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MOISTURE MONITORING IN
LARGE DIAMETER BOREHOLES

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Over the last ten years the role of the vadose zone in contaminant transport has come under increased scrutiny as a result of past and present waste disposal practices. Of critical importance for the licensing and safety of waste disposal facilities is the design and implementation of a monitoring strategy designed to measure the rate and magnitude of fluid migration towards the saturated zone. At the present time, however, vadose zone monitoring tools have not found universal acceptance due in part to: poor performance in harsh environments, depth requirements, and limited life expectancy. The objective of this paper is to extend the range of one vadose zone tool, the neutron-neutron borehole tool, to use in preexisting saturated zone waste disposal monitoring wells.

Monitoring the unsaturated zone below waste disposal/treatment facilities serves two purposes. It provides data on the integrity of the liner system used to reduce or prevent migration of wastes to an aquifer and provides data on the rate of contaminant movement in the unsaturated zone. In traditional soil physics studies of water movement in the unsaturated zone, parameters involving the hydraulic gradient, conductivity, and water content are often the minimum data requirements. In most monitoring scenarios however, the type of data needed to determine liner failure, or waste migration is most often measured as a change in the equilibrium of the system. For example, the start-up of a land treatment facility would result in an increase in the soil profile water content due to the increased infiltration. This increase in water content would move downward with time as the wetting front progressed. Therefore, unsaturated monitoring equipment must be able to detect changes in the soil water equilibrium; either the matric potential or the water content. The determination of the rate and magnitude of fluid migration in the unsaturated zone requires the measurement of the changes in soil water content and the velocity at which these changes are occurring. The magnitude of changes in water content provides the volume flux term, i.e., How much fluid is moving? The measurement of the velocity of the migration

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provides the time frame over which these changes are occurring.

The use of borehole geophysics in soil physics was first introduced in the 1950's. At that time, the downhole neutron-neutron or neutron moisture meter (Hillel, 1978) logging tools were introduced. The tool has the advantage of being non-destructive, repeatable, and not prone to failure with time as are most in situ instruments. The tool consists of three main components; a probe containing a source of high energy neutrons, a detector of low energy (or slowed) neutrons, and a scaler or ratemeter to monitor the low energy neutrons.

The principal of operation is well described by others (Hillel, 1978, Holmes, 1956). The basic operation of the tool consists of measuring the number of high energy neutrons slowed and returned of the detector. In theory, the number of returned neutrons is primarily a measure of the hydrogen atom density of the soil, which in most soils, is also a measure of the volumetric water content. The tool's range of influence from the borehole is generally inversely proportional to the volume wetness of the soil. In general, the tool must be calibrated for the soil used.

The data received from neutron logging is generally plotted as the volumetric water content verses depth. When logs of the same hole are plotted as function of time of measurement (the scheduling of logging times is generally dependent on the type of operation, for example, weekly or daily logs are often used on agricultural fields to determine irrigation scheduling), it is often quite easy to see the both the direction of moisture movement and the causes of this movement. For example, a strongly decreasing water content in the upper meter of soil zone during the summer months is indicative of moisture uptake by plant roots and/or evaporation. On the other hand, a uniform decrease in water content measured at each depth over time indicates that drainage by gravity is dominant (Scisson et al., 1982). Under these conditions, the change in the soil profile water content divided by the time over which this change occurred may be interpreted as the water flux (Kirkham, 1983). The presence of a sharp change in water content at some depth in the profile which appears to move downward over time indicates that a wetting front is moving downward. It is the type of behavior that might be expecting from a leaking landfill or impoundment liner.

Although this technique has been available for over 20 years, its acceptance in the waste monitoring field has been limited for several major reasons. The two primary difficulties are the borehole geometry traditionally used for neutron logging, and the limited range of influence of the instrument.

The first difficulty arises from the fact that neutron logging is highly dependent on borehole geometry and size, and borehole casing material. The most desirable borehole configuration for a 4.7 diameter probe is a 5 cm diameter thin-walled aluminum tubing installed in a hole augered only slightly larger than 5 cm. Calibration curves can, however, be generated for larger diameter boreholes (Abeele, 1978) but only limited work has been done in this area. Drilling techniques also will affect the logging results, especially if water is used in the drilling process.

The majority of borehole geometry difficulties can be overcome if one recalls that the purpose of the monitoring is leak detection and monitoring. If boreholes drilled under less than optimum conditions, results of logging following drilling may not reflect the conditions of the unsaturated zone outside the drilling radius. However, when results of routine monthly or quarterly logging are compared from this same borehole, relative change from the initial conditions may reflect changes other than the drilling effects. Changes such as a wetting front moving from below an impoundment will be easily abstracted from the logs even when drilling effects are evident.

The second major difficulty arising in waste site monitoring lies in the range of influence of the probe outside the borehole. Typical ranges of influences for smaller neutron loggers is 5 - 80 cm from the borehole. In the case of a large landfill or impoundment, peripheral monitoring wells will not detect point source leaks (seam failures or punctures of membrane liners). Many of these deficiencies may be overcome using slant drilling techniques or installation of off-vertical monitoring wells prior to landfill or impoundment construction. In addition, field studies (Johnson et al., 1981) have shown considerable lateral migration of fluids from landfills located above the water table. The source of this lateral migration is most likely cause by the natural inhomogeneities in the soils underlying the landfills. This lateral spreading would increase the detectability of a leak using a limited number of neutron access holes. In the case of land treatment facilities the difficulties of limited range of influence are insignificant provided an adequate number of monitoring wells are available to overcome the spatial variability of the soil and application rate properties.

Objectives of the Study

The objective of this study was to evaluate the applicability of neutron logging technology to large diameter boreholes similar to those used at waste site investigations. To accomplish these goals, both field and laboratory experiments were completed. Both of these studies were aimed at calibrating the neutron logger in larger (15 cm) diameter boreholes. The laboratory segment consisted of a calibration experiment to determine the sensitivity of the tools (in this case a Troxler model 3222 with a 10 millicurie Am-241/Be source) in a 15 cm diameter steel-cased borehole. The field experiment consisted of neutron logging two recently drilled steel-cased holes from which core samples were available for comparison. Large diameter PVC casing was not used in the calibration procedures due to its increased neutron adsorption and the limited use of large diameter PVC for monitoring wells. Small diameter PVC, on the other hand, is used extensively at waste disposal sites and has received considerable review in the literature (Abeele, 1978).

Laboratory Calibration

Laboratory calibration procedure for neutron loggers have been well documented (International Atomic Energy Agency, 1970). The standard procedure consists of logging a prepared material at several known water

Table 1
Laboratory Calibration Data

Gravimetric Water Content (gr/gr) 100%	Density gr/cm ³	Volumetric Water Content (cm ³ /cm ³) 100%	Count Ratio* 0.023	Standard Deviation of Count Ratio 0.0018
0.2	1.62	0.3	0.023	0.0018
3.4	1.56	5.3	0.074	0.0024
7.4	1.48	10.9	0.121	0.0034
11.5	1.52	17.5	0.168	0.0024
15.3	1.53	23.8	0.205	0.0039
18.6	1.59	29.6	0.237	0.0043

*Average of nine values.

contents. It is essential that the calibration material and casing be similar to that expected in the field. For this study, a steel culvert pipe, 90 cm in diameter was filled with 0.59 cubic meters of fine-grained sand. A 6 cm diameter steel water well casing was placed in the center of the calibration tank. The wall thickness of the casing was 4.0 mm. The sand was packed around the casing to achieve a dry bulk density of 1.6 gr/cm³. All neutron counts were taken 45 cm below the top of the sand surface with the probe centered in the casing using steel stabilizers. Keeping a non-directional tool centered in the borehole is essential if the results are to reproduceable. Steel stabilizers were attached to the bottom of the downhole probe to minimize interference with the counting.

Calibration counts were taken over six water contents, ranging from less than 1% to 28% by volume. Water contents were incremented between readings by removing the sand from the calibrating tank and mixing a measured quantity of water with the sand in a small rotary mixer. After thorough mixing, the sand was replaced in the tank and compacted to a dry bulk density of approximately 1.6 gr/cm³. At each water content, nine, one-minute neutron counts were collected to determine the degree of scatter or background noise introduced by the large casing. Core samples were collected at each water content for laboratory analysis of gravimetric water content and dry bulk density.

Table 1 shows the average values of the material properties and the corresponding neutron count ratios during the calibrations. Count ratio is a normalized variable, calculated by dividing the actual counts by the logger's standard count.

Figure 1 shows the gravimetric water content of the core samples plotted as a function of the count ratio. Figure 2 shows the same count ratio plotted against the volumetric water content. both plots show a strong linear dependence (Figure 1 $r^2 = 0.997$; Figure 2 $r^2 = 0.994$) of the

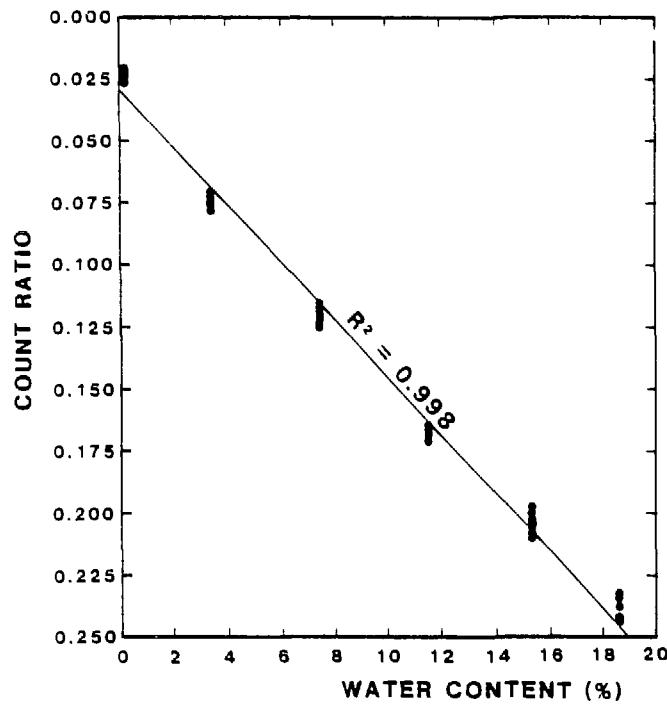


Figure 1. Laboratory calibration data; count ratio vs. gravimetric water content.

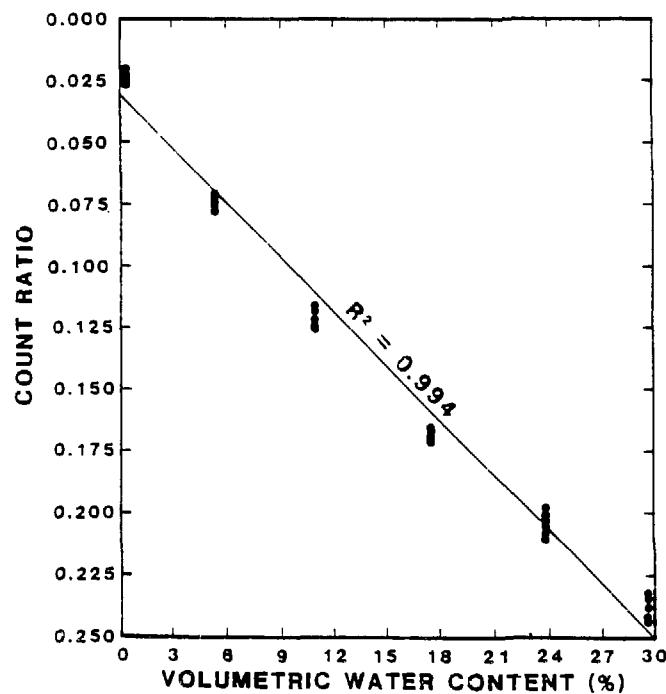


Figure 2. Laboratory calibration data; count ratio vs. volumetric water content.

form:

$$w = 87.372Cr - 2.687 \text{ (Gravimetric)}$$
$$\theta = 136.78Cr - 4.302 \text{ (Volumetric)}$$

where Cr is the count ratio, w is the gravimetric water content and θ is the volumetric water content.

Figure 2 shows a slightly better fit, best explained by the inaccuracies of the bulk density measurements used to calculate the volumetric water content for Figure 3. Although the measured bulk densities in Table 1 show a variation of 9%, the difference in bulk densities during the calibration as measured by the volume of soil in the calibration tank did not vary by more than 3%.

The laboratory data clearly shows that the linear or nearly linear relationship of returned thermal neutrons to the soil water content is preserved under borehole conditions not normally used in soil physics studies. Some deviation from linearity is evident at very low water contents, but this was expected since very few neutrons are being thermalized by interactions with soil water. Since few field soils exist in this range (0-3% by weight), a linear best fit should not effect most interpretations. It is clear from Figures 1 and 2 that gravimetric or volumetric water content changes of 1% - 2% or greater can accurately be measured in large diameter steel-cased boreholes similar to those used for saturated zone monitoring at hazardous waste sites.

Field Calibration

To better predict the behavior of the neutron logger under actual field conditions, logs were run on two deep boreholes drilled in support of the U.S. Dept. of Energy's Nevada Test Site. The boreholes logged (designated U3Fd-N1 and N2) were drilled to assess the moisture conditions in thick (>300 meter) unsaturated alluvial valleys. The holes were located approximately 200 meters apart. Both boreholes were drilled with a pneumatic downhole hammer system and cased with 15 cm O.D. steel casing. The drilling technique was optimal for preserving in situ moisture conditions since: a) no water was used in drilling, b) the casing diameter was only nominally smaller than the drilled hole diameter and c) the casing was driven directly above the drill bit, this minimizing the air flow past the formation.

In order to calibrate the neutron logs, core samples were collected at various intervals during the drilling. Laboratory analysis of dry bulk density and gravimetric water content allowed for the calculation of the volumetric water content. Figure 3 shows the volumetric moisture content from cores as a function of depth. This figure indicates that borehole U3Fd-N1 had significantly higher moisture content.

Neutron logs were run immediately after drilling. Counts were taken at 30 cm intervals. Count ratios taken at the core depths are plotted in Figure 4. As can be seen, two separate and distinct calibration lines must be used if a linear regression is to be used. The calibration

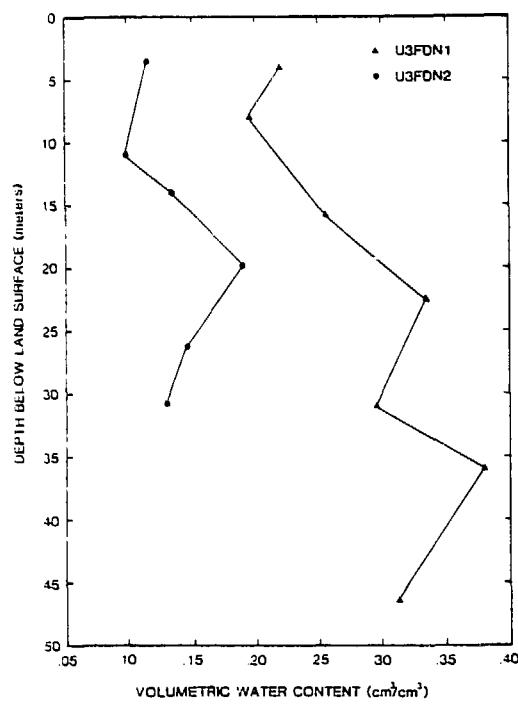


Figure 3. Soil moisture profiles from cores at U3FD-N1 and U3FD-N2.

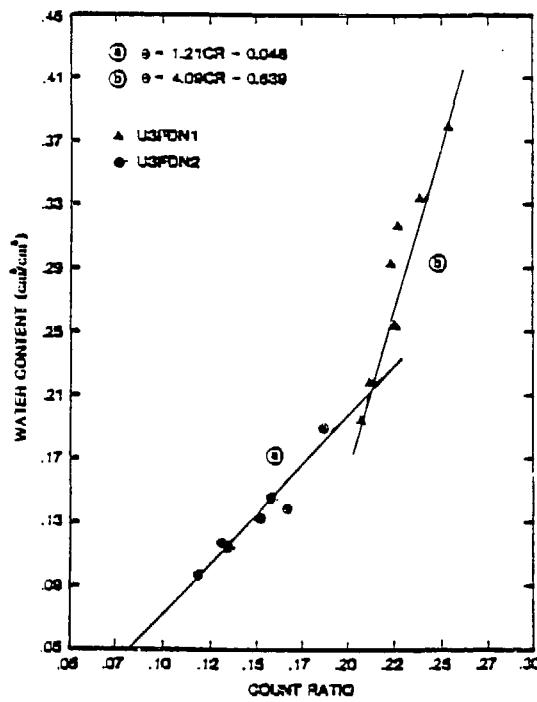


Figure 4. Count ratio vs. core water content from boreholes U3FD-N1 and U3FD-N2.

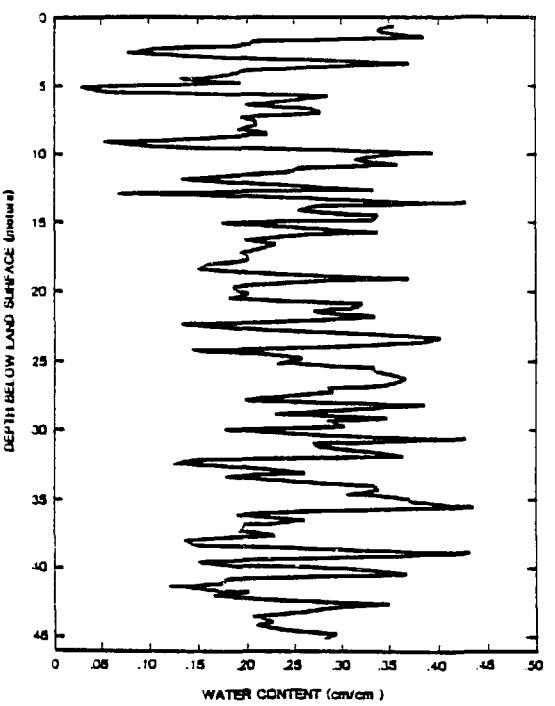


Figure 5. Calibrated moisture content vs. depth for borehole U3FD-N1.

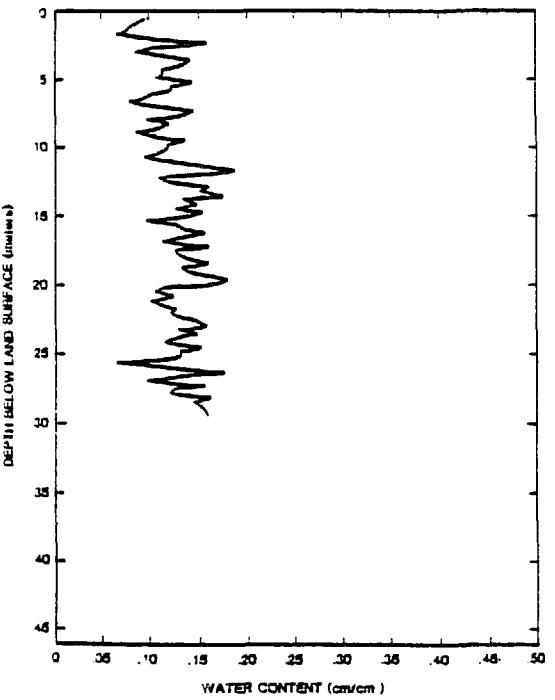


Figure 6. Calibrated moisture content vs. depth for borehole U3FD-N2.

Table 2
Field Calibration Coefficients

Borehole	Slope	Intercept	R^2
U3FD-N1	4.0858	-0.6388	0.96
U3FD-N2	1.2114	-0.0475	0.96

coefficients are given in Table 2. The high regression coefficients indicate that the linear regression approach is quite adequate.

Using this calibration data, moisture profiles for each borehole were calculated and are shown in Figures 5 and 6. These figures show that significantly more water is contained in the soil profile penetrated by U3FD-N1. This data, in combination with the increased variance of moisture content in U3FD-N1 can be used as indicators of water movement and redistribution.

Conclusions

The results of both laboratory and field experiments indicate that the neutron moisture gauge traditionally used in soil physics experiments can be extended for use in large diameter (up to 15 cm) steel cased boreholes with excellent results. This application will permit existing saturated zone monitoring wells to be used for unsaturated zone monitoring of recharge, redistribution and leak detection from waste disposal facilities. Its applicability to large diameter cased wells also gives the soil physicist and ground-water hydrologist a new set of monitoring points in the unsaturated zone to study recharge and aquifer properties.

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