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VADOSE ZONE MOISTURE MEASUREMENT THRU STEEL CASING
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7. Abstract Westinghouse Hanford Company has initiated investigation into the use of a standard moisture gauge for measurement of in-formation moisture content from cased wells. The presence of air in the borehole does not destroy the instrument response, in fact, the response is very sensitive to formation moisture from steel-cased boreholes. Calibration of the prototype instrument configuration and some experimental characterization for various borehole constructions have been performed and reported. Recommendations for future study are also provided.		
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Vadose Zone Moisture Measurement Through Steel Casing Evaluation

July 28, 1995

Russel R. Randall

Introduction

Two methods are commonly used to measure the water content of geologic materials in situ¹ using neutron irradiation and detection². One is used mostly in agriculture, mining, and civil engineering and is called a moisture gauge. The other is used principally in petroleum and mineral exploration and characterization. These two techniques have evolved very differently on separate technical paths, with quite different operational characteristics.

Vadose zone moisture characterization and monitoring at the Hanford site places many restrictions upon either of these in situ methods of borehole measurement. The wells are generally steel cased and air filled³. The petroleum industry has used neutron instrumentation^{4,5} since May 1940 to characterize the amount of hydrogen in earth formations surrounding a borehole. However, this environment is both fully saturated and the borehole is water filled, unlike the Hanford well conditions. The moisture gauge is generally run in a PVC pipe with the smallest air gap between tool and pipe wall^{6,7}. The Hanford wells range in inner diameter dimensions from 4 inches to 20 inches.

Moisture gauge experience in the agriculture industry indicates that access tubing larger than the probe causes significant problems with moisture measurement. Therefore, a proof of principal test was conducted in September of 1994. Moisture calibration models were constructed under PNL supervision⁸ in the Lampson facility of Pasco, Washington. These models were one phase of a Cooperative Research and Development Agreement, CRADA, between Westinghouse Hanford Company, Pacific Northwest Laboratories, Schlumberger, and Haliburton. The feasibility test was a simple measurement of a moisture gauge in the seven models. Three moisture contents for each an 6 inch and an 8 inch steel cased boreholes. The seventh model has a high water content and thickness of 18 inches sandwiched between low moisture zones.

The basic response of the moisture gauge in these models was encouraging. In fact, the response was a very sensitive function of the formation moisture. The results of this test indicated a moisture gauge could be used for a majority of the wells at Hanford. Therefore, a tool carrier was constructed to house a moisture gauge. The instrument response was then investigated at the Pasco models for this tool configuration. This report contains these results, as well as several well log examples. The overall conclusion is that an in situ measure of moisture for common Hanford wells is quite feasible.

Theory of Response

The basic premise used in neutron instrumentation measurement techniques for quantifying hydrogen content in earth formations surrounding a well bore is the moderating power of hydrogen as compared to the most common elements in these earth formations. Thus the original neutron tool in 1940 was a simple neutron source and thermal neutron detector housed in a pressure housing. The distance between source and detector in this sonde was long enough to place the instrument response in the characteristic region labeled far field. Typical environment for this logging sonde is fluid filled non cased borehole and formation pore space fully saturated.

The far field response is determined when the length between source and detector is larger than the characteristic radius of the thermal neutron cloud surrounding the source. Thus as the moderation power of the earth formation (higher porosity) increases, then the thermal neutron cloud compacts and the count rate observed in the detector decreases^{4,5}. Similarly, a very small separation between source and detector yields the opposite response called a near field regime, where increase in hydrogen density increases observed count rate.

The agriculture industry has adopted the near field response for there tools of choice^{6,7}. Petroleum and mineral exploration industries have alternatively used the far field for all versions of porosity measure of choice^a. These different choices are a result of the vastly different environments for the sonde in each industry. A near field response tool would be dominated by the water filled borehole in the petroleum industry. The agriculture industry only need shallow holes and can choose the construction for the measurement of moisture content. The petroleum industry chooses borehole construction for very different reasons, and any porosity measure must operate in the existing borehole configuration. There are many other reasons for this separate technologic evolution, but these are the major aspects.

The calibration of these instruments to formation hydrogen content is routinely performed for either industry sector. However, the instrument response is complicated by a host of other parameters in addition to the quantity of hydrogen. Borehole size, position of sonde within borehole, type of material in borehole, lithology of earth formation, salinity of pore fluids, clay or bound water, wellbore rugosity, thermal neutron absorption cross section, temperature, and pressure all influence¹⁰ the observed count rate. It is clear that the absolute quantification of any instrument design for hydrogen concentration is at best difficult. The petroleum industry developed a strategy of one basic calibration coupled with an exhaustive instrument characterization for all of the other variables. Typically, the agriculture industry calibrates for each environment encountered. Thus they have many calibrations and few if any applied corrections.

^a Schlumberger has recently introduced a new "porosity" measure⁹ that uses a very short spaced epithermal decay, but this measure is only used as a correction factor of standoff on the basic porosity response.

The near field regime for moisture measure has advantages for the conditions encountered at Hanford. Vadose zone is generally low moisture, thus the depth of investigation is large. The instrument does not require a high activity source. The steel casing and air filled boreholes enhance the instrument response. The moisture gauge is very low cost. Clay content and lithology range are minor effects for Hanford conditions.

Voids or air gaps behind casing are a potential problem for the application of a neutron instrumentation methods of moisture measure in typical Hanford conditions¹¹. The moisture gauge chosen for our present work has included in the instrument a ¹³⁷Cs source and a gamma ray detector. The Pasco models were used to investigate the use of this secondary detector as a data quality flag for the basic moisture response. That is, voids behind casing show up on the gamma ray observed count rate as an increase¹¹. Thus during log intervals where the "void detector" varies too high, the neutron response to moisture must be discarded. Later, it is hoped that an environmental correction can be applied to the thermal neutron count rate from this γ-ray response.

Cement completion behind casing, or between casing presents a problem for any neutron measure in the vadose zone. Low moisture content in the vadose can be dominated by the bound water in either cement or benonite seals. Cement between 6 and 8 inch casing was measured in the Pasco models. Surprisingly, the neutron moisture response retained formation moisture sensitivity, although reduced. At some thickness, a cement seal will reduce totally the formation moisture response.

In practical operation of in situ moisture measurement, the cement seals present another problem. The completion process does not necessarily insure that the annulus is 100% filled with cement. Any voids in the annulus can significantly interfere with the formation moisture response.

There is some question concerning a benonite seal. Theoretically, a benonite seal will self seal such that dry zones will remain dry in the benonite and wet zones will produce wet benonite. Therefore, the large amount of signal from the condition of the benonite may actually mirror the formation, and the final response is still characteristic of the formation moisture content. It may be that vertical depth resolution will be poorer in benonite sealed completion. This effect remains to be demonstrated. As with cement seals, the possibility of voids in the benonite may present a problem with the interpretation of the instrument response.

Calibration and Environmental Data

A CRADA, between Westinghouse Hanford Company, Pacific Northwest Laboratories, Schlumberger, and Haliburton was formed to look into the application of petroleum industry logging technology to the Hanford environment. Scintillation detection of radioactive contaminants, neutron measure of formation moisture, and gamma gamma density are the three aspects of the CRADA⁸. As part of the data quality objectives for

the moisture measurement, models were constructed at the Lampson facility in Pasco. The 7 models are property of Department of Energy, DOE.

There are 6 basic calibration models, 2 sets of 6 and 8 inch steel cased simulated formations. Each set contains three targeted formation moisture content, 5%, 12%, and 20% volume fraction of water. The seventh model is not a calibration standard. It contains an 18 inch "thin zone" with high moisture content sandwiched between 25 inch zones of low moisture content Table I

contains the laboratory assessment of the 6 calibration models as well as the seventh "thin zone" model. Note that the units for volume fraction of water are listed as VF. This is a definition established in this report as a means of avoiding confusion later when error discussion cannot easily distinguish between relative error in % from standard error in VF units. Thus 1 VF unit equals .01 by volume of water, or 1% water in formation.

Table I Calibration Models

Model	Casing Dia (inches)	Volume Fraction H ₂ O (VF)	Bulk Density (g/cm ³)
F	6	5.0	1.76
E	6	11.8	1.74
G	6	19.8	1.70
A	8	5.0	1.76
C	8	11.9	1.76
B	8	19.7	1.70
D-Bottom	8	5.1	1.56
D-Top	8	5.3	1.63
D-Middle	8	40.9	1.32

The tool was taken to Pasco models and data collected March 16 & 17, 1995. Prior experience with a moisture gauge in September 1994 demonstrated both azimuth and vertical homogeneity of each of the calibration models. Therefore, only vertical centering and one rotational setting was used for the data collected in March 1995. There was no selection of angle other than convenience given the hoist location and cable twist.

The tool was designed to house a moisture gauge and operate in a bow spring decentralized condition. A 3 3/8 inch diameter aluminum carrier mounted to the standard Radionuclide Logging System, RLS, cable head was constructed for this purpose. The moisture gauge is 1 7/8 inch diameter. A slot was milled out in the AL carrier through which the moisture gauge could be inserted. Its resting place is eccentric in the AL carrier just .25 inch from the front face (milled out slot) of the carrier. The gauge was secured in the carrier using hose clamps with the tightening bolt at the back of the carrier. A slot was cut in the outside circumference such that the hose clamp then rested below the face of the carrier. This was done to reduce points of snagging in a well logging operation, as well as performing reproducible placement of the fixtures and gauge during insertion. Also, the space between the moisture gauge and the back of the carrier was filled with foam to simulate 10% moisture. This was done in order to increase sensitivity to formation moisture.

Table II contains the results for the tool operation in carrier face parallel to borehole casing and flush with the casing. Included in Table II are the neutron count rates and the void indicator count

rates. These values are the average of 10 repeated runs of 100 seconds each. The quoted error is in c/s and is the observed rms of the 10 runs divided by square root of 10.

Table II Sidewall Instrument Observations

Model	Vol. Fraction H ₂ O (VF)	Neutron Count Rate (c/s)	Void Indicator (c/s)
F	5.0	53.76 ± .32	674.9 ± .57
E	11.8	82.76 ± .23	676.3 ± .85
G	19.8	109.14 ± .38	693.2 ± .85
A	5.0	41.65 ± .16	676.2 ± 1.0
C	11.9	62.80 ± .29	683.6 ± .95
B	19.7	76.17 ± .47	674.7 ± 1.4

The tool was also placed with the back flush and parallel with the casing wall. Table III contains data representative of the total loss of bow spring de-centralization. The intermediate moisture model was not used in this data set since there was very little effect upon the neutron moisture measure. Note that the void indication is very much influenced by the extreme de-centralization modes. Therefore, the use of this detector is demonstrated to be useful for

Table III Maximum Standoff Instrument Readings

Model	Vol. Fraction H ₂ O (VF)	Neutron Count Rate (c/s)	Void Indicator (c/s)
F	5.0	53.80 ± .21	876.5 ± 1.3
G	19.8	106.25 ± .34	902.1 ± .50
A	5.0	41.80 ± .16	891.9 ± .94
B	19.7	79.47 ± .14	934.7 ± .95

indications of changes in the borehole environment that may affect the neutron response. Calibration of this "void response" is not performed at this stage of the implementation of logging technology.

The data shown in Table III was taken in order to study the magnitude of standoff effects. The standoff measured in this data set is 2 5/8 inches for the models with a 6 inch casing. The bow spring is not expected to operate anywhere near this value. Therefore, the design of the bow spring need not be overly complicated in order for the instrument to function accurately. After a more final sonde construction design is established, a more fully characterized standoff error can be measured. At this proto type stage, it is deemed not to be cost effective to spend time in rigorous characterization since the overall magnitude of standoff effect is small.

The moisture response count rate is lowered going from the 6 to 8 inch borehole. This is reasonable since some of the material surrounding the tool has been replaced with air and a near field tool would then see lower count rates. However, the sensitivity to formation moisture content did not degrade as much as the gross count rates.

One possible explanation for the lack of standoff effects may be the iron casing. The iron casing may be acting as an extended source. Iron has a high cross section for neutron scattering, but very low loss of neutron energy for fast source neutrons. Therefore, the line of sight

from source to casing is interrupted, but the loss in energy is low. Effectively, the casing produces a shine of fast neutrons into the formation. More details need study because if this is true a centralized tool operation is safer in terms of tool hang up on some edge in the casing.

Another set of environmental effects was tested. A 6 and 8 inch dual string with air in the annulus between casings was simulated. A piece of 6 inch casing was

placed (centered) in each model with an 8 inch casing. Measurements were made with the tool face flush and parallel with the 6 inch casing. Table IV contains this

Table IV Two Strings Casing Air Between

Model	Vol. Fraction H ₂ O (VF)	Neutron Count Rate (c/s)	Void Indicator (c/s)
A	5.0	32.69 ± .93	675.4 ± 1.4
C	11.8	46.03 ± .23	683.8 ± .94
B	19.8	56.14 ± .33	703.4 ± 1.4

dual string completion configuration with air between the casing sets. The instrument response to formation moisture content is somewhat reduce from a single casing string, but only a small reduction in sensitivity. The count rate is nearly 1/2 the 6 inch single string models.

Hanford well completions have diverse configurations. This result is driven by the fact that many wells were constructed over the past 50 years, and by many different groups with different project goals. Therefore, dual casing string with cement filled annulus was also investigated. A 6 inch casing was used

as a center of a cement mold such that the outside diameter of the cement would fit into the 8 inch casing, in a centralized condition. Table V contains data recorded for these

Table V Two Strings Casing Grout Between

Model	Vol. Fraction H ₂ O (VF)	Neutron Count Rate (c/s)	Void Indicator (c/s)
A	.050	51.07 ± .14	680.9 ± 1.2
C	.118	61.60 ± .24	643.2 ± .68
B	.198	66.96 ± .35	688.8 ± 1.2

conditions. The tool is parallel and flush with the 6 inch casing.

Even though there is a demonstrated sensitivity to formation moisture content for the cement annulus between the 6 and 8 inch casing, practical well conditions may preclude the use of neutron measures for formation moisture, due to non uniform cement filling of the annulus. Changes in the volume of cement in the annulus would mask changes in formation moisture content.

Calibration Fitting

The transform commonly used for moisture gauges is a linear relationship^{6,7} between count rate and moisture content. The data plotted in Fig. 1 contains the calibration standard for the three 8 inch casing models as well as the other point obtained in the thin zone model. The standard calibration points are the filled squares, and the non standard point of the thin zone average is the open square. Clearly, the transform is not a linear function of count rate to volume fraction of water. With the large air gap inside the casing, one would

not expect a linear transform. The common usage of moisture gauges in the agriculture is in access tubes that are only large enough to pass the moisture gauge. Under these moisture gauge logging conditions, a linear transform may be optimum^{6,7}.

Model D was constructed as a thin zone investigation. Thus, the absolute values of the moisture content was sacrificed for the sake of uniformity and definite zone transition. Compacting the sand and alumna would have disturbed the zone interface, but not compacting results in

some ambiguity in the absolute value of the moisture content. Figure 1 contains the data for the zone average of the 40.9 VF reading, but as an open square since there is this error in the absolute value of the zone moisture content

Figure 1 Basic calibration data and fit for the too design implemented by WHC

The importance of this 41 VF reading is in the fact that the count rate to moisture transform is clearly not linear. Using only the three standard model readings shows only a minimal deviation from a linear response. However, the deviation from a linear relationship is outside of statistical precision. The amount of deviation from a linear relationship for the three data points in the 6 inch casing is even less. It is assumed here that the functional form for each casing set is to be the same form. Further, no polynomial will be used since these often yield oscillations which are not physical. That is, an asymptotic functional form is used to fit the three model sets for each casing size.

The three calibration points were used for the fit to a power law function for both casing sizes. An additional steering point near zero VF was used to better define a function in the extrapolated region. It is clear that there are some counts although a very small count rate at a zero level of moisture content. The functional is defined by the following equation:

$$V = a \cdot C^{\alpha} \quad \text{Eq. 1}$$

where a and α are the fit coefficients, V is the Volume Fraction of Water (VF units), and C is the dead time corrected count rate in counts per second. For the 6 inch casing, the resultant coefficients are:

$$a = 2.155\text{E-}3$$

$$\alpha = 1.946$$

The 8 inch casing set resulted in coefficients of:

$$a = 1.318E-3$$

$$\alpha = 2.210$$

The fitting results as well as the calibration points are shown in Fig 2 for both casing sets. The calibration data points used in computing the fit are shown in this figure, and the 41 VF data point for the 8 inch casing is shown, but was not used for the fitting process. A more complex functional relationship can fit the 41 VF data point better, but there are not enough points for many more coefficients. Also, there is some ambiguity for the absolute accuracy of this 41 VF value. In the future, a water point is recommended as an additional measurement for more complete characterization of the moisture response.

Figure 2 Basic calibration data and fit results, (solid lines) for both casing diameter sets.

Error Analysis

There are two basic error discussions. One error is the estimate of the absolute error from truth. Another error is the description of the instrument statistical precision or repeatability.

The absolute error can only be estimated by assuming that the models are absolute standards. Since these same models were used for the establishment of

Table VI Fit accuracy to models

Model	Vol Frac H ₂ O (VF)	Observed Vol Frac H ₂ O (VF)	Difference (VF)
F - 6"	5.0	5.0	0.0
E - 6"	11.8	12.0	0.2
G - 6"	19.8	19.9	-0.1
A - 8"	5.0	5.0	0.0
C - 8"	11.9	11.4	-0.5
B - 8"	19.7	20.4	0.7

the transform between count rate and volume fraction of water, the error of the fit from the models is very small. Table VI contains the resultant error of the fitted function from the quoted values of each of the models.

There are three regions of concern for a description of absolute error. The best established region is the region between the model values. Extrapolation of fit results outside of the fit points is generally problematic. This is one reason for choosing a functional form that is asymptotic with count rate. The region outside of the fit points below the 5.0 VF model is not too difficult. The absolute error is small

since the values are small. This condition does not hold for the region of high volume fraction of water, (i.e. higher than 20 VF in this study).

Estimates for the statistical precision of the instrument response is straight forward. The precision can be calculated based upon the count rates and sample times used. Alternatively, the precision can be measured by using multiple samples and analyzing the observed scatter. In fact, system integrity require a comparison of these two methods. Hardware instabilities and hidden variables in experimental design can be discovered using this approach of comparing the two statistical characterizations.

The six calibration models were each measured for ten repeat observations of 100 second samples. The observed root mean square standard deviation ranged between 0.5 and 1 c/s. The average difference between the computed and observed standard deviation is 0.03 c/s per 100 second samples. This is excellent agreement, and allows an accurate prediction of statistical precision from calculation based upon the counting statistics. Also, this result verifies that the instrumentation is stable and producing no extraneous sources of variance.

Figure 3 is a plot of the statistical precision for the instrument response given 30 second sample time. Initial field testing used sample times of 30 seconds. The predicted one standard deviation in VF units is plotted versus the observed volume fraction water in VF units. Note that the entire possible range of 0 to 100 volume fraction water is shown, even though values higher than 20 will rarely be observed in logged intervals. The error for moisture content below 20% by volume will be less than 1 VF.

The amount of statistical precision is a function of the data collection time. Therefore, it is possible to select a targeted precision based upon the goals of the particular project by choosing a suitable logging program. The depth sampling and time per sample can be tailored to the needs of the program. This can include different sampling within a single well. Stationary readings can significantly increase the statistical accuracy when required.

Field Testing Results

The first well chosen to log with the moisture gauge implemented by WHC was 299-E24-79. This well is one drilled as part of the Sisson-Lu infiltration study. Also, several of these wells were logged by the CRADA partner, Schlumberger. Moisture gauge measurements were also performed on selected wells as part of the original study, and these were repeated by Pacific Northwest Laboratory, PNL, this year.

The moisture gauge is typically sampled every 12 inches. The manufacturer often supplies a cable with tabs secured every 1 foot. The WHC system places a gauge into a carrier that is connected to the RLS logging truck. Therefore, depth sampling is computer controlled.

An anomaly was observed between one foot sampling and the WHC log sampling of 6 inches in the moist zone from 35 to 40 feet in the well. The expanded insert in fig. 4 shows the character of this discrepancy, which is well outside of statistical accuracy. A second log was performed at 1 inch sampling over this interval of question.

Figure 5 contains the data from these two logging passes sampled at 6 and 1 inch vertical depth spacing. Each sample point for the 6 inch spaced log is plotted with a closed square in order to demonstrate that the 1 inch spaced log matches (within statistical precision) at the same sample points. The conclusion is that the inherent instrument depth resolution is significantly finer than 6 inch vertical spacing. Note that all log data are displayed as collected and no processing filter has been applied.

The logging data sampled at 1 inch spacing demonstrates that the

Figure 4 Well log for moisture at 12 inch sampling, and an expanded section compared to a 6 inch sampling.

Figure 5 Comparison of log data sampled at 6 and 2 inches.

moisture lens from 35 to 38 feet in the well is in fact a laminated interval with at least two moisture zones separated by a drier interval in the center. Detail such as this is critical for modeling transport mechanisms and risk assessment.

Since the vertical depth resolution is so fine, the comparison of two logs run at different times is possible only if the sampling is at the exact same points in the well. Sampling every 6 inches in two monitor logging runs will generate very different data sets if the two passes are 3 inches different in the zero point. Small errors in the depth control may be caused by temperature expansion of the logging cable differences from summer to winter. A 0.17%, (17 parts out of 10,000), change in the expansion coefficient yields a 2 inch error at 100 feet into the well. If these differences are not adjusted for in the depth control system, then a monitor log may show differences that may either be erroneously attributed to statistical variations or changes in the moisture content of the formations.

Comparison of different instrument response can also be miss-leading if the instruments have different depth resolutions. A long spaced detector neutron response would not delineate the laminate character shown in fig. 5. Often a comparison between such an instrument and the moisture gauge would be concluded as error in one of the instruments, when both are reading correctly, but differently. Often the comparison would be labeled a statistical variation larger than expected.

Bed boundary definition with a non zero spaced detector instrument is troubled by non reciprocity¹². The measure point on a non zero spaced detector neutron instrument is skewed by the difference between a moderating formation and a relatively non moderating formation. The direction of logging changes the observed bed boundary of a contrasting zone change. This effect disappears for instruments with a zero spacing between source and detector.

Chronologically, the next well logged is located 75 feet north of the 2-7 crib. The well number is 299-W15-63. This well had been logged with the RLS in March of 1992, and showed man made contaminants of ⁶⁰Co and ¹⁵⁴Eu. Figure 6 shows a plot of the Cobalt and moisture content.

The first encountered formation of any significant moisture content is 95-100 feet in the well. This is also the first indication of cobalt contaminant in this well. This Touchet bed, a fine grained silt lens, has wicked the soluble cobalt north of the crib. In general, the moisture zones correlate well with the observed presence of cobalt. There is one interesting lack of correlation, in the Ringold from 111 to 120 feet. In this formation, the moisture content is somewhat uniform reading of 22 VF. Usually, this formation is

Figure 6 Log results for moisture and observed cobalt contaminant.

considered cemented. In this area, the cobalt contaminant occurs in a thin lens nearly centered in the Ringold. The log analysis interpretation of this behavior is the presence of a silt lens sandwiched in the Ringold.

Even though the character of the cobalt and moisture content are correlated, the magnitude is not. The zone centered at 124 feet has a higher moisture content of 32 VF and only 5 pCi/g of cobalt, while the zone centered at 97 feet has 26 VF and 22 pCi/g of cobalt. Each of these wicking zones between the crib and this well may not have the same thickness or permeability over this large a distance from the crib (75 feet). The conclusion drawn from this behavior is that the contaminant in the zone at 124 feet arrived from a lateral wicking from the crib and not from a downward movement of the zones above. Note that this type of correlation does not exist for the interval of 135 to 144 feet. The well bottom is 145 feet, and therefore, no further information is available for deeper intervals in this well. Therefore no conclusion can be reached for this type of correlation between moisture content and the intensity of contaminant.

Conclusion

Knowledge of moisture content is important for many reasons. Geologic description of earth formations requires moisture levels. Risk assessment of contaminant migration is driven¹³ by water movement.

Moisture measurement in situ is much more likely to accurately assess the levels of water than any sampling technique. If the area is a radiological zone, then surveying samples before processing causes extra possibilities for evaporation and resulting erroneous moisture values.

WHC geophysics group has demonstrated the use of neutron instrumentation to measure moisture levels in formations surrounding a cased well. The instrument has been calibrated and the data reported. The accuracy and precision estimates have been described. Several borehole construction conditions have been assessed for their effects upon the instrument response, and these have been included in the report. Quality of data integrity has been flagged using a γ -ray detection for the implemented instrument.

The observed high degree of vertical bed resolution for a zero spaced source to detector instrument gives rise to conditions that must be monitored. First, the comparison of time lapse logging measurements must be certain that the measure points are repeated if the sample space is larger than 2 inches. Second, comparisons with non zero spaced source and detector must include the change in instrument response. Third, monitoring or defining bed boundary changes must account for the skew in instrument response¹² if the instrument is not a zero spaced source to detector sonde.

Although there is more work indicated, the overall conclusion is that adaptation of moisture gauge technology is a viable in situ moisture measure of common Hanford wells.

Recommendations

Neutron instrumentation used for well logging of hydrogen index has been used since 1940. There are many known correction factors that are driven by the well condition that affect the quantification¹⁰ of the levels of hydrogen. Likewise, there are many formation correction factors that influence the final accuracy. Therefore, more study and measurement of these variables is recommended for the instrument design now tested in the proof of principal efforts by the geophysics group at Westinghouse Hanford Company.

In particular, air gap behind casing should be delineated. Radial depth of investigation should be studied. Matrix minerals and/or capture cross section effects upon instrument response should be included in future study. More moisture points must be added for a more complete transform of count rate to volume fraction water. These and other studies can be best performed by using both expanded measurements and Monte Carlo modeling.

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