An *In-Situ* Check of the Epithermal Neutron Log Calibration

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Abstract

The epithermal neutron log is used to measure the water content of the formation. The large hole epithermal neutron sonde (ENS) that we utilize at the Nevada Test Site (NTS) has been calibrated in the Hydrogen Content Test Facility (HCTF). These calibrations are used to correct the measured neutron count rate for the effects of tool stand-off and density. For sometime, the suspicion has existed that the water contents that are calculated from the ENS data are too large. Hole U2gj represented a unique opportunity to check the validity of the ENS calibration under realistic logging conditions; a portion of the hole had been cemented and re-drilled and then logged. The cements have a known water content and can be used as an *in-situ* calibration check. I found that the water contents from the log data after processing with the existing calibrations are consistent with these known cement water contents. In addition, the study indicates that the raw neutron data might be more appropriately smoothed by using a median smoother rather than the currently utilized mean smoother.

Introduction

The epithermal neutron log measures the total hydrogen content of the formation; the water content of the formation is calculated from the total hydrogen content. The large hole epithermal neutron sonde (ENS) that we utilize at the Nevada Test Site (NTS) has been calibrated in the Hydrogen Content Test Facility (HCTF) [1]. These calibrations are used to both convert the measured neutron count rate to water content and correct the measured neutron count rate for the effects of tool stand-off and formation density. For sometime, the suspicion has existed that the water contents that are calculated from the ENS data are too large. This suspicion is particularly strong when the measured water contents exceed about 20 wt % or 40 vol %. The implication is that the corrections that have been derived from the HCTF calibration data are, for some reason, not correct in a real logging situation.

Several hypotheses have been formulated to explain why the calibrations may not be correct. The calibrations are done in a static configuration with fixed standoffs with the sonde parallel to the calibrator's hole wall; the standoffs represent gaps between the logging sonde and the hole wall. However, the ENS is moving while counting is taking place in the real logging situation. Because of the size and geometry of the ENS logging sonde, the sonde is not always parallel to the hole wall since the tool is moving across a very rough hole wall. A real drill hole is not a right circular cylinder! While the gap between the sonde and the hole wall can be determined quite accurately in the calibration process, the gap between the sonde and the hole wall in a realistic logging situation is very difficult to determine. The gap cannot be measured at the neutron detector itself because the gap measuring device would interfere with the detection of the neutrons. Hence, the gap is measured at both ends of the sonde on the log. During processing, these gap measurements are combined with some assumptions about ENS tool behavior in order to derive a gap to be used to correct the raw neutron counts for tool standoff. The calibration data are also taken with the sonde stationary and the epithermal neutrons are counted for long time intervals to reduce the counting statistics errors. In the real logging situation, the sonde is not stationary; the ENS is run dynamically at logging speeds at about 30 ft/min (~0.15 m/s).

The LLNL hole U2gj provided us with the unique opportunity to determine whether the suspicions about the log were correct. Extensive caving occurred in U2gj during the drilling process. The portion of the hole that experienced this extensive caving was cemented and then redrilled. The hole was logged in normal manner after the drilling operation was completed. As the LLNL site geophysicist for U2gj, I had the normal log processing conducted for this site. In this process, the data from the cemented zone is removed (gapped out) from the log since it is not representative of the formation. Sometime later after considerable debate about the validity of ENS data in general, it occurred to me that the U2gj cement zone represented a unique opportunity.

The U2gj cement zone could be used to check *in-situ* the calibration of the ENS log if several conditions were meet. The cement after drilling needed to have an annular thickness which exceeded the depth of investigation of the ENS log. The cement zone needed to be sufficiently long to eliminate "end effects". The cement zone needed to have regions of distinctly different water content. The cement zone's roughness (rugosity) needed to be similar to rugosity of drill hole elsewhere so that gap measurements in the cement zone would have the same characteristics as the gap measurements in the rest of the drill hole.

The Cement Zone in U2gj

While drilling hole U2gj to a total depth of 1697 ft (517.2 m) during February, 1991, hole sloughing occurred several times. A caliper tool was run and a hole enlargement which exceeded the measurement limits of the caliper tool spanning the depth range 1340 ft to 1380 ft was discovered. After backfilling the hole to 1378 ft., the hole was cemented in six stages using Redi-Mix cement, Type II cement, and HPNS-3 grout. A small quantity of Type II cement was used to complete a 3 ft stage that first used 3240 ft^3 of HPNS-3 cement and was topped of with 162 ft^3 Type II cement. I have ignored the presence of the Type II cement in the analysis that I have conducted. The hole was redrilled and another caliper log was obtained. However, I do not know if the void that existed and was filled with cement was symmetric with respect to the original centerline of the hole. I also do not know if the drill bit upon redrilling followed the original centerline of the hole. Therefore, I cannot know what the exact thickness of the cement might actually be at any particular depth and orientation in the hole. However, if I assume that the void that was filled is circular symmetric and that the redrilling followed the original centerline in the hole, the thickness of the cement in all stages exceeds 25 inches (~63 cm) and for a significant portion of the hole exceeds 125 inches (~317 cm) (Figure 1).

The water contents of each cement type can be calculated from the mix formulas used for the U2gj cementing job. The water contents calculated from the mix formulas of HPNS-3 grout and the U2gj Redi Mix was 64 and 36 vol %, respectively (see Appendix 1). These calculated water contents ignore any evaporization losses, ignore any water loss to the surrounding formation, and ignore changes in volume percentage water content due to contraction of the cement or grout. Contractions of these cements are on the order of 2 vol % or less; a 2 vol % contraction would increase the water content in volume percent by less than this amount. Since drill holes are typically very humid and the cemented zone is very thick, it seems reasonable to assume that significant volumes of water were not lost to evaporization or into the formation. I cannot, however, demonstrate this. Therefore, I estimate that the error in the volume percent is about 3 vol % and that therefore, the water contents of the HPNS-3 and the U2gj Redi-Mix are 64±3 and 36±3 vol %, respectively.

The depth of investigation of the ENS log is a function of both the water content and density of the formation. The depth of investigation of the ENS log for moderate to high water contents is in the range of 20 to 50 cm (~8-20 inches) [2]. This depth is less than the thickness of the cement that would remain after the cement zone was redrilled, if I assume that the void that was filled is circular symmetric and that the redrilling followed the original centerline in the hole (void is not a one-sided directional break-out). If regions exist where the cement might not thick enough so that the logging sonde "saw" the native formation, the measured water contents would generally be less than the estimated cement water contents because the water contents of the cements are in general higher than the water contents of the native formation. The log itself can therefore be used to partially determine whether the cement behind the logging sonde is thick enough to avoid the effects of the formation.

The caliper log shows that the characteristics of the rugosity of the redrilled cemented portion is essentially the same as the characteristics of the rest of the drill hole (Figure 2). I assume that the logging tool's dynamic behavior in the cement region would therefore be on average the same as anywhere else in the hole. The measured proximities would have the same statistical variation.

The characteristics of the cemented zone (annular thickness, length, water contents, and rugosity) make this region of the hole an ideal location to conduct an *in-situ* check of the calibration of the ENS tool that was determined in the HCTF.

Results

Figure 3 shows the ENS log after processing with the LLNL techniques with and without a gap correction. The gap correction itself is a function of the neutron count rate, density, and gap. Superimposed on Figure 3 are the cemented regions where the cement values are known to be 64 and 36 vol %. The log water contents agree quite well with the high water contents in the cement zones *if a gap correction is performed.* Environmental or borehole effects typically make the epithermal neutron log read low. My first conclusion is that ENS log agrees quite well with the cement zone's high water contents. Proximity corrections for gap (tool standoff from the borehole wall) are clearly needed; otherwise, the log values would be too low.

The exact boundaries between the HPNS-3 and Redi-Mix cements and the cement-native formation are a little uncertain. Well loggers and drillers do not always use a common datum to reference the depths that they measure in the hole. This can often lead to a depth differences of up to 5 ft. In hole U2gj, this might be the case since the boundaries of higher water content from the drilling log for the cement zones do not exactly coincide with water content measurements from the ENS log. In addition, the blue-line log has the notation: "Log was recorded off depth. Log played back at correct depth." However, correct depth is really unknown; all that is known is the depth of the casing. If this was done, it appears as though the log is still off on the order of 2-

3 ft. Additional evidence of a potential discrepancy can be seen most clearly in the Rainier Mesa vitrophyre boulder region of the alluvium. As Figure 4 suggests, the ENS logger's depths disagree by about 3-4 ft with depths determined from a fisheye camera log run in the hole that was. Overall, I believe that the boundaries are uncertain by 2-5 ft.

Closer examination of the ENS log, however, indicates that gap corrections are sometimes applied that may not properly represent the logging tool sensor's standoff from the borehole. For example, in Figure 3, between 1340 and 1350 ft depths, the three largest water contents (at depths of approximately 1341.4, 1345.5, and 1348.5 ft) have a large gap at their respective depths but *the neutron count rate data shows almost no effect of a gap*. One could conclude that a gap correction was being made when the logging tool's sensor was not off or as far off the borehole wall as the proximity traces would indicate. In addition, Figure 3 shows that the gap corrected log has more and higher amplitude excursions in water content than does the uncorrected log over a similar depth interval.

I tried to reduce or eliminate this problem by preprocessing the proximity and neutron count rate data. I tried various forms of median filtering and in general found that the extreme points tended to be removed from the processed log. No analytical justification was discovered to justify using median smoothing. A median smoother tends to remove extreme values (data outliers). Since the ENS logging sonde neutron source to detector distance is approximately 3 ft long and therefore in some sense averages the formation properties across approximately a 3 ft interval, I decided to illustrate the advantages that extremal removal with a 3 ft median smoother on the proximity and neutron count rate data would have on the final processed log.

Figures 5 and 6 show the raw and 3 ft median smoothed data for the neutron count rate and proximity data, respectively. Figure 7 shows the ENS log in the cement region processed with the median smoothed count rate and proximity data and the ENS log with the standard LLNL processing. Note that the extreme values in the 1340-1350 ft range are gone and that in general, the spikiness of the processed log has been greatly reduced.

The figures tend to support the conclusion that gap corrections are sometimes being made when they are not warranted. Our measurements of the gap are not made at the sensing element of the tool, but rather at both ends with an average gap being applied in the processing to represent the logging sonde's standoff. In fact, Figure 6 supports the hypothesis that the logging sonde is on average at least 0.1 inches off the borehole wall.

I believe that a better method of measuring or calculating the actual logging sensor standoff from the borehole wall is desirable. 3 ft median smoothing as a preprocessing step may eliminate part of the problem; however, this "fix" is purely empirical.

Conclusions

The U2gj cement zones represent a unique opportunity to verify the *in-situ* performance of the ENS log in actual logging conditions. The U2gj ENS log processed using the standard LLNL ENS log processing algorithm utilizing the the calibrations from the HCTF agrees quite well with high water contents observed in cement zones. Gap (proximity) corrections are necessary to obtain good agreement with the cement water values. I conclude that there is no evidence that high water contents that have been previously measured (and sometime suspected as being too high) in other boreholes are suspect.

However, the current method of measuring gap appears to result in gap corrections sometimes being made when in fact no gap corrections may really be warranted. Preprocessing of the neutron count rate and proximity data with a median smoother appears to help reduce this effect. However, an improved method for proximity measurement could eliminate the problem of overcorrection and would negate my suggestion for preprocessing by median filtering.

Acknowledgements

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References

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