



Pulsed Neutron Log Interpretation in Carbonate Reservoirs: Environmental Challenges and Solutions

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Keywords

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Summary

Over the past two decades, Pulsed Neutron Logging (PNL) technology has provided an avenue for hydrocarbon estimation in cased-hole environments independent of formation salinity. Despite the environmental challenges faced during PN log interpretation certain key prevalent parameters including calculation of shale volume, effect of porosity, lithology, borehole size with respect to depth of investigation, type of annulus fluid, cement sheath, hydrocarbon density in the formation, completion fluid at the time of logging operation and availability of calibration zone against clean inorganic shale or water bearing zones, involves a significant impact on the C/O and Sigma results for saturation estimation.

The job pre-requisites for appropriate well selection, including factors such as porosity, cement quality, and borehole size based on depth of investigation of the tool also contribute to an integral segment for the success of PNL. This paper takes into consideration the sensitivity analysis of critical parameters related to the log data evaluation and interpretation of pulsed neutron logs with special reference to carbonate reservoirs of the Mumbai High Field. The authors analyzed all these critical parameters governing the PN log responses which are crucial for computation of remaining saturation that adds economic value with increase in production of depleted reservoirs in brown oilfields over time.

Introduction

Cased hole Pulsed-Neutron Logging (PNL) can provide three-phase formation fluid analysis to provide clear idea of formation fluid, hydrocarbon quantification and saturation, porosity estimation, lithology identification, identification of by-passed zones, flow mapping of water behind or inside pipe and premature water breakthrough as well as coning. Pulsed Neutron (PN) spectrometry is a multi-detector tool that combines two large size bismuth germination (BGO) scintillation detectors with a pulsed neutron source called Minitron. This combination produces high gamma ray count rates with good spectrum resolution. A 14 Mev neutron burst from the Minitron is released in all directions. This interaction between neutrons and nuclei produces two types of reactions: in-elastic and capture modes, which result in gamma rays. For assessment, the energy spectrum of gamma rays arising from the interaction between inelastic and capture is recorded. Carbon-oxygen (C/O) measurements are made using reactions brought on by inelastic scattering while Sigma measurements are based on neutron capture processes. The former measures carbon and oxygen content and the later one is focused on the decay rate of captured gamma ray to distinguish and figure out hydrocarbon as well as water saturation. The introduction of pulsed neutron

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logging concept includes the long detector for SATG measurements enables to precisely determine the gas saturation in interesting zones which is beneficial in terms of three phase fluid identification.

However, certain challenges are associated in accurately acquiring and measuring data using this technology. This paper primarily aims to discuss the factors such as hydrocarbon density, porosity and shale volume, lithology, casing size and type of cement, presence and type of annulus fluid, borehole size and so on which affects the data processing and eventually might lead to anomalies in conducting robust reservoir saturation monitoring. In connection with the discussion, the authors would like to include field studies of three wells of Mumbai High Field namely N-XX, N-YY and N-ZZ to understand and recommend best solutions for effective monitoring of the reservoir parameters based on a sensitivity analysis.

Well Selection Criteria

Sl. No.	Parameter	Value/Range/Remark
1.	Porosity	>12 pu
2.	Hole Condition	Not suitable for caved and rugged hole
3.	Cement Quality	Good Cement Bond
4.	Shut-in time prior to job	2-3 days
5.	Calibration	S_{hc} : 0% against inorganic shale, water bearing sand
6.	Maximum Hole OD	>16 inches
7.	Minimum Hole ID	2.375 inches

Table 1. Well Selection Parameters for PNL

Methodology

The parameters affecting the acquisition to the log data processing of pulsed neutron logging are taken into consideration. Initially, the lithology of the formation to be evaluated, for an instance the examples discussed included sandstone and limestone. The volume of shale is calculated based on two varied factors, one from the open hole gamma ray value and other from recorded SIGMA and C/O. On the same hand, the calibration factor is dependent on the presence of inorganic shale or pure water bearing zone which is a pre-requisite for the logging to be carried out. In this discussion, factors like lithology, borehole fluid density, presence of annulus fluid are taken into consideration while applying environmental corrections as a part of data processing for PNL with hypothetical parameters in the well N-ZZ.

Factors affecting C/O & Sigma based hydrocarbon saturation estimation:

1. Effect of Shale Volume and Porosity on computed saturation

a. Shale Volume:

Shale lithology might include carbon from carbonates or organic materials. This suggests that rather than hydrocarbons in the pore space, the shale itself may be the cause of a high C/O ratio in a shaly zone. On the other hand, the shale volume computation based on SIGMA & GR is around 30% against which S_o reads around 30% as shown in **Fig 1**. Therefore, in order to depict the effect of V_{sh} in the same zone of interest, it was increased by 10% and hence as evident from the figure that S_o is correctly estimated at 32% (Track 7 of the log motif) that depicts a correction of +3 % in hydrocarbon saturation. This in turn decreased the effective porosity by 2-3% which can be correlated from the fact that saturation (Track 8 of the log motif) will be on higher side in the Fan Chart depicted in **Fig. 2**. Thus, the use

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of corrected volume of shale based on recorded GR curve during PN logging becomes vital for estimation of saturation which further needs to be validated with open hole logs.

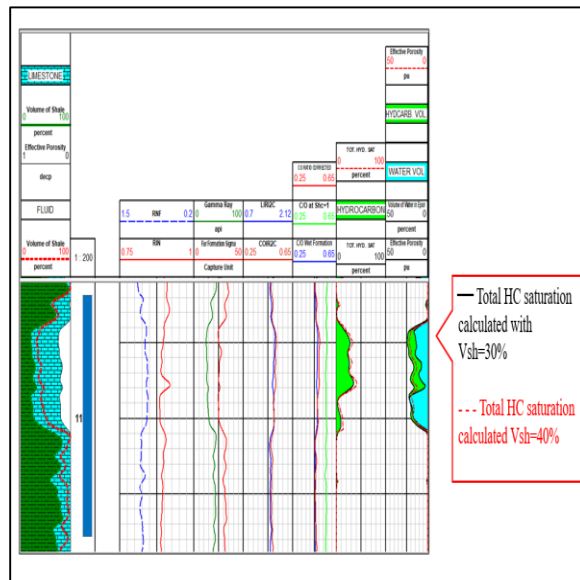


Figure 1. Effect Shale Volume in computed hydrocarbon saturation

b. Porosity:

When selecting a well for C/O mode logging, porosity is crucial. This is mostly because the PNL tool is radioactive, and as such, its measurements will exhibit stochastic fluctuations. The signal strength will be low and there will be greater variations if the formations being studied have poor porosity. The tool reaction is shown graphically in the Fan Chart, which provides an explanation. The porosity is on the x-axis, and the C/O ratio is on the y-axis. As per the window in the C/O Fan Chart in **Fig. 2.**, a slight change of about 5-10% in porosity can lead to pessimistic value of hydrocarbon saturation which is quite significant at lower porosity values which justifies the porosity cutoff for a PNL job. Thus, if porosity is around 10% in the Fan Chart, the saturation will be

much sensitive as compared to 20%.

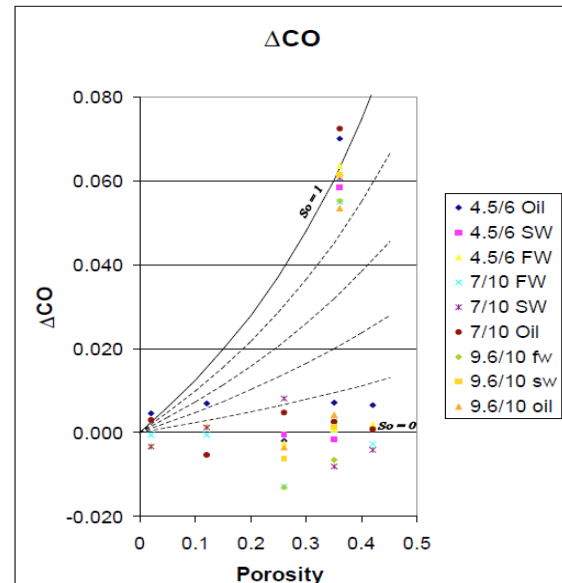


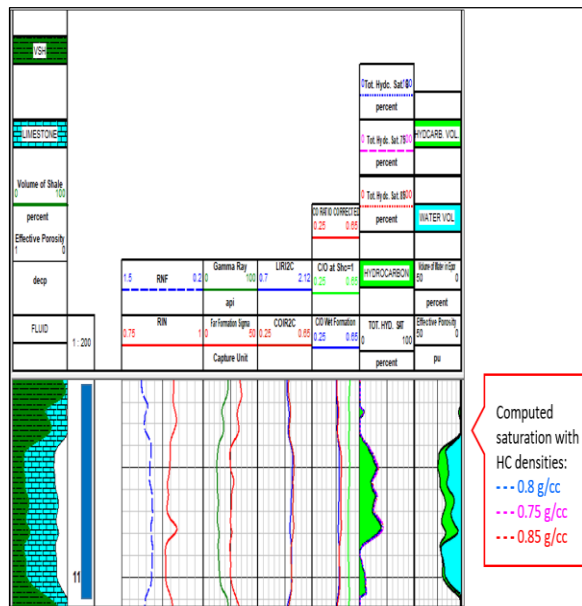
Figure 2. Effect of Porosity in computed hydrocarbon saturation (Fan Chart)

2. Effect of Hydrocarbon Density on computed saturation

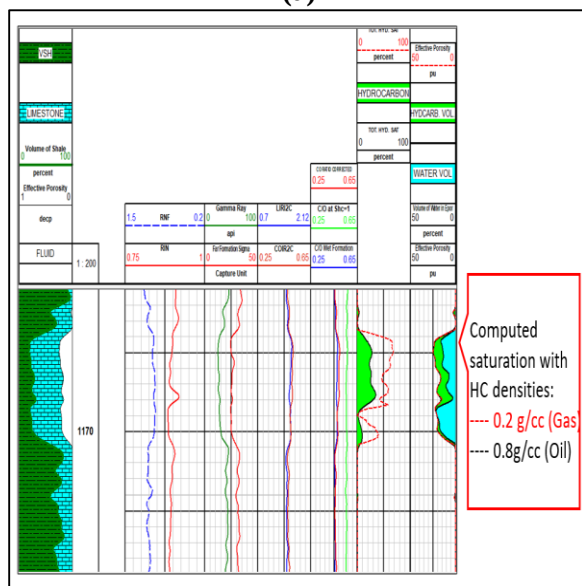
As evident from the above Fan Chart in **Fig. 4.**, the oil line ($S_o=1$) is dependent on variation in density of the formation fluid, as for high density formation fluid, the oil line will tend to shift upwards and vice versa in the case of low density formation fluid, which makes the window narrow for C/O. In the **Fig. 3 (a) & (b)**, two hypothetical representations are made to analyze the effect of hydrocarbon density in saturation estimation. As such, gas has low density (taken as 0.2 g/cc) which may affect C/O saturation in the way that it will be on higher side for gas where S_o is considerably higher with up to 55-60%, however oil with densities considered for three different case 0.75, 0.8 & 0.85 g/cc has least affect with S_o values to be in the order of $\pm 2\%$ only with the value to be 38-40% across the interesting zone. Hence, the accurate and precise hydrocarbon

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density value of known mature field should be provided by operations team and geoscientists to use it judiciously while applying the environmental corrections.



(a)



(b)

Figure 3. Effect of hydrocarbon density in computed hydrocarbon saturation

3. Effect of Lithology on computed saturation

The lithology and carbon-oxygen ratio are also dependent on the lithology of the formation investigated. In sandstone formations, the primary mineral constituent is Quartz (SiO_2) while on the contrast, in the carbonate formations, the constituent is calcite (CaCO_3). The latter is a challenge in C/O saturation estimation making it difficult to distinguish for actual hydrocarbon saturation due to the presence of carbon element in its composition as discussed relevantly in Case – I in the latter section of this paper.

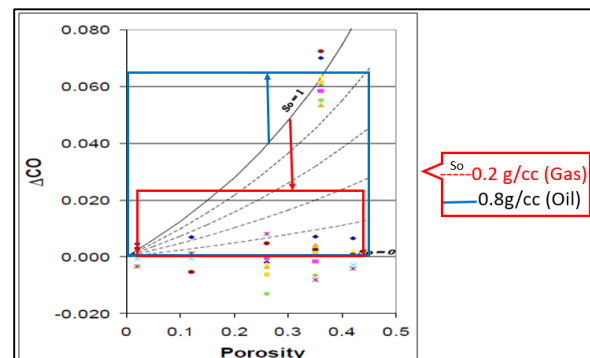


Figure 4. Effect of hydrocarbon density in computed hydrocarbon saturation (Fan Chart)

4. Effect of Calibration Zone

The presence of a water bearing or shale section is crucial and sensitive to determine the accuracy of the estimated hydrocarbon saturation. For calibration, the PNL tool should read hydrocarbon saturation at 0% against the water or pure inorganic shale section and forms a basis of log quality control of PNL as well. Hence, its proper recognition is a vital part during the interpretation against good cemented zones based on cement evaluation logs. The calibration parameters forms the basis of the entire PN log interpretation and has a combined

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effect of change in borehole fluid, cementation, salinity of formation fluid and lithology.

5. Effect of Borehole, Annulus Fluid & Cement Bonding

a. Borehole & Casing Size

If the borehole fluid's parameters (such as salinity for Sigma or type for C/O) differ significantly from its formation, then a larger borehole will have a greater impact on the recorded raw log response. With a shallower depth of investigation, normally 6 to 8 inches in inelastic mode and 10-18 inches in capture mode, the influence of the borehole fluid surrounding the casing becomes stronger in the recorded signal as the borehole size increases. In this case, the composition and density of borehole fluid is inserted in the parameters section of borehole correction.

b. Annulus Fluid

When measuring C/O, hydrocarbons in the annulus, which includes oil-based mud filtrate, bypassed oil, and even gas that moved into the annulus, as a result of channeling, leading to the C/O ratio to read on the higher side. This could overestimate the formation's hydrocarbon saturation, thus labeling a water-bearing zone as hydrocarbon-producing. The presence of extremely saline water (high Σ) in the annulus will have an overestimation effect on the overall Sigma computation, even if the formation itself contains hydrocarbons. In order to nullify the effect of annulus fluid, the isolation of the annulus is ensured with the operations team and if not isolated the known/expected formation fluid/borehole fluid density is considered for effective corrections.

c. Cement Bonding

An optimal cement job entirely fills the annulus and ensures a good bond between the formation and the casing. Poor cement quality, as indicated by voids, channels, or incomplete cement fill, such as, fluid-filled channels, gas cutting, indicates that the PNL tool is detecting not just the casing and formation, but also the fluids, like, drilling mud filtrate, and formation fluids, or even gas in these channels. If cement is missing or partially filled, the annulus effectively extends the borehole, letting borehole fluids as well as migrating formation fluids to fill the gap where cement should be present. In order to apply corrections for cement, the annulus fluid corrections and appropriate shale/water zone calibration is selected for PN interpretation as discussed in Case-II in the subsequent section.

Field Case Study

Case-I.

The well, N-XX (represented in **Fig. 5**.) was initially producing oil in Layer B of Mumbai High field but at a later stage it reported at 100% water cut. The layer B is a carbonate reservoir. The cement bond log was recorded in the well for 8.5" section with 7" casing. It was also decided to record CO/SIGMA log for estimation of current hydrocarbon saturation in A and B layers.

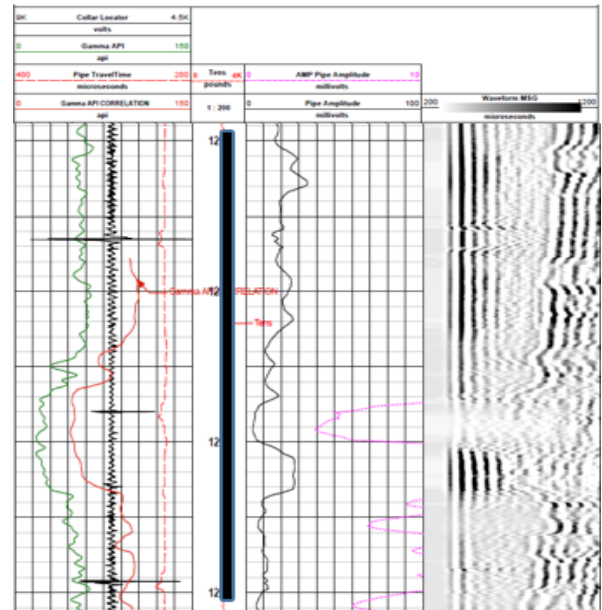
However, the challenge in this well was with regards to lithology, as the well was reported to laminated with both limestone and sandstone lithology. As shown in **Fig. 5 (b)** The Lithology ratio (LIRI) spectrum of limestone reads at 1.5 in the Track 6 of **Fig. 5 (b)** with respect to the spectra of sandstone in below section which reads at 1.2-1.3. A remarkable increase in the gamma counts tends to be at around 50, corresponding to the energy level of Calcium and a decrease in counts regards to the energy level of Silicon is observed. There is also an increase in the COIR (Track 6 of the PN log) counts corresponding to the energy window of Carbon about 10% as

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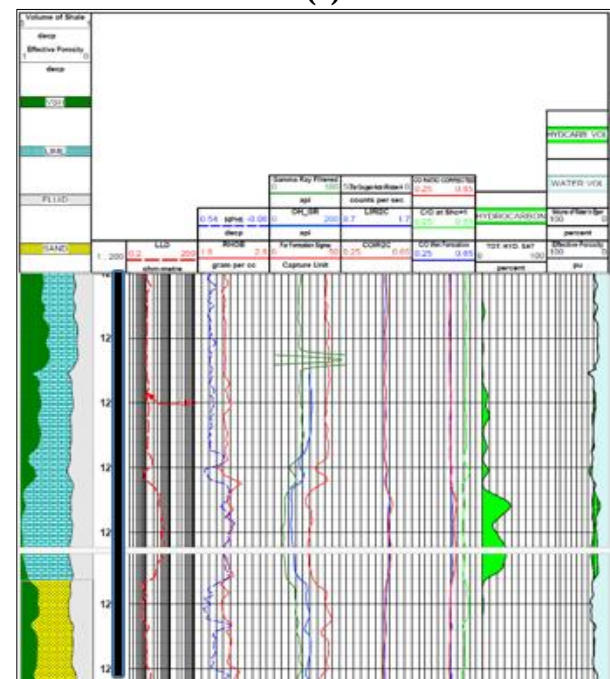
compared to sandstone which is actually due to the presence of hydrocarbons. The increase in gamma in carbon window is not due to hydrocarbons but due to presence of C in CaCO_3 in limestone, hence it is necessary to apply corrections for lithology during data processing. Another challenge, the possible presence of annulus fluids like hydrocarbon, water or mud in the casing-formation annulus as cementation is poor at places as evident from **Fig. 5 (a)**. In this regard, annulus fluid correction was applied to minimize errors in interpretation by avoiding pessimistic estimation of the saturation based on the PNL log including the density of borehole fluid density and assuming a known annulus fluid density. On the other hand, the rest of the factors such porosity was above 12 pu as evident from the log and hydrocarbon density was assumed to be of oil as it is a well-established reservoir. Hence, shale calibration zone was identified against the good cementation zone that enhances the reliability of remaining hydrocarbon saturation computation best to the true value. Based on PNL derived saturations & log motifs, perforated A reservoir in sub-layers I (carbonate) & II (clastic). Well became active soon after perforation. After the PNL job, the well started flowing oil at around 158 bopd with 45 % water cut. On the other hand, B layer was found to be watered out over time. Furthermore, the addition of A layer as an oil producer has been crucial in the improvement of production from the well as well as adding a new dimension to the development of the field.

Case II.

The well, N-YY (represented in **Fig. 6.**) of Mumbai High field is an inclined development well comprising of limestone reservoir dating back to the Miocene age. It was initially producing 1 bopd of oil with about 100% water cut from IV, V layers which are a part of B multi-layered limestone reservoir operating with a large gas cap and partial water drive mechanism before the consideration of PN log.



(a)



(b)

Figure 5. Cement Log (a) and PN log (b) of the well N-XX (Layer A)

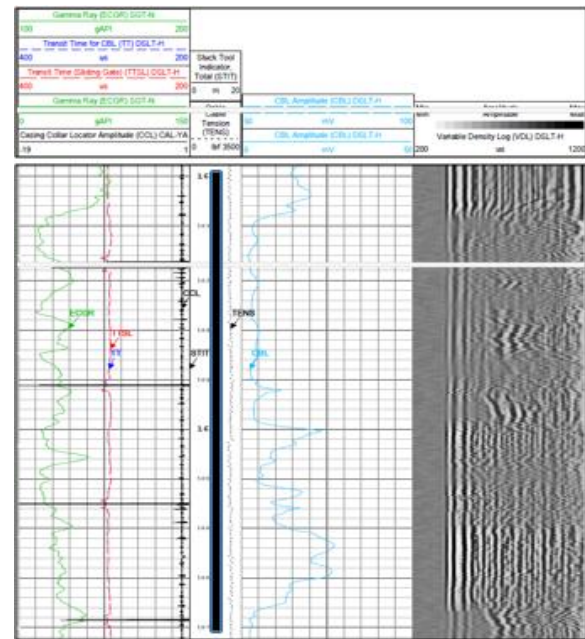
The cement bond log was recorded for 12.25" section with 9.625" casing. The petrophysical

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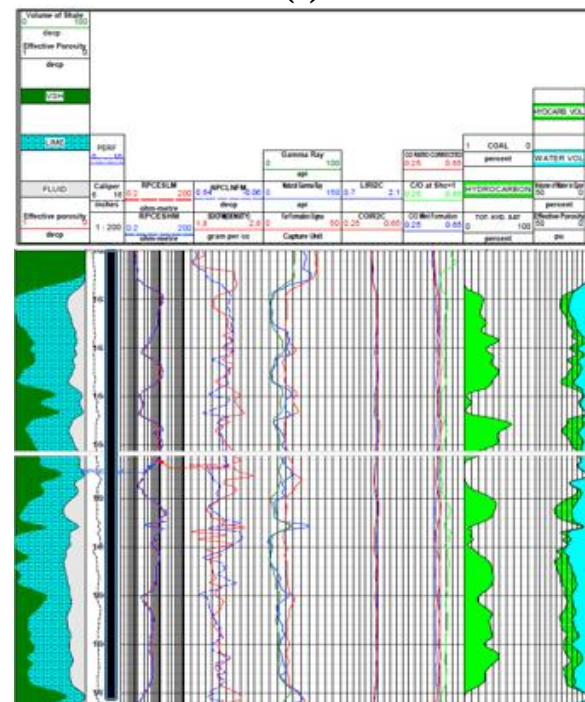
characteristics in this well although indicated the presence of gas with oil which requires further interpretation. Thereafter the CO/SIGMA log was recorded to ascertain the current hydrocarbon saturation so as to carry out workover job to complete the well in such a way to boost oil productivity and reduce water cut at the surface. As evident from the cement bond log, the first arrival in the cement log indicates poor cementation in the upper shale section. However, good cementation was observed against the lower marked shale section where S_o read to be 0% with a complete overlay of the corrected and C/O curve in the Track 7 of the represented PN log in the **Fig. 6 (b)**, making it a suitable zone for calibration in the absence of a 100% water bearing zone. Similarly, the density of annulus fluid behind the casing was taken into consideration due to poor cementation at certain sections as seen in **Fig. 6 (a)**.

In the same context, lithology ratio (LIRI) from the log data indicated a limestone lithology throughout which reduced the challenge of dual lithology as compared to the previous case. The porosity of around 20-25 pu was in conformance as observed in **Fig. 6 (b)** to the specified value of greater than 12 pu as discussed in the well selection criteria section of this paper and hydrocarbon density was assumed to be of oil at 0.81 g/cc based on known reservoir characteristics. The logged interval was in 12.25" section and accordingly the caliper reading of about in the range of 12.10" -12.40" represents an in-gauge borehole thereby ruling out washout against the shale calibration zone.

The oil production after the zone transfer to I, II & III zones post the PNL job was reported to be at 170 bopd with a water cut of 60%. This has led to the clear depiction of the leftover reserves estimation in upper zones of Layer B with due consideration of the environmental challenges faced during PN log interpretation. It also affirms the sanctity of the PN derived saturation, as it is clear from the production enhancement data as mentioned above.



(a)



(b)

Figure 6. Cement Log (a) and PN log (b) of the well N-YY (Layer B)

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Conclusions

The environmental factors that impact the Pulsed Neutron Logging technology have been discussed with relevant examples from Mumbai High Field. The important sensitive factors such as porosity, reservoir hydrocarbon density, type of lithology, calibration zones, presence of annulus fluid and borehole size correlated with the depth of investigation of the tool were taken carefully in the paper. A critical analysis was performed on all of these factors and it has been inferred that porosity, hydrocarbon type and density, shale volume, nature of cement bond are much sensitive to the computation of hydrocarbon saturation with the effect reported upto $\pm 5\text{-}10\%$ which should be avoided and hence to overcome these challenges it can be inferred, the PN logging must be carried out in moderate to high porosity reservoirs for better results which is effectively above 12 pu. On the other hand, demarcation of calibration zone should be against good cementation zones. The presence of annulus fluid in overlying or underlying layers may lead to pessimistic saturation estimation upto $\pm 5\%$ thereby becoming one of the key parameters as discussed in the concerned field studies. This sensitivity analysis of the major parameters signifies the integrated approach used in PNL right from pre-job planning, data acquisition, post processed results and recommendations for future health of the mature wells. The prudent consideration of the environmental factors affecting saturation log evaluation (PN logging), and their effective corrections during data analysis and interpretation has been instrumental in relocation of sub-layers within the reservoir, production enhancement, evaluation of bypassed zones and identification of additional leftover zones for exploitation of carbonate reservoirs with accurate and reliable hydrocarbon estimation.

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