Pulsed Neutron Capture Logging: Monitoring CO₂ Breakthrough in Multiple CO₂-EOR Fields

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Abstract

Large-scale, long-term carbon dioxide (CO₂) storage projects require comprehensive monitoring programs to understand behavior and migration of injected CO₂. The Pulsed Neutron Capture (PNC) logging tool has been implemented as a cost-effective technology which provides an effective method for monitoring gas (CO₂ and methane [CH₄]), oil, and water saturations in storage reservoirs. PNC logging has been applied in the Northern Niagaran Reef Trend geologic storage formations as part of the Midwest Regional Carbon Sequestration Partnership (MRCSP) assessment of CO₂ injection and storage during enhanced oil recovery (EOR) in depleted oil fields. The formations of interest for CO₂ storage in the reef trend in northern Michigan consist of depleted oil and gas reservoirs which have undergone primary production. In general, these reservoirs are complex carbonate pinnacle reefs which have average porosities less than 15% and have the potential for salt plugging, which diminishes permeability in the well. Low porosities and heterogeneous carbonate lithologies have historically been problematic for PNC log interpretation. However, new measurements exhibiting sensitivity to CO₂, coupled with geochemical analyses have been used to overcome these challenges and present PNC logging as a successful monitoring technology during CO₂-EOR operations.

This paper describes the different phases of PNC logging and analysis as applied to reservoir monitoring in the Northern Niagaran Reef Trend. These phases include:

- Phase I: logging and estimation of oil, water, and gas (CO₂/CH₄) saturations in an active CO₂-EOR setting.
- Phase II: PNC logging in reservoir reefs prior to any CO₂ injection and repeat logging post-CO₂ injection.
- Phase III: analysis of saturation change in storage reefs and monitoring CO₂ migration from the injection well(s) to breakthrough at monitoring or producing well(s).
- Phase IV: generation of models for PNC data analysis to account for different produced gas mixtures (CO₂ and CH₄).

For Phase I, the paper discusses PNC logging data from an active CO₂-EOR reef with historic CO₂ injection. These data show saturation changes over multiple logging sequences and correlates with
variations in pressure and geochemistry data. Examination of baseline and repeat logging data, show the percent of saturation change and pressure and temperature impacts during logging events.

The Phase II section of the paper describes representative case studies from the MRCSP PNC monitoring program. The case studies consider reefs and wells which were studied prior to CO₂ injection, and post injection during EOR operations. Results highlight wells that show fluid saturations changing throughout the course of the injection and production, moving from water saturated formations prior to injection, to mixed oil/gas/water saturation profiles as injection continues and reservoir fluids migrate within the formation.

Phase III considers the analysis of the well saturation profile(s) within reefs and wells included in the MRCSP study. The analysis of the saturation change profile is impacted by the understanding of the changing reservoir conditions, including reservoir pressure and temperature, and other CO₂-EOR operations. The analysis includes assessing the percent change in the saturation profiles within individual reservoir units, including low permeability overlying formations. The analysis of these changing profiles also includes geochemical and fluid sampling to help to confirm log data results. The assessment of the changing saturation profiles also considers reef geometry, geologic features, and the expected impact of injection/production operations throughout the reef on the network of wells within the study.

In Phase IV the paper discusses modeling of tool responses used for gas saturation analyses to account for mixtures of CH₄ and CO₂ within the storage/EOR reservoirs. New interpretation methodology using PNC measurements and corresponding forward-modeling results, combined with production samples and geochemistry are used to determine a saturation mixture of CO₂ and CH₄ downhole conditions.

This data, combined with geochemistry is used to determine if the gas saturation data are effective for modeling and solving for mixed gas conditions downhole.

Through multiple case studies, this paper presents:

- PNC monitoring through all phases of co-storage CO₂-EOR operations, including lessons learned from monitoring in less-than-ideal geologic formations,
- Pre- and post-injection PNC logging programs are designed to be a low-impact, low-cost reservoir monitoring technology,
- Fluid saturation profile analysis, including identifying breakthrough of CO₂ at monitoring wells during a CO₂ flood, and
- The development of models to account for mixtures of CO₂ and methane gas within the PNC saturation profiles through the incorporation of injection and production sampling data.

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