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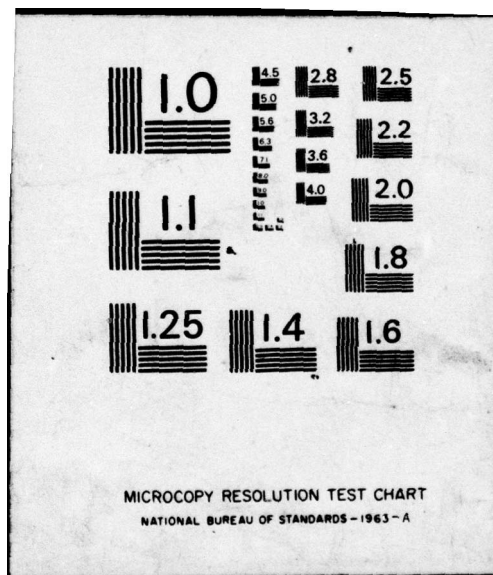
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USE OF CALIFORNIUM-252 IN LABORATORY TESTING FOR MOISTURE AND DENSITY OF SOILS

by

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20. ABSTRACT (Continued)

along thin, discrete soil layers in unopened 2.875-in.-diam steel-encased soil cores. Both gaging and film imagery methods were evaluated for their applicability in the detailed soil studies.

Through shielding devices, gamma and thermal neutron beams 1/4 in. wide by 2 in. high were used in direct radiation transmission for gaging. By using the proper detector for gamma rays and for thermal neutrons, radiation beams passed through a core were recorded in counts per second (CPS). The CPS is proportional to bulk density and weight of water, respectively. The data are plotted simultaneously on an X-Y plotter, thus producing a graphic log of the radiation characteristics of the sample investigated. Calibration curves prepared from samples of known moisture and density permit the interpretation of water and density from any position in a scanned tube of unknown moisture and density.

Several factors may contribute to errors; principal ones are variations in tube diameter, impurities in the steel, adsorbed water, and water of crystallization in clays. Correction factors can be applied.

The film imagery method uses a collimated beam of thermal neutrons for transmission through a sample and registration on radiographic film. A conversion screen converts neutrons into low-energy X-rays which, in turn, expose the film and produce an image of the distribution of water in a sample. Quantification of moisture is then accomplished from calibration and scanning of film density.

The exposure times, using a 5.0-mg californium-252 source, for a 2.875-in.-diam tube required as much as 16 hr for samples with up to 25% moisture. Images of samples with more than 25% moisture showed only slight variation in film density with an increase in moisture. Thin soil slabs (3/8 in. thick) cut from undisturbed soils did produce good neutron radiographs within practical time limits. Such radiographs from 3/8-in.-thick soil slabs have provided useful data with regard to moisture distributions.

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PREFACE

This study was funded by the Office, Chief of Engineers (OCE), U. S. Army, Project No. 4A161102AT22.

This report was prepared by Mr. Jack T. Lewis, Research Geologist, Engineering Geology Research Facility, Soils and Pavements Laboratory, U. S. Army Engineer Waterways Experiment Station (WES). This report concerns the first phase of the investigation entitled "Nuclear Interrogation of Soil for Discrete Measurement of Moisture and Density." A draft of the report was reviewed by Mr. W. B. Lane of the WES Weapons Effects Laboratory, and by Dr. Frank Iddings of the Nuclear Science Center, Louisiana State University, Baton Rouge, Louisiana.

The project was conducted under the supervision of Dr. Ellis L. Krinitzsky, Chief, Engineering Geology Research Facility. General direction was supplied by Mr. Don C. Banks, Chief, Engineering Geology and Rock Mechanics Division, and Mr. James P. Sale, Chief, Soils and Pavements Laboratory. OCE technical monitor of this investigation was Mr. A. F. Muller (DAEN-MCE-D).

Directors of WES during the conduct of this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	25.4	millimetres
feet	0.3048	metres
cubic feet	0.02831685	cubic metres
inches per minute	25.4	millimetres per minute
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
electron volts	0.160219	attojoules
million electron volts	0.160219	picojoules

USE OF CALIFORNIUM-252 IN LABORATORY TESTING FOR
MOISTURE AND DENSITY OF SOILS

PART I: INTRODUCTION

1. The U. S. Army Engineer Waterways Experiment Station (WES) is currently investigating the applicability of using the radioisotope californium-252 for detailed soil investigations. The studies are centered primarily around nondestructively determining moisture, density, and elemental analyses with radiologic methods on unopened soil cores.

2. The WES has recently completed construction of a radiation facility designed specifically for these nuclear interrogations of soil. Californium-252 is the source for both neutron and gamma radiation used in conducting the experiments. This radioisotope was selected primarily because of the large number of neutrons emitted from a relatively small source and its relatively long half life. A detailed report on the facility, theory of operation, equipment, and feasibility studies has been published in WES Miscellaneous Paper S-75-26.*

Background

3. Nuclear investigation of soil properties has been operative for more than 20 yr. The investigations have, for the most part, been devoted to field determination of moisture and bulk density of surface and near-surface soils. Only limited laboratory radiological studies of thin, discrete soil layers within opened or unopened soil samples have been conducted.

4. The earlier X-radiological studies of soils have shown that

* J. T. Lewis and E. L. Krinitzsky, "Design and Potentials of the Californium-252 Radiation Facility at WES," Miscellaneous Paper S-75-26, Sep 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

X-rays may reveal numerous internal features not otherwise seen in samples. Such features as roots, secondary mineralization, fractures, fossils, and shear planes all enter into the engineering characteristics of a soil. With the combined use of X-radiographs, gamma radiation, and neutrons, a considerable amount of data can be gathered from an unopened core. The above-mentioned internal features plus graphic print-out logs showing minute variations in moisture or density within an unopened core can be very useful in a testing program.

Scope

Abstract
5. This report is primarily concerned with illustrating methodology for the identification and quantification of moisture along thin, discrete layers of opened and unopened soil cores. A major portion of the work has been devoted to scanning of soils encased in a 2.875-in.-inside-diameter (ID) steel sampling tube. Some neutron film imagery, however, was also obtained to illustrate the distribution of moisture that can and does occur within individual soil samples.

Approach

6. The water content of a soil sample is defined as the ratio of the weight of water to the weight of dry soil. The nuclear determination of moisture is dependent on the degree of neutron attenuation or absorption by hydrogen ions contained in the soil sample. A measure of the nuclear interaction indicates the quantity of hydrogen present in a given volume of soil. If it is assumed that the hydrogen ion is present only in the form of pore water or free water, then the absorption or scattering of neutrons is proportional to the volume of water or weight of water present in the sample. To determine the water content, it is also necessary to determine the weight of solids (or dry weight of soil) present in the same volume of material. Since neutrons are

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

transmitted rather easily through matter with higher densities, it is necessary to use gamma ray techniques for measuring the density of the soil. This density measurement with gamma radiation yields a bulk unit weight (water and solid per unit volume). Two determinations must therefore be made: one for volume (or weight) of water, the other for bulk density. Simple arithmetic calculations indicate the ratio of weight of water to weight of solids or the water content of the soil sample. This report will therefore of necessity involve density studies of the soils under investigation.

7. Neutrons react with various elements present in a material. It was therefore essential to be aware of the material content of targets being bombarded with neutrons since such interactions can produce erroneous data. Corrections can be made, however, for soils, such as clays, that may contain adsorbed water or other absorbing elements in soil and in steel tubes. Also, the investigator must be aware of effects of changes in steel wall thickness, inside tube diameter, or tubing chemical composition. Generally, such variations occur only between tubes and not within one individual tube. Therefore, once a correction for any point on one tube is made for these factors, the correction can be applied over the entire length of the tube.

8. Since the nondestructive assessment of steel-encased soil cores is a major goal of this study, the investigation has concentrated on a soil core encased in a steel sampling tube of the type used in sampling at WES. This tube has a 2.875-in. ID with a ± 0.009 -in. tolerance. The tube is constructed of type MT 1010 to MT 1020 steel tubing and is manufactured in accordance with ASTM A-513 tubing specifications. The carbon, iron, and manganese contents vary in the designed chemical makeup of the steel. The following is a list of elements present:

Carbon	0.05 to 0.25%
Manganese	0.3 to 0.6%
Phosphorus	0.04% maximum
Sulphur	0.05% maximum
Iron	99.0% $\pm$

9. Several 3-1/2-in.-long segments of a sample tube constructed

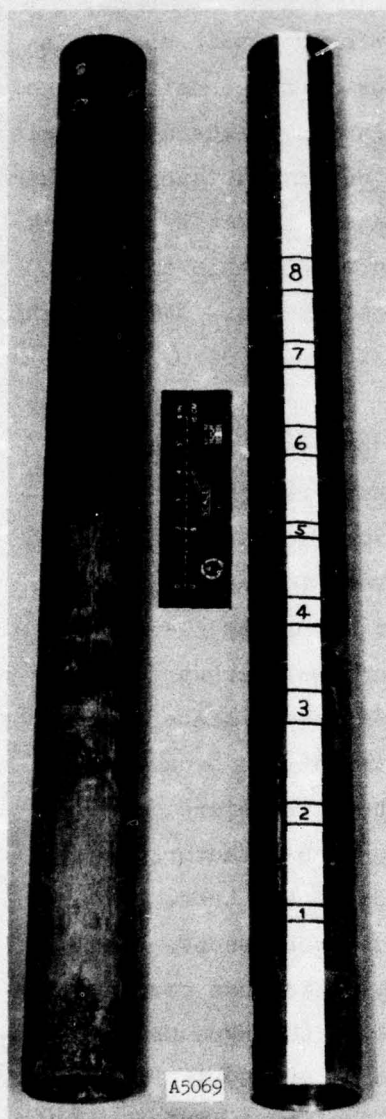


Figure 1. Field sample tube and laboratory standard tube

according to the above-mentioned tubing specifications were cut and machined for later connecting into a series. Eight soils with known moisture and density were compacted in single lifts in the 3-1/2-in.-long segments. The segments were connected with a threaded aluminum plug so as to duplicate as nearly as possible a full-length field sampled core and tube as shown in Figure 1. Techniques were developed to use the laboratory-prepared soils as controls and reference for the remaining density and moisture studies.

Methodology

Core scanning

10. For radiation scanning of cores, this study was made using a direct transmission of both gamma and thermal neutron beams. This involves essentially the construction of a desired radiation beam to the desired size, and the transmission of that beam directly through a core. By using the proper detector for either gamma or thermal neutrons, a radiation beam passed through a core can be detected and recorded in counts per second (CPS). The CPS detected is proportional to the bulk density or weight of water present, depending on type of radiation used and the corrections needed. The detected data can be plotted simultaneously on an X-Y plotter, thus producing a graphic log of the radiation characteristics of the sample investigated. Calibration curves prepared from CPS of radiation

transmitted through the sample of known moisture and density permit determination of weight of water (W_w) or bulk soil density (γ_m) from a CPS reading at any point on a plotted radiation scan of an unknown sample of like volume.

Film imagery

11. A second approach for quantification involved the making of X-ray and neutron film images of soil samples. X-rays are in comparable portions of the spectrum as gamma rays and are absorbed in varying amounts by soils of varying densities. Neutrons, on the other hand, are increasingly absorbed and scattered by an increase in hydrogen content but are not greatly affected by density. These radiation absorption characteristics will yield, in many instances, almost opposite images between X-ray and neutron radiographs. For example, Figure 2 shows X- and neutron radiographs of a portion of the control tube. All radiographs in this report are contact prints made directly from the original film but reduced slightly for reproduction. The tonal differences of the radiograph show good correlation with changes in density or moisture, depending on the type of radiation used. Film densities can be determined quantitatively by scanning the film with a film densitometer. From film densities of known moisture or soil density, additional calibration curves can be prepared, thus permitting determination of weight of water (W_w) or soil density (γ_m) from a film density of any point of an unknown sample. The differences are also reflected in the laboratory-determined W_w and the γ_m values shown in the log. The darker the tone in the neutron radiograph, the higher the hydrogen content. The darker the tonal image in the X-radiograph, the higher the bulk density. The aluminum shows dark (higher density) in the X-radiograph and light (low hydrogen) in the neutron radiograph. The paraffin, on the other hand, shows light on the X-radiograph (low density) and dark (high hydrogen) on the neutron radiograph. Features such as these reveal considerable information when X-radiographs are studied in conjunction with neutron radiographs.

12. The control or standard soil sample, as it will be referred to in the remainder of this report, generally contains from the midpoint

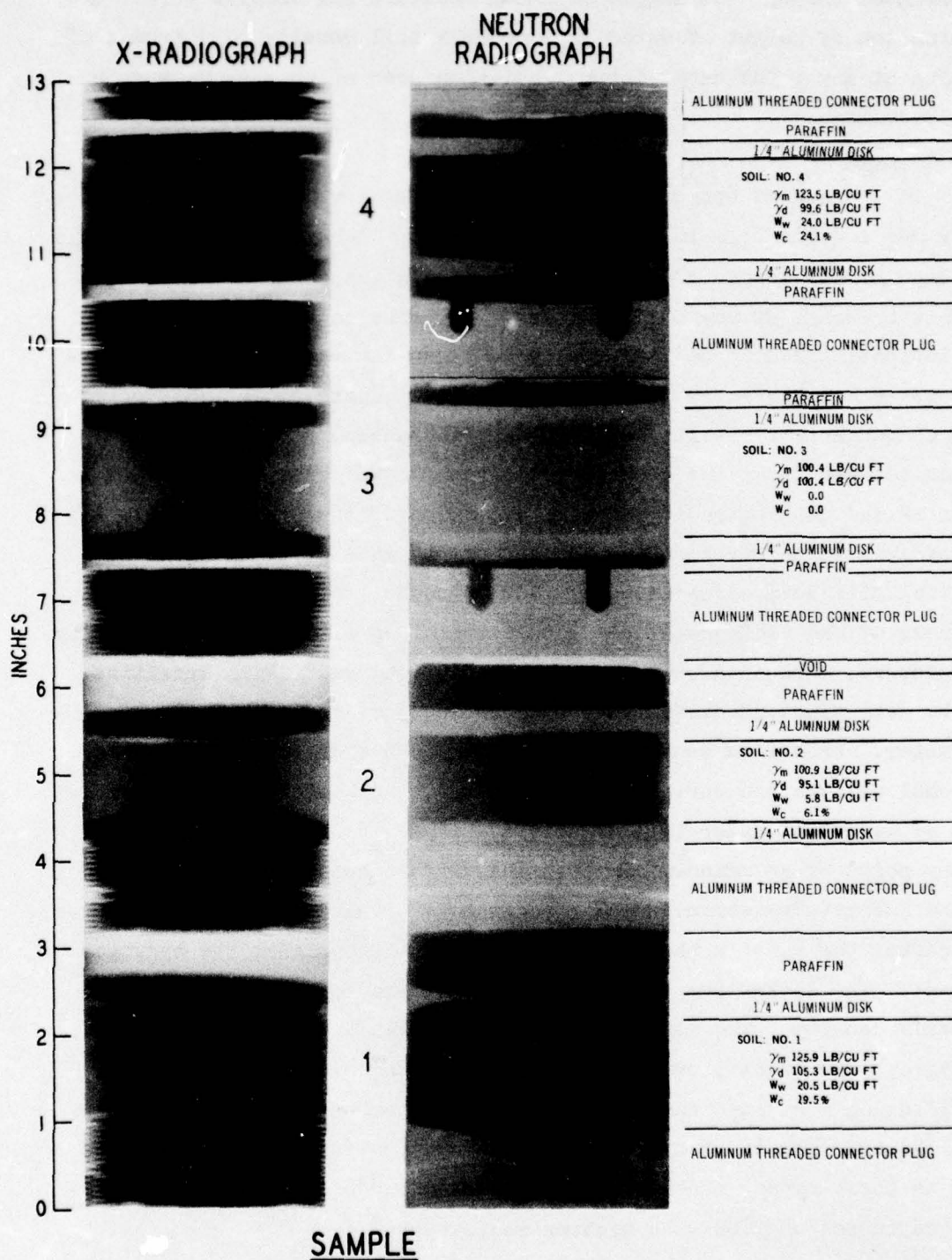


Figure 2. Laboratory-prepared soil tube. Illustration of differences between X- and neutron radiographs

of one threaded aluminum connecting plug to the midpoint of the next plug the following materials:

Threaded aluminum plug

Paraffin

1/4-in.-thick aluminum plate

Soil

1/4-in.-thick aluminum plate

Paraffin

Threaded aluminum plug

PART II: QUANTITATIVE INVESTIGATION

Core Scan Procedure

Thermal neutron attenuation

13. Neutrons with energy levels ranging from 0.025 ev to 13.0 Mev are emitted from the californium-252 through spontaneous fission. In order to obtain a thermal neutron beam, it is necessary that the neutrons be slowed to thermal neutron energy levels of 0.025 ev. This can be done by source positioning, neutron moderation, and beam configuration. A beam of such thermalized neutrons (0.025 ev) can then be transmitted directly through a sample and counted. A loss or gain in thermal neutrons CPS will occur with any increase or decrease in moisture, respectively. It is necessary when using this method that as pure a beam of thermal neutrons as possible be used. Also required is the shielding of gamma radiation from the detector. A $^6\text{LiI (Eu)}$ * thermal neutron detector was used for the counting purposes.

14. Figure 3 illustrates the geometrical setup of source, collimator, shielding, sample, and detector. A 2.1-mg californium-252 source was positioned in the water tank approximately 1/4 in. from the rear of the beam collimator. A 1/4-in.-wide by 2-in.-high aperture in a 2-in.-thick by 12-in.-square borated water extended polyester (WEP) plate restricts the beam dimensions at the sample position. Directly opposite the emerging neutron beam is another borated WEP plate with the same size opening as the front plate. A $^6\text{LiI (Eu)}$ detector is located immediately behind the beam openings and is shielded on the sides by borated polyethylene. Both restricting plates are positioned within 1/2 in. of the sample tube and centered along the midpoint of the tube. This permits a 1/4-in.-wide by 2-in.-high neutron beam to be transmitted directly through the horizontally oriented sample and to be detected with as little distortion or scattering as possible. The sample can be moved horizontally through the beam, and the thermal neutrons detected

* Lithium iodide, europium doped.

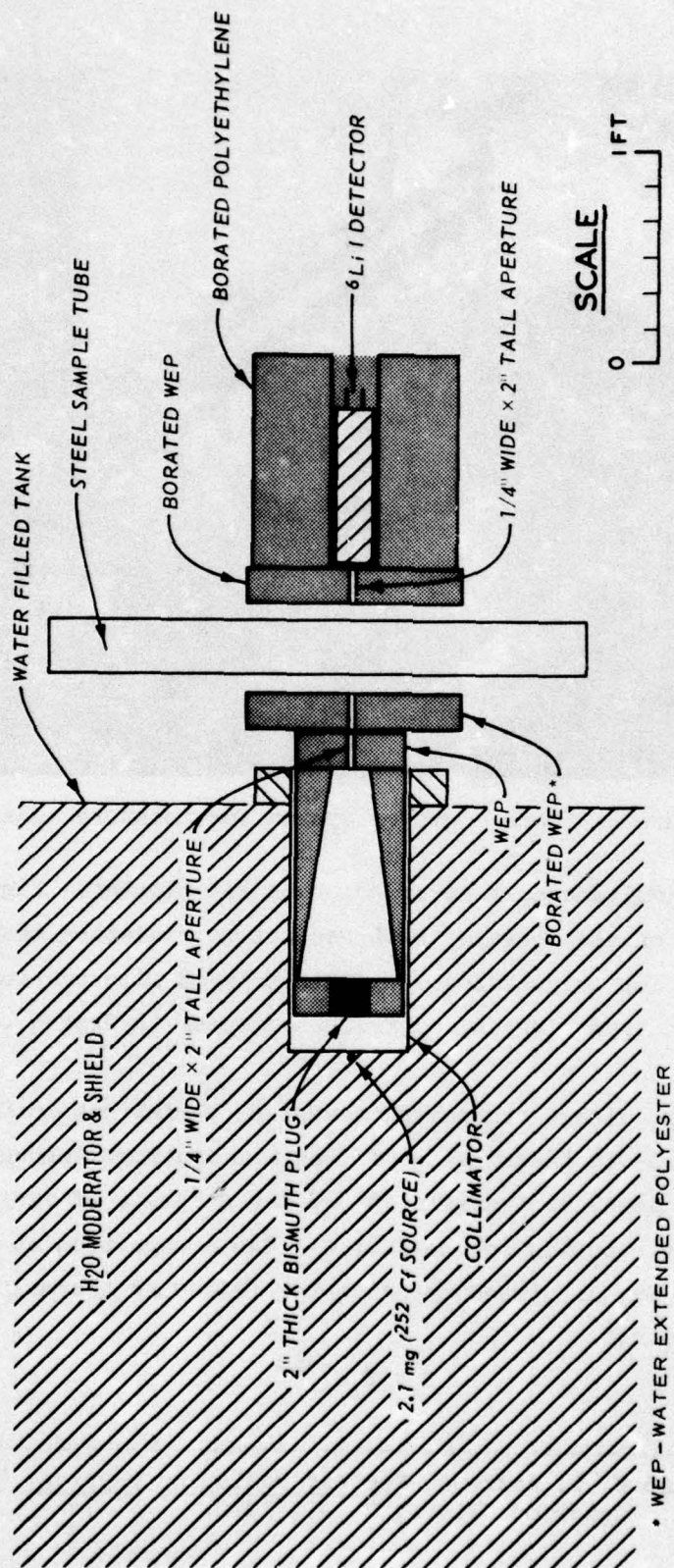


Figure 3. Top view of thermal neutron scanning system

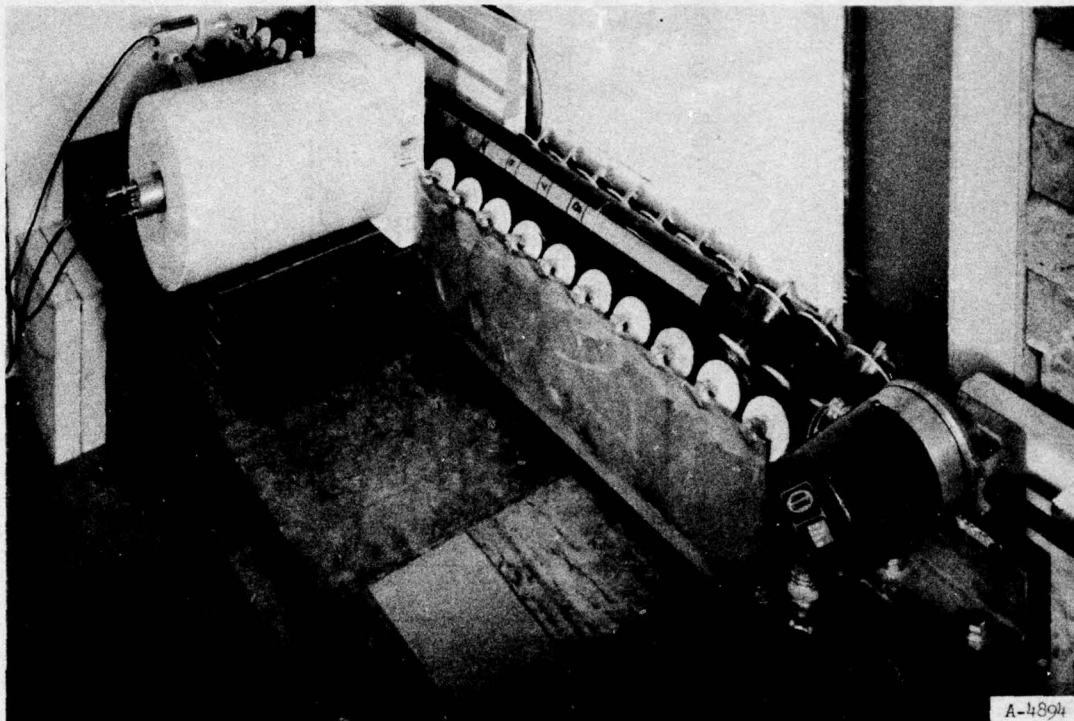


Figure 4. Core conveyor system for moisture scan

in CPS can be simultaneously recorded on an X-Y plotter. Figure 4 shows sample position on the conveyor with respect to radiation tank and beam port. The X-Y plotter provides a graphic printed illustration of variations in neutron transmission, or weight of water (hydrogen), in the sample.

15. In the direct transmission system, variations in CPS detected reflect variations in transmission of thermal neutrons through a material. The variations in transmitted CPS are a result of variations in the degree of attenuation by the sample. The attenuation at any point in a sample can be calculated by using the following thermal neutron attenuation equation:*

$$\phi = \phi_0 e^{-\sigma n x}$$

* R. E. Lapp and H. L. Andrews, Nuclear Radiation Physics, 4th ed., Prentiss-Hall, Englewood Cliffs, N. J., 1972.

where

ϕ = transmitted neutron flux density

ϕ_o = neutron (number) flux density

σ = total cross section for absorption in barns (i.e., 10^{-24} cm²)

n = number of atoms/volume (i.e., per cm³) in the absorber

x = absorber thickness (cm)

As mentioned previously, a pure, thermal neutron beam is desirable. Such is not attainable with this facility. However, electronic windows can be set in the counting equipment for the recording of only thermal neutrons.

Gamma ray density scan

16. Since bulk density must also be determined for calculations of dry density (or weight of solids) and hence the water content of the sample, the techniques and geometric arrangement for positioning a gamma beam will be discussed.

17. Gamma radiation is also emitted from the californium-252 source through spontaneous fission and fission product decay. The gamma ray spectrum from the fission process ranges from 0 to 6.5 Mev. Secondary gammas are also produced from capture of neutrons by boron in the shielding and hydrogen in the water moderator surrounding the source, as well as from decay of other activated products. Since neutrons were also emitted from the source and entered the collimator, it was necessary to have additional shielding to protect the gamma detector from possible neutron activation. The ²⁵²Cf source was positioned in the water tank approximately 6 in. behind the rear of the collimator. Most of the neutrons were thermalized or absorbed in the surrounding water. A 1/2-in.-thick by 6-in.-diam disk of powdered gadolinium oxide was placed in an upright position at the front of the collimator to capture any thermal neutrons transmitted through the collimator. A 1/8-in.-thick lead plate was positioned adjacent to the gadolinium. Additional gamma radiation was produced at this point, possibly through a gamma-gamma interaction from the high-energy fission gammas resulting from spontaneous fissioning of the californium. An illustration of the geometrical arrangement for a gamma ray scan is shown in Figure 5.

18. A 2-in.-thick by 12-in.-square borated WEP plate was placed

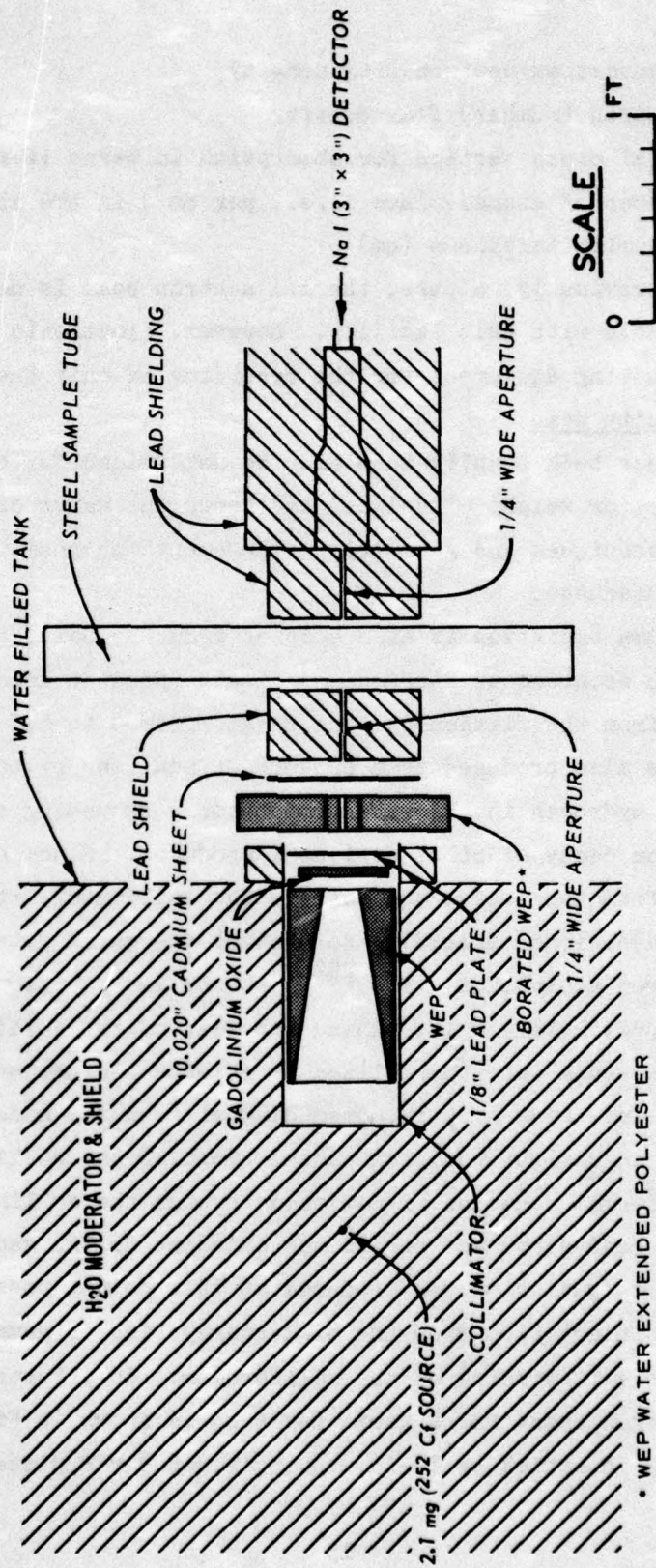


Figure 5. Top view of gamma ray scanning system

at the front of the 1/2-in. lead plate. An 0.020-in.-thick sheet of cadmium covers the face of the WEP. The WEP was provided an aperture for the gamma beam. Two-in.-thick lead with a 1/4- by 2-in. vertical slot between the cadmium and sample provides an extension of the aperture for the gamma beam being transmitted through the sample. A similar lead shield and aperture collimate the beam transmitted through the samples so as to strike an NaI (sodium iodide) detector and be subsequently counted and plotted on an X-Y plotter. An electronic window was set to record only the gamma rays of 0.4- to 0.7-Mev energy levels for the density studies. The gamma energy level was determined from calibration curves prepared from ⁶⁰cobalt and ¹³⁷cesium calibration sources. Bulk density measurements proceeded in a manner similar to those used in the moisture scan.

19. Absorption of X- or gamma rays transmitted through a material can be calculated by the exponential decay equation shown below:

$$I = I_0 e^{-\mu x}$$

where

I = intensity of transmitted beam

I₀ = intensity of incident

μ = absorption coefficient (cm⁻¹)

x = absorber thickness (cm)

A monoenergetic beam of gamma radiation will be assumed detected in these investigations for the direct transmission method.

Core Analyses

Standard tube and samples

20. Figure 6 shows an X-radiograph and neutron radiograph of the laboratory standard soil tube. To the left of the X-radiograph is a plot of a gamma transmission scan of the tube. To the right of the neutron radiograph is a plot of a thermal neutron transmission scan. The calibration curves shown in Figures 7 and 8 and also at the bases

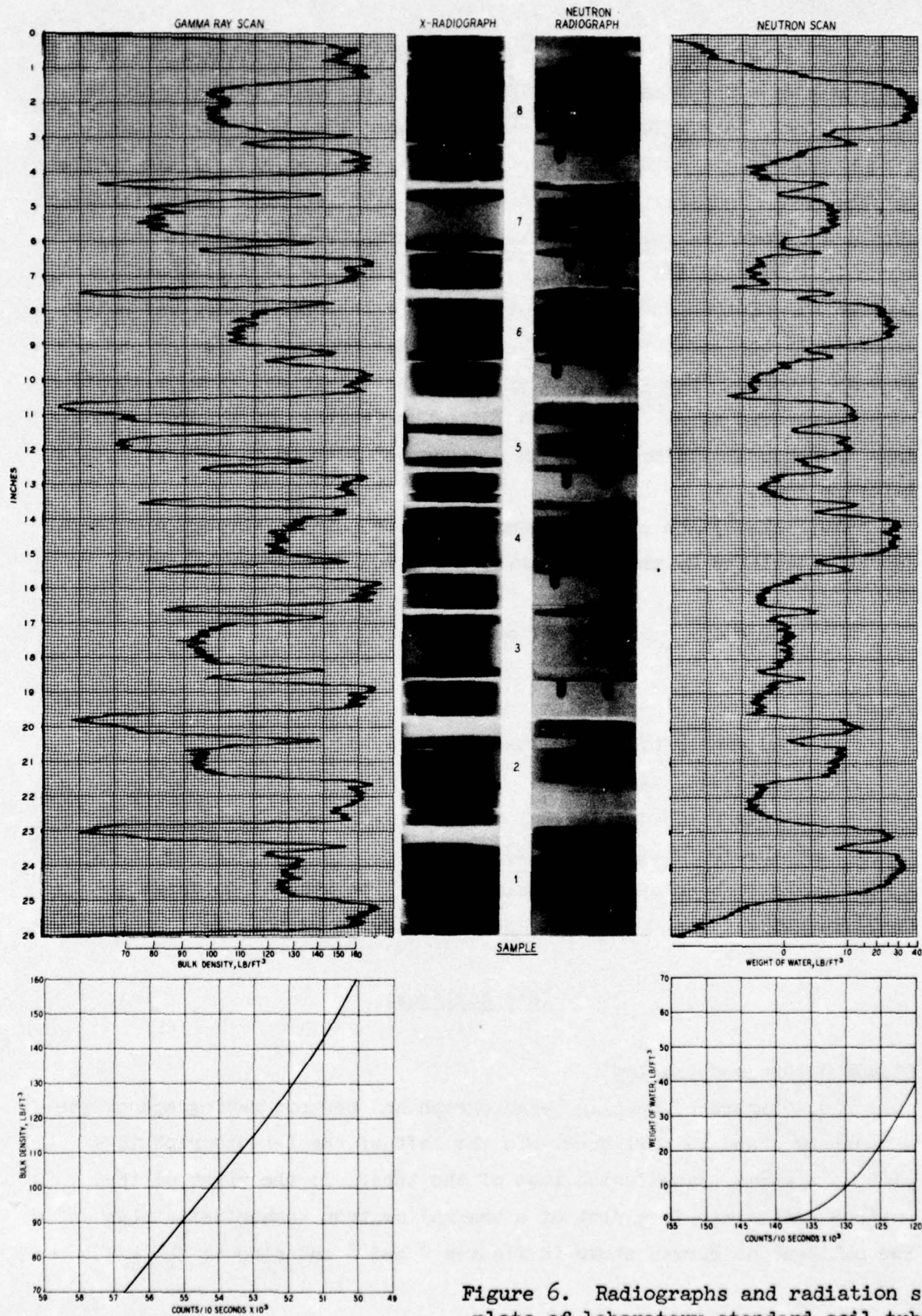


Figure 6. Radiographs and radiation scan plots of laboratory standard soil tube

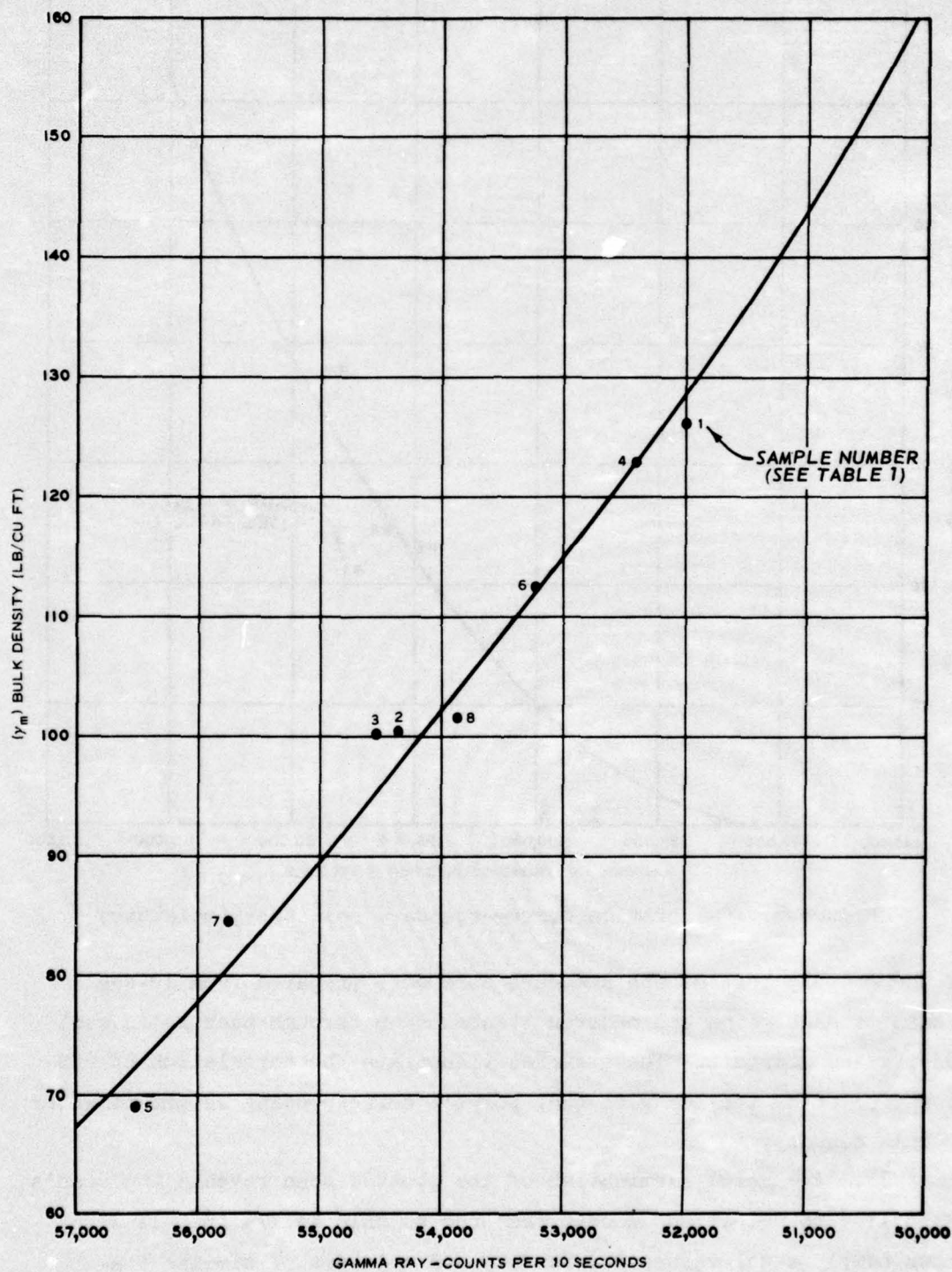


Figure 7. Calibration curve--standard soil tube (bulk density)

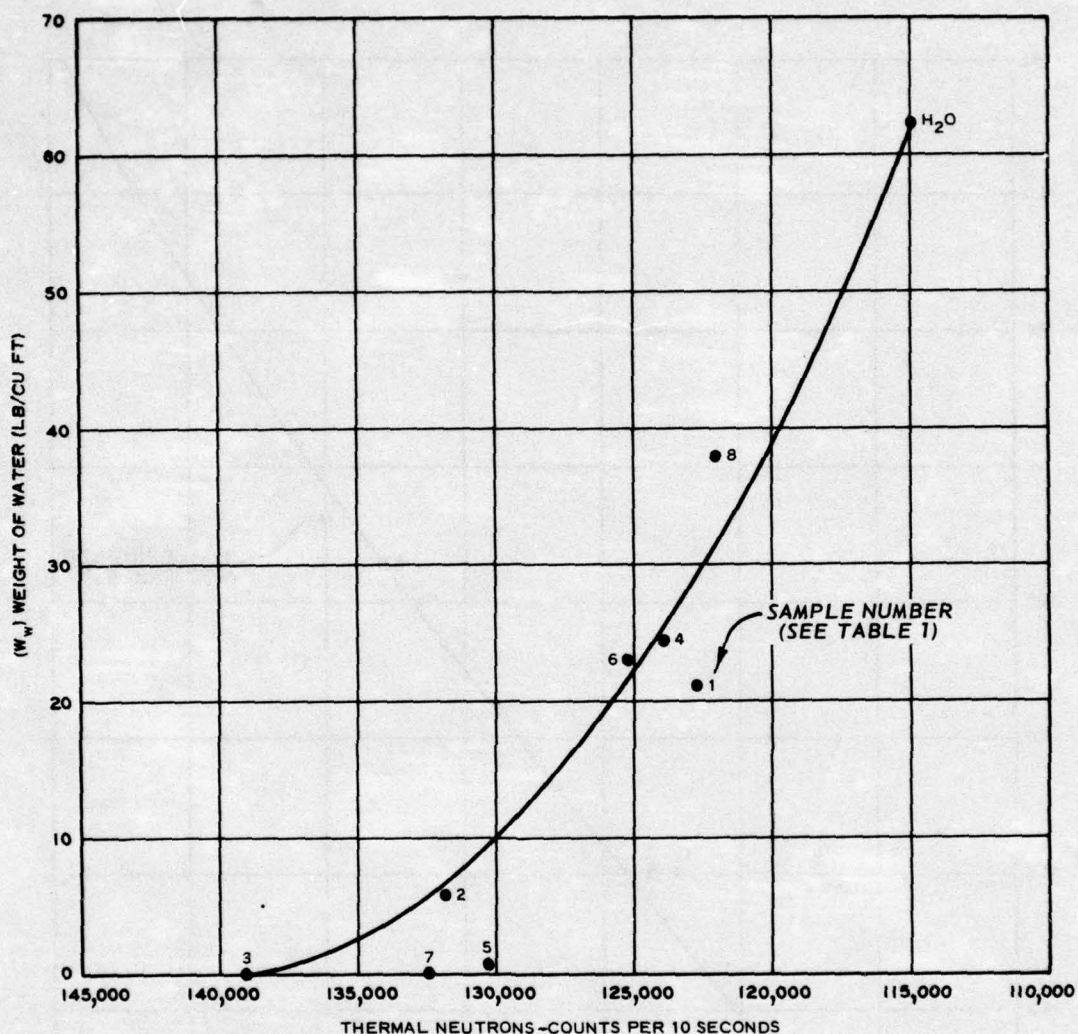


Figure 8. Calibration curve--standard soil tube (moisture)

of the graphic logs of the standard core were prepared from 10-sec counts of each gamma and neutron transmission through each known soil density and moisture. These curves illustrate the correlation of CPS at any point on the log with that point's corresponding weight of water or bulk density.

21. A careful examination of the plotted scan reveals the scan's capability to detect and locate features as thin as 1/4 in. It also shows nearly equal values for density and moisture of similar features. For instance, the aluminum threaded connecting plugs all show

approximately the same values on the density plot.

22. Table 1 gives the properties of the soil standards plus their soil classification as determined in the laboratory. Between each soil sample the 1-in.-thick threaded aluminum connecting plug can easily be identified in the radiographs. The dark 1/4-in.-thick layers in the X-radiograph are circular aluminum plates. The white zones in the X-radiograph adjacent to the aluminum plates or plugs consist of varying thicknesses of paraffin, except in the case of sample 5. This sample had a bulk density of 69.4 lb/cu ft and had approximately the same X-ray absorption as the nearby paraffin layer. Each of these features are readily identified by means of corresponding gamma or neutron peaks on the logs.

23. For the most part, the peaks representing the soil layers correlate very well with both the gamma and neutron calibration curve values for bulk density and weight of water. The peak heights of layers 1/4 in. thick or less do not show good quantitative comparisons. The difference is because of the size of the radiation beam being read. If the layer is thinner than the beam being transmitted and detected, then characteristics of the material on either side of the beam will also be detected. This results in an averaging condition for the area scanned. Such a condition can, in the future, be corrected by reducing the width of the radiation beam. However, to correlate data from narrow beams or thin soils with laboratory tests, it will be necessary to run laboratory density and moisture tests on correspondingly thin samples. Such methods are not available at this time. Instead, the laboratory data (Table 1) being used for comparison with these 1/4-in. beam scans represent an average moisture and density value over a 1-in.-thick specimen. Consequently, even the comparison between laboratory tests and radiation scans data reported herewith should be considered with this factor in mind.

24. Rather extreme moisture variations within a sample will have an effect on pen response time in plotting if the traverse is made at too high a speed. A 1-in.-per-minute scan of the standard tube is maximum for the geometry and type equipment used. Sufficient reading

and plotting time is needed in a scan to plot maximum pen deflection for a sample. Where moisture and density are relatively uniform in a sample, scanning speed is not quite so critical.

25. Quantitative determinations on layers less than 1 in. thick which show extreme variations within one tube would require slower scanning speeds. Tubes containing soils with minor variations in moisture or density can be scanned at 1 in. per minute. Variations within a tube can be determined quite readily with a preliminary scan or from an X-radiograph. Even though X-ray film images indicate primarily density variations in a tube, they are also useful for interpreting conditions likely to have moisture variations. A uniform soil generally will show low variation in density or moisture. A series of alternating thin soil types such as clay, silt, and sand within a sample can be expected to show a wider variation in moisture contents. In addition, such layers less than $1/4$ in. thick will produce the averaging condition described above within the $1/4$ -in.-wide beam. Again, future refinement of the beam to thinner layers will correct this limitation.

Test scans

26. Two unopened samples with unknown moistures and bulk densities were scanned with the neutron and gamma beams for determination of scanning accuracies. Techniques developed with the standard tube were followed on each scan. One tube contained a CH red clay from Meramec Caverns in Missouri. The other, a medium-grained sand, was from Fort Peck Reservoir, Montana. Several 1-in.-thick increments were pre-selected from X-radiographs of each tube for counting and for future use in the laboratory determination of moisture and density.

27. Each tube was checked for size, diameter, and also variations in neutron transmission through an empty portion of the steel tube. The Meramec core had been sampled in a 3.00-in.-ID steel tubing as compared to the 2.875-in.-ID standard tube, thus necessitating a correction for volume of sample scanned. Another correction factor was necessitated by a variation in the composition of the steel tube and its neutron scattering effects. Both of these factors must be corrected to a base standard tube size and steel tube in order to correlate the data with

standard values. To date, no other set of standards have been fully developed for correcting of such steel type and size discrepancies. However, WES is in the process of constructing a series of standard disks which can be inserted into an open end of a steel tube. In this manner, each tube will have its own reference for calibration purposes. For the current project, however, the CPS for one of the preselected zones was corrected to a standard base. This allowed the proper positioning of the unknown sample's graphic log for quantitative determination of moisture at any point with respect to the calibration curve. The procedure used was as follows:

- Step 1. A calibration curve was first made for laboratory-prepared standards 1, 2, 3, 4, 6, and 8 with neutron CPS being plotted against the individual known weights of water. A 10-second count was then made at a preselected location at approximately the midpoint of the test cores.
- Step 2. A neutron transmission count was made through an empty portion of the standard steel tube and also each of the two test cores' tubes.
- Step 3. The differences in CPS between the standard and each of the unknown tubes were recorded. This value represents the quantity in CPS to be either added to or subtracted from the unknown to bring values to the standard base.
- Step 4. A count was made at each of the preselected layers of the unknown cores. This transmission CPS was then subtracted from the CPS transmission for the empty portion of the standard. The resulting CPS represents the uncorrected absorption in the unknown core's preselected layer.
- Step 5. The correction value determined in Step 3 was then (in both unknown cases) subtracted from the uncorrected absorption in Step 4. This provided the corrected absorption for the test layer.
- Step 6. The corrected absorption value derived in Step 5 was then subtracted from the original transmission value (CPS) of the empty portion of its particular tube. This value represents the corrected transmission CPS for the unknown layer.
- Step 7. The corrected transmission value was then used with the calibration curve to determine its corresponding weight of water. If the tube is larger in diameter than the standard tube, as was the case with the Meramec core, then W_w must be adjusted by the following factor. It was assumed that the standard core and the unknown

contained like soil with like densities and moistures. The correction factor then was concerned only with the ratio of the thermal neutron attenuation through a 2.875-in.-ID core and the thermal neutron attenuation through a 3.00-in.-ID core. Since transmission values have been corrected to base, then the ratio is merely:

$$\frac{\phi_{2.875} = \phi_o e^{-\sigma_n x_{2.875}}}{\phi_{3.00} = \phi_o e^{-\sigma_n x_{3.00}}} = \frac{e^{-2.875}}{e^{-3.00}} = e^{0.125} = 0.88$$

or

$$\phi_{2.875} = \phi_{\text{standard}} = 0.88 (\phi_{\text{unknown}})$$

28. The corrected values of the preselected layers in each of the unknown cores were applied to their appropriate calibration curves and the graphic log was adjusted to coincide with that particular weight of water. This adjustment then automatically corrected for the entire core scan. The scales shown at the base of Figures 9 and 10 show the corrected CPS values and corresponding weight of water in lb/cu ft. It should be pointed out at this point that both of the unknown neutron scales are enlarged portions of the standard calibration curve, as is also the graphic print an expanded scale.

29. Readings were made from the graphic log at several points on the cores for comparison with later destructive laboratory moisture determinations. Density readings were also made using a gamma beam for the same preselected layers. Only the oversize correction factor was applied to density values since little or no differences in CPS transmission of the gamma rays through the empty portions of the tubes were noted. Graphic log adjustments were made on the density log in a manner like that of the neutron log.

Test scan analysis (Meramec core)

30. The Meramec soil consisted primarily of a stiff, waxy, CH, red clay with some isolated inclusions. Figure 9 shows an X-radiograph of the core with a density scan log to the left and a weight of water scan log to the right.

31. The upper 6 in. of the core shows some dolomitic rock

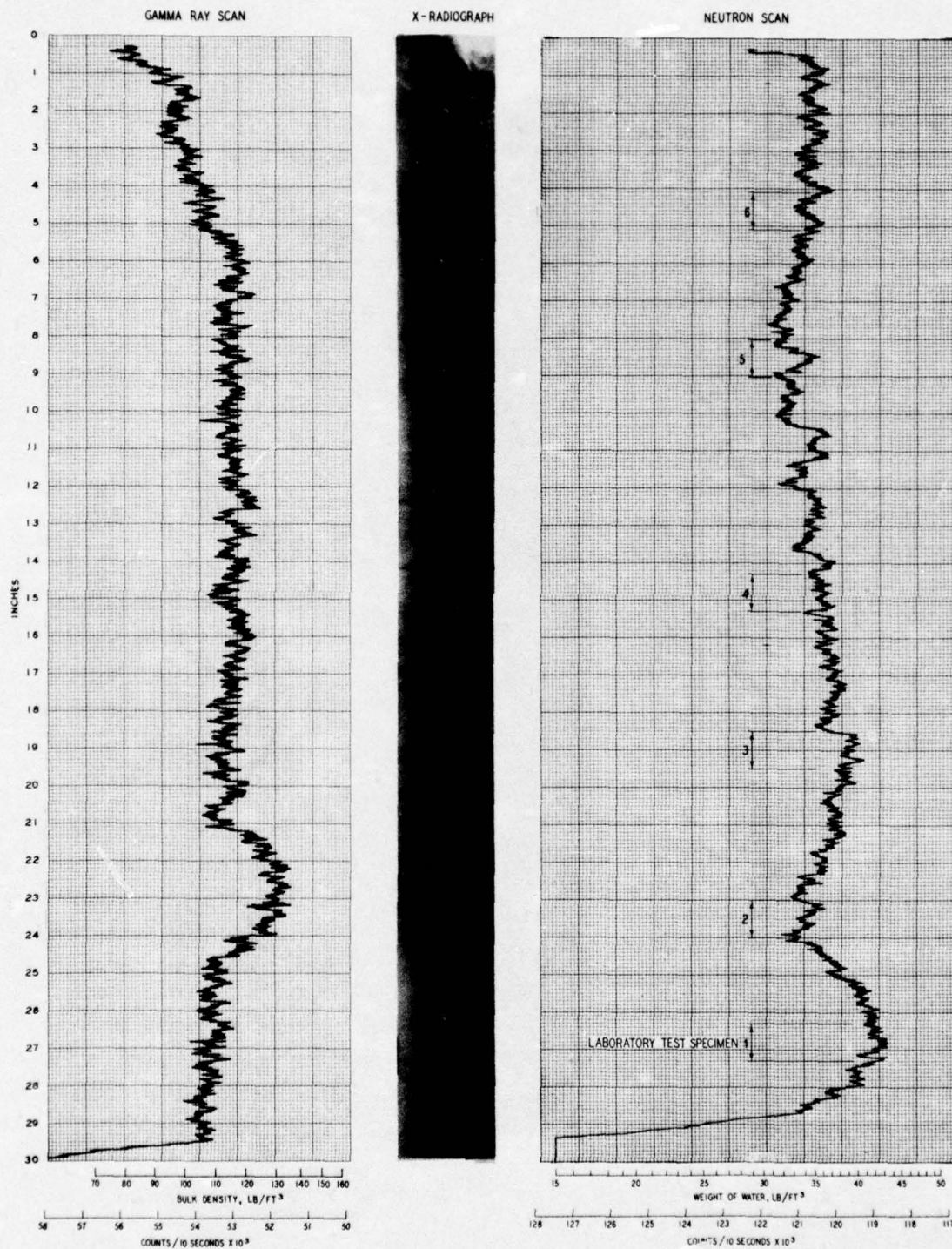


Figure 9. Plot of density and moisture values from radiation scan--Meramec core

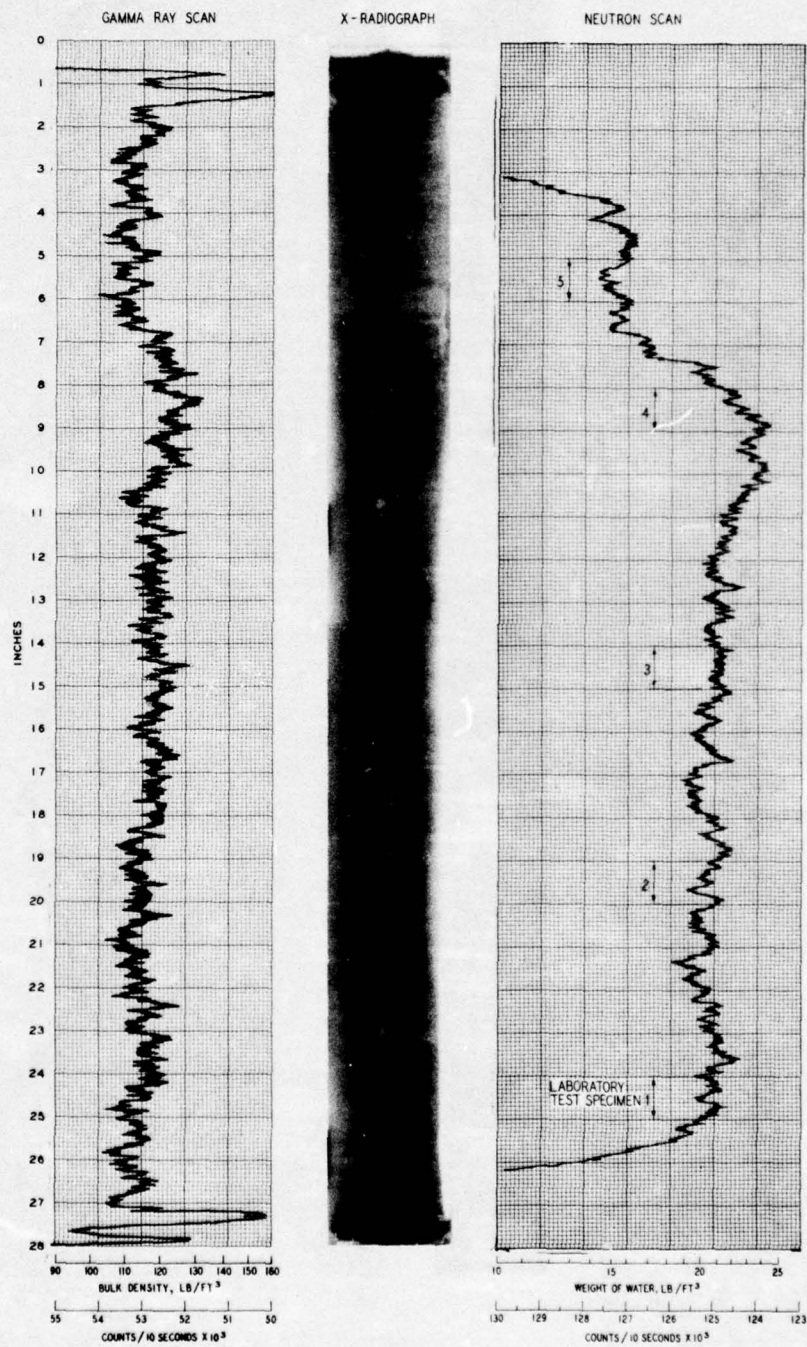


Figure 10. Plot of density and moisture values from radiation scan--Fort Peck core

fragments scattered throughout a slightly disturbed section of the core. A zone of slightly dipping, thin silt layers is present between 9- and 14-in. depth. Immediately below the 14-in. mark and extending to the 20-in. mark is a zone containing irregular fragments of green (chloritic) clay imbedded in the red CH clay matrix. A 1/2-in.-thick silt and silty clay layer separated by 1 in. of the CH clay overlies approximately 3 in. of a clay silt zone between the 20- to 24-in. depth. This is readily located in both the X-radiograph and the two radiation logs. CH clay occurs below the silt and extends to the bottom of the tube.

32. The dark horizontal line visible in Figure 9 approximately midway of the tube is a processing feature and should be ignored. Otherwise peaks on the graphic log do show some reflection of the various thin layers shown on the radiograph. The sample locations identified by numerals show the location of samples which were later cut from the tube and tested for moisture and density in the laboratory. The weights of water are shown in Table 2, which compares scan data with that obtained from laboratory tests.

Test scan
analysis (Fort Peck core)

33. The Fort Peck core consisted primarily of a fine- to medium-grained sand containing predominantly angular and crystal fragments of quartz. Some dark accessory angular minerals were also present, but in much lower quantities. Even though the mineral content and grain size apparently are rather uniform, there is a variation in the weights of water in the upper 8 in. of the sample. This is shown on the neutron scan log in Figure 10. The X-radiograph also reflects some structural variation at this point. In addition, there is some separation between the core and the tube wall. This separation is a result of tapping of the tube with a hammer for a prior unrelated test requirement.

34. Sample locations shown alongside the X-radiograph identify 1-in.-thick layers of soil which were later cut from the tube and tested for moisture and density values in the laboratory. Comparison of the radiation scan and laboratory-determined weights of water is shown in Table 2.

Neutron Scanning Limitations

35. Although the radiation scans generally show good preliminary results, there are a few soil characteristics that can create erroneous values and must be recognized. For example, a careful examination of the standard calibration curve (Figure 8) and the neutron log (Figure 6) for standard samples 5 and 7 shows a scanned weight of water of 9.5 and 5.5 lb/cu ft, respectively. Yet laboratory moisture tests conducted at 110°C show a laboratory-determined weight of water of 0.6 and 0.0 lb/cu ft, respectively. This rather large, unusual discrepancy is due mainly to the types of clay used in constructing the standard sample. Samples 5 and 7 were prepared from refined, relatively pure dry kaolin and montmorillonite clay, respectively. The structural formulas of both of these clays show that hydrogen, the key element in nuclear moisture determination, is present in the form of an attached hydroxyl group. Such hydrogen is not normally removed as H₂O from the clay by 110°C drying. The neutron scan, however, will read the hydrogen and indicate its presence as moisture. From calculation of each clay's molecular weights, the hydrogen present should be equivalent to 11.1 and 4.5 lb H₂O per cu ft of dry kaolin and montmorillonite, respectively. The following tabulation shows the theoretical structural formula used for calculations along with a comparison of calculated, scanned, and laboratory-determined moisture values.

Sample No.	Type Clay	Calculated Equivalent Weight of H ₂ O in Form of (OH) Group lb/cu ft	Indicated H ₂ O ($\bar{W}_w$) from Neutron Scan lb/cu ft	Laboratory- Determined ($\bar{W}_w$) lb/cu ft
5	Dry kaolin $(OH)_4Al_2Si_2O_5$	11.1	9.5	0.6
7	Dry montmorillonite $(OH)_2(Al_{1.67}Mg_{0.33})Si_4O_{10}$ Na _{0.33}	4.5	5.5	0.0

36. Fortunately, in this respect, most naturally occurring transported clays do not occur as homogeneous clays composed of one clay mineral only. This greatly reduces the degree of errors from the attached hydroxyl group. Illite, the most commonly occurring clay in nature, theoretically contains a maximum of 4% equivalent H_2O in the form of hydroxyl groups in the pure state. Illite also is most likely to occur as a mixture of clay, silt, and sand, especially in alluvial deposits. When samples from areas of known pure clays are scanned, then corrections should be considered. Corrections can be made only when the quantity of such hydrogen is known. A mineralogic analysis of the clay will provide the necessary data for a correction factor. It is anticipated that, in any one formation or in any soil type, the clay minerals will be the same for any group of samples.

37. Water of crystallization also occurs in some common minerals such as is present in gypsum. This water should also be taken into consideration when scanning with neutrons. The structural formula of $CaSO_4 \cdot 2H_2O$ shows by atomic weights that $2H_2O$ comprises 26.5% of the mineral as determined by dry weight. Highly gypsiferous soils can create problems in achieving constant laboratory dry weights in moisture determination at temperatures over $100^\circ C$. Neutron scanning will read this moisture however as though it were pore water, thus showing some variance with laboratory determinations. Here again, if highly gypsiferous soils are being investigated, some correction must be made. This perhaps produces a much greater problem than does the hydroxyl content of clays since a knowledge of the presence or lack of gypsum would normally not be determined. In general, a knowledge of the geologic and geographic location of the sample investigated will provide a basis for suspicion of the presence of gypsum. Dry, arid soils will generally contain larger quantities of crystalline gypsum than will more temperate area soils although gypsum is a very widely spread mineral and is present to some extent in many areas.

Film Imagery

38. Techniques for producing an image on film with X-rays have

been known for many years. Such images reflect the absorption of X-rays by density variations of materials. In recent years similar techniques have been applied using neutrons to image film moisture variations in materials. Although both principles are similar, the nuclear interactions and results obtained are almost completely opposite. A series of experiments were conducted to determine the feasibility of neutron film imagery as a practical method for quantifying moisture within a 3-in.-thick or greater steel-encased soil core. X-radiography of 3-in. soil cores requires exposures of only 2 to 20 min, depending on soil type, focal distance, voltage, milliamperes, and film type used. Exposures of up to 64 hr, however, are required in many instances to produce a satisfactory neutron film image. These neutron exposures are also dependent upon amount of H_2O present, distance, source strength, and type of film used. There are rapid imaging methods by image intensification. However, because of vignetting and other electronic manipulation, they are not satisfactory for quantification.

39. Most emphasis in this phase of the nuclear interrogation of soils through film imagery was also concentrated on investigation of 3-in.-diam steel sample tubes and soil cores. For comparison purposes both X-ray and neutron film images were made of the laboratory-prepared soil standards. This comparison was noted previously in this report. Samples and tubes with unknown moisture and densities were radiographed following the same procedures used on the standards. Good results were obtained for the standard soils using an AA type film with a gadolinium conversion screen, a source to film distance of 60 in., and exposure of 16 hr. Attempts to quantify moisture along the center line of the image with film densities were made. In addition, several relatively undisturbed soil slabs were radiographed. The film densities were determined using a Joyce-Loebl Isodensitometer. Comparisons were made with laboratory moisture data from tests of adjacent 3/8-in.-thick soil slabs cut from the same core. Beam collimation and geometric setup for neutron radiography are shown in Figure 11.

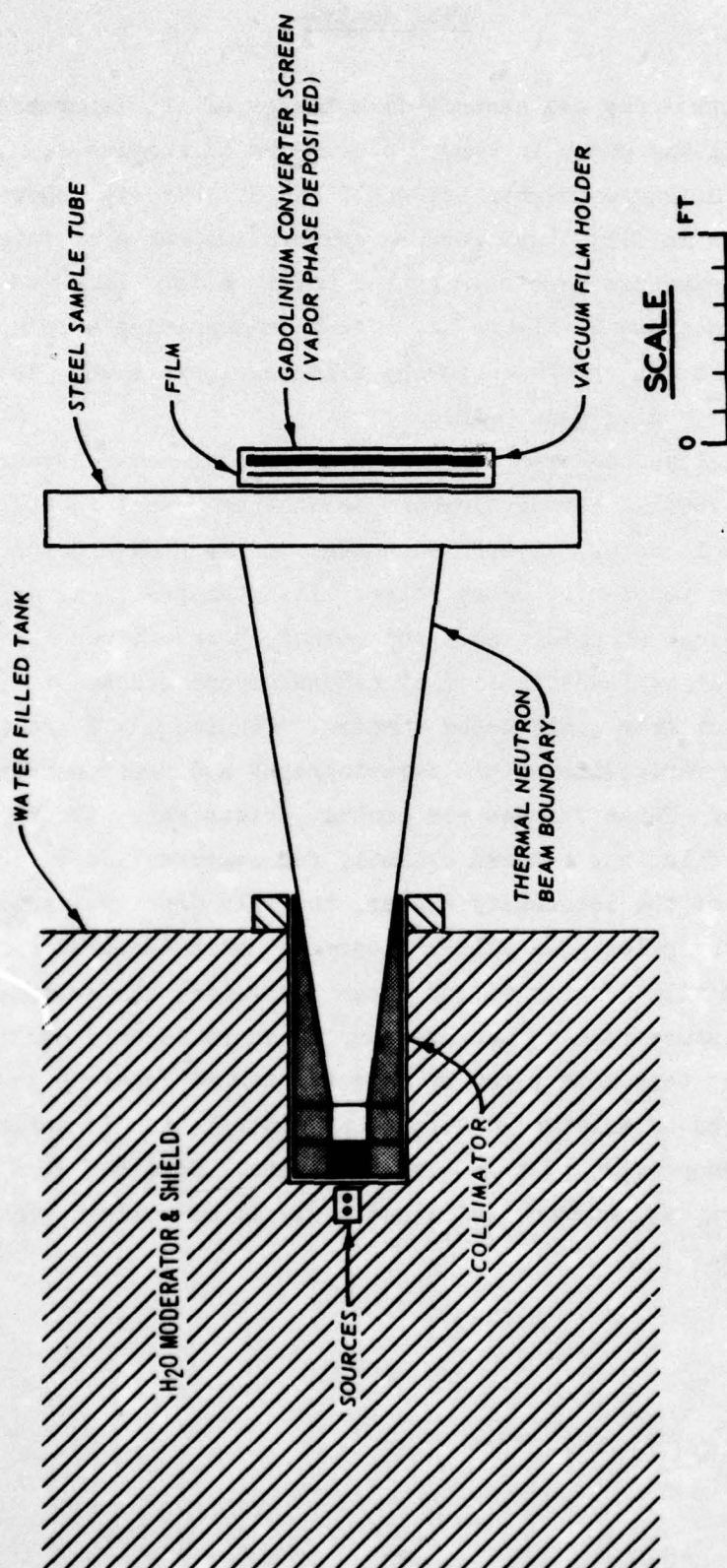


Figure 11. Typical setup for neutron radiograph

Film Analyses

40. Both X-ray and neutron film images of the laboratory-prepared soil standards are shown in Figure 6. Images of samples 1, 2, 3, 4, and 6, which had moisture weights between 0 and 25 lb/cu ft, show corresponding variations in film densities. A calibration curve of film densities from a 64-hr exposure versus weight of moisture for the 0- to 25-lb/cu-ft range is shown in Figure 12. The film densities were corrected in order to adjust for errors caused by film development and distortion resulting from a divergent beam.

41. Indications are that film densities of neutron radiographs offer some potential for development as another means of determining moisture in soil cores. The disadvantages of lengthy exposure times and distortion due to beam geometry rather limit the practical application of this technique at this time. The method, however, does have application in laboratory investigation of minute discrete zones in 3/8-in.-thick slabs cut from undisturbed samples. Figures 13-16 are illustrations showing variations within X-radiographs and neutron radiographs of soil slabs. These figures are contact prints made directly from the original film, but reduced slightly for reproduction in this report. With the aid of the isodensity tracer, the film density can be determined at any point of a film radiograph. With calibration curves prepared from film density versus weight of water, the corresponding weight of moisture from an unknown sample can be determined. The applicability of this method can be directed toward research in determining the effects of moisture movement and distribution in soils on engineering properties such as shear strength. Data can also be very useful in posttest interpretation and analysis of soils having undergone loading tests.

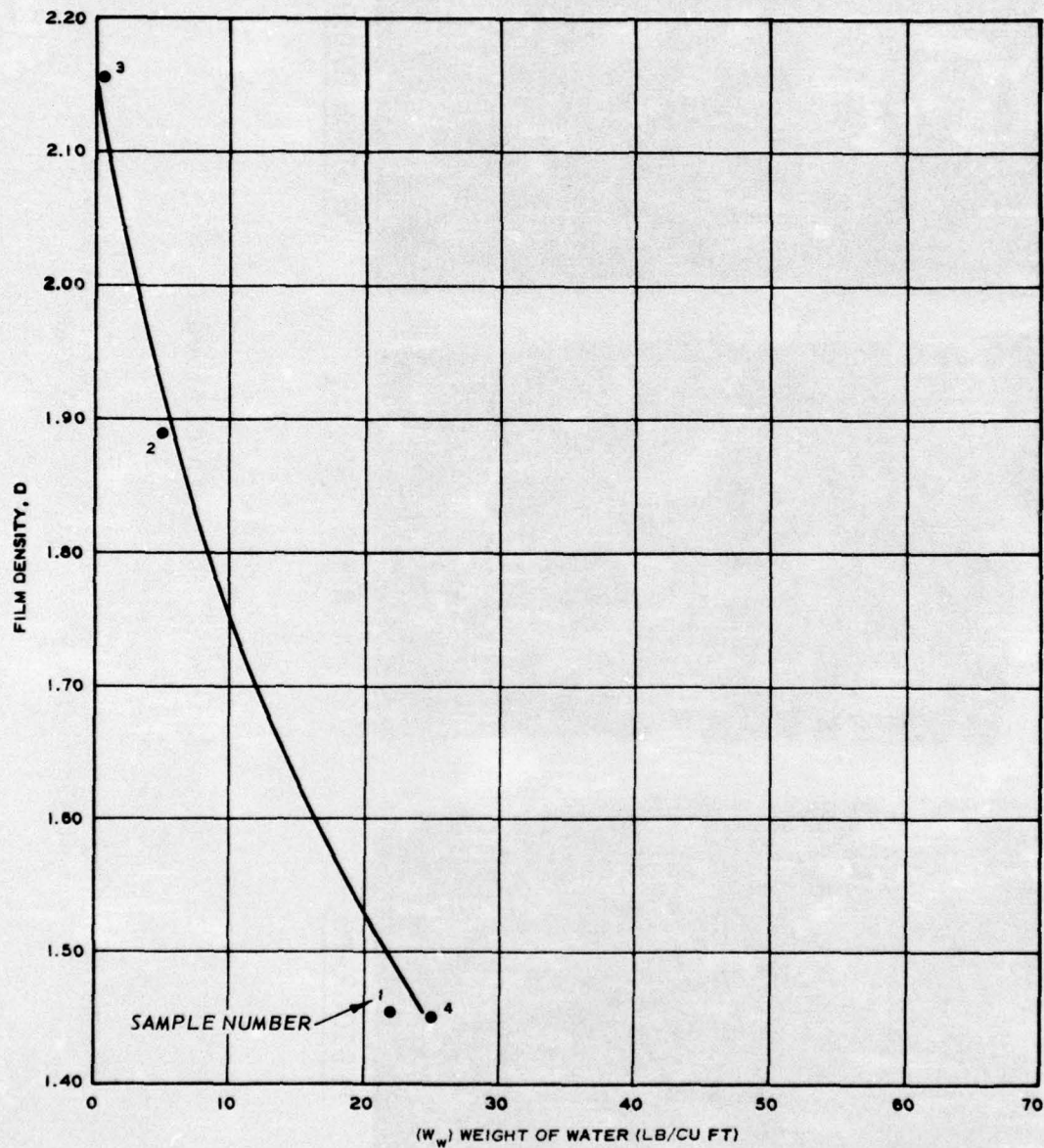
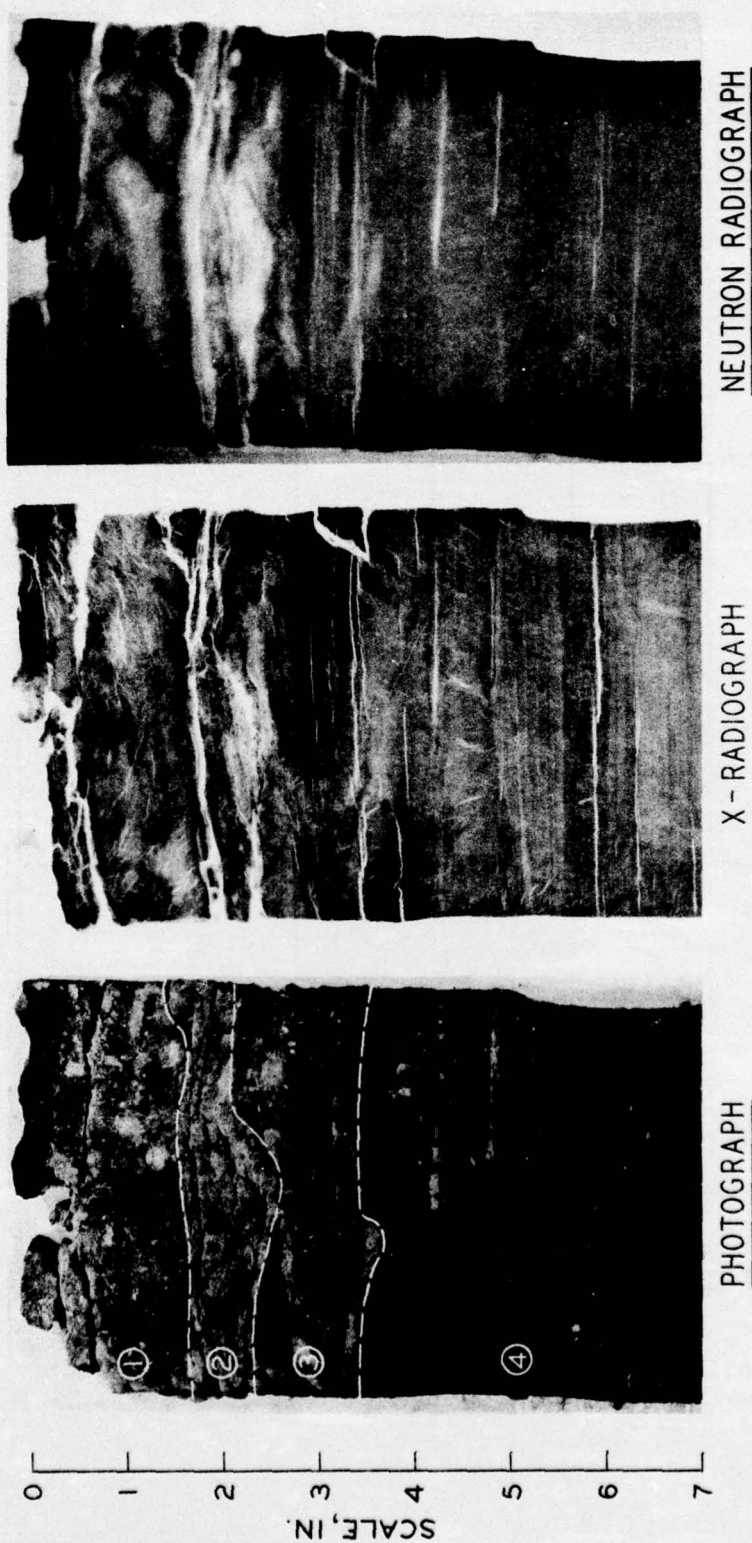


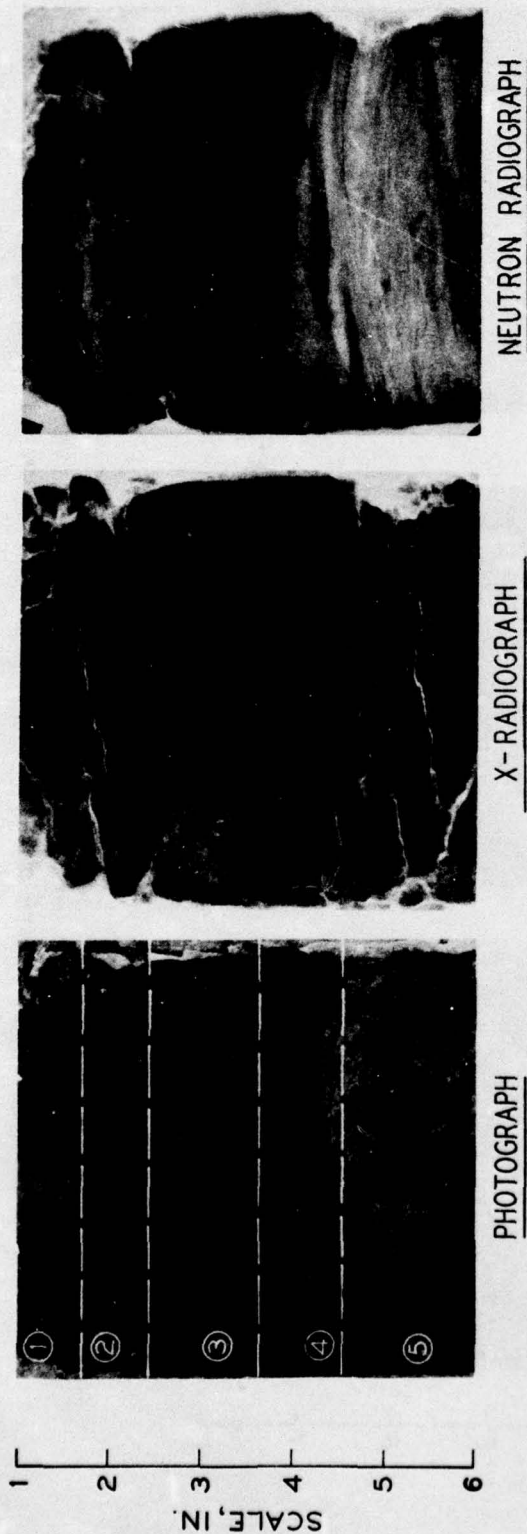
Figure 12. Film imagery calibration curve--standard soil tube (moisture)



LEGEND

- ① SANDY CLAY ③ SANDY CLAY AND CLAY
- ② SAND ④ CLAY

Figure 13. Comparison of photograph, X-radiograph, and neutron radiograph of a 3/8-in.-thick soil slab



LEGEND

SOIL DESCRIPTION	WATER CONTENT, %
① SILT (ML) WITH TRACE OF SAND AND FINE ORGANIC MATTER	22.2
② SILTY CLAY (CL), 50% SAND AND 50% CLAY	32.2
③ CLAY (CH), VERY PLASTIC	65.2
④ SILTY CLAY (CL) 50% SAND AND 50% CLAY	46.8
⑤ SILT (ML), WITH TRACE OF FINE SAND	20.0

Figure 14. Photograph and radiographs of 3/8-in.-thick soil sample. Note comparison of laboratory data (legend) with neutron radiograph (right).

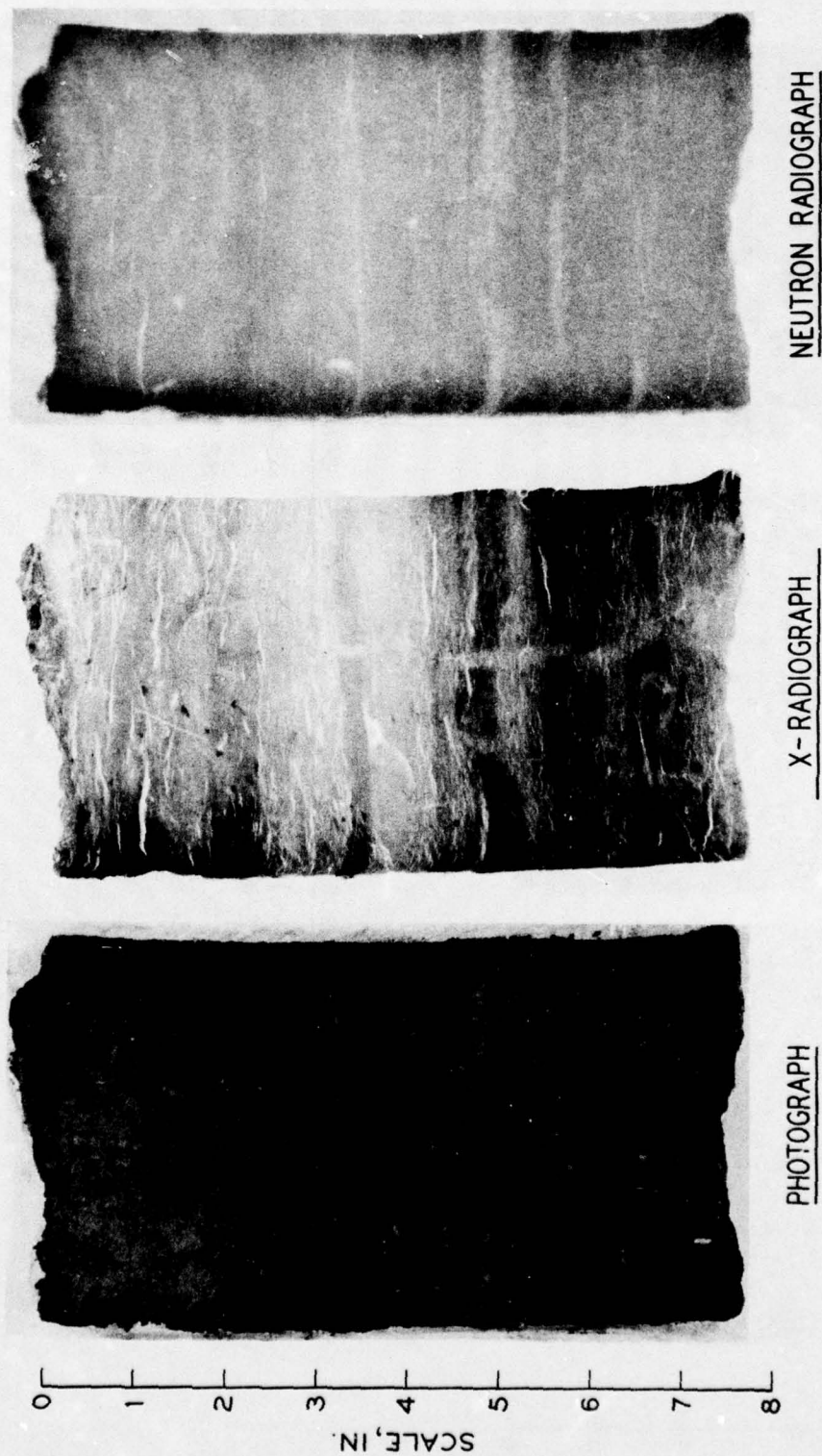


Figure 15. Images of a 3/8-in.-thick clay slab with intermittent silt layers. Note relatively uniform moisture content in neutron radiograph (darker areas)

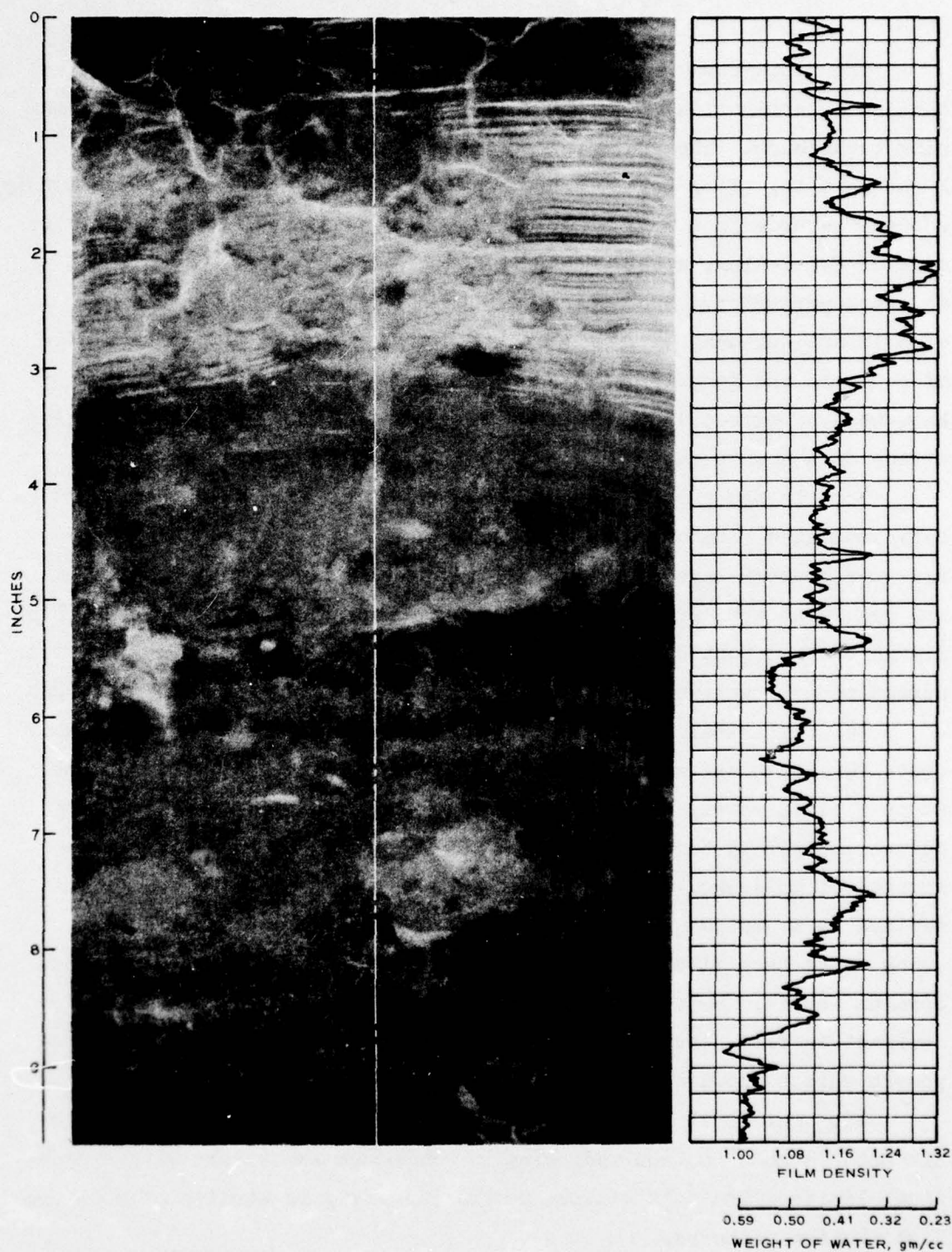


Figure 16. Neutron radiograph of a 3/8-in.-thick soil slab showing irregular moisture distribution. (The darker the tone, the greater the moisture.) Upper 3 in. is a relatively dry clean sand. Lower 6 in. consists of alternating layers of sand and sandy clay with an occasional sand pocket (circular patterns). White vertical line is path of film density scan shown at right

PART III: CONCLUSIONS AND RECOMMENDATIONS

42. This study has illustrated the practical applicability of nuclear determination of moisture in unopened soil cores through scanning techniques. The graphic logs, when viewed in conjunction with X-radiographs, offer a very thorough and detailed insight into previously unseen features in a soil core. Neutron and gamma scans can readily be made of 3-in.-diam, steel-encased soil cores at speeds of 1 in./min for each parameter. Such scans can define and quantify variations of moisture and density in layers as thin as 1/4 in. With a knowledge of geologic and geographic environments of a sample, one can generally know what to expect in terms of associated minerals and their potential effect on a scan's data.

43. In the current phase, accuracy within 1/4-in.-thick layers is only indicated from comparison of laboratory data obtained on 1-in.-thick or greater layers; however, comparisons of weight of water from the scan with the laboratory data show average differences to be within 2.1 lb/cu ft. Such differences, when related to water content (%), will depend to a large extent on the accuracy of bulk density determinations.

44. Film imagery for X-radiography on 3-in.-diam or greater soil cores for practical quantitative moisture determination is questionable at this time, partly because of the long exposure times that are required and partly because of a loss of definition of image for large amounts of moisture. Water contents of less than 25% were rather easily defined in a neutron radiograph with a film exposure time of 16 hr, using an AA type film, a gadolinium converter screen, and a 5-mg californium source. Water contents higher than this showed much less contrast in film density with increases in moisture using the same exposure values shown above.

45. Thin soil slabs (3/8 in. thick) cut from undisturbed soils did produce good neutron radiographs. Exposure times were within practical limits. The data will be useful primarily in studies of moisture distribution patterns.

46. It is recommended that work be conducted toward producing a

computer calculated and plotted curve of the percent water contents ($W_w/\gamma_d = W_c \%$) of soils from raw data produced by the gamma and neutron scans. A program can be written whereby corrections for steel type and size and soil type can be taken into account in the computer printout. Raw data can be fed directly to a minicomputer.

47. More emphasis should be directed toward core scanning rather than to neutron film imagery of 3-in.-diam or greater cores for rapid soil assessment. At the present time, the making of neutron radiographs is not practical from a time viewpoint for rapid assessment of steel-encased soil cores. Recent developments in image intensifying systems, however, are beginning to show more reliability. At present they are suitable for fast, nonquantitative imaging. In time they may become quantitative.

Table 1
Properties of Soil Standards (2.875-in.-ID Steel Tube)

Sample No.	Soil Type	Bulk Density (γ_m) lb/cu ft	Dry Density (γ_d) lb/cu ft	Weight of Water (W_w) lb/cu ft	Water Content (W_c) %
1	CL	125.9	105.3	20.6	19.5
2	ML	100.9	95.1	5.8	6.1
3	Dry sand	100.4	100.4	0	0
4	Wet sand	123.5	99.6	23.9	24.0
5	Dry kaolin	69.4	68.8	0.6	0.9
6	CL	112.2	89.5	22.7	25.4
7	Dry montmorillonite	84.7	84.7	0	0
8	CH	101.2	63.3	37.9	59.9

Table 2
Comparison of Radiation Scan Data and
Laboratory Tests

Sample	Weight of Water, lb/cu ft	
	Radiation	Laboratory
Meramec No. 1	41	40.2
2	32	28.0
3	39	37.8
4	35	37.1
5	33	35.5
6	34	38.5
Fort Peck No. 1	21	24.8
2	20	23.3
3	21	21.6
4	22	22.1
5	15	15.1

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Lewis, Jack T

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Army Engineer Waterways Experiment Station, 1976.

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