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**Integrated Approach Towards the Application of Horizontal Wells to
Improve Waterflooding Performance**

(Contract No. DE-FC22-93BC14951)

Submitted by

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Tulsa, Oklahoma 74104

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Objectives

The overall purpose of the proposed project is to improve secondary recovery performance of a marginal oil field through the use of a horizontal injection well. The location and direction of the well will be selected based on the detailed reservoir description using integrated approach. We expect that 2 to 5 % of original oil in place will be recovered using this method. This should extend the life of the reservoir by at least 10 years.

To accomplish the goals of the project, it is divided into two stages. In Stage I, we will select part of the Glenn Pool field (William B. Self Unit), and collect additional reservoir data by conducting cross bore hole tomography surveys and formation micro scanner logs through newly drilled well. In addition, we will also utilize analogous outcrop data. By combining the state of the art data with conventional core and log data, we will develop a detailed reservoir description based on integrated approach. After conducting extensive reservoir simulation studies, we will select a location and direction of a horizontal injection well. The well will be drilled based on optimized design, and the field performance will be monitored for at least six months. If the performance is encouraging, we will enter into second budget period of the project.

If continued, the second budget period of the project will involve selection of part of the same reservoir (Berryhill Unit - Tract 7), development of reservoir description using only conventional data, simulation of flow performance using developed reservoir description, selection of a location and direction of a horizontal injection well, and implementation of the well followed by monitoring of reservoir performance.

By comparing the results of two budget periods, we will be able to evaluate the utility of collecting additional data using state-of the-art technology. In addition, we will also be able to evaluate the application of horizontal wells in improving secondary recovery performance of marginal oil fields.

A successful completion of this project will provide new means of extending the life of marginal oil fields using easily available technology. It will also present a methodology to integrate various qualities and quantities of measured data to develop a detailed reservoir description.

Summary of Technical Progress

The overall report is divided into three sections. In the first section, we discuss the preliminary geological description of Self #82 which was drilled in the Self Unit. In the second section, we discuss the preliminary results based on the cross bore hole seismic surveys. In the last section, we present additional results of a well test conducted on Well #54 and comparison of the well test permeability with the core permeability data from Well #82.

As discussed in the last quarterly report, based on the preliminary flow simulation studies and the feasibility of obtaining reliable cross well seismic data, Well #82 was drilled at the end of December 1993. The location of Well #82 in the Self Unit is shown in Figure 1.

Geological Interpretation

(By D. Kerr and L. Ye)

The vertical test well (Self No. 82) was drilled for the collection of data using advanced technology, and to evaluate the subsurface mapping completed prior to drilling. The subsurface maps consisted of facies and net-sand isopach maps for each of seven discrete genetic intervals (DGI).

Core was cut from 1420 to 1575 ft. depth in 3 core runs. The amount of core recovered was 153 ft. with the unrecovered part accounted for from the basal 2 ft. of the Glenn Sandstone in core run no. 3. Well site observations noted that oil was bleeding from discrete stratigraphic intervals for 1 to 6 ft. thick in DGI A, C, D, and E. The core was archived and being processed at Amoco Research Lab in Tulsa, Oklahoma.

A detailed core description was made as the core was being processed and prepared for subsampling. The description is stored in a computer graphics software file used by Amoco. A final description will follow the completion of core plug sample processing.

Core plugs were cut using two spacing schemes and different orientations. The upper 46 ft. of core composed of mudstone and lower 41 ft. of core composed of sandstones largely depleted of hydrocarbons were plugged about 3-ft. intervals. The upper 46 ft. of the Glenn Sandstone, the interval of greatest interest to project, was plugged about 1-ft. intervals. Orientation of plugs in the mudstone interval were

horizontal, vertical, and 45-degrees inclined to the core axis; these oriented samples are of particular interest to the geophysical studies. Plugs cut in the sandstones were horizontal and vertical to the core axis at each sampled interval. Core plug measurements include: porosity, permeability, velocity, grain density, and mineralogy. Full results are expected within the next few weeks.

A microresistivity log (FMI) was successfully acquired in the Self No. 82 through the Glenn Sandstone. The data have been processed by Amoco Production Company well log services group in Houston, Texas. The processed log will be examined and analyzed after the core final description and photography tasks are complete. The microresistivity log will be evaluated at Amoco Research Labs in Tulsa, Oklahoma.

Drilling of the Self No. 82 well provided an opportunity to assess the predictive quality of the reservoir architecture maps developed prior to drilling. Overall, the expected thicknesses were within the contour interval used in the working facies and net-sand isopach maps (contour interval of 5 ft.) for each discrete genetic interval. Evaluation of the success of facies predictions is pending the final core description. The prediction of the presence of DGI B at the location of Self No. 82 was not validated by the results of Self No. 82; DGI B is markedly truncated by erosion prior to deposition of the channel-fill facies of the overlying DGI A. It is hoped that the interwell position of the termination of DGI B can be refined in the cross well tomographic images. In addition, the greater thickness and higher than expected oil saturations found in DGI D and E has caused a re-assessment of the correlation of the these two DGIs.

Geophysical Interpretation of Full Field Survey **(by C. Liner and G. Bozkurt)**

The full crosswell survey was completed in early 1994. The preliminary survey, as discussed in the previous report, resulted in high quality data, but the second encountered high ambient noise. The noise levels were high enough to prohibit first-arrival picking over in much of the data. Analysis of the data from the second survey shows that tube waves are emanating from the perforated interval in the receiver well. This is interpreted to be fluid flow or circulation noise through the perforations, even though the well was not flowing fluid at the surface.

Since this image plane was important for characterization of the reservoir, the survey was re-shot by reversing sources and receivers in the two wells. The resulting high-quality data indicates that shooting direction can be an important acquisition factor.

In general terms, crosswell seismic imaging is a method capable of resolving very thin beds relative to conventional surface seismic methods. The main advantage of crosswell seismic over surface seismic methods is the notable difference of frequencies encountered (i.e., 200-2000 Hz vs. 20-80 Hz, respectively) and the corresponding improvement in resolution. Also, the downhole vantage point allows tight integration with other borehole information. This can lead to inferences concerning reservoir properties such as porosity distribution and bed continuity.

The crosswell seismic objective at the Glenn Pool field is to create tomographic image planes to aid in reservoir characterization. Initial tomography results are discussed by Vassiliou, et al. (1994).

For the full crosswell work using the 82 well, acquisition involved Amoco's piezo-source and a proprietary 15-hydrophone receiver string developed by Conoco, Inc. Conoco also generously supplied personnel, on-site data processing and data editing services.

From early in the project the plan had been to use the Vertical Test Well (VTW) (82 well) as the crosswell seismic source well (see Figure 1). This was considered the best plan to minimize risk of losing the (expensive) source downhole.

The first full survey, 82→64, followed this plan and resulted in high-quality data. Figure 2 shows some features of the 82→64 survey including geometry of selected common source (CSG) and common receiver (CRG) gathers. The CSG and CRG data are plotted in Figure 3, and clear first breaks with good relief above ambient noise are evident on both.

Fresh from the success of the 82→64 survey, the acquisition team shot 82→63. This is labeled survey 2 in Figure 1. The survey geometry is nearly identical to that shown in Figure 2, and Figure 4 shows a CSG and CRG representative of the data. Compared to the 82→64 data quality, the high ambient noise in Figure 4 was surprising. It is important to note that in both surveys every precaution was taken to eliminate known sources of noise. Also, all information on wells 63 and 64 indicated that they were nearly identical in drilling, completion and production history.

On the CRG, ambient noise is strong before and after first-arrival times. This noise is incoherent on the CRG, but on the CSG in Figure 4, the noise is coherent and recognizable as tube wave energy. Upgoing tube waves exist above about 1500 ft and

downgoing ones exist below this level. As suggested by V. D. Cox, we interpret this as fluid flow noise associated with the perforated interval at 1460-1505 ft. It is curious that such strong tube wave energy should be generated by downhole (circulating?) fluid flow despite there being no fluid flow at the surface.

The ambient noise problem was serious enough that a significant portion of the wide-angle data could not be picked for first arrivals. Since picked first arrivals are the raw data for crosswell tomography, and since this image plane was deemed crucial to the characterization effort, it was decided to back-shoot the 82→63 survey as 63→82.

In an effort to enhance data quality for better characterization of the reservoir, the 82→63 survey was re-shot with reversed source and receiver wells. In theory, the fluid flow noise in the source well (63 well) would radiate very little energy into the formation to appear as ambient noise in the receiver well (82 well). In this way, the flow noise would be overwhelmed by the source signal.

Figure 5 shows CSG and CRG data over a common interval in the 63→82 survey. Comparing with Figure 4, the data quality is greatly improved. The data for this survey could be picked for first arrivals at all vertical offsets.

Shooting direction in a crosswell seismic experiment is usually based on operational issues such as borehole condition and casing size relative to the seismic tools. Beyond these concerns, it is tempting to invoke the principle of reciprocity, i.e., the data will be identical if source and receiver positions are interchanged. While reciprocity is a powerful principle known to be valid in arbitrarily complicated physical systems, it silently assumes that the medium is passive. If the medium is active, if it contains sources of energy, then reciprocity does not apply. Interchanging source and receiver in this case can give very different results. Our experience with crosswell seismic and fluid flow noise is a simple example of this fact.

We have shown that shooting direction can be a first order concern on data quality. Specifically, if a downhole source of noise exists in one well it is best to use this as the source well. Unfortunately, it is often not known before the survey that such a downhole noise source exists.

The next step in working with the Glenn Pool crosswell seismic data is tomographic inversion. This requires the data to be picked for first arrival times on all surveys to be inverted. This amounts to about fifty thousand seismic traces. As of late

March, 1994, all data traces for surveys 82→64, 63→82, and 81→82 have been picked by A. Vassiliou of Amoco. Survey 82→63 was judged too noisy for reliable picking.

These picks are being forwarded to the University of Tulsa so that tomographic processing can begin using the U. S. Bureau of Mines Tomography program (BOMTOM). Also, the picks will be used by Prof. L. R. Lines at Memorial University of Newfoundland to perform another tomographic inversion of the data. The three tomography sites are doing complimentary work by processing the data using different levels of complexity. Specifically, in order of increasing complexity,

Univ of Tulsa Straight-ray isotropic tomography using **BOMTOM**

Memorial Univ Curved-ray isotropic tomography using software developed at the University of Utah (courtesy G. Schuster)

Amoco Curved-ray anisotropic tomography using proprietary software

This multiple-processing exercise will result in information concerning how much effort is required to successfully image crosswell data in fluvial-dominated deltaic settings. In this way, we will be able to better judge the viability of currently available software and hardware for processing of crosswell data, and whether or not it is feasible for small-to-medium sized operators.

Engineering Description and Simulation

(By L. Thompson and M. Kelkar)

In the last report, we presented the flow simulation results which led to drilling of Well #82. The details about the procedure used for description and the flow simulation can be found elsewhere.⁴ We observed that preliminary comparison between observed oil saturation profile at Well #82 and the simulated profile was reasonable.

One of the difficulties we encountered in our reservoir description process is the limited permeability data. We had very limited core and no well test data. Since well test data provide permeability on a large scale, we decided to conduct well tests using Ecometer. In this report, we present the result of one such well test.

A 2-day pressure buildup test was run on Self-54 (see Figure 1). Prior to shut-in for pressure buildup, the well was producing 168 STB water/day and 2 STB

oil/day. Since the producing stream consisted of more than 95% water, the well was analyzed as a water producer. Relevant well and reservoir properties are summarized in Table 1.

Table 1
Properties Used in Well Test Analysis

Well Radius	ft	0.276
Net Formation Thickness	ft	31.
Sands Encountered	A, B, C	
Total Production Rate	STB/day	170
Formation Temperature	°F	100
Formation Volume Factor of Water	bbl/STB	1.
Compressibility	psi ⁻¹	3.76 × 10 ⁻⁶

The pressure buildup data were analyzed using the EPS PanSystem well-test analysis software; final analysis results were refined using a nonlinear regression well test analysis package which was developed at The University of Tulsa.

A log-log plot of the pressure and pressure derivative data (diamonds and circles respectively) is shown in Figure 6. The data exhibit wellbore storage effects at early times (i.e., 45° line in Figure 6 for times less than 70 min); after these early time wellbore effects, the reservoir begins to influence the wellbore pressure response, and the pressure derivative (circular data) goes through a maximum then decreases. There is no radial flow (i.e., horizontal derivative data) evident in the log-log plot, so semilog analysis is not strictly applicable; if semilog analysis were applied to the late-time data, estimates of the permeability to water would be low.

We analyzed the data using type curve matching with the “well with skin and storage” type-curves, as well as using automated type curve matching using nonlinear regression analysis. The analyses were consistent with each other, and the results obtained were as follows:

Permeability to water, md	5.5 ± 0.4
Wellbore Storage Coefficient, bbl/psi	0.049 ± 0.001
Skin Factor	-1 ± 0.5
Radius of Investigation, ft	700

The match from nonlinear regression analysis is shown in Figure 6 as the solid curves. The reported permeability value represents an arithmetic average permeability-thickness product over the three producing sands (i.e. A, B and C) in the well's drainage area; this result compares favorably with core data on Self-82 which indicates that the permeability in the A, B and C sands varies between 0.02 md to 20 md (see Figure 7). The slightly negative skin factor indicates that permeability in the near-well region is slightly higher than the average reservoir permeability. This could be due to a variety of reasons including: formation pinching out far away from the well; degrading sand quality and distance from the well increases; formation behind the casing washed out, etc. Regardless of the reason for the negative skin, the well will not benefit from stimulation.

We intend to collect additional well test data on at least four more wells. This should allow us to better evaluate the permeabilities used in flow simulation studies which are solely based on the limited core data. In addition, Well #82 may also allow us to better describe the geological environment. Using the revised geological description, and with the help of additional core and the well test data, we will improve our reservoir description and conduct additional flow simulation studies to better determine the ways to improve the reservoir performance. We expect to have those results by the next report.

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Figure 1: Glenn Pool Project location and site map. Only those wells involved in the crosswell seismic work are shown. Arrows indicate crosswell shooting direction by pointing at the receiver well.

Figure 2: Some features of the 82→64 survey including, generalized stratigraphic column and reservoir (Glenn Sand). Also indicated are representative Common Source (CSG) and Common Receiver (CRG) Gathers.

Figure 3: Selected CRG and CSG data from the 82→64 survey. Beside each gather is a frequency spectrum for a trace near the center of the gather. The data quality here is high and first arrivals stand out well above ambient noise levels. The receiver well (64) is perforated on the interval 1452-1473.

Figure 4: CRG and CSG data from the 82→64 survey. Note strong ambient, pre-first-arrival, noise in the data. The CSG data shows the noise to be coherent tube waves in the receiver well (63). The 63 well is perforated on the interval 1460-1505. It is interpreted that tube waves were generated by fluid flow in the perforated interval. See text for discussion.

Figure 5: Data from the 64→82 survey over the same range as shown in Figure 4. By simply reversing the shooting direction high-quality data has been acquired.

Figure 6: Match between field data and type curves.

Figure 7: Permeability of Well #82

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