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# USE OF BOREHOLE GEOPHYSICAL METHODS IN DETERMINING IN SITU BULK DENSITIES AND WATER CONTENTS IN UNCONSOLIDATED MATERIALS

by

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Final Report

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In situ bulk densities and water contents of unconsolidated materials have determined from geophysical logs obtained from borings in three separate geologic environments: desert alluvium, river alluvium, and loess. The geophysical logs used in the property determinations were natural gamma, gamma-gamma, neutron, and caliper. The geophysical (field) bulk densities and water contents were derived at depth intervals corresponding to sampled intervals → next page

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20. ABSTRACT (continued).

where similar property data from laboratory analyses were available for comparisons. The field bulk densities ranged from about 5 percent lower to 11 percent higher and had an overall average of 1 percent higher than the laboratory bulk densities. The field water contents ranged from about 12 percent lower to 18 percent higher with an overall average of about 6 percent higher than the laboratory water contents.

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## PREFACE

The study of downhole geophysical logging methods for determining in situ engineering property values was funded through the In-House Laboratory Independent Research (ILIR) Program, Project No. 4A161101A91D, Work Unit No. 101. The investigations were conducted by the Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES), during parts of 1975 and 1976.

The field work, data evaluations, and the preparation of this report were accomplished by Mr. Richard W. Hunt, Geology Branch, Engineering Geology and Rock Mechanics Division (EGRMD), WES. The investigation was under the general supervision of Mr. W. B. Steinriede, Jr., Chief, Geology Branch, Mr. D. C. Banks, Chief, EGRMD, and Mr. James P. Sale, Chief, S&PL.

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

CONTENTS

## 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:

| Multiply | By | To Obtain |
|---|---|---|
| inches | 25.4 | millimetres |
| feet | 0.3048 | metres |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic metre |
| gallons (U. S. liquid) | 3.785412 | cubic decimetres |
| miles (U. S. statute) | 1.609344 | kilometres |

USE OF BOREHOLE GEOPHYSICAL METHODS IN DETERMINING IN SITU BULK DENSITIES AND WATER CONTENTS IN UNCONSOLIDATED MATERIALS

# PART I: INTRODUCTION

## Background

1. Each year hundreds of borings are drilled by the districts within the Corps of Engineers to obtain subsurface data in unconsolidated materials for use in design and construction. While procedures used for obtaining subsurface information have not changed materially within the past 20 years, the cost of obtaining undisturbed samples for analysis has increased from about $5 per foot to more than $25 per foot. Most of this increase has taken place within the last 10 years with indications that the rate of increase will continue.

2. The Office, Chief of Engineers, has stressed the need to minimize rising sampling costs and advocates obtaining maximum information from each boring drilled by the Corps of Engineers. With this in mind, WES has conducted research on the capabilities of downhole, omnidirectional geophysical methods for determining in situ engineering properties.

## Purpose

3. The purpose of this study was to assess the capabilities of the WES geophysical downhole logging equipment for obtaining in situ bulk densities and water contents in unconsolidated materials, to establish a log analysis procedure applicable from one site to another, and to compare geophysically derived properties with those obtained from laboratory analysis of samples.

## Scope

4. This study consisted of (a) calibrating the neutron and gamma-gamma tool radiation counts in established calibration pits where

engineering properties were measured and controlled; (b) obtaining raw geophysical logs in 7 borings (4 in desert alluvium, 2 in Mississippi River alluvium, and 1 in loess); and (c) evaluating the geophysical data in relation to determining in situ engineering properties. This report describes the equipment used, the processes in reducing the calibration and raw geophysical data, and presents the results of the geophysical analysis, including comparisons of in situ properties with laboratory sample properties.

## PART II: GEOPHYSICAL EQUIPMENT

5. The geophysical logging equipment used in this study consisted of a caliper tool, a natural gamma tool (also used to make gamma-gamma logs), a neutron tool, a single-point resistance and self-potential tool, and a 3-D acoustic velocity tool. All of this equipment is a part of the greater geophysical and optical systems mounted in the WES geophysical logging truck. The equipment is available commercially and, with the exception of the 3-D acoustic velocity logger, which is a Birdwell product in its entirety, the other tools used in this study, including the uphole electronics, are part of the Well Reconnaissance Model 8903 Geologger. The equipment is typically used for qualitative geophysical investigations as opposed to quantitative investigations reported herein.

### Caliper Tool

6. The caliper tool has three spring-loaded radial arms which contact the borehole wall and actuate a potentiometer as they follow irregularities on the wall. Before lowering into a borehole, the caliper arms are calibrated in a scaled template so that variations in borehole diameter, as reflected by pen movement on the surface strip chart recorder, can be accurately determined. The caliper log (or borehole diameter data) is necessary for quantitative reduction of the nuclear logs.

### Natural Gamma Radiation Tool

7. The natural gamma radiation tool uses a thallium-activated sodium iodide scintillation detector to measure naturally occurring gamma radiation within the borehole. The tool or probe measures 1-1/4 in. in diameter by 5-1/2 ft long with the detector crystal located about 6 in. from the bottom. Radiation detection is omnidirectional, and the radius of investigation being approximately 1 ft. The probe is

unrestrained in its lateral location within the radius of a borehole; however, in data reduction, since most borings are not drilled truly vertical, the probe is assumed to be against the wall.

8. Gamma radiation is tranformed into light traces by the sodium iodide crystal. A photomultiplier tube detects the light traces and emits an electrical pulse for each gamma emission or light trace. The pulses from the photomultiplier tube are fed into an electronic circuit and from there are passed up the cable to the control unit on the surface. Pulses are recorded as radiation counts per second (CPS) by scaled deflections on the strip chart recorder.

9. Natural gamma logs can be obtained in either cased or uncased borings. The nature of the drilling fluid in the borehole has no effect on natural gamma readings, and moderate hole diameter changes have only minimal effects. The qualitative value of natural gamma logs lies in the fact that clays and clay-bearing materials generally emit higher CPS than clean sands and carbonates. Therefore, a consistent lithologic comparison within a given locality can be made to delineate zones of greater or lesser clay content. In quantitative evaluation of gamma-gamma logs it is necessary to subtract the natural gamma CPS from the gamma-gamma CPS.

## Gamma-Gamma Radiation Tool

10. The natural gamma probe and uphole electronics are also used for producing gamma-gamma radiation logs. The only difference is the addition of a gamma radiation source located below the detector and the addition of various length spacers to separate the source from the detector to preselected distances. There are two gamma sources available as part of the geophysical equipment: 5 millicuries of radium-226 and 10 millicuries of cobalt-60.

11. Gamma protons from the source penetrate and are scattered and absorbed by the fluid, casing, and formation material surrounding the probe. The gamma ray emission from the source may be visualized as an omnidirectional radiation cloud centered at the source. The volume of

material investigated is approximately contained in a sphere with a diameter equal to the distance between the source and detector and centered between the two. The resulting gamma-gamma log is a weighted average for all the volume of material within the sphere of investigation including the fluid within the borehole, the casing (if present), and the formation material.

12. The gamma-gamma radiation log is highly influenced by changes in borehole diameter, fluid density, casing, and positioning of the probe within the borehole with respect to distance from the borehole wall. Gamma-gamma logs can be obtained in cased or uncased holes that are filled with either air or fluid. The main uses of the gamma-gamma logs are for identification of lithology (especially useful in correlations from one boring to another) and with proper calibrations, the measurement of the bulk density and porosity of rock materials.

## Neutron Radiation Tool

13. The neutron logging tool is an epithermal type, similar in construction and size to the gamma probe. The uphole electronics are also similar. The radiation source is 3 curies of americium-241 beryllium, which can be separated from the lithium iodide detector by the addition of several different spacers of varying lengths.

14. The neutron radiation permeates omnidirectionally outward from the source in the form of fast neutrons having energies greater than $10^5$ electron volts. The volume of material investigated is approximately contained in a sphere with a diameter equal to the distance between the source and detector and centered between the two. The neutron loses its energy when passing through matter by elastic collision. The most effective element in slowing down and moderating neutrons is hydrogen. Because the nucleus of a hydrogen atom has approximately the same mass as a neutron, it takes fewer collisions with hydrogen nuclei to thermalize a neutron than with the nuclei of other elements. The high energy neutron is reduced to an epithermal neutron with an energy of 0.1 to 100 electron volts upon collision with a

hydrogen nucleus. The neutron detector responds almost entirely to epithermal neutrons; therefore, it is in effect measuring the hydrogen density within the volume of investigation. If the formation has a high hydrogen content, many neutrons are slowed and captured by the hydrogen before they reach the detector, resulting in a small CPS deflection on the strip chart recorder. If the hydrogen content is low, many neutrons might be slowed to epithermal levels but still escape capture and reach the detector, resulting in a high CPS deflection.

15. The neutron log is greatly affected by borehole diameter changes and by the position of the probe in the borehole relative to the sidewall. The log is affected to a lesser extent by the presence or absence of casing and by different types and weights of fluids in the hole. Another problem associated with neutron logs is that the neutron responds similarly for chemically bound water and for free water.

16. The neutron logs are useful in delineating zones of high hydrogen content and for measurements of porosity. When properly calibrated, the neutron measurements can be related to in situ water content.

## PART III: FIELD WORK

### Sites Investigated

17. The field work consisted of calibrating the gamma-gamma and neutron tools and obtaining complete suites of geophysical logs totaling 5000 ft in seven borings. The borings were drilled in unconsolidated materials of three distinct environments of deposition: four in desert alluvium at White Sands Missile Range, New Mexico; two in Mississippi River alluvium near Jonesville, Louisiana; and one in loess at WES. The borings ranged in depth from 50 to 300 ft. The two Jonesville borings were 6 in. in diameter and the other five were 8 in. in diameter. All of the borings were uncased and contained drilling mud at the time of logging. The White Sands borings had been sitting for two to three weeks and required reworking of the drilling mud prior to logging. The remaining borings were logged within a day after their completion.

18. None of the borings were drilled for geophysical requirements. They were instead sample borings that were drilled for three separated and unrelated projects. The borings, however, were available for logging at the time of the study and had representative laboratory data which could be compared with the geophysically derived data.

19. The borings were:

| Boring No. | Diameter | Depth | Project and Location |
|---|---|---|---|
| U-1 | 8 in. | 300 ft | Pre-Dice Throw II, White Sands Missile Range |
| U-3A | 8 in. | 50 ft | Pre-Dice Throw II, White Sands Missile Range |
| G-GA | 8 in. | 75 ft | MX Valley Studies, White Sands Missile Range |
| G-9 | 8 in. | 75 ft | MX Valley Studies, White Sands Missile Range |
| J-14-75U | 6 in. | 87 ft | Levee Studies, Jonesville, LA |
| J-15-75U | 6 in. | 75 ft | Levee Studies, Jonesville, LA |
| U-5 | 8 in. | 145 ft | Foundation Studies, New Soils Lab Building, WES |

## Selection of Geophysical Logs for Detailed Studies

20. All of the geophysical logs from each of the borings were reviewed to determine which offered information that could be reduced to quantitative engineering property data. The study was limited to include only those logs which could be related to determining in situ bulk densities and water contents. These logs included the caliper, natural gamma, gamma-gamma, and neutron logs. Only three of the borings (U-1, J-14-75U, and U-5), representing each of the sites investigated, were selected for detailed analysis.

## PART IV: ANALYSIS PROCEDURE

### Calibration of Nuclear Tools

21. Before any quantitative data can be obtained from nuclear logs, it is necessary to calibrate the logging tools in an established environment.

22. Calibration pits constructed from natural geologic materials where careful engineering property measurements have been made and controlled offer the simplest sources for obtaining quantitative calibration data. Calibration pits are expensive to build, however, and in most cases, require considerable attention to maintain. There are a number of pits at various locations throughout the United States, mostly under the control of oil companies or logging service companies and some universities. After contacting several owners of calibration pits and determining available facilities, two were selected as sources of calibration data for the gamma-gamma and neutron tools. One was the Schlumberger pits at Houston, Texas, and the other was the Birdwell pits at Tulsa, Oklahoma.

#### Schlumberger test pits

23. The Schlumberger Company consented to the use of their test facilities at no charge. The Schlumberger pits consisted of 11 separate unconsolidated and consolidated natural rock materials for which the porosity indexes* and saturated bulk densities were known. The gamma-gamma and neutron tools were calibrated in all 11 environments and the calibration data were evaluated against those taken later in the Birdwell pits.

24. Some of the data points from the Schlumberger pits would not fit relationships derived from the Birdwell data. Schlumberger personnel had not used their unconsolidated pits for a long time prior to WES calibration tests nor had there been a recent check on the engineering property values. In contrast, the Birdwell pits were recently constructed and in use almost every day. To avoid problems created from

* Value in percent equal to porosity times saturation.

mixing the calibration data from two sources, the Schlumberger data for the most part were not used in this study.

Birdwell test pits

25. The Birdwell Division, Seismograph Service Corporation, Tulsa, Oklahoma, completed construction of a set of calibration pits around February 1975. The pits are not ordinarily open to the public; however, they allowed access to them for two days at a cost of $600 per day.

26. The test pits are in nine separate sealed tanks averaging 10 ft square and 6 ft deep, all buried outdoors in an area measuring 32 by 34 ft. The surface area over the tanks was covered with asphalt. Six of the tanks contained natural aggregate materials that were penetrated by six holes. The holes measured 4, 6, 8, 10, 12, and 18 in. in diameter and were lined with 16-gage steel casing, which extended about 6 in. above the surface. The seventh tank contained three stacks of cut and well-fitted, 3-ft-square blocks of different rock types. Each of the three block stacks was penetrated by five borings: a 7-7/8-in.-diameter boring in the center, and 4-3/4-, 7-7/8-, 6-1/2-, and 9-7/8-in. borings positioned around the center hole with one in each corner. The eighth tank was filled with water only, and the ninth tank was not in use.

27. Carefully measured porosity indexes and bulk densities for each pit material were made available from Birdwell. They were:

| Pit No. | Material | Porosity Index (Percent) | Bulk Density (Saturated) $g/cm^3$ |
|---|---|---|---|
| (Unconsolidated) | | | |
| 1 | Wet Dolomite (crushed) | 29 | 2.08 |
| 2 | Dry Dolomite (crushed) | 0 | 1.82 |
| 3 | Dry Sand (quartz) | 0 | 1.80 |
| 4 | Chatt Sand (quartz) | 20 | 2.17 |
| 5 | Wet Sand (quartz) | 26 | 2.11 |
| 6 | Not In Use | --- | ---- |
| 11 | Limestone (crushed) | 22 | 2.35 |

| Pit No. | Material | Porosity Index (Percent) | Bulk Density (Saturated g/cm$^3$ |
|---|---|---|---|
| (Block Stacks) | | | |
| 7 | Indiana Limestone | 9.5 | 2.69 |
| 8 | Berea Sandstone | 17 | 2.28 |
| 10 | Carthage Marble | 2.4 | 2.64 |
| 13 | Open Water | 100 | 1.00 |

28. Time limits would not permit calibration of the gamma and neutron tools in all holes in each pit with all of the spacer combinations. Hole diameters and spacer lengths were chosen that were considered most applicable to the current ILIR Program. These included the 5- and 10-in. spacers for the gamma-gamma calibrations, using both the radium and cobalt sources, and the 2-, 5-, and 10-in. spacers for the neutron calibrations. In addition, the neutron tool was calibrated with the built-in spacing of the source holder and no additional spacer inserts. Calibration readings were obtained in the 4-, 6-, and 8-in.-diameter holes, of the six unconsolidated material pits, and in the 7-7/8-in.-diameter center hole of the three stacked block pits. A reading for each tool and spacer combination was also taken in the open water pit, No. 13.

29. The calibration procedure for both the gamma-gamma and neutron tools was essentially the same. Before any downhole measurements were made, the gamma and neutron control modules in the truck were calibrated by using a pulse generator to create controlled signals. The generated signals were monitored by a frequency counter to match each count range setting on the modules. Any necessary adjustments were made to the range setting pot so that pen deflections would match the appropriate scale on the strip chart recorder.

30. After the control modules were calibrated, natural gamma readings were taken in each of the calibration pit holes by positioning the probe against the sidewall halfway into the pit. Static measurements were recorded by manually rolling the paper on the strip chart

recorder past the pen for about 20-30 seconds. Calibration data for the gamma-gamma and neutron tools using the previously mentioned spacer inserts were taken in the holes at the same position as that for the natural gamma. Two separate calibration recordings were made in each pit hole. The first calibration run was made with the holes filled with water. The second calibration run was made with the water removed and the holes containing only air.

31. An aluminum block measuring 16 by 16 by 24 in. was mounted in the truck as a secondary field standard for the gamma-gamma tool. The block was constructed from six 4- by 16- by 16-in. milled slabs bolted together at two corners. A hole, slightly larger than the gamma tool, was drilled through the center to allow insertion of the gamma tool. The secondary field standard for the neutron tool was a 13-gallon plastic bottle filled with water.

32. Gamma-gamma data were obtained in the aluminum secondary standard block for the 5-in. spacer prior to each calibration run. The 10-in. spacer was too long to fit in the aluminum block. Similar neutron data were obtained with all spacers in the 13-gallon water bottle prior to each run. Table 1 presents the calibration data obtained in the Birdwell pits.

## Casing Effect Test

33. A series of tests was conducted at WES with the gamma-gamma and neutron tools in thin-wall casing constructed to match the dimensions of casings in the calibration pits. The purpose of these tests was to make predictions as to the effects of casing on the nuclear radiation count rates. The tests were made in a 5-ft-square plywood water tank containing 3 ft of clear water. The casing was made in 4-, 6-, and 8-in. diameters from flat, galvanized steel rolled into the preferred diameters and welded at the joints. The casings were placed in the water tank and radiation counts were measured with the gamma-gamma and neutron tools in a similar procedure to that run in the calibration pits.

34. Readings were taken in open water (without the casing) with both tools. Then readings were taken inside the casings against the sidewall with water on the inside and outside of the casing. A second reading was taken from inside the casing against the sidewall with air on the inside of the casing and water on the outside. Readings were also taken in the casing with air on the inside and outside and with water on the inside and air on the outside. Readings were then taken in the secondary standards to determine how the tools were functioning as compared to when data were obtained in the calibration pits. Results of these tests are shown in Table 2.

## Reduction of Radiation Counts to Applicable Engineering Property Values

35. The procedure for obtaining radiation data from both the calibration pits and the field borings, as stated earlier, involved running as many spacer combinations as time would permit for both the gamma-gamma and neutron tools. With the gamma-gamma logs, this procedure included two identical runs using first the cobalt source and next the radium source. These accumulations of data were then reviewed to determine which logs offered the best relationships for detailed analysis in connection with the ILIR Program.

36. As discussed in paragraphs 11 and 14, the distance between the source and detector determines the total volume of material represented by the radiation CPS at any given sample point in a borehole. For a small source-to-detector spacing, a great proportion of the volume measured could be entirely within the borehole. On the other hand, a long source-to-detector spacing would average such a large volume of material that effects of thin beds would be overlooked. The review revealed that the logs run with the 5-in. spacer, giving a total separation of about 15 in. from source to detector, appeared to give optimum results for both the gamma-gamma and neutron tools; therefore, all of the calibration data finalized for this study as well as the final analyses of field data are based on tool radiation counts using the 5-in. spacer insert. The total volume of material sampled at each point

by both tools represented a sphere 15 in. in diameter, including the volume of borehole fluids and formation materials within the sphere at each point.

37. In addition to the variations in representative radiation CPS caused by different source-to-detector spacings, the logging speed has a significant effect on how long the probe has to make a statistical count within any given change in the formation. Logging speeds that are excessive tend to round off or even obliterate the response to thinner beds. All of the nuclear logs in this study, including the natural gamma, gamma-gamma, and neutron logs, were made with a logging speed of 10 ft per minute. The gamma-gamma data used in the analyses were obtained with the radium source. Radium-226, having a half life of 1602 years, is considered relatively stable.

Calibration pit curves

38. The next step was to plot the calibration data obtained with the 5-in. spacer into graphs showing nuclear radiation count rates related to the pit bulk densities and porosity indexes. The gamma-gamma counts were plotted arithmetically versus the bulk densities with a separate plot for each hole diameter (4, 6, and 8 in.). Straight-line curves were fitted to the points for each hole size, favoring the quartz sand points from Birdwell pits 3, 4, and 5 (since silica is believed to be the basic material in the borings investigated). These curves are presented in Figure 1. The neutron counts were plotted semilogarithmically with the porosity index values on the linear scale and the radiation counts on the log scale. As with the gamma-gamma data, the neutron plots were made for each hole size, and curves were drawn through these points. These curves are presented in Figure 2. The top point on the curve is from the open water pit (No. 13) and is assumed to have a porosity index of 100 percent.

39. The problem remained as to how raw radiation counts from different field logs could be applied systematically to these calibration data curves in order to determine the field properties.

Procedure for reducing raw field counts

40. Raw nuclear radiation counts from field logs in most cases include extraneous elements that have to be corrected before direct comparisons between the field and calibration data curves can be made. These elements include changes in borehole diameter or washouts, variations in mud weights, differences in soil composition, positioning of the logging tool in the borehole, casing effects, and variations in the functioning of the logging equipment.

41. The ideal solution would be to remove all of these variables from the raw radiation count rates and be able to apply the resulting corrected field counts directly to the calibration curves for determining the field bulk density and water content values. This approach was attempted in this study.

42. Some of the corrections are assumptions based, in part, on previous experiences. The logging tool was assumed to be positioned against the sidewall in all borings during logging operations. The material composition was assumed to consist primarily of silica or quartz in all borings.

43. The other variables have been corrected by calculations using the known calibration data as a basis, including borehole washout effects, mud weights, casing effects, and tool count fluctuations.

44. The functioning of the nuclear logging tools was determined from count rates recorded in the secondary standards before and after logging a boring and compared with those counts taken at the time of calibration in the pits. In some cases, these differences were extreme, with counts at some borings being higher and at others lower than those taken at the pits. Because of the relatively short time interval within which all logging operations were conducted, source decay was not considered as a problem. The most logical reason for the count fluctuations appeared to be related to the tool construction. The detector crystals in both the neutron and gamma-gamma tools are not mechanically fixed in a given position. During movement and handling the crystals could change position within the housing, creating slightly longer or

shorter spacing between the source and detector. This repositioning would easily account for the variations in the tool count rates.

45. To correct this tool count fluctuation, a percentage correction factor was determined by relating the secondary standard data from each site to the standard reading at the time of calibration. The raw field log radiation counts were then multiplied by this correction factor. These count rate correction procedures were applied to both the gamma-gamma and neutron logs.

Gamma-gamma log correction procedures

46. The process of reducing raw field gamma-gamma counts to a value that could be applied to the calibration curves can be related to the formula:

$$G_c = \left[G_r - G_n\right] \times T_c \times M_c \ (\pm)\ H_c \times C_c$$

where: $G_c$ = corrected gamma-gamma counts

$G_r$ = raw gamma-gamma counts

$G_n$ = natural gamma counts

$T_c$ = tool count correction factor

$M_c$ = mud weight correction factor

$H_c$ = hole diameter correction

$C_c$ = casing correction factor.

47. Initially, the depths in the borings were listed at which laboratory sample data were available. The actual sampled interval ranged from several inches to a couple of feet. In many instances, the borehole diameter and radiation count rates varied in the longer sampled intervals. Therefore, the first step in reducing the raw field counts was to obtain the average count rates in the sampled interval from the natural gamma and gamma-gamma logs and the average boring diameter from the caliper logs. The second step was to subtract the natural gamma counts from the gamma-gamma counts. The third step was to correct the tool count fluctuation based on the secondary standard data (previously discussed in paragraph 45). The resulting gamma-gamma counts

represented radiation values that would be expected from the tool recording at the same count rate as when the calibration data were obtained.

48. The fourth step was to remove the count variations caused by drilling mud which occupied each boring. In effect, the counts were converted to values that represented what would be expected if the holes were filled with pure water instead of a mud solution. To arrive at a relationship as to how the tool would read in mud of varying weights, the calibration data from the air-filled holes were assumed to represent data in "fluid" that weighed 0 $lb/ft^3$ and in the water-filled holes, fluid weighing 62.4 $lb/ft^3$. These values were considered to be two points on a straight-line curve from which radiation counts for increasing fluid weights could be calculated by the formula:

$$y = mx + b$$

where: $y$ = fluid weight
$x$ = count rate
$m$ = line slope
$b$ = line intercept

Since material composition also influences the count rates, the values in Birdwell pit No. 5 (wet quartz sand), which best suited the field materials, were used to calculate the varying mud weight values.

49. These calculated radiation count values for increasing mud weights were then converted to fractional correction factors, with water representing 1.0. Correction factors for the 4-, 6-, and 8-in. borings were calculated in this manner. They were:

Birdwell Pit No. 5 - Wet Sand

| Hole Fluid Weights lb/ft$^3$ | 4-in. hole: Gamma-Gamma Radiation Counts CPS | 4-in. hole: Correction Factor | 6-in. hole: CPS | 6-in. hole: Correction Factor | 8-in. hole: CPS | 8-in. hole: Correction Factor |
|---|---|---|---|---|---|---|
| 0 (air) | *6375 | 0.37 | *9200 | 0.33 | *10,975 | 0.32 |
| 62.4 (water) | *2335 | 1.00 | *3060 | 1.00 | * 3,540 | 1.00 |
| 70 (mud) | 1843 | 1.26 | 2312 | 1.32 | 2,634 | 1.34 |
| 75 (mud) | 1519 | 1.54 | 1820 | 1.68 | 2,039 | 1.74 |
| 80 (mud) | 1196 | 1.95 | 1328 | 2.30 | 1,443 | 2.45 |
| 85 (mud) | 872 | 2.68 | 836 | 3.66 | 847 | 4.18 |

* Measurements made in pits.

50. Linear plots were made relating mud weight correction factors to borehole diameters, and separate curves were drawn for each mud weight. Intermediate correction factors were interpolated between or beyond the calculated values where necessary. These mud weight correction curves are presented in Figure 3.

51. Unfortunately, mud weight measurements were obtained in only one field boring, U-5 in loess. A measurement of 82 lb/ft$^3$ was obtained at 50.0 ft and 84 lb/ft$^3$ at 125 ft. As verified by these measurements, the mud weights generally increase with depth in a given boring due to the settlement of cuttings. This increase in mud weight with depth can be related semilogarithmically where mud weights increase as the logarithmic function of increasing depth.

52. Rather than guess at a mud weight in borings other than U-5, the top and bottom samples for which laboratory bulk densities were available were used to calibrate the gamma-gamma count to a reasonable mud weight at these two points. The points were then plotted semilogarithmically with mud weights on the linear scale and depths on the log scale and a straight line was drawn connecting the two points.

53. Mud weights for all sample points in between the top and bottom points were then chosen from these curves. The mud weight values were used to determine the mud correction factor for the proper hole diameter as shown on the curves in Figure 3.

54. The gamma-gamma counts, having been previously corrected for tool fluctuations, were then multiplied by the corresponding mud correction factor. The gamma-gamma counts now represented values that would be expected from the tool if the borings had been filled with water.

55. The fifth step in reducing the gamma-gamma data was to correct the counts for variations in hole sizes. The data obtained in both the Schlumberger and Birdwell calibration pits revealed that the gamma-gamma tool registered an increasing count rate with increasing hole size at a predictable rate within a few CPS± regardless of the pit materials.

56. The radiation counts in the 4-in.-diameter borings were adjusted to 0. At the same level of adjustment, the 6-, 8-, 10-, and 16-in. borings (10- and 16-in. boring data from the Schlumberger pits) revealed radiation counts of 700, 1280, 1775, and 2325 counts, respectively. These values were plotted on a linear scale, and a calibration curve was constructed relating count rates to hole sizes as shown in Figure 4. This curve was used to adjust the field counts in washed out or closed in portions of the boring to a common hole diameter (the diameter originally drilled) by either adding or subtracting the appropriate number of CPS.

57. The sixth and final step was to adjust the field radiation counts from uncased to cased boring conditions. The following relationships were determined from casing tests run in a water tank at WES.

| | Open Water | 4-in. Casing | 6-in. Casing | 8-in. Casing |
|---|---|---|---|---|
| CPS | 11,600 | 7950 | 8200 | 8500 |
| Correction Factor | | 0.69 | 0.71 | 0.73 |

58. The correction factor was determined by dividing the counts in casing by the counts in open water. The raw field radiation counts, having been adjusted for variables in steps 1 through 5, were then multiplied by the appropriate diameter casing correction factor. The count rate in the 6-in. boring was multiplied by 0.71 and in the 8-in. borings by 0.73.

59. All variables having been corrected, the field gamma-gamma radiation counts were applied to the Birdwell calibration data curves in Figure 1 for determination of the bulk density for each sample point.

Neutron log correction procedure

60. To reduce the raw field neutron radiation counts into a form that could be applied to the calibration curves required similar but less processing than the gamma-gamma reduction. The method of reducing the data can be related to the formula:

$$N_c = \left[N_r \times T_c\right] (\pm)\ H_c \times C_c$$

where: $N_c$ = corrected neutron counts

$N_r$ = raw neutron counts

$T_c$ = tool correction factor

$H_c$ = hole diameter correction

$C_c$ = casing correction factor.

61. The effects of varying mud weights on the neutron count rate, if any occurred, were not determined in the scope of this study. The neutron counts are actually related to the hydrogen content within the borehole fluids as well as the surrounding formation. Any addition of mud materials to the drilling fluids would possibly reduce the amount of hydrogen by reducing the amount of water in the sampled sphere (neutron measurements described in paragraph 14). However, it is believed that the medium weight fluids in which the logs were made had very little effect on the total hydrogen content and thus the neutron counts as measured. It is suggested, however, that any future studies concerning engineering property evaluations include careful measurements in

controlled mud environments. Such studies will determine if indeed there is any appreciable changes in count rates in different mud weights.

62. In reducing the raw neutron data, the first step was to obtain the average raw neutron counts at the selected sample depths from the neutron log along with the average borehole diameter at the same depth from the caliper log. In the second step, the average raw neutron counts were corrected for tool count fluctuations based on secondary standard field data (described in paragraph 45).

63. Data obtained in the calibration pits revealed that changes in borehole diameters have definite effects on the total neutron counts; however, relationships between total counts and borehole sizes are highly influenced by the properties of materials penetrated. The neutron counts from one hole size to another in each pit varied from pit to pit.

64. Since the quartz sand material in Birdwell pit No. 5 was similar to the materials in the field borings, the neutron data in this pit were used to construct a curve for correcting counts caused by changing borehole diameters. The curve relates decreasing neutron counts to increasing hole sizes as shown in Figure 5. The neutron counts in the 8-in. hole were adjusted to 0. The corresponding counts in the 6- and 4-in. holes were 155 and 310 counts, respectively. In the third step, using the information obtained from the caliper log, the field neutron counts (having been corrected for tool fluctuation) were adjusted to represent counts in a standard hole diameter (bit diameter in each hole drilled) by either adding or subtracting the necessary counts obtained from the hole diameter correction curve.

65. The fourth and final step in correcting the field neutron counts to a value that could be correlated to the calibration curves was to adjust the counts from an uncased boring condition to a cased condition. This adjustment was accomplished by multiplying the counts by a casing correction factor. Casing effects were determined from tests run in a water tank at WES (the same as for gamma-gamma). The results of the tests are:

| | Open Water | 4-in. Casing | 6-in. Casing | 8-in. Casing |
|---|---|---|---|---|
| CPS | 980 | 890 | 910 | 910 |
| Correction Factor | | 0.91 | 0.93 | 0.93 |

66. The correction factors for casing effects were determined by dividing the counts in casing by the counts in open water.

67. All variables having been corrected, the resulting neutron counts were applied to the Birdwell calibration curves in Figure 2, and the porosity index was determined for each sample point.

68. Given the bulk density determined from the gamma-gamma log and the porosity index from the neutron log, the water content was determined by using the following relationship:

$$w_c = \frac{PI}{\frac{\sigma_B}{\sigma_w} - PI}$$

where: $w_c$ = water content, percent
PI = porosity index, percent
$\sigma_B$ = wet bulk density, $gm/cm^3$
$\sigma_w$ = weight of water = 1.0 $gm/cm^3$.

## PART V: RESULTS OF ANALYSIS

### Boring U-5

69. Boring U-5 was an 8-in.-diameter sample boring drilled to a depth of 145 ft at the site of the new soils laboratory building at WES. The caliper log indicated a slightly rough hole with only two major washouts, one to about 10 in. at 39 ft and one out to 13-1/2 in. at 20 ft. The boring encountered loess to a depth of 43 ft; terrace, clay silt, and sand with occasional small gravels from 43 to 52 ft; tertiary deposits identified as Catahoula interbedded clays, silts, and sand from 52 to 114 ft; Buccatuna clay from 114 to 116 ft; Byram marl from 116 to 133 ft; and Glendon limestone and marl from 133 to 145 ft. Data from laboratory analysis of samples were for the upper 55 ft only. The drilling mud was at a depth of 20 ft; therefore, only the sample points below 20 ft were analyzed. These included five laboratory data points ranging in depth from 25 to 55 ft that were available for comparison with the geophysical data. The bulk densities and water contents at these five depths, determined from both laboratory and geophysical methods along with a summary of procedures used to reduce the geophysical logs, are shown in Table 3. Figure 6 presents natural gamma, gamma-gamma, and caliper logs, and a plot of gamma-gamma points that have been corrected for extraneous variables. A plot of field bulk densities (developed from gamma-gamma log data) versus laboratory bulk densities is shown in Figure 7.

70. The laboratory and field bulk densities were identical for the bottom three samples. The top two samples varied by only 0.01 and 0.02 g/cm$^3$. As mentioned previously in paragraph 51, U-5 was the only boring for which the mud weight correction factors were determined from actual inhole measurements. The field values in this boring should have greater significance than those in the other borings for which mud correction factors were determined through calibration of radiation counts with laboratory values.

71. The large increase in corrected gamma-gamma radiation counts from raw counts was caused by the tool count fluctuation correction factor and the heavy mud correction factor. Gamma-gamma counts in the secondary standard indicated that the tool was recording 47 percent lower in boring U-5 than the count rate recorded at the time of calibration.

72. Figure 8 presents caliper and neutron logs and a plot of neutron radiation count points that have been corrected for extraneous field variables in boring U-5. A plot of field water contents as compared to laboratory water contents is shown in Figure 9. The field water contents averaged 4.42 percent lower than the laboratory values and showed changes about parallel to the laboratory values with depth.

73. The corrected neutron radiation points are about one-half the value of the raw neutron log values, primarily because of the tool count fluctuation correction. Neutron counts in the secondary standard indicated that the tool was recording 45 percent higher counts in boring U-5 than the count rate recorded at the time of calibration.

## Boring J-14-75U

74. Boring J-14-75U was a 6-in.-diameter sample boring drilled to a depth of 87 ft. The boring was positioned on a levee in the Mississippi River alluvial valley about two miles south of Jonesville, Louisiana. The materials penetrated consisted of 8 ft of lean clay and silt (levee construction materials) overlying fat and lean clays to a depth of about 70 ft which was in turn underlain by silty sand and sand extending to the bottom depth. The caliper log indicated a rough hole down to 40 ft, washed out to as much as 11 in. in one place, and a less rough and fairly consistent 6-in.-diameter hole from 40 to 73 ft. From 73 to 86 ft, the boring was washed out to about 9-1/2 in. Data from laboratory samples were available on 5-ft intervals from 10 to 70 ft with one exception. There was no sample data at 40 ft. Bulk density and water content data were determined from the geophysical logs at the corresponding laboratory sample depths. The geophysical and

laboratory property data along with a summary of procedures in reducing the geophysical logs are given in Table 3.

75. Raw natural gamma, gamma-gamma, and caliper logs and a plot of gamma-gamma points that have been corrected for extraneous variables in boring J-14-75U are shown in Figure 10. A plot of field bulk densities as compared to laboratory bulk densities is shown in Figure 11. The field bulk densities for the five bottom sample points from 50 to 70 ft either match or fall within 0.01 $gm/cm^3$ of the laboratory values. The field bulk densities from 30 to 45 ft parallel the laboratory values but range from 0.07 $gm/cm^3$ to 0.10 $gm/cm^3$ less than the laboratory values. The field density values were higher than lab values from 10 to 25 ft, ranging from 0.08 $gm/cm^3$ higher at 25 ft to in excess of 0.70 $gm/cm^3$ above the laboratory values at 20 ft. Washouts in a boring generally cause the gamma-gamma counts to increase accordingly as shown at the 74-ft depth in Figure 10. The gamma-gamma radiation counts show a reversal of the normal trend in the large washout at the 20-ft sample depth where gamma-gamma counts decrease with increasing hole size. Also, in this same interval, the neutron log shows a reversal of its normal trend which is decreasing counts with increasing hole size. This anomaly has been left unexplained.

76. The large increase in corrected gamma-gamma counts over the raw gamma-gamma counts was caused by the tool count fluctuation factor and the mud weight correction factor.

77. Figure 12 presents the raw neutron and caliper logs of boring J-14-75U along with a plot of neutron points that have been corrected for extraneous variables. A plot of field water contents as compared to the laboratory water contents is shown in Figure 13.

78. The field water contents from 25 to 70 ft run 2.8 percent to 9.5 percent higher than and about parallel to the laboratory values. No field value was obtained for the 20-ft sample. The field water contents for samples at 10 and 15 ft are 3.1 percent and 10.1 percent less than the laboratory values.

## Boring U-1

79. Boring U-1 at White Sands Missile Range, New Mexico, penetrated 300 ft of desert alluvium consisting of stratified clays, silts, sands, and gravels. The original drilled diameter was 8 in. The caliper log revealed a rough and irregular hole throughout, closed in to almost 2 in. in two places, one at 118 and one at 278 ft, and enlargements ranging out to an extreme greater than 18 in. at about 25 ft.

80. Bulk densities and water contents were available from 30 laboratory samples taken at depths ranging from 8 to 287 ft. The sample depths regulated the selection of depths at which bulk densities and water contents were obtained from the geophysical logs. The engineering properties determined from laboratory and geophysical methods along with a summary of reduction procedures applied to the geophysical logs have been tabulated in Table 3.

81. Raw natural gamma, gamma-gamma, and caliper logs from boring U-1 as well as a plot of gamma-gamma points that have been corrected for extraneous field variables are shown in Figure 14. Comparisons between the geophysical and laboratory derived bulk densities with depth along with a plot of percent differences in the two types of values with depth are shown in Figure 15.

82. As can be seen in Figure 15, the bulk densities derived from the geophysical logs generally peak in the same direction as the lab values, and in some cases, the two values are close or the same. In most instances, the field values are higher than the lab values. The maximum difference is recorded at two sample points, 141 and 192 ft, where field values are about 10.7 percent higher than lab values. In a few instances, field values are less than the lab values with the maximum difference being about 4-1/2 percent less. Totaling all of the field values, the average field bulk density is 2.8 percent higher than the laboratory densities.

83. Figure 16 shows raw neutron and caliper logs from boring U-1 and a plot of corrected neutron counts at the sample depths. Comparison of the field and laboratory derived water contents with depth

along with differences between the two types of values are shown in Figure 17.

84. The field water contents show less variation from point to point than do those from the laboratory test, but peaks generally trend in the same direction. The field water contents at depths greater than 200 ft average 27.9 percent or about 5 percent higher than the laboratory values, and for all practical purposes, are parallel to the lab values. At depths less than 200 ft, the field values cross back and forth from extremes of 18.7 percent higher than lab values at 45 ft to 12.8 percent lower than lab values at 14 ft. The average water content in the upper 200 ft of hole is 29.2 percent for the laboratory samples and 30.0 percent for the geophysical in situ values. The average field water content for the entire hole is 2.03 percent higher than the average for the lab values.

## PART VI: SUMMARY AND CONCLUSIONS

85. This study revealed that the gamma-gamma and neutron tools described in this report are capable of producing repeatable raw data, applicable to determining in situ bulk densities and water contents in different unconsolidated materials.

86. In order for the raw radiation data to have quantitative meaning, the logging tools must be calibrated in established environments (calibration pits) where property values are known. Also, the raw radiation data have to be corrected for a number of variables such as changes in borehole diameter or washouts, different drilling mud weights, casing, and variations in the functioning of the logging equipment. Once the effects of these extraneous variables have been reduced or removed, the corrected radiation data are applied to curves constructed from information obtained in the calibration pits for determining bulk densities and water contents.

87. Under this study, the in situ (field) bulk densities and water contents were derived from the geophysical logs at a total of 46 sample points or depths in three borings. These field properties were compared to bulk densities and water contents obtained in the laboratory from samples taken at depths that corresponded to the field sample points. The comparison revealed that field bulk densities had extremes ranging from about 5 percent lower to 11 percent higher than laboratory values and an average for all points of about 1 percent higher than the average for laboratory samples. The field water contents had extremes ranging from about 12 percent less to 18 percent higher than laboratory values and an average for all sample points of about 6 percent higher than the laboratory average.

88. Future studies should concentrate on smaller diameter borings, say 4 in. or less, in order to reduce borehole effects. A study should be conducted to determine the effects on the radiation counts caused by various mud weights in different hole sizes. Borings logged in future studies should include taking a mud sample for weighing at least every 25 ft and even closer spaced if warranted.

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Table 1

Nuclear Tools Calibration Data, Birdwell Test Pits,

| Pit No. | Lithology | Bulk Density Wet gm/cc | Porosity Index % | Spacer Insert Length in. | Neutron CPS* (Americium-241 Beryllium Source) Hole Diameters: 4 in. Water Filled | 4 in. Dry | 6 in. Water Filled | 6 in. Dry | 8 in. Water Filled | 8 in. Dry | Open Water | Gamma-Gamma ( Hole Dia: 4 in. Water Filled | 4 in. Dry | 6 in. Water Filled |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unconsolidated Materials** | | | | | | | | | | | | | |
| 1 | Wet dolomite | 2.08 | 29.0 | None | 6210 | Not run | 6000 | Not run | 5675 | Not run | | | | |
| 2 | Dry dolomite | 1.82 | 0.0 | | 7020 | | 6800 | | 6540 | | | | | |
| 3 | Dry sand | 1.80 | 0.0 | | 6800 | | 6500 | | 6200 | | | | | |
| 4 | Chatt-sand | 2.17 | 20.0 | | 6210 | | 5935 | | 5710 | | | | | |
| 5 | Wet sand | 2.11 | 26.0 | | 5900 | | 5800 | | 5575 | | | | | |
| 11 | Crushed limestone | 2.35 | 22.0 | | 6100 | | 5815 | | 5625 | | | | | |
| 13 | Water | 1.00 | 100.0 | | | | | | | | 4000 | | | |
| 1 | Wet dolomite | 2.08 | 29.0 | 2 | 3725 | Not run | 3400 | Not run | 3175 | Not run | | | | |
| 2 | Dry dolomite | 1.82 | 0.0 | | 6110 | | 5550 | | 5050 | | | | | |
| 3 | Dry sand | 1.80 | 0.0 | | 5780 | | 5210 | | 4675 | | | | | |
| 4 | Chatt-sand | 2.17 | 20.0 | | 4020 | | 3700 | | 3440 | | | | | |
| 5 | Wet sand | 2.11 | 26.0 | | 3585 | | 3410 | | 3165 | | | | | |
| 11 | Crushed limestone | 2.35 | 22.0 | | 3850 | | 3525 | | 3330 | | | | | |
| 13 | Water | 1.00 | 100.0 | | | | | | | | 1620 | | | |
| 1 | Wet dolomite | 2.08 | 29.0 | 5 | 1420 | 4500 | 1225 | 4750 | 1075 | 4550 | | 2200 | 6,125 | 2880 |
| 2 | Dry dolomite | 1.82 | 0.0 | | 4310 | 5090 | 3640 | 4940 | 3100 | 4600 | | 2500 | 6,580 | 3225 |
| 3 | Dry sand | 1.80 | 0.0 | | 4190 | 3700 | 3615 | 3680 | 3125 | 3400 | | 2885 | 7,075 | 3500 |
| 4 | Chatt-sand | 2.17 | 20.0 | | 1820 | 4300 | 1510 | 4400 | 1415 | 4150 | | 2130 | 6,200 | 2825 |
| 5 | Wet sand | 2.11 | 26.0 | | 1475 | 4050 | 1320 | 4300 | 1165 | 4160 | | 2335 | 6,375 | 3060 |
| 11 | Crushed limestone | 2.35 | 22.0 | | 1640 | 4190 | 1350 | 4340 | 1300 | 4200 | | 1920 | 5,600 | 2650 |
| 13 | Water | 1.00 | 100.0 | | | | | | | | 425 | | | |
| 1 | Wet dolomite | 2.08 | 29.0 | 10 | 303 | 1970 | 250 | 2550 | 220 | 2840 | | | | |
| 2 | Dry dolomite | 1.82 | 0.0 | | 2355 | 3750 | 1915 | 3775 | 1505 | 3660 | | | | |
| 3 | Dry sand | 1.80 | 0.0 | | 2600 | 2825 | 2030 | 2935 | 1645 | 2765 | | | | |
| 4 | Chatt-sand | 2.17 | 20.0 | | 465 | 2000 | 370 | 2400 | 378 | 2575 | | | | |
| 5 | Wet sand | 2.11 | 26.0 | | 330 | 1760 | 305 | 2260 | 255 | 2625 | | | | |
| 11 | Crushed limestone | 2.35 | 22.0 | | 400 | 1900 | 325 | 2350 | 280 | 2590 | | | | |
| 13 | Water | 1.00 | 100.0 | | | | | | | | 60 | | | |
| | | | | | 7-7/8 in. Water Filled | 7-7/8 in. Dry | | | | | | 7-7/8 in. Water Filled | 7-7/8 in. Dry | |
| | Rock Materials Stacked Blocks | | | | | | | | | | | | | |
| 7 | Indiana limestone | 2.46 | 9.5 | None | 6200 | -- | | | | | | -- | -- | |
| 8 | Bera sandstone | 2.28 | 17.0 | None | 6000 | -- | | | | | | -- | -- | |
| 9 | Carthage marble | 2.64 | 2.4 | None | 6410 | -- | | | | | | -- | -- | |
| 7 | Indiana limestone | 2.46 | 9.5 | 2 | 4130 | -- | | | | | | -- | -- | |
| 8 | Bera sandstone | 2.28 | 17.0 | 2 | 3310 | -- | | | | | | -- | -- | |
| 9 | Carthage marble | 2.64 | 2.4 | 2 | 4570 | -- | | | | | | -- | -- | |
| 7 | Indiana limestone | 2.46 | 9.5 | 5 | 1910 | 5000 | | | | | | 3725 | 13,300 | |
| 8 | Bera sandstone | 2.28 | 17.0 | 5 | 1615 | 4975 | | | | | | 4125 | 14,700 | |
| 9 | Carthage marble | 2.64 | 2.4 | 5 | 2305 | 4620 | | | | | | 3600 | 12,960 | |
| 7 | Indiana limestone | 2.46 | 9.5 | 10 | 525 | 3500 | | | | | | | | |
| 8 | Bera sandstone | 2.28 | 17.0 | 10 | 410 | 3380 | | | | | | Not run | | |
| 9 | Carthage marble | 2.64 | 2.4 | 10 | 825 | 3370 | | | | | | | | |

Note: Secondary Standard:

| Neutron, CPS | Gamma-Gamma |
|---|---|
| (13-gal Water Bottle) | (Aluminum Block) |
| 5-in. spacer, 425 | Radium source: |
| 10-in. spacer, 43 | 5-in. spacer, 575 |
| | Cobalt source: |
| | 5-in. spacer, 1515 |
| | 10-in. spacer, 7800 |

* CPS = counts per second.

** Unconsolidated materials holes were lined with 0.075-in.-thick steel casing. Rock holes had no casing.

Table 1

ibration Data, Birdwell Test Pits, Tulsa, Okla., 15 Apr 1975

| | Gamma-Gamma CPS (Radius-226 Source) | | | | | | | Gamma-Gamma CPS (Cobalt-60 Source) | | | | | | | Natural Gamma CPS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hole Diameters | | | | | | | Hole Diameters | | | | | | | Hole Diameters | | |
| pen Water | 4 in. Water Filled | 4 in. Dry | 6 in. Water Filled | 6 in. Dry | 8 in. Water Filled | 8 in. Dry | Open Water | 4 in. Water Filled | 4 in. Dry | 6 in. Water Filled | 6 in. Dry | 8 in. Water Filled | 8 in. Dry | Open Water | 4 in. Water Filled | 6 in. Water Filled | 8 in. Water Filled |
| | | | | Not run | | | | | | | Not run | | | | 8 | 4 | 3 |
| | | | | | | | | | | | | | | | 3 | 3 | 3 |
| | | | | | | | | | | | | | | | 25 | 23 | 20 |
| | | | | | | | | | | | | | | | 16 | 14 | 13 |
| | | | | | | | | | | | | | | | 23 | 21 | 20 |
| | | | | | | | | | | | | | | | 13 | 12 | 12 |
| 4000 | | | | | | | | | | | | | | | | | |
| | | | | Not run | | | | | | | Not run | | | | | | |
| 1620 | | | | | | | | | | | | | | | | | |
| | 2200 | 6,125 | 2880 | 8,860 | 3490 | 10,475 | | 5900 | 14,200 | 7320 | 19,800 | 8600 | 21,500 | | | | |
| | 2500 | 6,580 | 3225 | 9,190 | 3775 | 11,350 | | 6700 | 15,700 | 8015 | 20,200 | 8950 | 23,000 | | | | |
| | 2885 | 7,075 | 3500 | 9,775 | 3960 | 11,560 | | 6900 | 16,950 | 8700 | 21,000 | 9750 | 23,200 | | | | |
| | 2130 | 6,200 | 2825 | 8,800 | 3425 | 10,700 | | 5375 | 15,200 | 7065 | 19,800 | 8500 | 22,200 | | | | |
| | 2335 | 6,375 | 3060 | 9,200 | 3540 | 10,975 | | 6150 | 15,400 | 7650 | 20,050 | 8600 | 22,800 | | | | |
| | 1920 | 5,600 | 2650 | 8,500 | 3220 | 10,400 | | 4600 | 12,400 | 7100 | 18,800 | 7400 | 21,500 | | | | |
| 425 | | | | | | | 9,030 | | | | | | | 19,200 | | | |
| | | | | Not run | | | | 1175 | 4,650 | 1750 | 7,800 | 2100 | 11,800 | | | | |
| | | | | | | | | 1675 | 6,230 | 2185 | 9,620 | 2765 | 12,400 | | | | |
| | | | | | | | | 1770 | 6,640 | 2225 | 9,950 | 2875 | 12,800 | | | | |
| | | | | | | | | 1185 | 5,800 | 1875 | 9,400 | 2515 | 11,875 | | | | |
| | | | | | | | | 1425 | 6,000 | 2035 | 9,390 | 2525 | 12,180 | | | | |
| | | | | | | | | 1050 | 5,175 | 1670 | 7,550 | 2180 | 11,950 | | | | |
| 60 | | | | | | | | | | | | | | 7,800 | | | |

| 7-7/8 in. Water Filled | 7-7/8 in. Dry | 7-7/8 in. Water Filled | 7-7/8 in. Dry |
|---|---|---|---|
| -- | -- | -- | -- |
| -- | -- | -- | -- |
| -- | -- | -- | -- |
| -- | -- | -- | -- |
| -- | -- | -- | -- |
| -- | -- | -- | -- |
| 3725 | 13,300 | 8860 | 25,675 |
| 4125 | 14,700 | 9150 | 28,500 |
| 3600 | 12,960 | 8100 | 25,100 |
| Not run | | 2580 | 14,080 |
| | | 2780 | 16,075 |
| | | 2575 | 14,150 |

Table 2

Casing (0.078-In.-Thick Steel) Effects on Nuclear Radiation Counts

with 5-In.-Spacer Insert, Oct 1975

| Materials Inside Casing | Materials Outside Casing | Gamma-Gamma CPS* Radium-226 Source Hole Diameters 4 in. | 6 in. | 8 in. | Gamma-Gamma CPS* Cobalt-60 Source Hole Diameters 4 in. | 6 in. | 8 in. | Neutron CPS Americium-241 Beryllium Source Hole Diameters 4 in. | 6 in. | 8 in. |
|---|---|---|---|---|---|---|---|---|---|---|
| Water | Water | 7,950 | 8,200 | 8,500 | | | | 890 | 910 | 910 |
| Water | | | | | 16,600 | 17,000 | 17,300 | | | |
| Air | ↓ | 13,000 | 16,000 | 18,000 | | | | 3850 | 5300 | 5900 |
| | | | | | 24,000 | 26,650 | 28,100 | | | |
| ↓ | Air | 5,300 | 6,300 | 6,925 | | | | -- | -- | -- |
| | | | | | 8,400 | 10,000 | 10,800 | | | |
| Water | ↓ | 3,920 | 4,850 | 5,100 | | | | 290 | 410 | 435 |
| Water | | | | | 6,725 | 8,100 | 8,625 | | | |

| Open Water-CPS Gamma-Gamma Radium | Open Water-CPS Gamma-Gamma Cobalt | Open Water-CPS Neutron | Open Air-CPS Gamma-Gamma Radium | Open Air-CPS Gamma-Gamma Cobalt | Open Air-CPS Neutron | Secondary Standards, CPS Aluminum Block Gamma-Gamma Radium | Secondary Standards, CPS Aluminum Block Gamma-Gamma Cobalt | Secondary Standards, CPS 13 gal Water Bottle Neutron |
|---|---|---|---|---|---|---|---|---|
| 11,600 | 22,800 | 980 | 7,700 | 10,800 | 185 | 820 | 2,200 | 835 |

* CPS = counts per second.

Table 3

Summary of Procedures Used to Reduce Raw Geophysical Data, and Comparisons of Geophysical and Laboratory Derived Engineering Property Values

| | | | Gamma-Gamma Data | | | | | | | | | Neutron Data | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Sample Depth ft | Boring Diameter Caliper Log in. | Raw Gamma-Gamma CPS | Natural Gamma CPS | Tool Correction Factor | Mud Correction Factor | Hole Diameter Correction CPS | Casing Correction Factor | Corrected Gamma-Gamma CPS | Geophysical (Field) Bulk Density (Wet) gm/cm$^3$ | Laboratory Bulk Density (Wet) g/cm$^3$ | Raw Neutron CPS | Tool Correction Factor | Hole Diameter Correction CPS | Casing Correction Factor | Corrected Neutron CPS | Porosity Index % | Geophysical (Field) Water Content % | Laboratory Water Content % |
| **Boring U-5** | | | | | | | | | | | | | | | | | | | |
| 14 | 25.3 | 8.0 | 1200 | 17 | 1.53 | 2.79 | 0 | 0.73 | 3694 | 1.99 | 1.97 | 1550 | 0.55 | 0 | 0.93 | 793 | 38.6 | 24.1 | 29.4 |
| 16 | 30.2 | 7.6 | 1150 | 17 | ↓ | 2.83 | +100 | ↓ | 3653 | 2.02 | 2.01 | 1575 | ↓ | -30 | ↓ | 777 | 39.8 | 24.5 | 29.6 |
| 19 | 43.2 | 7.6 | 1100 | 15 | ↓ | 2.97 | +100 | ↓ | 3672 | 2.00 | 2.00 | 1600 | ↓ | -30 | ↓ | 790 | 38.7 | 24.0 | 26.5 |
| 22 | 48.5 | 8.0 | 1100 | 16 | ↓ | 3.05 | 0 | ↓ | 3691 | 1.99 | 1.99 | 1475 | ↓ | 0 | ↓ | 754 | 40.3 | 25.2 | 30.1 |
| 27 | 55.7 | 7.2 | 1050 | 15 | ↓ | 3.04 | +220 | ↓ | 3676 | 2.00 | 2.00 | 1510 | ↓ | -60 | ↓ | 717 | 42.0 | 26.6 | 30.9 |
| **Boring J-14-75U** | | | | | | | | | | | | | | | | | | | |
| 2A | 10.5 | 8.3 | 2520 | 43 | 1.43 | 1.49 | -660 | 0.71 | 3215 | 1.98 | 1.88 | 720 | 1.024 | +180 | 0.93 | 853 | 40.3 | 25.5 | 28.6 |
| 3A | 15.5 | 7.1 | 2105 | 40 | ↓ | 1.49 | -340 | ↓ | 2827 | 2.21 | 1.83 | 705 | ↓ | +85 | ↓ | 750 | 44.5 | 25.2 | 35.3 |
| 5A | 25.5 | 7.1 | 2187 | 37 | ↓ | 1.52 | -340 | ↓ | 3214 | 1.98 | 1.90 | 680 | ↓ | +85 | ↓ | 726 | 45.5 | 29.9 | 27.[illegible] |
| 6A | 30.5 | 7.6 | 2475 | 41 | ↓ | ↓ | -480 | ↓ | 3445 | 1.84 | 1.91 | 690 | ↓ | +125 | ↓ | 773 | 43.4 | 30.8 | 28.0 |
| 7A | 35.5 | 6.8 | 2525 | 44 | ↓ | ↓ | -310 | ↓ | 3640 | 1.73 | 1.83 | 615 | ↓ | +60 | ↓ | 641 | 49.4 | 39.9 | 33.8 |
| 9A | 45.5 | 6.7 | 2382 | 43 | ↓ | ↓ | -220 | ↓ | 3491 | 1.82 | 1.91 | 620 | ↓ | +55 | ↓ | 642 | 49.4 | 37.2 | 29.0 |
| 10A | 50.5 | 5.9 | 2335 | 52 | ↓ | ↓ | +30 | ↓ | 3562 | 1.78 | 1.77 | 620 | ↓ | -10 | ↓ | 581 | 52.8 | 42.1 | 35.0 |
| 11A | 55.5 | 5.9 | 2250 | 47 | ↓ | ↓ | +30 | ↓ | 3442 | 1.85 | 1.85 | 645 | ↓ | -10 | ↓ | 605 | 50.5 | 37.5 | 31.5 |
| 12A | 60.5 | 6.4 | 2235 | 47 | ↓ | 1.53 | -130 | ↓ | 3325 | 1.92 | 1.91 | 660 | ↓ | +30 | ↓ | 656 | 49.0 | 34.2 | 26.8 |
| 13A | 65.5 | 5.9 | 2117 | 48 | ↓ | 1.53 | +30 | ↓ | 3325 | 1.92 | 1.93 | 670 | ↓ | -10 | ↓ | 629 | 50.1 | 35.3 | 25.8 |
| 14A | 70.5 | 5.9 | 2015 | 36 | ↓ | 1.54 | +30 | ↓ | 3203 | 1.98 | 1.97 | 875 | ↓ | -10 | ↓ | 824 | 41.3 | 26.3 | 22.6 |
| **Boring U-1** | | | | | | | | | | | | | | | | | | | |
| 6.4 | 8.8 | 9.4 | 5225 | 50 | 1.06 | 1.10 | -370 | 0.73 | 3885 | 1.85 | 1.92 | 550 | None | +110 | 0.93 | 614 | 46.9 | 33.9 | 28.9 |
| 7.B.1 | 10.9 | 9.7 | 5150 | 50 | ↓ | 1.10 | -430 | ↓ | 3781 | 1.92 | 1.84 | 550 | ↓ | +135 | ↓ | 637 | 45.8 | 31.3 | 34.0 |
| 9.T.1 | 12.6 | 9.6 | 5180 | 50 | ↓ | 1.10 | -410 | ↓ | 3820 | 1.90 | 1.88 | 535 | ↓ | +125 | ↓ | 614 | 46.9 | 32.8 | 35.6 |
| 10.T | 13.9 | 9.6 | 5175 | 30 | ↓ | 1.15 | -410 | ↓ | 4020 | 1.77 | 1.74 | 540 | ↓ | +125 | ↓ | 618 | 46.7 | 35.8 | 48.7 |
| 23.3 | 37.4 | 8.3 | 4900 | 40 | ↓ | 1.15 | -80 | ↓ | 4021 | 1.77 | 1.78 | 530 | ↓ | +25 | ↓ | 516 | 52.4 | 42.1 | 36.5 |
| 27.4 | 45.4 | 8.3 | 3750 | 75 | ↓ | 1.34 | -80 | ↓ | 3536 | 2.10 | 2.06 | 590 | ↓ | +25 | ↓ | 572 | 49.2 | 30.6 | 11.7 |
| 31.T.1 | 50.2 | 8.2 | 3600 | 40 | ↓ | 1.36 | -60 | ↓ | 3490 | 2.13 | 2.13 | 640 | ↓ | +15 | ↓ | 609 | 47.1 | 28.4 | 17.2 |
| 35.1 | 58.1 | 7.5 | 3500 | 50 | ↓ | 1.40 | +140 | ↓ | 3628 | 2.04 | 1.91 | 640 | ↓ | -40 | ↓ | 558 | 49.9 | 32.4 | 29.2 |
| 38.B.1 | 62.4 | 8.2 | 3700 | 65 | ↓ | 1.42 | -60 | ↓ | 3724 | 1.97 | 1.82 | 600 | ↓ | +15 | ↓ | 572 | 49.2 | 33.3 | 44.1 |
| 43.1 | 69.0 | 8.2 | 3500 | 45 | ↓ | 1.44 | -60 | ↓ | 3588 | 2.06 | 2.05 | 690 | ↓ | +15 | ↓ | 656 | 44.9 | 27.9 | 20.8 |
| 45.B | 71.7 | 7.9 | 3350 | 45 | ↓ | 1.45 | +20 | ↓ | 3512 | 2.12 | 2.03 | 730 | ↓ | -10 | ↓ | 670 | 44.1 | 26.3 | 22.6 |
| 48.B.1 | 77.0 | 7.6 | 3500 | 45 | ↓ | 1.45 | +100 | ↓ | 3730 | 1.97 | 2.02 | 680 | ↓ | -30 | ↓ | 605 | 47.3 | 31.6 | 23.0 |
| 50.M.3 | 79.3 | 7.9 | 3600 | 45 | ↓ | 1.47 | +20 | ↓ | 3829 | 1.90 | 1.97 | 650 | ↓ | -10 | ↓ | 595 | 47.9 | 33.7 | 23.2 |
| 66.1 | 107.8 | 8.8 | 3500 | 90 | ↓ | 1.55 | -220 | ↓ | 3698 | 1.99 | 1.92 | 635 | ↓ | +65 | ↓ | 651 | 45.0 | 29.2 | 27.6 |
| 79.1 | 129.4 | 8.2 | 3100 | 90 | ↓ | 1.61 | -60 | ↓ | 3494 | 2.13 | 2.11 | 800 | ↓ | +15 | ↓ | 758 | 40.2 | 23.3 | 16.7 |
| 88.B.1 | 141.2 | 8.2 | 3200 | 120 | ↓ | 1.62 | -60 | ↓ | 3598 | 2.06 | 1.86 | 820 | ↓ | +15 | ↓ | 777 | 39.4 | 23.8 | 36.6 |
| 93.T.1A | 148.3 | 8.3 | 3050 | 50 | ↓ | 1.63 | -90 | ↓ | 3504 | 2.12 | 1.99 | 780 | ↓ | +25 | ↓ | 749 | 40.5 | 23.6 | 26.5 |
| 94.1 | 155.5 | 8.0 | 3050 | 100 | ↓ | 1.65 | 0 | ↓ | 3553 | 2.09 | 1.97 | 690 | ↓ | 0 | ↓ | 642 | 45.2 | 27.6 | 28.5 |
| 103.B.1 | 174.7 | 7.3 | 3100 | 100 | ↓ | 1.67 | +180 | ↓ | 3667 | 2.01 | 1.89 | 700 | ↓ | -52 | ↓ | 696 | 42.9 | 27.1 | 34.4 |
| 105.B.1 | 183.0 | 7.0 | 3000 | 50 | ↓ | 1.68 | +270 | ↓ | 3815 | 1.91 | 1.79 | 770 | ↓ | -78 | ↓ | 644 | 45.2 | 31.0 | 41.0 |
| 108.M.1 | 192.9 | 6.7 | 2750 | 100 | ↓ | 1.68 | +360 | ↓ | 3512 | 2.12 | 1.91 | 850 | ↓ | -102 | ↓ | 696 | 42.9 | 25.4 | 27.8 |
| 110.1 | 201.3 | 7.4 | 3100 | 110 | ↓ | 1.70 | +160 | ↓ | 3827 | 1.90 | 1.98 | 710 | ↓ | -48 | ↓ | 616 | 46.9 | 32.8 | 26.9 |
| 114.M.1 | 211.9 | 6.0 | 2600 | 50 | ↓ | 1.68 | +580 | ↓ | 3550 | 2.09 | 1.98 | 900 | ↓ | -155 | ↓ | 693 | 44.9 | 27.4 | 23.9 |
| 117.1 | 220.4 | 6.2 | 2500 | 50 | ↓ | 1.70 | +510 | ↓ | 3412 | 2.19 | 2.21 | 1000 | ↓ | -140 | ↓ | 800 | 38.3 | 21.2 | 18.0 |
| 122.T.1 | 233.1 | 5.5 | 2400 | 85 | ↓ | 1.68 | +840 | ↓ | 3452 | 2.14 | 2.04 | 860 | ↓ | -195 | ↓ | 618 | 46.7 | 27.9 | 21.1 |
| 125.1 | 249.5 | 6.0 | 2500 | 70 | ↓ | 1.74 | +580 | ↓ | 3509 | 2.12 | 2.02 | 900 | ↓ | -155 | ↓ | 693 | 44.9 | 26.9 | 24.8 |
| 131.T.1 | 258.2 | 5.8 | 2425 | 50 | ↓ | 1.75 | +640 | ↓ | 3501 | 2.12 | 2.09 | 840 | ↓ | -170 | ↓ | 623 | 46.3 | 27.9 | 22.1 |
| 132.1 | 266.0 | 7.1 | 2650 | 50 | ↓ | 1.80 | +240 | ↓ | 3591 | 2.06 | 2.03 | 750 | ↓ | -70 | ↓ | 632 | 46.0 | 28.7 | 20.0 |
| 133.M.1 | 267.7 | 7.1 | 2750 | 50 | ↓ | 1.80 | +240 | ↓ | 3723 | 1.97 | 2.02 | 710 | ↓ | -70 | ↓ | 595 | 47.9 | 32.1 | 25.8 |
| 138.T.1 | 287.6 | 6.0 | 2450 | 100 | ↓ | 1.80 | +580 | ↓ | 3511 | 2.12 | 2.05 | 850 | ↓ | -155 | ↓ | 646 | 45.1 | 27.0 | 23.0 |

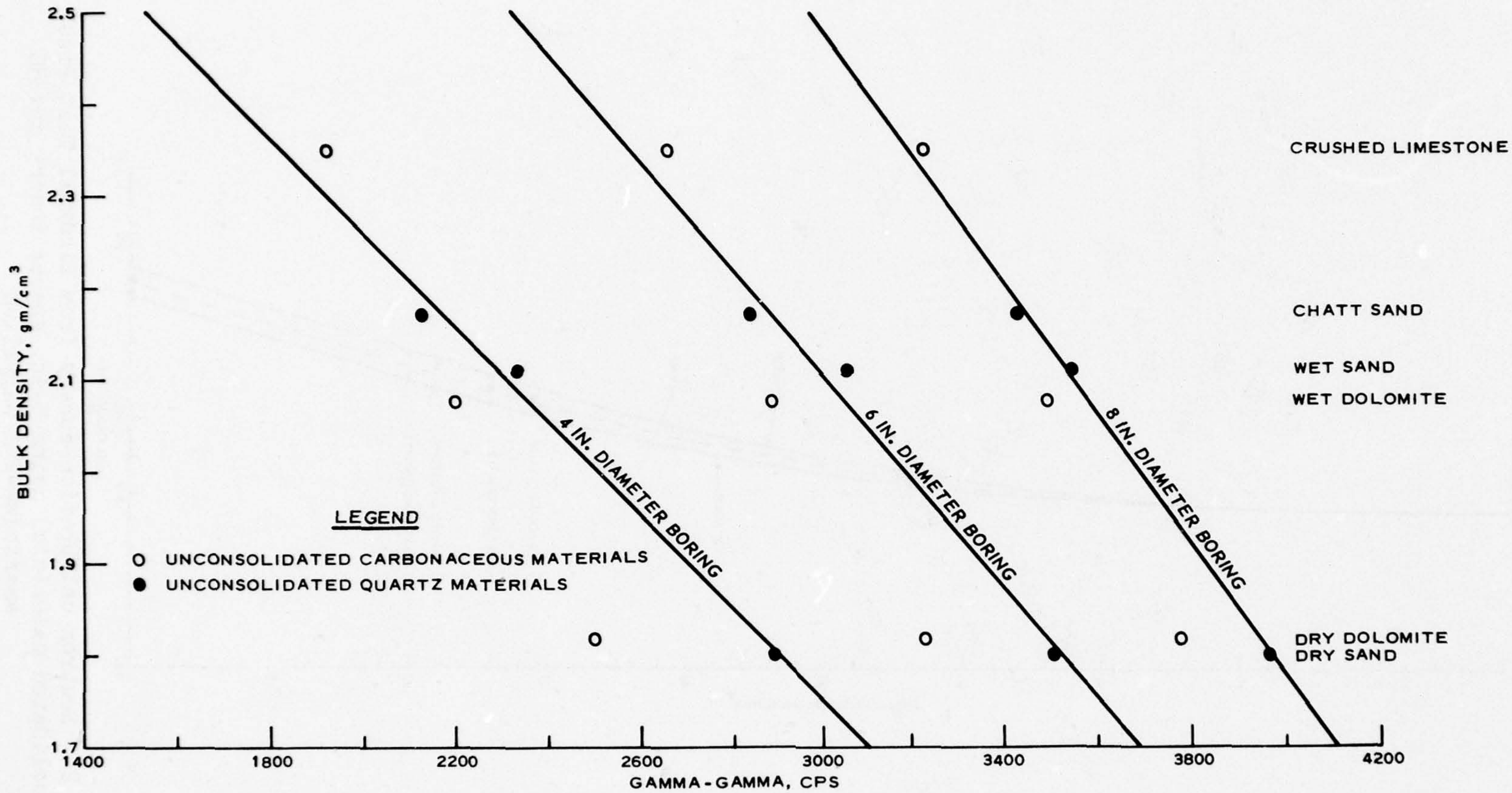



Figure 1. Gamma-gamma calibration curves from Birdwell Test Pits (unconsolidated materials) using 5-in. spacer insert and 5 mc radium-226 source

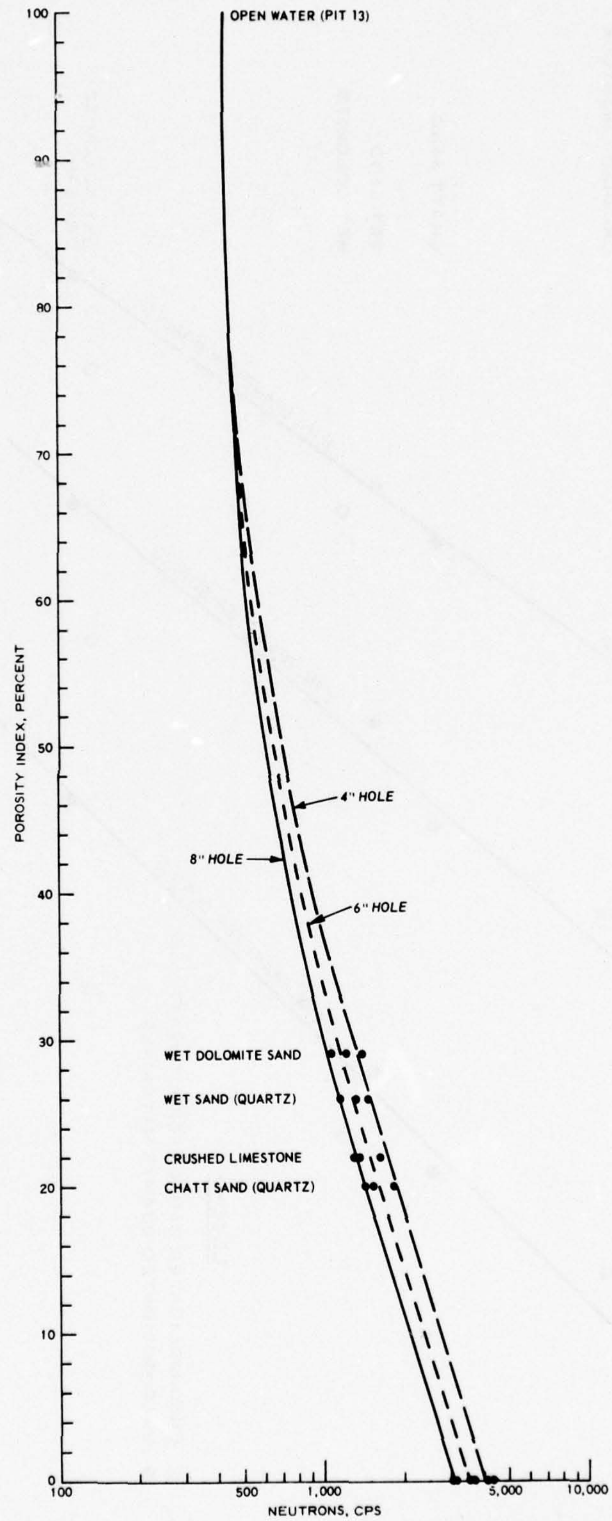



Figure 2. Neutron calibration curves from Birdwell Test Pits (unconsolidated materials) using 5-in. spacer insert and 3C americium-241 beryllium

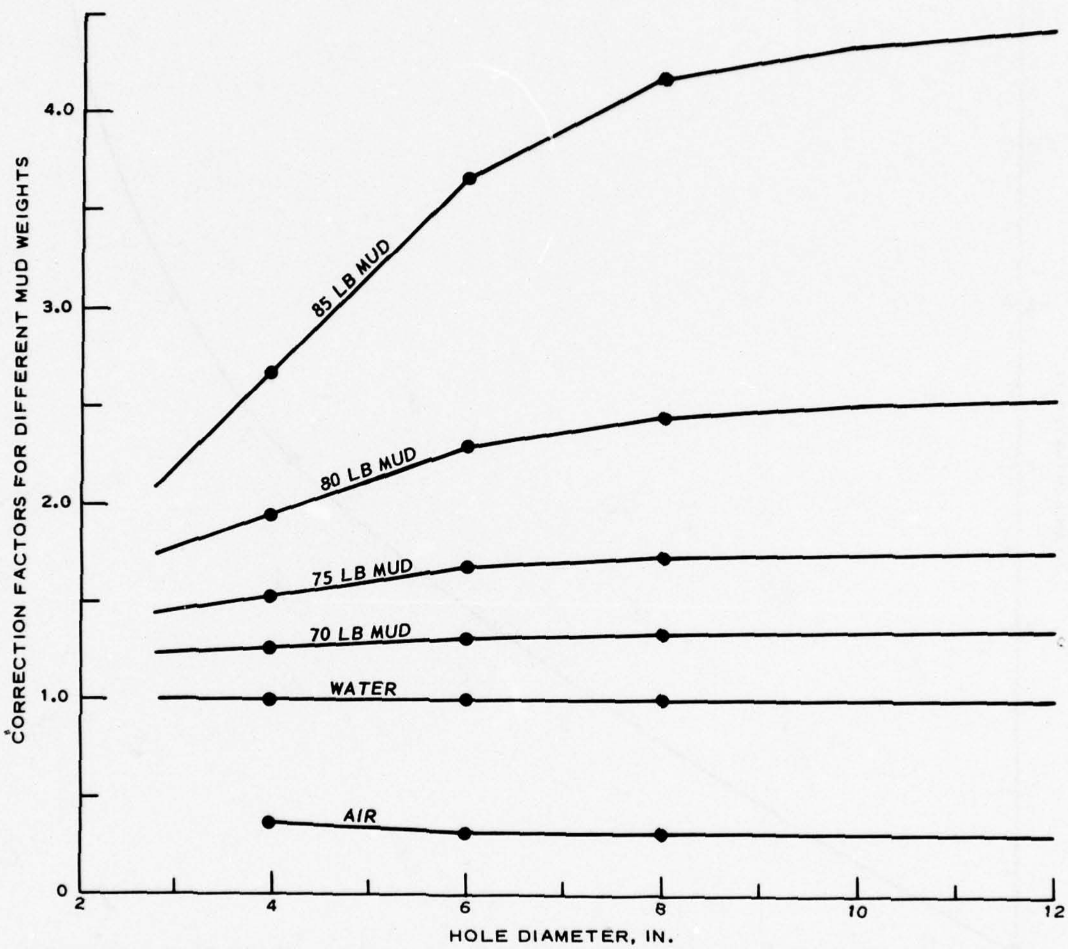



Figure 3. Curves relating different mud weights to correction factors versus different borehole diameters

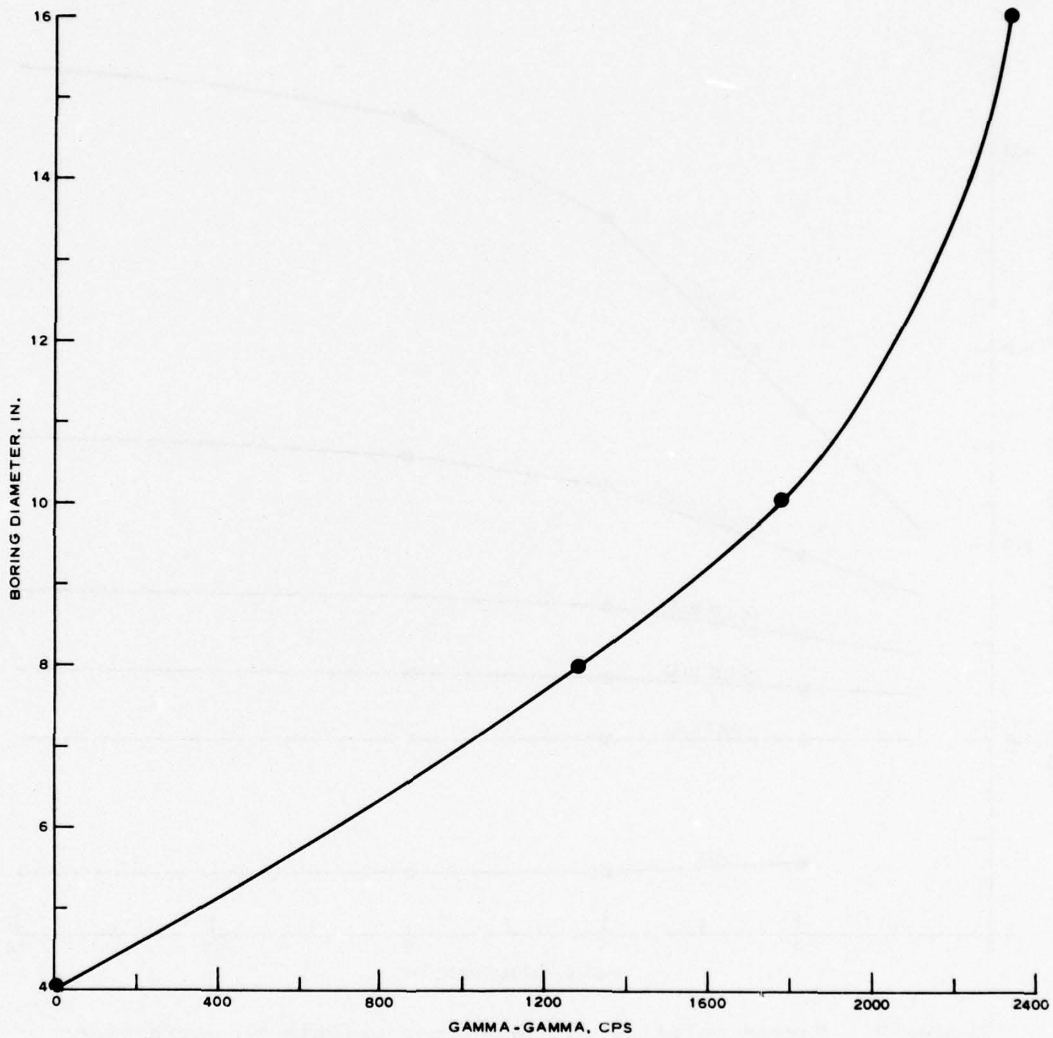



Figure 4. Curve relating borehole diameter to gamma-gamma CPS

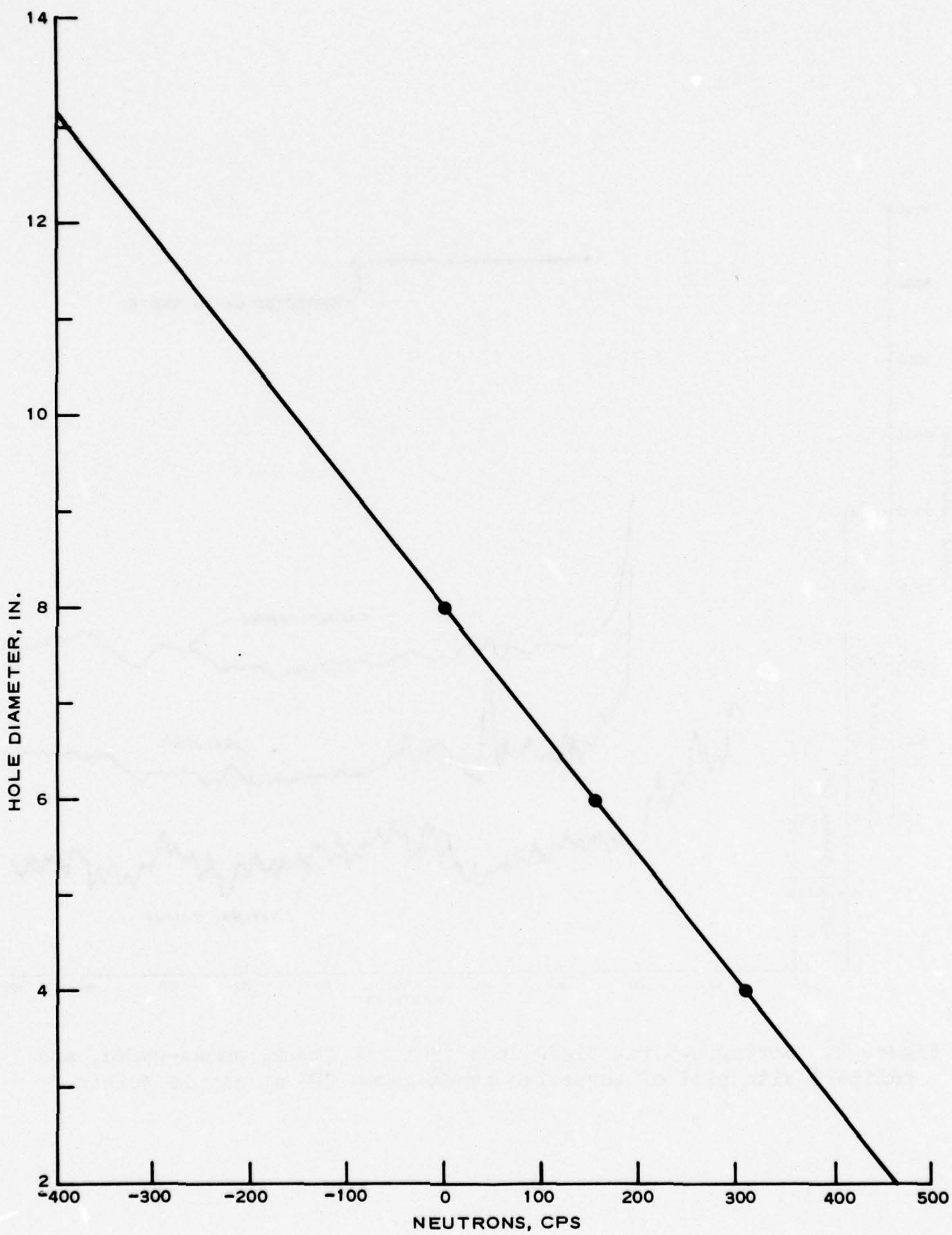



Figure 5. Curve relating borehole diameters to neutron CPS

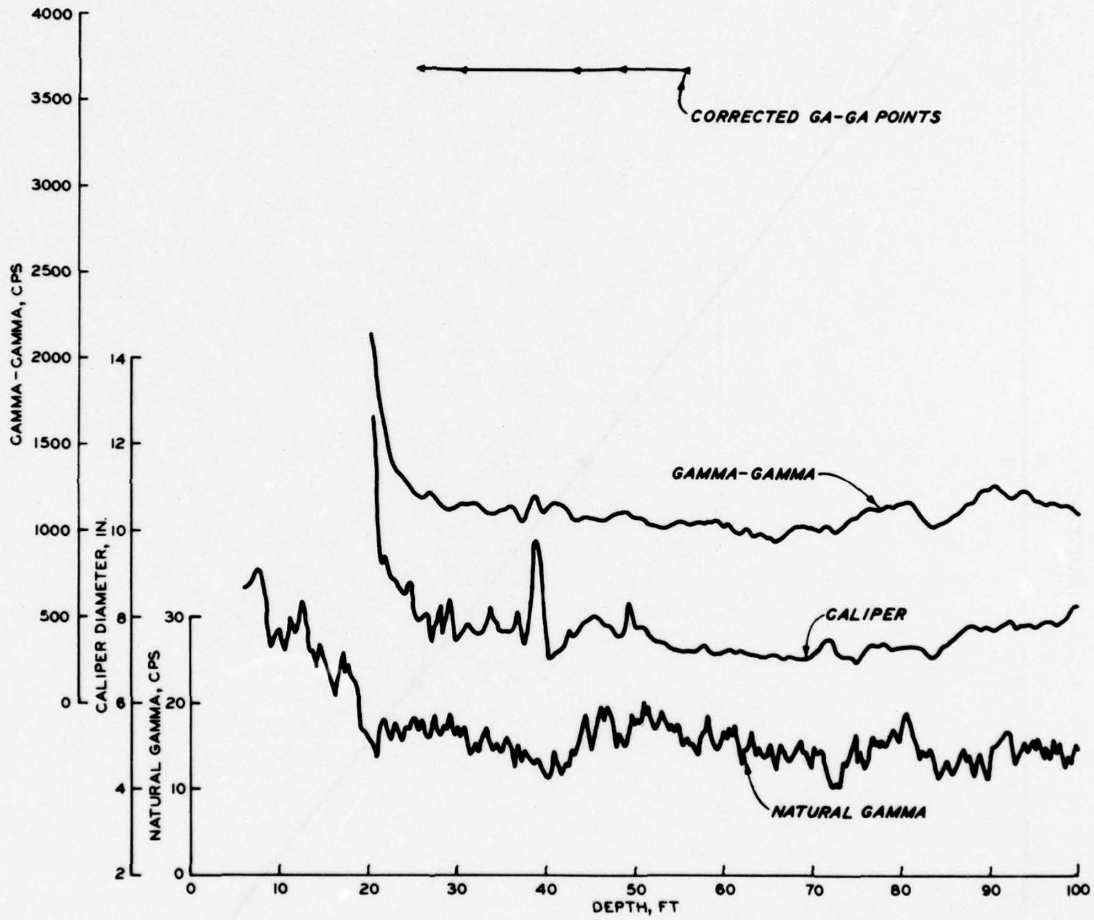



Figure 6. Boring U-5 raw field logs (natural gamma, gamma-gamma, and caliper) with plot of corrected gamma-gamma CPS at sample points

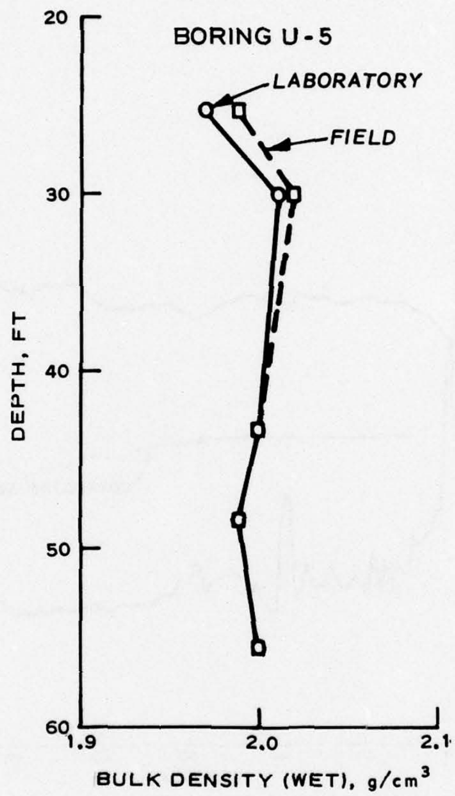



Figure 7. Boring U-5, comparison of field and laboratory bulk densities with depth

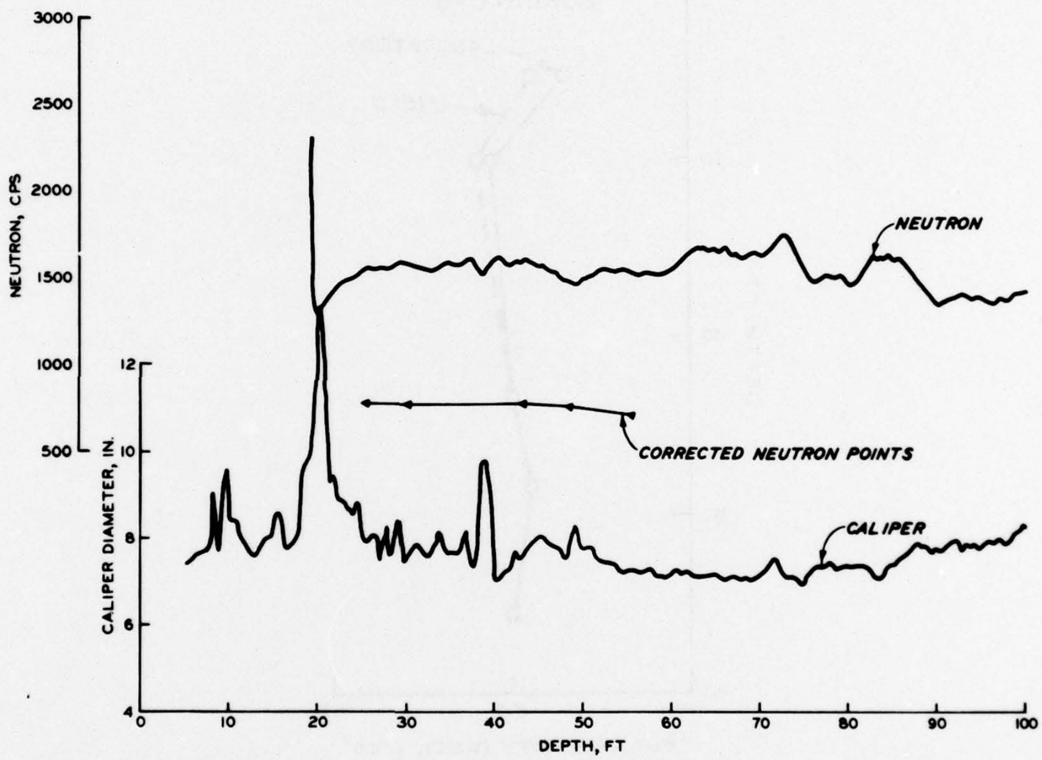



Figure 8. Boring U-5, raw field logs (neutron and caliper) with plot of corrected neutron CPS at sample points

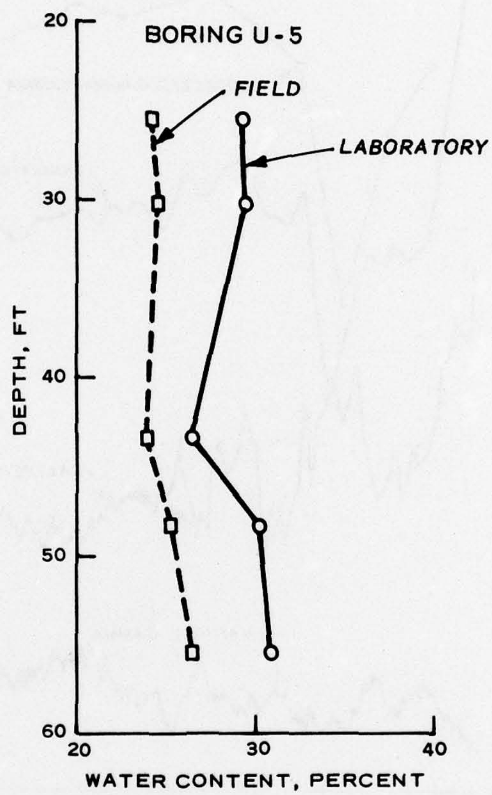



Figure 9. Boring U-5, comparison of field and laboratory water contents with depth

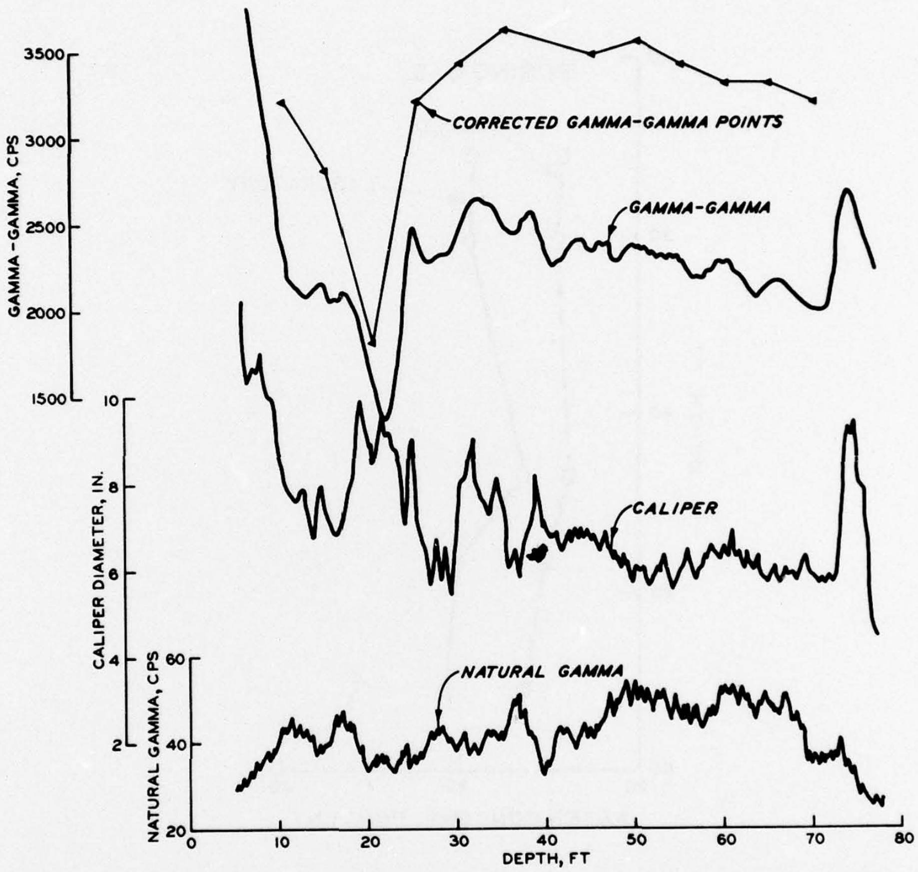



Figure 10. Boring J-14-75U, raw field logs (natural gamma, gamma-gamma, and caliper) with plot of corrected gamma-gamma CPS at sample points

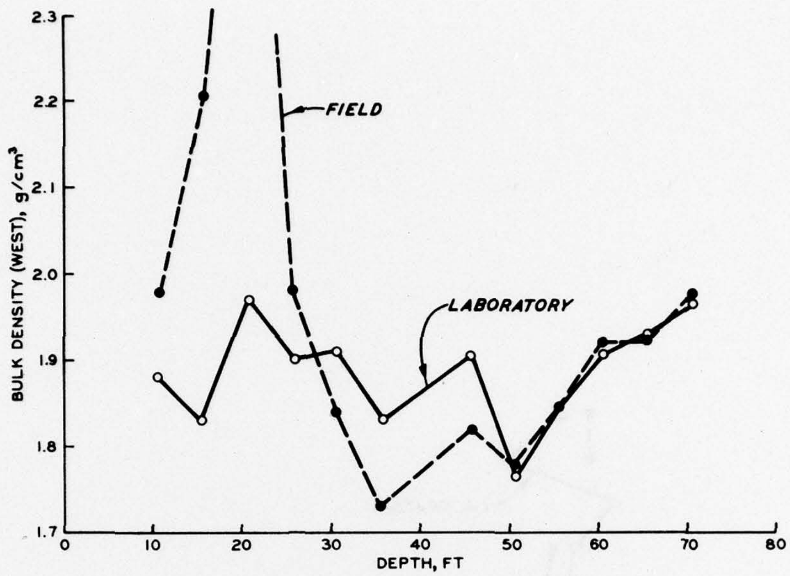



Figure 11. Boring J-14-75U, comparison of field and laboratory bulk densities with depth

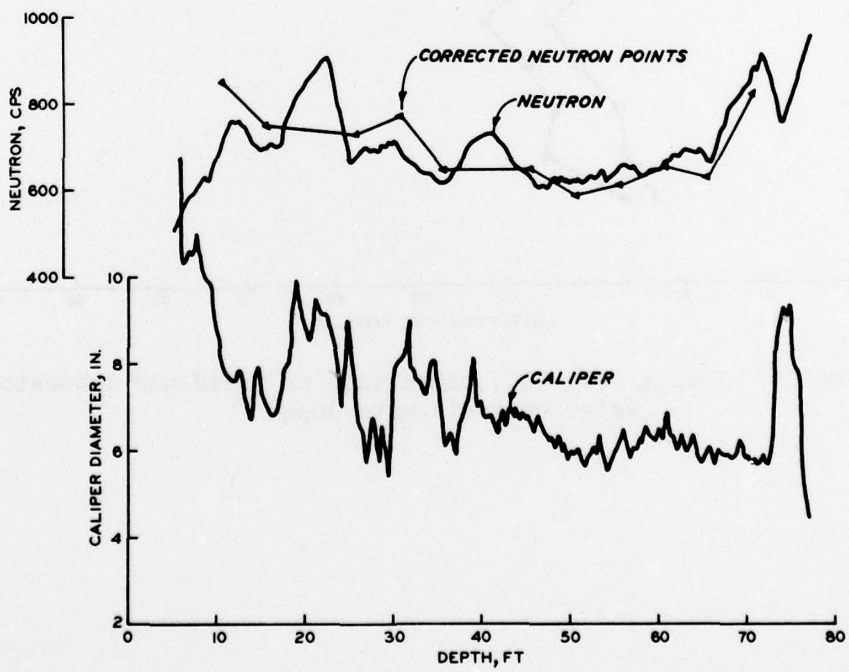



Figure 12. Boring J-14-75U, raw field logs (neutron and caliper with plot of corrected neutron CPS at sample points

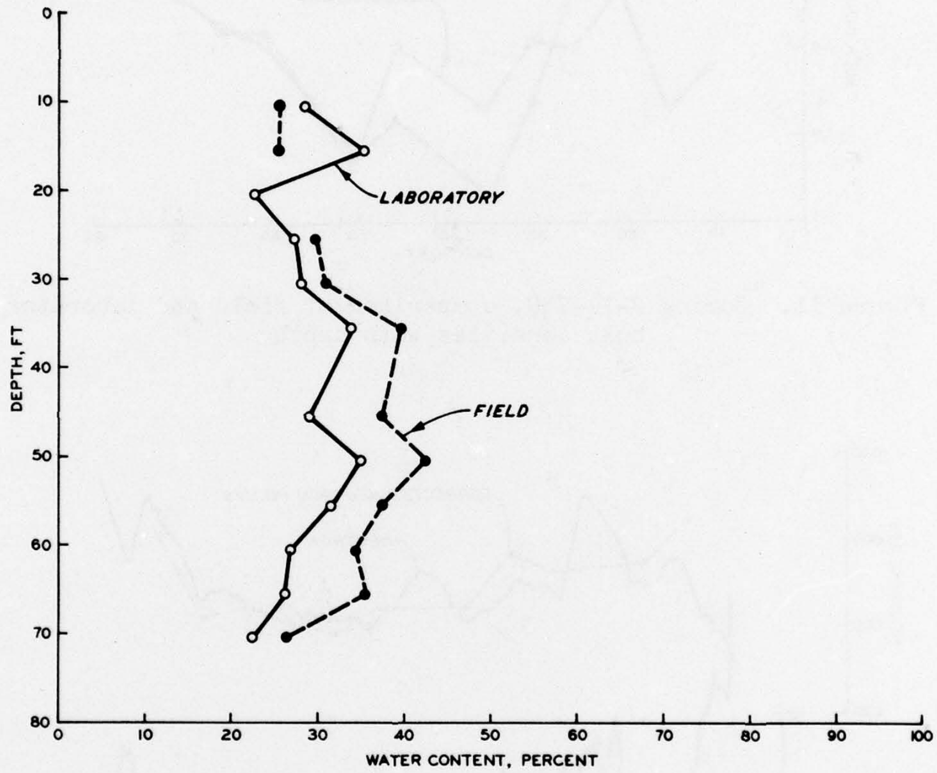
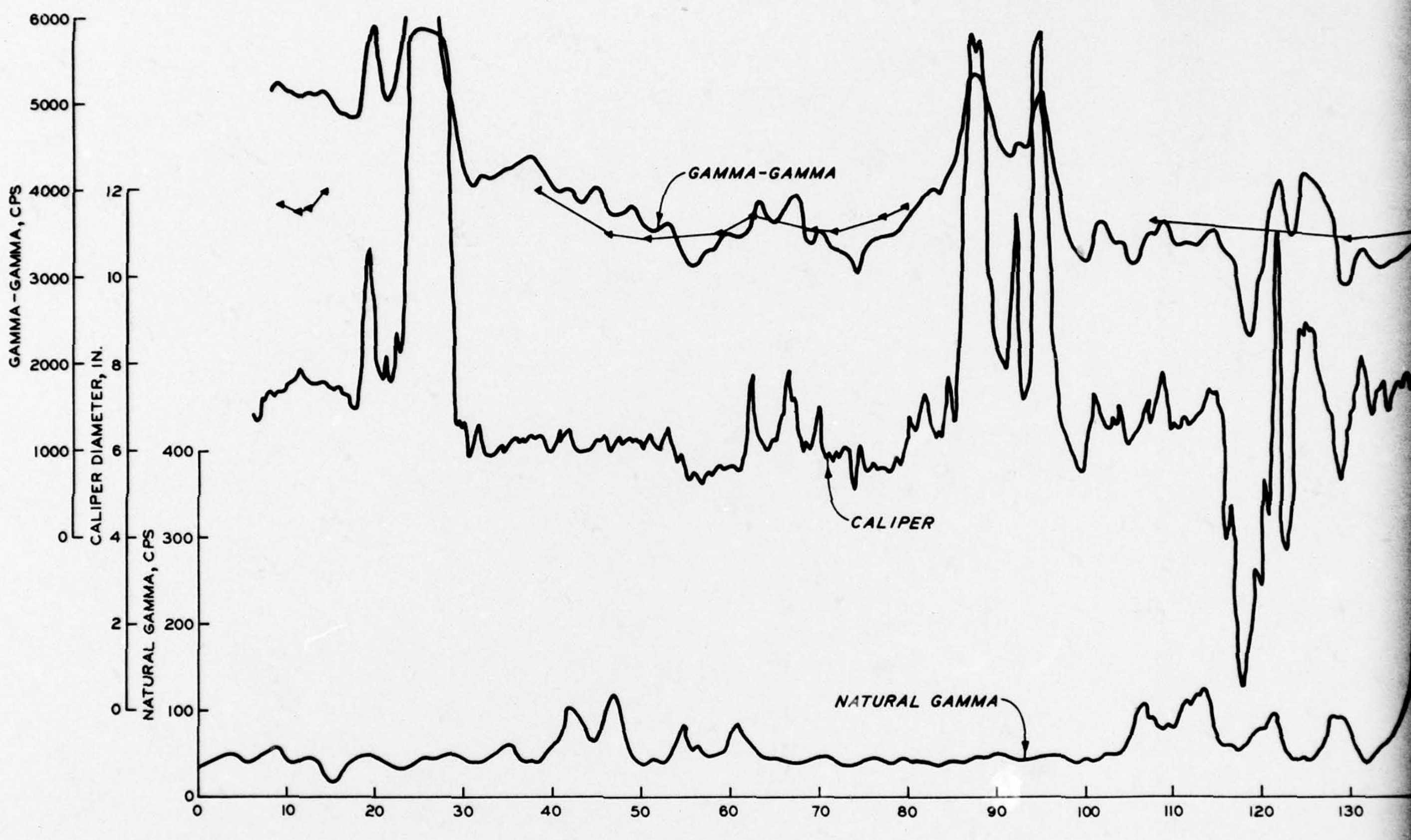



Figure 13. Boring J-14-75U, comparison of field and laboratory water contents with depth


GAMMA-GAMMA, CPS
CALIPER DIAMETER, IN.
NATURAL GAMMA, CPS
GAMMA-GAMMA
CALIPER
NATURAL GAMMA
6000
5000
4000
3000
2000
1000
0
12
10
8
6
4
2
0
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
110
120
130

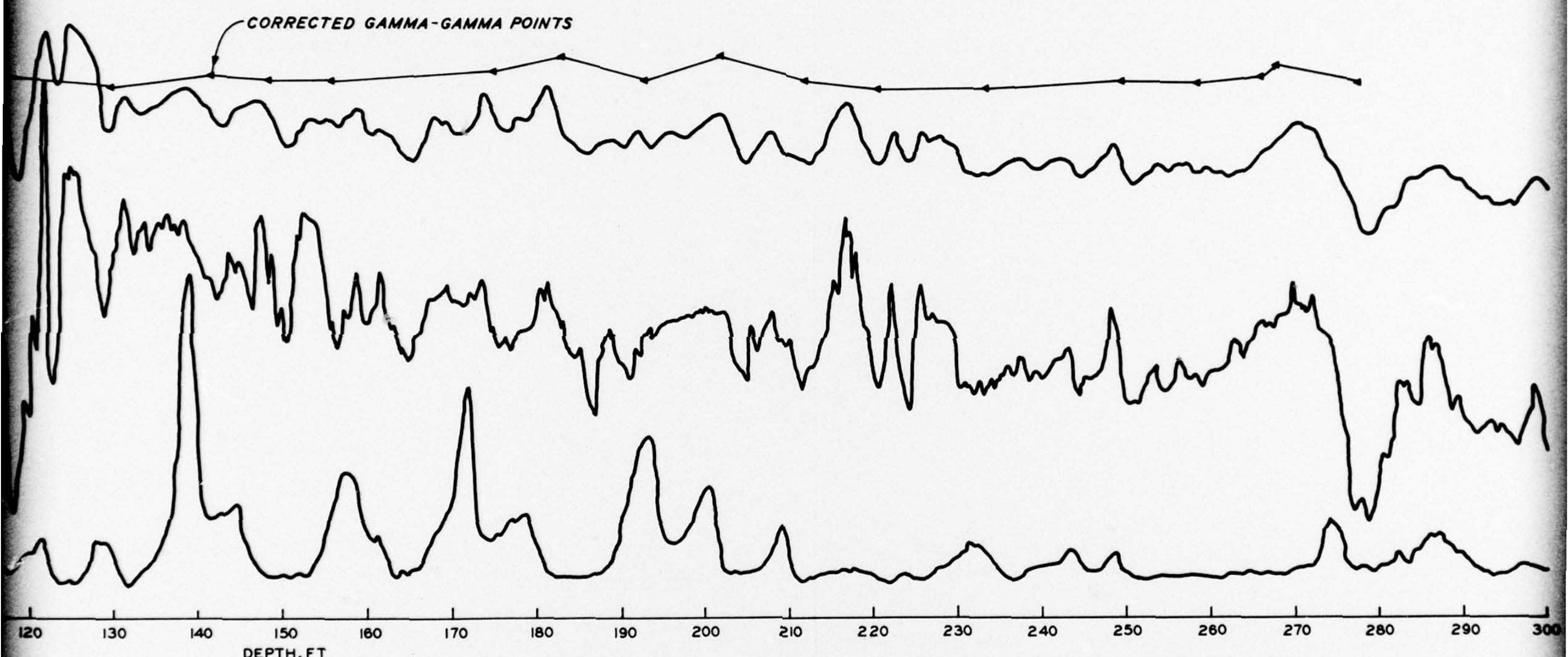
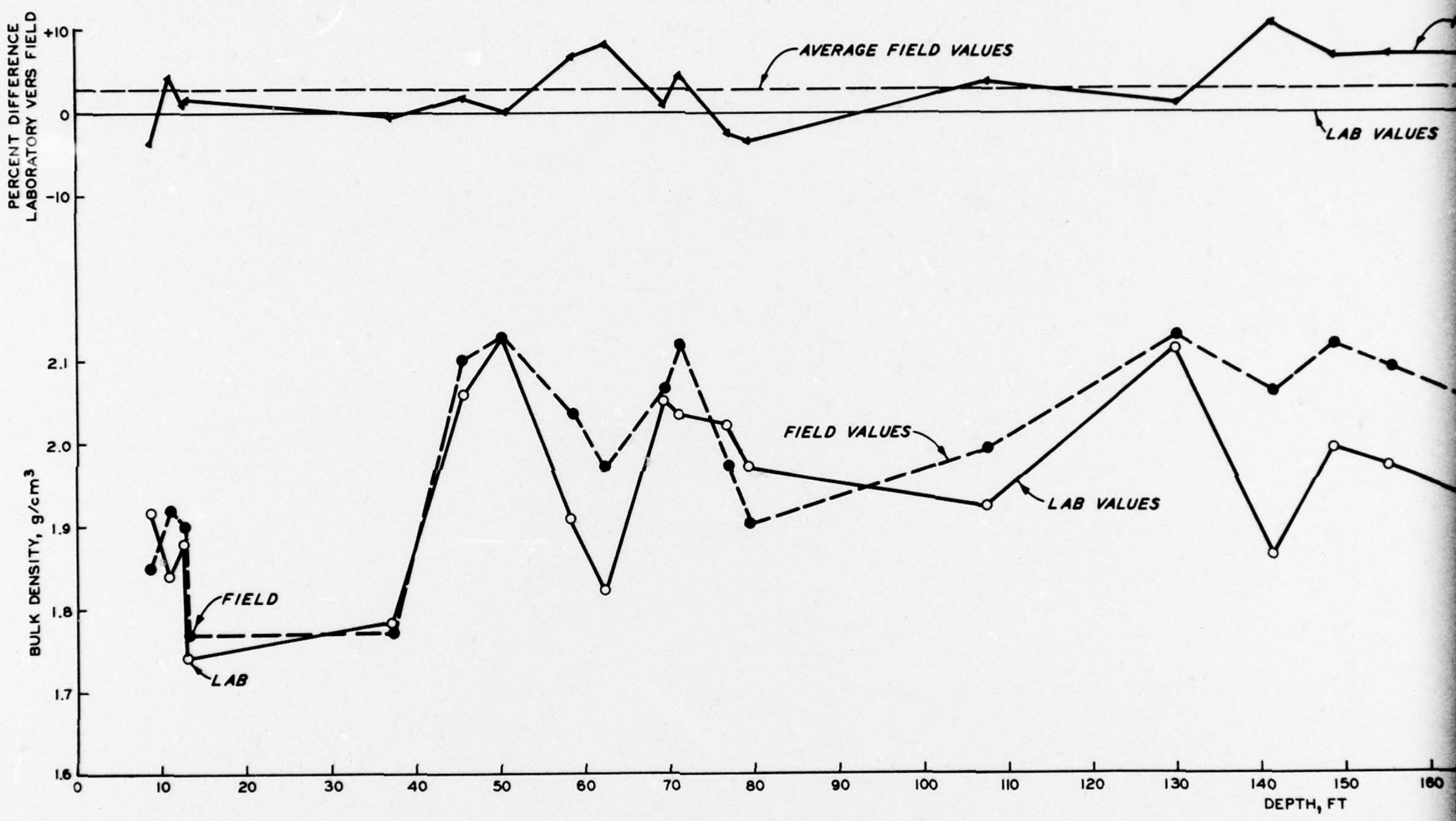



Figure 14. Boring U-1, raw field logs (natural gamma, gamma-gamma, and caliper) with plot of corrected gamma-gamma CPS at sample points



PERCENT DIFFERENCE LABORATORY VERS FIELD
+10
0
-10
AVERAGE FIELD VALUES
LAB VALUES
BULK DENSITY, g/cm3
2.1
2.0
1.9
1.8
1.7
1.6
FIELD VALUES
LAB VALUES
FIELD
LAB
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
DEPTH, FT

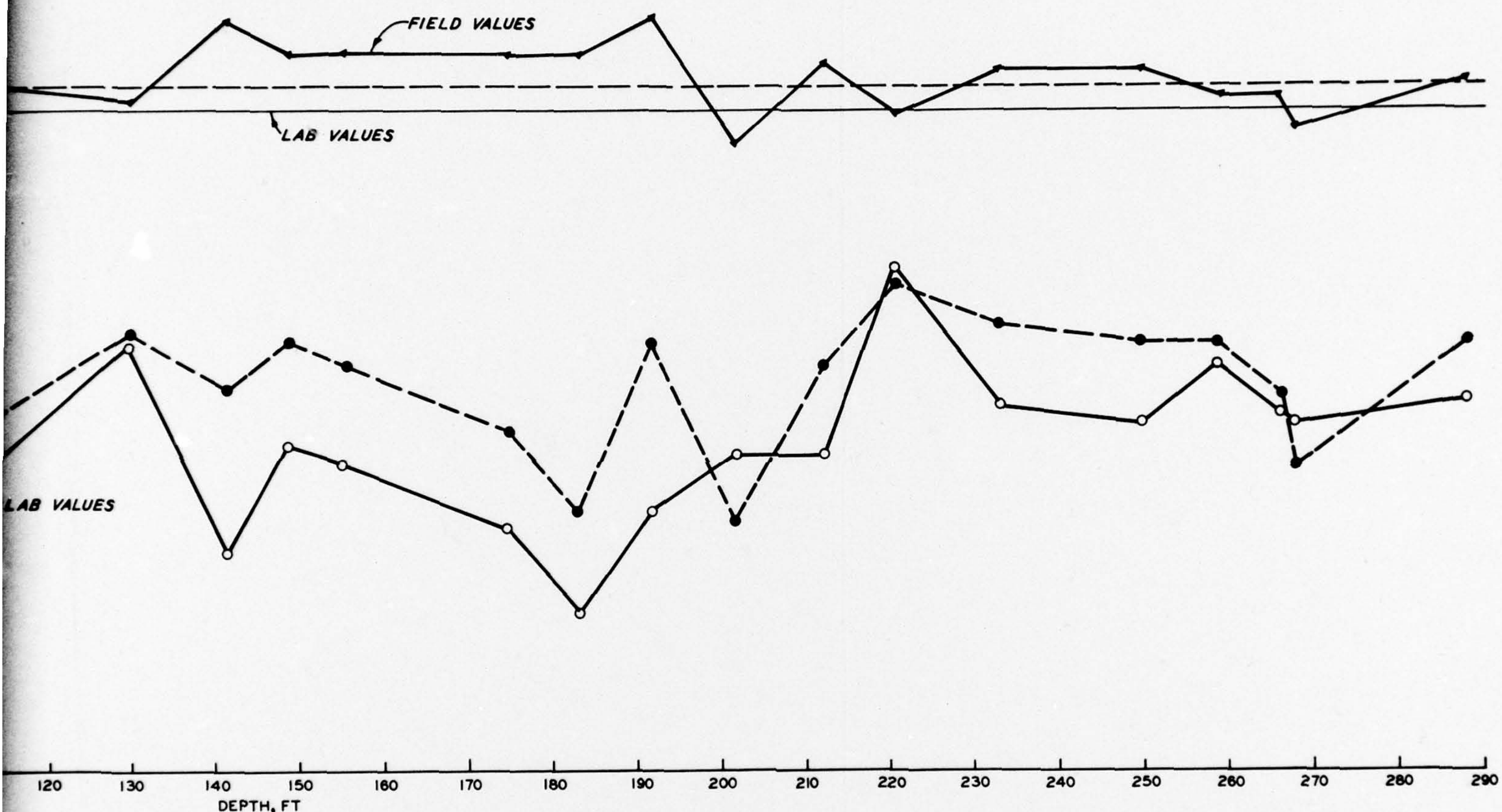
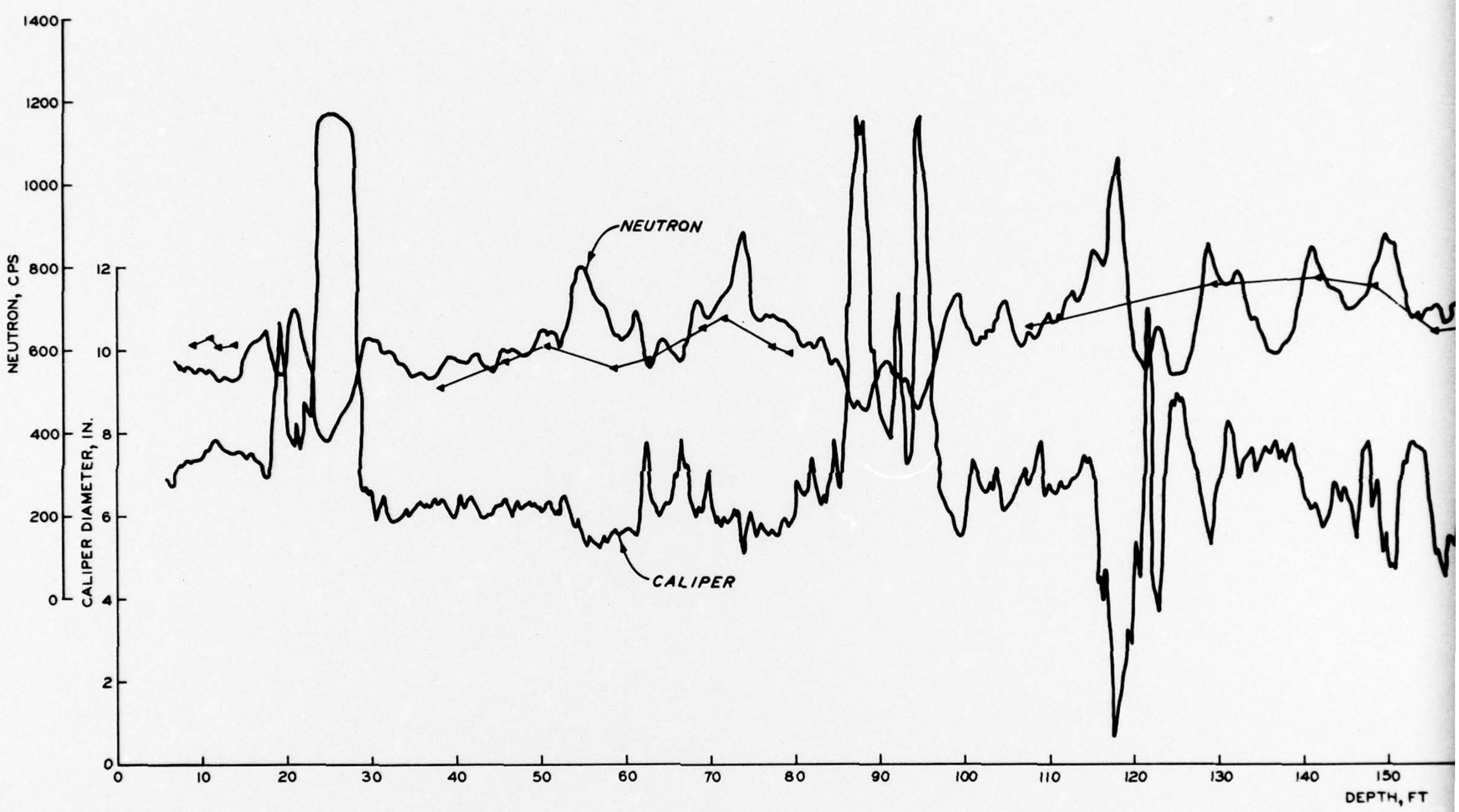



Figure 15. Boring U-1, comparison of field and laboratory bulk densities with depth


NEUTRON, CPS
CALIPER DIAMETER, IN.
NEUTRON
CALIPER
DEPTH, FT
0
200
400
600
800
1000
1200
1400
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

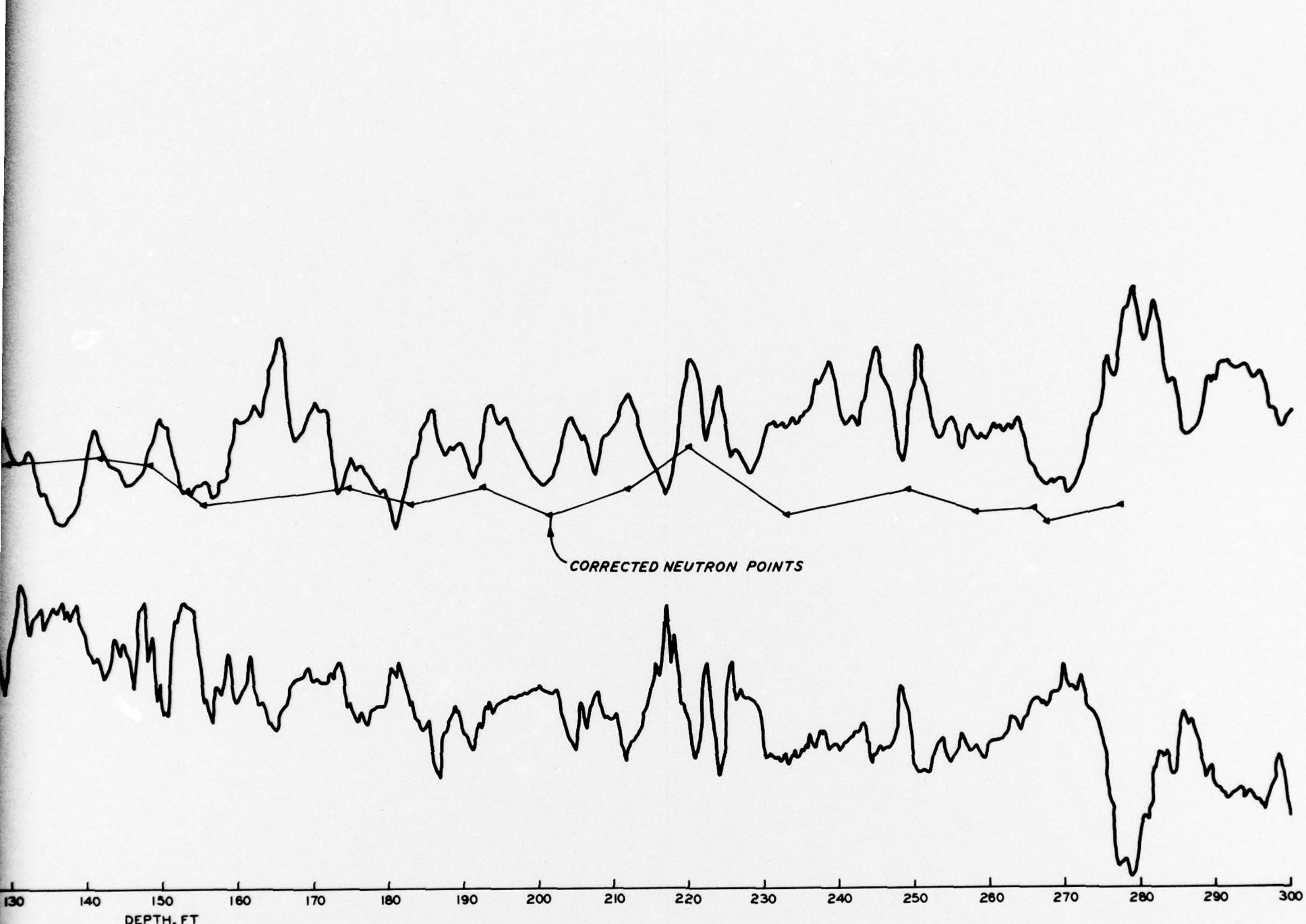
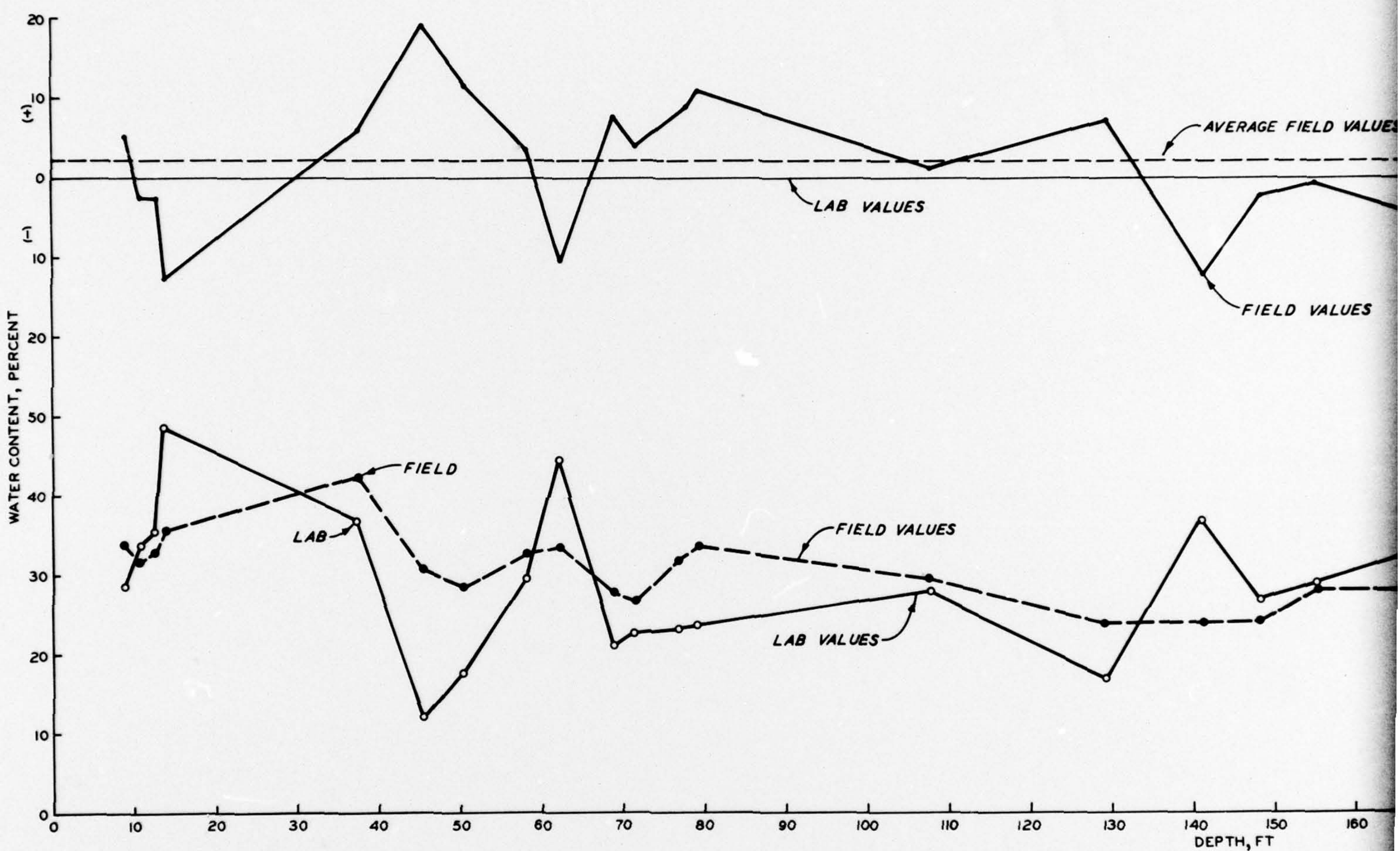



Figure 16. Boring U-1, raw field logs (neutron and caliper) with plot of corrected neutron CPS at sample points



AVERAGE FIELD VALUES
LAB VALUES
FIELD VALUES
FIELD
LAB
FIELD VALUES
LAB VALUES
WATER CONTENT, PERCENT
(+)
(-)
DEPTH, FT

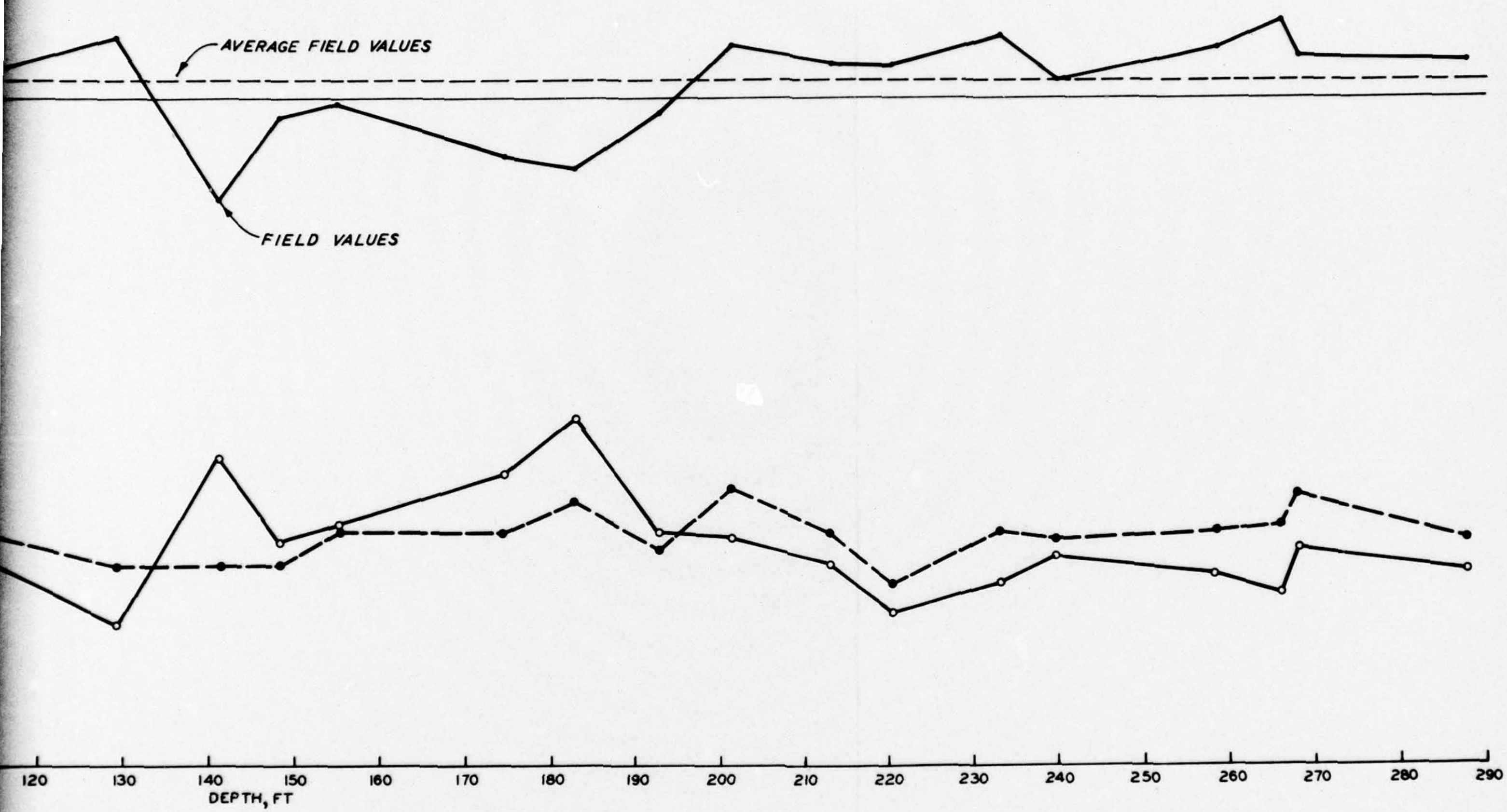



Figure 17. Boring U-1, comparisons of field and laboratory water contents with depth