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BOREHOLE-CALIBRATION METHODS USED IN CASED AND UNCASED TEST HOLES TO DETERMINE MOISTURE PROFILES IN THE UNSATURATED ZONE, YUCCA MOUNTAIN, NEVADA

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Abstract

The use of drilling and coring methods that minimize the disturbance of formation rock and core has permitted field calibration of neutron-moisture tools in relatively large diameter cased and uncased boreholes at Yucca Mountain, Nevada. For 5.5-inch diameter cased holes, there was reasonable agreement between a field calibration in alluvium-colluvium and a laboratory calibration in a chamber containing silica sand. There was little difference between moisture-content profiles obtained in a neutron-access hole with a hand-held neutron-moisture meter and an automated borehole-logging tool using laboratory-generated calibration curves. Field calibrations utilizing linear regression analyses and as many as 119 data pairs show a good correlation between neutron-moisture counts and volumetric water content for sections of uncased 6-inch diameter boreholes in nonwelded and bedded tuff. Regression coefficients ranged from 0.80 to 0.94. There were only small differences between calibration curves in 4.25- and 6-inch uncased sections of boreholes. Results of analyzing field calibration data to determine the effects of formation density on calibration curves were inconclusive. Further experimental and theoretical work is outlined.

Introduction

Careful calibration of borehole-logging tools is necessary to obtain useful quantitative geophysical data from logging operations both above and below the water table. Calibration establishes a relation between the logging-tool output signal and the physical property of the rock affecting that signal; calibration can be accomplished either in the laboratory or under field conditions. Laboratory calibrations require constructing models that simulate borehole conditions as closely as possible. However, constructing a calibrator that accurately duplicates these conditions usually is difficult; Keys and MacCary (1971) provide a detailed discussion of problems associated with laboratory-calibration techniques. Hearst (1979) successfully calibrated a neutron-porosity tool in simulated alluvium, ash fall, and ash-flow tuff at the Nevada Test Site for large boreholes with diameters between 0.98 and 6.6 feet. However, the laboratory simulators and materials used in these simulators are not suitable for neutron-moisture tools and the smaller diameter boreholes examined in this study.

Field calibrations involve correlating logging-tool output with the appropriate rock property, as measured in representative samples (usually core) of the formation, taken from the same depth as the tool measurement. The major problem with field calibration in the vadose zone has been an inability to obtain geologic samples that have moisture properties that represent conditions in the formation rock. If enough representative samples can be obtained, field calibration can be a viable alternative to laboratory calibration where borehole conditions are difficult to simulate. Ideally, both laboratory and field calibrations need to be conducted.

Recently, air coring and drive-core methods have been used on Yucca Mountain to obtain core samples with water contents and related properties that are representative of the formation rock (Hammermeister et al. 1985, this proceedings). In addition, the air-coring process as well as the drilling and reaming methods (Odex 115 system[1]) were shown to minimally disturb the water content of the formation walls. These results provide an unprecedented opportunity for field calibration in a variety of rock types in the vadose zone. This paper presents laboratory- and field-calibration methods and results and, where possible, compares laboratory-calibration data with field-calibration results.

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[1] Use of brand names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

The work described in this paper is a part of the U.S. Geological Survey's studies at Yucca Mountain designed to provide information to the U.S. Department of Energy for their evaluation of the hydrologic and geologic suitability of this site for storing high-level radioactive waste in an underground mined repository. The U.S. Geological Survey studies are part of the Nevada Nuclear Waste Storage Investigations Project conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

Neutron-moisture-tool Calibration Methods

Laboratory Calibration Procedures

Neutron-moisture logging can be used to monitor moisture movement in the vadose zone (Wilson, 1982). Because characterizing moisture movement in the unsaturated zone is one of the major objectives of the U.S. Geological Survey studies at Yucca Mountain, a concentrated effort has been made toward calibrating neutron-moisture tools in the laboratory and the field. This report is concerned only with neutron-moisture-tool calibration.

According to Wilson (1981), neutron-moisture logging should be carried out in small diameter holes, preferably cased with aluminum pipe, and with a minimum of void space between the logging tool and casing and between the casing and borehole walls. In practice, these conditions often are difficult to meet especially in drilling circumstances such as those presented by bouldery alluvial-colluvial deposits, highly fractured welded tuff, and poorly consolidated, bedded and nonwelded tuff that occur at Yucca Mountain. The Odex 115 drilling system used at Yucca Mountain kept the disturbance of the water content of the formation rock to a minimum. This drilling method also minimized the void space between the casing and formation rock in two of the three rock types mentioned above (Hammermeister et al. 1985, this proceedings). The Odex 115 system was used both to drill shallow neutron-access holes and to drill and ream parts of core holes. The casing was pulled up to near the ground surface in core holes leaving most of the hole uncased for future down-hole instrumentation. The neutron-moisture logging of both types of holes is discussed hereinafter.

The Odex 115 system utilizes a relatively large diameter casing (5-inch inside diameter (I.D.)) compared with the 1.5-inch outside diameter (O.D.) of the Campbell Pacific Nuclear (CPN) neutron-moisture tools used in this investigation. A review of the technical literaature provided no insight as to whether this poor fit between the tool and casing wall would cause problems during neutron-moisture logging, and the U.S. Geological Survey was prepared to employ a neutron-porosity tool if neutron-moisture logging had proved unsatisfactory. Shortly before the start of the logging program, other researchers at the Nevada Test Site (Scott Tyler, Desert Research Institute, written commun.,

1984) collected preliminary data indicating that the neutron-moisture meters could be used successfully in boreholes of this diameter. On the basis of this finding, the U.S. Geological Survey proceeded to calibrate neutron-moisture tools inside the 5-inch I.D. casing using both laboratory and field methods.

Laboratory calibrations were performed in the 5-inch I.D. casing, which was in turn centered inside a calibration chamber 36 inches in diameter and 42 inches high (Figure 1). The annular space between the casing and the walls of the chamber was filled with Monterey 40-80 sand to simulate the siliceous alluvial-colluvial deposits. Simulation of alluvium-colluvium and nonwelded and welded tuff, utilizing actual borehole cuttings from those units, is planned. The dry bulk density of the hand-packed dry sand in the calibration chamber was approximately 103.4 lb-mass/ft^3 (pound-mass per cubic foot) with a grain density of 165.0 lb-mass/ft^3. An air-powered vibrator was used in an attempt to minimize the porosity resulting from less than optimum packing of sand grains. The calculated porosity was 37.4 percent, and the measured porosity was 35.3 percent.

Average volumetric water contents of 0, 8, 16, and 24 percents were achieved in the sand-filled calibration chamber. The zero water content was obtained by oven drying the sand. Higher water contents were obtained by adding measured quantities of water to 33-pound samples of sand with known original water contents. After the appropriate quantities of water were added as evenly as possible to the 33-pound sand samples, the bags were sealed and rotated periodically to hasten equilibration. Just prior to beginning the calibrations, contents of the bags were added to the chamber, and the chamber was sealed. Transfer from the bag to the chamber and then resealing usually took less than 0.5 hour. The contents of the chamber periodically were vibrated with an air-powered vibrator to help maintain the same density and porosity as the oven-dried sand.

Calibration of two CPN neutron-moisture tools began immediately after the chamber was filled. One of the tools was attached to the CPN Model 503 moisture meter; the other tool was attached to a Mt. Sopris II borehole geophysical-logging unit. Minor modifications of the CPN tool were made by the U.S. Geological Survey to make the tool compatible with the Mt. Sopris system. Shallow holes were logged with the CPN system, whereas holes deeper than 70 feet were logged with the Mt. Sopris system. In the following discussion, the CPN system is referred to as the "moisture meter," and the combined Mt. Sopris/CPN system is called the "moisture logger."

The moisture meter was placed against the "down-slope" wall of the 5-inch I.D. casing and positioned so that the midpoint between source and detector in the tool corresponded to the midpoint of the sand column in the chamber (Figure 1). Two sets of ten 30-s readings were taken at 15-minute intervals, and the mean was calculated for each run. The average of the two sets then was assumed to equal the moisture-tool output at the particular water content. The moisture logger then was tested in a similar manner with two sets of fifty 2-s

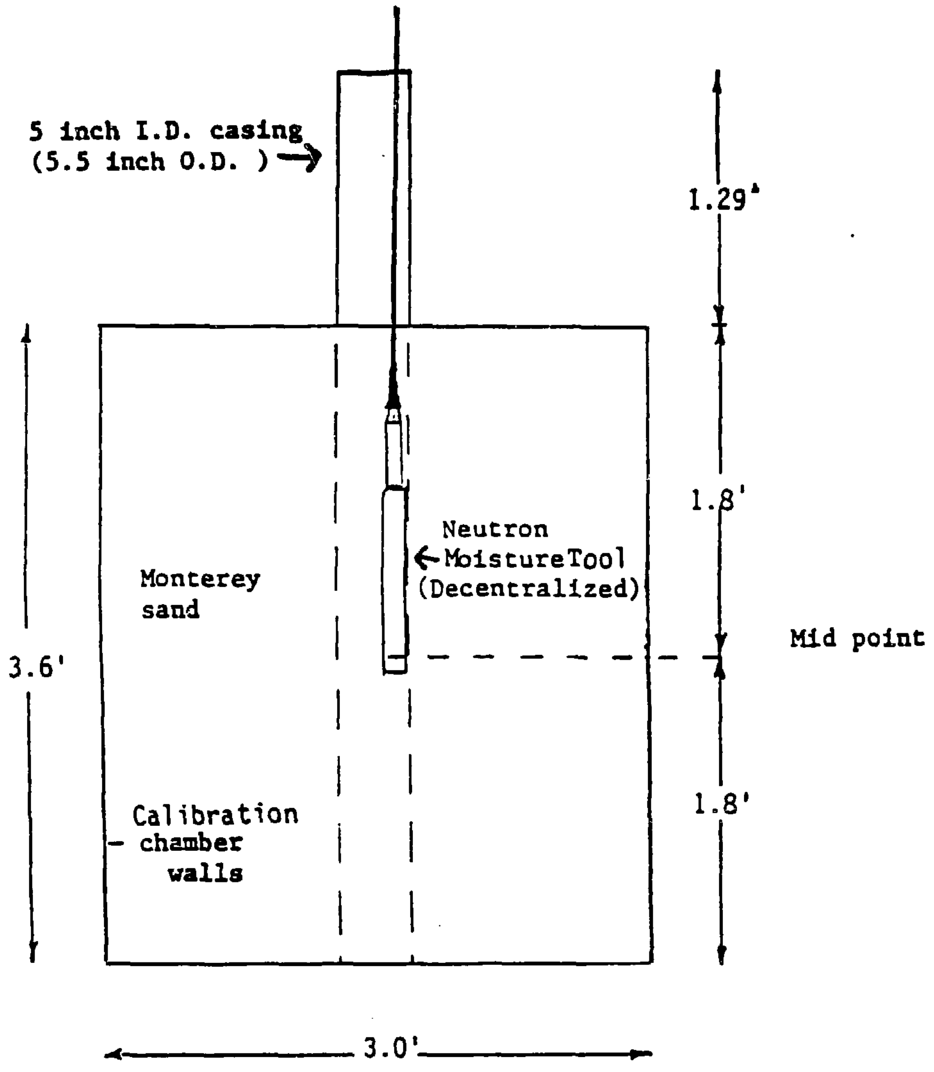

Figure 1. Diagram of cross section of laboratory-calibration chamber.

readings taken at 15-minute intervals and averaged to yield the logger output. After completion of logging, sand was removed from the chamber in approximately 33-pound portions. From these portions, 1-pound subsamples were collected at selected depths and placed in a large moisture tin to determine the post-logging moisture content.

Field Calibration Procedures

Because the key element in any field calibration is the collection of representative geologic samples, every effort was made to minimize the evaporative loss of water from both drive-core and rotary-core samples prior to water-content measurements (Hammermeister et al. 1985, this proceedings). Gravimetric water-content determinations were made on both types of core following standard procedures (Gardner, 1965). Dry bulk-density and grain-density measurements were performed by Holmes and Narver, Inc., Mercury, Nevada, using American Society of Testing Materials procedures. These measurements were made on subsamples from the same rotary-core intervals as the gravimetric water-content samples and from adjacent intervals for drive-core samples. Rotary-core volumetric water contents were calculated from the product of bulk densities and gravimetric water contents. Drive-core volumetric water contents were measured directly on the core. Direct measurement of volumetric water content on preserved core samples is planned.

Neutron-access holes were logged with the moisture meter as soon as possible after completion of the hole. The logging consisted of 30-s counts of thermalized neutrons at each depth interval. The distance between logging points for the upper 16.4 feet of the hole was 0.33 foot and then increased to 0.98 foot for the total depth of the hole.

Core holes were logged with a neutron-moisture logger as soon as possible after hole completion. Because of equipment problems, some logs were made as much as 9 months after hole completion. This delay is not considered a source of error in the calibrations. The relatively low water contents and water potentials found in geologic samples suggest that very low rates of water movement occur in all rock units except alluvial-colluvial deposits occurring directly beneath stream channels.

Results and Discussion

Laboratory Calibration

Results of laboratory calibration of the neutron-moisture meter and neutron-moisture logger are presented in Figures 2 and 3. A regression coefficient of 0.95 was obtained for the moisture-meter calibrations; a regression coefficient of 0.94 was obtained for the moisture-logger calibration. The deviation of the data points from a straight line probably is, in part, the result of a water-content

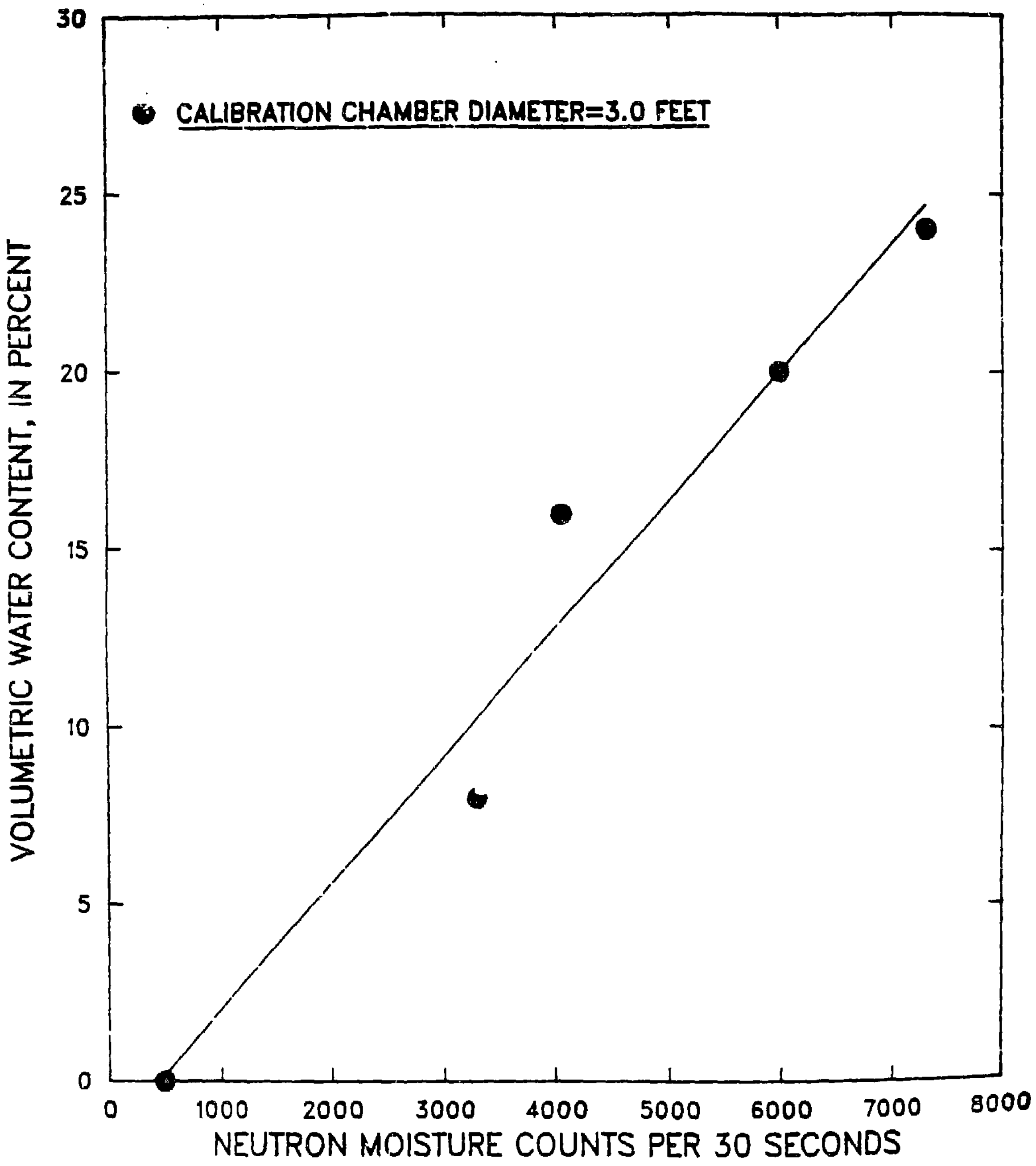

Figure 2. Laboratory-calibration data for neutron-moisture meter with linear-regression line.

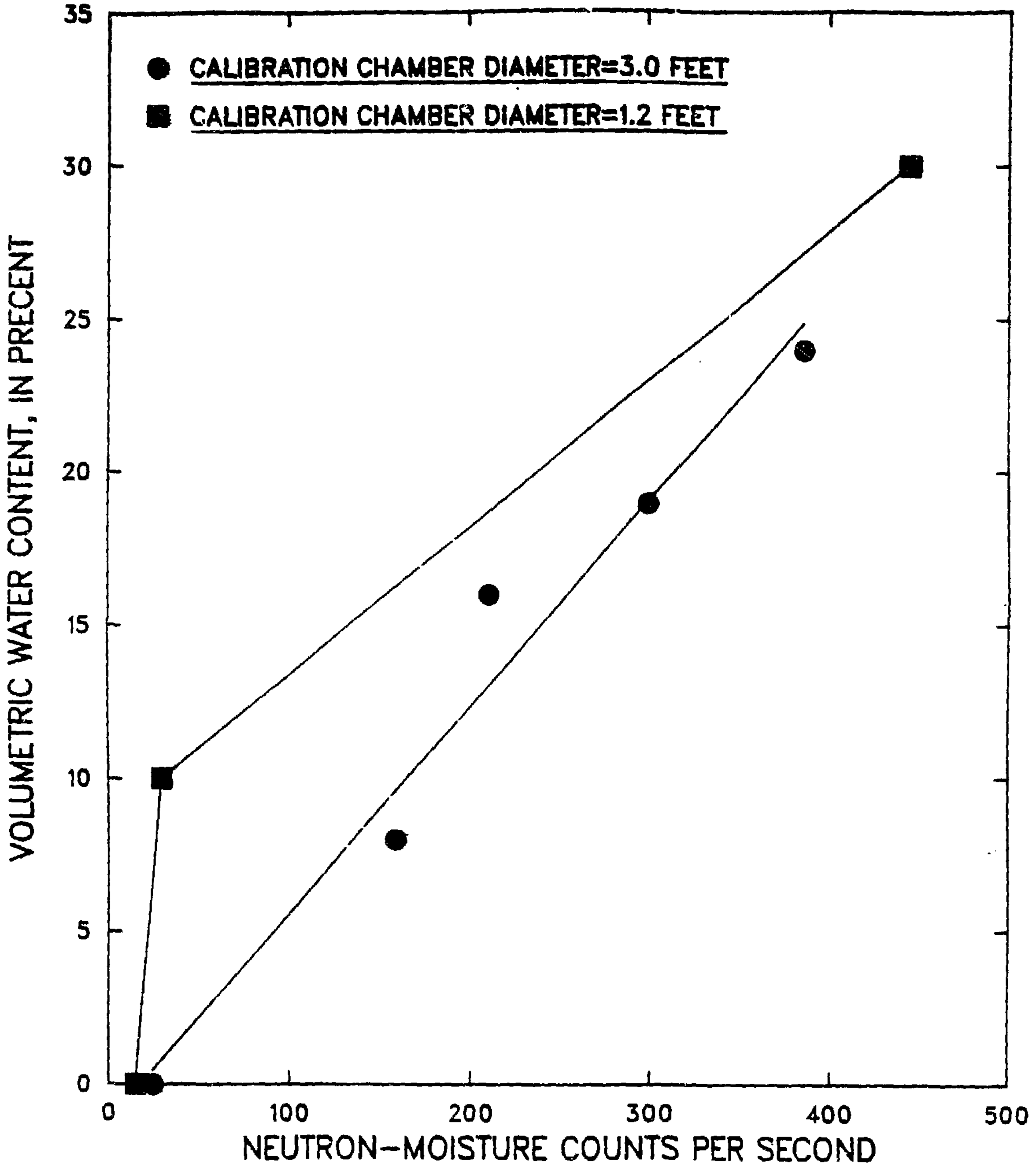

Figure 3. Laboratory-calibration data for neutron-moisture logger in calibration chambers of different diameter. Linear-regression line shown for 3-foot diameter chamber.

gradient in the calibration chamber. The relatively coarse sand used in the chamber permitted some gravity drainage during logging at 16 percent and 24 percent water contents; post-calibration measurements indicated that water contents increased with depth in the chamber; for example, the water content of the sand varied from 7 percent near the top of the chamber to as much as 32 percent near the bottom of the chamber. However, several factors probably worked together to keep this water-content variation from more seriously affecting the expected linear relationship between tool output and water content. First, calibrations were performed immediately after filling the chamber, thus minimizing the time for gravity drainage to occur. Second, the moisture tools respond to an average water content in the central region of the chamber, and this effect reduces the error resulting from variation in water content with depth. A finer mesh sand will be used in future calibrations to minimize this potential source of error, and resistivity probes will be used to monitor any changes in water-content distribution over time.

The radius of investigation for neutron-moisture probes has been shown to decrease with increasing water content when all other factors such as source-detector spacing, borehole diameter, and rock density are held constant (Olgaard, 1965). The calibration chamber needs to be constructed large enough to completely contain the maximum radius of investigation (the neutron cloud) of the moisture probe. Two smaller calibration chambers having outside diameters of approximately 1.2 and 1.9 feet with distances of 0.38 and 0.71 foot, respectively, between the 5.5-inch O.D. casing and the chamber walls also were tested with the neutron-moisture logger. They were successively filled with sand having moisture contents of approximately 0, 10, and 30 percents before calibrations were made. Resulting calibration points for the smaller of the two chambers are plotted in Figure 3. The nonlinearity of the plot indicates that the radius of investigation of the tool at 0 and 10 percents water contents was greater than the chamber radius and that neutrons escaped into the atmosphere. Data from the 1.9-foot diameter chamber (not shown) indicated the same problem. Approximate linearity of the calibration data from the 3.0-foot diameter chamber (Figure 3) with its similarity to a field calibration test discussed hereinafter indicated that this chamber is large enough to contain the neutron cloud even at lower water contents.

Field Calibration Results in Neutron-Access Holes

Results of the linear-regression analysis of moisture-meter counts versus gravimetric water content of drive core in alluvium-colluvium are presented in Figure 4 and Table 1. Gravimetric water content was used in place of volumetric water content because the drive-coring process was found to disturb the porosity and all volume-related properties of the drive-core samples (Hammermeister et al. 1985, this proceedings). The linear-regression equation for the laboratory calibration, in which volumetric water content was

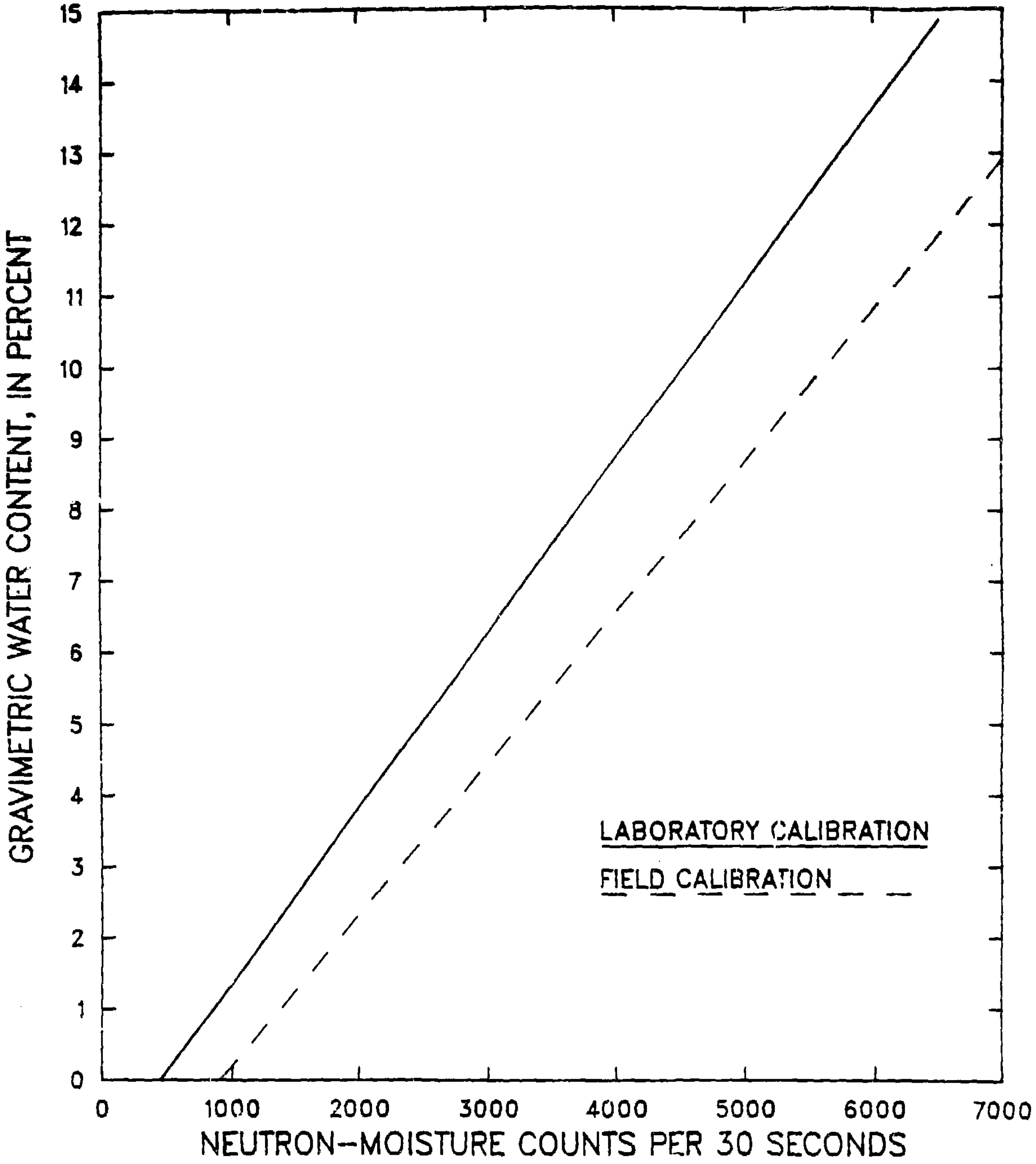

Figure 4. Regression lines for alluvial-colluvial field and laboratory calibrations.

Table 1
Summary of laboratory calibration curve linear-regression analyses

Independent variable	Dependent variable	Number of samples	Regression coefficient	Inter-cept	Slope
Neutron moisture-meter counts	Volumetric water content (percent)	4	0.95	-1.57	$3.58\text{x}10^{-3}$
Neutron moisture-logger counts	Volumetric water content (percent)	4	.96	-1.21	$6.77\text{x}10^{-2}$
Neutron moisture-meter counts	Gravimetric water content (percent)	4	.95	-.94	$2.16\text{x}10^{-3}$

converted to gravimetric water content, also is presented in Figure 4 for comparison. Note that reasonable agreement occurred between these calibration curves. At 7,000 counts (which was the upper limit of moisture-meter outputs in neutron holes in this study), the calibration curves predict water contents to differ by about 1.37 lb-mass/ft^3. This difference is not surprising considering the many possible sources of error in laboratory and field calibrations. Some of the sources of error in laboratory calibrations have been discussed above. Additional error may result from simulating alluvial-colluvial deposits with silica sand. Effects of the chemical composition of rock on calibration curves (Cotecchia et al. 1968) are discussed in more detail hereinafter in conjunction with core holes.

Vertical resolution of the neutron tool and errors involved with core sampling probably are the major sources of error in field calibrations. Vertical resolution of the CPN tools was no less than the depth interval between measurements: 0.33 foot in the upper sections of neutron-access holes and 0.98 foot in the lower sections of holes. Samples of core generally were less than 0.3 foot in length; usually their depth interval did not correspond exactly to the logging depth. Moisture-meter counts were taken from the measurement nearest in depth to the core-depth interval. Visvalingam and Tandy (1972) review vertical-resolution limits encountered by other investigators.

Using calibration curves generated in the laboratory, the neutron-moisture meter and neutron-moisture logger produced virtually identical moisture-content logs of the same neutron-access hole (Figure 5). A time constant of 2 s and a logging rate of 5 ft/min were used on the moisture logger to achieve these results. Longer time constants and faster logging rates produced logs that did not match as well with the neutron-moisture meter.

The methods used to calculate moisture movement in the unsaturated zone relied on differences between successive neutron-moisture-content logs rather than on absolute values of water content. Very little difference was obtained in moisture-movement calculations if either the laboratory- or field-calibration equation was used consistently.

Field-calibration Results in Uncased Core Holes

Results of field calibrations in uncased nonwelded and bedded-tuff sections of core holes are summarized in Table 2. Good correlations were found between neutron-moisture-logger output (counts) and the volumetric water content of rotary cores in both 6- and 4.25-inch diameter sections of the uncased boreholes, UE-25 UZ-4 and UE-25 UZ-5 (Figures 6, 7, 8, and 9). Regression coefficients (r^2) ranged from 0.80 for the 6-inch diameter nonwelded section of borehole UE-25 UZ-5 to 0.94 for the 4.25-inch diameter section of borehole UE-25 UZ-4. The slightly higher regression coefficient in the 4.25-inch diameter section compared to the 6-inch diameter section of borehole UE-25 UZ-4 may not be significant. Regression coefficients did not improve in the 6-inch diameter hole when an attempt was made to improve the fit of the tool in the borehole by decentralizing the tool (Table 2). Similarity in the slope and intercept of the regression equations in the two boreholes with different diameters also indicates that "fit" probably was not an important factor affecting regression coefficients. Differences in the regression coefficients (if significant) probably were the result of sampling and measurement error with core samples.

Five cored intervals in cased sections and eight cored intervals in uncased sections of welded tuff constitute the available data on volumetric water contents. Because of the small size of the data set, field calibrations from these sections are not discussed in this paper. As additional holes are cored and logged and more data become available, an attempt will be made to field calibrate the moisture logger in welded-tuff sections in these holes.

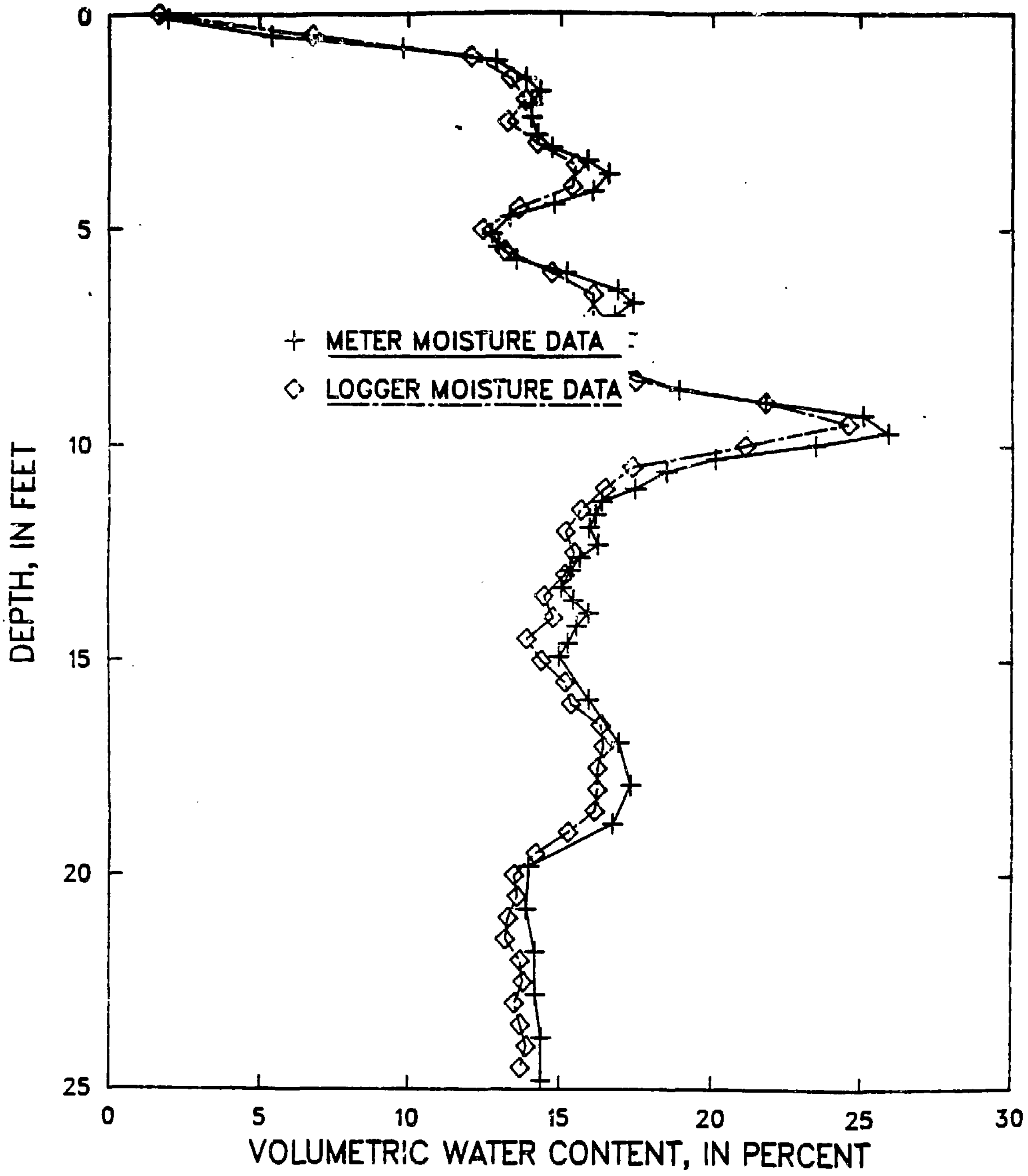

Figure 5. Comparison of water-content profiles in borehole UE-25 UZ-N13 obtained with the neutron-moisture meter and the neutron-moisture logger.

Table 2
Summary of field calibration-curve linear-regression analyses

Borehole number	Borehole description	Rock type	Depth interval (feet)	Independent variable	Dependent variable	Number of samples	Regression coefficient	Intercept	Slope
UE-25 -N4, -N6, -N8, -N12, -N13, -N14	6-inch cased neutron access hole	Alluvium/ colluvium	0-50	Neutron-moisture-meter counts	Gravimetric water content of drive core	39	0.67	**-1.60**	**1.73x10^{-3}**
UE-25 UZ-4	6-inch uncased reamed core hole	Nonwelded and bedded tuffs	78.0-227.8	Neutron-moisture-logger counts	Volumetric water content of rotary core	40	.89	**-6.92**	**5.36x10^{-2}**
UE-25 UZ-4	do.	do.	do.	Neutron-moisture-logger counts with decentralized tool	do.	40	.87	**-6.93**	**5.57x10^{-2}**
UE-25 UZ-4	4.25-inch uncased core hole	do.	241.5-358.6	Neutron-moisture-logger counts	do.	21	.94	**-7.86**	**5.11x10^{-2}**
UE-25 UZ-5	6-inch uncased reamed core hole	do.	100.9-343.7	do.	do.	79	.80	**-3.54**	**4.49x10^{-2}**
UE-25 UZ-4, UE-25 UZ-5	do.	do.	78.0-227.8 100.9-343.7	do.	do.	119	.86	**-5.88**	**5.07x10^{-2}**

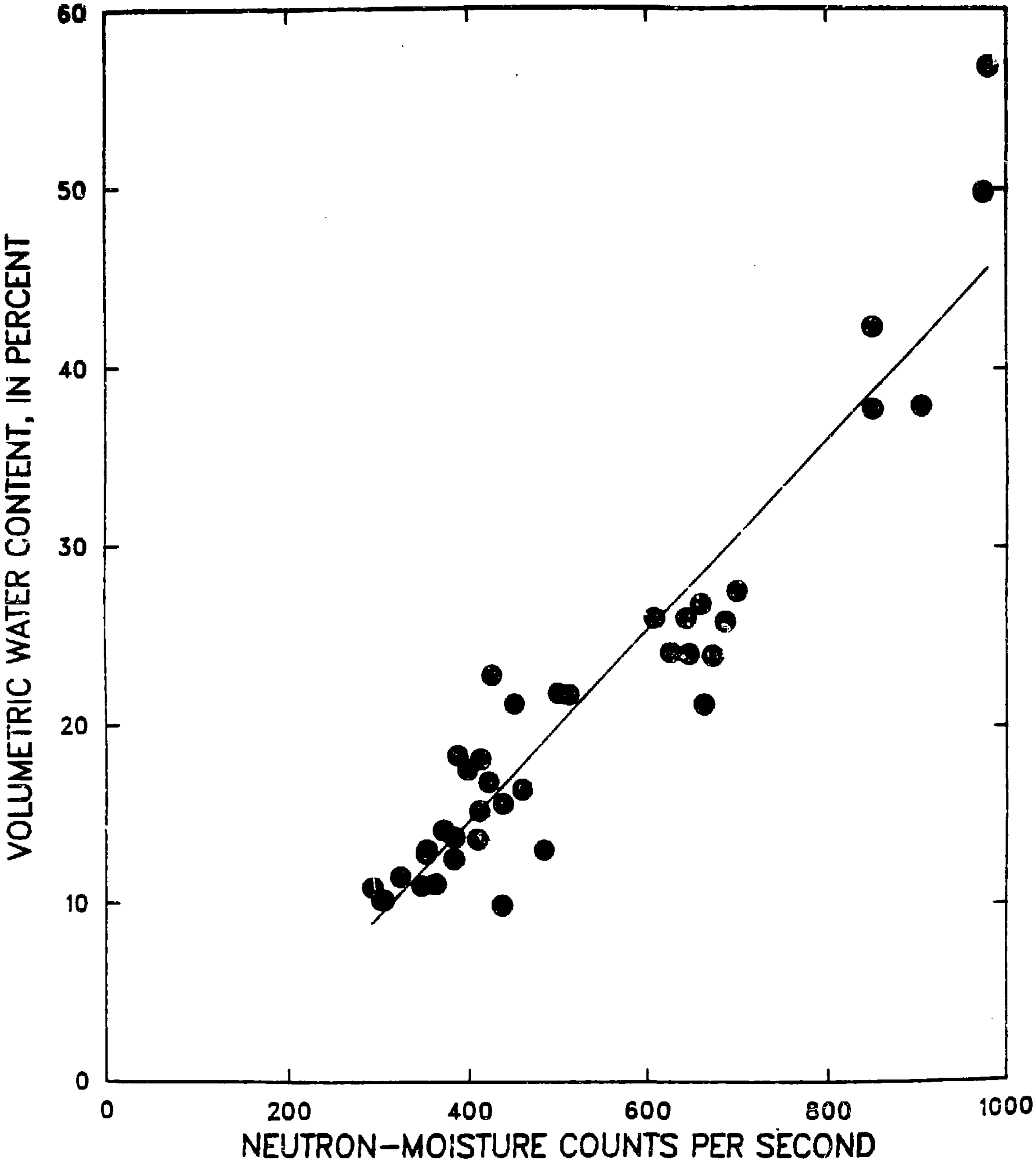

Figure 6. Field-calibration data with linear-regression line for neutron-moisture logger in 6-inch uncased section of borehole UE-25 UZ-4.

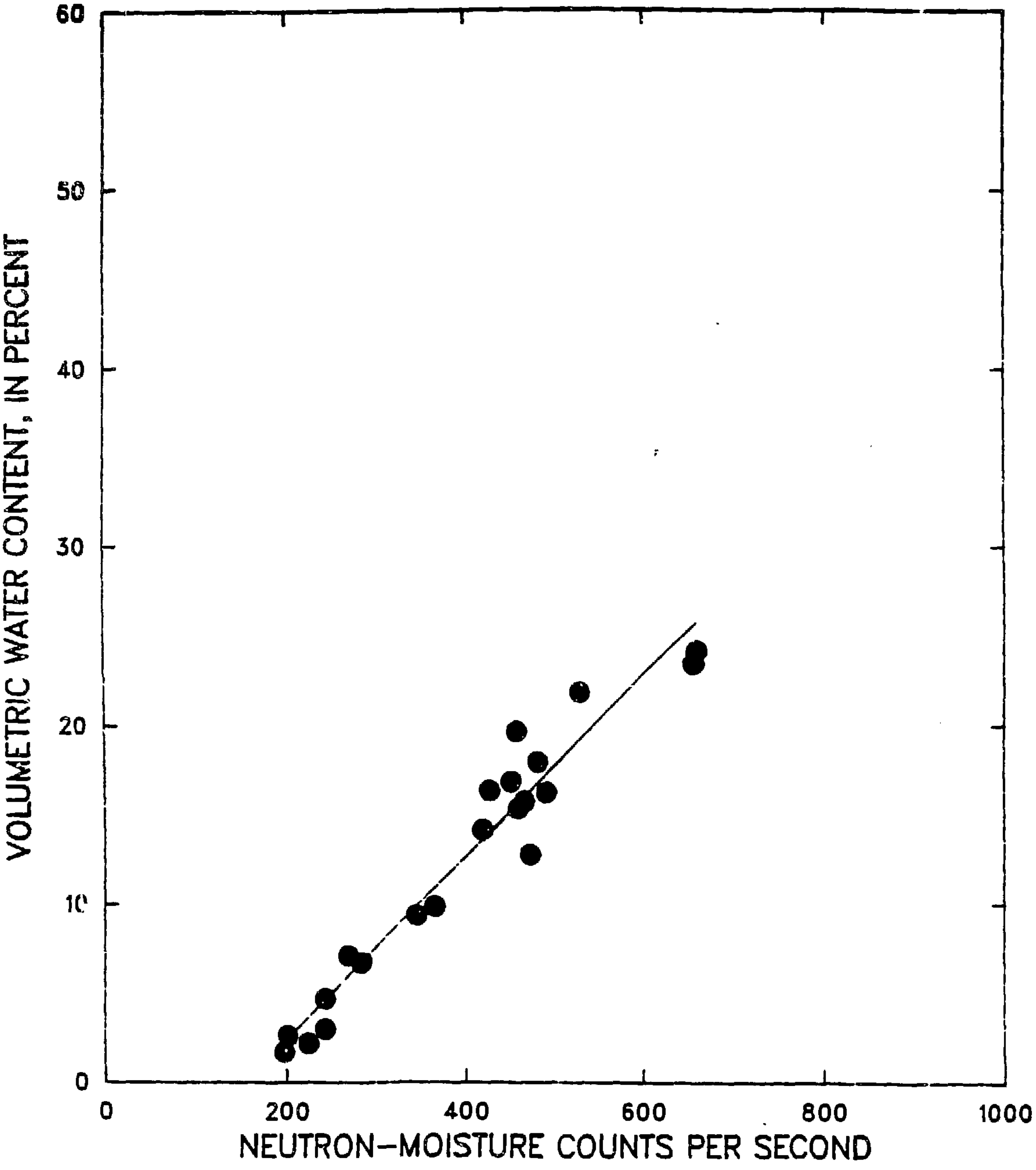

Figure 7. Field-calibration data with linear-regression line for neutron-moisture logger in 4.25-inch diameter uncased section of borehole UE-25 UZ-4.

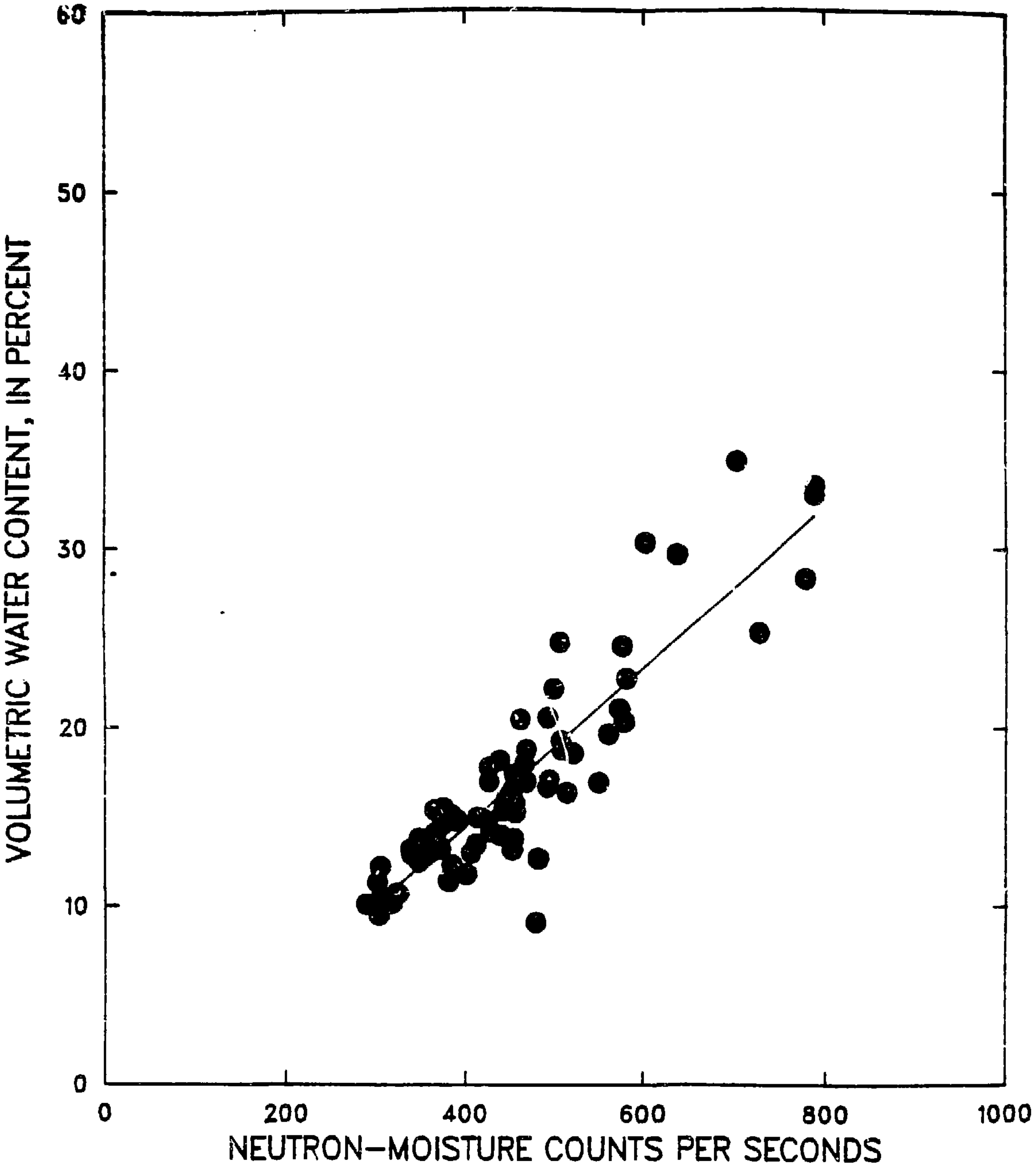

Figure 8. Field-calibration data with linear-regression line for neutron-moisture logger in 6-inch uncased section of borehole UE-25 UZ-5.

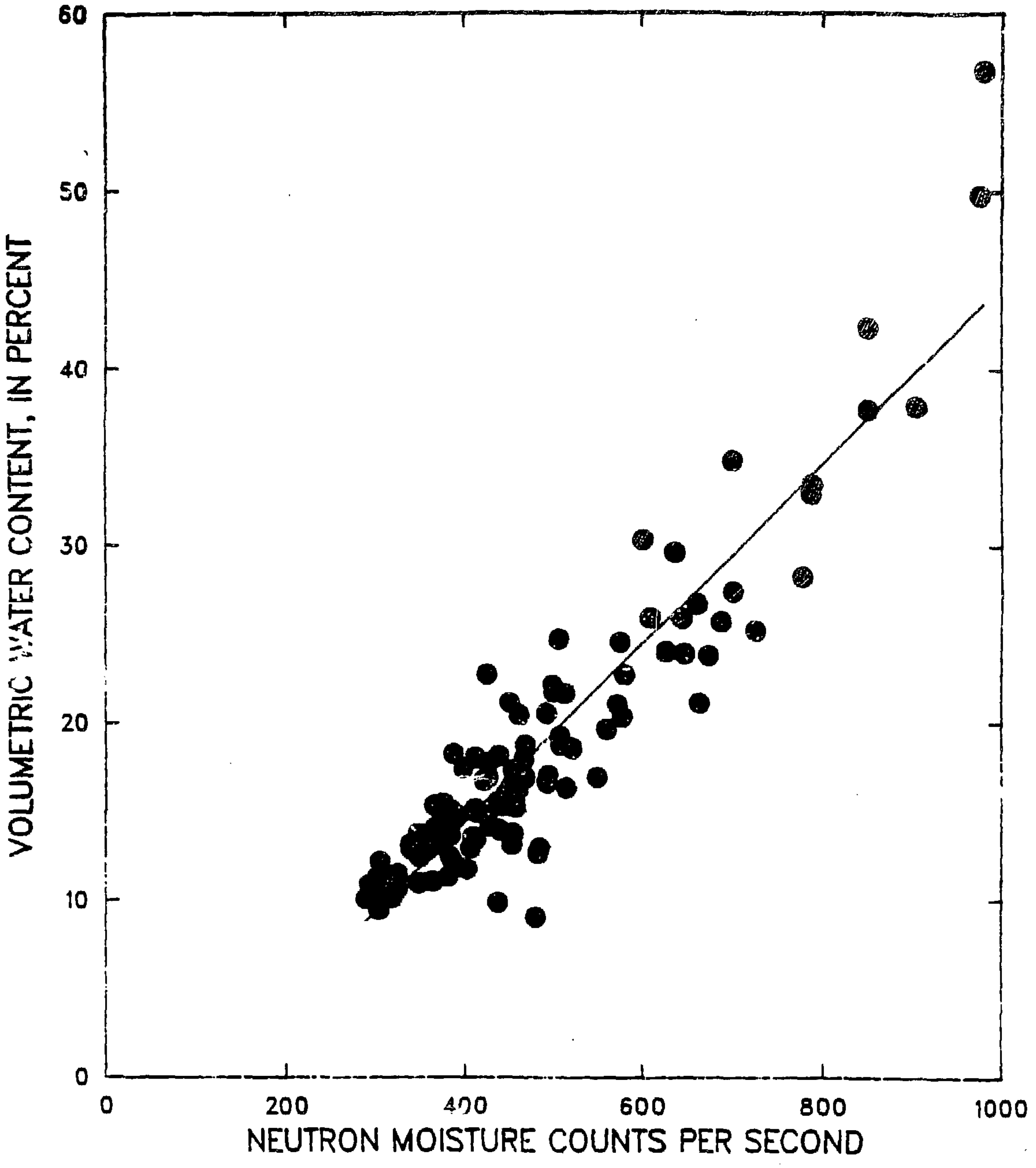

Figure 9. Field-calibration data with linear-regression line for neutron-moisture logger in 6-inch uncased section of boreholes UE-25 UZ-4 and UE-25 UZ-5.

Both the density (Holmes, 1966; Olgaard and Haarh, 1968) and the chemical composition (Cotecchia et al. 1968) of the formation rock have been shown to significantly affect neutron-moisture-tool calibration curves. Some of the variation in the data for the uncased holes in nonwelded and bedded tuff was the result of these factors. However, the expected variation in chemical composition of the formation rock in the core holes examined in this study was relatively small. Scott and Castellanos (1984) present data showing little variation in the chemical composition of rock units with depth over a large area of Yucca Mountain. All penetrated rock units originated from the same highly siliceous magma chamber and contained approximately the same content of elements with relatively large thermal neutron-capture cross sections, for example CA, Fe, and Ti; therefore, variations in the geochemistry are not expected to affect the calibration curves. An analysis of the effects of geochemical variations on count rates from borehole intervals with similar density and water content will be conducted after more data has been collected.

If the chemical composition of the formation rock is assumed insignificant, then a qualitative examination of the effects of rock density on the calibration curves is possible. To attempt this examination, core samples from the nonwelded and bedded tuff zones were divided into three intervals: less than 81.2 lb-mass/ft^3, 81.2 to 96.8 lb-mass/ft^3, and greater than 96.8 lb-mass/ft^3. Results of correlating tool output with volumetric water content for each of the three density intervals are summarized in Table 3. Virtually no difference was observed in regression equations for the two lower-density intervals. However, a much larger difference was observed between the two lower-density intervals and the higher interval. The slope of the higher-density interval was larger, which agrees with results from Holmes (1966) and is the opposite of findings by Olgaard and Haarh (1968). The field-calibration data base definitely needs to be expanded with further laboratory calibrations. Further, theoretical calculations similar to those of Olgaard and Haarh (1968) are needed to quantify the density effects on the calibration curves for the rock types encountered in this study.

Summary

The use of innovative drilling and coring techniques, which minimizes disturbance of the formation rock and core, permitted the field calibration of neutron-moisture tools in relatively large diameter cased and uncased test holes and in several rock types. Reasonable agreement was observed between field calibrations in cased neutron holes completed in alluvium-colluvium and in a laboratory-calibration chamber containing sand packed around a section of casing. Field calibrations utilizing linear-regression analyses showed a good correlation between neutron-moisture counts and volumetric water content for sections of uncased boreholes in nonwelded and bedded

Table 3
Calibration regression analysis for different density intervals
[lb-mass/ft³, pound mass per cubic foot]

Density data				Linear regression results		
Density interval (lb-mass/ft³)	Number of core points	Average core density (lb-mass/ft³)	Standard deviation (lb-mass/ft³)	Regression coefficient	Intercept	Slope
<81.2	39	76.8	3.1	0.61	2.60	4.40×10^{-2}
81.2-96.8	40	89.3	4.4	.78	3.60	4.37×10^{-2}
>96.8	39	103.7	5.0	.85	10.6	5.90×10^{-2}

tuff. Variations in chemical composition were considered to have little effect on calibration curves. However, bulk density variations were shown to produce significant effects on the calibration curves; these effects are not understood at this time.

Further laboratory calibrations are planned using rock materials that more closely simulate the geochemistry and density of the formation rock. Theoretical calculations are needed to estimate the effects of variations in chemical composition and to estimate the effects of density on count rate. As the field-calibration data base increases in size, statistical analysis of these data will continue; curves will be generated for cased and uncased sections of welded tuff to obtain calibration curves that compensate better for the effects of density variations.

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Biographical Sketch

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