

MEASUREMENT OF MOISTURE CONTENT AND DENSITY OF SOIL MASSES USING RADIOACTIVITY METHODS

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ABSTRACT

This paper deals with the application of methods involving the scattering of neutrons and gamma rays to the measurement of moisture content and density of granular materials. The measurement of moisture content is based on the principle that when fast neutrons emitted from a radioactive source collide with hydrogen atoms they are slowed down to a much greater extent than by collisions with other atoms. The number of slow neutrons thus produced is a measure of the number of hydrogen atoms present in the vicinity of the source. Water is the principal contributor of hydrogen atoms in a soil medium. A probe, containing a source of fast neutrons and a slow neutron detector, is inserted into the soil. The probe is connected by a cable to a suitably calibrated scaling instrument, and the moisture content determined from the count rate.

The density of a soil is measured with a probe that is similar but provided with a source and a detector of gamma radiation. The gamma rays emitted from this source are scattered by collisions with electrons of atoms in their path. The higher the density of the surrounding medium, the greater the scattering. In the range of densities normally occurring in soils, greater scattering results in fewer gamma rays returning to the detector. Thus, the density of the medium can also be related to the count rate obtained with the scaling instrument.

The advantages of the radioactivity methods are that continuous or repeated measurements of moisture content and density at any desired depth can be made, and that measurements are integrated over a large volume of soil, so that representative values are obtained. In addition, water may be detected in the solid or vapor states as well as in the liquid state. The soil undergoes a minimum of disturbance because the probe is lowered into an access tube slightly greater than 1 inch in diameter. Measurements can be made in a short time; once the access tube has been placed, it takes an average of about six minutes to determine both moisture content and density at a given depth. The instruments are not influenced by ordinary temperature changes. The method appears to be relatively independent of soil type, so that a single calibration curve for moisture content, and one for density, may be applicable to a wide range of materials.

A description of the theory of scattering of neutrons and gamma rays is included in this report as well as a discussion of the various types of sources and detectors which can be employed in the procedure. Field and laboratory tests utilizing these instruments are described, and the accuracy of test results discussed.

It is concluded that application of this method will provide a rapid, simple and accurate means for measuring moisture content and density of soils or similar granular materials. On this basis, recommendations for future research and more extensive applications of the method are reviewed.

INTRODUCTION

In research related to the investigation of the properties of soil-water systems, the problem of how to determine the moisture content and the

density of soils either in the laboratory or in place is often encountered. In connection with the study of moisture movement in soils, or density changes of soils over a long period of time, many devices have been developed for the determination of these quantities at a specific point in a soil mass. Obviously, the method of sampling by borings is not suitable for this purpose because once a sample is taken at a particular point, the soil at that point is disturbed, its properties are changed, and another location in the immediate vicinity must be chosen for the next sample. This procedure allows another variable, the heterogeneity of the soil, to be introduced into the moisture or density measurements.

The other devices which have been generally used to date for the in-place determination of soil moisture content or density have several inherent disadvantages. First, a relatively long time may be required for equilibrium to be attained between the soil and the measuring device; second, a separate calibration curve is usually required for each material encountered; third, the surrounding medium may be greatly disturbed in the process of placement of the measuring instrument; and finally, in many instances, measurements may be made only at relatively shallow depths.

One of the most promising methods thus far developed for the determination of soil moisture content and density without the necessity for sampling entails the use of radioactive materials. The original work on development of instruments for this procedure was done by the Civil Aeronautics Administration, through a contract with Cornell University. This investigation demonstrated that the scattering of neutrons could be quantitatively related to moisture content and scattering of gamma rays to density (Belcher *et al.*, 1950; Kreuger, 1950; Pieper, 1949; and Yates 1950). Further work by these organizations resulted in improvements in the measuring devices and verification of the aforementioned relationships (Belcher *et al.*, 1952; and Carlton *et al.*, 1953).

Work along similar lines with specific reference to soil mechanics has been conducted by Lane, Torchinsky and Spinks (1952), and Hosticka (1952). In the field of agriculture, Gardner and Kirkham (1952), Vomocil (1954), and Underwood, van Bavel and Swanson (1954) developed instruments utilizing these principles.

Investigations of the radioactivity or nuclear * methods were undertaken by the authors primarily in an effort to find a technique for the measurement of moisture movement in soils. It was desired that fluctuations in moisture content and density of the soil at specific points beneath a highway or airfield pavement be measured over a long period of time with minimum interruption to traffic. Evaluations of this procedure in full-scale field tests have already been published by the authors (Horonjeff and Goldberg, 1953, Horonjeff, Goldberg and Trescony, 1954).

Although the probes contain radioactive materials, they may be operated

* Methods involving radioactivity are also called nuclear methods, because radioactivity is a phenomenon caused by the disintegration of unstable atomic nuclei.

with safety as long as the personnel observe simple precautions. The probes should be manipulated with long-handled tongs, and they must be stored in shielded containers when not in use. It is recommended that some type of personnel protective device that will indicate exposure to neutron and gamma radiation be worn and checked regularly.

GENERAL DESCRIPTION OF THE PROCEDURE

The elements necessary for construction of a nuclear moisture or density measuring system are a source of neutrons and a source of gamma rays, a detection instrument, a power supply and a device for recording the output pulses of the detector. A schematic diagram of a typical arrangement of the elements is shown in Figure 1.

The source and detector are contained in the probe which is placed in a cased bore hole in the soil mass. This probe is connected to a power supply and recording device by a cable containing the signal lead and the power leads.

In moisture determination, fast neutrons emanating from the source are slowed by collisions with atoms of the surrounding medium, particularly by

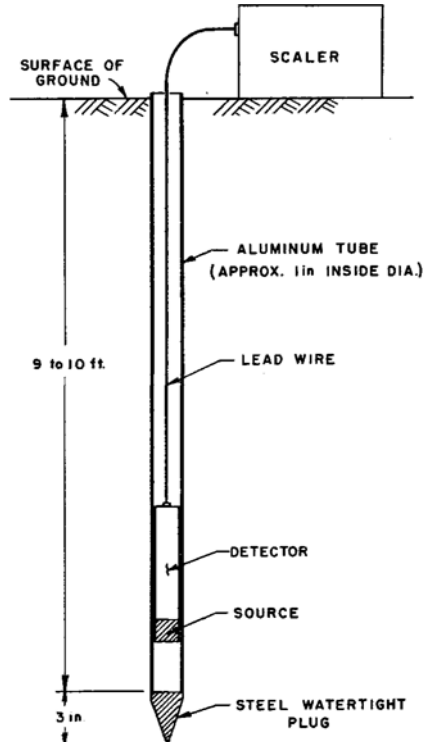


FIGURE 1. — Sketch of moisture and density measuring device.

the hydrogen atoms in water. Some of the slow neutrons produced in this manner return to the detector where they produce pulses which are recorded during a pre-set time interval.

In the determination of density, some of the gamma radiation from the source is back-scattered by the surrounding medium, is detected and the count recorded in the same manner.

Comparison of neutron or gamma ray count rates in the field with calibration curves which have previously been determined on soils in the laboratory provides the quantitative data desired.

THEORY OF THE NEUTRON AND GAMMA RAY SCATTERING METHODS

Neutron Scattering

Unstable isotopes spontaneously disintegrate and release energy in the form of alpha or beta particles and/or gamma radiation, and these radioactive isotopes can be used as a source of one or more desired radiations.

If an alpha emitting isotope is intimately mixed with a finely divided light element, such as beryllium, the bombardment of the atoms of the light element by the alpha particles will result in the ejection of a neutron from the nucleus. This fast neutron has a mass approximately equal to that of a hydrogen atom, has an average kinetic energy of 4 or 5 million electron volts (mev.), and is electrically neutral.

If a point source † of fast neutrons is placed within a homogeneous medium, the neutrons travel radially outward from the source until they collide with atoms of the surrounding material. In these collisions the neutron may be absorbed by the nucleus of the atom, or it may be elastically or inelastically scattered. For the elements contained in soils, the cross section, ‡ or probability of collision, for elastic scattering is predominant. The elastic scattering collisions conform to the laws of Newtonian mechanics, and it can be shown that a fast-moving neutron will lose energy in a collision with a slower moving atom. In a mass of soil, a fast neutron is slowed, or moderated, primarily by a series of elastic collisions until its kinetic energy approaches the average kinetic energy of the moderating atoms, as determined by the ambient temperature. When a neutron has the same energy as the surrounding atoms, it is called a slow or thermal neutron. In the thermal region a neutron may gain or lose energy with equal probability, so the thermal energy § is a lower limit to the slowing process.

† Actually, a source of small but finite dimensions is used instead of the mathematical point source postulated here.

‡ The microscopic cross section of an atom is measured in units of cm^2 , or "barns" (10^{-28} cm^2) and represents the effective target area of the atomic nucleus for an incident neutron.

§ At thermal equilibrium, the neutron energies and velocities are distributed according to the Maxwell-Boltzmann law for the particular ambient temperature. It is usually assumed that all the neutrons have an energy which corresponds to the most probable velocity. At ambient temperature of 27° C , this energy is 0.026 electron volts.

Thermal neutrons do not have a definite velocity direction with respect to the source, but move in a random fashion throughout the medium. Their motion can be described by the principles of diffusion theory.

Hydrogen is more effective in slowing fast neutrons than any other element; therefore, if an instrument which can detect slow neutrons, but which is insensitive to fast neutrons, is placed near a source in a medium such as soil, the counting rate of the detector will primarily be due to the hydrogen content of the soil. Hydrogen is a good moderator because its cross-section for elastic scattering is large, and because in a collision with a hydrogen atom a neutron may lose a large fraction of its kinetic energy. This latter phenomenon occurs because the mass of a neutron is about the same as that of a hydrogen atom, and in a head-on collision with a stationary hydrogen atom, a neutron may transfer all its energy and momentum to the hydrogen nucleus.

Since neutron moderation by other elements in the soil is small, and since in normal soils most of the hydrogen present is contained in the soil moisture, the detector response can be calibrated in terms of moisture content. Although the mineralogical, or grain, structure and aggregation of soils vary widely, the elemental composition of most soils is remarkably similar (Kerr *et al.*, 1951). As the neutron scattering properties of soils depend upon the elemental composition (diffraction effects due to variation in crystal structure being neglected) a single calibration curve will serve for most soils.

The presence in a soil of significantly large quantities of a strong neutron absorber such as boron, lithium, cadmium or chlorine may introduce errors in the moisture determination. Likewise, measurements of moisture in soils containing a high percentage of organic matter may be erroneous because the hydrogen content of the organic matter will contribute to the total count rate. The hydrogen contained in the crystal lattice of clay minerals will contribute in the same manner to the count rate. In general, soils containing large amounts of organic matter or clay contain proportionally larger amounts of moisture in the field condition. For this reason, the effect of the hydrogen from sources other than water becomes relatively small in actual practice.

In the investigations described herein no serious difficulty was encountered in the moisture determination due to the presence of the interfering elements previously mentioned. It is believed that if instances should arise where the accuracy of the moisture determination is in question due to this cause, it will be necessary to correct the calibration curve experimentally in order to take into account the presence of these elements.

The isotopes which have been employed in neutron sources for moisture probes are radium 226, polonium 210 and lead 210 (radium D).

A neutron source containing radium 226 has a long half-life || (1590

|| Half-life is defined as the time required for a radioisotope to lose half its activity.

years) and is the most efficient neutron producer per millicurie # of radioisotope (see Table I, column 4). However, it is unsuitable for use with moisture probes, containing Geiger counter detectors, because the intense gamma radiation from radium 226, to which the Geiger counter is sensitive, cannot be separated from counts due to neutrons.

Compared with radium 226, the gamma radiation from polonium 210 is much less intense. Even though the cost is less, the neutron output for comparable amounts of isotope is less, and the half-life is short, being only 138 days.

Lead 210 (also called radium D) has a 22-year half-life and is a weak beta and gamma emitter. It decays to bismuth 210, which is an alpha emitter. Its low intensity of gamma radiation and fairly long half-life make lead 210 an excellent isotope for use with moisture probes. It is expensive, however, costing approximately 50 percent more than the same amount of radium 226.

In Table I are summarized some of the properties of various neutron sources.

Column 5 lists the relative cost per millicurie of each source material based on a 5 millicurie quantity. For example, a 5 mc. Ra : Be source would cost 2.39 times more than the same quantity of a Po : Be source. The information in column 6 is more significant, however, as it gives the relative cost per unit neutron output. The values for Ra : Be and Po : Be are close, with Ra : Be being slightly higher. Perhaps of more significance than the purchase price is the relative depreciation due to decay of the source, which is indicated in Columns 7 and 8. Column 7 shows the half-life of the radioisotope used in each of the sources, and Column 8 illustrates the relative rate of decay more clearly. If strong gamma emission can be tolerated, it is more economical to use Ra : Be because the longer half-life eliminates

One millicurie (mc.) is defined as that quantity of a radioisotope which must be present in order to supply 3.7×10^7 disintegrations per second.

TABLE I. — PROPERTIES OF VARIOUS NEUTRON SOURCES¹

Source (1)	Neutron energy		Approx. neutrons per sec. per mc. (4)	Relative cost		Decay rate	
	Avg. (mev.) (2)	Max. (mev.) (3)		Per mc. (based on 5 mc.) (5)	For same emission (based on 1 mc. Ra : Be) (6)	Half-life (7)	Relative (based on Ra : Be) (8)
Ra : Be	4.4	12	16,000	2.39	1.00	1,590 yrs.	1
Po : Be	4.1	10	2,500	1.00	2.68	138 days	4,206
Ra-D : Be	4.1	10	2,500	3.44	9.21	22 yrs.	72

¹ Information from Catalogue C (1954) Atomic Energy of Canada, Ltd.

the necessity for replacing the source at frequent intervals as would be necessary if Po: Be were used.

Gamma Ray Scattering

The mass density of soils or granular materials is measured by counting the gamma rays which are back-scattered to a detector by collisions with atoms of the material.

The scattering of gamma rays is somewhat analogous to the scattering of neutrons in that gamma photons suffer a change of direction and loss of energy in a collision. Unlike neutrons, which interact with atomic nuclei, gamma rays are scattered primarily by electrons of the atoms in their path. Although the detectors commonly employed in density probes are somewhat energy dependent, the difference in energy of the source radiation and the scattered radiation is not sufficiently great to allow the detector to distinguish between the two. For this reason, it is necessary to shield the detector from the source, so that only gamma rays scattered around the shield by collisions with atoms of the medium being measured will enter the detector.

If the source and shielded detector are placed in a vacuum, the gamma rays will travel radially outward from the source and not reach the detector. If the region around the source contains atoms of scattering material, some of the gamma rays will be scattered into the detector by single collisions and a definite count rate will be observed. As the numerical density (number of atoms per unit volume) is increased, the probability of scattering by single collisions increases, and the count rate increases. However, as an increase in numerical density interposes a greater number of atoms between the point of first collision and the detector, there is an increase in probability that the gamma rays will be scattered away from their path to the detector by secondary collisions. This secondary scattering also results in significant energy loss to the gamma rays, and further decreases the probability of their ultimate detection. Thus the count rate at first increases with density, reaches a maximum, and then decreases with increasing numerical density. The mass density of a homogeneous material is proportional to the numerical density, so the above-described scattering phenomenon can serve as a measure of mass density.

Cobalt 60 and radium 226 have been used as sources of gamma radiation although other isotopes emitting radiations of similar energy could probably be used. Radium emits gamma rays of various energies, the major constituents ranging from 0.5 mev. to 2.5 mev. Krueger (1950) states that the presence of the 0.5 mev. components makes the probe response especially sensitive to voids and irregularities in the surrounding medium. This situation arises because the low energy rays have a short range in the surrounding medium and the number of rays reaching the detector is influenced greatly by conditions close to the source. The higher energy rays have a longer range and travel further into the surrounding mass before being

scattered back to the detector and thus traverse a larger and more representative sample of the medium being measured. The placement of the measuring instrument undoubtedly results in some disturbance of the natural state of the adjacent material, so it is desirable that the influence of this disturbance be minimized if valid measurements of true density are to be obtained. A discussion of the effect of placement of access tubes on the moisture and density results will be presented in a later section.

Cobalt 60 emits two gamma radiations with energies of 1.17 and 1.33 mev. The absence of low energy components makes cobalt 60 a desirable source for density measurements. This isotope has the additional advantage of lower initial cost although it decays more rapidly than radium 226 (half-life of 5.3 years, compared with 1,590 years for radium). The relatively rapid loss in source strength for Co^{60} also necessitates application of a correction factor to the readings obtained.

The source strength must be large enough so that adequate statistical accuracy of the count rate can be obtained within reasonable counting periods, but small enough so that its portability is not impaired by the necessity for heavy lead safety shielding. When used in conjunction with a Geiger counter detector, 2 to 5 millicuries of radium meet the above requirements. A somewhat smaller Co^{60} source is required because Co^{60} has a 55 percent greater output per millicurie than does radium.

Table II summarizes several important properties of some gamma ray density sources.

From this table, particularly column 6, radium 226 is shown to be preferable as a gamma ray source, as it was for use in a neutron source.

RADIATION DETECTORS

Geiger Counter

The self-quenching type Geiger tube used for the moisture content and density measurements consists of a gas filled, cylindrical metal cathode with a coaxial wire anode of small diameter. The major constituent of the gas

TABLE II. — PROPERTIES OF VARIOUS GAMMA RAY SOURCES¹

Source (1)	Energy range (mev.) (2)	Relative cost		Decay rate	
		Per mc. (based on 50 mc.) (3)	For same emission (based on 1 mc. Co^{60}) (4)	Half-life (yrs.) (5)	Relative (based on Ra : Be) (6)
Ra 226	0.5-2.5	6.94	10.76	1,590 yrs.	1
Co^{60}	1.17, 1.33	1.00	1.00	5.3 yrs.	300

¹ Information from Catalogue C (1954) Atomic Energy of Canada, Ltd.

in the tube is an inert element, such as argon or helium, at a pressure of a few centimeters of mercury. A small quantity of alcohol or other organic vapor is added to the inert gas as a "quenching agent." When a high potential. (800 to 1,200 volts for a typical tube) is applied between the anode and the cathode, the tube serves as a sensitive detector of charged particles arising from radioactive decay processes.

A charged particle such as an alpha or beta particle entering the tube collides with the inert gas atoms, ionizing some of them. The electrons thus formed in the ionizing collision are accelerated toward the center wire (anode) by the electric field resulting from the applied potential. In their movement toward the center wire the electrons gain sufficient energy to ionize other neutral atoms with which they may collide. The electrons formed in these later collisions will subsequently ionize more atoms and form more electrons. In this manner the number of electrons formed by the action of a single ionizing particle is greatly multiplied by the time the electrons reach the center wire and a large output pulse results. The size of this pulse is practically independent of the initial amount of ionization. The positive ions formed during the ionization drift to the outer cylinder after the electron pulse has reached the wire, and the space charge arising from these ions makes the tube insensitive to entering particles until the ions are neutralized. This insensitive time, or "dead time," is of the order of 100 microseconds and imposes a limit on the detection rate of the counter. The organic "quench" gas neutralizes the positive ions before they strike the cathode, thus preventing secondary electron emission at the wall which might initiate a new discharge and provide erroneous pulses.

As gamma rays are electrically neutral, their detection in a Geiger tube depends upon their ability to eject electrons from the gas atoms or from the cathode material. These secondary electrons provide the initial ionization in the gas.

As the potential applied between the anode and cathode is increased from zero, a value will be reached, known as the "starting potential." Below this potential the pulses are too small to be detected, but with rising potential the gas amplification increases and pulses are recorded in increasing numbers. A voltage known as the "Geiger threshold potential" is reached beyond which the count rate becomes essentially constant. The range of potential over which this occurs is called the "Geiger plateau." Beyond this plateau continuous discharge takes place and counting is not possible.

The operating voltage of a Geiger tube is chosen at a point approximately midway on its characteristic plateau. At this point small fluctuations in supply voltage will not materially affect the count rate.

Proportional Counter

Proportional counters containing boron trifluoride (BF_3) gas have been used as slow neutron and gamma ray detectors in work connected with nuclear reactor research (Hughes, 1953), and they have several features

which make them desirable for use in moisture and density probes. The useful life of a BF_3 counter is quite long, exceeding that of a Geiger tube by a factor of at least 1,000. The neutron sensitivity of these counters is good, and the pulses due to gamma radiation, being of much lower magnitude than those due to slow neutrons, can be prevented from contributing to the count rate. This is possible through the use of a discriminator circuit, by means of which the pulse height which is accepted and recorded by the scaler can be varied to exclude all pulses of lower than the set height.

The construction of a proportional counter is similar to that of a Geiger tube in that it consists of a gas-filled cylindrical cathode with coaxial wire anode. The initial ionization occurring within the tube is amplified by electron multiplication within the gas. However, the gas pressure and applied voltage are selected so that the electron multiplication takes place in a small region near the center wire instead of throughout the tube as in a Geiger counter. Electrons ionized anywhere within the main volume of the tube by entering radiations are equally amplified when passing through the multiplying region in their journey to the wire. The magnitude of the output pulse is, therefore, proportional to the initial amount of ionization caused by the entering radiation.

A counter containing BF_3 gas can detect thermal neutrons because, after absorbing a neutron, a boron 10 atom emits an alpha particle and an excited atom of lithium 7. Both of these recoil particles are highly ionizing, and a large pulse is produced. After absorbing the neutron, disintegration of the boron atom occurs almost immediately so it is not necessary to wait for the counter to attain radioactive equilibrium.

The neutron-alpha reaction is a property of the boron 10 isotope only, and the cross-section for this reaction is high, with a value of 3,990 barns. Natural boron contains only 18.8 percent boron 10 so the BF_3 gas used in counters is enriched to 96 percent boron 10, thus increasing the counter efficiency by a factor of approximately 5. The efficiency can be further increased by raising the gas pressure, thus increasing the number of boron 10 atoms per unit volume since the efficiency is directly proportional to the gas density. However, at these higher pressures it is necessary to increase correspondingly the operating voltage, thus creating problems of electrical leakage in the electronic equipment and connecting cables.

For slow neutron detection, the proportional counter exhibits a plateau similar to that of a Geiger counter. The gamma count is insignificant except at voltages above the upper end of the plateau where the gas amplification will increase the gamma pulse height to a value large enough to pass the discriminator. At these high voltages pulses will be registered which are due both to thermal neutrons and to gamma radiation, the net effect being to increase the count rate. In this case the discriminator can be so set that the scaler will register either counts due only to neutrons or counts composed of both neutrons and gamma rays. Subtracting the former count from the latter results in the count for gamma rays alone.

In this manner, the proportional counter can be made to operate as a combined moisture-density probe.

Scintillation Counter

Certain liquid or solid materials, called phosphors, which possess a property called luminescence, are rapidly becoming one of the most useful tools in the field of radiation detection. When an ionizing particle impinges on one of these phosphors, some of the energy dissipated in molecular excitation and ionization is re-emitted as visible or ultra-violet photons. A scintillation counter utilizes the observation and measurement of these individual light flashes or scintillations by means of a photomultiplier tube at a rate about a million times faster than that of a Geiger counter.

The photomultiplier tube is optically coupled to the phosphor. A series of electron-emitting surfaces within the tube are capable of amplifying the original minuscule light flashes into electrical output pulses with amplifications as high as one billion fold. A small flash of light from the phosphor, striking the first surface, releases electrons which strike a second, there producing a larger group of secondary electrons. These strike a third surface, and so on, until the original weak emission has been built up into an avalanche of electrons.

DESCRIPTION OF APPARATUS

One of the principal problems in a research project of this type is to adapt well-known and proven principles and laboratory measuring devices to a design which will be suitable for the requirements of field measurements. These requirements are to combine reasonable portability with minimum loss in accuracy and dependability.

Geiger Counter Moisture Probe

Details of this moisture probe are shown in Figure 2. It is similar in construction to the one developed by the CAA, consisting of a thin-walled cylindrical brass casing approximately 1 inch in diameter and 7 inches in length. The neutron source is contained in a brass plug attached to the bottom of the probe. A 1B85 Thyrode Geiger tube manufactured by the Victoreen Instrument Company has proved most successful as the detector in this probe. This Geiger counter has a sensitive length of 2.75 inches with an overall length of 4.125 inches and maximum diameter of $\frac{1}{8}$ inch. Its size enables it to be contained in the 1-inch diameter probe which has the advantage of being able to be used in small bore holes. The wall of this counter is constructed of aluminum (about 0.004 inches thick), and it is more shock and vibration resistant than a glass tube of similar dimensions. However, it must be handled gently when installing it in the probe to avoid crushing. The operating voltage of this Geiger tube is 875 volts, a value which can be obtained from the power supplies of most scalars. At the

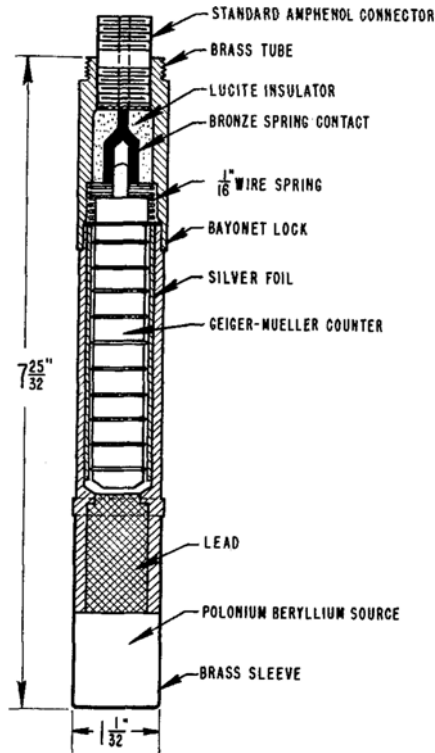


FIGURE 2. — Moisture probe—details of construction.

maximum count rates encountered in this investigation (750 counts per second) the tube might be expected to last about 2 months if used continuously.

For detection of slow neutrons a silver foil 3 mils thick was wrapped around the Geiger tube. A slow neutron striking a silver atom of the foil results in the formation of a radioactive isotope of silver. Silver foil thus activated decays with 270 day, 2.3 minute and 24.5 second half-lives. The cross section for formation of the short half-life product is much larger than the cross sections for the 2.3 minute and 270 day products, with the result that the foil can reach saturation in about 3 minutes. Beta particles and gamma rays which are products of decay of the silver isotope are detected by the Geiger counter and recorded on the scaler.

Geiger Counter Density Probe

Details of this probe are shown in Figure 3. In construction it is identical with the one used by the CAA. The density probe is of the same diameter as the Geiger counter moisture probe, approximately 6 inches longer, and constructed of aluminum.

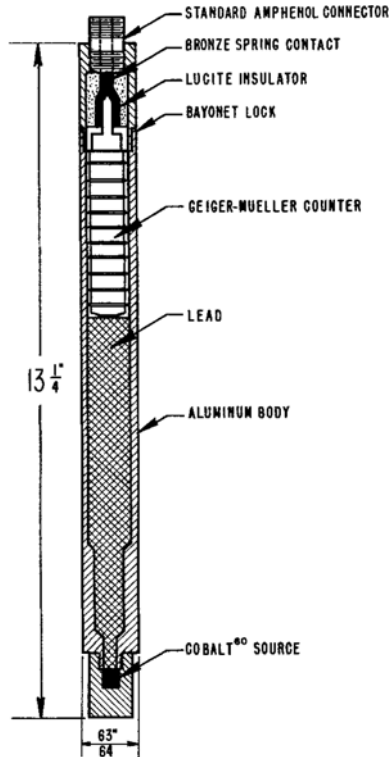


FIGURE 3.—Density probe—details of construction.

In designing the density probe it was desired that the count rate be as high as possible, but that radiation received directly from the source be minimized by sufficient lead shielding. Thus the lead plug placed between the source and the detector permits only gamma rays scattered from the source to be detected. The plug is tapered at the source end to allow more gamma rays to enter the soil and thereby increase the count rate. As long as the taper angle of the plug is greater than or equal to the solid angle between the source and detector, the detector will be shielded as effectively as if a straight cylindrical plug were used.

BF₃ Proportional Counter Probe for Moisture and Density

Details of the BF₃ proportional counter used are shown in Figure 4. This counter, a Mark 3, Model 2, manufactured by Radiation Counter Laboratories, Inc., has an active length of six inches, a 1-inch outside diameter, and an aluminum wall 0.035 inch thick. The filling of 96 percent enriched BF₃ gas to a pressure of 12 cm. of mercury has provided a counter efficiency calculated to be 3.2 percent.

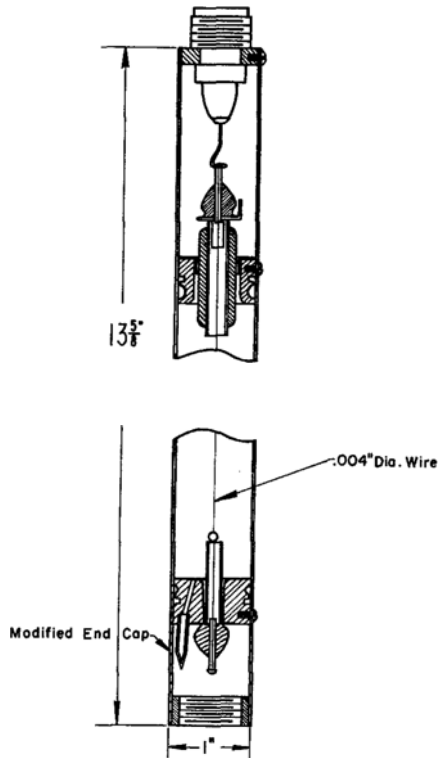


FIGURE 4. — Sectional view of boron trifluoride proportional counter moisture probe.

When used with a fast neutron source for the measurement of moisture only, the source is attached as close as possible to the lower end of the counter. If, however, the source used emits gamma rays in addition to the neutrons, as would be the case in a combined moisture and density probe, it is necessary to interpose a lead plug between the detector and source to minimize direct gamma radiation reaching the detector. The length of the lead plug is calculated to be the minimum required to absorb almost all of the direct gamma radiation from the source. For the 5.3 millicurie radium-beryllium source used in this investigation, this length was calculated and constructed to be 4 inches.

Scintillation Counter Probe for Moisture and Density

Details of the scintillation counter probe construction are shown in Figure 5. The authors have initiated an investigation of the use of a thermal neutron and gamma sensitive crystal as a detector in a combined moisture and density probe. A tin activated lithium iodide crystal has been combined with a $\frac{3}{4}$ inch photomultiplier tube in the development of this probe. The

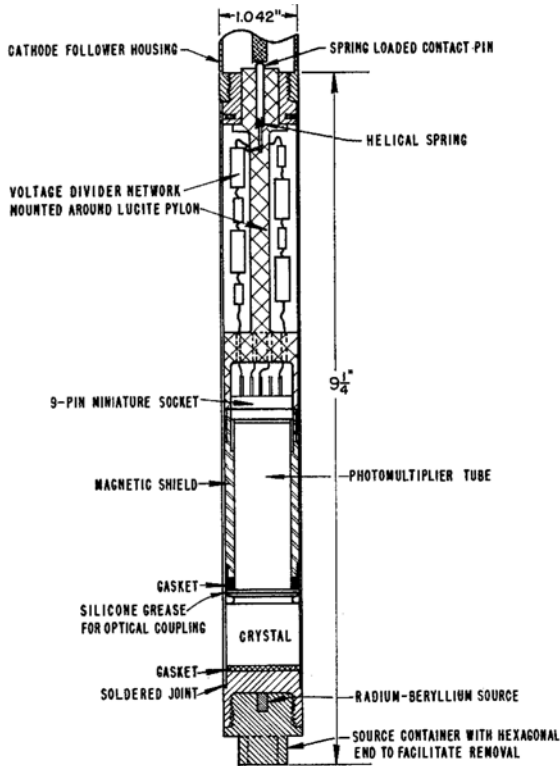


FIGURE 5. — Sectional view of scintillation counter probe.

natural lithium in the crystal contains a 7.4 percent abundance of lithium 6, which has a large absorption cross section (about 900 barns) for thermal neutrons. The product nuclei of the lithium 6 (n, α) H^3 have a combined energy of almost 5 mev., and these pulses may be detected against a gamma background by proper discrimination.

Cathode Follower

Figure 6 illustrates the cathode follower used with the BF_3 proportional counter probe. A cathode follower is connected between the counter and the cable from the scaler to prevent attenuation of the signal by the self-capacity of the cable. The device consists of a single stage vacuum tube amplifier (6J6) which has a high impedance to the pulses from the counter and a low output impedance. In the usual arrangement, the center wire of the counter is connected to the grid of the vacuum tube through a capacitor, which blocks the D. C. bias of the counter and admits only the signal pulses. The output is taken from the cathode of the tube.

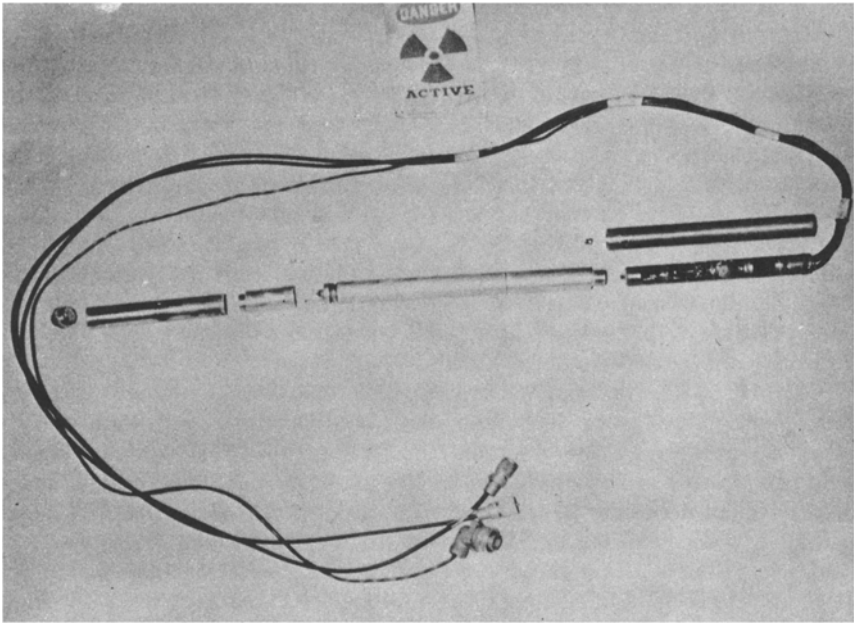


FIGURE 6. — Proportional counter probe, disassembled to show source, lead plug, counter, cathode follower, and leads.

Scaler

A scaler is a device which senses the individual pulses from the counter and registers the total number arriving in a given time interval. The count rate is obtained by dividing the number of pulses by the time. The accuracy of the count rate is limited by the statistical error in the accumulated counts and the error in measuring the time interval. As the disintegration rate of a radioactive material is a random process, the accuracy in determining the rate by the scaler method is dependent upon the total number of counts recorded, and not the count rate. Thus, very low rates can be measured accurately by operating the scaler over a long time interval to record a large number of counts.

Comparison of the Various Probes

Compared with the other types of measuring devices proposed, the principal advantage of the Geiger counter probe is its simplicity of construction and the minimum of required electronic components. Geiger counter life is relatively short, but replacement is inexpensive. With the equipment described herein, it was possible to make use of cable lengths up to 30 feet without the necessity for providing a cathode follower. They have proved

to be rugged, dependable instruments for field use, being substantially shockproof and unaffected by ordinary temperature fluctuations.

The use of silver foil around the Geiger tube in the moisture probe necessitates a certain period of time in which radioactive equilibrium must be reached, *i.e.*, the time required for saturation activity to be reached, where the activation rate equals the decay rate. Although for the foil thickness used, this time is not long (maximum of 3 minutes), the method is somewhat slower than others when a large number of moisture determinations are to be made. In addition, since the detector is also sensitive to gamma radiation, it is essential that such radiation from the neutron source be negligible. From Table I, it is observed that the two sources (Po:Be and RaD:Be) which would be suitable possess the disadvantages of either relatively short half-life or high cost.

The principal advantage of the use of a proportional counter is that it is readily adaptable for the determination of both moisture content and density using a single probe and a single Ra:Be source. Thus, readings can be made in shorter periods of time, and in addition some time can be saved since it is not necessary to wait for saturation activity of a silver foil in the moisture determination. Although the BF₃ proportional counter has a longer life than a Geiger counter, cost of replacement is considerably higher. It has a relatively high efficiency for neutron detection. The use of a single source and detector for both moisture and density determination eliminates the possibility of error in the positioning of the second probe when both these values are desired at a single point or depth.

The number of accessory electronic instruments required for the proportional counter probe is greater than that required for a Geiger counter probe. It has been found necessary to use a cathode follower for cable lengths of over 5 feet. The output pulses of this counter are smaller than those of a Geiger tube, so the scaler must contain a linear amplifier to increase the height of the pulses before they reach the scaling section of the circuit. In order to differentiate between the neutron and gamma ray pulses, it is necessary to provide a discriminator circuit in the instrumentation. A stable high voltage supply providing up to 5,000 volts is necessary to operate a proportional counter, particularly when the higher pressure types are used. It is, however, possible to obtain commercially a single instrument in which are incorporated all the electronic components necessary to operate a proportional counter with the exception of the cathode follower.

Although a scintillation counter probe has already been constructed and tested by the authors, a field testing program comparing its operation with the other devices is not yet completed. It has all the advantages of the proportional counter probe. In addition, its principal advantage appears to be its expected high efficiency in counting neutrons and gamma rays. Useful life should be very long and replacement cost relatively low. Electronically, this device is the most complex of those described, but it appears likely that a field instrument employing this counter can be constructed which is as reliable as those already used.

LABORATORY CALIBRATION OF INSTRUMENTS

In order to utilize the nuclear method in the field, it is first necessary to establish calibration curves showing the relationships between count rates and the known moisture contents and densities of the granular materials to be investigated. The calibration curves shown in Figures 8 through 11 were developed using four materials of the following textures: fine river sand, sandy clay, silty clay and an artificial mixture of silica sand plus 5 percent southern bentonite and 2 percent fire clay. The latter mixture is a commonly used foundry molding sand.

For each test 600 to 1,000 pounds of air-dried soil was thoroughly mixed with predetermined amounts of tap water in a batch mixer and then placed in a volume calibrated 55-gallon steel drum in 5 or more layers, each layer being compacted by hand tamping. A $1\frac{1}{8}$ -inch I.D. by $\frac{1}{8}$ -inch wall aluminum access tube was supported coaxially within the drum by steel spokes. Prior to filling with soil the drum volume had been calibrated by placing weighed quantities of water within it and measuring the distance from the open end of the drum to the water surface. The volume of water was computed from its known weight and density, and a plot of volume of drum contents vs. the depth from the open end was prepared. The uniformity of the moisture content throughout the drum was checked by drying samples taken from the several layers, and the density was checked by weight and height measurements to insure that the density remained constant. The measurements of volume and weight were accurate to within less than 1 percent so the discrepancies in the density calculations were considered to be caused by non-uniform compaction of the soil. The discrepancies were small, however, not exceeding 3 percent in any of the tests.

The probes were placed in the access tube one at a time, with the source end positioned at the center of the soil mass, and at least 3 determinations made. In each of these, sufficient counts were recorded to insure that 95 percent of the time the statistical error would be less than 1 percent. Readings were repeated with the source placed approximately 3 inches above and below the center of the mass. The close agreement of the count rates for the three positions indicated that the amount of soil was sufficiently large and that the source was sufficiently close to the center of the soil mass to avoid a change in the counting rate due to excess radiation leakage at the surface and bottom. These results also provided a check on the uniformity of the distribution of moisture and the uniformity of compaction.

When counting was completed the soil was removed from the drum in three layers, and soil samples taken from each layer for oven-drying. The soil surface was leveled after the removal of each layer so that weight and volume measurements could be made. These density determinations indicated that there was a negligible compaction effect in the lower layers of soil due to the tamping in the placement of the upper layers.

Determinations were repeated for the various soil types and with the various probes over a range of moisture content and density to provide a

sufficient number of points from which the calibration curves in Figures 8 through 11 were drawn. An over-all view of the experimental setup for calibration appears in Figure 7.

The calibration curve as shown in Figure 8 was drawn as the best fitting curve through the plotted points. In Figure 9, a straight line was drawn through the observed values. The position of the line was determined by the method of least squares. In Figures 10 and 11, the uncertainty in the position of the points is indicated by the length of extension lines projecting from each point. The uncertainty is almost all in the direction of the moisture content axis because the nuclear count rates were consistent within 1 percent. Within the experimental error the position of the line could vary somewhat from that shown, but it is believed that the line through the center of each of the points (average value of moisture) provides the best fit.

For both moisture calibration curves, the slope of the line apparently decreases at low moisture contents, and for 0 pounds of water per cubic foot the count rate is not zero. As it is not possible to draw a straight line through the origin that will also lie within the experimental error of each of the other points, the flattening of the curves at low moisture probably represents a true phenomenon.

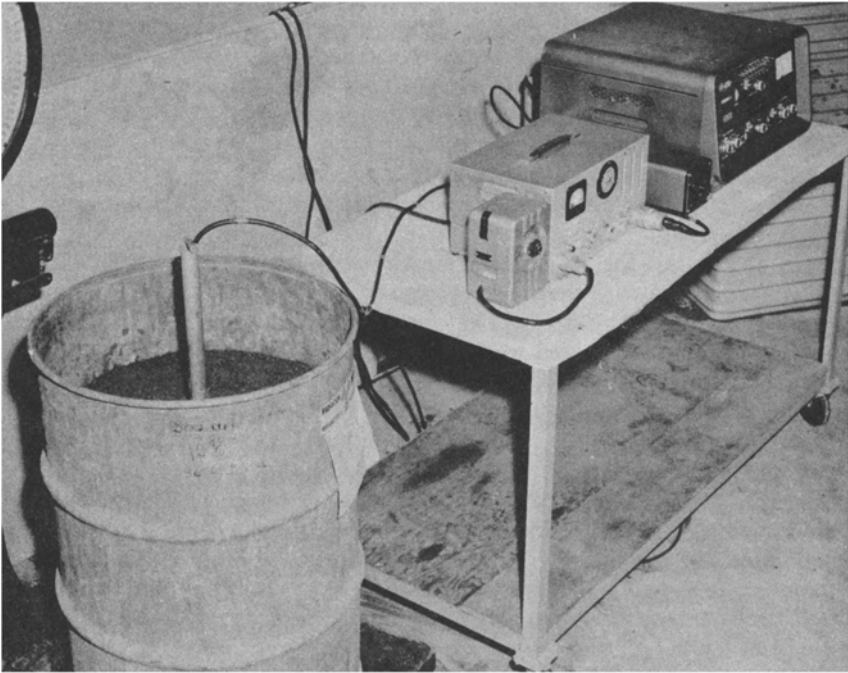


FIGURE 7.— Experimental setup for calibration procedure.

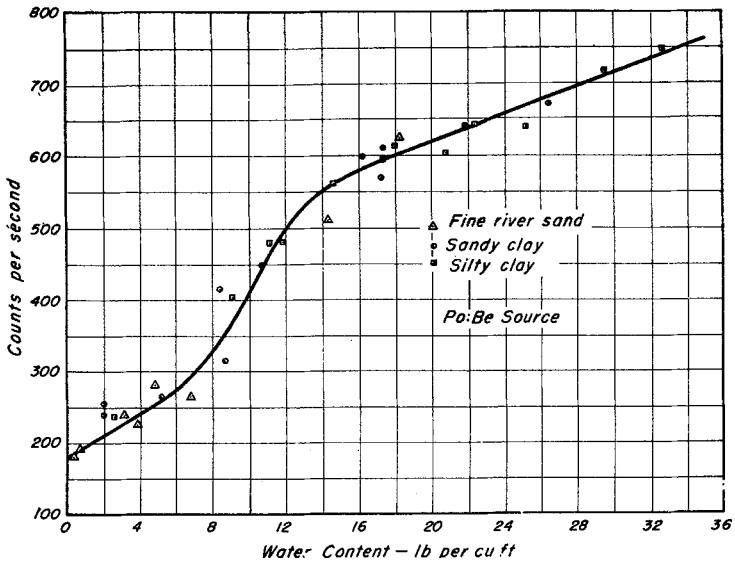


FIGURE 8. — Water content — laboratory calibration chart.

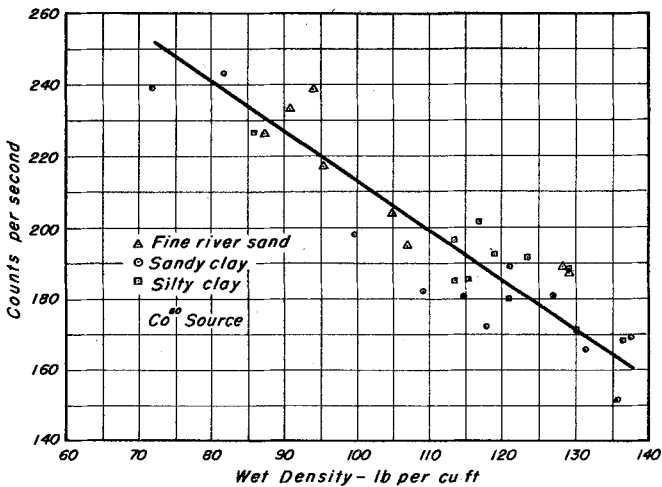


FIGURE 9. — Wet density — laboratory calibration chart.

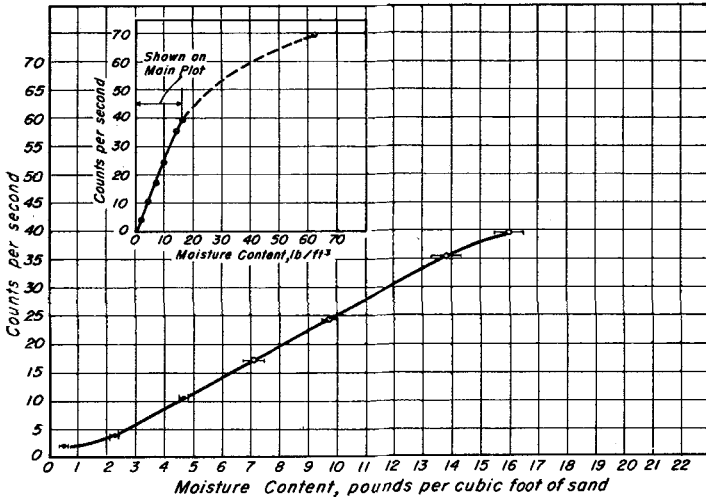


FIGURE 10. — Calibration curve for proportional counter, with 5mc Ra:Be source.

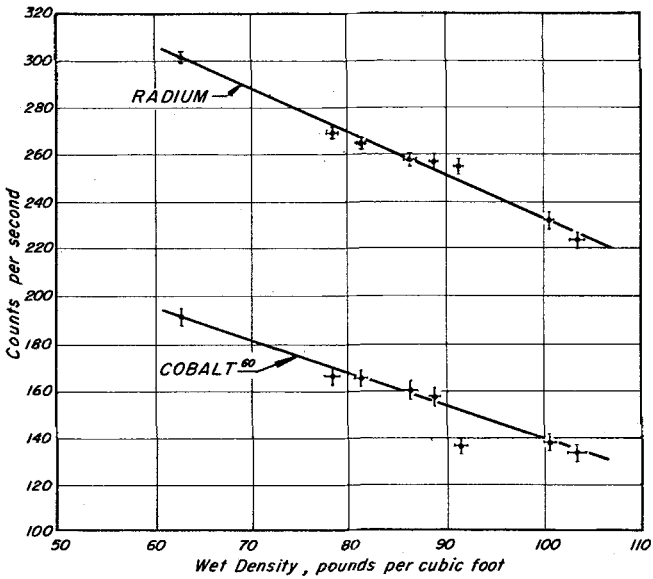


FIGURE 11. — Calibration curves for density probes.

The count rate at zero moisture content obtained by extrapolation of the curve in Figure 10, representing determinations with the BF_3 proportional counter, is probably due to slow neutrons emanating directly from the source, cosmic ray background and scattering and slowing of fast neutrons by the soil atoms. The cross section for scattering of fast neutrons for water is about 4 times the magnitude of the scattering cross section of the soil and the logarithmic energy loss per collision in water is $3\frac{1}{2}$ times that in soil; but the greater the proportion of soil molecules to water molecules, the more significant the scattering in soil. Figure 8, derived using a Geiger counter moisture probe, has a much higher count rate when extrapolated to zero moisture content than does the curve of Figure 10. Since the Geiger counter is sensitive to both beta and gamma radiation, the effect could be accounted for by the detection of some gamma radiation coming from the source, in addition to the other possibilities listed for the proportional counter.

In the inset of Figure 10 the abscissa has been extended to a point obtained with the probe in a drum of water. The count rate for pure water is much less than would be predicted by extrapolation of the linear portion of the curve. This decrease of the slope of the count rate versus moisture curve can also be observed in Figure 8 which was determined over a much greater range of moisture content and assumes a definite "S" shape. The count rate for the probe in water (not shown in Fig. 8) was 900 counts per second, and it is apparent that if the curve were extrapolated to this point a much greater decrease in slope would result.

The reasons for the leveling off of the count rate at high moisture contents are not definitely known, but it may be partially due to absorption of slow neutrons by hydrogen atoms (Gardner and Kirkham, 1952). The absorption cross section of hydrogen for slow neutrons is large compared to that of elements in the soil (mostly silicon and oxygen), and as the number of hydrogen atoms increases as in wetter mixtures, absorption may begin to counteract the increase in slow neutron density due to increased scattering.

Figures 9 and 11 are the density curves obtained using probes with both cobalt and radium sources. It is significant that the deviation in the test results appears to be much greater in the density determinations than for moisture determinations. It would thus appear that the accuracy of density determinations may not be as high as for moisture. There is some evidence to indicate that moisture content may influence the determinations of density, since the scattering of gamma rays from water is in some respects different from that in soils. The data of some unpublished investigations in this laboratory suggest that for two soils of the same wet density the count rate is lower for the drier one.

A comparison of the accuracy of moisture and density values obtained by the various probes used for these determinations is shown in Table III. The values for the sensitivity are obtained from the slopes of the linear portions

TABLE III. — SENSITIVITIES AND UNCERTAINTIES OF MOISTURE AND DENSITY PROBES

Type of probe	Source used	Sensitivity (lb./ft. ³ per count/sec.)	Statistical error (counts/sec.)	Uncertainty (lb./ft. ³)
Moisture, Geiger counter	Po: Be	0.023	5.5	0.13
Moisture, proportional counter	Ra ²²⁶ : Be	0.375	0.4	0.15
Density, Geiger counter	Co ⁶⁰	0.70	2.3	1.60
Density, Geiger counter	Ra ²²⁶	0.70	2.3	1.60
Density, proportional counter	Ra ²²⁶	0.58	3.0	1.74

of the calibration curves in Figures 8 through 11. The statistical error was determined by calculating the change in count rate produced by a 1 percent deviation at the maximum count rate of the linear portion of the curves. The maximum uncertainty in the value of moisture content or density was thereby obtained, by multiplying the statistical error in the count rate by the value of the sensitivity.

The uncertainty of the moisture content as determined by oven drying proved to be 0.5 lb./ft.³. The density measurements made for the calibration were uncertain by about 3 percent, corresponding to 2 or 3 lb./ft.³. These values are both greater than corresponding uncertainties obtained by measurements with the nuclear probes, as shown by Table III. It can therefore be concluded that the limiting factors in the accuracy of the probe calibrations are the errors inherent in the methods of determining moisture and density, rather than the nuclear count rate.

The uncertainties in moisture content and density determinations which are listed in Table III are based upon the upper limits of statistical error in artificial calibration media. These values do not take into account any variables which might be present when in-place field measurements on soils are made. These results thus demonstrate the accuracy of the instruments when used under the most ideal conditions in the laboratory. However, it is possible that conditions approaching this ideal situation might exist in certain applications involving laboratory measurements.

RESULTS OF FIELD TESTS

Even though results of the laboratory calibration tests may be encouraging, the utility of these instruments as in-place moisture and density measuring devices can be evaluated only by observation of the actual performance of the instruments in the field. Several such tests have been made, some of which will be described in this section.

Before beginning each day's field tests, a calibration count was determined in the laboratory with the moisture probe in an access tube placed in the center of a barrel of water. All of the aluminum access tubing used for laboratory calibration and field testing was purchased at the same time and presumably came from the manufacturer's same lot. These similar tubes

were used so that variations in wall thickness or composition would not affect the count rates obtained. The density probe was also calibrated while inserted in its lead shield. The values for these laboratory calibrations were used to apply a correction to the readings which were obtained that day. The correction factor thus included the effects of the decay of the sources, and any changes in counter characteristics or in the electronic components of the measuring system.

At most of the field locations where tests were made, a supply of electric power was not available. Consequently, it was necessary to provide power by means of a portable gasoline generator. Close control of both line voltage and frequency was essential in order for the electronic instruments to function properly.

Upon arrival at the test location, it was possible to begin the readings immediately after lowering the probes into the access tubes. For most of the determinations, a counting period of 200 seconds could be used. With the count rates obtained, this time interval was equivalent to a 1 percent deviation of duplicated results, 95 percent of the time. All of the equipment required for the field tests could be carried in an ordinary sedan or panel truck. It was possible to move to various locations within reasonably short distances without disconnecting the apparatus from the power supply. In this manner, it was easily possible to take 80 readings of both moisture content and density in one day.

A description of the results of the investigation of a portion of the sub-grade at the San Francisco International Airport has already been published by members of this organization (Horonjeff *et al.*, 1954). This research demonstrated the feasibility of making continuous moisture and density measurements in a location where other methods for these determinations would have proved unsuitable. Comparisons with core sampling methods were made, showing that, of the hundreds of moisture content measurements made by the nuclear procedure in a period exceeding 1½ years, 71 percent agreed within 5 percent moisture content and 50 percent agreed within 3 percent. Of the density measurements made at the same time, 77 percent agreed within 10 pounds per cubic foot, and 54 percent agreed within 5 pounds per cubic foot. Some of the moisture and density profiles obtained in this research are depicted in Figures 12 and 13.

Experiments with the Geiger counter density probe are being conducted at the present time in cooperation with the California Division of Highways. Under construction in the San Joaquin River delta area of California is a section of highway which is underlain by peat ranging up to 36 feet in depth, and having a moisture content in some places exceeding 1,000 percent by dry weight. It was planned to compare the density changes as determined by the gamma ray scattering procedure with standard settlement measurements in the peat taken during the placement of the fill forming the pavement base. Three thin-walled aluminum access tubes were driven to a depth of 12 feet below the existing peat surface, and 1-foot sections were added to the tops of the tubes as the sand fill was being placed. In this

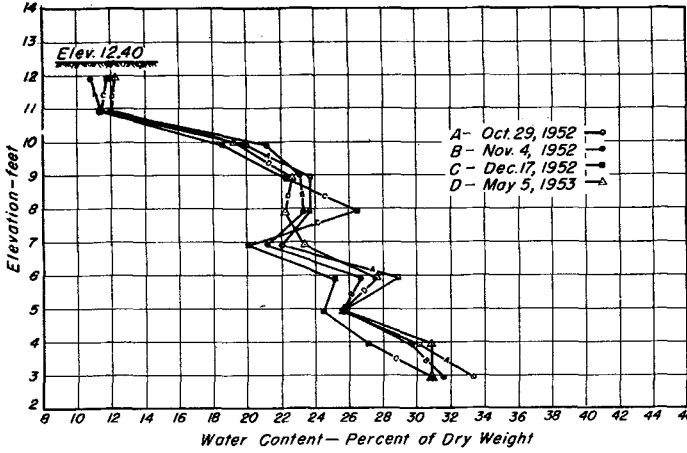


FIGURE 12. — Water contents at access tube no. 3A — nuclear procedures.

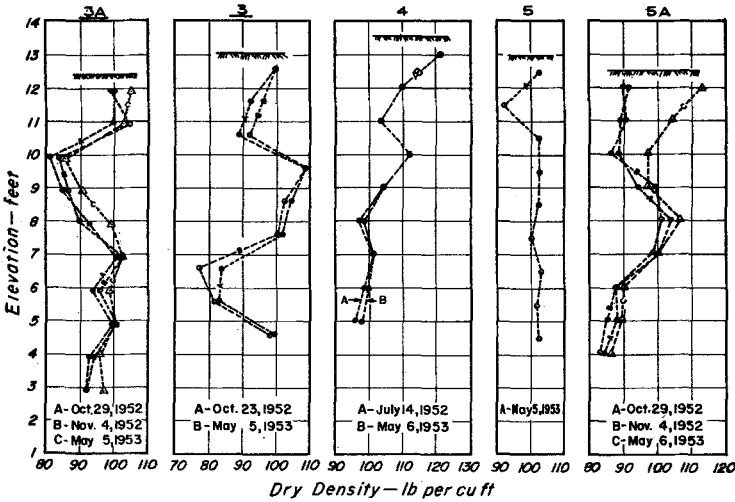


FIGURE 13. — Densities by the nuclear procedure.

manner, it has been possible to make periodic density measurements at increments of 1 foot in the peat during and after construction of the highway section, and as the peat compacted, at depths up to 25 feet below the present road level. The extremely low density and high water content of this organic material presented a unique situation in which core sampling procedures could not have been used to obtain comparable results.

In Figure 14 are indicated some of the results comparing the density obtained by the gamma ray scattering procedure with settlement data obtained by the use of a standard settlement platform. The figure shows a

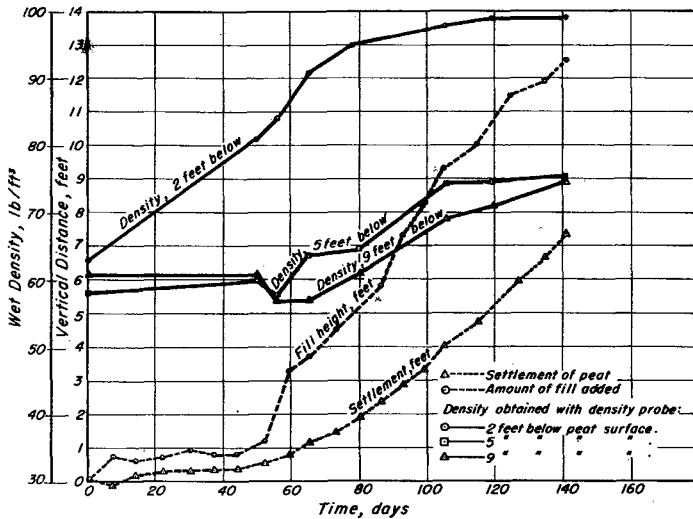


FIGURE 14.— Relationship between density and settlement during placement of sand fill on peat soil.

plot of settlement and density changes as the fill increased in depth with time. It is apparent that settlement is proceeding at an appreciable rate at the present time. After 140 days, the 12.5 feet of fill has gone down 7.5 feet.

One of the most significant findings which can be observed from these curves deals with the changes of density with time at the various indicated depths below the original peat surface. The slopes of these curves indicate that consolidation is taking place from the upper surface of the peat downward; that is, it appears that the uppermost layers of the peat must compress to a certain extent before they transfer the load to the deeper portions of the material.

The other locations studied in this experiment vary with respect to the original density of peat and the height of fill. Results of the density measurements at these locations are not plotted, but they do indicate that the same type of compaction as is shown in Figure 14, is taking place.

Some investigations have been made to determine the effect upon moisture content and density readings in the field, of various methods of placement of access tubes. A report by Javete (1954) describes these experiments, made with the Geiger counter probes previously described.

Four methods of placing access tubes were investigated. These experiments were as follows:

1. A hole was bored with a 3-inch soil auger, the soil removed being placed in a covered pan. When the hole had been drilled to a depth of three feet, the soil was returned to the hole, and gently tamped to avoid large

voids. The aluminum access tube was then driven into the center of the hole.

2. The same as method 1, except that a 1½-inch soil auger was used to bore the hole.

3. The access tube was driven into a hole made by a 1-inch soil sampler after the soil removed from the boring by the sampler had been replaced therein without tamping.

4. The access tube was driven directly into the ground.

Each of the methods described above was run in duplicate, at two locations, having widely different soil conditions.

This investigation indicated that the results of the moisture content measurements did not vary appreciably between the different methods of placing the access tubes, with the exception of the 3-inch soil auger hole, which consistently showed lower water contents.

Another way of showing the effect of method of placement of access tubes upon the nuclear measurements is to indicate for each method the percentage of the readings that are within certain limiting percentages of the moisture contents which have been determined by oven drying a soil sample. The comparisons obtained in this experiment are listed in Table IV.

It is notable that almost all of the nuclear measurements, regardless of the method of placing access tubes, were within 5 percent (moisture content) of the measurements made by oven drying soil samples. On the other hand, only 40 percent of the measurements made using the 3-inch auger (method 1) were within 1½ percent moisture content determined by oven drying while 90 percent of the measurements were within 1½ percent for the driven tubes (method 4).

Nuclear density measurements were not directly compared with core sampling determinations. It was observed, however, that the density determinations showed much more variation due to method of placement than the moisture content determinations. The densities obtained for the 3-inch auger hole were lower than for any other method of placement. Densities for the 1½-inch auger hole were slightly less on the average than those for the driven tube and the tube placed in the 1 inch soil sampler hole. The densities obtained with the access tube driven directly into the ground were

TABLE IV. — COMPARISON OF PERCENT DIFFERENCE BETWEEN NUCLEAR AND OVEN-DRYING PROCEDURES BY METHOD OF PLACEMENT OF ACCESS TUBES

Method of placement	Percent of readings within percent shown, of oven-dry moisture content		
	5%	3%	1½%
1	100	70	40
2	90	80	60
3	100	100	70
4	100	100	90

not significantly different from the densities in the access tubes driven into the 1-inch soil sampler holes.

Based on these observations, the following conclusions were drawn:

1. All of the methods of placing the access tubes which were studied appeared to give sufficiently accurate determinations of moisture content. However, the method of driving the access tube directly into the ground yields results which are consistently in closer agreement with the results obtained by oven drying soil samples than the results for any other method of placement studied.

2. For the soils present at the locations used, it would appear that there is very little difference in densities obtained from access tubes driven directly into the ground and those placed in a hole made by a 1-inch soil sampler. Even placing the access tube in a $1\frac{1}{2}$ -inch soil auger hole has only a small effect on the density readings. However, the use of a 3-inch soil auger will cause the readings of density to be lowered appreciably.

DISCUSSION OF RESULTS

A most important question in the application of a measuring instrument concerns its accuracy as compared with other methods of making the same measurement. It has become increasingly apparent to the authors that in a comparison of field sampling results and nuclear measurements, the errors inherent in the sampling procedures are the limiting factors in the comparisons. When core samples are removed, it must be expected that, in addition to weighing errors, some variations occur due to heterogeneity of soil structure and to non-uniformity in moisture content, even at distances within 1 foot. Field moisture and density measurements made by the authors using core sampling methods, where the samples were taken at 1 foot intervals on the same day, usually agreed only to within 5 percent of each other. On the other hand, average deviations of the nuclear method in the field, while not as low as those made in the laboratory, were 0.9 pounds of water per cubic foot of soil, and 5.5 pounds per cubic foot respectively, for moisture and density determinations with the Geiger counter probes. These figures are within the same order of magnitude as the 5 percent uncertainty shown by the core sampling results.

From these considerations, it could be concluded that the nuclear procedures provide at least the same accuracy as do other methods for moisture and density determinations. However, it is conceivable that the nuclear data have presented an even more precise characterization of the true status of these soil conditions. Experiments by Whyte (1954) have shown that the volume of soil over which the moisture and density are measured by the nuclear scattering techniques varies depending upon the values of these properties. The volume of soil over which moisture is measured by neutron scattering with a Ra:Be source, varies between 20 and 36 inches in diameter, and the volume over which the density is measured, by gamma rays scattered from the same source, varies between 26 and 36 inches in diameter.

In addition, research published by the National Bureau of Standards (DeJuren and Rosenwasser, 1953) indicates that, at least for thermal neutrons, the nuclear measurements possess the unique advantage of measuring throughout a relatively large sample volume. Thus, by integrating into the results small differences arising from heterogeneities in the soil, it may be possible that better over-all values are being obtained with the nuclear methods.

FUTURE PLANS

In the development and testing of these measuring instruments, there have been indicated several avenues of approach in which improvements in application to field problems may be obtained. These improvements will require considerable further laboratory study.

The development of a more efficient detector for thermal neutrons and gamma rays is of prime importance for several reasons. A detector of higher efficiency will result in a higher count rate for equal conditions of the scattering medium and source strength. The resulting possibilities can be enumerated as follows: (1) A lower strength source may be used, which will in turn lower cost and require less elaborate safety precautions. (2) For a source of the same strength the time required to obtain a sufficient number of counts for statistical accuracy can be reduced. (3) With a reasonably strong source, a count rate meter could be substituted for the presently used scaler. With the rate meter it might be possible to calibrate the dial to read the moisture content or density directly. This would result in a great reduction in time required for the measurement, and less training would be required for the personnel operating the device.

The authors are currently conducting research in this direction on both higher pressure proportional counters and scintillation counters. Using a higher pressure of boron trifluoride gas in the proportional counter results in an increase in counting efficiency for thermal neutrons but also involves higher voltages and more complexity in the related electronic equipment. The scintillation counter may prove to be another excellent possibility since it appears to be the most efficient radiation detector known at the present time. Plans have been made to conduct a research program in which the three types of counting devices will be tested, compared and their properties evaluated.

Other investigations which have appeared to be desirable in connection with this work include: (1) A determination of the zone or volume of the material in which the nuclear scattering phenomenon occurs, and which influences the results obtained by the detector. The determination of these boundary limits would prove valuable in applications such as process control, where relatively small samples are available for measurement. (2) An investigation of the effects of moisture content changes upon the density readings. Experimental evidence has indicated that there is a mutual inter-relationship between these conditions. By developing a method whereby

the moisture content of a soil may be varied independently as the dry density remains constant, the effect of the moisture content upon the wet density reading may be evaluated. In addition, if a sufficiently large effect is observed, it may be possible to use the density probe alone for the determination of moisture contents under conditions where the dry densities of materials remain relatively constant. (3) In some applications it is desirable to have an instrument which is able rapidly to determine moisture content and density in the field to perhaps only a few inches or a foot below the surface. Some research was conducted on an instrument of this type by the CAA (Belcher *et al.*, 1952), and studies of the theoretical and design problems involved with such an instrument are being made in this laboratory.

POSSIBLE APPLICATIONS

At the present time there is a wide demand in many fields for an instrument which will measure moisture content and/or density of granular materials rapidly and accurately, which is relatively inexpensive, and which is sufficiently simple to be used with a minimum of preliminary training and experience.

Engineers working in construction of roads, airports, earth dams and foundations depend to a large extent upon knowledge and control of soil moisture content and density in their operations. In addition, knowledge of the movement of ground water and of settlement under loads is sometimes valuable.

The location and movement of ground water is also of primary importance to those engaged in the fields of agriculture and forestry. In particular, there are many instances in irrigation practice where the close control of soil moisture is essential.

Petroleum engineers have applied neutron scattering measurements in the location of strata likely to contain hydrogenous material, and gamma ray logs have been used extensively in studies of porosity of the materials surrounding wells.

This method might be applied to the determination of moisture contents or densities of a wide variety of granular materials, such as sand or clay used in industrial applications, or perhaps grain, lumber or seed. The method is limited where the number of hydrogen atoms from sources other than those in the water is large, or where the elemental composition varies greatly. However, if these quantities remain relatively constant throughout the material, the only problem to be considered is the development of a representative calibration curve.

In some process industries where the control of moisture content is required, the neutron scattering method might be applicable. For example, it is important that the moisture content of foundry molding sands be closely controlled in order to help eliminate defective castings. The equipment in this case must be adapted to making moisture measurements while the ma-

terial is being processed, for instance, in a large mixer. Indeed, automatic control of water content in such processes should be possible through modifications of the apparatus.

SUMMARY

1. The neutron and gamma ray scattering technique offers a method for the measurement of moisture content and density of a variety of soils or other granular materials, and is rapid and simple.

2. The accuracy of laboratory measurements with the nuclear probes is dependent upon the accuracy of the methods used to measure moisture content and density, and to which the results are compared.

3. Field measurements of soil moisture content and density have been made with the nuclear probes under conditions where the use of other types of measuring instruments would not have been practical. Results of these tests have proved to be satisfactory under the limitations of the uncertainty of sampling results with which they were compared.

4. A large sampling volume is integrated into the results which indicates that a truly representative sample of the mass is being measured.

5. A sensitive, reliable probe can be constructed using a BF_3 proportional counter and a radium-beryllium source for slow neutrons and gamma rays. As a moisture probe, it is free of gamma ray background counts so the response is linear over the range of moisture from 1 to 15 pounds per cubic foot. The same probe can be used as a density measuring device.

6. It appears likely that still further improvement in the performance of the apparatus can be afforded by the use of a scintillation counter as the detector.

7. For the soils used in the laboratory and field tests, the soil type does not appear to influence the behavior of the moisture or density probes. It has been shown that with few exceptions there is no reason to expect that more than one calibration curve each for moisture and density are required for soils normally encountered.

8. Radiation hazard to personnel operating the equipment is negligible if certain simple precautions are observed.

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