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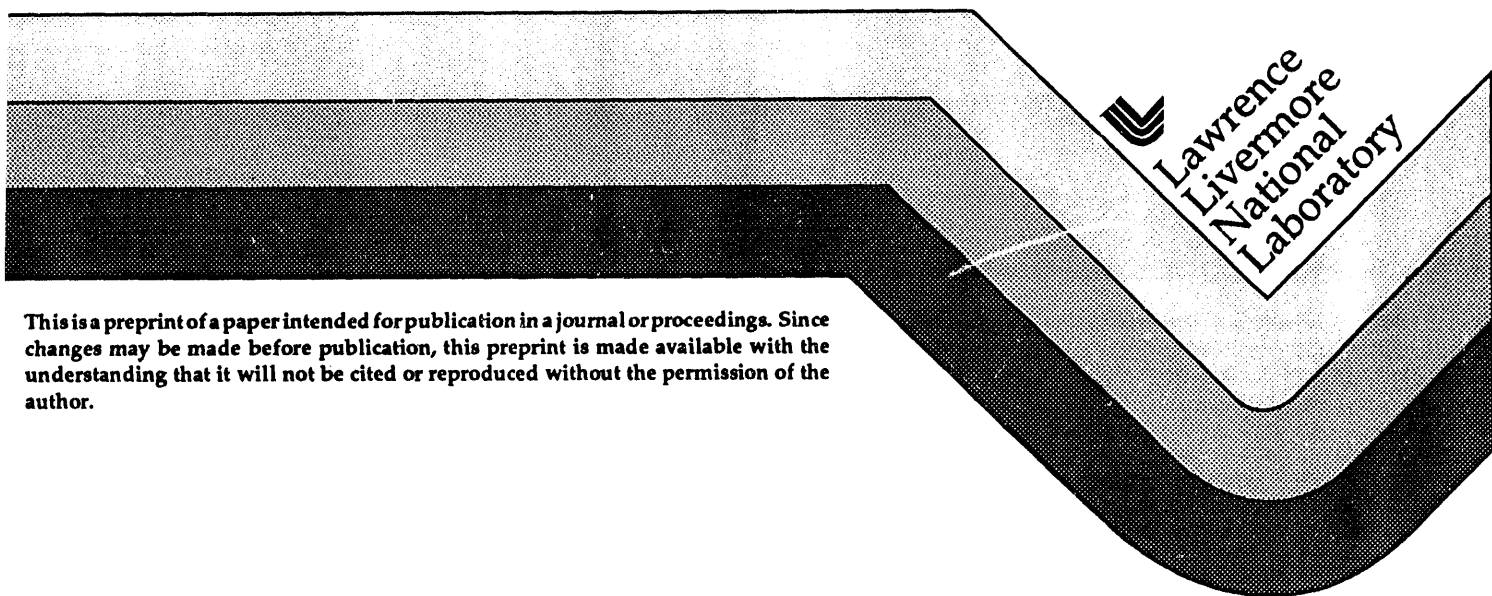
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A COMPARISON OF THE MOISTURE GAUGE AND THE NEUTRON LOG IN AIR-FILLED HOLES AT NTS

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Two methods are commonly used to measure water content of geologic materials by neutron diffusion. One is used mostly in agricultural, mining and civil engineering areas and is called a moisture gauge. The other is used principally in petroleum and mineral exploration, and is called a neutron log. Both are used at NTS, the moisture gauge principally in tunnels, the neutron log in vertical drilled holes. There is little communication between the two industrial groups, and the measurement instruments have evolved with very different operational characteristics, and one important physics difference, the source to detector spacing. The moisture gauge has a very short, 0-6 cm, spacing, with little internal shielding, and count increases with water. In contrast, the neutron log has a long spacing, 30-50 cm, substantial internal shielding, and exhibits decreasing count with increasing water. Because of its short spacing the moisture gauge gives better bed resolution than the neutron log. Because its count increases with water, the moisture gauge is more strongly affected by water in the borehole, especially in dry formations. In these conditions the neutron log is the method of choice. In air-filled holes, if source size or logging time is not a constraint, the relative sensitivity of the two tools to water is determined by the relative strengths of borehole effects as fluid, holesize, or tool-wall gap. If source size is a constraint for safety reasons, the short spacing provides higher countrates for a given detector efficiency and thus better relative precision in determining the true count. If source size is limited because of detector or electronics saturation, the short spacing will be better at high water content, while the long spacing will be better at low water content. In any case the short spacing may have an advantage because it can make better contact with the hole wall and it can be more easily corrected for gap. We currently use the long spacing tool in vertical holes at NTS because that is the only tool available from logging contractors. Since we are most concerned with high water contents, the short spacing tool could prove to be better.

INTRODUCTION

Neutron diffusion has been used for many years to measure the water content of geologic materials. A large literature describing the technique has evolved. But in fact two methods, each with its own literature, have come into use. Many years ago workers in different industries made independent decisions to use different methods. The instrument used in soil science, agriculture, and construction is called a moisture gauge. The moisture gauge is often used in tunnels at NTS, and in the Yucca Mountain Project (Buscheck et al, 1991.) The instrument used in the petroleum industry and to some extent in the mining industry, is called a neutron log. A modified version of the neutron log is routinely used in vertical holes at NTS (Axelrod and Hearst, 1984.) The two methods exhibit very different operational characteristics, and, in addition, one important physics difference: the source to detector spacing.

The physics difference between the two methods is illustrated by Figure 1 (Tittman, 1956), which shows a simple calculation of the thermal neutron flux as a function of distance from a fast-neutron source. On the left side of the plot, the flux increases with increasing water content; on the right side the flux decreases with increasing water

content. Moisture gauges use short source-detector spacings (the left side). Neutron logs use long source-detector spacings (the right side).

Many users of each method are almost unaware of the other method, and they are certainly unaware of its capabilities. It is unfortunate that with all the possible design choices, within each industry the tools of the various manufacturers are remarkably similar. This gives the user only two choices for an instrument best suited to the task at hand. This paper compares the two methods and suggests ways in which their virtues could be combined. The result may surprise users of both methods.

Since the two methods use somewhat different terminologies, some quantities need to be specified for this paper:

1. Water content is expressed in volume percent, and it is assumed that this is equivalent to the volume percent of fresh water, or the "hydrogen index." (It should be kept in mind that all neutron tools measure total hydrogen content, and hydrogen is present in many rocks and soils in forms other than free water.)

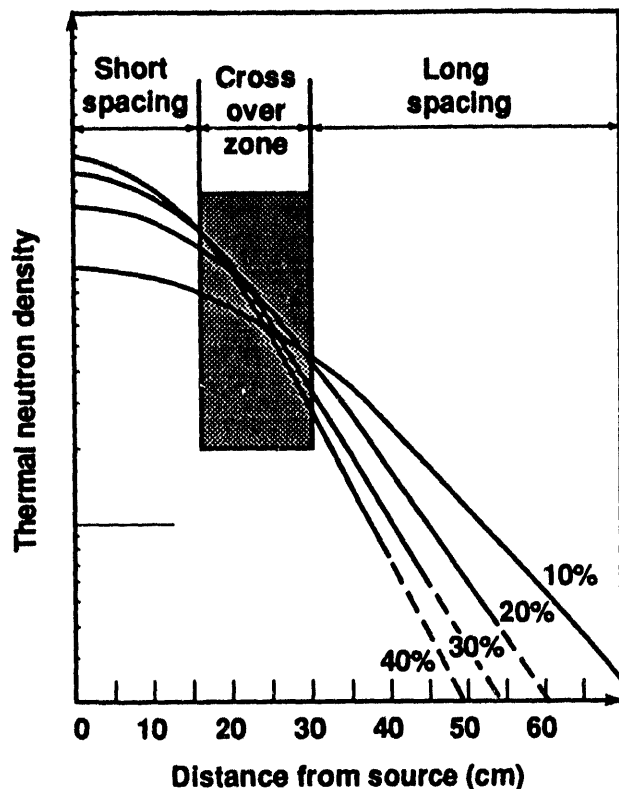


Figure 1. Thermal neutron density for a point source of Ra-Be neutrons in infinite formations with different water content. These curves were calculated using age theory, which is known to apply poorly to hydrogenous media. Thus they must be used as qualitative guides only. (Tittman, 1956)

2. We define the radius of investigation as the distance into the formation beyond which, if all material were removed, there would be no more than a 10% change in the neutron count rate.

3. A "tool" is the sensor portion of the instrument system used to make the water content measurements.

4. We define the source-detector spacing as the distance from the center of the source to the center of the detector. Note that detector lengths differ significantly from tool to tool.

5. We define the sensitivity as the change in the neutron count rate caused by a given change in water content.

To compare tools with greatly different count rates,

it is convenient to express the sensitivity of a tool as

$$S = \frac{dc/dw}{(c_{\max} - c_{\min})/2}$$

where c is the count rate, w is the volume percent water, and c_{\max} and c_{\min} are the maximum and minimum values of the count rates over the range of water contents desired to be measured. (In practice, since different tools are calibrated over different ranges of water content, it is convenient to choose the range of water content to be the same for all tools being compared, and determine c_{\max} and c_{\min} from each tool's response curve.) Then, if all count rates are normalized by dividing by $(c_{\max} - c_{\min})/2$, the sensitivity as defined will simply be the slope of the plot of count rate vs water content.

Since the slope of the count rate vs water content plot for the neutron log is opposite in sign from that of the moisture gauge, all plots for the neutron log have been inverted. Thus the plotted sensitivities are comparable. We shall discuss the sensitivities as if they were the same sign.

THE MOISTURE GAUGE

A good general reference for the moisture gauge is *Neutron Moisture Gauges*, published by the International Atomic Energy Agency (1970). (It should be noted that some authors refer to the moisture gauge as a "moisture probe," "moisture meter," or occasionally even "neutron log.") The source-detector spacing of a moisture gauge is generally between zero (the source is a ring around the center of the detector) and 6 cm or so. The detector is designed for thermal neutrons. Figure 2 shows that the spacing strongly affects the sensitivity of the measurement, in agreement with Tittman's (1956) calculation. Calibrations above 40% water content are not shown in this figure, but it is evident in Figure 1 that the moisture gauge must lose sensitivity and become nonlinear at some water content above 40% (Preiss and Grant, 1964).

The tool is usually designed to either lie on the ground surface or be a close fit in a small-diameter (approx. 5 cm) tubing-lined borehole. The source is usually very weak (approx. 50 mCi AmBe or PuBe), and the tool is hand-held while being placed on the surface or lowered into the borehole. In a hole, the tool is lowered to different depths, and a measurement lasting tens of seconds is made at each depth.

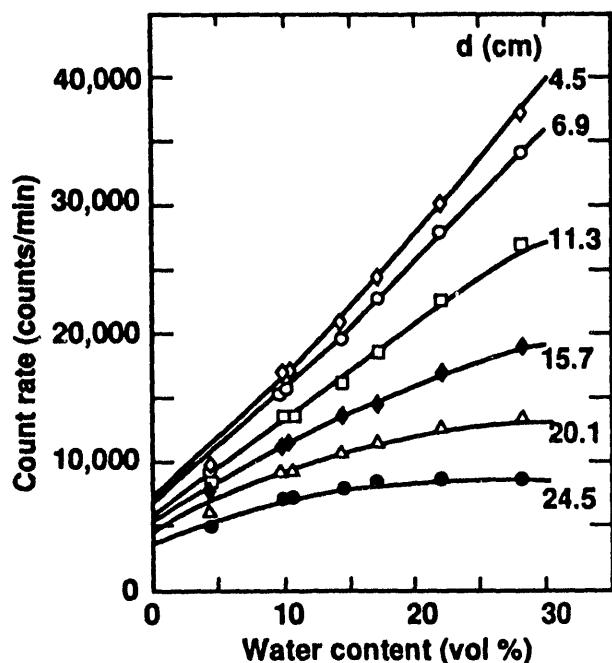


Figure 2. Effect of source-detector distance d on the calibration curve for a sub-surface neutron moisture probe with a short (1.25 cm long, 2.5 cm diameter ^6Li glass) detector situated at different distances from the source. (Olgaard and Haahr, 1967).

Because of the close fit, the borehole fluid and the gap between the borehole wall and the tool are usually irrelevant. However, experiments in boreholes significantly larger than the tool diameter have shown that placing the tool centered or decentralized in an air-filled hole 12 to 15 cm in diameter does not affect its sensitivity (Tyler, 1988; Klenke and Flint, 1991). On the other hand, because the count rate increases with water content, filling the hole with hydrogenous material, or even lining it with a thin layer of hydrogenous material, greatly reduces sensitivity (Tittman, 1956; Klenke and Flint, 1991; Goncalves et al., 1992).

The radius of investigation of any neutron tool depends on the water content. In the case of the moisture gauge, different investigators report different radii of investigation for tools with approximately the same source-detector spacing, depending on the design of their experiments. The most plausible values appear to range from about 20 cm for 5% water to about 14 cm for 32% water (Silvestri et al., 1991; Nyhan et al., 1983).

THE NEUTRON LOG

A good general reference for the neutron log is *Well Logging for Earth Scientists* by Ellis (1987) or *Well*

Logging for Physical Properties by Hearst and Nelson (1984). The neutron log often has two detectors: a long-spaced one, with a source-detector spacing of 55 to 65 cm, and a short-spaced one, with a source-detector spacing on the order of 40 cm, which is used to correct the long-spaced data for borehole effects. If a two-detector tool is used, the detectors are generally designed for thermal neutrons, and the count rate is therefore perturbed by materials with a high capture cross section. If a single detector is used, it is generally surrounded by a thermal-neutron absorber such as cadmium so that mostly epithermal neutrons are counted, and the perturbation caused by absorbers is reduced.

The tool is generally run in uncased holes significantly larger than the tool diameter. It has a housing designed to resist formation fluid pressures as high as 150 MPa. It is commonly pulled up the hole at a speed of about 20 m/min, for distances on the order of km, and consequently the source is fairly large, often several curies.

Because the tool is smaller than the hole, its data are significantly perturbed by borehole diameter, rugosity, and fluid. The correction procedure developed by industry for the two-detector tool, which uses the ratio of counts in the two detectors, is designed for holes filled with hydrogenous liquid, and it is not satisfactory for use in dry holes (Alger et al., 1972). It is possible to correct the data from the long-spaced detector for these perturbations (Axelrod and Hearst, 1984). Consequently, we shall only discuss a single-detector tool in the remainder of this paper.

Sherman and Locke (1975) performed an elegant experiment that showed that the radius of investigation of both single- and two-detector thermal and epithermal neutron logs for water contents of both 22 and 35 vol% is about 18 to about 25 cm, depending on the design of the tool. This radius is somewhat larger than the radius for the moisture gauge. Note that the volume of investigation of the neutron log is markedly larger than that of the moisture gauge because of the much greater source-detector distance.

RELATIVE SENSITIVITIES

A good way to compare the moisture gauge and the neutron log is to compare their normalized sensitivities to water. Figure 3a shows sensitivity, as defined earlier, for different moisture gauges under various conditions. Although the absolute count rates vary greatly with differences in conditions, the sensitivities are essentially the same.

Figure 3b shows a similar plot for a single-detector epithermal neutron log in a water-filled and an air-filled

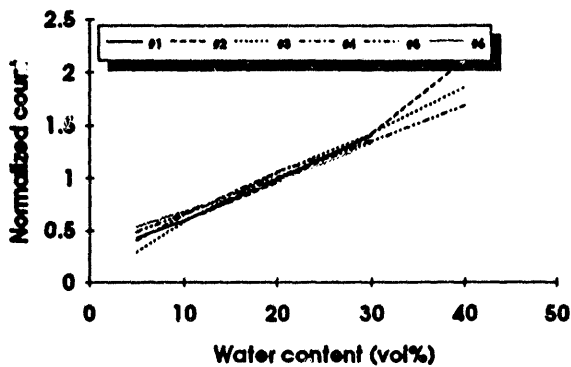


Figure 3a. Normalized count rate for moisture gauges: #1, 4.5-cm spacing 3 cm-dia gauge in tight-fitting hole (Olgaard and Haahr, 1967); #2, 5-cm spacing, surface gauge (IAEA, 1970); #3, 14-cm spacing 5.25 cm dia gauge in 7.5 cm tube (van Bavel et al, 1954); #4, zero spacing, 3.8-cm-diam gauge centered in 14-cm-diam casing (Tyler, 1988); #5, 8-cm spacing 3.8-cm-diam gauge sidewalled in 12.8-cm-diam casing (Klenke and Flint, 1991); #6, 5-cm-spacing, surface gauge with 0.038 cm Cd shield (Preiss and Grant, 1964). Normalization extrema at 10% and 30%.

hole, and a thermal neutron log (with a gamma-ray detector, because data for single detectors of two-detector tools are not available in the literature) in a water-filled hole. Note that the thermal log is less sensitive than the epithermal log. Since that tool uses a gamma-ray detector, this difference in sensitivity does not necessarily indicate that a neutron log based on a single thermal-neutron detector would be less sensitive than an epithermal log.

It is clear that the epithermal neutron log is significantly more sensitive than the thermal moisture gauge at water contents below about 20%, and that the moisture gauge is significantly more sensitive than the neutron log at water contents above about 30%. For example, the slope for a moisture gauge in an air-filled hole (van Bavel et al., 1954) is about 0.038. For a neutron log in an air-filled hole between 5% and 10% water (Tittman et al., 1966), the slope is about 0.11. Between 30% and 40% water, it is about 0.016. Evidently the neutron log is at least twice as sensitive as the moisture gauge in the 5 to 10% range and half as sensitive in the 30 to 40% range.

The observable quantity for these tools is the number of neutrons detected by the detector over a specific time interval: the count rate. The precision expected in the measurement of the water content then depends on the precision of the measurement of the count rate, the relative change in count rate that is caused by a given change in

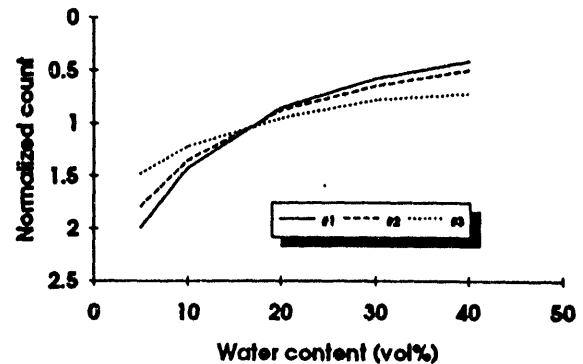


Figure 3b. Normalized count rate for sidewalled neutron logs: #1, Epithermal neutron log in 20-cm water-filled hole (Tittman et al., 1966); #2, epithermal neutron log in 20-cm air-filled hole (Tittman et al, 1966); #3, thermal-neutron gamma-ray log in 15-cm-diam water-filled hole (Tittman, 1956). Normalization extrema at 10% and 30%.

water content, and changes in the count rate due to perturbations other than water content. In principle, with any of these tools one can select a source strength and/or counting time large enough that the relative error in determining the true count rate is insignificant. In that case, the difference in sensitivity is unimportant. Adequate precision can be obtained with either tool. Frequently, however, the maximum count rate is limited in two distinct ways. If the source must be very small, higher counts will be seen with the moisture gauge, and thus its precision will be better. If the count rate is limited by detector or electronics saturation, then the sensitivity is a useful way to compare different tools.

For any tool that depends on neutron transport through the formation, when both water content and bulk density are zero, no neutrons are returned to the detector, and so the count rate must also be zero. Consequently, at some combination of low values of density and water content the neutron log must have a maximum count rate. Below those values its count rate must decrease with decreasing water content, and it will behave like a moisture gauge. For example, we test tools for leakage through the shielding by suspending them in air. The count rate under those conditions is very small.

PERTURBATIONS

The literature (IAEA, 1970, for example) recommends that a moisture gauge be calibrated for each

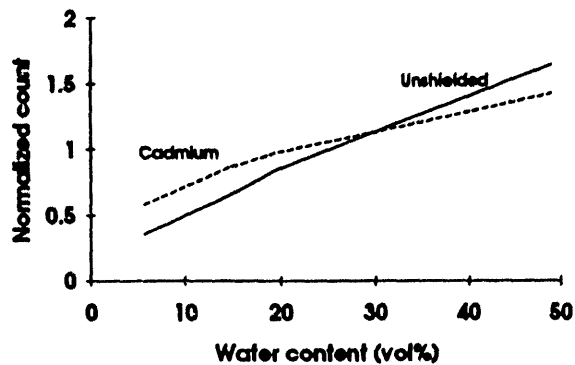


Figure 4a. Normalized count rate for an 8-cm-spacing moisture gauge in a 2.4-m hole in the NTS neutron calibrator, with and without cadmium shield. Normalization extrema 6 to 49%.

specific soil in which it is used. Normally three properties of the formation cause perturbations in the neutron count rate: elements with high neutron-absorption cross sections, bulk density, and hydrogen that is not associated with free water. In addition, the count rate can be affected by changes in the size of the borehole and by gaps between the tool and the wall of the borehole.

The effect of non-pore water is independent of the type of tool, and some corrections can be made by measuring the non-pore water content of samples of the formation by heating to high temperatures or using nuclear magnetic resonance (McKague et al., 1992).

The effect of high-cross-section elements can be reduced by shielding the thermal-neutron detector with a shell of a thermal-neutron absorber such as cadmium (Preiss and Grant, 1964). This procedure, however, can affect the sensitivity of the tool.

The effect of the other perturbations in small boreholes is discussed in the literature, but each discussion refers to a specific tool. It would be useful to compare the magnitudes of each effect on the moisture gauge and the neutron log, to help users select a tool for a specific application. Therefore we compared the effects of bulk density and sonde-wall gap on a moisture gauge and a neutron log in the Nevada Test Site (NTS) neutron log calibrator. We also used calibrator data to investigate the effect of the cadmium shield.

The calibrator consists of two cylindrical aluminum shells, each 2.4 m inside diameter, 4.8 m outside diameter, and 2.3 m high. Each cylinder is divided into six 60°

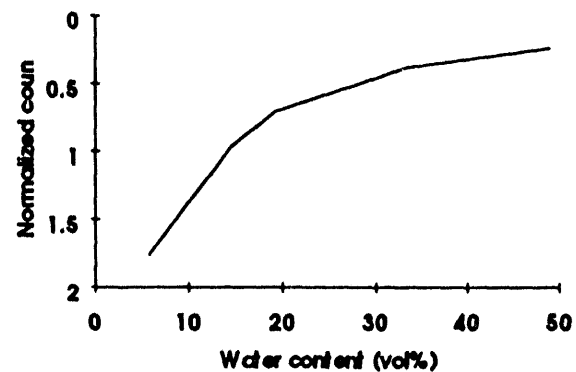


Figure 4b. Normalized count rate for a collimated 43-cm spacing epithermal neutron log in a 2.4-m hole in the NTS neutron calibrator. Normalization extrema 6 to 49%

segments, and each segment is filled with a different mixture of silica sand, alumina, aluminum hydrate, and water. The mixtures are chosen to provide desired values of density and effective water content. Aluminum casings 30 and 5 cm in diameter pass vertically through each segment. In this experiment five cells, all having a bulk density of approximately 1.4 g/cm^3 , were used to create a constant-density calibration curve. Water contents were 5.8%, 14.6%, 19.3%, 33.4%, and 48.9%. Then two other cells, with different bulk densities but the same water content as two of the first five, were used to investigate the density effect.

To reduce hole-size effects, the neutron log tools used at NTS are in most cases surrounded by polyethylene shields except where the tool contacted the wall of the hole. The shields are roughly elliptical in cross section, with the minor axis normal to the wall of the hole, and each tool is inserted into a cylindrical hole tangent to the circumference of its shield. For the 2.4-m hole, the major axis is about 45 cm and the minor axis about 22 cm.

Figure 4a shows the sensitivity of a moisture gauge in the 2.4 m central hole, with and without a 0.079-cm cadmium shield. This shield has twice the thickness of the shield used by Preiss and Grant (1964), for which the sensitivity is shown in Fig. 3a, and the same thickness as the shield in our commercial epithermal neutron log. The sensitivity of the unshielded tool agrees with those shown in Figure 3a. The 0.079-cm cadmium shield substantially reduces the sensitivity of the gauge to the point that it is not much more sensitive than the neutron log at high water content. Evidently, although a 0.038-cm cadmium shield

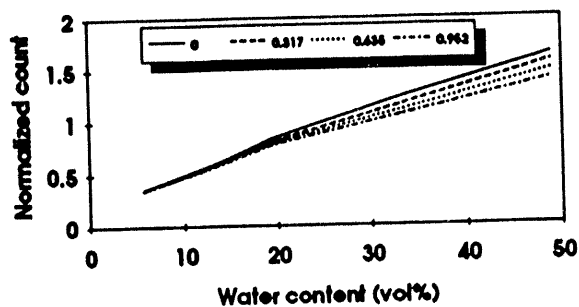


Figure 5a: Normalized count rate for an 8-cm-spacing moisture gauge in a 2.4 m hole in the NTS calibrator at different gaps between the tool and the wall of the hole. The legend shows the gap in cm. Normalization extrema 6 to 49%

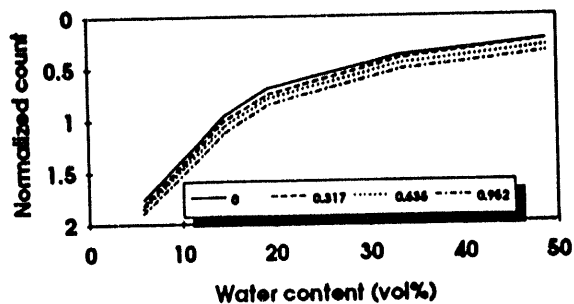


Figure 5b: Normalized count rate for a collimated epithermal neutron log in the NTS calibrator at different gaps between the tool and the wall of the hole. The legend shows the gap in cm. Normalization extrema 6 to 49%.

does not significantly affect the sensitivity, doubling the thickness does. We have no data on the effect of cadmium thickness on reduction of the effect of high absorption cross-section elements. Figure 4b is a similar plot of a neutron log, with a built-in 0.079 cm cadmium shield, again in the 2.4-m-diameter central hole. The sensitivity of this tool agrees with those seen in Figure 3b. Each tool was forced against the wall of the hole.

The simplest way to compare the effects of other perturbations among tools is to calculate the water content that would be obtained using a standard calibration curve, such as those in Figure 4, with and without the perturbation, and then compare the derivative of the calculated water content with respect to the size of the perturbation.

Effect of density

The effect of bulk density on a moisture gauge in a small-diameter hole is discussed by Couchat (no date), cited in IAEA (1970). No hole size or gauge type is stated. Couchat found that a change in bulk density of 0.4 g/cm^3 changed the apparent water content by about 4 vol% at water content values of both 20 vol% and about 35 vol%. This change gives a derivative of 10 vol% water per g/cm^3 . The effect of density on an epithermal neutron log in a 30-cm hole is similar to the effect seen in the 2.4-m hole, discussed below (Axelrod and Hearst, 1984.).

In our tests in the 2.4-m hole, we used two cells with densities higher than those used to obtain the curves in Figure 4. One had a bulk density of 1.88 g/cm^3 and water

content of 20.3% to compare with the cell of bulk density of 1.34 g/cm^3 and water content of 19.3%. The other had a bulk density of 2.44 g/cm^3 and water content of 32.9% to compare with the cell of bulk density of 1.34 g/cm^3 and water content of 33.4%. We found that the density effect was a function of water content and was approximately the same for the moisture gauge and the neutron log. The derivative is about 5 vol% per g/cm^3 at 20 vol% water and 15 vol% per g/cm^3 at 33 vol% water. It is, of course, feasible to correct the water content for the effect of density using data from a density log (Axelrod and Hearst, 1984). In fact, some moisture gauges include density logs, and automatic, in-field, corrections could easily be developed.

Effect of borehole size

Abee (1979) observed the effect of hole size from 5.1 to 10.2 cm on a centralized moisture gauge and found it to vary from 0.07 vol% per cm at 5 vol% water to 1.2 vol% per cm at 27 vol% water. Tittman et al. (1966) obtained similar results for a decentralized neutron log over a larger range of hole sizes: 0.08 vol% per cm at 5 vol% water to 1.1 vol% per cm at 30 vol% water.

Effect of tool-wall gap

In small air-filled holes, data are sparse for both tools. Abee (1979) states that the count rate of a 5-cm-dia moisture gauge does not depend on whether a tool is centered or ecentered in an air-filled hole up to 10.2 cm in diameter. Tyler (1988) suggests that an effect is observed in a 14-cm hole. The effect of gap on an epithermal neutron log in a 30-cm hole is similar to that in the 2.4-m hole discussed below (Axelrod and Hearst, 1984).

Figure 5 shows the effects of gap on the moisture gauge and the neutron log in the 2.4-m hole in the NTS calibrator. For the moisture gauge the effect is negligible at 10 vol% water and becomes as high as 0.8 vol% per cm at 40 vol% water. For the neutron log, the effect is somewhat larger: 0.2 vol% per cm at 10 vol% water and 1 vol% per cm at 40 vol% water. For either tool, it is possible to measure the gap and apply a correction if desired (Axelrod and Hearst, 1984).

DISCUSSION

The petroleum industry has, quite justifiably, used the neutron log because the moisture gauge is overwhelmed by hydrogenous fluids in fairly large, liquid-filled holes, which are normal in petroleum wells. It is clear that the neutron log is the appropriate method for any hole filled with hydrogenous fluid unless the tool is a tight fit in the hole.

At NTS, however, we commonly use neutron diffusion to measure water content from air-filled boreholes. The effects of perturbations are similar for the two tools. The effects of density and borehole size are about the same for the two methods and so need not be considered. The moisture gauge is affected somewhat less by the gap between the tool and the wall of the hole than the neutron log and, because it is much shorter than the neutron log, the gap is likely to be smaller. This difference, however, is not usually a major consideration. The remaining choice then concerns the sensitivity, because the more-sensitive tool can be used with a smaller source or run at a higher logging speed.

If a smaller radius of investigation is desired, the moisture gauge is the tool of choice in high-water-content formations (but note that even the moisture gauge loses sensitivity above about 40 vol% water). If a large volume of investigation (with its consequent poor depth resolution) is acceptable, the neutron log is the tool of choice for low-water-content formations. If the entire range of water content is expected, the moisture gauge will give better thin-bed resolution and a smaller overall numerical uncertainty, whereas the neutron log will give a smaller overall fractional uncertainty.

It is not practical to run a conventional moisture gauge in a deep hole because its cable is so short, it is not watertight, and its source is so small that it must be operated at fixed stations. It is also impractical to use the logging winch, the many-km-long cable, and the heavy pressure casing of a neutron log in short holes. It would not be difficult to produce moisture gauges with long spacings or neutron logs with short spacings. (Some laboratory tools

have already been built with variable spacings; such tools might also be commercially feasible.) Then we could choose the spacing on the basis of bed-thickness resolution and sensitivity to water, without being constrained by operating characteristics such as source size, logging speed, cable length, or the need for a winch with depth-drive mechanism.

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