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**DESIGN AND IMPLEMENTATION OF A CO2 FLOOD UTILIZING
ADVANCED RESERVOIR CHARACTERIZATION AND HORIZONTAL
INJECTION WELLS IN A SHALLOW SHELF CARBONATE APPROACHING
WATERFLOOD DEPLETION**

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OBJECTIVE

The first objective is to utilize reservoir characterization and advanced technologies to optimize the design of a CO₂ project for the South Cowden Unit (SCU) located in Ector County, Texas. The SCU is a mature, relatively small, shallow shelf carbonate unit nearing waterflood depletion. The second objective is to demonstrate the performance and economic viability of the project in the field. This report includes work on the reservoir characterization and project design objective. In addition, the initiation of the demonstration project objective includes work done in November and December, 1995.

SUMMARY OF TECHNICAL PROGRESS

PHASE I

Integrate Geological, Petrophysical, and Seismic Data into a 3-D Geologic Description

Permeability was computed for each well with digital log data using correlations to core permeability measurements and well production rates. This data was imported into the STRATAMODEL software, and a 3-dimensional interpolation of the permeability distribution was completed. A three-dimensional porosity distribution had previously been completed for the model.

Visual inspection of the porosity and permeability distribution in the geologic model indicated that the E zone interval (the primary target for the CO₂ flood) could be separated into four units. These flow units are distinguished by small variations in porosity or permeability that are somewhat correlatable between wells. These four layers in the E, in addition to the F layer, upper D layer, and C layer, comprise the 7 flow units in the reservoir simulation model.

Maps of structure, thickness, average porosity, and geometric average permeability were extracted from the geologic model for each of the seven simulation layers. Examples of the maps for the E1 layer are attached (Figures 1-4), which illustrate the dissimilarity between the porosity and permeability distribution in the field.

These data will be imported to the reservoir simulator to create a new, more heterogeneous description. After updating the history match, it is hoped that the new description will better match individual well production performance, and provide a more reliable forecasting and reservoir monitoring tool. The new simulation model will be used to optimize drilling locations for the horizontal injectors and other future wells in the field.

Technology Transfer

Ahmad Moradi made a presentation titled "Laboratory and Field Evaluation of CO₂ Foam" at the

Petroleum Recovery Institute Forum on EOR Foam, Calgary, Alberta, Canada, November 15, 1995.

Ahmad Moradi, E.L. Johnston, D.R. Zornes and K.J. Harpole submitted an abstract entitled "Laboratory Evaluation of Surfactants for CO₂-Foam Applications at South Cowden Unit", for the International Symposium on Oilfield Chemistry, February 18-21, 1997 in Houston, Texas. A copy of the abstract is attached (Attachment I).

A technical paper entitled "Integrated Geological and Engineering Characterization of an Upper Permian Carbonate Reservoir, South Cowden Unit, Ector County, Texas" was presented at the American Association of Petroleum Geologists Midcontinent Section Meeting, in Tulsa, Oklahoma, October 9-10, 1995. The paper was presented by Craig Caldwell. A copy of the abstract is attached (Attachment II).

PHASE II

Drill, core, and complete reservoir characterization well RC-3 (SCU Well 6-24)

The third reservoir characterization well for the project has been given the well number SCU 6-24. This well was drilled in November and December, 1995. The location of the well is shown on the attached map (Fig. 5). Core was taken from the depth interval 4586-4766', recovering 179.5 feet of core. Routine whole core analysis measurements of porosity, permeability, and fluid saturations have been completed. The core has been slabbed and sent to the Phillips core facility in Bartlesville. There a petrographic study will be completed, including macroscopic core description and thin sections.

Well logs indicated greatly reduced porosity in the Upper E and F zones, compared to offset wells. Initial examination of the core indicates that anhydrite cementation may be responsible for the porosity reduction, and that the permeability is also low. The well was perforated in the lower E, upper D, and C zones. The well tested 200 BWPD and 0 BOPD flowing, and has been temporarily abandoned. The well may be reactivated as a producer or CO₂ WAG injector after CO₂ injection has begun in the project.

Drill two vertical CO₂ injection wells

Two vertical CO₂ WAG injection wells were planned for Tract 2 in the northwest portion of South Cowden unit (Fig. 5). Tract 2 is in the structurally highest part of the unit, where Zones C and A, underlying the main pay zones E and D, are oil bearing. The vertical injection wells in this area of the field will permit direct flooding of all four zones with CO₂, and improve the oil recovery of the project.

The proposed injection wells SCU 2-26W and 2-27W were drilled in December, 1995. The SCU 2-27 has been temporarily completed as a producing well, and tested 10 BOPD, 100 BWPD from zones C through F. This well will be converted to CO₂ injection when the pipeline and injection facilities

have been completed, in July 1996. SCU Well 2-26W has not yet been completed, pending completion of the injection facilities and pipeline.

Drill four production wells

Two additional production wells, the SCU 6-22 and SCU 7-12, were drilled and completed in November and December, 1995. The well locations are shown in Figure 5. These wells are needed to drain areas of the field offsetting the horizontal injection wells, replacing old wells which have been plugged and abandoned. The SCU 6-22 tested 100% water from the D and E zones. It was plugged back to the G zone and tested 9 BOPD and 148 BWPD. The SCU 7-12 was completed in zones D through F and tested 5 BOPD and 270 BWPD.

Figure 1

Figure 2

Figure 3

FEET 0 1000 2000
 STATUTE MILES 0 1 2 3 4 5

SOUTH COWDEN PROJECT
 ECTOR COUNTY, TEXAS

E1 ZONE POROSITY

CI 2 %

DATE: 11-1-66 BY: H. G. GERRARD 21-488-96

Figure 4

Figure 5

ATTACHMENT I

LABORATORY EVALUATION OF SURFACTANTS FOR CO₂-FOAM APPLICATIONS AT THE SOUTH COWDEN UNIT

Ahmad Moradi-Araghi, E. L. Johnston, D. R. Zornes and K. J. Harpole

An extensive laboratory study was conducted to evaluate foaming ability of four surfactants, Chaser[®] CD-1045, CD-1050, Rhodapex[®] CD-128 and Foamer[®] NES-25 were tested in South Cowden Unit (SCU) cores. The objective of this study was to identify suitable surfactants to produce stable CO₂-foam for possible application at SCU for mobility control and diversion of CO₂ in horizontal injection wells. This study is a part of a Department of Energy (DOE) Class II demonstration project, partly funded by DOE.

Several core tests were performed with foams produced by co-injection of surfactant solutions at various concentrations in a synthetic SCU brine, and CO₂ under about 2000 psi of pressure and 98° F at 20-90% foam quality. All field cores (diameter: 1", length: 4-6") used in this study were highly inhomogeneous with significantly varying permeability in different sections of the core. A typical core which was equipped with three pressure taps along its length exhibited permeabilities of 10 to 600 md in its four sections. The resistance factors (RF) determined for flowing the foam in each section of the core appeared to vary with the permeability of that section. The foams exhibiting this behavior were referred to "smart foams" by J.P. Heller. Resistance factors measured for CO₂-foams produced in the same core with the four surfactants under identical conditions showed the best performance equally for Chaser CD-1050 and Rhodapex CD-128, followed by Chaser CD-1045 and Foamer NES-25 which were also comparable. However, Rhodapex CD-128 and Chaser CD-1045 were chosen for further studies based on availability and previous field experience. RF values measured for the foams produced with these surfactants at various concentrations maximized between 50% to 70% foam quality. The maximum, however, shifted to higher foam qualities with increased surfactant concentration.

The chosen surfactants were secondly evaluated each by co-injection as well as SAG (Surfactant Alternating with Gas) processes to investigate the effect of surfactant concentration and frontal velocity. The resulting foams exhibited a shear thinning behavior with resistance factors increasing with surfactant concentration. The performance of the foams produced by the SAG process with both surfactants in the same core at 70% foam quality diminished with slug size.

Both chosen surfactants evaluated for their CO₂-foam properties in a test core at residual oil saturation produced lower RF values than the tests performed in cores with practically no movable oil to CO₂ flow. These tests which were performed at varying frontal velocities and foam quality, also showed the shear-thinning property and dependency of RF values on foam quality. This data coupled with adsorption tests being carried out presently in our laboratory, should help in selecting Rhodapex[®] CD-128 or Chaser[®] CD-1045 as candidate surfactant.

ATTACHMENT II

INTEGRATED GEOLOGICAL AND ENGINEERING CHARACTERIZATION OF AN UPPER PERMIAN, CARBONATE RESERVOIR, SOUTH COWDEN UNIT, ECTOR COUNTY, TEXAS --- A WORK IN PROGRESS

Gerard, M.G. and Johnson, J.V. and Snow, S.C., Phillips Petroleum Company, Odessa, TX;
Caldwell, C.D., Phillips Petroleum Company, Bartlesville, OK

South Cowden Unit, located on the eastern margin of the Central Basin Platform, has produced 35 million barrels of oil since initial development in the late 1940's. The Unit, under waterflood since 1965, has been proposed for a CO₂ flood using horizontal injection wells. A team of geologists and engineers was formed to characterize the reservoir. The early and complete integration of geologic and engineering work has resulted in a detailed reservoir description to be used in reservoir simulation.

Regional mapping and 3-D seismic data indicate that sediments within the reservoir interval were draped over a paleohigh resulting in an unfaulted, anticlinal-like structure. A field-wide stratigraphic framework was developed using two to four-foot thick, gamma-ray log markers which correspond to low permeability, sandy dolomite layers recognized in core. These log correlations indicate fairly simple and uniform structure and stratigraphy. The gamma-ray markers delineate four zones within the 150 foot reservoir interval. Rocks composing these zones are extensively dolomitized and display a complex color mottling.

Color mottling which characterizes the reservoir interval is due to variable hydrocarbon staining and reflects a variation in porosity and permeability. This mottling is related most likely to bioturbation of carbonate sediments in a shallow, subtidal marine environment. Extensive and interconnected bioturbated areas have core analysis porosities averaging approximately 20% and permeabilities generally ranging from 2 to 350 md. The intervening, nonburrowed and unstained areas have porosities averaging 5% and permeabilities typically ranging from 0.01 to 2 md.

Variations in the quality and thickness of the mottled facies are major parameters controlling oil recovery. A belt of better reservoir-quality rock runs roughly parallel to structure and results in an area of higher cumulative oil production. Good waterflood response and uniform pressure distribution indicate continuity of the pay zones within this belt.