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Accurate Identification of Gas-Bearing Formation in a Mature Field Using Pulsed Neutron Logs Prevented Well Abandonment

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Abstract

Operators typically update formation fluid saturation from producing wells as production impacts changes in formation fluid type and volume. An operator in India deployed a multi-detector pulsed neutron well logging tool on one of the old wells in a mature field to evaluate saturation profiles across multiple clastic formations. Production from the subject well had ceased due to water loading. The objective of the logging was to identify possible bypassed hydrocarbon zones before the operator decided on the well abandonment.

A multi-detector pulsed neutron tool acquired a salinity-independent gas-sensitive time-based measurement from short-spaced and extra-long-spaced gamma-ray detectors. In addition, inelastic energy spectra-based carbon/oxygen (C/O) ratios were recorded to quantify formation oil saturation in a low water salinity environment. Another critical component in the saturation analysis workflow was the forward modeling of tool responses. We used the Monte Carlo N-particle (MCNP) stochastic method to predict gas-sensitive and C/O ratio responses in logging conditions.

We had limited information on well conditions, such as cement bond condition and formation fluid properties, as no recent well logging was carried out to evaluate these. Thus, we performed saturation analyses in various conditions to reduce uncertainties in the results, including well-cemented, partially-cemented, and uncemented annulus conditions and different oil and gas densities.

The analysis results identified one shallow sand unit containing gas. The sand was initially considered a water-dominant zone because the same zone produced water from adjacent wells. We evaluated the uncertainty in the gas saturation calculation attributed to cement bond quality and formation gas density. This helped to remove uncertainties in cement bond conditions and in-situ gas density on gas saturation. The identified sand unit was perforated and produced a large amount of gas. The accurate result of the gas saturation analysis saved the well from abandonment and increased reserves and production capacity. Additionally, the analysis revealed that water-filled formations were predominant in other sands. The C/O log analysis showed no bypassed oil in the lower sands.

This paper further discusses case studies on candidate selection for pulsed neutron well logging, uncertainties in formation parameters, and the implications for saturation results.

Introduction

This section briefly overviews the background of pulsed neutron well logging and through-casing saturation analysis methods.

The first pulsed neutron logging application was oxygen and silicon activation logging in the late 1950s (Youmans et al., 1959). Activation logging is based on a relatively simple principle, and the first logging was made with this advantage of simplicity. Since the first pulsed neutron logging, the areas of pulsed neutron logging applications have been expanded.

Thermal neutron capture cross-section measurement, or Sigma, is the first pulsed neutron log for through-casing formation saturation application (Youmans et al., 1964; Bishop et al., 1971). Water saturation evaluation with Sigma is applicable in saline water environments as Sigma is highly dependent on the chlorine concentration in porous media. Pulsed neutron well logging for formations where Sigma cannot be used was developed in the 1970s. Salinity-independent measurements that can differentiate oil from water are carbon/oxygen (C/O) ratios (Schultz et al., 1979). C/O ratios are extracted from inelastic energy spectral data from two gamma-ray detectors. C/O logs are, therefore, insensitive to the formation water salinity.

Advances in pulsed neutron well logging include developing and upgrading logging instruments, data acquisition techniques, and post-data analysis workflows (Gilchrist et al., 1999; Mickael et al., 1999; Kim et al., 2023). The tool's outer diameter (OD) has decreased, allowing for through-tubing deployment, whereas the number of gamma-ray scintillation detectors in a pulsed neutron tool has increased. Most pulsed neutron tools in the industry have three or more gamma-ray detectors. Different detector materials have been used to improve the quality and resolution of spectral data. Furthermore, the pulsed neutron generator (PNG) and detector electronics system have been upgraded to deliver enhanced pulsed neutron data quality. As part of through-casing formation saturation analysis, methods for known high-formation salinity environments and low, mixed, and unknown salinity environments are available. In addition, saturation analysis techniques for three-phase reservoir conditions have been established (Kim and Chace, 2016).

In this paper, the study focuses on the gas saturation quantification method using an inelastic gas-sensitive measurement for a well in a marginal hydrocarbon field.

Forward Modeling-Assisted Formation Gas Quantification

We discuss conventional and forward modeling-based formation gas saturation analysis techniques.

Conventional Approaches

Two conventional approaches have been commonly used for gas saturation analysis in cased wells using pulsed neutron well logs. The first conventional method compares two pulsed neutron logs exhibiting different degrees of gas sensitivity and detects the presence of formation gas. Like an overlay of bulk density and neutron porosity logs for formation gas indication in openhole conditions, a graphical overlay of pulsed neutron logs can also provide the same indication in a cased-hole environment. This method is useful for formations containing freshwater and gas in porous media across the same well-completion interval. However, this technique's weakness is that the gas indication is subjective and gas saturation quantification is impossible. Additionally, when completion changes across the evaluation interval, two pulsed neutron logs show different magnitudes of variations on completion specifications, resulting in inaccurate gas indication.

The other conventional gas saturation approach uses Sigma in saline water conditions. Key factors that determine the applicability of the Sigma analysis are formation water salinity and porosity. The favorable condition is that both water salinity and porosity are high. Typically, the criteria for water salinity and porosity to obtain reasonable saturation results are water salinity greater than 100 kppm and porosity of 15 percent or higher (Clavier et al., 1971)—the uncertainty of water saturation increases as water salinity and porosity decrease. Therefore, Sigma-based water saturation analysis is not applicable if water salinity or

porosity is low. For instance, water saturation from Sigma analysis for the formation in this study, where water salinity is 30-50 kppm and effective porosity range is 15-20 percent is unreliable.

A Model-Based Approach

A stochastic model-assisted gas saturation analysis compares environmental-effect-corrected forward modeled responses and a gas-sensitive pulsed neutron measurement. This method overcomes the shortcomings of the previously mentioned pulsed neutron overlay approach. As forward modeling defines water- and gas-saturated formations in specific logging environments such as wellbore and formation conditions, and measured data are compared to defined models, quantifying formation gas is possible.

In addition, using a salinity-independent gas-sensitive measurement allows for gas saturation quantification in a freshwater environment where the Sigma-based approach is not feasible.

For this method to work, it is essential to have an accurate forward modeling capability for pulsed neutron measurements sensitive to formation gas. Inaccurate modeling leads to incorrect or highly uncertain gas saturation results. Furthermore, stochastic modeling involves numerically intensive simulations; accordingly, sufficient computing capability must be designed and equipped to handle millions and even billions of simulations within a reasonable timeframe to complete the gas saturation analysis for timely reservoir management decisions.

Salinity-Insensitive Yet Gas-Sensitive Measurement

Sigma-based saturation analysis does not require forward modeling as the thermal neutron capture cross-section is an intrinsic property of formation components. Thus, water saturation is computed with the Sigma material balance equation. This method is more straightforward than model-based approaches; however, the applicable conditions of Sigma are limited. As discussed earlier, Sigma-based saturation analysis highly depends on the formation water salinity. A salinity-independent but formation gas-sensitive pulsed neutron measurement is required for freshwater environment applications. Thus, a hydrogen-index sensitive (or gas-sensitive) measurement was developed using the inelastic scattering of fast neutrons and gamma rays measured at the short- and extra-long-spaced detectors (rather than short- and long-spaced detectors).

In this paper, we use RIN13 as a gas-sensitive pulsed neutron measurement. RIN13 is a ratio of gamma-ray count rates produced by inelastic scattering of fast neutrons in time-based spectral data from the short- and the extra-long-spaced detectors. The acquisition is more efficient than energy-spectra-based data because the measurement is derived from time spectra (i.e., the logging speeds can be faster in RIN13 acquisition). In addition, the extra-long-spaced detector data were used; as a result, the gas-filled formation sensitivity was improved. A study showed that the formation gas sensitivity was enhanced about threefold compared to the same time-based gas-sensitive measurement from short- and long-spaced detectors (Trcka et al., 1999).

Compared to Sigma, RIN13 exhibits gas-to-water differentiation in a more comprehensive porosity range, including a low porosity range. Uncertainty of computed gas saturation for a porosity range less than 10 percent is higher in Sigma analysis than in RIN13-based analysis. Indeed, the RIN13 sensitivity is high in porosity, as low as 5 percent, and has been used extensively in tight gas formations worldwide. Integrating RIN13 and its forward-modeled response allows quantifying formation gas saturation in any reservoir environment.

Probabilistic Modeling of Tool Responses

Pulsed neutron tool responses are predicted using the Monte Carlo Neutron Particle (MCNP)-based simulation method. MCNP modeling is a probabilistic approach to simulate interactions between neutrons and nuclei and the resulting induced gamma-ray count rates, thereby predicting tool responses in well logging environments.

Simulation parameters include tool-, well- and formation-specific information. Tool specifications are distances between PNG and detectors, the detector crystal material and sizes, the OD of the tool, the tool position in the wellbore, such as a centralized or decentralized position in a casing or liner, etc. The leftmost column of [Table 1](#) summarizes parameters related to well and formation specifications: hole and tubular sizes, wellbore fluid properties, annular space material properties such as chemical composition and density, formation lithology, porosity, formation fluid types, and densities.

Table 1—MCNP modeling parameters

Model	(a)	(b)	(c)	(d)	(e)	(f)
Parameter						
Annular space content	15.8 lb/gal cement	75% cement and 25% gas or 1.45 g/cc mixture	50% cement and 50% gas or 1.0 g/cc mixture	1.0 g/cc water	0.74 g/cc oil	0.10 g/cc gas
Tool position	Decentralized					
Hole size	8.5 inches					
Casing outer diameter	5.5 inches					
Lithology	Sandstone					
Wellbore fluid and density	Water and 1.0 g/cc					
Formation water density	1.0 g/cc					
Formation oil density	0.74 g/cc					
Formation gas density	0.10 g/cc					

Influence of Annulus Content

We performed six different modeling cases with varying annular space contents. [Table 1](#) summarizes the parameters for each case. Since RIN13 is an inelastic measurement with a depth of investigation (DOI) of about 6-10 inches, it varies as near-wellbore properties change. For instance, the cement bond condition influences the RIN13 responses. We have focused on the effect of cement bond quality on gas saturation analysis as the cement bond log was not available in this old well, so six models representing different annular space contents, such as well-cemented (case (a)), 25% and 50% gas-cut cement-filled (cases (b) and (c)), and fluid-filled (cases (d) to (f)) annular spaces were generated.

[Fig. 1](#) shows the RIN13 modeling results of six annulus conditions. Modeled data are plotted against porosity, and three solid lines in each plot represent water-, oil- and gas-saturated formation responses. Plot (a) displays three gas lines representing different in-situ gas densities. Horizontal and vertical scales are the same for all six plots.

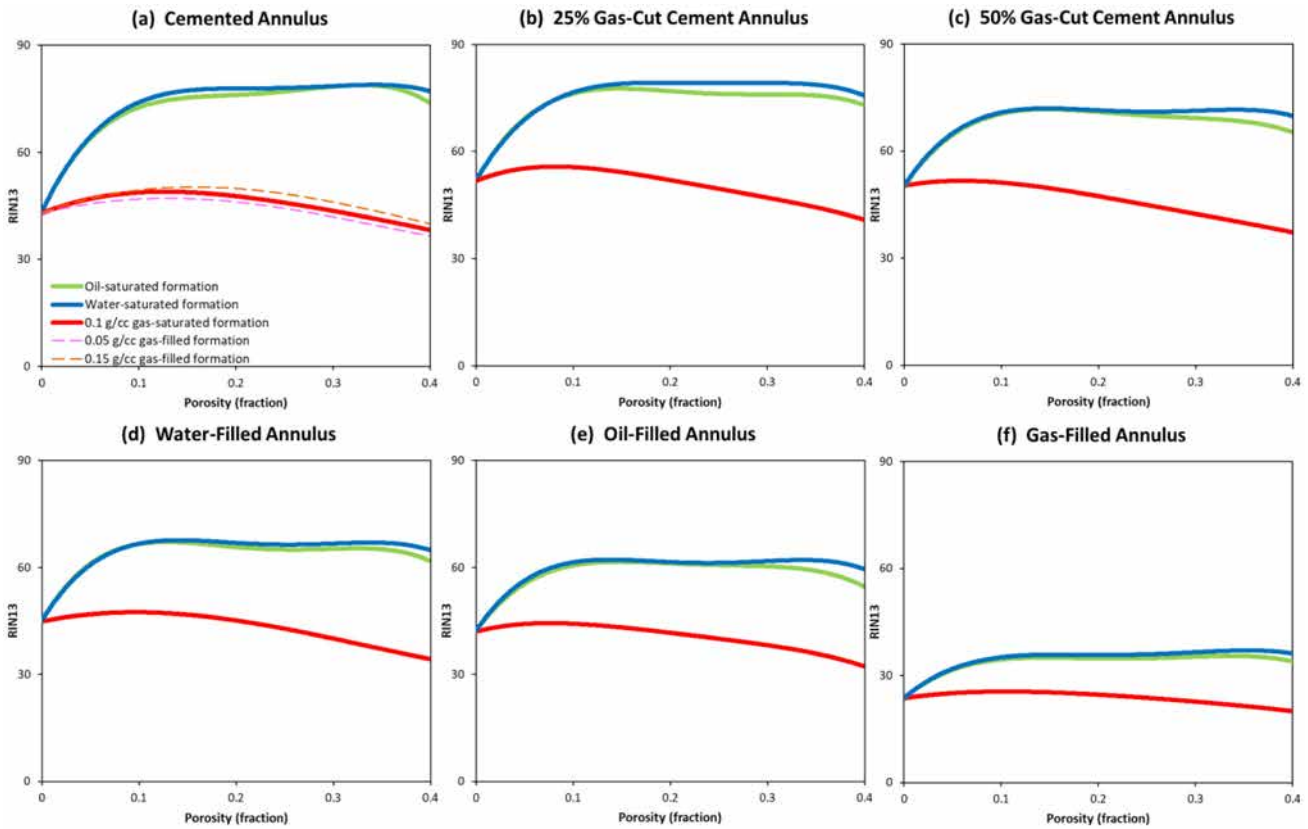


Figure 1—MCNP models for six different annular space conditions

The RIN13 responses at zero porosity, i.e., matrix point RIN13 responses, increase from the cemented annulus case to 25%, 50% gas-cut cement annulus case, or water-filled annulus case. The well-cemented model's matrix point is almost the same as that of the oil-filled annulus case and higher than that of the gas-filled annulus model (also refer to the figure on the right side in Fig. 2). The annular space material's hydrogen index increases from the well-cemented case to gas-cut cemented cases, and so do the fluid-filled annulus cases.

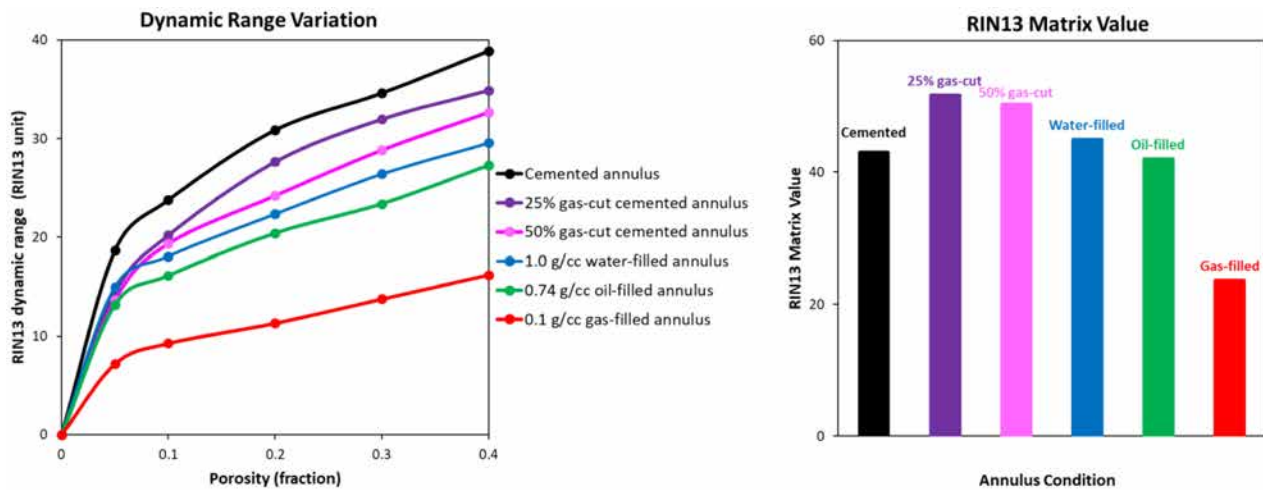


Figure 2—Dynamic ranges and matrix points of MCNP models for six different annular space conditions

The water-filled annulus case's matrix point is higher than the oil- or gas-filled condition. However, the well-cemented case whose annular material's hydrogen index is lower than the water- or oil-filled annulus

case shows a higher matrix point than liquid-filled annulus cases. This indicates that the matrix point is related to the hydrogen index and density of the annulus content.

Furthermore, the span between liquid and gas lines, i.e., dynamic range or formation sensitivity, declines from well-cemented to gas-filled conditions. The dynamic range decreases as cement volume decreases and the density of the material in the annular space decreases. The reduction is more pronounced in liquid-filled formation responses (i.e., blue or green lines) than in gas-filled ones (i.e., red lines). Due to reduced formation responses, the formation gas sensitivity is reduced as the cement volume or material density in the annular space decreases.

Fig. 2 illustrates the comparisons of dynamic ranges and matrix points of MCNP models from various annulus materials shown in Fig. 1.

The left plot presents the dynamic range comparison from zero to 40 percent porosity. As porosity increases, the dynamic range increases in all cases, but the increase in dynamic range is proportionally more significant with the increase in the annulus material's density. A drastic suppression of formation sensitivity was observed in the 0.1 g/cc gas-filled annulus case compared to other cases. This is attributed to a considerable reduction in the annulus material density.

The comparison of matrix points is displayed in the bar chart on the right. The comparison indicates that the matrix point variation is related to the annulus material density (from the 25% gas-cut cemented case to the 0.1 g/cc gas-filled annulus case) and the hydrogen index of the annulus material (from the well-cemented to gas-cut cement or water-filled annulus cases).

Impact of Annular Space and Borehole Specifications

The annular space volume and borehole fluid properties and volume primarily determine the impact of the annular space material on the RIN13 responses.

First, as the annular space increases, the impact of the annular content increases. The annulus volume generally increases as the bit size increases. For example, in typical combinations of bit and casing specifications, the annular space of a 12.25-inch bit with a 9.625-inch casing is larger than an 8.5-inch bit with a 7-inch casing or a 6.5-inch bit with a 4.5-inch casing. The subject well in this study has a larger annulus volume than a large hole case (e.g., a 12.25-inch bit with a 9.625-inch casing case), as the bit and casing sizes are 8.5 and 5.5 inches, respectively. When the same properties of annular space contents are assumed, the annulus content effect on the gas-sensitive measurement in the subject well case is more significant than a well with an 8.5-inch hole with a 7-inch casing (a common bit and casing combination).

Secondly, the wellbore fluid type and volume also influence the magnitude of the annulus content effect on RIN13. As the borehole size increases and is filled with liquid, the annular space material effect decreases due to the increase in wellbore content impact. Suppose the borehole is filled with low hydrogen index fluid such as gas or a mixture with gas. In that case, the annular space content does not impact formation sensitivity as much as observed in liquid-filled borehole cases, regardless of borehole size. Formation sensitivity is suppressed if the borehole becomes a hydrogen-poor environment. This is due to fewer scattering events that can direct neutrons into the formations than in hydrogen-rich environments such as water- or liquid mixture-filled borehole conditions. Thus, the wellbore effect is amplified, and the annulus effect is minimized.

It is worth noting that the annular content effect is less on capture measurements, such as a capture gamma-ray count rate ratio-based gas-sensitive measurement, or Sigma, because of its deeper DOI than inelastic data. However, thermal neutron capture measurements reveal less sensitivity to formation gas than the inelastic measurement but higher sensitivity to formation salinity, oil-to-gas sensitivity (in the case of gas-sensitive capture ratio data), and shale volumes. Consequently, the use of RIN13 for gas saturation analysis is prioritized.

Formation Gas Density Variation

Variations in the annular content properties influencing the RIN13 responses (and eventually the computed gas saturation) are typically more significant than those in in-situ gas density attributed to reservoir condition uncertainty. Formation gas density can be estimated with an equation of state for gas, gas compositions and specific gravity, reservoir pressure, and temperature.

The uncertainty of an estimated gas density is usually less than 0.05 g/cc. Fig. 1 (a) reveals the impact of a gas density change by 0.05 g/cc from the reference gas density of 0.1 g/cc for a well with an 8.5-inch hole and a 5.5-inch OD casing. The RIN13 responses to in-situ gas densities of 0.05 g/cc and 0.15 g/cc are presented in dashed lines. The base case with a gas density of 0.1 g/cc is displayed as a solid red line.

Compared to variations in the RIN13 responses caused by changes in annulus properties, the difference between the 0.1 g/cc line and the 0.05 g/cc or 0.15 g/cc gas line is insignificant. Furthermore, differences in RIN13 responses from gas density changes by about 50% are negligible for formations with less than 15% porosity. Therefore, uncertainty in computed gas saturation is more related to uncertainty in annular space content than in downhole gas density, especially in low gas density formations (i.e., gas density less than 0.2 g/cc).

Candidate Well Selection Criteria

Criteria for Sigma-based saturation analysis were described in the previous section. Similarly, we discuss the main criteria for modeling-based saturation analysis and uncertainty of the computed saturation; thereby, pulsed neutron logging feasibility and uncertainty in saturation can be evaluated in a pre-job stage.

Uncertainty in Gas Saturation

Uncertainty of gas saturation in water-gas two-phase formations is directly proportional to the ratio of measurement's statistical error and the difference of expected maximum and minimum RIN13 values, or ΔRIN13 .

$$\delta(S_g) \propto \frac{\sigma(\text{RIN13})}{\text{RIN13}_{\text{water}} - \text{RIN13}_{\text{gas}}} \quad (1)$$

where $\delta(S_g)$ is the uncertainty of gas saturation, $\sigma(\text{RIN13})$ is the statistical error of the measurements, $\text{RIN13}_{\text{water}}$ is the maximum theoretical RIN13 value, and $\text{RIN13}_{\text{gas}}$ is the minimum theoretical RIN13 value.

The measurement's statistical error is mainly related to the number of logging passes and speeds at a defined source output. Because gamma-ray count rates of time spectra for RIN13 are high, the RIN13 repeatability of multiple passes is generally excellent, i.e., the standard deviation of multiple passes in most cases is less than 1-1.5 RIN13 units.

The denominator of equation (1) is the dynamic range of RIN13 at specific well and formation conditions. The maximum RIN13 value represents a water-filled formation, and the minimum RIN13 value indicates a gas-filled formation. MCNP models define these two RIN13 values. A graphical representation of the denominator is presented in Figs. 3–5 marked as ‘Envelope.’ Numerous factors determine the envelope's width, but the primary factor is the porosity in most pulsed neutron well logging conditions except gas- or air-filled borehole conditions.

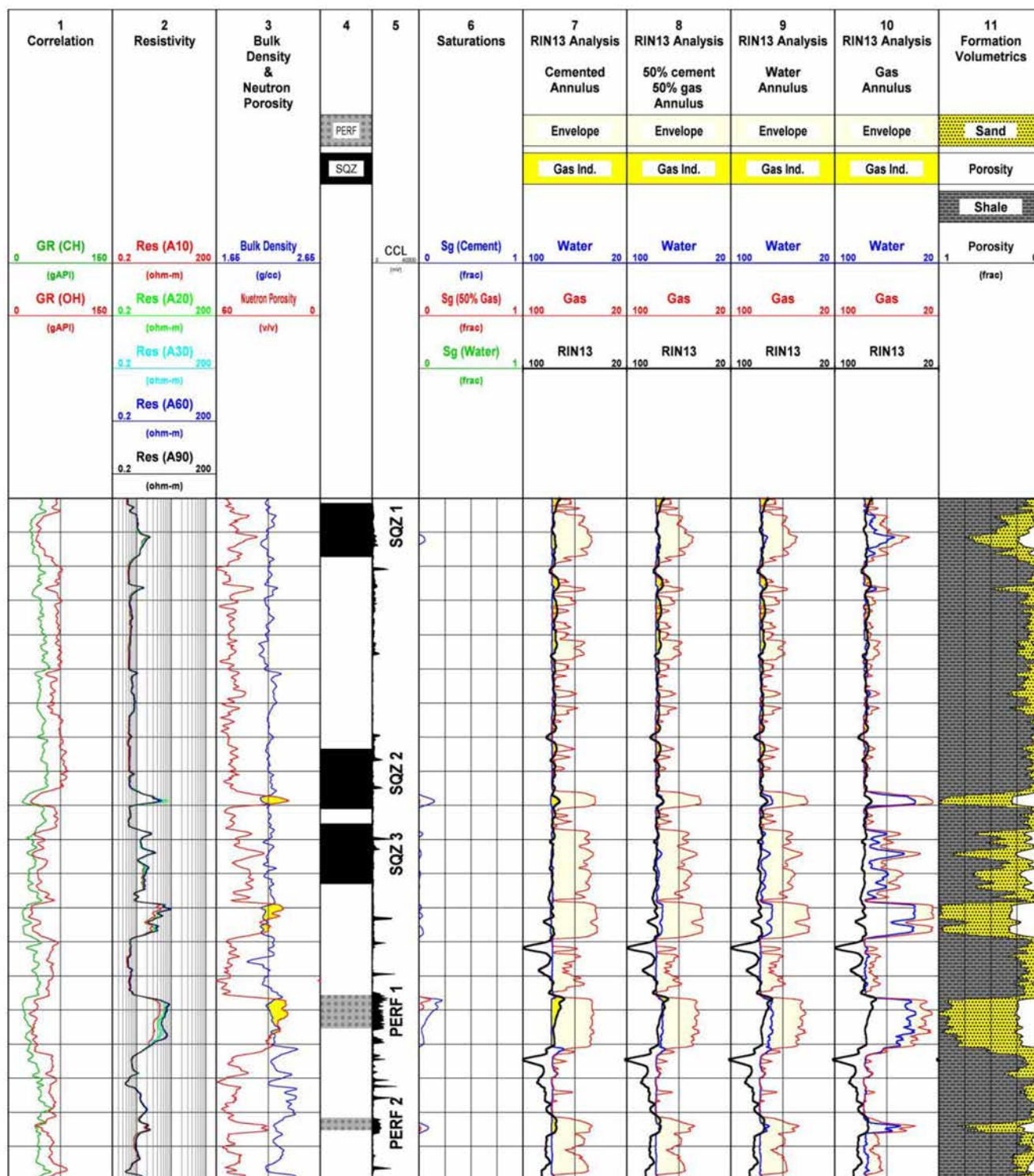


Figure 3—A composite log plot presenting RIN13 analyses from four annulus contents for intervals from 'SQZ1' to 'PERF2'

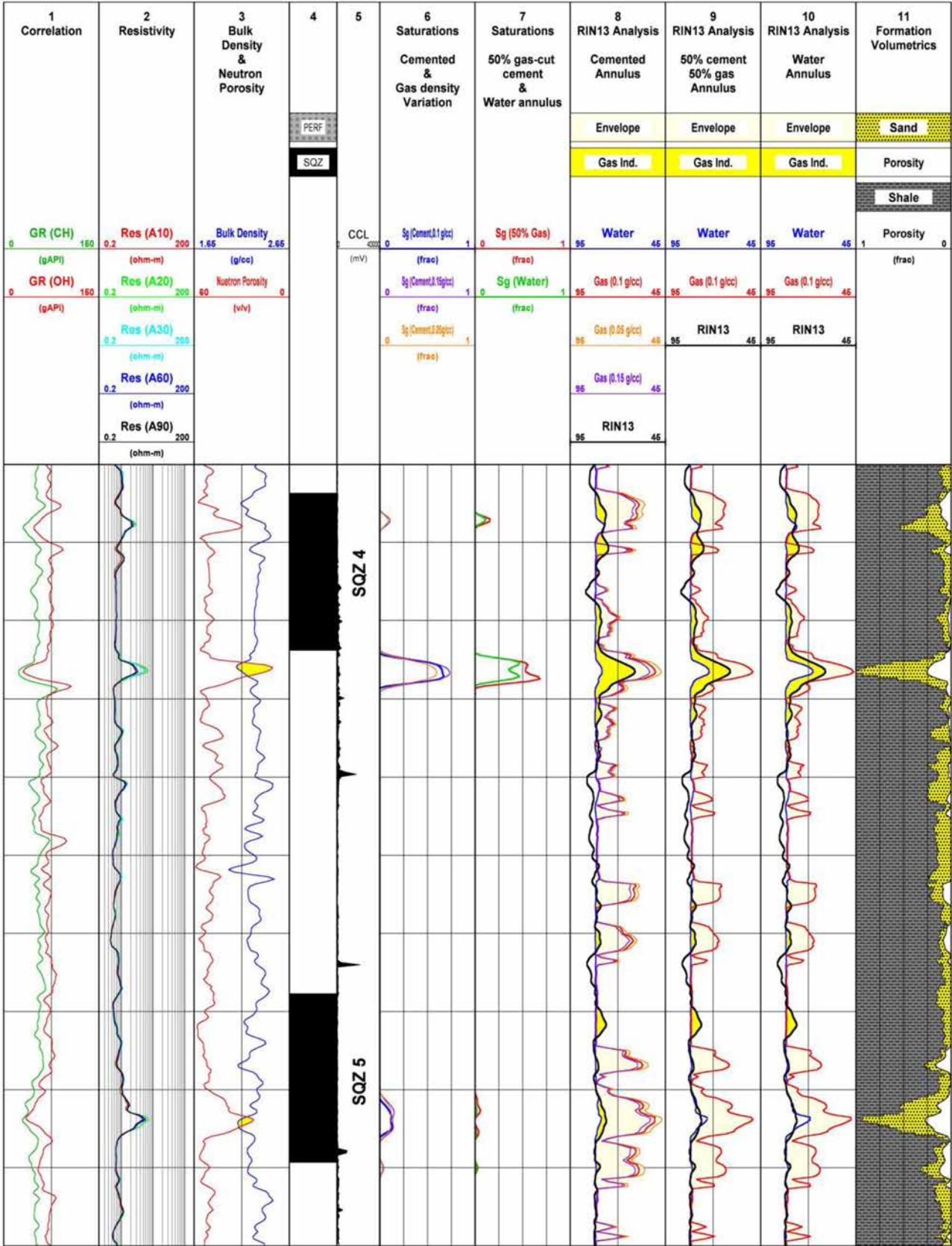


Figure 4—A composite log plot presenting RIN13 analyses from three annulus contents for intervals from ‘SQZ4’ to ‘SQZ5’

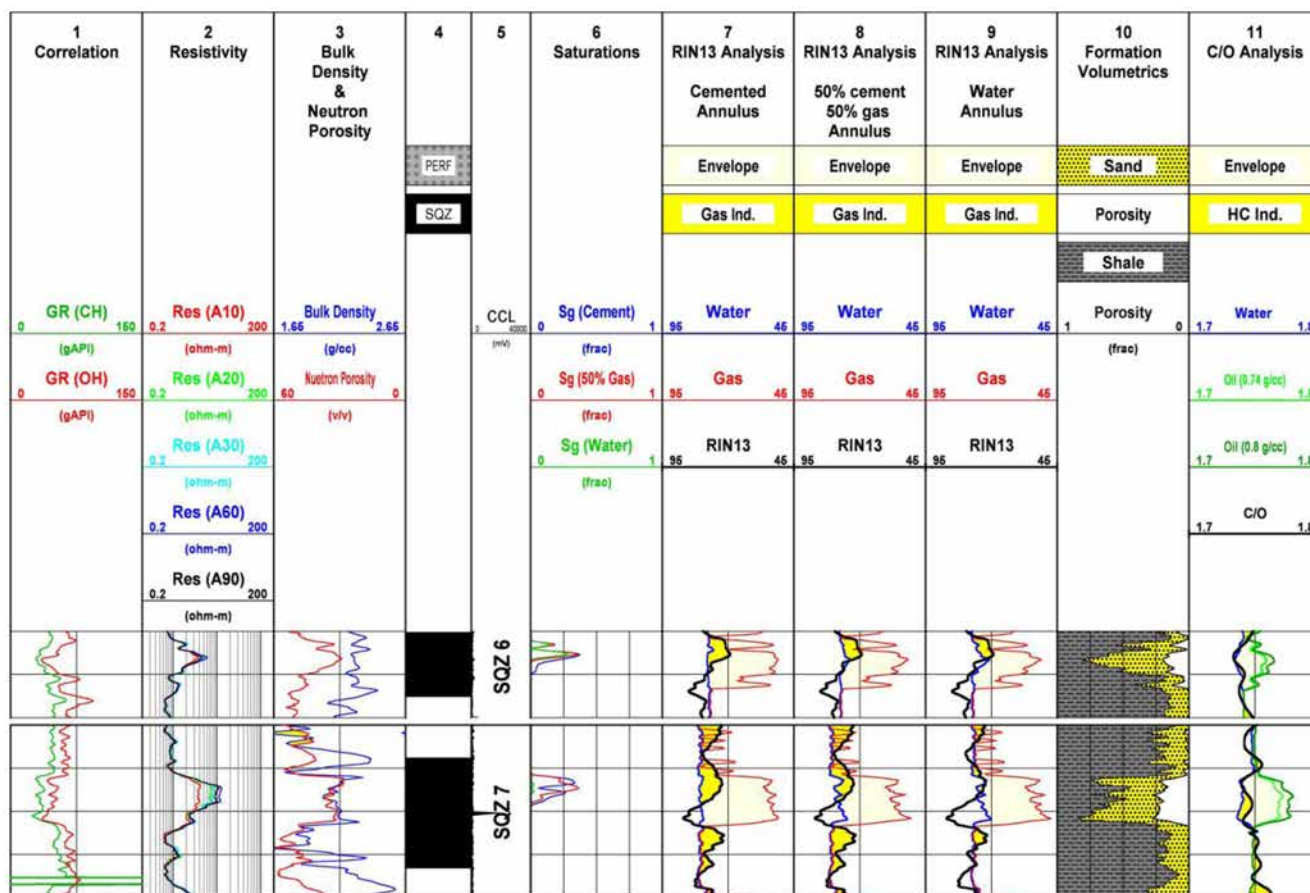


Figure 5—A composite log plot presenting RIN13 analyses from three annulus contents and C/O analysis for intervals from 'SQZ6' to 'SQZ7'

Tubular Sizes

The size and weight of the tubular affect the pulsed neutron measurements. As borehole size increases, more effects from the borehole fluid contribute to the measurement, resulting in less sensitivity to formation. Additionally, in the case of centralized liner or tubing strings in the casing, the pulsed neutron tool is centralized in the borehole; thus, the borehole fluid impact increases. Therefore, accurate holdups become essential to obtain reliable saturation results as the borehole fluid impact increases with a casing size.

Borehole Fluid Type

The wellbore fluid type affects the formation sensitivity of the measurements, as briefly mentioned earlier in the paper. Hydrogen is the most efficient element that slows down fast neutrons. Thus, hydrogen-abundant borehole conditions facilitate the scattering of neutrons and increase formation sensitivity. In contrast, in hydrogen-poor borehole environments, fast neutrons are more propagated along the wellbore than to the formation, therefore losing formation sensitivity.

Pulsed neutron logging for producing wells in gas fields frequently encounters gas-filled wellbore segments. Formation sensitivity is significantly reduced in the gas-filled wellbore case. The degree of reduction in formation sensitivity is related to the volume and density of gas in the wellbore.

Injecting water before or during logging is one solution for creating a hydrogen-rich environment. However, water injection may cause formation damage, injected water re-invasion across the perforated intervals, and extra operating costs and time. An alternative solution is to use a sleeved pulsed neutron well logging tool. A sleeve pulsed neutron tool contains hydrogen-rich fiberglass material covering the pulsed

neutron source and gamma-ray detectors; thus, this decreases the gas volume in the wellbore and increases the hydrogen density (Zhang et al., 2017).

Porosity

Porosity primarily determines $\Delta RIN13$ in equation (1); therefore, the porosity is inversely proportional to uncertainty in the calculated saturation. The RIN13 dynamic range in a liquid-filled wellbore of less than 10 percent porosity is good, as observed in Fig. 1. RIN13-based saturation analysis can be performed for formations in low porosity ranges. In a 5-10 percent porosity range, the dynamic range of RIN13 is much wider than that of Sigma in an extremely saltwater environment. Thus, saturation analysis using RIN13 is applicable in low porosity formations, irrespective of water salinity.

Bed Thickness

Vertical continuity of the formation is a significant factor affecting saturation uncertainty in shaly sand formations, tight sand-shale sequences, multilayers of thick shales and thin sands, etc. The agreement between forward modeled and measured responses can be challenging if a sand bed is thin. Minor vertical log offset between input parameters and cased-hole logs may result in incorrect or uncertain saturation. If the porosities of such formations are not high (i.e., less than 10 percent porosity), the saturation analysis uncertainty becomes higher.

Although the bed thickness, vertical continuity, or homogeneity of formation is not in equation (1), these factors often affect saturation results. Therefore, the bed thickness and porosity range of the sand (i.e., minimum, maximum, and average porosities) must be reviewed simultaneously to determine the feasibility of pulsed neutron logging and assess the saturation uncertainty.

Hydrocarbon Initially In Place

Reservoir management or workover decision, such as adding or squeezing perforations, based on the cased-hole saturation analysis is more challenging for the formation where the original volume of hydrocarbon is low. The current hydrocarbon saturation is likely similar to or less than the initial hydrocarbon saturation. In this case, the pulsed neutron measurement mostly stays on or inclined to the modeled water-filled formation responses because the formation is predominantly filled with water.

A small normalization or measurement's statistical error, which changes the saturation profile or results in saturation uncertainty, may influence the workover decision more on the formation with high water saturation than that with low water saturation. This factor is also closely related to porosity; the effect of low hydrocarbon saturation is amplified as the porosity decreases.

Through-Casing Pulsed Neutron Logging in the Hazira Field

We discuss gas saturation analysis in a depleted hydrocarbon field in western India. We demonstrate how to address the uncertainty of computed gas saturation. We assumed various well and formation conditions and minimized the uncertainty in gas saturation computation—consequently, this enhanced confidence in perforation decision.

In-Well Surveillance in a Marginal Gas Field

Wells in the Hazira field penetrate multiple stacks of sands, and gas and oil have been produced over the years. As hydrocarbon production has dropped, identifying bypassed oil and gas sands was increasingly important. The subject well production had ceased because the current open perforated intervals produced water due to water loading in the wellbore. The operator decided to log pulsed neutron data sets to perform reservoir saturation analysis to identify bypassed hydrocarbon-bearing sands. Based on the cased-hole saturation analysis, the operator planned to decide on zone transfer or abandon the well.

Gas Saturation Analyses Under Various Scenarios

The subject well was drilled with an 8.5-inch bit and completed with a 5.5-inch casing. Pulsed neutron logging included two passes of standard pulsed neutron capture (PNC) data acquisition for about 550 meters covering multiple sand units and three passes of C/O data acquisition for two sand units. The PNC logging interval contained seven squeezed zones and two open perforated intervals.

Fig. 3 presents openhole logs and cased-hole gas saturation analyses. One horizontal grid line represents five meters.

The leftmost track shows gamma-ray logs from openhole and cased-hole conditions. Track 2 presents array induction resistivity logs. Track 3 shows bulk density and neutron porosity logs acquired in the openhole condition. Tracks 4 and 5 indicate squeezed (black box) and open (gray box with dots) perforated intervals.

In tracks 7-10, RIN13 envelopes created with four different MCNP models for varying annulus contents are plotted in the same scales: track 7 for the well-cemented condition, track 8 for the 50% gas-cut cement annulus condition, tracks 9 and 10 for water- and gas-filled annulus conditions.

Each RIN13 envelope consists of water- and gas-saturated lines. Two lines represent the maximum and minimum RIN13 responses predicted by MCNP modeling and input formation volumetrics, such as porosity and volumes of sand and shale. The displayed envelopes were compensated with shale content in the data analysis process because the forward modeling did not include shale volumes. The input formation volumes were the same for all four analyses.

The envelope size was the widest for the well-cemented model. It became smaller as the cement volume decreased in the annulus (from track 7 to track 9 or 10) or the annulus fluid's hydrogen index decreased (from track 9 to track 10). As the cement volume decreased, the RIN13 water line declined. The RIN13 gas line increased by about 1-2 RIN13 units from the well-cemented to 50% gas-cut cement conditions and dropped from these two conditions to the water- and gas-filled annulus conditions.

Sands for squeezed perforated intervals marked with 'SQZ1,' 'SQZ2,' and 'SQZ3' showed that RIN13 stayed on the water side of the envelope for well-cemented or gas-cut cemented analyses, indicating water-filled formations. However, RIN13 responses were higher than the water side of the RIN13 envelopes for fluid-filled annulus cases, meaning the annular space was not fully occupied with formation water or gas.

The 4.5-meter-thick sand located about 5 meters deeper from the bottom of the 'SQZ3' perforation showed gas indication by an overlay of bulk density and neutron porosity logs in the openhole condition. However, no significant formation gas was identified from the cased-hole surveillance. Gas in this layer had been produced from nearby wells.

Across the sand with perforation, marked with 'PERF1,' showed an average gas saturation of 12% from the cement model-based RIN13 analysis. However, no formation gas was identified from the 50%-gas cut cement model-based analysis. The interval that RIN13 decreased matched the perforated interval, suspecting that the perforation activity induced some loss of cement sheath. The RIN13 response was on the water side of the 50% gas-cut cement-based envelope, suggesting the possibility of some cement loss due to perforation or a not-perfect pre-perforation cement condition resulting in some gas saturation in the well-cemented model-based analysis. The flow rates at the surface when the well flowed indicated that the water cut was close to 100%, and the production ceased afterward; thus, this gas indication is likely due to the cement volume reduction in the annular space.

The RIN13 log was higher than modeled RIN13 responses between two perforated intervals. This is because extra hardware, as indicated by the casing collar locator (the curve mnemonic is CCL) on track 5, affected the RIN13 responses. RIN13 increases as the volume of hardware increases because the hardware or completion jewelry decreases the propagation of neutrons farther toward formations, resulting in lower count rates recorded in the extra-long-spaced detector, and thereby RIN13 increases. The 'PERF2' zone showed no to little gas in the formation.

Fig. 4 presents a composite log plot for gas saturation analyses about 200 meters deeper from the ‘PERF2’ zone covering two sand units. One horizontal grid line represents five meters.

The sand corresponding to the upper part of the ‘SQZ4’ section showed little gas in the formation, as shown in track 8. RIN13 was inside the envelope for some zones, but the volume of shale was high, and heterogeneous shale properties might have induced some of the gas saturation. Therefore, this zone was not considered for re-perforation.

The 2-meter-thick sand immediately below ‘SQZ4,’ which is the top of a formation, revealed an average gas saturation of 60%, as indicated in blue on track 6. This sand layer showed the highest gas saturation in the logging interval. The openhole logs indicated gas presence; however, the same zone from the offset wells had produced gas and showed evidence of being watered out. Thus, the RIN13 responses across the identified gas zone were suspected of being affected by the poor cement condition. This section's cement bond log was unavailable; thus, RIN13 was compared to 50% gas-cut cemented (track 9) and water-filled (track 10) annulus model-based envelopes. The water side of the envelope in track 8 was higher than that in track 9, but the RIN13 gas line was marginally higher in track 9 than in track 8.

Considering that 50% of the cement volume is replaced with formation gas in the annular space, the computed average gas saturation was approximately 54%, as presented in red on track 7. In addition, the water-annulus RIN13 envelope-based analysis showed about 42% gas saturation, as shown in green on track 7. Table 3 summarizes the gas saturation analysis results of three annulus content cases.

Table 3—Summary of gas saturation analysis results with varying annulus contents

	Well-cemented case	50% gas-cut cement case	Water-filled annulus case
Average RIN13 water line	79	75	72
Average RIN13 gas line	53	54	52
Average RIN13 dynamic range	26	21	20
Normalized RIN13 measurement	64	64	64
Gas saturation	60%	54%	42%

The cement volume would be more than 50%, referencing other offset wells where cement bond logs were available. This means the modeled water response representing the in-situ condition across the target sand unit should be higher than the one from the 50% gas-cut cement-based envelope with a similar gas line to the 50% gas-cut cement-based model, suggesting the gas saturation is at least 54%.

Concern about the uncertainty in formation gas density estimation after production from the offset wells was presented. The uncertainty of gas saturation attributed to in-situ formation gas density for the interval was analyzed. The initial gas density for the target formation was 0.1 g/cc. Two gas densities, which are 50 percent higher and lower than the initial estimate, were considered, and corresponding MCNP gas responses were generated. In track 8, the red gas line is for the 0.1 g/cc gas-saturated formation as a base case, and gas lines in purple and orange represent 0.15 g/cc and 0.05 g/cc gas-saturated formations. Since a denser gas's hydrogen index is greater than a lighter gas, the 0.15 g/cc gas line is higher than the base gas line. In contrast, the 0.05 g/cc gas line was lower than the base gas line. The gas line changes appeared the most prominent near the peak of porosity (i.e., approximately 20% porosity), and gas density variation in lower porosity sections did not impact much on RIN13 responses (also refer to Fig 1. (a)).

Computed saturations from two new densities are plotted in orange and purple on track 6. The analysis with 0.15 g/cc gas density revealed an average of about 4% increase from the base case (60% base case and 64% from the increased gas density), and that with 0.05 g/cc gas density showed an average of 8% decrease

(i.e., gas saturation of 52% from the reduced gas density). Table 4 summarizes gas saturation analysis results with three gas densities.

Table 4—Summary of gas saturation analysis results with varying gas densities

	50% lower gas density	Base case	50% higher gas density
Formation gas density	0.05 g/cc	0.1 g/cc	0.15 g/cc
Average RIN13 gas line	50	53	56
Gas saturation	52%	60%	64%

The potential for gas production was evaluated based on the gas saturation analyses considering varying annulus contents and formation gas densities. The results showed a maximum gas saturation of 64% from the well-cemented with the 0.15 g/cc formation gas case and a minimum gas saturation of 42% from the water-filled annulus with 0.1 g/cc formation gas case. Gas saturation analyses under different well and formation conditions helped to understand the uncertainty in formation gas volume estimation and enhanced confidence in the perforation decision.

Less than 10% of gas saturation was quantified for the lower part of the ‘SQZ5’ interval from the well-cemented envelope. A small volume of gas might be left in the formation in the post-production stage.

Fig. 5 presents a composite log plot, including openhole logs, and cased-hole saturation analyses using RIN13 and C/O logs. Sands labeled ‘SQZ6’ and ‘SQZ7’ contributed to oil production from the offset wells. Thus, C/O logging was performed across the two sand units squeezed earlier to evaluate the current oil production potential.

Like the method for creating the RIN13 envelope, the C/O envelope, as shown in track 11, was created with MCNP models of short- and long-spaced C/O ratios and input formation volumetrics (Mickael et al., 1999; Kim et al., 2023). MCNP models were generated for a well-cemented annulus condition at two formation oil densities. Two oil densities were considered because the in-situ oil density was not well defined. The water line represents the water-filled formation or minimum C/O ratio, and two C/O oil lines represent two different types of oil-filled formations (i.e., 0.74 g/cc in light green and 0.8 g/cc in dark green) or maximum C/O ratios.

In the ‘SQZ6’ sand, the C/O-based saturation analysis revealed that the sand was filled with water because the measured C/O log in black was on the water side of the C/O envelope. RIN13 analysis showed about 15% average gas saturation near the top of the sand. Gas saturation assumed the uncemented condition was less than the well-cemented case. If poor or no cement was presented in the annular space, the C/O log would be lower than the water side of the envelope because gamma-ray count rates from water in the annulus would contribute to the C/O ratios. The measured C/O log was on top of modeled water line; thus, there is less likelihood that no cement was presented. The zone was not re-perforated as the gas saturation was low, and no formation oil was indicated.

Similarly, the ‘SQZ7’ sand, located 50 meters deeper than the ‘SQZ6’ sand, showed some gas saturation near the top of the sand. The C/O log was close to the water side of the envelope, indicating no oil saturation in the same section. This could also indicate the presence of gas in the formation because the C/O responses between water and low-density gas-filled formations were similar. The spike in RIN13 at the mid-squeezed interval was due to the casing collar effect. A minor indication of formation oil was identified from the C/O analysis, which might be residual oil saturation.

Zone Transfer Based on Formation Saturation Analyses

In the sand unit immediately below the ‘SQZ4’ zone (refer to Fig. 4), average gas saturations were 42-64% under various scenarios. Thus, the operator decided to add perforation and test the production.

A new perforation was created for a one-meter interval, and production was tested. The surface production test results showed that the sand started producing an initial gas rate of 80,000 m³/day (equivalent to 2.83 mmscf/day). The gas production rates suggested that this zone was an un-perturbed zone from the offset well productions, and the reservoir pressure was close to virgin pressure.

Conclusion

We demonstrated advanced gas saturation analysis in a marginal gas- and oil-producing field. The low formation water salinity prevented using the Sigma log for gas saturation analysis. Furthermore, accurate gas quantification was essential in the marginal hydrocarbon field to identify bypassed oil and gas zones; thus, using the conventional pulsed neutron overlay technique to detect gas-bearing zones qualitatively was not an option. The other challenge was that the sand layers were relatively thin, with an average porosity of less than 15-20%. High degrees of heterogeneity in shale properties also rendered the analysis complex.

We used a gas-sensitive time spectra-based inelastic pulsed neutron measurement from the short- and extra-long-spaced detectors, i.e., RIN13. The measured data were compared to predicted tool responses. The MCNP-based modeling technique predicted the RIN13 responses in a probabilistic framework reflecting logging environments. Finally, gas quantification was computed by incorporating salinity-independent gas-sensitive log and MCNP models.

C/O logs were also recorded to evaluate oil-producing sands from adjacent wells. The combination of C/O and RIN13 analyses using respective MCNP-based envelopes provided information on gas and oil saturations and clues on the annulus content.

In addition, we presented the effects of annular space content and in-situ formation gas density variation on the RIN13 responses. This allowed for evaluating gas saturation and its uncertainty under various circumstances before a perforation decision was made.

As a result of the comprehensive and accurate gas and oil saturation analyses behind the casing, the operator perforated one prospective sand interval with confidence and produced a large amount of gas from the untapped sand unit.

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