CHARACTERIZATION AND TIME-LAPSE MONITORING UTILIZING PULSED-NEUTRON WELL LOGGING:
ASSOCIATED CO_2 STORAGE AT A COMMERCIAL CO_2 EOR PROJECT

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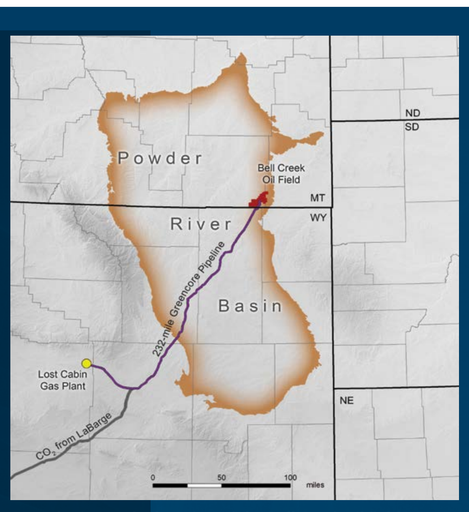
Background

The Bell Creek oil field in southeastern Montana has produced over 130 million barrels (MMbbl) of oil from the Lower Cretaceous Muddy Sandstone since its discovery in 1967. Original-oil-in-place is estimated to be over 350 MMbbl, and it is estimated that carbon dioxide enhanced oil recovery (CO_2 EOR) operations being carried out by Denbury Onshore LLC will produce an additional 40–50 MMbbl of oil from the field while injecting large volumes of CO_2 into the subsurface.

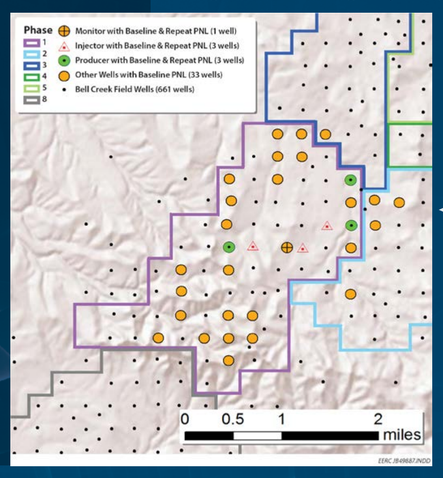
The Muddy Sandstone in the Bell Creek oil field is dominated by high-porosity (25%–35%), high-permeability (150–1175 mD) sandstone deposited in a nearshore marine environment.[1] The oil field is located structurally on a shallow monocline with a 1° to 2° dip to the northwest. The overlying Mowry Shale provides the primary seal to the Muddy Sandstone reservoir. On top of the Mowry Shale are several thousand feet of sealing rocks including the Belle Fourche, Greenhorn, Niobrara, and Pierre Shales, which provide redundant layers of protection in the unlikely event that the primary seal fails to prevent upward fluid migration.

Carbon dioxide is sourced from the ConocoPhillips Lost Cabin and ExxonMobil LaBarge natural gas-processing facilities. Approximately 50–60 million cubic feet of CO_2 is delivered to the Bell Creek Field for CO_2 EOR operations daily. CO_2 injection began in May 2013, and ongoing operations have injected 1,123,341 tonnes of CO_2 through July 2014.

The Plains CO_2 Reduction (PCOR) Partnership is focused on site characterization, modeling and simulation, risk assessment, monitoring, and associated storage that occurs as part of EOR operations. This is accomplished through an adaptive management strategy for monitoring designed to select fit-for-purpose, cost-effective techniques. Modeling and simulation activities were developed to identify gaps in site characterization, aid in identification and monitoring of risks, and help develop effective monitoring strategies.



Map depicting the location of the Bell Creek oil field in relation to the Powder River Basin and the completed 232-mile Greencore Pipeline route to the site from the Lost Cabin gas plant. Additional CO_2 is being supplied from ExxonMobil's Shute Creek gas plant in LaBarge, Wyoming.



Map of wells showing where baseline and repeat PNLs were collected in relation to the Bell Creek oil field.

Discussion

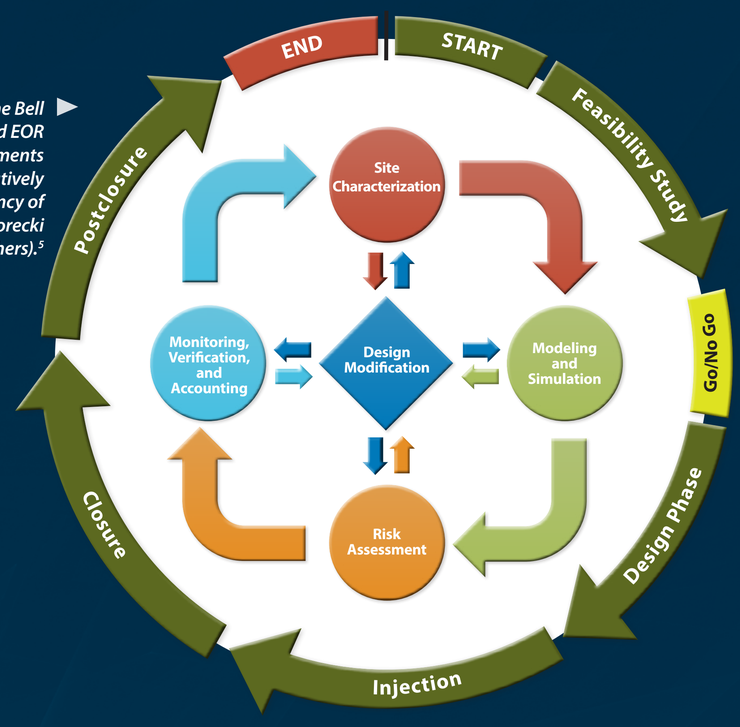
The low-salinity environment (<5000-ppm total dissolved solids) caused difficulty in quantifying water and oil saturations because of the low contrast in thermal neutron capture cross section (22.2 capture units [cu] for freshwater, ~20 cu for oil).[4] To better understand the reservoir interval, C/O logging was used to provide saturation data. Because of a naturally low gas-to-oil ratio (GOR), any changes in gas saturation can be attributed to the presence of CO_2.

Baseline C/O logging provided additional lithology data by interpreting the inelastic and capture interactions and spontaneous releases of gamma radiation measured by the tool. Each level of gamma ray spectra can be attributed to different elements and thereby provides data regarding the complex mineralogy and heterogeneity in the reservoir. A model was generated with these data to produce a base-case water and oil saturation that will guide dynamic history-matching results over the course of the project.

PNL monitor passes provided additional information on fluid saturation changes within the reservoir interval. Saturation changes were calculated between the baseline and monitor pass for three injectors and three producers. The results showed preferential pathways for CO_2 migration by quantitatively assessing CO_2, oil, and water saturations with 2-foot vertical resolution. Logs show a higher concentration of CO_2 in the upper sand bench compared to the lower benches, and oil saturation decreases throughout the reservoir interval.

The monitor pass of PNL was also employed to confirm that no out-of-zone migration has occurred, with locations chosen from field production data and predictive simulations of geologic models. Sigma values are expected to decrease with the abundance of CO_2 near the wellbore. Injected CO_2 arrives at production wells first through zones of high transmissibility, which appear in sigma logs as a reduction from baseline.

Project elements of the Bell Creek CO_2 sequestration and EOR project. Each of these elements feeds into another, iteratively improving results and efficiency of evaluation (modified from Gorecki and others).[5]

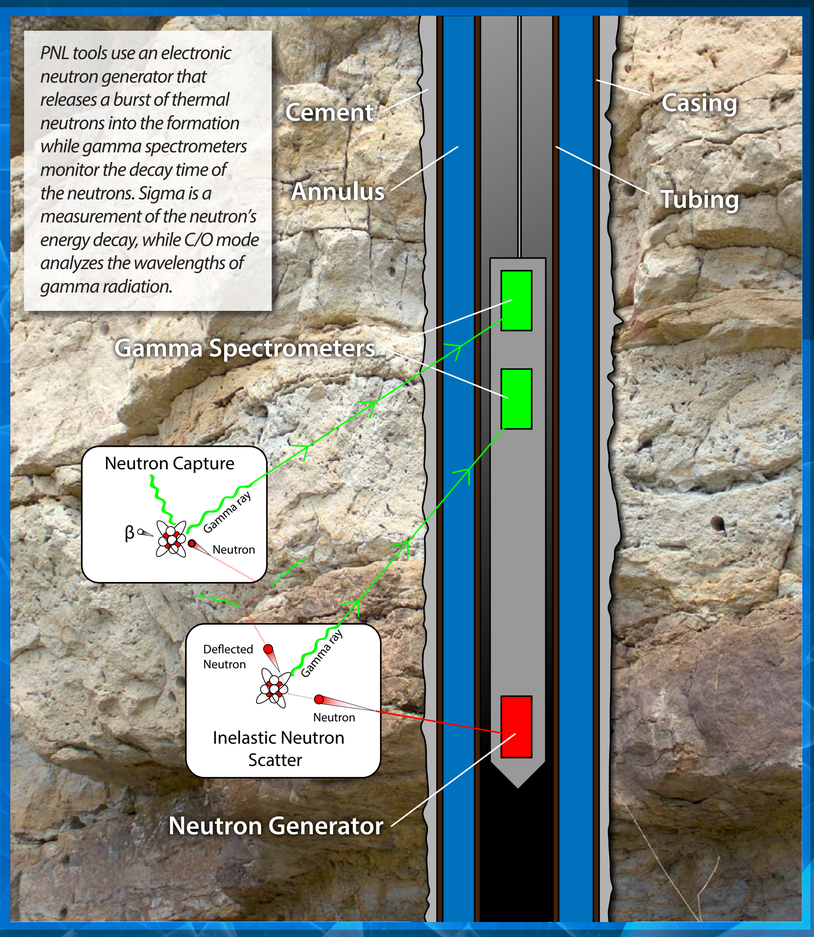


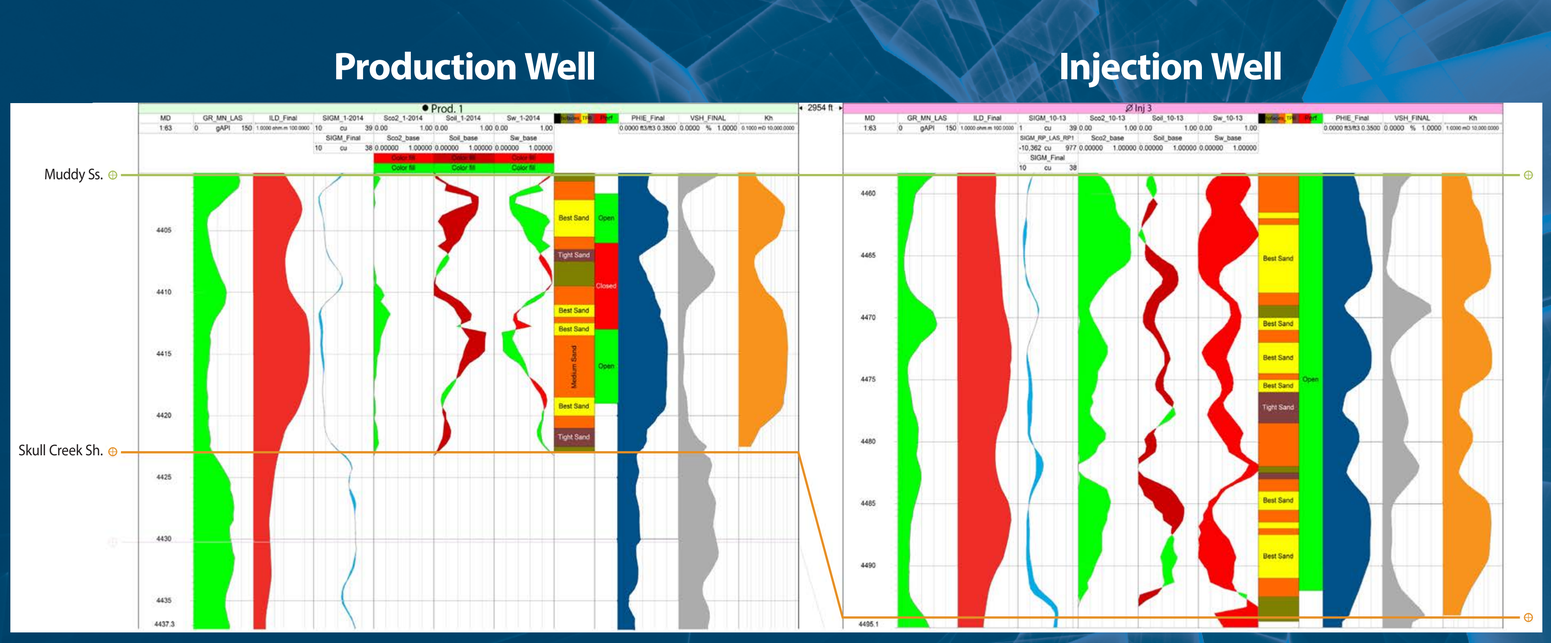
Pulsed-Neutron Logging

Pulsed-neutron logging (PNL) tools emit pulses of neutrons, then measure different responses from the downhole environment. Outputs of the tool can display carbon/oxygen ratios (C/O), elemental composition, thermal neutron capture (sigma), porosity, fluid saturations, and water salinity. One of the products of PNL tools is the sigma log, a quantification of the thermal neutron capture cross section, often highly influenced by chlorine, and is used as a measurement to differentiate fluid saturations.[2]

A time-lapse PNL campaign will assist in understanding several geologic and monitoring, verification, and accounting factors and will aid the project through design, and deployment, of monitoring tasks. This technique monitors saturation changes in the subsurface with limited impact to field operations.[3] Baseline logs were collected on 33 wells from November 2012 to June 2013, and the first set of monitor pass logs was collected on seven wells from August 2013 to January 2014.

The PNLs have provided for the adjustment of structural tops from 200 feet below the surface to the bottom of the reservoir, often shifting previous interpretations of formation tops on the order of 30 feet. Baseline sigma logs were collected to interpret porosity and current fluid saturations and to evaluate fluid and gas saturation changes through the Muddy Sandstone and overlying formations during EOR operations. Understanding near-wellbore fluid and gas saturations provides a mechanism to identify and quantify vertical migration and accumulation of CO_2 throughout the injection area.





PNL logs from production well (left) and injection well (right). Logs from left to right: reference track (measured depth in feet), gamma ray log, resistivity log, sigma logs, CO_2 saturation, oil saturation, water saturation, facies, perforated interval, effective porosity, shale volume, and horizontal permeability. Blue-filled sigma depict a decrease in log response from baseline to monitor pass. Green-filled saturations depict an increase compared to baseline, and red fill means there was a decrease.

Findings and Future Work

- CO_2 has the ability to dry out the irreducible water saturation present near the wellbore by a complex evaporation and dissolution process.[5] This process will be assessed in the future by evaluating decreasing water saturation along the wellbore.
- PNL provided valuable data for characterizing system porosity, lithology, and fluid saturations in a historic reservoir with limited data outside of the injection horizon.
- Repeat sigma log measurements were lower than their baselines in all injection wells, often by 6 to 9 cu, indicating the presence of CO_2. Production wells were lower by 1 to 4 cu, indicating initial CO_2 breakthrough in highly transmissive zones which correlate to the cleanest gamma intervals in the Muddy Sandstone.
- Sigma and C/O logs will be used to construct fluid saturation maps, which will help validate history matching and predictive simulation efforts on geocellular models. Time-lapse monitoring will identify how CO_2 moves through the reservoir and which parts of the reservoir are accessed.
- An additional 18 PNL monitor passes were collected in summer 2014, all of which have baseline logs. These are being processed to evaluate saturation changes along the wellbore.
- Future monitoring passes are scheduled to coincide with any repeat 4-D seismic surveys or may be run as needed based on operational and monitoring considerations. These logs, along with repeat seismic data and other modeling and monitoring data, will be used to estimate fluid saturation between wells in the field.

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