TITLE: APPLICATION OF RESERVOIR CHARACTERIZATION AND ADVANCED TECHNOLOGY TO IMPROVE RECOVERY AND ECONOMICS IN A LOWER QUALITY SHALLOW SHELF CARBONATE RESERVOIR

Cooperative Agreement No.: DE - FC22 - 94BC14990

Contractor Name and Address: Oxy USA, Inc. (Oxy), Midland, Texas

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OBJECTIVES

The Class 2 Project at West Welch was designed to demonstrate the use of advanced technologies to enhance the economics of improved oil recovery (IOR) projects in lower quality Shallow Shelf Carbonate (SSC) reservoirs, resulting in recovery of additional oil that would otherwise be left in the reservoir at project abandonment. Accurate reservoir description is critical to the effective evaluation and efficient design of IOR projects in the heterogeneous SSC reservoirs. Therefore, the majority of Budget Period 1 was devoted to reservoir characterization. Technologies being demonstrated include:

1. Advanced petrophysics
2. Three dimensional (3-D) seismic
3. Cross-well bore tomography
4. Advanced reservoir simulation
5. Carbon dioxide (CO_2) stimulation treatments
6. Hydraulic fracturing design and monitoring
7. Mobility control agents

SUMMARY OF TECHNICAL PROGRESS

West Welch Unit is one of four large waterflood units in the Welch Field located in the Northwestern portion of Dawson County, Texas. The Welch Field was discovered in the early 1940's and produces oil under a solution gas drive mechanism from the San Andres formation at approximately 4800 ft. The field has been under waterflood for 30 years and a significant portion has been infill drilled on 20-ac density. A 1982-86 pilot CO_2 injection project in the offsetting South Welch Unit yielded positive results. The recent installation of a CO_2 pipeline near the field allowed the phased development of a miscible CO_2 injection project at the South Welch Unit.

The reservoir quality is poorer at the West Welch Unit due to its relative position to sea level during deposition. Because of the proximity of a CO_2 source and the CO_2 operating experience that would be available from the South Welch Unit, West Welch Unit is an ideal location for demonstrating methods for enhancing economics of IOR projects in lower quality SSC reservoirs. This Class 2 project concentrates on the efficient design of a miscible CO_2 project based on detailed reservoir characterization from advanced petrophysics, 3-D seismic interpretations and cross wellbore tomography interpretations.

During the quarter, progress was made in both the petrophysical analysis and the tomography processing. The final geologic model is dependent upon the petrophysical analysis and the seismic and tomography interpretations. The actual reservoir simulation has started using the base geologic model, with which, all the preliminary simulation work is being done. Progress was also made in understanding the abnormal fracture wing orientation obtained in well 4807 and the cyclic CO_2 demonstration results.

PETROPHYSICAL ANALYSIS

Open hole logs were used to calculate permeabilities[1] for wells in the area. Fig. 1 shows the comparison of the log, plug and whole core permeabilities where core and modern open hole logs were available for the same wells. The interval where core and log calculated permeabilities failed to match was described as oolitic in the core description. Otherwise, differences in sample interval size caused the apparent difference in core and log calculated permeabilities.

Grids of porosity and permeability values, for use in the numerical simulator, were then generated using well log and core data. Wellbore data values, that were obviously too high, were discarded for the initial grid generation. The discarded values were from cased-hole compensated neutron log to core porosity correlations.

3-D SEISMIC INTERPRETATION

Depth structure maps of the base of Woodford and the Atoka horizons were generated from the 3-D seismic volume. This was used to better define the deep seated (Pennsylvanian and deeper) faulting that lies beneath the producing San Andres formation. A coherency slice map of the base of Woodford horizon was produced to help delineate the small faults in the deep section. This information aided in the hydraulic fracture orientation evaluation discussed later.

TOMOGRAPHY

Integration of the cross well seismic velocities and wellbore data showed a distinct correlation to core porosity (Fig. 2); however, the correlation appeared limited at a maximum value. As a result, cross well velocities were modeled, using a 1-D model, to better define the time interval where the tomography event should be picked. The model resolves variations in picking arrivals from changes in source waveform due to changing source positions, and changes in receiver orientation resulting in phase and polarity changes between receiver stations.

FRACTURE STIMULATIONS

The 3-D seismic fault maps, described previously, showed the reason the orientation of the western fracture wing, during the fracture treatment of the 4807w well, was different than general field evidence suggested the orientation would be[2]. The presence of a deep fault, running parallel to the fracture orientation observed with passive seismic measurement, changed the stress field in a very localized region around the fault. The change in stresses changed the orientation of the fracture as the fracture grew away from the wellbore and encountered the different stress field.

CYCLIC CO_2

Evaluation of the data generated from the five well treatments has demonstrated the process can be economic with pipeline CO_2 in some cases. Fig. 3 shows the incremental production versus the wellbore porosity feet for actual and predicted recovery. The incremental production is calculated from production above the rate prior to treatment, allowing for reduced base production while the well is actually flowing or producing with very high fluid levels. Lost or deferred production from the period the well is shut-in for injection or soaking is not included in the incremental oil calculation.

The calculation of incremental recovery uses fractional flow theory, and laboratory PVT data to estimate the volume of oil affected by the treatment. An example calculation is shown in Appendix A. The treated radius is calculated using the average gas saturation, from the gas oil fractional flow curve, with the total CO_2 volume pumped and the total pore volume in the volumetric equation. The CO_2 volume dissolving in water and the free gas volume is estimated, to determine the CO_2 volume available for swelling oil. This volume determines the CO_2 mole fraction in the oil and the oil swelling factor. Using the oil swelling factor the incremental oil is calculated from the difference in oil saturations before and after swelling and the residual oil saturation to waterflooding.

NUMERICAL SIMULATION

Simulation, using the base geologic model discussed previously, has matched individual well rates for the time interval from 1/93 to 7/94, using total permeability-thickness multipliers. The multipliers have varied from about 0.6 to 5.0 in different areas of the field. The largest multipliers are in the northern portion of the project area, where there is an additional producing interval developing but has very little permeability data available. The interpolation and extrapolation of data from the limited data points in each layer should improve when the seismic data is incorporated into the model.

TECHNOLOGY TRANSFER

The seismic attribute to log property conversion method[3] was presented to the Society of Independent Petroleum Earth Scientists (SIPES) in Dallas and was video-taped to show to other SIPES members. The same presentation was made at the Oklahoma Geological Society Workshop on Platform Carbonates in the Southern Midcontinent, plus another presentation on reservoir characterization using interpreted log and core analysis[4].

Two technical papers and a poster session were presented at the Society of Petroleum Engineers (SPE) Permian Basin Oil and Gas Recovery Conference in March, 1996, covering the passive seismic and hydraulic fracturing results (SPE 35230)[5] and the permeability estimation methods (SPE 35160)[6]. The poster session covered the cyclic CO_2 results and evaluation[7]. An article discussing the cyclic CO_2 demonstration results appeared in the March 1996 Oil and Gas World[8].

REFERENCES

1. Hinterlong, G.D., and Taylor, A.R., Application of Reservoir Characterization and Advanced Technology to Improve Recovery and Economics in a Lower Quality Shallow Shelf Carbonate Reservoir, DOE Contract No. DE-FC22-94BC14990, *Quarterly Report,* October 1- December 31, 1995.

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6. Hinterlong, G.D. and Taylor, A.R. Characterization of Rock Types with Mixed Wettability using Log and Core Data - DOE Project Welch Field, Dawson County, Texas. *SPE 35160,* Permian Basin Oil & Gas Recovery Conference, Midland, TX 27-29 March 1996.
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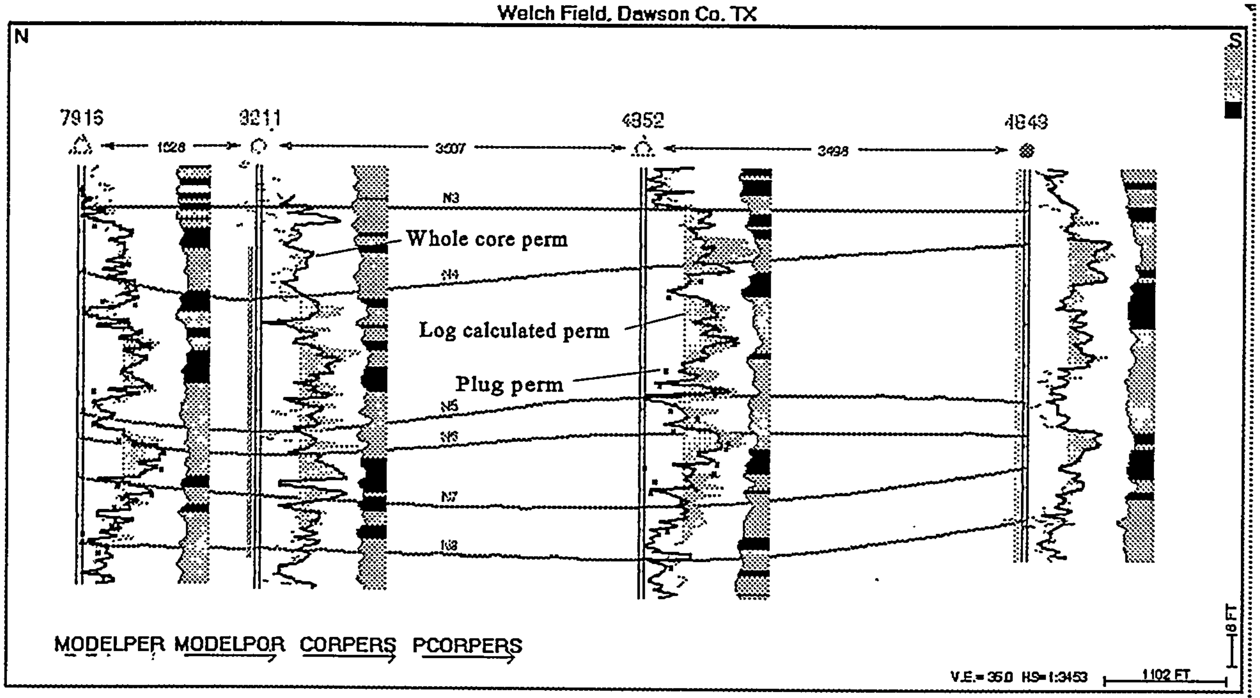

Figure 1 Cross section showing the comparison of log, core plug and whole core permeabilities. The shaded grey to the right of the wellbore is log permeability. Plug permeabilities are the points (x) and whole core values are the curve. The geo column shows values of deep resistivity greater than 50 Ohms in black, indicating an oil wet pore system dominates the interval.

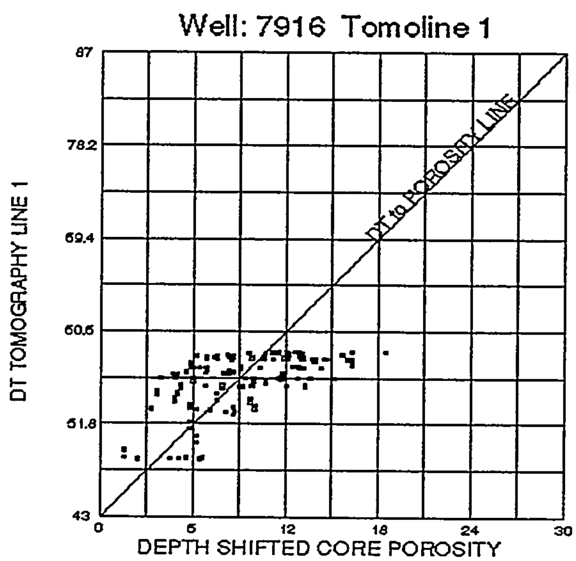

Figure 2 Cross well computed velocities vs core porosity from the initial processing.

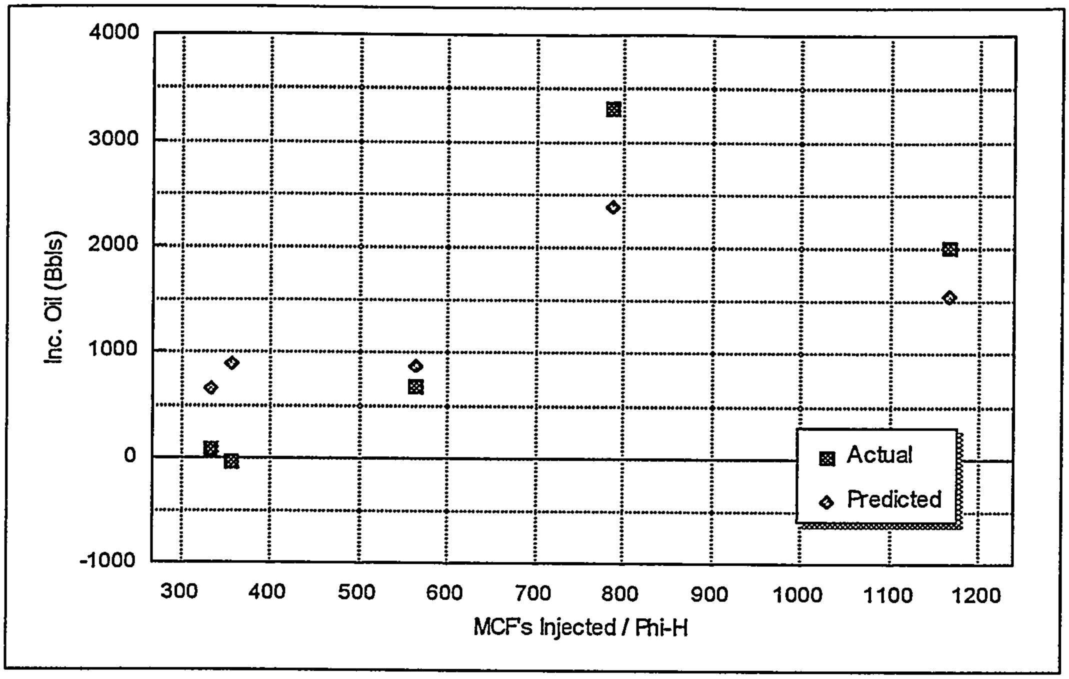

Figure 3 Incremental oil recovery versus the MCF of CO2 injected per porosity-foot for the producing interval.

Appendix A

Recoverable Oil Calculation for Cyclic CO2 Treatments

The reservoir CO2 volume is calculated from the injection volume using the formation volume factor.

$$I_{CO2} \times Bg_{CO2} = Res.Vol_{CO2}$$

From gas fractional flow curves, the average gas saturation behind the front is found from the tangent to the fractional flow curve, at the gas saturation at breakthrough, extrapolated to a gas fractional flow of 100%. For the West Welch project immiscible gas-oil relative permeability data shows an average saturation from fractional flow curves of 14%.

Assuming an average gas saturation over the entire completion interval, the equivalent radius of affected oil is found by

$$r_{eg} = \sqrt{\frac{Res.Vol_{CO2} \times 5.615}{\Pi \times \phi \times H \times S_{gave}}}$$

Due to the preferential diffusion of CO2 into the water phase the volume of CO2 dissolving in the reservoir water is found from the solubility of CO2 in water and the volume of reservoir water.

$$Vol_{gw} = \frac{\Pi \times r_{eg}^{2} \times H \times \phi}{5.615} \times S_{gw}$$

The reservoir volume of free CO2 remaining after the oil is saturated after soaking is estimated. From Welch cyclic CO2 data the free gas volume is about 15-20% of total injection for the five wells tested.

$$Vol_{fg} = G_f \times B_g$$

The volume of CO2 available to swell oil is found from the difference in the total injection and the volumes of CO2 dissolved in water and free gas remaining.

$$Vol_{go} = I_{CO2} - Vol_{gw} - Vol_{fg}$$

The volume of oil swelled depends on the radius the CO2 covers r_{eg}.

$$Vol_{oil} = \frac{\Pi \times r_{eg}^{2} \times H \times \phi}{5.615} \times S_o$$

The oil swelling factor is based on the mole % of CO2, therefore the moles of CO2 and the moles of oil need to be calculated. The molar volume of oil is found by

$$molevol_{oil} = \frac{Mw_o}{350 \times SG_o}$$

The actual moles of oil and CO2 are calculated.

$$mole_{oil} = \frac{Vol_{oil}}{molevol_o} \qquad mole_{CO2} = \frac{VOl_{go}}{vol_g}$$

The mole% of CO2 is then

$$CO2mole\% = \frac{mole_{CO2}}{mole_{CO2} + mole_{oil}}$$

The oil swelling factor for the mole % CO2 is found from the laboratory test data. The swelling factor for Welch crude is about 1.2 for 40% CO2 in the oil. The total oil recovered from the CO2 treatment is the oil in place in the affected radius less the residual oil,

$$N_p = N \times \frac{(S_o \times S_f - S_{orw})}{(S_o \times S_f)}$$

The incremental oil is found from the difference in recovery with swelled versus unswelled oil.

$$N_{pinc} = N \times \left[\frac{(S_o \times S_f - S_{orw})}{(S_o \times S_f)} - \frac{(S_o - S_{orw})}{S_o} \right]$$

The symbols used are

- I_{CO2} = The volume of CO2 injected in MCF
- Bg = The formation volume factor RB/MCF
- r_{cg} = The radius affected by CO2 injection, feet
- H = Net pay interval, feet
- Φ = Average porosity over the net pay interval, fraction
- S_{gave} = Average gas saturation behind a front from fractional flow curves
- S_{gw} = The solubility of CO2 in water at reservoir pressure, barrels per barrel
- Vol_{gw} = The volume of CO2 dissolved in the water phase, Barrels
- Vol_{fg} = The volume of free CO2 not dissolving in the oil or water, Barrels
- G_f = The volume of free CO2 not dissolved in oil or water in the reservoir, MCF
- Vol_{go} = The volume of CO2 dissolved in the oil, barrels
- Vol_{oil} = The volume of oil affected by the CO2 injection, barrels
- S_o = The current oil saturation, fraction
- $molevol_o$ = The barrels of oil in one mole of unswelled oil
- Mw_o = The molecular weight of the oil, lbs/mole
- SG_o = The oil specific gravity,
- $mole_o$ = The moles of oil affected by CO2
- $mole_{CO2}$ = The moles of CO2 dissolved in the oil
- Vol_g = The reservoir volume of CO2 per mole of CO2, barrels/mole
- S_f = The swelling factor of the reservoir oil at the mole% of CO2
- S_{orw} = The residual oil saturation to water flooding, fraction
- N = The current oil in place based on the calculated radius of oil affected by CO2, STB
- N_p = The total production during the stimulation period, STB
- N_{pinc} = The incremental oil production from the stimulation treatment, STB

Budget removed. at