inch inside diameter, pointed and sealed at the lower end, was inserted coincident with the central axis of the drum

Brief studies were made of soil masses in other sizes of drums in order to correlate the laboratory measurements, involving limited volumes, with field observations where an infinite soil mass prevails Studies with glacial drift were made on samples built up in 55-gallon drums so that stones of various sizes could be placed at a series of known locations

The moisture content of the soil mass was determined by taking several, usually four, samples from different positions in a drum and then weighing and drying them in the standard manner The density of the soil was determined from the net weight of the filled drum and its volume

A measure of the number of slow neutrons was obtained by placing one or more small cylinders (0 875-inch diameter by 1 inch by 0 003-inch wall) of rhodium metal foil within the soil mass and subsequently measuring the degree of radioactivity induced in the foil by its selective capture of slow neutrons This method is simple, dependable, and requires a minimum of expensive equipment The details of the procedure follow

An assembly consisting of a neutron source and suitable cylindrical holders for the rhodium foils was inserted into the aluminum tube and lowered to the desired position Such an assembly is shown in Fig 2, where one foil holder symmetrically surrounds the source, other holders are immediately above and below After the foil detector had reached "radioactive equilibrium" (20- to 30-minute interval) the foil in its holder was rapidly withdrawn and slipped over a Geiger counter mounted inside a lead

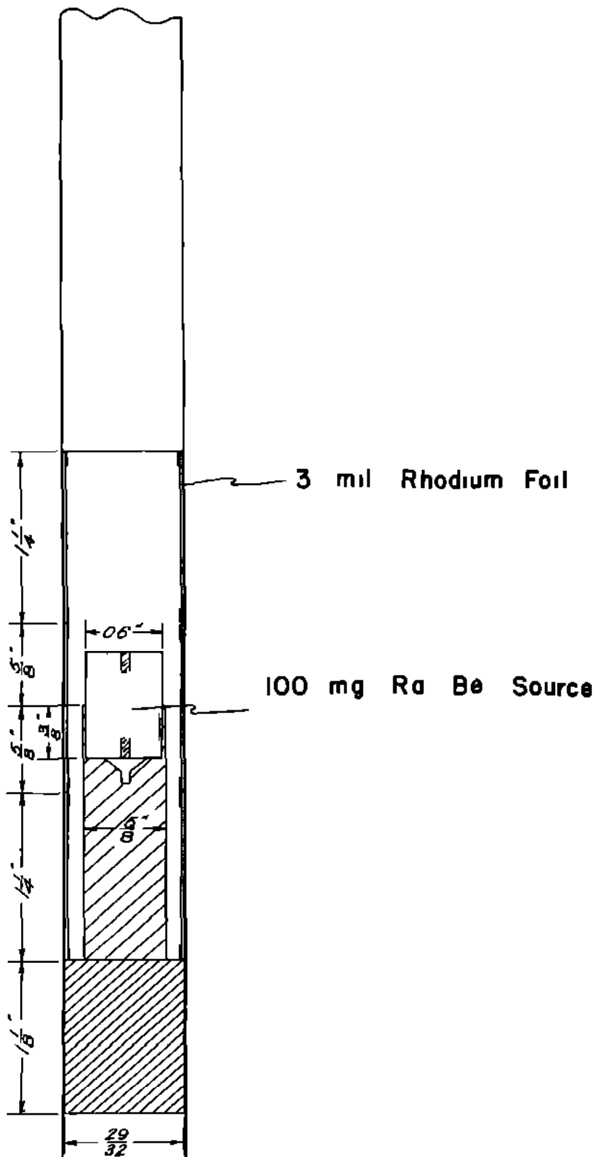

Fig 2 Assembly of Neutron Source and Detector Foil Holders Within a Tube Section

shield provided to reduce background counts * The degree of activity of the foil, proportioned to the slow neutron intensity at the place where the foil had been exposed, was determined from the rate at which beta rays from the foil cause the counter to "count" The counting rate, in counts per minute, properly corrected for background counts, was then plotted for successive experiments as a function of the soil moisture and a calibration curve for the soil was thus obtained

In order to obtain precise results, the time interval between removal of the detector foil from the proximity of the source and the time at which counting of the foil activity is started must be determined by stop-watch technique, and be held constant to about ±1/2 second

The special equipment employed was a neutron source, ** a Thyrode 1B85 Geiger counter manufactured by the Victoreen Instrument Corp, a Model No 161 pulse amplifier and scaler manufactured by the Nuclear Instrument and Chemical Corp, and an ordinary telephone message register

It is not possible to place the Geiger counter in the soil adjacent to the detector foil because the intense gamma rays emitted from the radium would mask the neutron count However, in a few tests, a polonium-beryllium mixture, having very weak gamma-ray emmission, was used as a neutron source For these tests it was possible to place the rhodium foil permanently around the Geiger counter and to locate it adjacent to the neutron source Then the Geiger counter continuously recorded the beta activity built up in the foil under the impact of slow neutrons The need for withdrawing the foil for measurement is thus avoided and a continuous automatic reading can be taken This method has been used for the telemetering tests to be described later Unfortunately, a polonium-beryllium mixture decays to one-half its initial strength in about four months

Since radioactive processes are random processes, the experimental precision is determined by the total number of counts In fact, if N is the number of counts taken during a given experiment, $\sqrt{N}$ is the mean error attached to this measurement and, therefore, $\sqrt{N}/N$ is the percentage error In most experiments approximately 16,000 counts were taken for maximum moisture (saturation) the percentage error is of the order of one per cent and accordingly higher if fewer counts (lower moisture) are measured However, it is doubtful whether the overall precision is as good as one per cent because the stability of the counter tube and other equipment is probably not better than two per cent

Since there is always the possibility of changes in sensitivity of the counter tube, or of the amplifier system, it is essential to check the arrangement from time to time by means of a standardizing arrangement, i e, by an arrangement in which one can expect to find the same number, and same quality of slow neutrons at all times This has been achieved for the moisture measuring device by inserting the assembly in a paraffin cylinder approximately 13 inches in diameter and 13 inches high At regular intervals a check was made by inserting the assembly into this block During the ordinary lifetime of the counter tube the results obtained with the standard were always the same within the statistical error

The assembly for the measurement of density (see Fig 3) consisted of a four millicurie radium source and a Geiger counter of the same type as described earlier Between the source and the Geiger tube is a lead block as indicated in the figure The assembly is lowered into the tube penetrating the soil mass, and the counting rate determined at the desired position in the soil by the same counter, scaler, and register In order to calibrate the system, a very weak source of gamma rays was placed in a rigorously reproducible position with respect to the Geiger counter As long as the counter is counting correctly, readings taken with this standard must be the same

Fig 4 is a photograph of the scaler-arrangement, and Fig 5 of the drums and tubes Fig 6 shows the assembly used in the moisture determination, the tube has been cut away to show the arrangement of the neutron source on its support, the lower foil

* Extraneous radiation from contamination, cosmic rays, etc, cause a certain number of residual counts, known as "background counts"

** 100 millicuries of radium mixed with beryllium powder and sealed in a capsule 1/2-inch diameter by 3/4 inch long

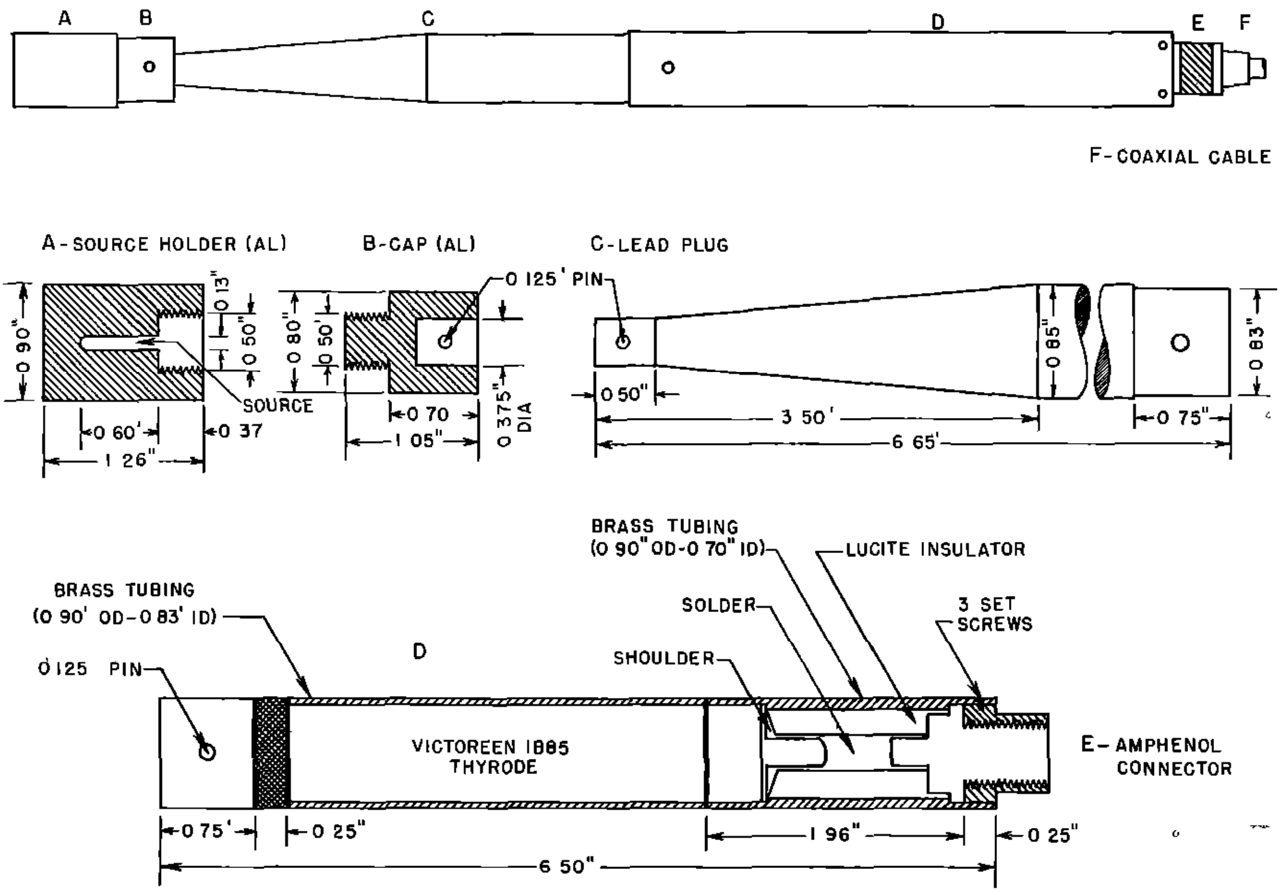

Fig 3 Assembly for Density Measurements by Gamma-Ray Scattering

holder and the center foil holder which has been partially pulled out so as to make visible the source Fig 7 shows the assembly for density measurements, the conically terminated lead cylinder between the source and counter tube can clearly be seen

RESULTS OF LABORATORY TESTS

Moisture Content

In the diagrams which follow, the length of the vertical line indicates the probable statistical error of the readings while the horizontal lines indicate the range of the moisture determinations obtained by the standard method The following factors were studied

(1) Sensitivity, Accuracy, Reproducibility From Fig 8, which shows the results of a great number of measurements with silt, taken over an extended period of time, it is clear that the sensitivity of the method is more than adequate It can be seen that these points lie on a smooth curve within the error of the moisture determination and that the statistical precision of the counting rate is higher than the precision of the ordinary moisture determination

Since this method measures moisture content in pounds of water per cubic foot of volume, the comparison of these results with the moisture content expressed in percentage of dry weight requires that the density of the material be known Under normal conditions, when the density remains constant, the density factor can be eliminated by taking one moisture observation and then converting the calibration curve into counting rate versus moisture in percentage of dry weight

(2) The effect, if any, of the type of soil on the shape of the curve (Fig 8) has not yet been thoroughly explored However, Fig 8 includes results obtained with sand and glacial drift to show that the dependence on the type of soil is negligible

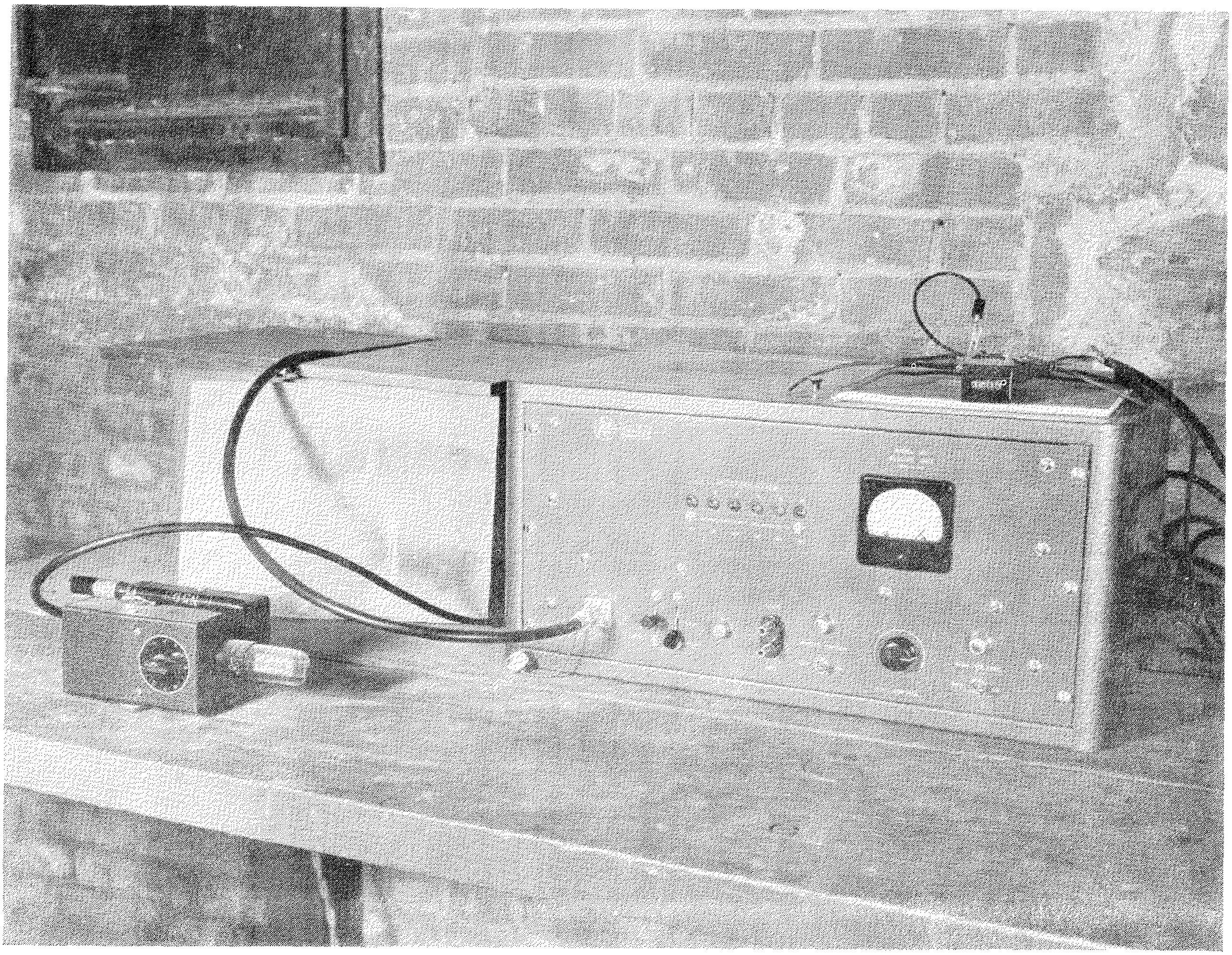

Fig. 4 Electronic Scaling Unit With Lead Chamber at Left Housing the Geiger Counter. In Front is a Dosimeter (Pen-Shaped) Carried by the Personnel for Measurement of Radiation to Which They Had Been Exposed

(3) Since this method is based on a scattering process and since this scattering takes place over some reasonable volume, the results given by this method will represent an average moisture content over a more or less extended volume. It is important to investigate the order of magnitude of the effective volume. One can expect that for low moisture contents the volume over which an average is taken is greater than that for higher moisture contents. Experiments in drums of different sizes have shown that for a moisture content higher than 13 pounds of water per cubic foot any increase of size beyond 17 inches diameter does not increase the number of counts, but for low moisture contents the number of counts increases slightly if a bigger drum is used. In order to compare laboratory results directly with field tests in which the soil-medium is infinitely extended, a correction to the curve, Fig. 8, must be applied. Though the laboratory measurements are not quite precise for this purpose, a corrected calibration curve can be drawn and is seen in Fig. 8 as a broken line. This, then, would be the calibration curve that holds for field tests. The calibration curve and the correction for the extended soil-medium will change with changes in the geometric arrangement of source and detector, and the wall thickness and material of the tube. The curve given in Fig. 8 is obtained with the detector foil centered around the source, and with an aluminum tube of 1/32-inch wall thickness.

Fig. 5 Drums and Tubes Used in Laboratory Tests

(4) A further point of importance is the influence of inhomogeneities; rocks, for example. Several curves were run with glacial drift in a 55-gallon drum in which rocks of well-defined size and shape were placed at known positions near the tube. Fig. 9 shows the variations of the counting rate as the measuring device was moved up or down. The location and size of the rocks is also indicated. Since this method gives an average of moisture content over moderately large volumes, it can be expected that the influence of inhomogeneities is small; in fact, it can be seen from Fig. 9 that, though some fluctuations are present, the indicated moisture is still within 1.25 pounds (one per cent dry weight) of the average.

(5) It can be expected that in certain parts of the country a considerable amount of salt will be present in the soil. Chlorine, which is one of the main constituents of the inorganic salts that may be present, shows a strong interaction with neutrons; it "captures" them, and thus reduces the number of neutrons that can reach the detector. If chlorine is present, the use of the normal calibration curve (Fig. 8) will result in an incorrect (low) moisture determination. In Fig. 10 the solid line is again the curve of Fig. 8; the crosses indicate the measurements in the same type of soil to which about 5 lbs./ft.^{3} of salt of the following composition has been added: 40 per cent $CaCl_2$; 30 per cent NaCl; 20 per cent $MgSO_4$; 10 per cent $NaSO_4$. It can be seen that the effect of the salt is relatively small and since the amount added in these experiments is much higher than can be reasonably expected in the field, it can be assumed that the presence of salts will not influence appreciably the precision of the measurements. If more salt is present than in saline soils, a new calibration curve should

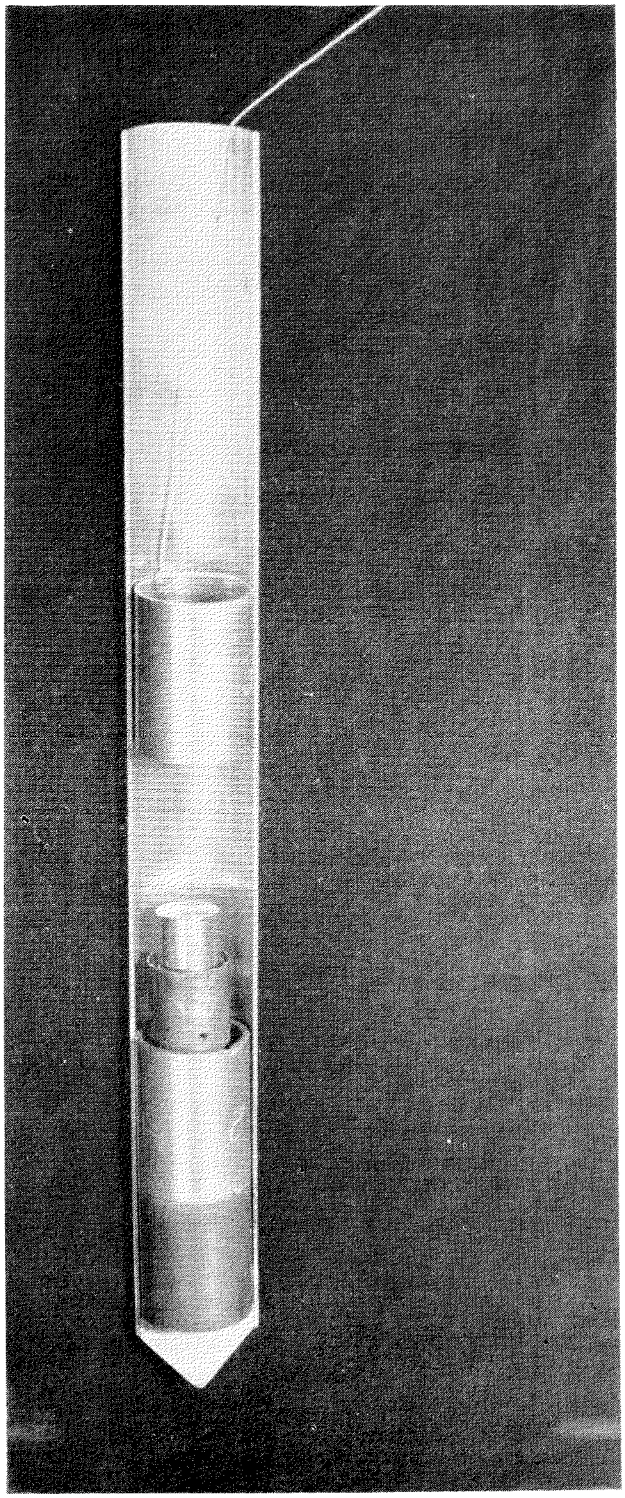

Fig. 6 Assembly Used in Moisture Determinations. The Center Foil Holder Has Been Partially Pulled Out so as to Make Visible the Neutron Source and Its Support

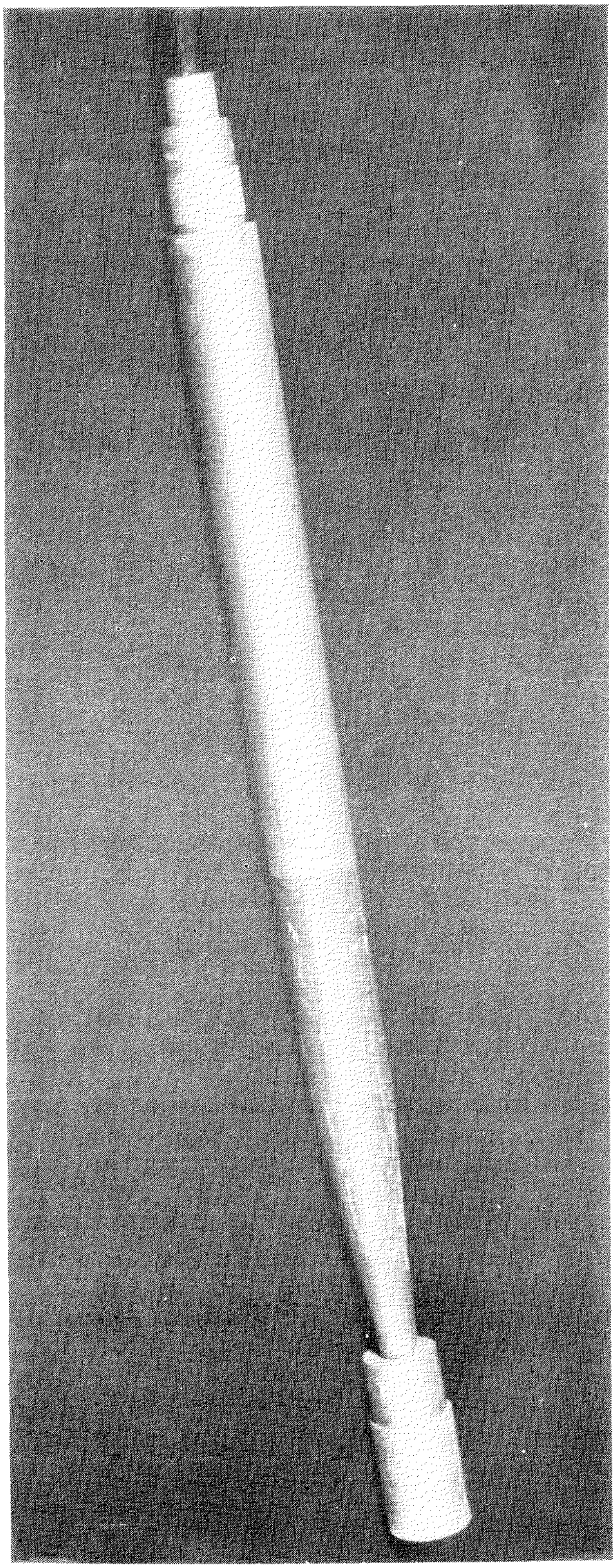

Fig. 7 Assembly Used in Density Determinations

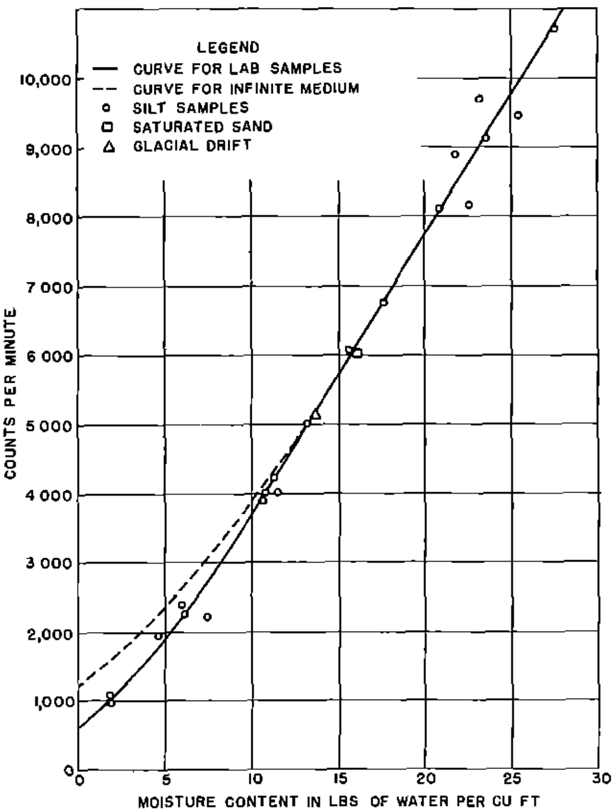

Fig 8 Counting Rate vs Moisture Content

be made

(6) Another factor that may alter the calibration curve is the presence of organic matter in the soil Organic matter contains hydrogen (in the form of hydrocarbons, for instance) and since the new method cannot distinguish between hydrogen in water or in any other chemical compound, an excessively high counting rate may be observed Measurements of a sample of a high groundwater soil with a highly developed organic top soil containing about 75 per cent moisture gave a reading that falls on the calibration curve, thus showing that the influence of organic matter, to the extent present in this soil sample, at least, is negligible

(7) Some preliminary experiments were made with the objective of investigating the ability of this method to differentiate between different moisture contents occurring in relatively thin horizontal strata By means of a particular arrangement of source and detector, it was possible to measure accurately the moisture content of a layer of four to six inches, independently of the moisture content of adjacent layers, provided the measured layer was not too dry It is felt that there are a number of other possibilities, such as shielding arrangements, and variations in the geometry of the assembly that may still further improve the usefulness of this method for the study of thin layers These factors are possible fields for future study

Density

The arrangement of equipment was as indicated in Fig 3 Fig 11 shows the counting rate as a function of density observed with various types of soils of various moisture content The fact that the counting rate decreases as the density increases is consistent with the simple theory of gamma-ray scattering This figure shows that the sensitivity of this method is very great The results are reproducible within the statistical error

Again, this method measures the density as an average over an extended volume Experimentation with drums of various sizes and with one arrangement of source and Geiger counter showed that for soil weights greater than 85 pounds per cubic foot this region is less than 18 inches in diameter However, the experiments indicate that the phenomena are much more complex in the case of gamma-ray scattering than obtains for neutron scattering, accordingly, some details have still to be clarified, although as a whole, the method seems to be practical

FIELD TESTS

Two sets of tests were made to check the performance of the new device under field conditions In the first test the laboratory equipment which is manually operated was used to explore the profile of a soil to nine feet below the surface In the second test, exploring a soil-layer of 4-foot thickness, automatic equipment specially designed for this purpose was used, and the counts were telemetered from the field station to the laboratory where the results were automatically recorded

Tests With Manually-Operated Laboratory Equipment

For this test a place was selected approximately 100 feet distant from the building where the laboratory tests were performed Excavation at the site subsequent to the meas-

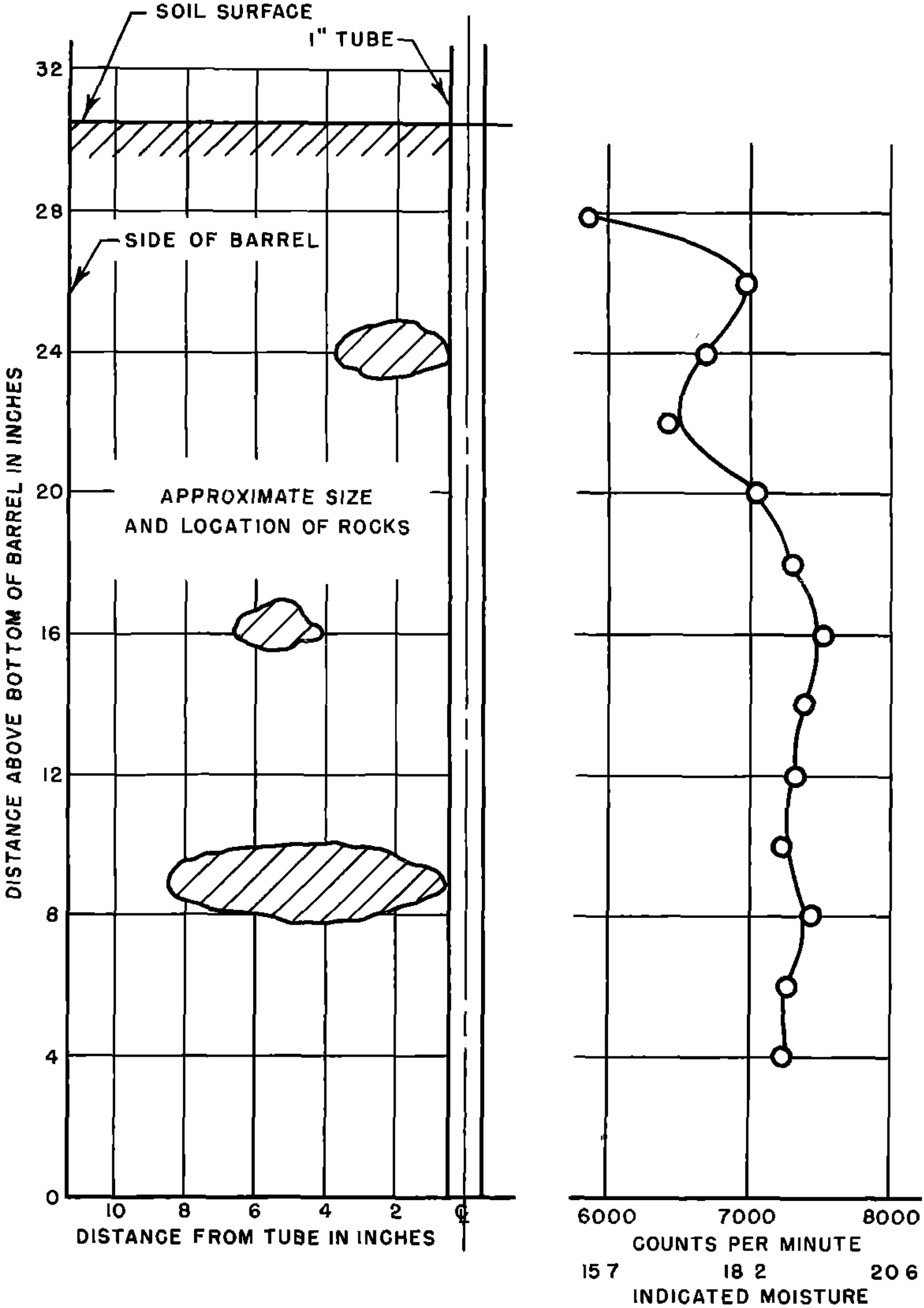

Fig 9 Cross Section and Moisture Curve Showing Influence of Rocks in Glacial Drift Soil

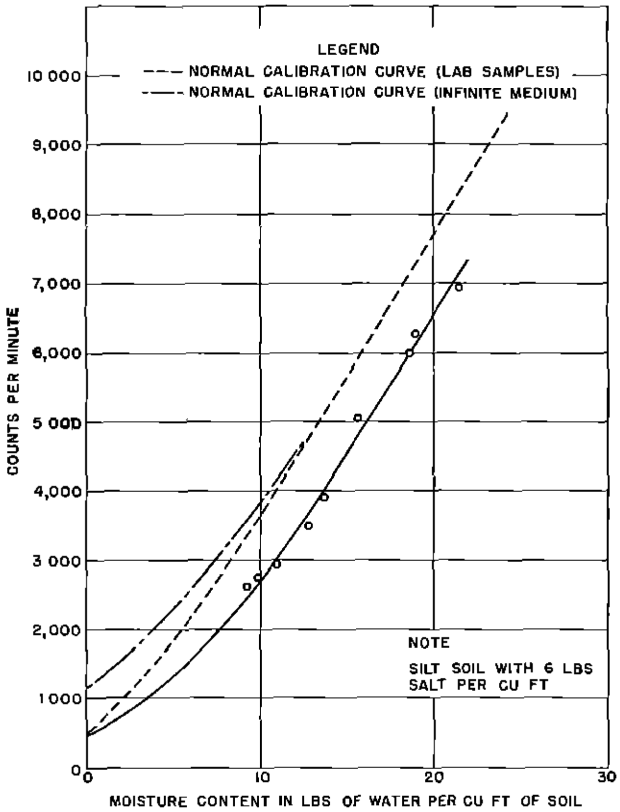

Fig 10 Counts Per Minute vs Moisture Content

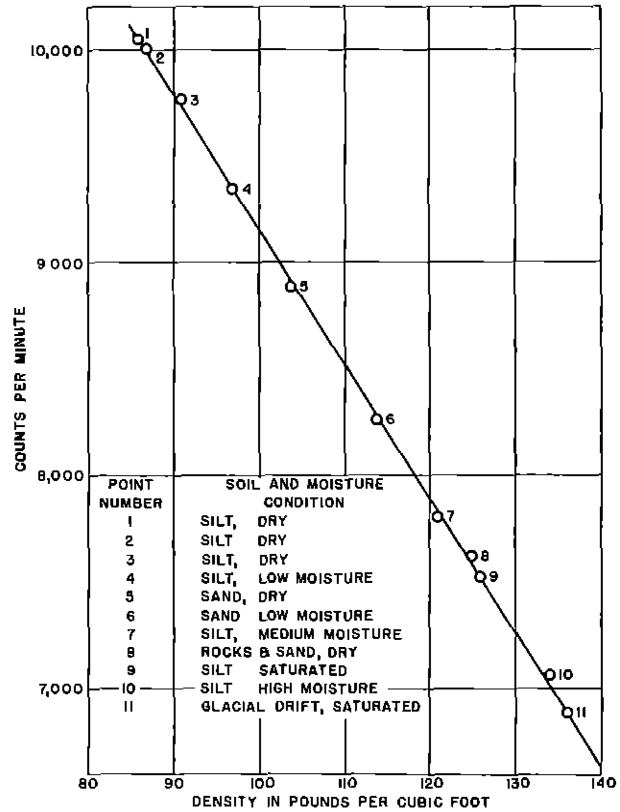

Fig 11 Counting Rate vs Wet Density of Soils

urements showed that the soil consists of a 4-foot layer of gravelly loam underlain by medium sand with occasional minor strata of sandy clay approximately one inch in thickness, which turned at about eight feet into clean sand down to the water table at 9 to 9 5 feet A 9-foot stainless steel tubing, 1-inch inner diameter, 1 25-inch outside diameter, * was provided on one end with a solid point A hole was drilled with an auger down to approximately six feet The steel pipe was inserted into this hole and then driven down for the remaining three feet In the drilling, the auger struck rocks in the upper horizon resulting in a loose fit between the outside of the steel pipe and the soil This space was filled with sand as well as possible While drilling the hole, soil samples were taken at regular intervals for weighing and drying For the moisture determination the assembly used in the laboratory test was lowered into the hole and observations were made at different predetermined positions In the most complete run, measurements were taken every six inches After each exposure of one-half hour the rhodium foil was withdrawn and quickly carried to the counting device in the laboratory Care was taken that always exactly the same time (60 seconds) elapsed between the withdrawal of the foil and the beginning of the counting For the density measurements the count rate meter was placed near the hole and the density-measuring assembly (Fig 7) directly connected by a coaxial cable, so that readings were taken on the spot Several runs were taken on different days

The observations expressed in counts per minute were transformed by means of the laboratory calibration curves into values of moisture content in pounds of water per cubic foot of soil and into soil density in pounds per cubic foot These results, plotted as a function of the distance below the surface, are shown in Fig 12 for measurements made on one particular day Other runs, made within

* Tubes of different wall thicknesses may yield different calibration curves

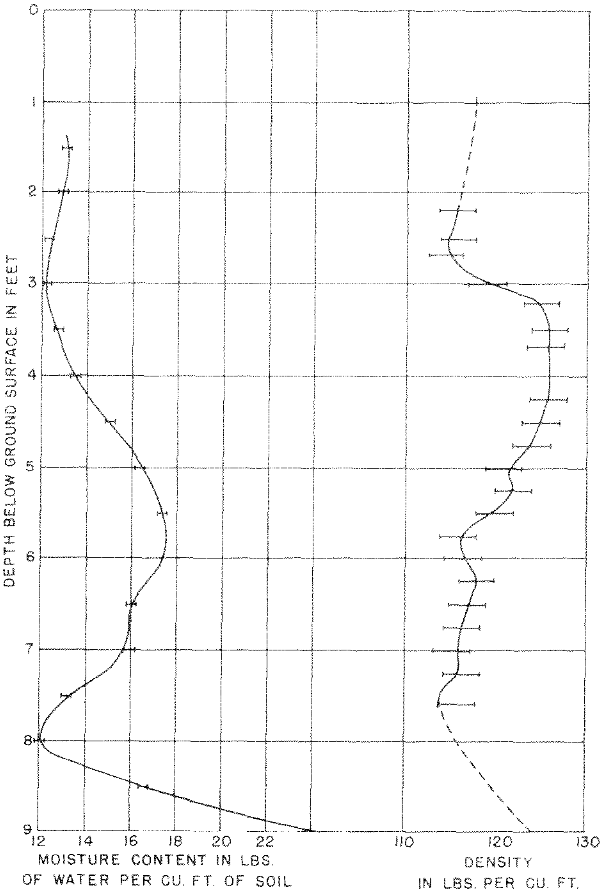

Fig. 12 Moisture and Density Logs - Field Test Hole

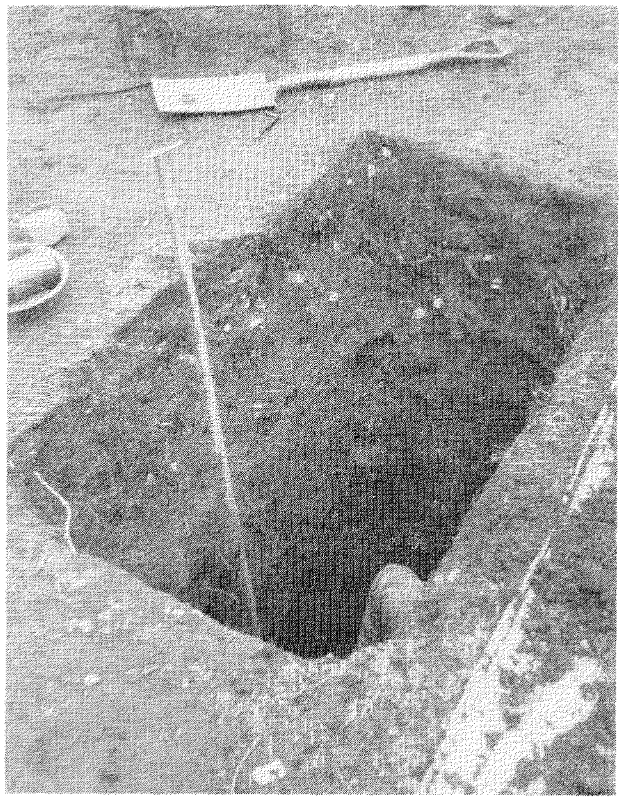

Fig. 13 The Excavation at Test Site. The Tube for Moisture and Density Measurements is Seen on One Wall

one or two days during which there was little probability for a change in moisture, gave practically identical results.

In order to judge the reliability of this method, it was desired to compare the results with moisture and density determinations made by standard methods. For this purpose, a hole, 4 by 3 by 9 feet, was excavated as shown in Fig. 13. As the hole was excavated, one or two samples of approximately 75 grams were taken every six inches for the moisture determination. In order to determine the density, a steel tube, eight inches long and of three inches inner diameter, was pressed to its full length into the undisturbed wall, at a given depth, and then carefully taken out without disturbing the soil contained in the tube. The weight of the soil withdrawn, divided by the volume of the tube, was taken as the soil density in that region. The unit weights thus obtained at four different depths were, in general, lower than those obtained with the new device, the maximum difference being 10 pounds per cubic foot.* This is ascribed to the fact that the volume used in the direct method is too small for obtaining a good average, particularly in the locations where stones are present.

* It should be mentioned here that at the start some difficulties were encountered in getting reliable results with the new density measuring instrument, and that the curve reproduced in Fig. 12 was finally the result of a series of measurements in a second steel tube of the same length inserted into the soil three feet away from the first. The difficulty seemed to reside in the fact that, during the process of placing the first tubing, the soil in its immediate neighborhood, perhaps over one or two inches, was disturbed. Care was taken to avoid this in placing the second tube, and it is believed that these results are reliable.

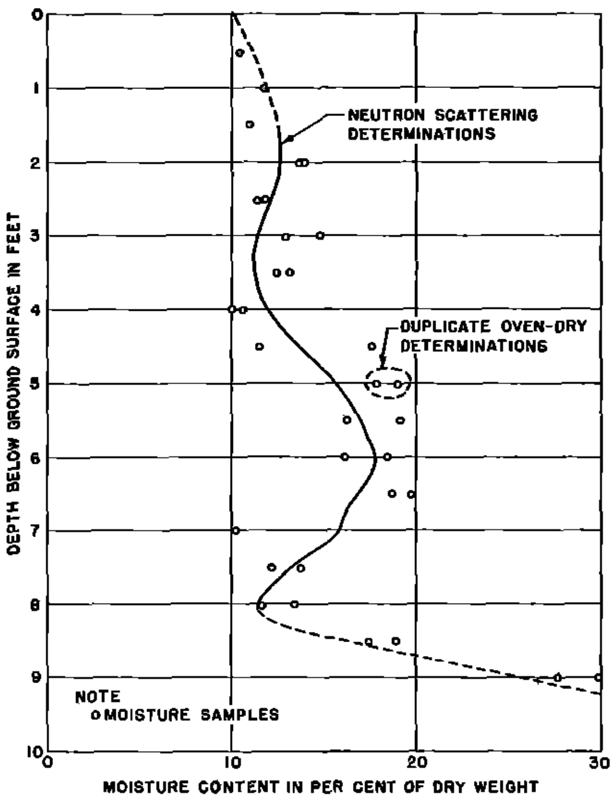

Fig 14 Moisture Content Log - Field Test Hole

The moisture content, expressed in terms of pounds of water per unit weight in Fig 12, has been transformed into units of moisture content expressed as a percentage of dry weight by means of the density values taken from the density curve of Fig 12 This more conventional curve is shown in Fig 14, where the smooth curve represents values determined by the neutron device, the symbols represent moisture as given by the standard technique This figure demonstrated that, within the spread of values obtained by sampling, good agreement is obtained It is not clear whether the "smooth" aspect of the curve from the nuclear device, as compared to the variation of the standard measurements, is due to inherent difficulties of the drying and weighing method, or is a result of the fact that the nuclear device reads an average moisture over a radius of perhaps six inches or even more

Tests with Automatic Equipment

The "field station" was chosen 50 feet away from a building so that 110 volt 60 cycle power could be made available at the site It was one mile distant from the laboratory where the results were recorded The soil consisted of a 4- to 4 5-foot thick clay layer over shale The steel tube was inserted to a depth of four feet below the surface The source-detector assembly consisted of a polonium-beryllium source and a Victoreen Geiger counter surrounded by a rhodium foil and placed close to the source but separated from it by a block of lead See Fig 15 The assembly is connected by a coaxial cable to the electronic counting devices A calibration curve was taken by making simultaneous measurements with this assembly and the one normally used in the laboratory Though called a "gamma ray free" source, some gamma radiation is present and causes a relatively large background With the fresh source, in a soil containing 20 pounds of water per cubic foot, the total number of counts per minute was approximately 7,000, of which 2,400 were due to the background It must also be stressed that the strength of the source is continually decreasing, the number of counts, under identical conditions, decreases approximately 0 5 per cent per day, and the results have to be adjusted accordingly

In describing the electronic equipment, it should be emphasized that the aim of this test was only to prove the feasibility of telemetering and continuously recording of moisture content in soil and not to develop a final apparatus for that purpose Therefore, the equipment here used was chosen primarily from a point of view of availability or simplicity of construction at low cost-"bread board models" and is not, therefore, indicative of a field model The pulse amplifier and scaler used in the laboratory experiments were placed, in a protective box, near the tube and were connected to the source-detector assembly by a coaxial cable The output of the scaler went to a relay, which amplitude-modulated a 1-watt, 144-Mc continuous wave oscillator, feeding into an antenna mounted on a convenient flagpole outside the building The transmitter was located in the building, and connected to the relay by an ordinary electric cable Fig 16 is a photograph of the field station, showing the tube, the scaler in the box, the assembly held beside the tube, and the connecting cables

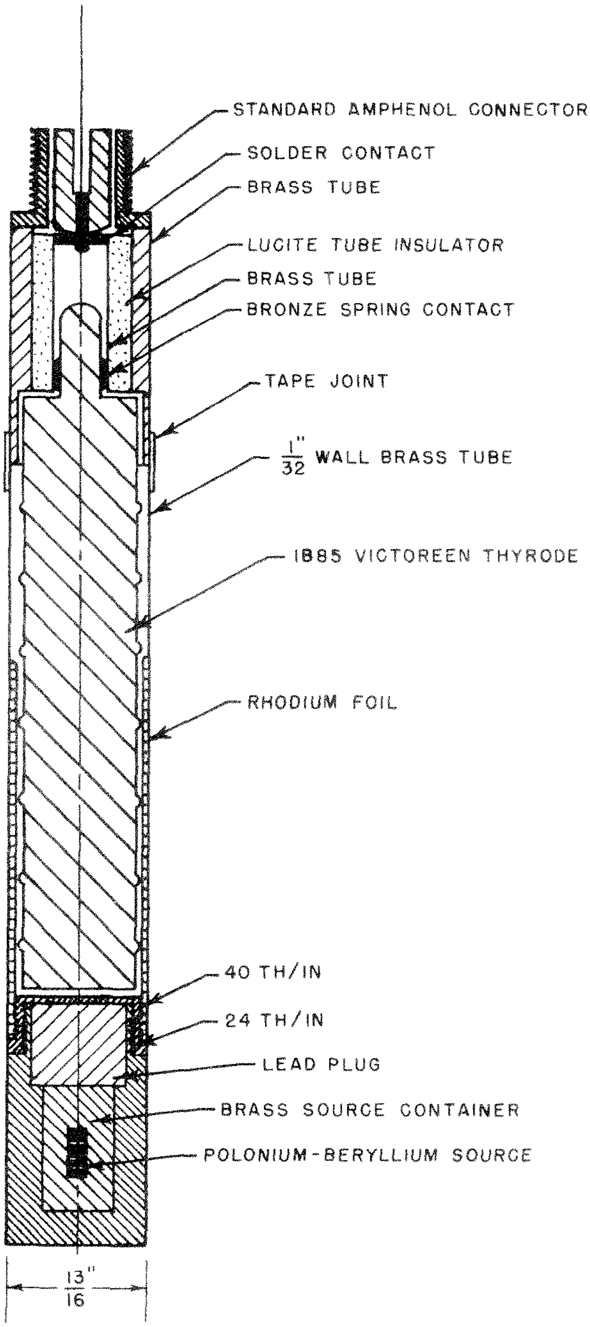

Fig. 15 Polonium-Beryllium Moisture Detection Device

The pulsed radio wave (one pulse for every 64 counts in the Geiger counter) was received in the laboratory about one mile away, by a receiver seen on the table at the left in Fig. 17. The demodulated pulse is amplified (pulse amplifier of a commercial scaler) then fed into a count-rate meter (home-

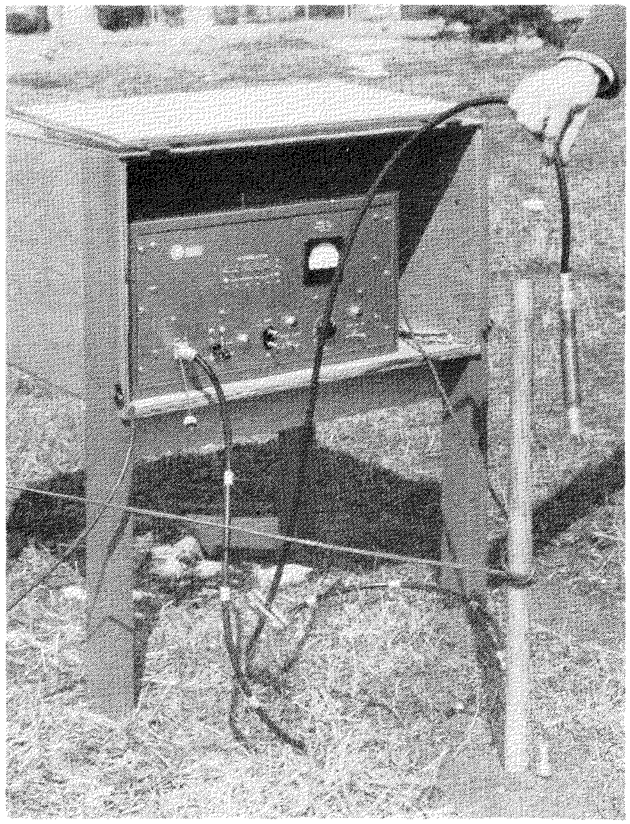

Fig. 16 Field Station in Telemetering Test

built, using a mechanical relay) the output voltage of which was measured and recorded by an Esterline-Angus Recorder (far right*). The deflection of the needle of the recorder is directly proportional to the number of counts received per minute. At both the transmitter and receiver stations mechanical registers were added (seen in middle foreground of Fig. 16) in order to permit frequent checking of the correct functioning of the equipment.

Fig. 18 is a record taken over a 4.5-hour interval of continuous operation. One division corresponds to 14.1 register counts per minute (885 neutron counts per minute). Shortly before 1300 hours with the assembly 45 inches from the surface, the equipment was turned on; at about 1315 the final adjustment of the voltages was made, the assembly raised to 42 inches and a slight increase in counts noted. The reading was 0.74 divisions,

* On the top shelf in Fig. 17 may be seen auxiliary equipment such as loudspeaker, power supplies, etc.

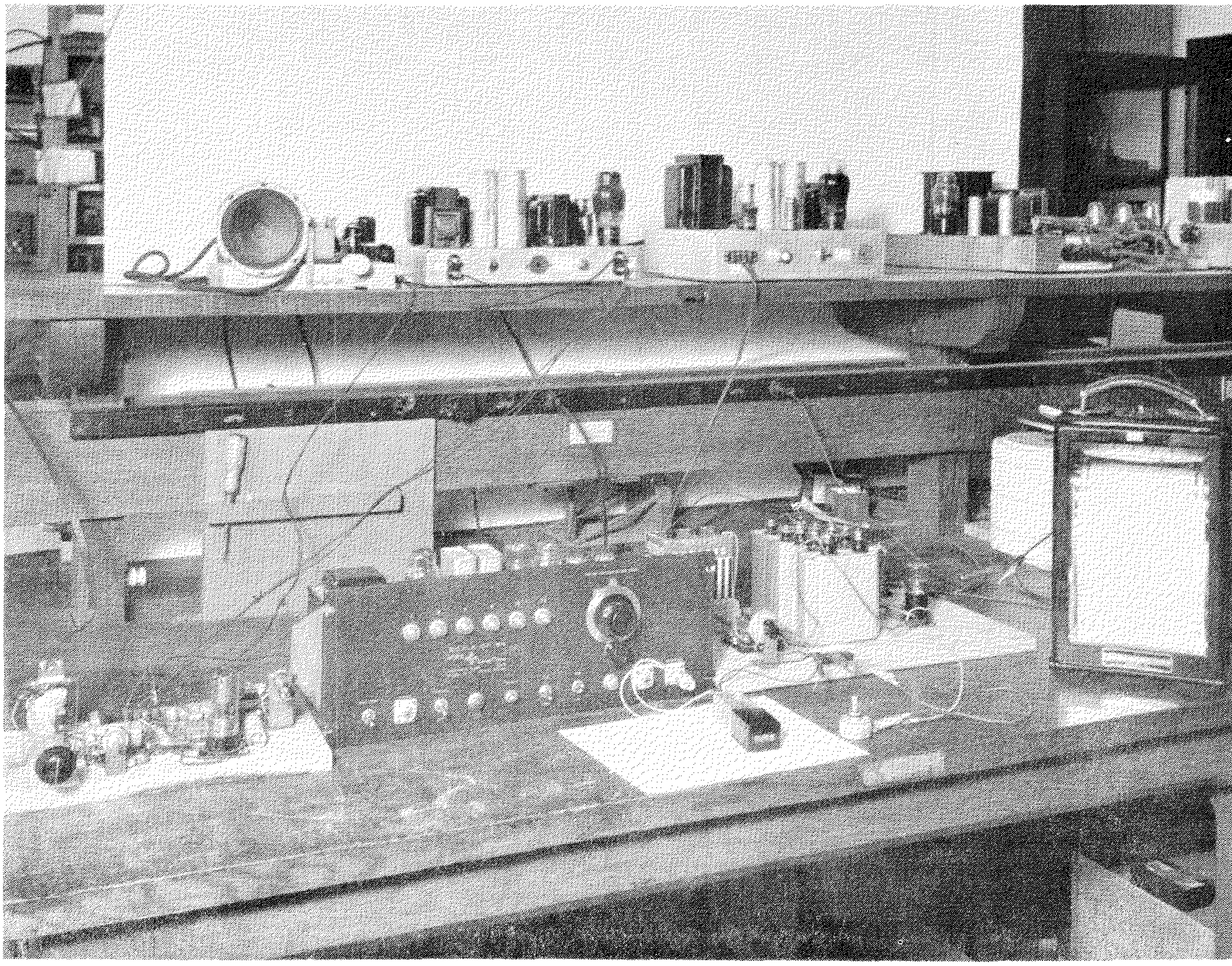

Fig. 17 Receiver and Recording Equipment Used in Telemetering Test

which corresponds to about 18.4 pounds of water per cubic foot, according to the calibration curve. At 1330 the assembly was raised to 36 inches; the counts remained practically the same; the moisture content did not change. At 1400 it was raised to 30 inches and the counts dropped sharply, but due to the long-time constant of activation and decay of the rhodium foil, a time of 20 to 25 minutes elapsed before equilibrium was reached and the reading could be taken. The tape registered 0.68, corresponding to 16.0 pounds of water. At 1430 the assembly was raised to 24 inches, the deflection was slightly less than 0.66, equaling 15.2 pounds of water. At 1500 it was placed at 18 inches with only a very slight increase in deflection; the moisture content remained practically unchanged. At about 1520 the power failed in the building at the field station; no counts could be transmitted, hence the sharp dip in the deflection. A few minutes later power was restored. At 1530 the assembly was raised to a point 12 inches below the surface with no change in indicated moisture. For a check, the assembly was lowered again, every half-hour, in 12-inch steps, and at the end raised again to 12 inches below the surface; the record indicated identical results to those obtained earlier. At 1720 the experiment was terminated.

Radiation Hazard

The moisture-measuring device employing the radium-beryllium source emits radiations which are dangerous to the health of personnel; therefore, suitable safety procedures were established. These are not difficult to carry out and do not significantly

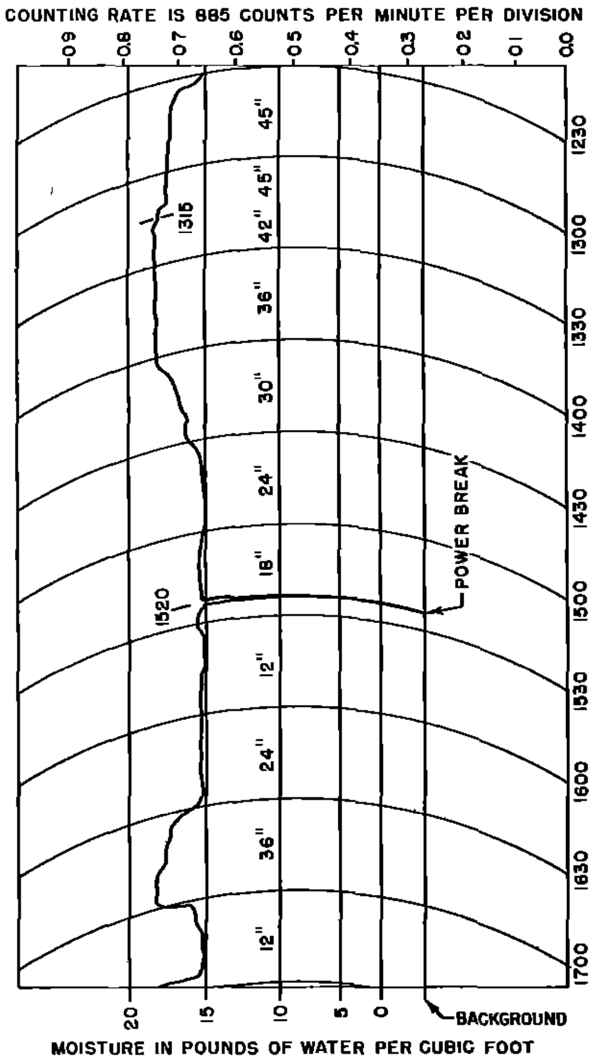

Fig 18 Recording of Moisture Content Taken During Telemetering Test

complicate soil moisture studies Personnel working on the project were required to obey the following regulations

(1) The unshielded radium-beryllium source shall be kept at least three feet away from any part of the body during the short-time intervals it is not in the soil or in the lead storage container

(2) Personnel shall not remain for extended periods of time (one hour or more) in the vicinity of the soil-filled drum while the radium capsule is in place Work may be carried out safely for very long periods in the region beyond a 6-foot radius

(3) Personnel shall wear suitable "radiation monitors" of an ionization chamber or of a photographic film type Readings of the ionization monitor shall be recorded after each period in which the radium source has been used

In order to comply with regulation (1), the radium capsule has fittings so that it may be picked up, suitably mounted in the assembly, or otherwise "handled" as desired, by a tong arrangement at the end of a 3-foot handle Since it takes but a minute or two to transfer the source from its lead-walled container to the soil mass, the following table illustrates how regulation (1) reduces the hazard to negligible proportions

Distance (feet) from unshielded source to body	4 5	3 0	2 0	1.0
Time (minutes) to receive exposure equivalent to about one-tenth safe daily dose	60	35	18	3

In the field there is no hazard when the capsule is in the soil unless personnel sit or stand for a long period (more than one hour) directly over the tube passing into the soil The soil mass acts as a satisfactory shield

Government regulations for the handling and shipping of polonium-beryllium sources do not require any special safety measures The gamma-ray source used in the density measurements was much too weak a source to require special handling Nevertheless, the personnel on this project were warned not to carry either of these sources unshielded in the pocket or otherwise in close contact with the body

The radium-beryllium source used in the studies was a more intense source than necessary for adequate performance of the soil-moisture equipment, a weaker source will obviously further minimize the radiation hazard

SUMMARY AND CRITICAL EVALUATION OF LABORATORY AND FIELD TESTS

The following conclusions can be drawn from the test results described in "Results of Laboratory Tests" and "Field Tests."

Concerning Moisture Determination.

(1) The neutron-scattering method proves to be a reliable method for determining, without disturbing the soil mass, the moisture content The precision is ±1 pound of water per cubic foot or better, corresponding to about ±1 per cent moisture content

(2) The laboratory method lends itself to practical measurements in the field without giving rise to any essential difficulties

(3) The results obtained are averages over a radius of approximately from 6 inches for high to 15 inches for low moisture contents, a fact that should be kept in mind in analyzing the readings obtained by this device

(4) The method permits exploration of the profile by simple movement of the measuring device inside a tube

(5) Different soils seem to have the same calibration curve although this fact has still to be thoroughly established The calibration curve obtained by laboratory experiments can be used for measurements in the field

(6) Inhomogeneities, such as ordinary rocks in glacial drift, do not introduce serious disturbances

(7) Addition of salts or humus in quantities encountered under normal conditions will not alter the calibration curve

(8) With the present equipment variations of moisture occurring within a time interval as short as one-half hour can be detected

(9) By using a polonium-beryllium source, readings can be continuously and automatically recorded and telemetered from the test site to a central station

Concerning Density Determination

(1) The gamma-ray scattering method proves to be a reliable method for determining density without disturbing the soil mass, at least if care is taken that the placing of the tube does not disturb the soil mass near the tube It is desirable to make efforts to eliminate this sensitivity to soil disturbances near the tube and ways can be seen to achieve this goal by changing the geometric arrangement of the source-detector assembly

(2) The precision, at present, is ±2 pounds per cubic foot

(3) The readings represent averages over a radius of less than nine inches

(4) The method lends itself to the continuous exploration of profiles by moving the measuring device inside a tube penetrating the soil The readings may be telemetered and automatically recorded

(5) The calibration curve is independent of the type of soil

(6) Small inhomogeneities, such as rocks, do not seriously disturb measurements, provided they do not occur in the immediate proximity of the tube There is hope that this shortcoming can be overcome (see (1) under "Concerning Density Determination")

Summarizing, it can be said that both methods have proven themselves in laboratory and field tests and promise to become satisfactory and very useful tools for the measurement and continuous recordings of moisture content and density of soils

POSSIBILITIES AND DESIRABILITY OF FUTURE DEVELOPMENT

It is desirable that future development work be conducted in four directions

A The theory of scattering of neutrons and gamma rays should be further developed, in order to permit a prediction of the effects of certain field conditions without the need of studying experimentally each change in conditions This would save effort and, at the same time, give a firmer basis to the new method.

B Until such a theory is developed, tests under more varied conditions than have been made up to now should be performed in the laboratory as well as in the field In field tests, locations should be chosen showing great variety in the type of soil, drainage conditions, etc , and permitting access to an extent as to assure good soil analysis by standard methods

C More accurate information is needed concerning the size of soil volume over which the moisture is measured, then methods should be further studied to restrict one dimension of the volume over which slow neutrons are scattered back to the detector Certain source-detector geometrical arrangements and certain ways of shielding the detector seem to offer promise of restricting the moisture determination to reasonably thin layers Similarly, much more work of this nature is required in connection with density measurements in order to develop a device which is not too sensitive to minor disturbances close to the tube

D The instrumentation of the device needs further development although the manual procedure employed in these studies is well developed and is reliable Other methods of detecting slow neutrons, such as boron counters and scintillation counters, should be studied and tried from the point of view of their usefulness and adaptability to the present problem The choice of the kind of source to be used has to be discussed taking into consideration costs, simplicity of instrumentation, ease of operation and safety of personnel The telemetering process, if it is to be employed, has then to be adapted to the specific problem

The question of continuous long-time tests must be studied in view of possible modifications that may be required Finally, it is clear that the studies completed so far demonstrate the practical possibility of a device which brings about a great advance in soil moisture and density measurement techniques Eventually, engineering design and development work is required in order to make the device into a fully useful field instrument

ACKNOWLEDGMENTS

In addition to the principals involved in the program of research, development and testing, there have been many that have assisted in special phases of the work Among these have been G F Pieper, Jr , who conducted many of the preliminary moisture tests necessary to the development of the equipment Subsequently, the calibration and testing of both field and laboratory experiments was ably carried to completion by E P Yates Mr P G Krueger initiated and carried to completion the parallel work involved in the development of equipment and techniques in the density studies