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Reservoir Monitoring With Basic Saturation Tools

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Abstract
The need for proper and closer monitoring of reservoirs has become paramount in recent past following the ageing of most of the fields. This has led to the use of available technology in the acquisition of relevant parameters in addition to usual production data in order to monitor the performance of the reservoirs and optimise their management.
The determination at current fluid contacts is mandatory for successful intervention in reservoirs which due to production for many years develop gas/water production problems. Gamma Ray Spectrometry Tool (GST'), Reservoir Saturation Tool (RST) and MultiparameterSpectroscopy instrument Continuous Oxygen (MSI CO) are among the tools that have been employed in our bid to monitor the movement of fluid contacts, especially' between oil and water in those sands producing under active water-drive mechanism. Here the oil saturation is recorded by the tool in the producing zone during work over operations and compared with the initial situation recorded in open hole.
Although the different tools compute and record oil saturations, they perform differently due to their individual characteristic and limitations: while RST can be run through tubing and in the following wells because of its slim size, GST and MSI C/O cannot. Other limitations are porosity and salinity dependent.
Both RST and MSI C/O were widely used by operator between 1995 and 2007 for reservoir monitoring, work over operations and planning. Most of the results obtained were satisfactory, except for a case where the logs and subsequent interpretations gave misleading information that led to wrong decisions being taken. The postmortem of these mishaps also showed instances of the contractor personnel's inadequacies and/or carelessness in calibrating the tools, while logging and interpreting the log data. All these therefore warranted reviewing the rationale for using these tools in many operations.
Despite the foregoing, reservoir saturation tools still appear formidable 'and relevant in reservoir monitoring. They should for now continue to be supported with DST, etc. until all doubts are eliminated.
Keywords; *Reservoir, Saturation, Salinity, Saturation tools, Porosity ,Work over operation, Technology, logs, Depletion, Data and Fluid.*

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I. Introduction

Most of the oil fields in many concessions (Fig. 1) are ageing, hence the need for proper monitoring of gas and water encroachment. The measurement and differentiation of reservoir fluid saturations in producing fields have two primary applications: monitoring oil depletion in producing zones, which leads to improved reservoir management and evaluating remaining untapped oil pay within producing fields.

In many operators , the use of GST is familiar and satisfactory. To confirm the reliability of RST, GST was run parallel to RST during the workover of one of the producing wells. GST confirmed that RST evaluation and the test was considered completely successful. For this reason, the new tool. RST was recommended for monitoring our producing reservoirs as well as for workover optimisation.

Service Companies A and B have been used extensively for fluid saturation logging jobs within the recent past, 1995 - 2007. Company A has been the major service company carrying out GST and RST jobs over the years. Company B came briefly in 1999 for similar services, but only reappeared about three years ago and since has been performing saturation logging jobs .

Equipment And Data Acquisition

Both Services Companies have the state-of-artequipment. However, more downtime has been experienced during operations with Company B.

In general, downtime has resulted mainly from other peripheral equipment failures rather than from the malfunctioning of the logging tools themselves.

The RST is slim and has both through-tubing and insidecasing models whose configurations are shown in Fig. 2, but the MSI CO is limited to use inside casing after retrieving the completion string during workover. RST also has the additional advantage that it can be run in a flowing well. A setback of through-tubing RST is the masking effect by blast joints when present in the completion string — the tool's readings will not be reliable.

Data acquisition is done in two modes: elastic and inelastic. During the inelastic stage a carbon/oxygen ratio (COR) is recorded. Since carbon and oxygen are principal components of hydrocarbon here we have a means of quantifying the amount of hydrocarbons present in the formation. The Calcium/Silicon ratio (CASI), being an inelastic measurement, has the advantage of being independent of formation water salinity effect and can indicate lithology. The Silicon/Calcium ratio (SICA) has a deeper depth of investigation than CASI but it is salinity dependent. Apart from the three primary curves: COR, SICA and CASI, several other measurements are made with the system each serving a specific purpose such as correlation, porosity estimation, salinity or gas indication etc. For monitoring gas saturation, the pulse Neutron Capture is adequate.

The Short-Comings of Logging Techniques

Both service companies have good presentation formats of the saturation logs. The major shortcoming in the log results being displayed is that the instrument can only read within the borehole radius i.e. depth of investigation is shallow. Such measurements therefore should not be applied globally because the effect registered could be localised e.g. the coning of water in a well. On the other hand, information obtained from another level not being produced by the same well where such measurement is being recorded can give a good indication of what is happening in that reservoir.

From experience both MSI CO and RST seldom give a sharp OWC; however there is a progressive graduation of Sw from bottom of the sand to the top. Thus the cut-off to be used depends on the expectation derivable from such a workover job. This may even require use of DST for further evaluation of the level.

Two major parameters are essential for the results of MSI CO or RST if they are to be meaningful:

- Water for calibration must be compatible with the reservoir of interest.
- Porosity value must not be too low so as not to lead to wrong interpretation (since the porosity is a major factor in the logging speed and reliability of the data acquired).

The primary objective of Carbon - Oxygen analysis is to determine cased hole hydrocarbon saturations. If saturations are available from open hole logs, then a comparison of the two gives indication of depletion that might have occurred over the production period.

What Is The Degree Of Success Recorded?

The application of saturation logs has been for three broad reasons:

- for workover and infill well drilling planning purposes.
- for reservoir monitoring and
- for workover optimisation the last is most prevalent.

Irrespective of the purpose for running saturation logs, there have been cases that can be categorised as direct success, doubtful results or outright misinformation; also instances arose when both RST and MSI CO were run side-by-side in order to clear doubts. The following field examples enumerate some of these experiences:

Work over Planning

Well-A Example

This well is located in a swamp field in which a number of workovers were proposed as part of the field development strategy. RST in the well was to be used for the planning of those workovers. ln November 1995, the advantage of RST was taken by logging through tubing across most of the oil-bearing levels in the well. Levels G, H, I, K and M were logged. Some workovers were thereafter planned for execution. In February 1996, RST was repeated in the same well; this time during workover and inside casing across levels A, G, H, I, K, and M.

The two sets of readings show the same saturation curves.

Apart from level K where the presence of blast joint masked the through-tubing readings, the two modes were in good agreement. Another observation is that in front of perforations the RST (through tubing) shows some spikes that are not seen in RST (through casing) See Fig. 3. Again in level A, it could be seen that RST reading is highly affected by washout thus inhibiting the oil saturation (So) reading.

No significant difference was observed between the RST COR curve and the open hole determined oil saturation, indicating that no depletion has occurred in levels A, G, and H. Also from the analysis of the RST, level M was to be abandoned because it was water flooded. Oil in level K on the other hand, was displaced by bottom-water up to X811.OmRT. So the existing lower perforations had to be squeezed off during workover. Level I has shown appreciable water advancement, from original OWC = - X732.5m to OWC from RST = - X725.5m.

On the basis of the above results, the well was worked over between January and March 1996 and re-completed in levels K as long string (LS), G as LS (selective) and A1 as short string (SS). The initial flow tests data are as follows:
LS: Q = 1962 BOPD; FTHP 768psi; BS&W 22.5%
SS: Q 413 BOPD; FTHP = 149psi; BS&W = 40.0%
Level A1 has stopped flowing since 13th January 1997 when the water-cut exceeded 70% with an oil rate of about 150 BOPD. However WELL-A (LS), level K is still following with oil rate of 1200 BOPD and water-cut of 50% as at August 1997.

Reservoir Monitoring
Well-B Example
Short History

A well performance analysis was carried out by means of SAM (System Analysis Model) on WELL-B in September 1992 with the main objective of optimising the production on level F on the basis of the results of the investigation.

The reservoir has an initial static pressure of 4352 psi and a bubble point pressure of 2304 psi with a solution GOR of 486scf/bbl. WELL-B was completed single on this level and put on production in October 1990. Thereafter, a strong decline of well production performance was observed. At production start-up the well tested 2784 BOPD on 32/64" choke size with FTHP of 782 psi, GOR of 157 scf/bbl and W.C of 0.5%. Few days after the production start-up the water cut steadily increased to 20% and then 30%. Production rate as at July 1993 was I6OBOPD on 24/64" choke size with FTHP of 284 psi, GOR of 896 scf/bbl and BS&W of 66.5%. The well is presently shut-in due to high water cut.

The conclusion of the above well performance analysis then was that a water table advancement of less than 1.Om was established. No well damage or reservoir depletion had occurred since the same reservoir and well completion data were used to obtain the matches. Therefore considering the rapid increase of the water cut just few das alter the well start-up, the water being produced might have come through channeling in the annulus behind the casing due to bad cement bond etc.

Results Of Rst

RST was run through tubing in the well to monitor oil depletion in producing zones and evaluate the remaining untapped oil pay within the producing level.

The resulting fluid analysis on the reservoir saturation log confirmed oil depletion up to the bottom of the lower perforated interval at Y111.0 – Y113.Om. The new OWC could be seen at Y113.Om with some pocket of oil saturation by-passed. It appeared that little or no oil production was coming from the lower zone.

From the RST results, it was quite evident that the high water cut experienced in this well was mainly due to water breakthrough. The level has strong water drive mechanism prevalent in the field. There was no shale break to protect the perforated zones from water advancement. This is coupled with the fact that we might be dealing with a smaller reservoir than earlier envisaged.
The envisaged workover was thus abandoned as a consequence of the through-tubing RST results.

Workover Optimisation
WelL-D Example
Situation Before Workover

This well was initially completed single selective in the lower and upper zones of level Z2 in January 1995. The lower zone was opened to production in March 1995, but various attempts, including lifting with liquid nitrogen, to keep it flowing failed. Hence the upper zone was brought on stream in June 1995 by opening the selective completion. This zone though flowed oil, its initial performance was not satisfactory and this warranted further investigation that led to rigless interventions. Subsequently the well was re-perforated through-tubing, and there was significant improvement in its performance. The well however stopped flowing since October 1996. It was therefore proposed for workover in order to restore its oil production from a single completion in the same level Z2 (upper).

Carbon/Oxygen Results

MSI CO and Segmented Bond Tool (SBT) logs were run in the well by Service Company B between 24/10/97 to 27/10/97. The MSI CO was logged across the following intervals: Z545.0 - Z575Mm and Z600.0 - Z700.Om; while the SBT was logged across the interval Z600.0 - Z700.Om The cement bond log revealed good bond across the whole sand interval. The CO on the other hand revealed a lot of information that needed to be properly analysed.

The level Z2 group is divided into four layers:
A: Z626.0 - Z670.0 mRT
B: Z675.0 - Z689.0 mRT
C: Z693.0 - Z726.0 mRT
D: Z729.0 - Z777.0 mRT
The RST revealed a highly flushed reservoir from Z729.0 - Z755.0 mRT indicating that layer D is already water flooded as proved by its earlier production performance. In layer C; lower part of the sand registered Sw close to 90% while the upper part has Sw of 55%. However, layers A and B still look okay with Sw ranging between 25 and 50%. These results were not in perfect agreement with the CPI results even in some layers that have not been on production before. This therefore necessitated carrying out Production tests in order to determine the nature of the fluid in the level Z2 upper and to determine some formation parameters (permeability, skin, etc.).
The production testresults confirmed that layers C and D are water flooded while layer B was reperforated at interval Z675.5 - Z688.OmRT and gave the following result:
On 2464" : FTHP = 2016 psi; Oil rate = 2112 BOPD; BS&W= 10%.
On 32/64": FTHP = 1880 psi; Oil rate 2640 BOPD; GOR 4123; BS&W = 15%
The well has since been completed on level Z2 group (layer B) and put back on production.

Resolving Doubtful Log Results: Msi Co VersusRst

Service Company A utilises the RST while Company B runs MSI CO. The following exemplifies a case in which both tools had to be run in the same well in order to clarify issues by comparing one result with the other during a workover job. At the end of it all, a DST had to be used to take a definite stand on the affected level in the well.

Well-E Example

Well-E is in the same swamp field as Well-A where workovers have been proposed for the field's development as recommended by 1992 Field Reservoir Study. Well-E was identified as a workover candidate based on the review of that study. MSI CO was therefore run in the well across levels M, K, I, H, G and A during the workover operation. Owing to the inconclusive results obtained from CO. RST was subsequently recorded to further clear issues. Of particular interest was the case of level M that had not been produced from this well:

Level M MSI CO results:

The log was run across upper water-bearing sand level H to calibrate the tool for evaluating level M. It was found that the salinity found in level M was quite different from that of level H. The total salinity was said to be higher in this level. The tool therefore saw OWC that seems none- existent in the well.

Level M - RSl results:

Because of the doubt in the MSI CO results of Service Company B, Company A was invited to intervene with RST measurement. Company A gave the following submissions:

- That the RST revealed a good quality yield. Also the reservoir parameters used were considered okay. But the Elan was not properly checked before the job was done.
- In the first RST interpretation, too much silt was considered for the lower part (X950.0 - Y000.Om; see attached logs in Fig. 5). The second RST reprocessed, reduced the silt by almost half thus reducing the porosity and increasing the shaliness.

There is an OD1 now at X966.Om, which seems to be in perfect agreement with the open hole FDC-CNL that saw only an ODT at X957.Om with possible shaly oil sand below X964,5m.
Because of the conflicting results from the tools, it was decided to carry out a DST on the interval X952.0 — X954.Om in order to clear any doubt. The result of the DST gave 100% oil.
At this stage, questions arose about the reliability of the saturation tools in general. In order to be able to give correct interpretation of these logs, it is imperative to look at the saturation tools globally and not just on one to one basis.

How Successful In Terms Of Well Performance?

The success ratio depends mainly on the objectives, but to evaluate this, it is necessary to give a breakdown of some jobs done within the cited period and the type of results obtained after the workover. The following examples will serve as illustration.

A) Failures

The next well is a case in which the workover result was adversely affected by misleading information from C/O logging.

Well-F Example

The RST program planned for WELL-F was run across levels A, B and C; both in inelastic mode (in order to verify the actual OWC) and sigma mode (in order to verify the actual GOC in case of level A). 1 he objective was to improve oil production reducing the gas/oil ratio (GOR). C/O saturation measurements were chosen over Pulse Neutron Log (PNL) measurements as the well as being invaded by formation water of low salinity.

For level A, the RST results show that there is an appreciable depletion that necessitated the raising of the perforations up structure. In case of level B (Fig. 4) the oil depletion is quite evident. Only a small interval was left for re—perforation while the rest was just residual oil in water zone.

In level C/C1 on the other hand, high water saturation vas ascertained. Particularly both the bottom and the top parts of the level are completely flooded while any zone of about 2m has an oil saturation of 45% compared to the original oil saturation of 80%, Based on this new information, the level was squeezed off and abandoned. The well was therefore completed dual in levels A and B.

Post-workover test results are as follows:

Level A:- The well was worked over in October 995: and level A was re-completed as SSwith gravel pack. Currently oil production rate is I 300BOPD without water production.

Level B:-This level as completed as LS but only produced water. This contradicted RST run in the interval Y286.5 - Y289.0mRT, shown as oil-bearing zone on the RST results upon which interval Y284.0 to Y290.0m was the service Company that recorded the log then came with the following explanations:

The zone where the results contradicted the RST has an average porosity of 17 Pu and is relatively shaly: At this porosity to achieve 95% confidence on the saturation results, 9 passes at 120 ft per hour would have been needed. This was not done as an average porosity of 25pu was assumed for calibration. Such an assumption has contributed to the poor results since the porosity is a major factor in the logging speed and hence reliability of the data acquired.

The logging speed during the acquisition of this zone exceeded 200 ft/hr on three out of the six passes. This was caused by the inattention of the logging crew when the unit increased speed. These passes subsequently distorted the averaged results.

The data was recorded with the RST-B. From the tool design. RST-B should have been the best for this situation but the data by the tool is very much affected by statistical variation. The RST-B main application is under flowing conditions, large hole (121/4" hole or 95/8" casing) or when the borehole fluid is unknown.

As a follow-up of the above, the service company has improved on the use of the RST-A under situations similar to the above. Thus when the borehole fluid is known (as in WELL-F), this model should be logged since it can be run much faster than the B and is less prone to statistical variations.

B) Successes

The following examples in addition to earlier successful ones typify the degree of success achieved by NAOC in using saturation logging in recent past.

Well-G Example

The RST run in this well in August 1997 gave the following results in the levels:

Level A: The reservoir is flushed from W957-W973m. Average Sw(RST) was about 40% and it is not uniform vertically. The silt at W973 might constitute vertical permeability barrier. The level was squeezed off for production in another well.

Level I: The reservoir is divided into two sand bodies by a shale intercalation. For the bottom sand, the OWC is now at X734.5m. The upper sand body from X721-X726m is not flushed. Above the new OWC the sand is slightly flushed with Sway = 30%.

Level K: RST gave a new OWC at X833m. Although the reservoir is not disturbed above this new contact, it is not ideal for completion here.

Level G: There was no indication of depletion in the level that has never been produced in this well; mean water saturation = 25%. The zone is thus good for re-completion. It flowed 100% oil when it was finally perforated.

Level H: This level revealed slight depletion zone; although it has never been produced in this well. When it was perforated at interval X636-X639m it flowed 100% oil.

Saturation logs were successfully used for optimising the work-over in this well.

Based on the above results and that presented earlier (Well-E Example), the well has since been re-completed dual with LS on level M and I (selective), and SS on level G and H (selective).

The LS was opened to flow after the work over on 26th September 1997 with the following parameters: Oil rate = 1788B0PD; BS&W =0.6%. The short sting was opened to flow on 7th October 1997 with the following parameters: Oil rate = 2026B0PD; BS&W = 19%; GOR = 448scf/bbl. This BSW was believed to be due to work-over fluid losses.

Well-H Example

After analysis of the well during the work-over planning stage, drilling of a side track hole was suggested as an alternative to conventional work-over to cut down on time and also eliminate the doubtful results inherent in isolating several perforations (with gas production problems) where poor cement bond was indicated from CBL information.

However, after retrieving the completion string, CBI run across levels A, H and I was found to show good cement bond. Thereafter MSI CO was run in levels A1, A, G, H, I, K, L/Ll and M to monitor the water advancement. The results showed level H completely flooded with water: while good chances of completion still exist in levels A and 1(1 has Sw = 40-45%)

Saturation log results were once again used in this example to select and scrutinise zones for completion. The well was re-completed dual on levels A as SS and level I as LS in July 1997. As at October 1997 level I could not flow due to the invasion of the lower perforations by water, while level A was flowing with an oil rate of 1500 BOPD BS&W = 7%.

Well-I Example

Situation Before Workover

Production commenced in the S3 in September 1973. The SS level 2l/L has been flowing since production startup at increasingly high WC values. Water cut in the last two years has been hoveringaround 90°/a. Actually the well was flowing intermittently at very low oil rate. The LS started production from level 3B also in September 1973. After about ten years, due to HBSW and low oil ratefrom this level the LS selective in level 3A was opened plugging off 3B. The well eventually stopped to flow in June 1995 due to low wellhead pressure and HBSW. The well was subsequently planned to be worked over.

Carbon/Oxygen Results

The aim of the C/O logging is to determine the actual position of the water table and also to establish if there is enough space above the present perforation intervals as to recomplete in the levels. Level 2M-north water table was also checked in order to consider the possibility to provide an additional drainage point for its production.

MSI CO was run in the following levels 21/L, 2M-north, 3A and 3B. The results showed level 21/L completely water flooded while levels 2M-north, 3A and 3B were not flushed and good for completion.

The well was re-completed dual selective in July 1996 with LS on 3B, 3A (LS selective) and the SS on level 2M- north. The following flowing parameters were recorded thereafter:

SS: Oil rate = 2000BOPD; GOR =758; BS&W = nil

LS: Oil rate = 1000BOPD; GOR = 987; BS&W = 42%

II. Conclusions I Recommendations

RST and MSI CO have proved to be invaluable logging tools for purposes of reservoir monitoring, planning and optimising work-over operations using fluid saturations as indicators.

NAOC has applied the results from these tools with reasonable level of success. Immense benefits have been derived using them within the period cited. Such benefits include quick decision-making resulting in rig-time saving, acquiring data without production losses etc.

Cases of failures however arose mainly through logging contractor personnel's mistakes and erroneous judgment that resulted in doubtful analyses and even misleading information that produced dismal post-work-over performances in some wells.

These odd instances prompted this review on the use of saturation tools for the objectives mentioned above.

The service companies should therefore improve their performance in order to minimise logging downtime and such failures that contributed to or were even responsible for the poor work-over results.

However, these saturation-logging tools remain relevant in our operations within the foreseeable future for the stated objectives with the proviso that:

the log results should also be used with more caution.

Occasional support with DST to validate such log results should be envisaged.

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Nomenclature

COR	Carbon/Oxygen ratio
FCOR	Far detector Carbon/Oxygen ratio
NCOR	Near detector Carbon/Oxygen ratio
So	Oil saturation
CASI	Calcium/Silicon ratio
SICA	Silicon/Calcium ratio
CBL	Cement Bond Log
SBT	Segmented Bond Tool
PNL	Pulse Neutron Logging
GST	Gamma Ray Spectrometry Tool
RST	Reservoir Saturation Tool
MSI CO	Multiparameter Spectroscopy Instrument Continuous Carbon/Oxygen

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