Title Page

TITLE: ECONOMIC RECOVERY OF OIL TRAPPED AT FAN MARGINS USING HIGH ANGLE
WELLS AND MULTIPLE HYDRAULIC FRACTURES

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General Information

DOE Project

Project Description

The distal fan margin in the northeast portion of the Yowlumne field contains significant reserves but is not economical to develop using vertical wells. Numerous interbedded shales and deteriorating rock properties limit producibility. In addition, extreme depths (13,000 ft) present a challenging environment for hydraulic fracturing and artificial lift. Lastly, a mature waterflood increases risk because of the uncertainty with size and location of flood fronts.

This project attempts to demonstrate the effectiveness of exploiting the distal fan margin of this slope-basin clastic reservoir through the use of a high-angle well completed with multiple hydraulic-fracture treatments. The combination of a high-angle (or horizontal) well and hydraulic fracturing will allow greater pay exposure than can be achieved with conventional vertical wells while maintaining vertical communication between thin interbedded layers and the wellbore. The equivalent production rate and reserves of three vertical wells are anticipated at one-half to two-thirds the cost.

Budget Period One Activities

An analogous well was hydraulically fractured to obtain fracture-treatment design parameters for the proposed high-angle well. This was the first frac in the northwest fan margin. It treated with a higher frac gradient (1.06 psi/ft) than the 0.91 psi/ft gradient observed in the northeast fan margin (where the high-angle well is proposed to be drilled).

Microseismic events were passively monitored during the frac from an offset well to determine fracture geometry and azimuth. A NW-SE azimuth was detected, compared to the expected NNE-SSW azimuth. Knowledge of fracture azimuth was useful for determining location and azimuth for the proposed high-angle well. Figure 1 shows the project location.

The reservoir geology of the northeast fan margin was re-evaluated. Petrophysical properties were derived from core, log, and RFT data. Only slight modifications of previous interpretations were necessary. As expected, rock properties deteriorate in an easterly direction towards the distal margin.

The five major flow units were subdivided into ten layers. Rock properties were calculated and mapped for each layer. The detailed reservoir geology was then inserted in a fine-grid, partial-field reservoir simulation model (Fig. 2). The model was history matched, with some layers appearing to be more swept than expected.

Upon completion of history matching, the model was used to test a variety of development alternatives aimed at optimizing project economics. Model forecasts compared slant well performance to more conventional development options and quantified rate impacts from changes in well location, orientation, and completion technique. An east-to-west slant well with multiple hydraulic fractures proved to be the optimal alternative to develop the fan-margin region. Model results indicated the well could initially produce 2180 BOPD and recover 724 MBO of reserves (net of interference).

Yowlumne Field History

Field Discovery

The Yowlumne field is located in Kern County, California, approximately 25 miles southwest of Bakersfield (Figs. 3 and 4). The field was discovered in January 1974 by Texaco Exploration and Production, Inc., on a farmout agreement from Tenneco Oil Company. The discovery well was the San Emidio no. 1, which later became the Yowlumne Unit A 81X-14 well. It proved to be located in the southeastern corner of the field (Fig. 5). The well was completed in the Yowlumne sand, an Upper Miocene Stevens turbidite sequence, through perforations at 11,305 ft to 11,465 ft. The initial flowing rate was 863 BPD of 32° API oil at 1% water cut with 491 MCFPD gas.

Primary Recovery

The field produced solely by primary recovery until 1976, when a small amount of water was injected into two wells to partially offset declining production rates and pressure. Figure 6 shows the production plot for the entire field. Oil production from the field peaked in November 1978 at 26,400 BOPD. However, due to a lack of pressure support, the production rate rapidly declined. The reservoir behaved as a closed volumetric system with two adjoining aquifers providing little, if any, pressure support. In addition, the reservoir was initially undersaturated. The discovery pressure of 5670 psi was roughly 3000 psi higher than the bubble point pressure. The primary recovery drive mechanisms were fluid expansion and solution gas drive.

Decline curve analysis was used to extrapolate the primary recovery production decline as if enhanced recovery operations had never been implemented. This methodology yielded an estimated primary recovery efficiency of 17.6% of the original oil in place (OOIP).

Secondary Recovery

In 1978, a southeastern piece of the field was unitized and called Yowlumne Unit A. Unitizing a portion of the field permitted early implementation of waterflooding while the rest of the field (later known as Unit B) was being developed and delineated.

The Unit A waterflood was designed to take advantage of a directional permeability trend which was parallel to the central axis of the field. As shown in Figure 7, four wells in the heart of the reservoir were converted to injection wells to form a “crestal line drive” pattern. Full scale injection in Unit A began in January 1979.

Initially there were no water injection operations in the northwest portion of Unit A to avoid displacing fluid out of the unit. In 1983, six additional wells were placed on injection coinciding with the startup of the Unit B waterflood. Three of the wells were located on the western unit boundary.

Response from water injection in Unit A was very strong. The average reservoir pressure was boosted from 2000 psi at the start of the flood to almost 5000 psi by 1984. Oil production increased from a low of 2500 BOPD to over 6500 BOPD in 1980 (Fig. 8). Water injection in Unit A continued until July 1993.

In 1982, the northwestern portion of the field was unitized to commence water injection in the rest of the Yowlumne field. Yowlumne Unit B occupied a much larger portion of the field than Unit A. The Unit B waterflood design attempted to account for geological differences in the southwestern and northeastern regions of the unit. In the southwestern region, the reservoir was thought to be composed of channel-type desposits, much like Unit A. Consequently, a similar line drive pattern was employed, as shown in Figure 9. In the northeastern region, the reservoir was described as being made up of fan-type deposits. In this region a peripheral flood pattern was used. It resulted in a series of irregular five spot patterns around a large central area (Fig. 10). The central pattern occupied the thickest portion of the reservoir.

A review of production data shows the Unit B waterflood to be very successful. Reservoir pressure was increased from 1600 psi to over 5200 psi. The total unit oil rate was improved from a low of 4000 BOPD to a peak of 20,000 BOPD (Fig. 11). The ultimate recovery efficiency is estimated to be 47.4% of OOIP, resulting in an incremental recovery efficiency due to waterflooding of 29.8%.

Yowlumne Field Well Statistics

The following table provides well count statistics for the Yowlumne field:

Well Status	Well Count
Wells drilled in field	157
Wells penetrating Yowlumne sand	155
Total completions to date in field	135
Total current completions	122*
Total current producers	48*
Total inactive producers	35
Total current injection wells	27
Total inactive injection wells	12
Flowing wells	None

* Includes one Etchegoin sand well.

Miscellaneous Project Information

DOE Project Team

The DOE project team members are ARCO Western Energy (Operator and Project Manager), California Department of Oil, Gas, and Geothermal Resources, Dowell Schlumberger, University of California Santa Barbara, and Specialist Contractors (Microseismic Logging).

Working Interest Ownership

The Working Interest Ownership of Yowlumne Unit B (greater than 10%) are as follows:

1. ARCO Western Energy, 68.9%
2. Texaco Exploration and Production Inc., 15.9%
3. Cal Resources LLC, 14.3%

Technical Contacts

The technical contacts at ARCO regarding this project are:

1. Mr. Mike L. Laue, Principal Investigator, (805) 632-6601
2. Mr. Rick K. Prather, Senior Operations/Analytical Engineer, (805) 321-4104
3. Dr. Michael S. Clark, Senior Geologist, (805) 632-6254

Three Dimensional Description Of Reservoir (Model Area)

Areal And Vertical Description

Areal Extent

Figure 2 shows the reservoir model grid that defines the project area. The grid encompasses approximately 695 acres.

Structure

The Yowlumne sand dips in a northerly direction at 20-23° (Fig. 12). A number of faults have been identified from seismic data and are shown on Fig. 12. Evidence of other minor faults also exists.

Reservoir Layers

Layering in the reservoir model was set up to explicitly represent each hydraulic unit defined in the fan margin characterization. This resulted in ten layers whose stratigraphic sequence is shown on Figure 13.

The W sand is a wet non-pay interval. It was included in the model to examine possible rate impacts of downward hydraulic fracture growth. The reservoir layers are continuous from well to well. They act as flow conduits and have reached varying pressures based upon injection into each layer. Cross flow between layers has not been quantified, but is considered insignificant.

Reservoir Parameters

Average porosity and permeability for the project area are 15.2% and 25 md, respectively. Figures 14 and 15 are cumulative capacity plots of core porosity and permeability (to air). These values are uncorrected for overburden. Figure 16 is a cross plot of core permeability vs. porosity. Vertical profiles of porosity and permeability are shown in Figures 17 and 18. These values are averages for each model layer.

Rock properties in the project area deteriorate towards the eastern edge of the field. These are illustrated by contour maps of porosity, permeability, gross thickness, and net-to-gross ratio (Figs. 19 - 22).

At initial conditions the reservoir was undersaturated and no gas saturations were present. The original oil saturations by layer and grid block are shown in Figures 23 - 32. Figures 33 - 42 depict current oil saturation by layer and grid block from reservoir modeling.

Geologic Characteristics

Lithology

The Yowlumne sandstone is a clay-bearing arkosic wacke that contains quartz, potassium feldspar, and plagioclase with subordinate plutonic and metamorphic rock fragments. Most of the plagioclase is albitized and was altered in the source area before transport (Clark et al., 1997). The mineralogy indicates derivation from uplifted plutonic and metamorphic terranes in the nearby Tehachapi and San Emidio Mountains (Whelan, 1984; Tieh et al., 1986). The geologic age of the Yowlumne field is upper Miocene (Delmontian benthic foraminiferal stage).

Facies Analysis For Each Reservoir

a. Description Of Depositional Facies

The Yowlumne sand is composed of turbidites organized into three lithologic facies on the basis of the Mutti and Ricci-Lucchi (1972) facies model. Depositional lobes have progradational geometries characterized by proximal turbidites that are laterally continuous. Channel facies have aggradational geometries characterized by proximal and distal turbidites that are laterally discontinuous. Levee facies contain a significant proportion of distal turbidites deposited by overbank processes. Thus, the frequency of sand and shale interbedding increases, and sand/shale ratios decrease, from lobe to channel to levee facies (ARCO, 1996).

b. Distribution Of Facies Across Project Area

The Yowlumne sand is a fan-shaped reservoir body with a north-south axis of thickening and a south-to-north direction of progradation. The west margin and axis are dominantly lobe and channel facies, whereas the east margin is levee deposits. Thus, the west margin and axis are dominantly clean sands, whereas the east margin contains interbedded sands and shales. The abundance of shale interbeds, and the clay content of the sands increase from the fan axis eastward towards the fan margin (ARCO, 1996; Clark et al., 1997).

c. Distribution Of Porosity, Permeability, Oil Saturation, And Net Pay By Facies

Because the abundance of shale interbeds (net/gross sand = 80% to 65%) and the clay content of the sands (<6% to >12%) increases from the reservoir axis eastward towards the margin, net pay thickness decreases (445 ft to 0 ft) and reservoir quality, measured as porosity (16% to 12%) and liquid permeability (25 to <1 md), decreases towards the zero edge of the sand. The eastward decrease in porosity is associated with a corresponding eastward decrease in oil saturation (>60% to <40%). A cross plot of core porosity vs. air permeability is provided in Figure 16.

d. Wireline Log Response To Depositional Facies

Sands in Yowlumne field are non-radioactive and permeable, whereas the shales are organic-rich with high radioactivity and low permeability. Because lobe and channel facies are dominantly sands, these result in clean gamma ray and SP response with the amount of deflection from a shale baseline proportional to the clay content of the sands. By contrast, levee facies contain interbedded sands and shales that result in erratic gamma ray and SP response.

e. Horizontal Continuity And Vertical Communication Of Facies

The Yowlumne sand produces from seven lobe-shaped reservoir compartments. Lateral progradation of these to the west during deposition resulted in left-stepping geometries. Thus, compartments on the left (west) side of the reservoir are younger than those on the right. Also, compartments located at the base of the reservoir, such as sand E, are thickest on the east side, whereas compartments located at the top, such as sand A, are thickest on the west (Fig. 43). Contemporaneous basinward progradation to the north resulted in basinward-stepping geometries. Thus, compartments in Unit B are younger than those in unit A (Fig. 44).

Most likely, these compartments represent separate permeability pathways that are in pressure communication over geologic time, yet develop weak compartmentalization over the life of the field. Thus, compartments equilibrate with adjacent compartments over thousands of years to develop the same oil-water contact. Yet, permeability variations cause these same compartments to flow oil at different rates and acquire slightly different pressures as the field is rapidly produced over tens of years (Clark et al., 1997).

Description Of Geological Elements

a. Depositional Environment

The Yowlumne sand is one of several discontinuous sands, of local extent, that collectively make up the Stevens, a clastic facies of the Miocene Monterey Shale. Stevens deposition (Fig. 45) in the southernmost San Joaquin basin coincided with north-directed thrusting in the Tehachapi and San Emidio Mountains—a tectonic event associated with northward migration of a triple junction along a Miocene subduction zone that preceded the modern San Andreas Fault (Graham and Williams, 1985). Individual sand bodies within the Stevens, such as the Yowlumne sand, represent the sedimentation response to eustatic drops of sea level integrated with source area uplift and basin subsidence events.

The confined submarine fan model of Scott and Tillman (1981) is applicable to the Yowlumne sand. Cores taken from within the sand indicate that it is composed dominantly of turbidites. The sand in map view is fan shaped, and lens shaped in cross-section without significant incision into the underlying strata (Fig. 43). An apparent fault-bounded paleotopographic high existed on the west side during deposition (Fig. 12), whereas Coriolis forces resulted in the preferential buildup of levees on the east—thereby forcing northward-prograding lobe and channel deposition to the west with subsequent confinement of lobe and channel sands between the bounding paleohigh and levee buildups. Consequently, lobe and channel facies, composed dominantly of clean sands, make up the west margin and axis of the fan, whereas levees, composed of interbedded sands and shales, make up the east margin.

b. Reservoir Diagenesis

Porosity in the Yowlumne sandstone is primarily intergranular and results from compaction of an original depositional porosity that is reduced by minor carbonate and quartz cementation, and slightly enhanced by plagioclase dissolution. Clays lining pores are dominantly authigenic kaolinite derived from feldspar diagenesis. Some mixed-layer smectite/illite clays, probably detrital in origin, are also present between grains (Clark et al., 1997).

c. Structural Style

The productive area of the Yowlumne sand represents two oil accumulations with different trapping mechanisms. Unit A is a structurally controlled accumulation that produces from a small anticline with about 50 feet of four-way dip closure and approximately 600 acres under the area of closure (Fig. 12). Onlap of basal Pliocene sands onto this structure indicates a late Miocene to early Pliocene age of formation. Unit B is a stratigraphically controlled accumulation that produces from the north dipping flank of the anticline, and contains an oil-water contact that sits two-thousand feet structurally lower than the contact in Unit A.

Because Units A and B represent different depositional bodies, in which Unit B is younger than Unit A (Clark et al., 1997), the nature of the barrier separating these units is presumed to be depositional—possibly a shale bed. Most likely, the oil in Unit B represents a kinetic accumulation in which a permeability bottleneck, corresponding to the proposed shale barrier, results in migration of oil into Unit B faster than the oil is able to leak updip out of B into Unit A.

Evaluation Of Reservoir Heterogeneity

a. Microscopic Heterogeneity; Pore Throat Size Distribution

Core-derived capillary pressures indicate that the Yowlumne sand is moderately to poorly sorted with pore throat diameters of 4 to 10 μ . Although core-derived porosity and permeability vary widely within the data set, the pore geometries are similar. Hydraulic units were used to group similar pore geometries. A hydraulic unit represents a unique pore geometry that plots on a log-log plot of RQI (reservoir quality index) vs. PR (porosity ratio) as a straight line with unit slope. In general, higher hydraulic unit numbers represent pore geometries characterized by coarser grain size and lower clay content. Details regarding hydraulic units can be found in ARCO Western Energy's project evaluation report and continuation application (1996). About 43% of the study area samples have geometries represented by type-12 hydraulic units, and 83% are within the type-11 to type-13 range (Fig. 46).

b. Macroscopic Heterogeneity; Features At Interwell Scale

Macroscopic heterogeneity is controlled by the relative thicknesses of sands A through W in a given well. These thicknesses, in turn, result from left-stepping geometries such that compartments at the top of the reservoir (i.e., sand A) are thickest on the west side of the field, whereas those located near the bottom (i.e., sand E) are thickest on the east. In general, sand A tends to be tighter than other sands. Therefore, current oil saturations in sand A are higher,

but only because the oil is more difficult to produce. Because sands B through D are permeable, they have lower oil saturations due to more efficient flushing by the waterflood. By contrast, sand E is permeable but relatively unswept. Therefore higher oil saturations in sand E equate to higher volumes of remaining recoverable oil. The W sand is wet.

c. Megascopic Heterogeneity; Features At Field/Reservoir Scale

Heterogeneity at the field/reservoir scale is a function of basinward-stepping geometries that result in the apparent pressure separation of Units A and B. This when combined with the structural configuration results in Unit A being an anticlinal accumulation, whereas Unit B is a stratigraphically-controlled kinetic accumulation with deeper production depths and a structurally lower oil-water contact.

Fluid Characteristics

The initial reservoir pressure for the Yowlumne field was 5,660 psia at -10,500 ft subsea datum. Reservoir pressure in the project area was depleted below 2000 psia during primary production. Waterflood operations raised reservoir pressure above initial pressure. Figure 47 shows reservoir pressure vs. time.

There is some degree of variation in fluid properties measured initially and over time. Reservoir temperatures range from 240° to 280° F. The bubble point pressure varies from 2,480 to 3,000 psia and the initial solution GOR from 500 to 800 SCF/STB (R_s). Oil viscosity ranges from 0.5 to 0.6 cp at reservoir conditions (240° F and 5,000 psig) and from 1.5 to 2.0 cp at standard condition (60°F and 14.7 psia). The oil gravity varies from 29° to 34° API with corresponding initial oil formation volume factors (B_o) of 1.32 to 1.46 RB/STB.

The fluid composition of well YUB 32-3 given on Figure 48 is representative of Yowlumne field. The gas gravity is 0.862 and the initial gas formation volume factor (B_g) is 0.533 RVB/MCF. Table 1 shows B_o , B_g , and R_s as a function of reservoir pressure. The water density is 1.025 ppg with a viscosity of 0.25 cp at reservoir condition (250°F and 5000 psi). A water analysis of the Yowlumne field is shown on Fig. 49. The water salinity was determined to be 8600 mg/l.

Field Development History

Yowlumne Field

Field Recovery Techniques

The Yowlumne field produced by primary recovery from 1974 through 1979 when full-scale waterflood began in Unit A. The waterflood project is considered advanced secondary because of a horizontal producer drilled in 1990. The project is expected to end in 2008 with an incremental secondary recovery of 29.8% of OOIP.

Figure 6 shows historical production and injection and active well count for the field. Monthly production and injection by well is public information and may be obtained from

various sources such as ARCO Western Energy, California Division of Oil, Gas, and Geothermal Resources, and Petroleum Information Corporation.

Project Area

Field Stimulation History

Tables 2-4 provide detailed information regarding existing wells in the project area (Fig. 2). These wells were vertically drilled, cased and perforated. Typically, producing wells at Yowlumne were not stimulated by acidizing or hydraulic fracturing. On occasion, wells were reperforated to remove skin caused by the formation of scales on perforations at breakthrough.

Two wells in the project area were hydraulically fractured upon completion: Yowlumne Unit B 56X-34 was frac'd with 304,000 lbs. proppant and Yowlumne Unit B 57X-34 was frac'd with 48,300 lbs. proppant.

Field Production Constraints And Design Logic

Qualitative Review

Development History

The Yowlumne field, located in Kern County, California, was discovered in January 1974 by Texaco Exploration and Production, Inc. The discovery well was the San Emidio no. 1, located in the southeastern corner of the field.

The field produced by primary recovery until 1976, when a small amount of water was injected into two wells to partially offset declining production rates and pressure. In 1978, Yowlumne Unit A was formed in the southeastern part of the field. Unitizing a portion of the field permitted early implementation of waterflooding while the rest of the field (later known as Unit B) was being developed and delineated.

Response from water injection in Unit A was very strong. Water injection in Unit A continued until July 1993. In 1982, the northwestern portion of the field was unitized as Unit B to commence water injection in the rest of the Yowlumne field. Although Unit B continues to be an active waterflood project, it has reached the mature stage. For additional information, please refer to the section on "General Information."

Reservoir Description

The Yowlumne sand is interpreted as a layered, fan-shaped, prograding turbidite complex containing several lobe-shaped sand bodies that represent distinct flow units. These flow units are labeled A, B, C, D, and E in order of increasing geologic age. The flow units are in limited pressure communication and act as separate permeability conduits that respond uniquely to waterflood. Sand W is an unproductive flow unit found at the base of the Yowlumne sand.

Reservoir quality of the Yowlumne sand significantly deteriorates near the distal fan margin in the northeast region of the field. Clay content increases as does the frequency and length of interbedded shales. For further details, please refer to the section on “3-D Description of Reservoir, Geologic Characteristics.”

Constraints On Further Producibility

The Yowlumne field has been the subject of several detailed reservoir engineering and characterization studies aimed at developing a long-term reservoir management plan. Model results show that although the waterflood at Yowlumne has been very efficient, several large oil accumulations will remain at field abandonment. Much of the remaining oil is banked and trapped in the more heterogeneous and thinner reservoir sections at the distal fan margins of the field (Fig. 50 and Fig. 51). Past work indicates this oil is not economically recoverable using conventional vertical wells.

Proposed Solution For Reduction Of Constraints

Development Plan

The objective of this project is to couple several advanced technologies to economically develop potential reserves of by-passed oil trapped within thinning and deteriorating fan margin portions of Slope-Basin Clastic reservoirs. A high angle well will be drilled to obliquely penetrate the reservoir in an east-west direction. This will increase vertical communication between layers and provide increased formation penetration (Fig. 52 and Fig. 53). Multiple hydraulic fracture treatments will be used to provide connectivity between layers and to provide sufficient rate capability. Detailed geological modeling, reservoir characterization and fine grid reservoir simulation were used to select the most economic location and orientation for the well. The reservoir description and fine-grid simulation will be validated using actual production rates and reservoir properties from the slant well, in a postmortem analysis.

Projected Incremental Production

Decision tree analysis was applied to production and costs in the economic evaluation to account for the numerous outcomes that are possible (Fig. 54). For example, there is mechanical risk in successfully drilling the well and pumping multiple fracs. There is also geologic and reservoir risk with rock quality and saturations. Finally, successfully pumping each frac does not guarantee desired frac height, length, width, conductivity, and azimuth.

The production streams for each scenario consisting of a slant well with no fracs up to a slant well with three fracs were input into the economic evaluation (Fig. 55). Each stream was factored based upon decision tree analysis. The expected-value incremental production stream (Fig. 56) represents a starting rate of 967 BOPD and reserves of 407 MBO. Expected-value reserves are 55% of the three-frac success case reserves.

Method Of Problem Detection

Application Of New Tools Or Techniques

In order to obtain fracture orientation, rock mechanics, and standard lithology-resistivity-porosity measurements, a suite of logs such as the Formation Micro Imager (FMI) and Dipole Sonic Imager (DSI) will be run. Three thirty foot cores will be taken to obtain data for vertical, liquid and continuous permeability, capillary pressure, maximum principal stress, and shear and compressional wave.

Evaluation Of Cost-Share Project Results

Final results of the cost-share project will not be available until the end of Budget Period Two (BP2). Partial results will be reported throughout the five year duration of BP2.

Supporting Data

All logs, maps, seismic interpretations and other related tests were not included in this report. Much of the data are public information and are available at ARCO Western Energy, California Division of Oil, Gas, and Geothermal Resources, and Petroleum Information. Other pertinent project data that are not in the public domain will be maintained by ARCO and can be made available for review upon request.

Environmental Information

Surface Conditions

The Yowlumne field is on the valley floor at the southern end of the San Joaquin Valley, some 500 ft. above sea level. There is no navigable surface water within a five mile radius. The project area is located in a non-attainment area for ozone.

Produced Water

Surface casings throughout the project area are set at approximately 2500 ft. to protect groundwater with less than 10,000 PPM TDS (Total Dissolved Solids). The volume of water produced per day in the project area is about 13,000 BBLS. Oil and solids are removed from the water using Wemco flotation cells. The effluent water is then re-injected into the reservoir at the edge of the field in five designated wells. A copy of a produced water analysis is included as Figure 49.

Drilling Mud

A water-based gel mud will be used in drilling the project well. The volume of mud required is estimated at 2250 BBLS. The mud will be handled in an open system and will use an unlined pit.

Well Integrity Tests

All casings in the Yowlumne field are tested once every five years or whenever a packer is reset, whichever is lesser. The casings are tested to 500 psi. Currently all injection wells have passed their mechanical integrity tests and are in functioning condition.

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Fig. 1: Map of Yowlumne field showing test well, monitor well, and the proposed well.

Fig. 2: Areal location of project and partial field model grid.

Fig. 3: Map of California showing location of the San Joaquin Valley and the Yowlumne field in relation to other oil-producing basins in the state.

Fig. 4: Map of the southern San Joaquin basin showing the location of the Yowlumne field and other fields in relation to Bakersfield.

Fig. 5: Location of discovery well.

Fig. 7: Initial Unit A injection pattern.

Fig. 9: Initial southwestern injection pattern at Unit B.

Fig. 10: Initial northeastern injection pattern at Unit B.

Fig. 12: Structure map of Yowlumne field drawn on the N-point marker, a regional correlation horizon that marks the approximate top of the Stevens sandstone. The map shows the relationship of Units A and B to the small anticlinal closure at Yowlumne.

YUB 27X-34

Fig. 13: Type log of well 27X-34 showing subdivision of six major stratigraphic intervals into ten model layers.

Fig. 14: Cumulative capacity plot of core porosity (840 samples)

Fig. 15: Cumulative capacity plot of core permeability in air (840 samples)

Fig. 16: Core porosity versus air permeability (840 samples).

Fig. 17: Porosity profile of Yowlumne sand in project area.

Fig. 18: Permeability profile of Yowlumne sand in project area.

Fig. 19: Map of effective porosity of net sand.

Fig. 20: Map of liquid permeability of net sand.

Fig. 21: Map of gross sand thickness.

Fig. 22: Map of net/gross sand ratio.

Fig. 23: Layer 1, Sand A - oil saturation map at initial conditions.

Fig. 24: Layer 2, Sand B1 - oil saturation map at initial conditions.

Fig. 25: Layer 3, Sand B2 - oil saturation map at initial conditions.

Fig. 26: Layer 4, Sand C1 - oil saturation map at initial conditions.

Fig. 27: Layer 5, Sand C2 - oil saturation map at initial conditions.

Fig. 28: Layer 6, Sand D1 - oil saturation map at initial conditions.

Fig. 29: Layer 7, Sand D2 - oil saturation map at initial conditions.

Fig. 30: Layer 8, Sand E1 - oil saturation map at initial conditions.

Fig. 31: Layer 9, Sand E2 - oil saturation map at initial conditions.

Fig. 32: Layer 10, Sand W - oil saturation map at initial conditions.

Fig. 33: Layer 1, Sand A - oil saturation map at initiation of project.

Fig. 34: Layer 2, Sand B1 - oil saturation map at initiation of project.

Fig. 35: Layer 3, Sand B2 - oil saturation map at initiation of project.

Fig. 36: Layer 4, Sand C1 - oil saturation map at initiation of project.

Fig. 37: Layer 5, Sand C2 - oil saturation map at initiation of project.

Fig. 38: Layer 6, Sand D1 - oil saturation map at initiation of project.

Fig. 39: Layer 7, Sand D2 - oil saturation map at initiation of project.

Fig. 40: Layer 8, Sand E1 - oil saturation map at initiation of project.

Fig. 41: Layer 9, Sand E2 - oil saturation map at initiation of project.

Fig. 42: Layer 10, Sand W - oil saturation map at initiation of project.

Fig. 43: Seismic line and cross-section A-A' showing the lens shape of the Yowlumne fan. The line and section cut from west to east across the main body of the fan, perpendicular to the direction of sediment transport.

Fig. 44: Map showing left-stepping and basinward-stepping geometries exhibited by depositional lobes that compose the Yowlumne fan.

Reservoir Statistics

Discovery Date	1974
Reservoir Depth	3,410-4,050 m (11,200-13,300 ft)
Ave. Thickness (gross)	69 m (225 ft)
Max. Thickness (gross)	150 m (493 ft)
Area	1,243 ha (3,070 acres)
Producing Wells	48 active & 40 SI
Water Injection Wells	30 active & 9 SI
Cumulative Production (all zones thru 1995)	16.38 x 10 ⁶ m ³ of oil (103 MMBO) 2.60 x 10 ⁹ m ³ of gas (92 BCF)

Rock Properties

	<u>fan axis</u>	<u>east margin</u>
Effective Porosity	16%	12%
Air Permeability	50-100 md	5-10 md
Liquid Permeability	10-20 md	2 md
Net/Gross Sandstone	80%	65%
Clay Volume (Vsh)	<6%	>12%

Fluid Properties

 relative magnitude
 of oil production

Oil Gravity	882-855 kg/m ³ (29-34° API)
Fm Water Density	1019 kg/m ³ (22,000 ppm)
Oil Viscosity	.52 cps @ reservoir temperature
Drive Mechanism	fluid expansion and solution gas
Res. Temperature	113-132°C (235-270°F)
Original Res. Pressure	39.02 MPa (5,660 psi)
G.O.R.	107 m ³ /m ³ (600 cf/bbl)
Rw @ 25°C	.41 ohm-m

Fig. 45: Type log for Yowlumne field showing producing reservoirs, and the rock and fluid properties of the main reservoir (the Yowlumne sandstone).

Fig. 46: Histogram showing frequency of hydraulic units in the Yowlumne sandstone.

Fig. 47: Yowlumne pressure history for the project area.

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS

Company <u>Tenneco Oil Company</u>	File <u>RFL 78899</u>
Well <u>32-3</u>	Date Sampled <u>12-11-78</u>
Field <u>Yowlumne</u>	County <u>Kern</u>
	State <u>California</u>

Hydrocarbon Analyses of Separator Products and Calculated Well Stream

<u>Component</u>	<u>Separator Liquid</u> <u>Mol %</u>	<u>Separator Gas</u> <u>Mol %</u>	<u>Separator Gas</u> <u>GPM</u>	<u>Well Stream</u> <u>Mol %</u>
Hydrogen Sulfide	Nil	Nil		Nil
Carbon Dioxide	Nil	2.24		1.00
Nitrogen	0.04	0.37		0.19
Methane	2.38	69.02		32.10
Ethane	1.67	10.21	2.730	5.48
Propane	4.83	10.29	2.831	7.26
iso-Butane	1.47	1.57	0.513	1.51
n-Butane	4.96	3.63	1.144	4.37
iso-Pentane	2.40	0.85	0.311	1.71
n-Pentane	2.54	0.72	0.261	1.73
Hexanes	4.70	0.46	0.188	2.81
Heptanes plus	<u>75.01</u>	<u>0.64</u>	<u>0.291</u>	<u>41.84</u>
Totals	<u>100.00</u>	<u>100.00</u>	<u>8.269</u>	<u>100.00</u>

Properties of Heptanes plus

API gravity @ 60°F	<u>27.5</u>		
Specific gravity @ 60/60° F	<u>0.89</u>		<u>0.889</u>
Molecular weight	<u>239</u>	<u>103</u>	<u>238</u>

Calculated separator gas gravity (air = 1.000) = 0.862

Calculated gross heating value for separator gas = 1430 BTU
per cubic foot of dry gas @ 14.73 psia and 60°F.

Primary separator gas collected @ 130 psig and 118 °F.

Primary separator liquid collected @ 130 psig and 121 °F.

Primary separator gas/separator liquid ratio	<u>471</u> SCF/Bbl @ 60°F
Primary separator liquid stock tank liquid ratio	<u>1.031</u> Bbls @ 60°F/Bbl

Fig. 48: Yowlumne fluid composition.

ZALCO LABORATORIES, INC.

Analytical & Consulting Services

Mr. Jim Etherton, Laboratory Director

4309 Armour Avenue

Bakersfield, CA 93308

Tel.No: (805) 395-0539; Fax No: (805) 395-3069

Arco Western Energy
P.O. Box 147
Bakersfield, CA 93302
Attention: Rick Prather

Laboratory No: 42188
Date Received: 12-9-94
Date Reported: 12-15-94

Sample Identification: Injector Feed Pump To Field
Sampled on 12-9-94

GEOCHEMICAL ANALYSIS

pH	8.0
Specific Gravity @ 60°F	1.007
Electrical Conductivity (millimhos/cm @ 25°C)	15.01
Resistivity (ohm meters @ 25°C)	0.67

<u>Constituents</u>	<u>mg/l</u>	<u>meq/l</u>	<u>Reacting %</u>
Calcium, Ca	60	2.99	0.95
Magnesium, Mg	8.6	0.71	0.23
Sodium, Na (calculated)	3500	151.53	48.26
Potassium, K	69	1.76	0.56
Iron, Fe (dissolved)	0.24	0.01	0
Alkalinity as:			
Hydroxide, OH	0	0	0
Carbonate, CO ₃	0	0	0
Bicarbonate, HCO ₃	1400	23.54	7.5
Chloride, Cl	4600	129.67	41.3
Sulfate, SO ₄	140	2.98	0.95
Sulfide, S	13	0.81	0.26
Totals (Sum)	9100	314	100
Boron, B	33		
Total Dissolved Solids, (Grav)	9900		
Calculated hardness, CaCO ₃	190		
Total Alkalinity, CaCO ₃	1200	Primary Salinity	84.5
Sodium Chloride, (total)	8600	Secondary Salinity	0
		Total Salinity	84.5
Cation/Anion Balance, %	0.1		
Sodium, Na (determined), mg/l	3500	Primary Alkalinity	13.14
Langelier Scale Index	1.50	Secondary Alkalinity	2.36
Stiff/Davis Stability Index	0.90	Total Alkalinity	15.5

Fig. 49: Water analysis for the Yowlumne field.

Conventional Technology

Advanced Technology

Fig. 50: Producibility problem. (Note: Recoveries assume waterflooding or natural water drive).

Note: The overall fan is made up of multiple fan cycles. Each cycle truncated and erodes the preceeding and fines upward and laterally. The fan margin is composed of the depositional edge of individual lobes and interbeds of basinal shales.

Fig. 51: Distal fan-margin sequence with exaggerated vertical scale cross-section.

The slant well allows penetration and logging of all layers.
Hydraulic fractures connect layers to the wellbore.

Fig. 52: Slant well with multiple hydraulic fractures.

FRAC'D SLANT WELL DRAINAGE PATTERN

VERTICAL WELL DRAINAGE PATTERN

Fig. 53: The frac'd slant well achieves better rates and recovers more reserves than three vertical wells, for less total cost.

Fig. 54: Decision tree used with economic analysis.

Fig. 55: Sensitivity of incremental production rates to the number of fracs for East-West slant well.

Fig. 56: Incremental production rate and recovery for East-West slant well (expected values).

TABLE 1

Model Fluid Property Tables

PRESSURE (psi)	BO (RVB/STB)	BG (RVB/MCF)	RS (MCF/STB)	μ_o (cp)	μ_g (cp)
15	1.0825	219.246	0.005	1.356	0.011
315	1.1373	10.395	0.06004	1.088	0.01246
615	1.1834	5.301	0.13749	0.893	0.01365
915	1.2234	3.548	0.21494	0.758	0.01465
1215	1.2595	2.66	0.29238	0.67	0.01553
1515	1.2942	2.124	0.36983	0.615	0.0164
1815	1.3298	1.765	0.44728	0.58	0.01734
2115	1.3687	1.508	0.52473	0.551	0.01843
2415	1.4132	1.315	0.60218	0.515	0.01976
2715	1.4583	1.164	0.67962	0.485	0.02141
3015	1.5032	1.044	0.75707	0.455	0.02348
3315	1.5483	0.945	0.83452	0.425	0.02604
3615	1.5933	0.863	0.91197	0.395	0.02919
3915	1.6383	0.793	0.98942	0.365	0.03301
4215	1.68	0.733	1.06687	0.335	0.03758
4515	1.7178	0.681	1.14431	0.305	0.043
4815	1.752	0.636	1.22176	0.275	0.04934
5115	1.7832	0.596	1.29921	0.245	0.05671
5415	1.8116	0.56	1.37666	0.215	0.06517
5715	1.8375	0.528	1.45411	0.185	0.07482
6015	1.8612	0.5	1.53155	0.155	0.08575
7015	1.9201	0.422	1.78971	0.105	0.13248
8015	1.9639	0.363	2.04787	0.085	0.19753

TABLE 2

Project Area Cored Wells

Well Name	Core Interval, MD, ft.
YUB 14X-3RD	11871-11905, 12055-12080
YUB 22X-3	11814-11842, 11862-11878, 11892-11908, 11922-11954, 11976-12044, 12066-12096, 12112-12136
YUB 45X-3	11726-11892
YUA 65X-3	11798-11890
YUB 27X-34	12254-12352
YUB 27X-34ST	12346-12383
YUB 46X-34	12660-12674, 12712-12742
YUB 55X-34	12908-13142

* Redrill (RD), Side-Track.

TABLE 3

Perforated Intervals

Well Name	Perforations (MD, ft)
YUB 11X-3	11876-11887, 11918-12076, 12088-12220, 12262-12282
YUB 14X-3	11578-11610, 11620-11714, 11724-11797, 11872-11902
YUB 14X-3RD	11840, 11845, 11851, 11857, 11860, 11868-11884, 11895-11908, 11913, 11921, 11925, 11930-11984, 11989, 12003-12038, 12042, 12047, 12052-12099
YUB 21X-3	11941-11975, 11990-12039, 12054-12138, 12153-12208, 12223-12312
YUB 22X-3	11834-11860, 11870-11932, 11944-11982, 12010-12070, 12080-12160
YUB 23X-3	11788-11854, 11858-11936, 11448-11926, 11980-12040
YUB 25X-3	311576-11683, 11697-11778
YUB 32-3RD	11784-11856, 11870-12006, 12018-12042, 12062-12075, 12103-12118, 12142-12157
YUB 41X-3	12062-12402
YUB 42X-3	11836-11930, 11945-12090
YUB 44X-3	11742-11804, 11819-11871, 11887-11982, 11997-12040
YUB 45X-3	11658-11733, 11748-11797, 11812-11853
YUA 54X-3	11739-11838, 11850-11849, 11910-11970
YUB 61X-3	12086-12152, 12180-12254, 12266-12300, 12310-12354, 12357-12388
YUA 64X-3	No casing in original hole
YUA 64X-3ST	11780-11820, 11840-11900, 11928-11950
YUA 65X-3	11766-11812, 11831-11902
YUB 73X-3	11910-11944, 11984-12016, 12038-12058, 12070-12106, 12132-12162
YUA 81X-3	Dry Hole
YUB 84-32	13061-13108, 13112-13136, 13152-13258
YUB 86-32	12370-12585
YUB 88X-33	11971-11976, 11985-11990, 12138-12166, 12310-12228, 12219-12179, 12130-12072
YUB 16X-34	12540-12603, 12620-12715, 12735-12838
YUB 25X-34	12742-12776, 12788-12844, 12854-12901, 12912-13001
YUB 27X-34	12235-12262, 12276-12304, 12318-12386, 12400-12450, 12468-12510, 12524-12548
YUB 36X-34	12480-12510, 12554-12730, 12746-12874
YUB 38X-34	12028-12090, 12107-12202, 12217-12302, 12317-12334
YUB 38X-4RD	12508-12583
YUB 45X-34	12792-12876, 12892-12972, 12994-13085
YUB 46X-34	12620-12674, 12709-12719, 12722-12724, 12738-12852, 12865-12922
YUB 47X-34	12320-12330, 12390-12450, 12470-12530, 12550-12670, 12690-12750
YUB 55X-34	12831-12840, 12876-12888, 12910-12950, 12972-13050, 13068-13120
YUB 56X-34	12686-12693, 12714-12718, 12726-12740, 12756-12768, 12774-12783, 12803-12833, 12839-12851, 12861-12882
YUB 57X-34	12439-12448, 12452-12492, 12511-12516, 12588-12645, 12655-12768, 12773-12778
YUB 66X-34	12785-13011 (perforations cemented)
YUB 67X-34	12492-12545, 12632-12772

* Redrill (RD), Side-track (ST).

TABLE 4

Historical Well Count for Project Area

Well ID	Well Name	Well Type	Lift Type	top of A sand		top of W sand		Total Depth	
				MD,ft	TVD,ft	MD,ft	TVD,ft	MD,ft	TVD,ft
0402967022	YUB 11X-3	P	HL	11,902	11,798	12,220	12,102	12,595	12,595
0402956194	YUB 14X-3	I		11,551	11,547	11,796	11,792	12,100	12,095
0402956194	YUB 14X-3RD	I		11,809	11,678	12,104	11,963	12,345	12,199
0402958026	YUB 21X-3	P	HL	11,930	11,923	12,315	12,306	12,497	12,497
0402974730	YUB 22X-3	P	HL	11,817	11,811	12,161	12,154	12,350	12,350
0402967101	YUB 23X-3	P	HL	11,764	11,753	12,046	12,034	12,192	12,192
0402967324	YUB 25X-3	I		11,555	11,542	11,779	11,765	11,948	11,948
0402957853	YUB 32-3RD	I		11,770	11,765	12,185	12,179	12,375	12,368
0402968190	YUB 41X-3	P	HL	12,041	11,994	12,435	12,384	12,577	12,525
0402967763	YUB 42X-3	I		11,820	11,810	12,163	12,152	12,336	12,336
0402957684	YUB 44X-3	P	HL	11,725	11,723	12,038	12,034	12,250	12,250
0402969707	YUB 45X-3	I		11,640	11,629	11,875	11,862	12,058	12,058
0402958123	YUA 54X-3	P	HL	11,738	11,736	12,085	12,083	12,300	12,300
0402958313	YUB 61X-3	P	SL	12,150	12,131	12,405	12,383	12,520	12,498
0402955422	YUA 64X-3	P	HL	11,733	11,729	11,893	11,889	12,150	12,150
0402955422	YUA 64X-3RD	P	HL	11,756	11,547	11,897	11,674	12,139	12,139
0402969754	YUA 65X-3	SIP		11,753	11,741	11,908	11,896	12,020	12,020
0402959569	YUB 73X-3	SII		11,897	11,892	12,188	12,183	12,365	12,358
0402960620	YUA 81X-3	DH		12,294	12,294	12,361	12,361	12,619	12,611
0402959180	YUB 84-32	P	RL	13,067	12,726	13,284	13,229	14,680	14,441
0402958025	YUB 86-32	I		12,373	12,353	12,605	12,578	12,742	12,711
0402984870	YUB 88X-33	P	SL	11,970	11,956	12,314	12,295	12,540	12,540
0402968382	YUB 16X-34	I		12,539	12,520	12,996	12,963	13,131	13,131
0402959402	YUB 25X-34	P	HL	12,739	12,732	13,171	13,163	13,288	13,288
0402958943	YUB 27X-34	SIP		12,223	12,200	12,709	12,685	12,298	12,298
0402968189	YUB 36X-34	I		12,542	12,518	12,972	12,937	13,019	12,983
0402975044	YUB 38X-34	P	HL	12,000	11,986	12,496	12,475	12,652	12,652
0402975044	YUB 38X-34RD	P	HL	12,130	12,080	12,624	12,548	12,648	12,590
0402959271	YUB 45X-34	P	HL	12,778	12,766	13,161	13,148	13,340	13,340
0402976808	YUB 46X-34	P	HL	12,595	12,584	12,980	12,967	13,097	13,097
0402958784	YUB 47X-34	P	HL	12,370	12,356	12,807	12,791	12,948	12,948
0402959786	YUB 55X-34	I		12,862	12,851	13,158	13,146	13,000	13,288
0402981902	YUB 56X-34	I		12,633	12,615	12,944	12,924	13,150	13,127
0402984871	YUB 57X-34	P	SL	12,409	12,390	12,788	12,769	12,919	12,901
0402985373	YUB 66X-34	SIP		12,745	12,701	13,019	12,973	13,100	13,054
0402959090	YUB 67X-34	P	HL	12,477	12,463	12,774	12,758	13,816	13,785

* Dry-Hole (DH), Hydraulic Lift (HL), Injector (I), Producer (P), Redrill (RD), Rod Lift (RL).

* Shut-In (SI), Side-Track (ST), Submersible Lift (SL).