STATE OF THE ART PULSED NEUTRON SERVICE UNLOCKS “STRANDED OIL” IN CO₂ EOR RESERVOIRS

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ABSTRACT

Historically, peak oil production in the United States was at an all-time high in the early 1970’s. The decline of oil production after this peak, initiated the interest in carbon dioxide enhanced oil recovery floods (CO₂ EOR) in 1972 to help extend the production life of some fields. With some exceptions, (Turkey, Abu Dhabi, Brazil, China, Malaysia, and the North Sea) the use of CO₂ for EOR has been minimal outside the US. The Permian Basin (PB) alone accounts for over 50% of CO₂ EOR worldwide projects (Melzer, 2012).

The PB encompasses over 300,000 acres of various reservoirs under CO₂ EOR floods. Through 2014, current oil production is in excess of 190,000 BOPD which represents 65% of CO₂ EOR production in the US. Production is projected to increase to 323,000 BOPD by 2020. Constant surveillance of the CO₂ migration during flooding is critical so that the injection pattern can be modified to optimize oil sweeping efficiency.

One common method for CO₂ monitoring is wireline well logging. Open-hole (OH) logs are normally acquired and then interpreted to evaluate the fluid saturation of the three phases¹ (oil, water and CO₂). At times, due to operational conditions and efficiencies, OH logs are not available. This limits the capability for a reliable CO₂ monitoring for the surveillance teams. Cased-hole logging (CH) offers an operational advantage as well as a base line log for Time-Lapse monitoring.

Quantitative reservoir evaluation through casing has been accomplished for decades using a combination of neutron logging tools with different neutron sources and a variety of gamma-ray detector materials. The primary measurements of these tools are: Sigma (Σ), Thermal Neutron porosity (TPHI), Carbon-Oxygen ratio (C/O) and Gamma Ray Spectroscopy. A multimineral petrophysical analysis is then performed to provide quantitative volumetric results. One of the main challenges of this interpretation is the ability to differentiate gas filled porosity from very low porosity formations. Both measurements; Σ and TPHI respond similarly in these conditions. Unless porosity is known from other sources (i.e. OH logs), neither of these measurements alone can provide a reliable answer. A different petrophysical measurement would be desirable to allow for this differentiation.

This paper shows the application of a new pulsed neutron wireline service that measures a new formation property, fast neutron cross section (FNXS). This measurement makes possible differentiating gas-filled porosity and low porosity formations. FNXS is sensitive to the formation’s atom density which is independent from Hydrogen Index and is sensitive to the gas-filled porosity. Other new features of the new tool is the ability to self-compensate for the influence of the borehole (like for instance gas filled boreholes) and the completion using a combination of near, far and deep detectors and various timing gates. These new measurement advancements allow the log analyst to solve the three phase problem via a multi-mineral solver when OH logs are not available.

This paper shows three CO₂ EOR case studies in the PB where CO₂ has been quantified for identifying estimating volumetric as if oil and CO₂ were in two separate phases.

¹ Under reservoir temperature and pressure, oil and CO₂ may be miscible and in one phase. Saturation analysis is...
good versus poor sweep efficiencies. The analysis shown here, helped the operator to design and optimize their completion strategy as well as having better understanding of the reservoir behavior under CO₂ flood.

INTRODUCTION

Carbon dioxide enhanced oil recovery has been successfully used by the oil industry for more than 40 years. The injection of CO₂ into aging fields to sweep residual oil has helped extend the production life of some fields by more than 25 years. CO₂ EOR projects face many technical challenges during their implementation. Among the most critical are; accurate characterization of the reservoir and understanding the CO₂ migration during flooding. Oil operators often rely on wireline well logging for addressing these two challenges. Open hole logging evaluation is limited to new wells and is not always available due to operational challenges. In addition, the life span of wells in CO₂ EOR fields demand the need for a reliable cased hole logging evaluation and monitoring.

Pulsed neutron logging (PNL) tools are commonly used for reservoir evaluation through casing and traditionally provide measurements that are sensitive to formation hydrogen index (HI) and sigma. The limitation of these measurements in CO₂ EOR reservoirs, is the challenge to distinguish gas filled porosity from low porosity rock. Porosity from other source (i.e. OH logs or correlations) would be needed to help solve a 3-phase problem (oil, water and CO₂ saturations) to assist managing the flood of the field.

This paper shows the application of a recently introduced (Rose et al., 2015) measurement (FNXS) that allows for the quantification of the 3-phase problem in CH environments, where no open hole logs are available. In following chapters, we will be presenting a new standalone CH formation evaluation method based on FNXS. Three case studies in the SACROC field in the Permian Basin, will then be shown.

A REVIEW OF CO₂ EOR CH FORMATION EVALUATION ALTERNATIVES

With any formation evaluation, total pore volume (PHIT) is needed for an accurate pore fluid saturation of water, oil and gas. The porosity measurement choices in cased holes are generally limited to either neutron or sonic porosity. Complex lithology, secondary porosity and the variability of fluid types in the borehole and formation also affect the assessment of PHIT that is first needed before saturations methods can be applied.

Carbon/oxygen (C/O) and capture sigma (SIGM) from pulsed neutron are the two primary methods used with PHIT to determine saturations. Some pulsed neutron workflows also attempt to make a gas correction based on count rate ratios but often mistakes low porosities and lithology changes for gas. Also available is the Cased-Hole Formation Resistivity (CHFR) with an operational range between 1.0 and 100 ohm-meters but it can have limitations in old wells with scale and corrosion.

Formation evaluation programs in CO₂ EOR fields for either new drills or existing holes must consider the dynamics of the fluids in the near well bore environment. New wells may have filtrate near wellbore, mixed salinities and flushed hydrocarbons outside the depth of investigation. Wells with open perforations may have dynamic borehole fluids or kill fluids invading perforations further complicating what is actually being measured. These are factors that must be considered when planning an initial assessment or a time lapse survey.

The properties of CO₂ at or near the critical phase for HI or the near equivalent thermal porosity (NPHI) and the capture cross section (Sigma) are nearly zero. This unique response is very useful if the formation porosity is known since the resulting deficit can be used volumetrically to determine CO₂ content. In the event that PHIT and NPHI baseline is known prior to CO₂ flooding, time lapse compensated neutron logging can be used to identify zones swept with CO₂. Then, using Sigma, the saturations of oil and water can be determined with a simple linear equation if the water salinity near well bore is greater than 35 parts per thousand (ppk) which has a sigma endpoint of nearly 35 Capture Units (CU). Similarly, the sigma endpoint of a dead oil is approximately 20 CU. As the hydrocarbon becomes more volatile to the gas phase SIGM can be reduced to 2 CU. Sigma values for water and oil can be found in the Schlumberger 2013 Chartbook, charts Gen-12 and Gen-14 respectively (Appendix A).
The method of using sigma to determine hydrocarbon saturations becomes more certain with higher water chlorides and subsequently higher SIGM values since the difference between water and hydrocarbon is significantly greater. However, the water salinity may prove difficult to determine in new drills due to filtrate dissipation and in older reservoirs that have a history of varying water salinities during water flooding.

In formations where water salinity is less than 35 ppk determining oil saturation in cased holes primarily is accomplished from the C/O' measurements. Porosity and lithology must be defined very accurately. In the Permian Basin, the minimum porosities need to be at least 15% for C/O to be a viable solution. Many of the Permian EOR fields are in the San Andres formation which is mostly dolomite, but most of these carbonate reservoirs have varying amounts of secondary porosity, anhydrite, gypsum, limestone and silt that further complicate the pore system characterization. Having open hole logs and core data to characterize the reservoir in the specific EOR field can help determine what the challenges will be and how to best address those for an effective fluid evaluation.

Without a neutron porosity baseline prior to CO2 injection or an open hole formation density log, the sonic-neutron overlay method in casing has been the most common logging suite in the Permian Basin to identify formation porosity with the sonic and then CO2 volume by the neutron porosity attenuation. Occasionally, a cased hole resistivity or a pulsed neutron Sigma could be utilized to further determine oil and water volume. The time for one logging tool to provide a spectral lithology, gas corrected total porosity as well as formation sigma to determine saturations in a single logging pass is now been realized with the new PNL tool as explained in the next section.

NEW PROPOSED METHOD

A slim pulsed neutron logging tool (Rose et al., 2015) was designed and introduced recently. It provides an independent formation measurement, fast neutron cross section (FNXS), which is sensitive to gas-filled porosity variation, but insensitive to liquid-filled porosity variation. It can provide interpretation functionality similar to that of density logging, but with a different response. A standalone CH formation evaluation is possible based on FNXS, HI, and sigma measurements, which can all come from this pulsed neutron logging tool.

The performance and workflow of FNXS measurement were studied thoroughly (Zhou et al., 2016). The interpretation based on FNXS measurement is essentially solving a series of linear equations, as shown in Equation 4 of the previous reference. In the case studies presented in this paper, we are trying to solve 4 unknowns, which are volume of limestone, water, CO2, and oil. The measurements used to solve the volumes are sigma, neutron porosity (TPHI), and FNXS, which are all measured by the same pulsed neutron tool in a single pass. The series of linear equation for this case study is shown below. The theoretical values of sigma, TPHI and FNXS for limestone, water, CO2 and oil are input parameters and can be found in the previous reference.

\[
\begin{align*}
\text{SIGMA} &= V_{\text{matrix}} \cdot \text{SIGMA}_{\text{matrix}} + V_{\text{water}} \cdot \text{SIGMA}_{\text{water}} + \ldots \\
&\quad \ldots V_{\text{co2}} \cdot \text{SIGMA}_{\text{co2}} + V_{\text{oil}} \cdot \text{SIGMA}_{\text{oil}} \\
\text{TPHI} &= V_{\text{matrix}} \cdot \text{TPHI}_{\text{matrix}} + V_{\text{water}} \cdot \text{TPHI}_{\text{water}} + \ldots \\
&\quad \ldots V_{\text{co2}} \cdot \text{TPHI}_{\text{co2}} + V_{\text{oil}} \cdot \text{TPHI}_{\text{oil}} \\
\text{FNXS} &= V_{\text{matrix}} \cdot \text{FNXS}_{\text{matrix}} + V_{\text{water}} \cdot \text{FNXS}_{\text{water}} + \ldots \\
&\quad \ldots V_{\text{co2}} \cdot \text{FNXS}_{\text{co2}} + V_{\text{oil}} \cdot \text{FNXS}_{\text{oil}} \\
1 &= V_{\text{matrix}} + V_{\text{water}} + V_{\text{co2}} + V_{\text{oil}}
\end{align*}
\]

APPLICATION TO FIELD DATA

The following three case studies take place in the SACROC Unit field. The SACROC Unit was discovered in 1948 and is one of the first and largest oil fields in the US using CO2 technology for EOR. The field is located in the Permian Basin in Scurry County, Texas. A map of the field location can be found in Appendix B (Vest, 1970).

The SACROC field started CO2 flood in 1972 and it is developed in Pennsylvanian carbonates, typically referred as the Canyon Reef (Raines et al., 2001). The Canyon Reef is divided up into four major divisions: Cisco, Green Zone, Upper Middle Canyon and Lower Middle Canyon (Figure 1). The majority of the productive interval (in excess of 750 ft), where the case studies concentrate, is composed of limestone with minor amounts of dolomite,
anhydrite, sand, chert and shale. Wolfcamp shales provide a seal above the carbonate and around the flanks. After almost 70 years of life, the field has produced 1.39 BBOE with a 2015 production of 33,775 BPD.

The first case study focuses on the new proposed method for a standalone CH formation evaluation. The second case study shows implications to infill program design and the last case study shows a time lapse application. For reference, a map of the well location can be found in appendix B.

From the formation evaluation stand point, the goal for this well was to quantify fluid (water, oil and CO$_2$) saturations as well as total porosity. The new PNL tool acquired the measurements described throughout the paper that feed into equation 1 (SIGM, TPHI and FNXS). The equation was parameterized as per the table below. Note that for simplicity of the model, the matrix component was assumed to be 100% Calcite. Spectroscopy data for mineralogy can be incorporated in the model if the formation requires it.

Table 1: Values of sigma, TPHI and FNX used in the petrophysical model.

<table>
<thead>
<tr>
<th></th>
<th>Calcite</th>
<th>Water</th>
<th>CO$_2$</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigma</td>
<td>8.5</td>
<td>50</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>TPHI</td>
<td>0</td>
<td>1</td>
<td>-0.08</td>
<td>0.99</td>
</tr>
<tr>
<td>FNXS</td>
<td>7.5</td>
<td>7.8</td>
<td>2.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

The results of the recorded CH data and its analysis can be seen in Figure 2. Track #2 contains the solved mineral and fluid volumes. Track #3 shows the fluids breakdown of the porosity in the formation, including CO$_2$, which is critical to accurately determine porosity. The PHIT curve is the computed total porosity taking into account the CO$_2$ in the system, enabled by the FNXS measurement.

The results of this “blind test” were later compared against OH logs (density and neutron logs). Track #4 displays the computed CH porosity (PHIT) versus the OH density porosity in limestone matrix (DPHI_LIME). The porosity agreement confirms the CO$_2$ effect on the neutron porosity is corrected. Track #5 shows the classic gas density-neutron crossovers, also in agreement with where CO$_2$ was identified using CH logs.
Case Study I: Porosity and CO$_2$ saturation

This case study confirms the robustness of the new methodology. Porosity and CO$_2$ saturations found in this well, agreed with other observations in the field and helped to make decision on future infill programs.

The well in question (18-18) is only 325 feet from a horizontal CO$_2$ injector (11-15H).

In this well, no open hole logs were available, which is typical in this field due to operational and cost limitations. A CH CNL was run after casing was set and a low porosity was observed compared with nearby wells. A repeat CNL was run confirming the first CNL log. A CNL log alone can be ambiguous when it shows low porosity because it can either indicate the presence of CO$_2$ or low porosity. Interpreting an estimate of PHIT from offset wells can be helpful, but PHIT is known to change laterally and vertically very abruptly in this particular limestone reef formation. This cast doubt on the continuity of the reservoir and economics of the horizontal CO$_2$ injector.

A decision was made to run the new slim PNL log for its ability to see CO$_2$ and differentiate its effect on the neutron porosity from actual low porosity. The computed total porosity log fits with nearby

Fig. 2 Track #1, GR, Track#2 standalone CH answer with formation volumes (mineralogy and fluid volumes). Track#3 water, oil and CO$_2$ volumes. In track #4 porosity comparison between the CH solution and the OH density porosity. Track#5 density-neutron OH logs and PE.

Fig. 3 - Well 18-18 layout with adjacent wells. 11-15H well represented with a green line is a horizontal CO$_2$ injector.
wells much better as it can be seen in the cross-section of figure 4. The standalone answer also shows substantial CO₂ presence in multiple zones, including the LECN2/LECN1 and also the MCN3 and ELCN zones, which could be indicating the horizontal CO₂ injector placed in the lower LECN1 zone, was able to inject CO₂ in more zones above than previously anticipated.

This is the early indication of the effective fracture height of the horizontal injector and its effectiveness of injecting CO₂ in different zones. Confirmation of the horizontal injector flood connectivity into many zones provides valuable information for the planning of the horizontal injector infill program. This information helps confirm that it is economical and leads to recovery of more oil from patterns which are not economical for conventional vertical injectors.

Case Study III: Time Lapse Application

High levels of CO₂ production were observed in well 11-13A, where no open hole logs were available. A CNL ran in June 2014, could not discern what zones contributing to this high CO₂ production due to ambiguity between low porosity and CO₂. It became evident, after logging the new slim PNL in August 2015, that two zones above MCN1 (~6575 ft and ~6795 ft) were of very high porosity which (in 2014) were, most likely, flooded with CO₂ and therefore ‘invisible’ for a CNL log. The computed porosity helped understanding the flooding pattern occurring here; water replacement was taking place in these high porosity intervals and considerable amounts of CO₂ were still present especially in the deeper high porosity zone. Figure 5 shows the log measurements (TPHI, Sigma and FNXS) along with the solved saturations and the CNL logged in 2014. The yellow shading represents the change in CO₂ saturations in between the CNL and the PNL log.

Fig. 4 Well x-section. New PNL was ran in well 18-18 providing porosity and saturations. Left track on well 18-18 is GR. Middle track is porosity and right track water, oil and CO₂ volumes. Note the CO₂ presence (in red shading) above the LECN1 zone indicating effective fracture height from the horizontal injector.
Running a second CNL log instead the new PNL tool would have left the problem still unclear. Neither the porosity nor the actual CO\(_2\) saturations could have been accurately quantified. The new PNL tool with the new FNXS measurement, confirms the higher CO\(_2\) saturation above MCN1 zone which is confirmed by production test to be the main CO\(_2\) producing zones.

The tool also indicates ineffective CO\(_2\) flood below MCN1 zone. This is consistent with observation in the field from production and other test data. The unflooded oil-charged zones are opportunity and challenges for further flood optimization.

**SUMMARY**

Pulsed neutron FNXS measurement is sensitive to the presence of gas and offers a reliable new way to solve the 3-phase problem in CH environment. Three field case examples demonstrated several applications in CO\(_2\) EOR fields.

**REFERENCES**


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APPENDIX A: CAPTURE CROSS SECTION CHARTS FOR WATER AND HYDROCARBONS

Fig. 6 Capture Cross Section of NaCl water

Fig 7 Capture Cross Section of Hydrocarbons
APPENDIX B. SCROC FIELD MAP & WELL LOCATION

Fig. 8 SACROC Unit geographic field location.

Fig. 9 Case study wells location in the SACROC Unit field.