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Optimisation of Plug and Abandonment Process Utilising Nuclear Technology for through Tubing Cement Evaluation

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Abstract

One of the major factors in the well plug and abandonment (P&A) process is to provide a proper isolation in aging wells which requires effective placement of the cement plug in the most suitable location in the well. Identifying cement placement is usually achieved by running cement evaluation logging to define the quality of cement and top of cement depth behind and in between the casing annuli.

However, this comes with significant costs due to tubulars or casings removal requirement prior to logging run in order to conduct a proper evaluation. This is necessary since acoustic and ultrasonic based cement evaluation technologies will not be able to determine cement quality behind several casing layers if the job is done through tubing. The cost involved is substantial especially in offshore operation in which the daily operating rate is significantly higher compared to an onshore operation.

A new approach to cement evaluation has been tested during the well P&A campaign in one of the aging oil fields in offshore, Peninsular Malaysia. A nuclear based technology comprised of Gamma-Gamma, Neutron-Neutron and Neutron-Gamma measurements were utilized to evaluate cement integrity behind production casing and between production casing as well as intermediate casing while logging run was deployed through tubing in memory mode.

Log data was compared with acoustic and ultrasonic based cement evaluation technology that was deployed after the tubing was pulled out in one of the wells. Results had shown a consistent finding with the conventional ultrasonic based cement evaluation data. Based on the logging results, cement placement design and depth was finalized and the cement plug was successfully tested as outlined in the well P&A guideline.

Findings from this logging run had provided useful insight to the operator to validate the nuclear based thru tubing cement evaluation technology for wells P&A application. Huge cost saving could be captured through this application as a result of eliminating total rig days via offline cement evaluation logging and based on the results obtained planning for the exact well P&A design requirement prior to the rig arrival.

This paper will outline the method, tools used to acquire the cement evaluation data and its operational advantages. Acquired data will be presented and discussed along with the methodology used to determine cement volume and top of cement depth behind and in between the casings.

Measurement Principle

There are limited physics that can be applied to measurements through multiple strings of pipe either due to the medium the measurement must pass through to see the annulus or due to its limited depth of investigation.

A relative evaluation of the presence of cement in annulus can be accomplished utilizing 4-detector Neutron-Thermal Neutron (NN)-Neutron-Gamma (NG) device using both Neutron and Gamma sources. Gamma-Gamma (GG) application for cement evaluation is well-known in the industry. It is based on the fact that density of the cement and water is different. If there is a change in the annulus from cement (1830 kg/m^3) to water (1000 kg/m^3) the density change is significant i.e. 83%. Even more if there is a change from cement to gas-filled annulus.

NN/NG method is not widely used for cement evaluation. It is based on the fact that counts on NN detectors are a function of the hydrogen index of the measuring environment and presence of elements with elevated thermal neutron cross-section. Counts on NG detectors are a function of the hydrogen index, chemical composition and density of the measuring environment. By combining the two physics, it is possible to maximize density dependency of the NG physics, minimizing its dependency from other parameters.

Measured changes on the detectors are attributed to either changes in the measuring environment (CSG, fluid, formation) or changes in the cement. Since we are interested in changes associated with the amount of cement, other changes should be removed or their effect minimized.

Wellbore/CSG changes can be identified as a linear shift on the measured curves at the interface(s). They are identified evaluating counts on Neutron-Neutron (NN), Neutron-Gamma (NG) and Gamma-Gamma (GG) detectors and the curves calculated based on these counts. The evaluation process utilized for this case study included:

- Identifying uniform shifts in the single detector responses,
- Vshale differences between Vshale Clay (Vsh_C) and Vshale Gamma ray (Vsh_GR)
- Total Porosity (TP)/Dual Detector Neutron (DDN) and Total Porosity/Porosity Error due to Liquid component in the pore space (PL) overlays and curve behavior,
- Borehole Resistivity Measurement (BRM)/Temperature (TEMP),
- Relative Density (RD), Neutron field changes due to changing geometry of the well (NC)
- Gamma-Gamma short space (SGG),
- Gamma-Gamma long space (LGG),
- Gamma-Gamma ratios

Wellbore changes are usually seen on BRM/TEMP – BRM will be high in low conductive environments. The temperature gradient will change in different fluids.

Gas in the wellbore can be identified by low Vsh_C, high Vsh_GR, low QTP, DDN, QL.

Change from water to oil can be identified on TP/PL, TP/DDN, NN-NG singles, Vsh_GR/VSH_C.

Formation changes could play affect on measured curves. In order to minimize the effect from the formation changes, cement evaluation should be performed using the curves which are mostly driven by changes in the bulk density, but they should receive most of their signal from the change of the bulk density in the desired volume. In order to identify such curves Monte-Carlo modeling has been performed for different completion designs.

Cement index is calculated as follows:

$$\text{CEMENT INDEX} = (\text{CR} - 0\%\text{CL})/(100\%\text{CL} - 0\%\text{CL}) \quad (1)$$

Where,

CR – curve response at the particular depth
0% CL – curve response in free pipe
100% CL – curve response in fully cemented pipe.

The gamma-gamma (GG) measurement will have a very high sensitivity to near wellbore (especially GG SS) and will typically not be able to measure outside the heavier casings or through any double casing scenarios. The reason for this is the low penetrating power of the gamma source (CS 137 ~660keV gamma energy) and the shorter depth of investigation of the short-spaced detector.

When changes in the wellbore are identified, zones are created to compensate curves for these changes. When wellbore effects are removed, curves are compared to identify casing (CSG) changes as follows:

- Second CSG, which will be seen on Vsh_GR/Vsh_C overlay – Vsh_GR is low due to extra shielding; Vsh_C is high due to the same reason. TP will be elevated due to bigger bit size required for the 2^{nd} CSG, elevated RD.
- Dependent on the size of the CSGs, GG measurement will be used to confirm presence of additional CSG. When additional CSG is identified, zones are created to compensate curves for CSG changes.

The next step is to identify changes in the annuli. These changes could be either due to presence of cement and the amount of it or changes in the formation.

In order to remove effect from the formation changes, most of the curve response should come from the cement volume and not a formation. Monte-Carlo (MC) modelling allows to pick the desired curve.

MC modelling shows that GG method should be used to identify amount of cement behind the first CSG and GG has low sensitivity to the changes in the second annuli. GG curves and their application for cement evaluation are going to be described later in the document.

When desired curve is identified, cement index in the first annuli is going to be calculated based on equation 1.

In order to evaluate cement index behind the 2^{nd} CSG, method with deeper DOI compared to GG method is required.

Curves build based on combination of NN and NG physics allows to obtain the response sensitive to density change in the 2^{nd} annuli. Requirements for the curves based on NN/NG are similar to requirements for the curves built based on GG:

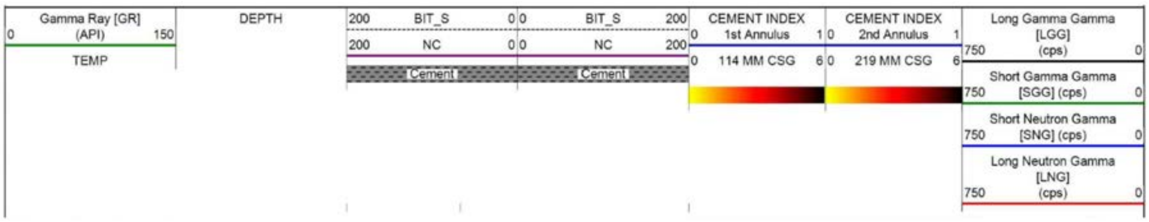
1. Curve should be sensitive to the bulk density change in the desired volume.
2. Curve should be insensitive to changes in the close proximity to the tool and the first annuli and formation changes.

MC modeling allows to identify curves satisfying these requirements.

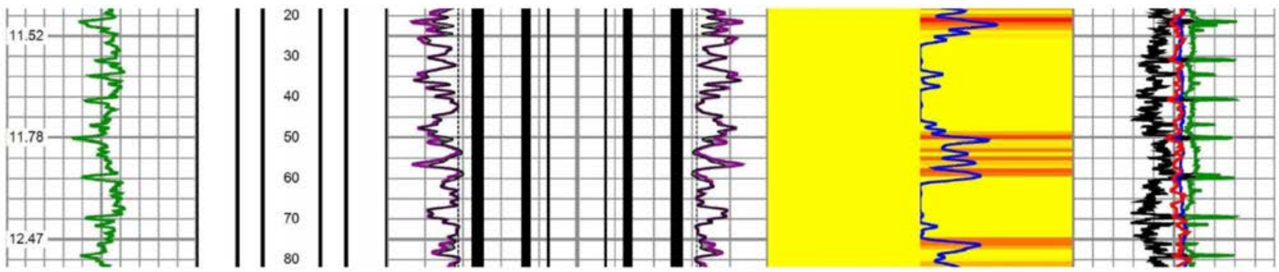
When desired curve is identified, cement index in the second annuli is going to be calculated based on equation (1).

Example of the calculated cement indices with respective cement maps in different situations is presented below:

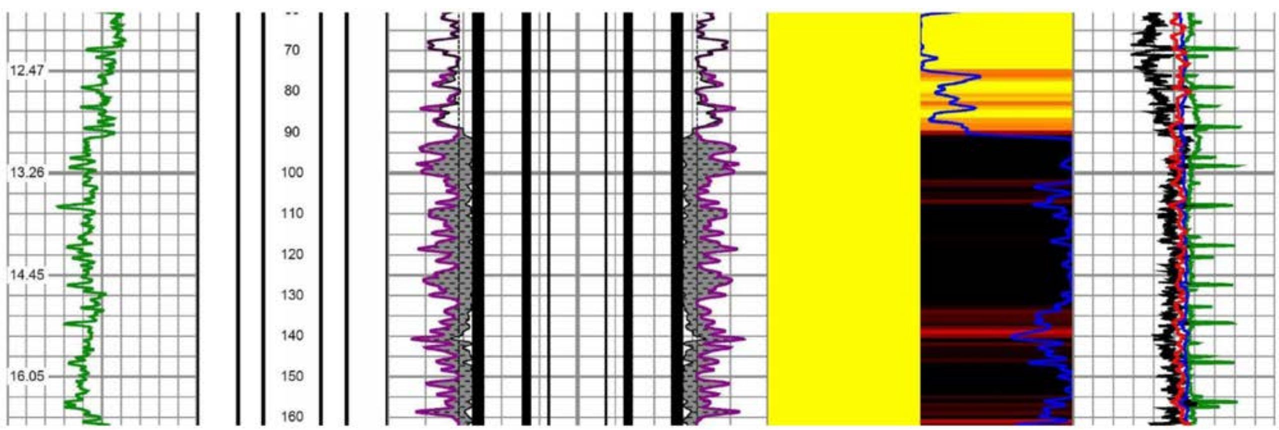
Examples



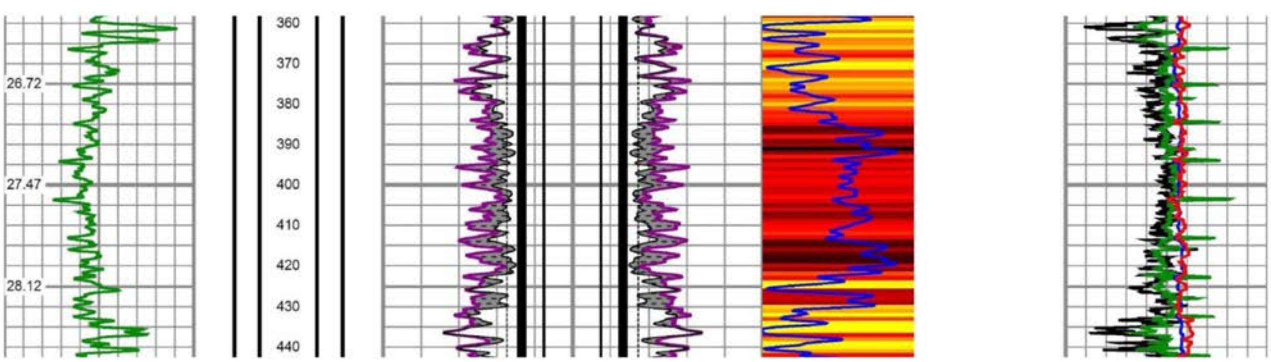
Bad Cement behind both CSGs



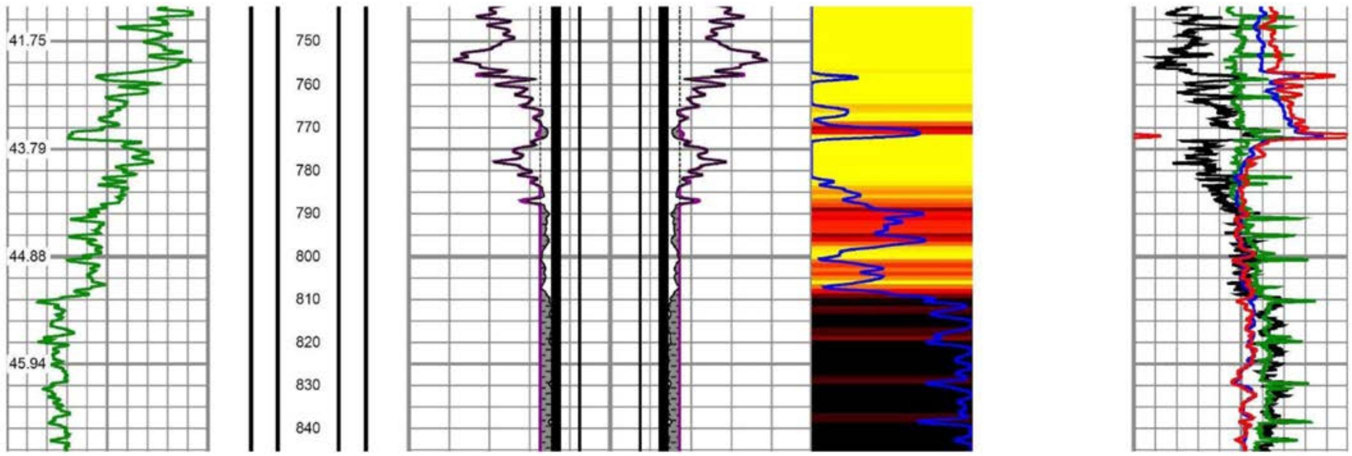
Good Cement behind 2nd CSG with TOC and no cement behind 1st CSG



Partial Cement behind 1st CSG



Good Cement behind 1st CSG with TOC



Case Study

When a well is no longer economically producing oil and/or natural gas, the well is evaluated for retirement and will undergo a process of plug and abandonment. Such plug and abandonment operations normally consist of placing several cement plugs in the wellbore to isolate the reservoirs. In this well, caprock restoration techniques was used for P&A operation. This technique focuses on achieving permanent Isolation by restoring the caprock penetrated the well. Competent Caprock chosen based on impermeable rock which has a rock strength that can withstand the maximum anticipated pressure. Prior caprock restoration, cement evaluation is required to evaluate the cement condition in the annulus across the determined competent caprock.

NN-NG nuclear technology was used in this well to evaluate the cement quality and to allow the proper selection of the caprock locations for plug placement.

In order to best prepare for the data analysis phase, the Monte-Carlo (MC) Modeling was conducted for several different scenarios and actual data compared to forecasted result.

Monte Carlo modeling has been used to model propagation of the particles (fast neutrons for and gamma rays) through the formation. Thermal neutron decay has been measured on two neutron detectors. Decay of neutron gamma and gamma-gamma fields have been measured on two gamma detectors.

Radial integrated geometrical factors have been calculated for multiple curves (curves acquired on the detectors) and their ratios.

Based on the modeling results, curves which provide the best description to the measured parameter are determined. These curves are used for the processing of the measured data.

GG MC Modeling. 7" CSG

MC modelling has been performed for measuring environment: 10" Bit size completed with 7" CSG and single 3.5" Tubing, cement behind the CSG, water in the tubing, and annulus.

Results are presented on Fig 1.

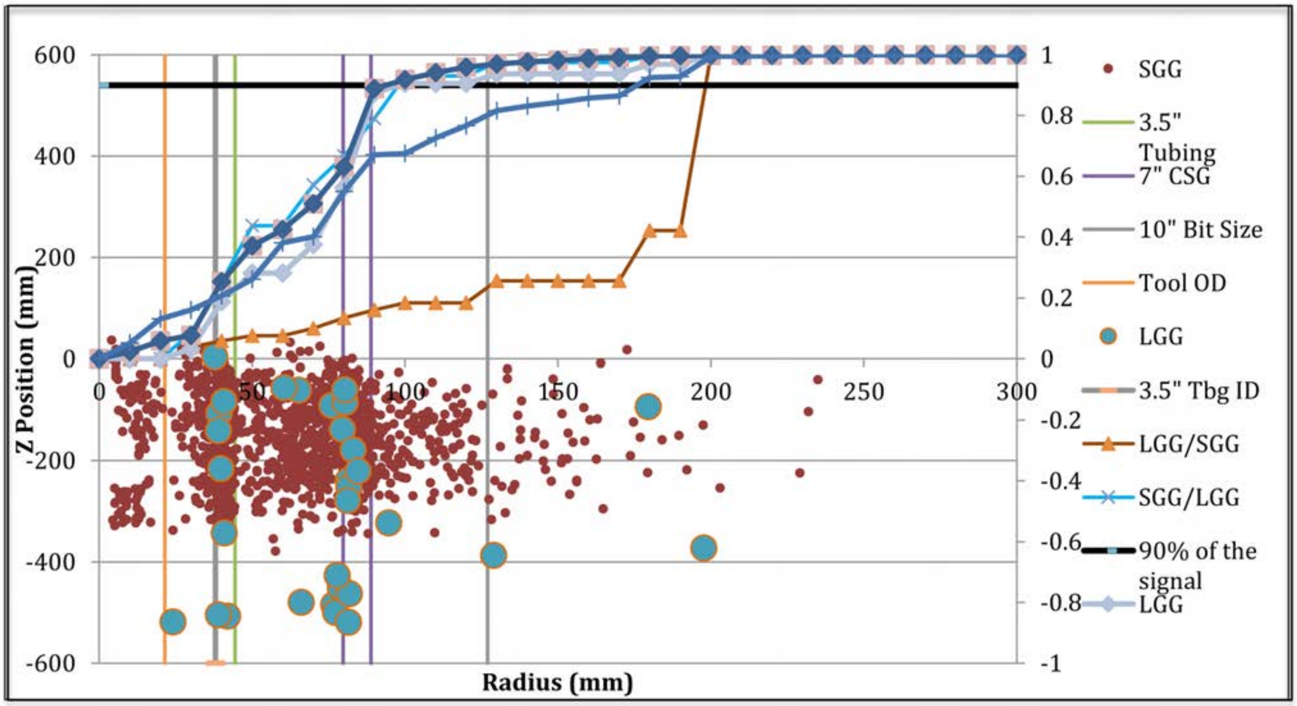


Fig. 1—GG MC modeling 7" CSG.

Integrated radial geometrical factors for single detectors (SGG and LGG), their ratios (SGG/LGG and LGG/SGG), and difference between LGG and SGG normalized to LGG (SGGn-LGG) have been calculated.

For presentation purposes integrated radial geometrical factors have been normalized to total counts, for geometrical factors to read between 0 and 1.

The target of the MC modeling is to find the curve which will be comprised from the signal which comes mostly from the cement volume.

Depth of investigation is the depth from where 90% of the signal is acquired.

Modelling shows that:

SGG same as SGGn and LGG reach DOI at the 7" CSG.
SGG/LGG "sees" signal behind the 7" CSG.
LGG/SGG is mostly responding to formation.

But in the situation with two CSGs, this curve will be the deepest curve, and will cover cement volume behind the 2nd CSG.

SGGn-LGG is the only curve which is sensitive to cement volume. This curve "sees" signal between the tool and 7"CSG. That's why it is important to make sure that measuring environment between tool and 7" CSG is not changing (tubing, CSG fluid across logging zone is homogeneous). If measuring environment between tool and 7" CSG is not changing, then changes in the curve will represent changes behind the CSG. deltaGG =SGGn-LGG curve has been used for cement evaluation behind the 7" CSG.

In order to define cut offs required to convert this curve to cement index, curve response in the cemented 7" CSG and free 7" CSG has to be known (100% cement line and 0% Cement line).

Due to the absence of clear (Top of Cement) TOC in this well, both lines have been derived based on modeled response:

Below is the modeled response for 2 detectors in the cemented 7" CSG and 7" Free pipe with calculated values for deltaGG curve:

Table 1

2031-2064m	Cs 137 7" Cemented			Cs 137 7" Free Pipe	
Curve name	Modeled counts	Real Counts	LGG-SGGn	Modeled counts	LGG-SGGn
LGG	193	190	0	287	100.69
SGG	6491	6453		6266	

SGGn is normalized to LGG thru 100% cemented interval. Normalization factor calculated as

$N=LGG_{(100\%Cement)}/SGG_{(100\%Cement)}$
$N=193/6491$
$N=0.029733$

This normalization factor is used to calculate SGGn response in 0% cement = $SGGn_{(0\%\ cement)}=SGG_{(0\%\ cement)}*N$.

And difference in 0% cement is calculated as LGG-SGGn=287-0.029733*6266=100.69

0% Cement line was set to 100,
100% cement line set to 0.
For two CSG environment.

GG MC Modeling. 7" and 10-3/4" CSG

MC modelling has been performed for interval competed with two CSGs.

As could be seen on the modeled data (Fig 2), ratioGG = LGG /SGG - is the curve which is least affected by changes between 7" and 10 ¾" CSG and formation.

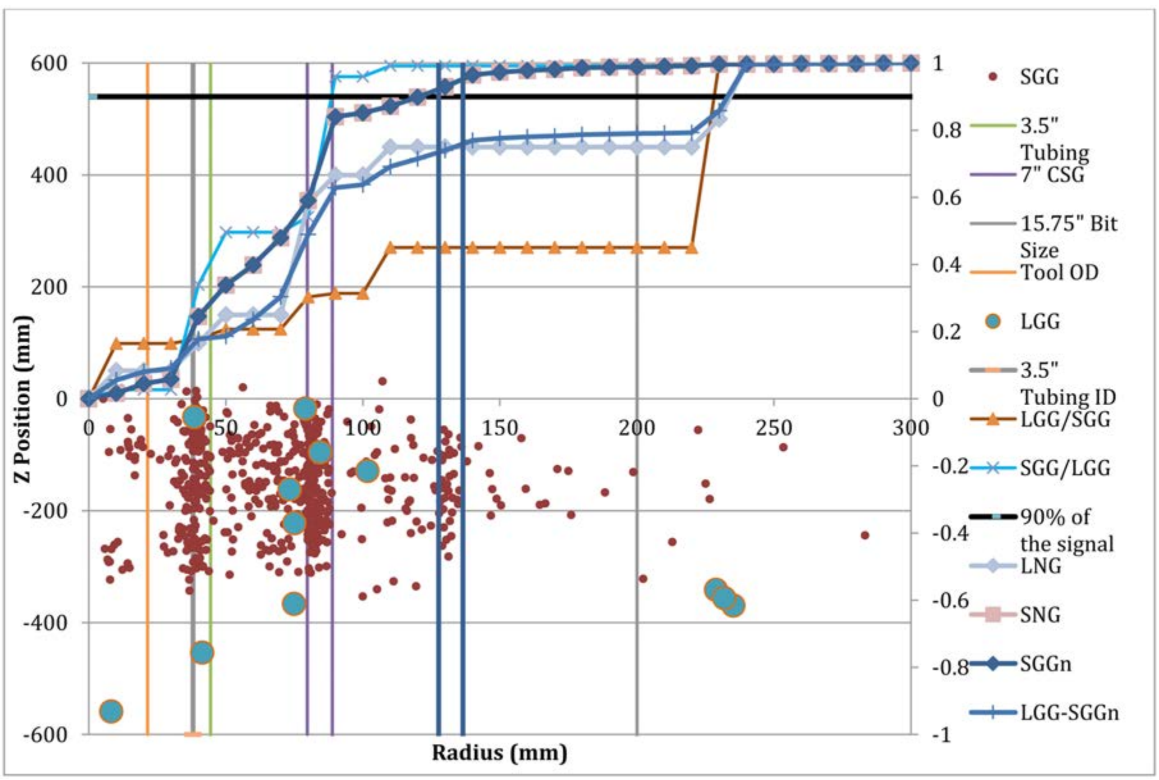


Fig. 2—GG MC modeling 7" and 10 ¾" CSGs

For cement evaluation between the CSGs, deltaGG curve represents the most of interest. It is affected by volume behind the 10 ¾" CSG (10% of the total signal will come from this volume).
deltaGG curve has been used for cement evaluation between the 7" and 10 ¾" Casings and ratoGG has been used for cement evaluation behind the 10 3/4" CSG.

Below is the modeled response for 2 detectors in the 100% cement thru interval completed with two CSGs, with comparison to measured values:

100% cement between the CSGs picked through zone 665-689m :

$LGG\text{-}SGGn_{(100\%\ cemented)}$=LGG(100% cemented)-N*SGGn(100% cemented)
$LGG\text{-}SGGn_{(100\%\ cemented)}$=168-0.029733*6143=-14.47
$LGG\text{-}SGGn_{(0\%\ cemented)}$=LGG(0% cemented)-N*$SGGn_{(0\%\ cemented)}$
$LGG\text{-}SGGn_{(0\%\ cemented)}$=268-0.029733*6429=77

Table 2

665-689m	Cs 137 7-10" Cemented			Cs 137 7-10" Free	
Curve name	Modeled counts	Real Counts	LGG-SGGn	Modeled counts	LGG-SGGn
LGG	168	168	-14.47	268	77
SGG	6143	6119		6429	

100% cement behind 10 ¾" CSG picked through zone 710-714m :

Table 3

710-714m	Cs 137 7-10" Cemented			Cs 137 7-10" Free	
Curve name	Modeled counts	Real Counts	LGG/SGG	Modeled counts	LGG/SGG
LGG	163	161	215.384615	240	320.0
SGG	7571	7583		7500	

In order to calculate cement volume, two lines were defined:

Due to the lack of clear top of cement, 100% cement line for deltaGG and ratoGG curves was defined using modelled results which has been checked against measured results.

0% Cement line has been picked based on the modeled results.

NN-NG MC Modeling. 7" CSG

As could be seen on the modeled data (Fig 3), NN-NG_Cem = SNG^2/(LNN*SNN) curve has least amount of signal from the formation, and it is highly dependent on the signal which comes from the volume behind the 7" CSG.

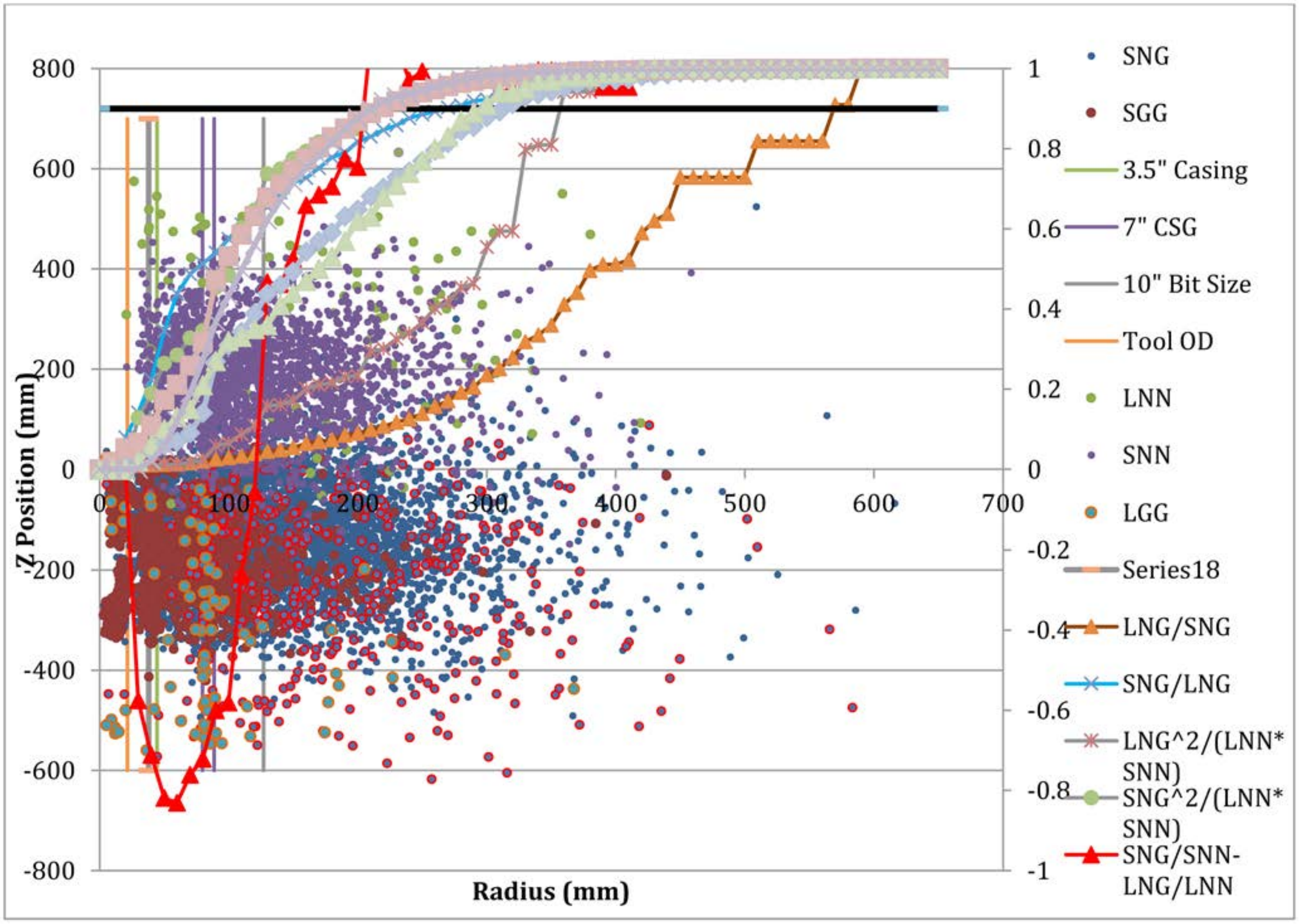


Fig. 3—NN-NG MC modeling 7" CSG

This curve has been used for cement evaluation behind the 7" CSG.

In order to define cut offs required to convert this curve to cement index, curve response in the cemented 7" CSG and free 7" CSG has to be known (100% cement line and 0% Cement line).

Due to the absence of clear TOC in this well, both lines have been derived based on modeled response.

Below is the modeled response for 4 detectors in the cemented 7" CSG and 7" Free pipe with calculated values for NN-NG_Cem curve.

Table 4

1790-2050m	AmBe 7" Cemented			AmBe 7" Free Pipe	
Curve name	Modeled counts	Real Counts	SNG^2/(LNN*SNN)	Modeled counts	SNG^2/(LNN*SNN)
LNG	777	708	247	696	783
SNG	8458	8421		8608	
LNN	117	121		59	
SNN	2477	2451		1604	

These values were used to convert NN-NG_Cem to cement volume.

As could be see on the log, NN-NG_Cem does not exactly match DEN_DIF_SGG_LGG. This could be due to deeper DOI on NN-NG_Cem (could be due to the gap between Cement and formation), also as could be seen on modeling NN-NG_Cem curve reads some signal which comes from the formation, which is not going to be seen on the DEN_DIF_SGG_LGG curve. This effect will be even stronger where bit size is smaller than modeled. NN-NG_Cem curve could read lower than 0% cement line thru such zones.

NN-NG MC Modeling. 7" and 10-3/4" CSG

As could be seen on the modeled data (Fig 4), NN-NG_cem_10.75=SNG/SNN-LNG/LNN is the curve which is least affected by changes between 7" and 10 ¾" CSG and formation.

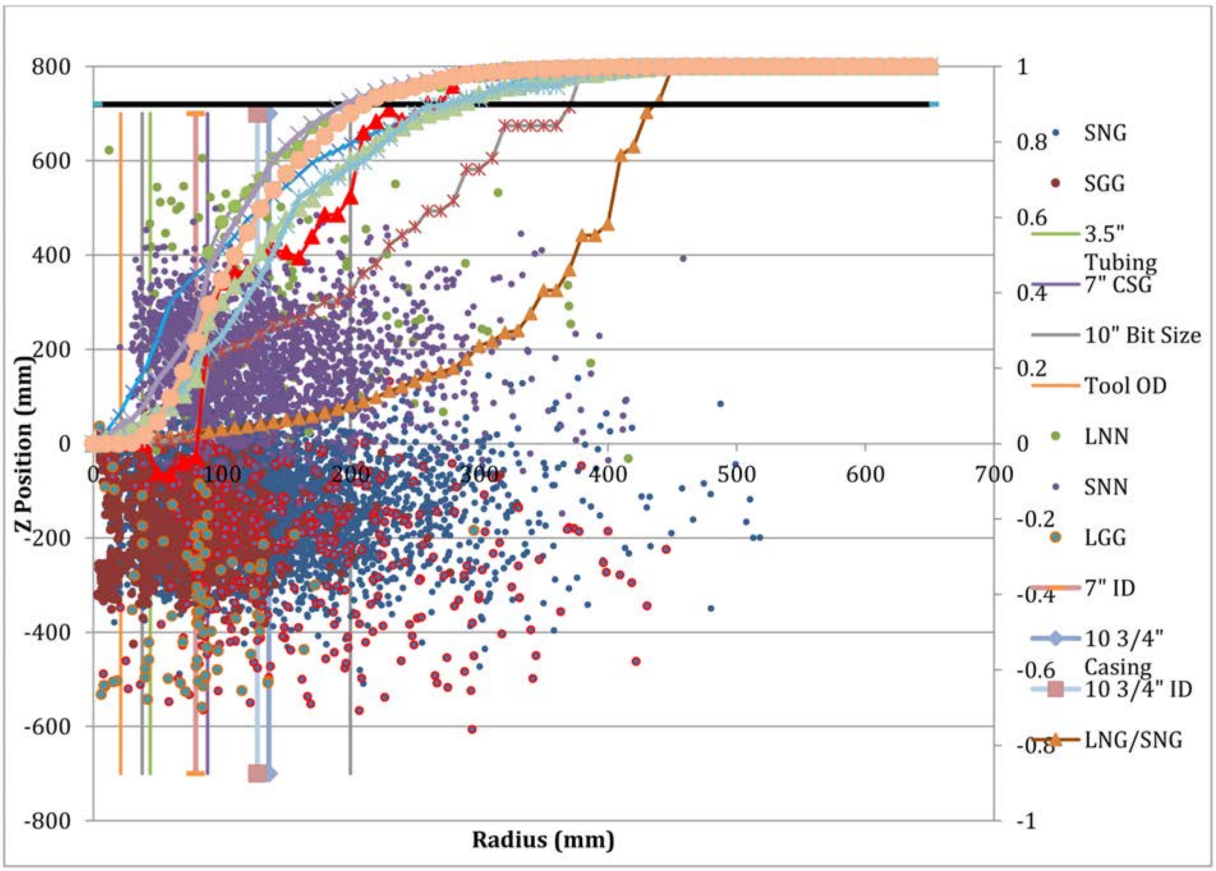


Fig. 4—NN-NG MC modeling 7" and 10 ¾" CSGs

For cement evaluation between the CSGs, SNG curve represents the most of interest. It is affected by volume behind the 10 ¾" CSG (10% of the total signal will come from this volume). This curve has the biggest dynamic range through volume between two CSGs. Unfortunately, SNG depends not only on density of the measured volume, but it is also dependent on porosity. In order to remove porosity component, neutron porosity curve could be considered, but that will increase DOI of the resulted curve, which will lead to higher uncertainty of the result due to the signal acquired from deeper zones.

Next best curve which will be slightly affected by the volume behind the 10 ¾" CSG will be NN-NG_Cem curve.

NN-NG_cem curve has been used for cement evaluation between the 7" and 10 ¾" Casings and NN-NG_cem_10.75 has been used for cement evaluation behind the 10 3/4" CSG.

Below is the modeled response for 4 detectors in the 100% cement thru interval completed with two CSGs, with comparison to measured values:

Table 5

662-693m	AmBe 7-10" Cemented				AmBe 7-10" Free		
Curve name	Modeled counts	Real Counts	SNG/SNN-LNG/LNN	SNG^2/(LNN*SNN)	Modeled counts	SNG/SNN-LNG/LNN	SNG^2/(LNN*SNN)
LNG	562	558	-4.6	579.9	476	-10.1	1323.6
SNG	7668	7609			6218		
LNN	61	61			29		
SNN	1659	1702			1003		

In order to calculate cement volume, two lines were defined:

Due to the lack of clear top of cement, 100% cement line for NN-NG_Cem and NN-NG_cem_10.75 curves was defined using modelled results which has been checked against measured results.

0% Cement line has been picked based on the modeled results.

Case Summary

Cement evaluation based on the radioactive measurements thru the intervals completed with single/multiple CSG strings requires data acquired with different depth of investigation. Modelling confirmed by in-situ measurements shows that data acquired with both Neutron and Gamma-Gamma sources are required in order to fully differentiate effects from close proximity (behind 1st CSG) and further from the tool (behind 2nd CSG).

Cement evaluation behind the 1st CSG requires methods with short DOI. GG methods are excellent for performing this task. Neutron methods have a deeper DOI compared to GG method and are excellent for cement evaluation behind the 2nd CSG.

In this case there are three (3) caprock identified in this well to be restored. Thus, cement evaluation was done to evaluate the quality of the cement in the annulus across the 3 targeted caprock. Based on the data acquired, cement quality was identified across the caprock interval (Fig 8).

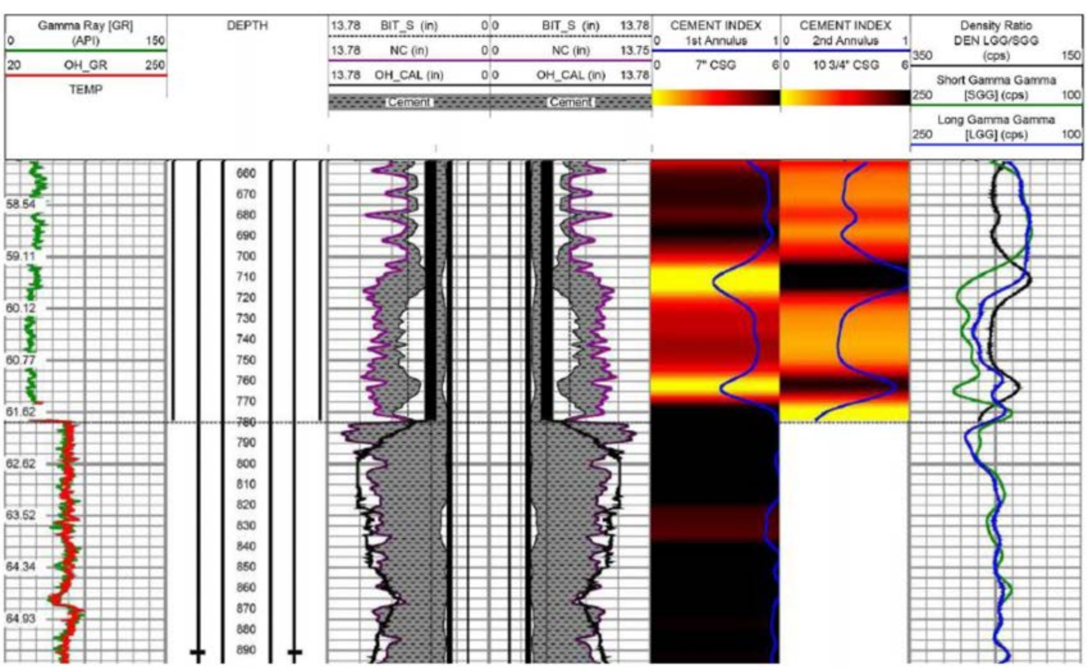


Fig. 5—Cement plug placement Zone 676 – 868 m

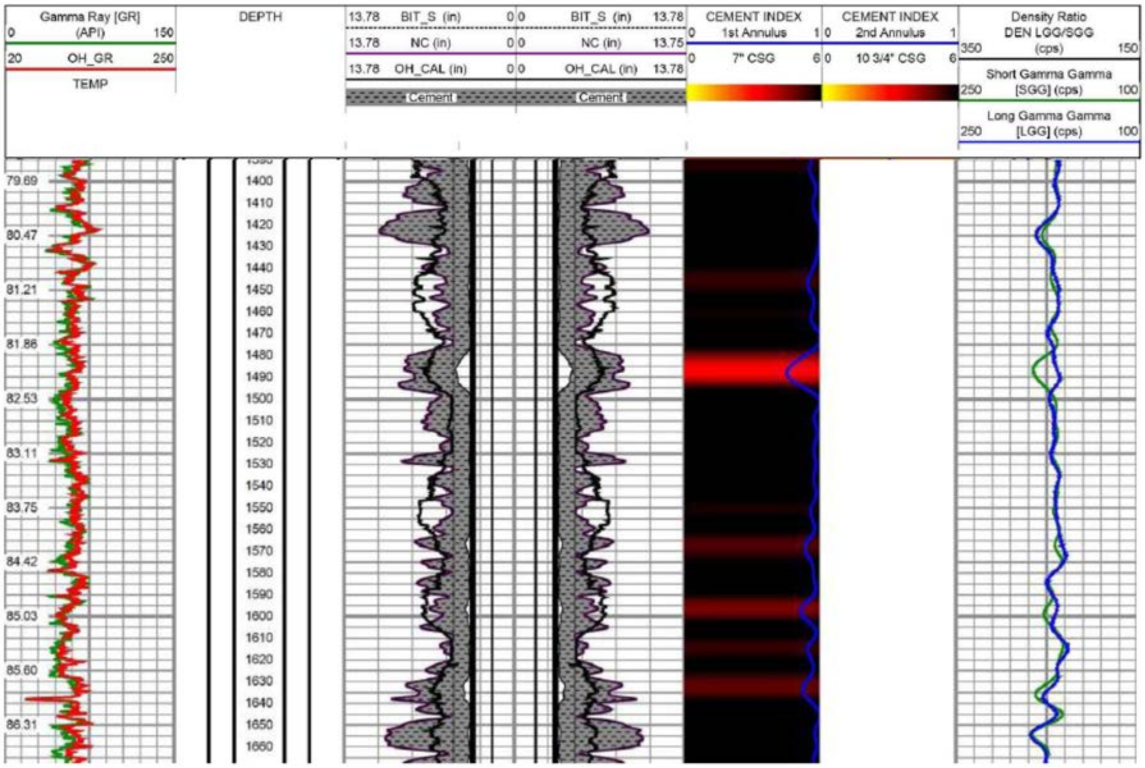


Fig. 6—Cement plug placement Zone 1414 – 1566 m

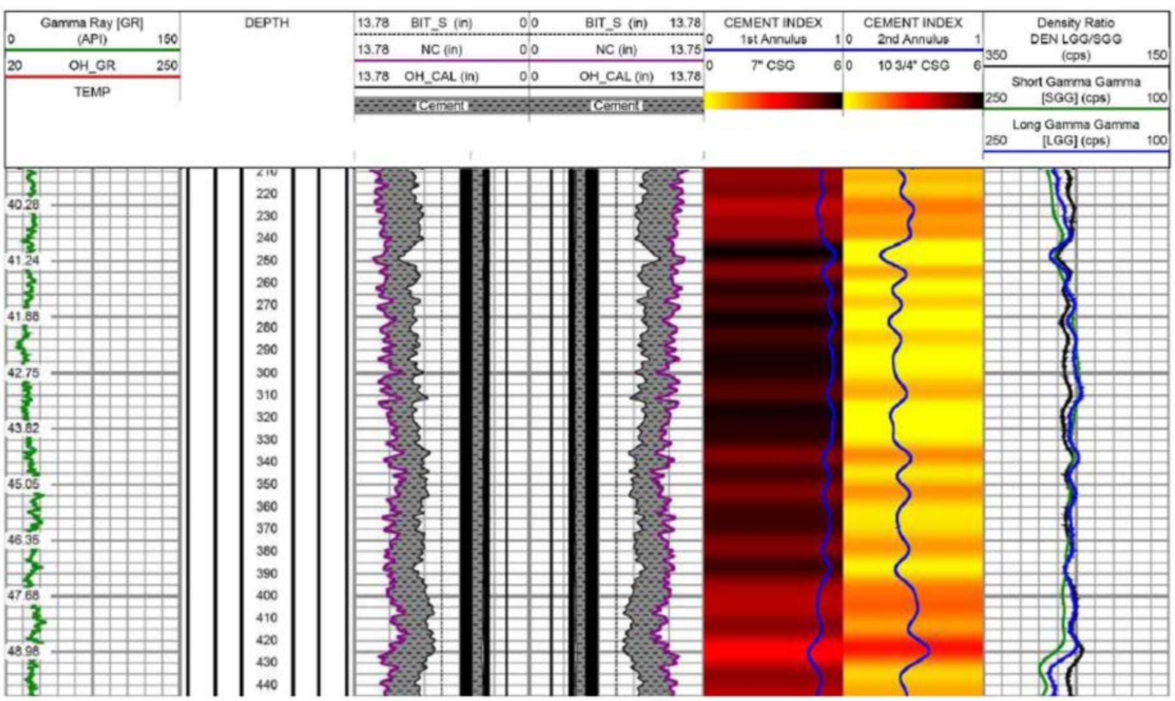


Fig. 7—Cement plug placement Zone 222 – 428 m

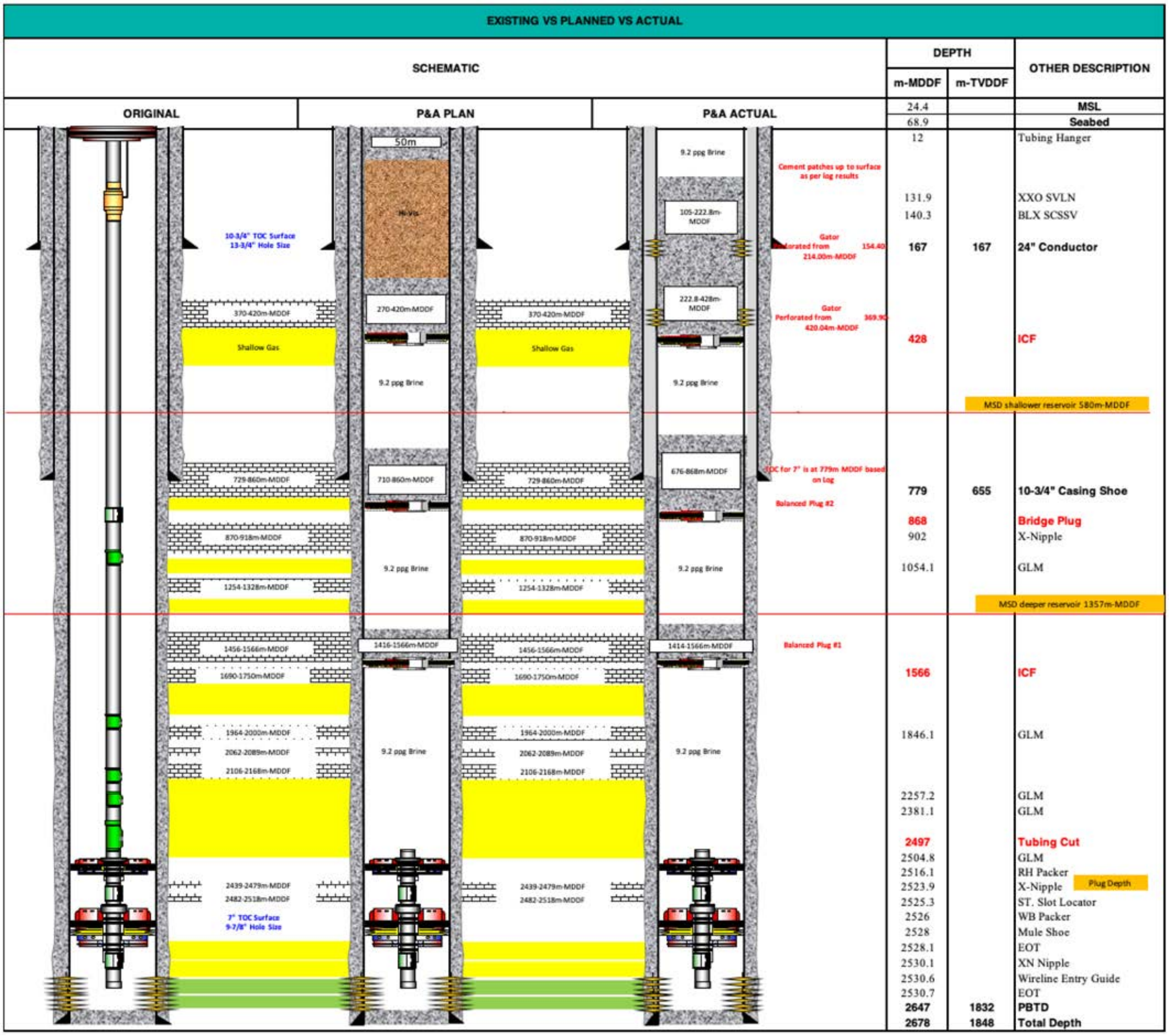


Fig. 8—Planned vs. Actual P&A

Cement evaluation verified that cement quality in the annulus across cement plug #1 and cement plug #2 is competent and sufficient in length with minimum length of 30m measured depth good cement quality. Consequently, a bridge plug was set followed by spotting a balance cement plug was done across cement plug #1 and cement plug #2 where the two (2) deep caprock was determined (Fig 5 and 7).

Across the shallowest caprock, poor cement quality was evaluated in the annulus. This caprock is crucial to cater the shallow gas isolation penetrated in this well. Hence, remedial cement was taken in place where the casing was punch and cement was circulated to establish cement plug #3 (Fig 7).

Conclusion

The cost of P&A operations is known to be substantial. Hence, any technology that could contribute to optimizing cost for P&A operations is highly anticipated in the industry. Cement evaluation using nuclear based technology, could really benefit in planning and optimizing the P&A operation.

Eliminating the unnecessary tubulars or casings removal prior to logging operation to verify the cement condition behind multiple casings shall allow the cement evaluation job to be performed offline prior to the rig entry, hence reducing the rig time and well P&A scope accordingly. Generally, cement evaluation logging operation will take approximately a day to complete. Conducting logging operation offline prior to the rig entry will save minimum one day of rig time which roughly contributes to around 4% of the total well P&A cost in savings.

In addition, this application will also help to improve resource planning efficiency especially for annulus cement remedial equipment and manpower on standby at the rig. Annulus cement remedial equipment, manpower and some of other equipment are typically on standby condition during the cement logging and while waiting for cement evaluation results to cater for any annulus cement remedial requirement. By deciding upfront whether or not to conduct annulus cement remedial job prior to the rig entry, a more efficient planning on those resources' mobilization can be made. The estimated amount of cost saving is 8% from the total well cost.

It is a known fact that well abandonment will not generate any revenue. Therefore, project cost optimization through the application of new and efficient technology is highly critical to ensure minimum cost spent without compromising safety. Through tubing cement evaluation using nuclear based technology has shed some light to achieve this aspiration.