Design Concepts of a Heavy-Oil Recovery Process by an Immiscible CO_2 Application

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Summary

Batı Raman oil field, in southeast Turkey, represents Turkey's biggest single oil reserve.

The rapid production decline of the field and increases in the price of crude oil has led Turkish Petroleum Corp. (TPAO) to consider intervening with EOR techniques. Since 1967, various recovery schemes have been attempted, including steam and water injection. Extensive laboratory, modeling, and comparative engineering studies of various immiscible CO_2 application techniques resulted.

This paper presents the reservoir engineering aspects of immiscible CO_2 application as applied to Batı Raman oil field.

Introduction

Batı Raman Oil Field. Batı Raman field, discovered in 1961 in southeast Turkey (Fig. 1), contains low-pressure, low-gravity (12°API [0.986-g/cm^3]) oil at an average depth of 4,300 ft [1310 m]. It is the largest oil field in Turkey, with an estimated initial reserve of about 1.85×10^9 STB [300×10^6 stock-tank m^3].

The producing formation is Garzan limestone, a long, partly asymmetric anticline oriented in the east-west direction. The field is 10.5 miles [17 km] long with a width of 2.5 miles [4 km]. The reservoir is limited by an oil/water contact (OWC) at 1,970 ft [600 m] subsea in the north and west, by a fault system in the southwest and south, and by a permeability pinchout in the southern and southeastern part of the field (Fig. 2). The formation has a gross thickness of 210 ft [64 m]. The oil column from the top of the structure to the OWC is about 690 ft [210 m].

The Garzan limestone is of Cretaceous age, has a reefal origin, and exhibits rather pronounced heterogeneities both areally and vertically. The reservoir rock is a fractured vuggy limestone in the western and central parts, but is chalky and tighter to the east. Average porosity is 18% and mainly vugular and fissured in type. The typical matrix permeability by core analysis is 10 to 100 md; however, well tests show effective permeabilities in the range of 200 to 500 md, confirming the contribution of secondary porosity (fractures, vugs, and connecting cracks). In the central and western parts of the field, a well-developed system of secondary porosity and permeability is believed to exist. In these areas, a secondary vugular porosity interconnected by fissures appears to be superimposed over a low primary porosity matrix.

The main production mechanism is rock and fluid expansion. Water drive appears to be insignificant, except for a very weak aquifer influence at the central north-flank wells. The solution GOR is 18 scf/bbl [3.24 std m^3/m^3], resulting in a low bubblepoint pressure of 160 psi [1100 kPa]. There is practically no solution gas drive below the bubblepoint. The reservoir oil is just above the bubblepoint pressure with a viscosity range of 450 to 1,000 cp [0.45 to 1.00 Pa·s]. The original reservoir pressure was about 1,800 psi [12.4 MPa] at a datum of 1,970 ft [600 m] subsea. The average reservoir pressure has now declined to 400 psi [2758 kPa], after a cumulative production of 30 million STB [4.8×10^6 stock-tank m^3] oil (Fig. 3).

The field was developed on 62 acres [251 000 m^2] per well spacing. There are 103 active producers. All are on pump with a total oil production of 2,600 B/D [413 m^3/d], compared with a peak rate of about 9,000 B/D [1431 m^3/d] in 1969. Initial well producing rates ranged up to 400 B/D [64 m^3/d] but now are averaging about 25 B/D [4 m^3/d]. Reservoir and fluid characteristics are summarized in Table 1.

Because of the unfavorable oil properties (such as low gravity, low solution gas, and high viscosity), low reservoir energy, and the type of driving mechanism, primary recovery prospects are very low. It is estimated that ultimately 1.5% of initial oil in place (IOIP) can be produced from Batı Raman field through primary production.

The current trend in primary recovery and the rapid decline in reservoir pressure suggest the need for a suitable EOR method to produce a significant fraction of the vast reserve. In the past, we carried out laboratory and engineering studies as well as some field tests to enhance recovery, including water injection, steam cycling, steamdrive, and air injection (for in-situ combustion). Most of these studies, however, were empirical, exploratory in nature, and of limited scope. Of these, only the five-spot waterflood project proved conclusive. About 3.2 million bbl [500 000 m^3] water were injected in the central area of the field between 1971 and 1978. This process resulted in a marked increase in oil production over the decline

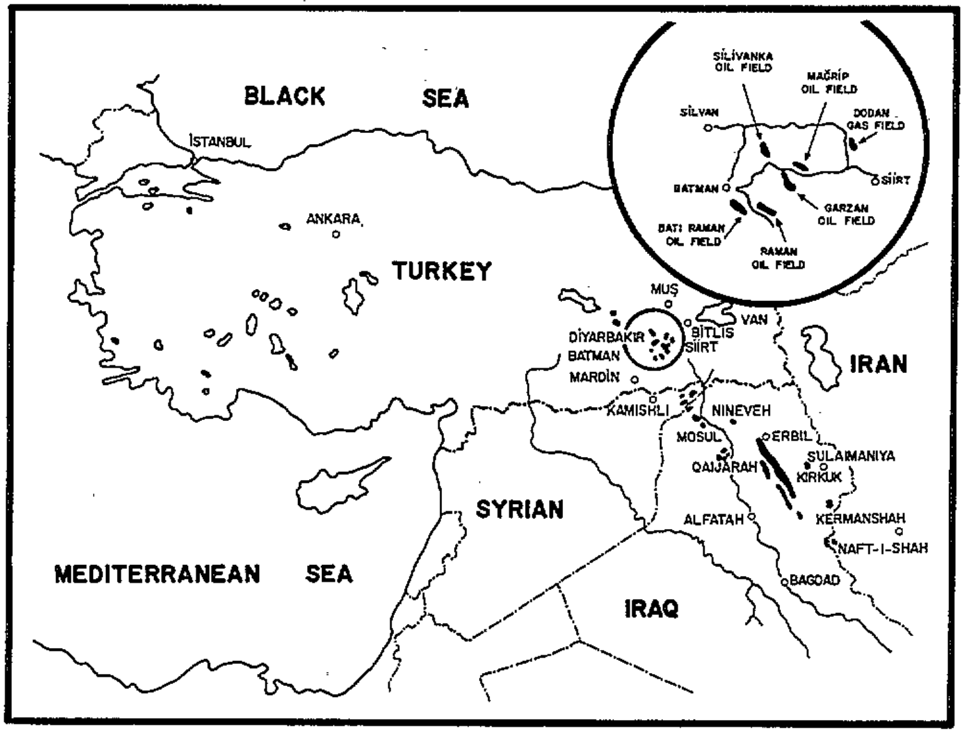

Fig. 1—Location of the Batı Raman field.

trend from wells on the entire central area (Fig. 2) but indicated that only a moderately increased recovery to 5% of the oil in place could be achieved.

Dodan Gas Field. Dodan field, 55 miles [89 km] from Batı Raman, is a vast source of CO_2.

The Dodan structure is a northwest-southeast-trending anticline 5.5 miles [8.9 km] long and 1 mile [1.6 km] wide. Upper Sinan, Garzan, and Mardin limestones, at depths of about 2,800, 5,900, and 7,300 ft [853, 1798, and 2225 m], respectively, constitute three different reservoirs for CO_2 production. The compositions of the natural gas contained in each formation are similar, consisting predominantly of CO_2. The average compositions are given in Table 2.

With the latest development, total reserves for wells drilled in 1979 and 1980 are estimated at 250 billion scf [7.1×10^9 std m^3].

The reservoir pressure of Dodan field varies from 1,650 to 2,400 psig [11.4 to 16.5 MPa] with depth. Wellhead static pressures, however, are almost the same, about 1,000 to 1,100 psig [6895 to 7584 kPa]. Well tests have shown an average open-flow capacity of 10×10^6 scf/D [280 000 std m^3/d] per well, indicating an allowable capacity of 3 to 5×10^6 scf/D [90 000 to 140 000 std m^3/d] per well, which is limited by hydrate and dry ice formation conditions.

For the full development of the field, approximately 20 wells are planned; drilling will be completed simultaneously with the activities at Batı Raman field. It

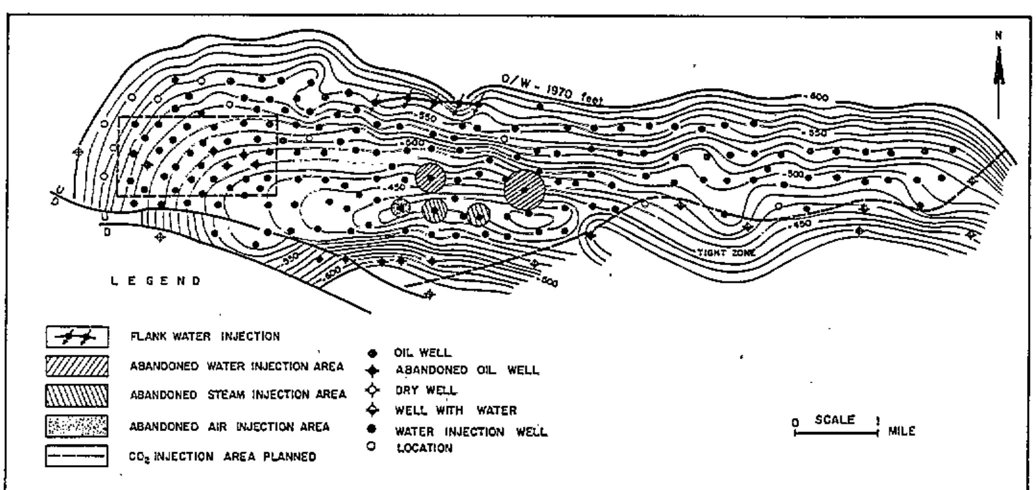

Fig. 2—Structural contour map of the Batı Raman field.

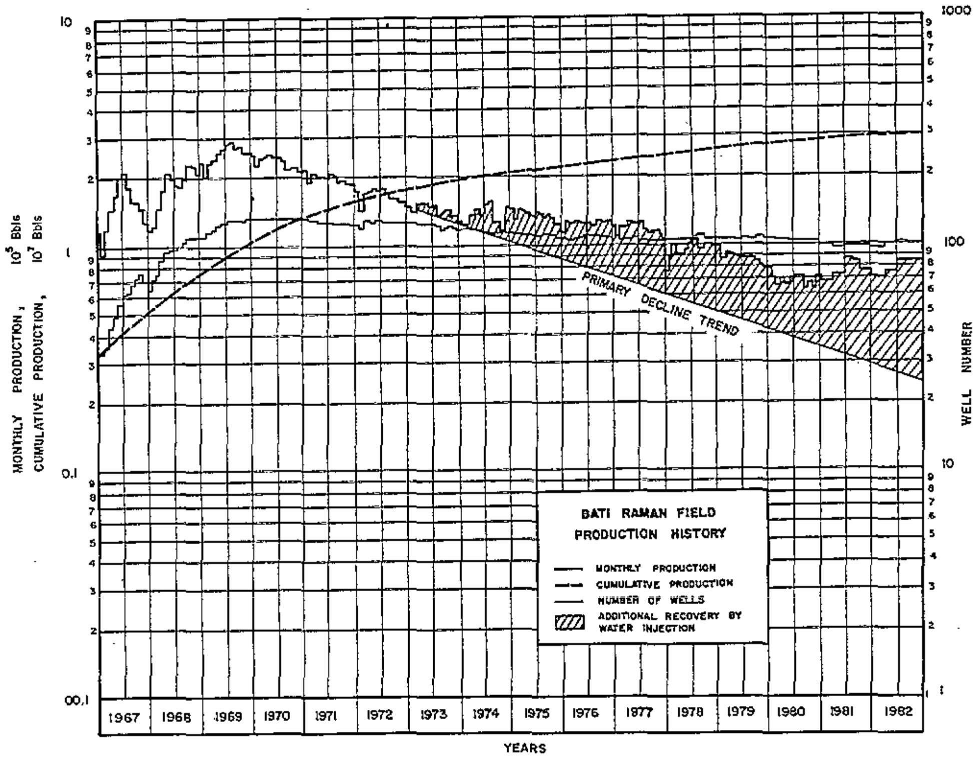

Fig. 3—Production history of the Batı Raman field.

is anticipated that approximately 60×10^6 scf/D [1.7×10^6 std m^3/d] total field production rate will be realized.

The coexistence of these two fields has led us to direct our sources to find a suitable method to enhance oil recovery from Batı Raman field.

Preliminary Studies

Laboratory. Various laboratory investigations were conducted by TPAO development center. These studies mainly involve the PVT behavior of Dodan gas and Batı Raman oil at different pressures and temperatures. Oil samples were received from Batı Raman Wells 14 and 77. Two sets of tests were conducted with a mixture of 99% pure CO_2 and Dodan gas. These include (1) a constant-composition flash gas liberation test at 145°F [63°C] (Batı Raman field reservoir temperature), (2) a differential gas liberation test at 145°F [63°C], (3) viscosity tests, and (4) separation tests. These test results are summarized in Table 3 and Fig. 4.

Theoretical. A TPAO report compiles all preliminary studies to date. This was prepared after a thorough evaluation of available logs, cores, pressure distribution, production history, and past reservoir behavior data. Selecting the pilot test area, determining the pilot mode of application, establishing injection flow rates, and predicting production performance were the aims of this report.

The studies indicated that the Batı Raman central area was the most suitable place for a pilot application (Fig. 2). In selecting the mode of application, the following factors played an important role.

Because of the oil's high molecular weight, the miscibility pressure between oil and CO_2, even by

TABLE 1—RESERVOIR AND FLUID CHARACTERISTICS OF BATI RAMAN FIELD

Oil in place, STB [stock-tank m^3]	1.85×10^9 [294×10^6]
Productive area, acres [km^2]	11,830 [48]
Formation depth (average) ft [m]	4,300 [1310]
Gross thickness (average) ft [m]	210 [64]
Net thickness (average) ft [m]	165 [50]
Cutoff porosity, %	10
Porosity (average), %	18
Connate water saturation (average), %	21
Matrix permeability (average), md	16
Effective permeability range (from tests), md	200 to 500
Oil gravity, °API [g/cm^3]	12 [0.986]
Viscosity range (in reservoir) cp [Pa·s]	450 to 1,000 [0.45 to 1.00]
Solution GOR, scf/STB [std m^3/stock-tank m^3]	18 [3.24]
Original reservoir pressure (at 1,970 ft subsea) psig [kPa]	1,800 [12 400]
Bubblepoint pressure, psig [kPa]	160 [1100]
Present average pressure, psig [kPa]	400 [2758]
Reservoir temperature (at 1,970 ft subsea) °F [°C]	160 [71]
Number of producing wells	103
Well spacing, acres [km^2]/well	62 [0.25]
Daily oil production, BOPD [m^3/d]	2,600 [413]
Cumulative oil production STB, [stock-tank m^3]	30×10^6 [4.8×10^6]

TABLE 2—AVERAGE COMPOSITIONS OF DODAN FIELD GAS (vol%)

CO_2	91.0
N_2	3.1
C_1	2.6
C_2	3.3
C_3+	trace
H_2S, ppm	3,000

TABLE 3—PVT PROPERTIES OF BATI RAMAN OIL PLUS DODAN GAS VS. PRESSURE

Pressure (psig)	Pressure (kPa)	Relative Volume* (gas + oil)	Oil FVF (RB/STB)	Solution GOR (vol/vol)	Liberated Gas Specific Gravity (air = 1)	Liberated Gas 10^{-3} FVF (std vol/res vol)
3,000	20 690	0.9788	1.117	43.5	—	—
2,500	17 240	0.9819	1.119	43.5	—	—
2,000	13 790	0.9854	1.122	43.5	—	—
1,500	10 340	0.9909	1.130	43.5	—	—
1,100	7580	0.9978	—	43.5	—	—
1,000	6890	1.000	1.134	43.5	—	—
920	6340	1.0263	1.125	40.8	1.200	15.106
820	5650	1.0677	1.120	37.2	1.325	17.478
710	4900	1.1655	1.105	32.2	1.395	20.674
500	3450	1.4949	1.085	23.9	1.455	29.727
360	2480	—	—	17.5	1.477	42.814
300	2070	2.2273	1.065	—	—	—

*Volume at 1,000 psig [6895 kPa]; saturation pressure is 1.

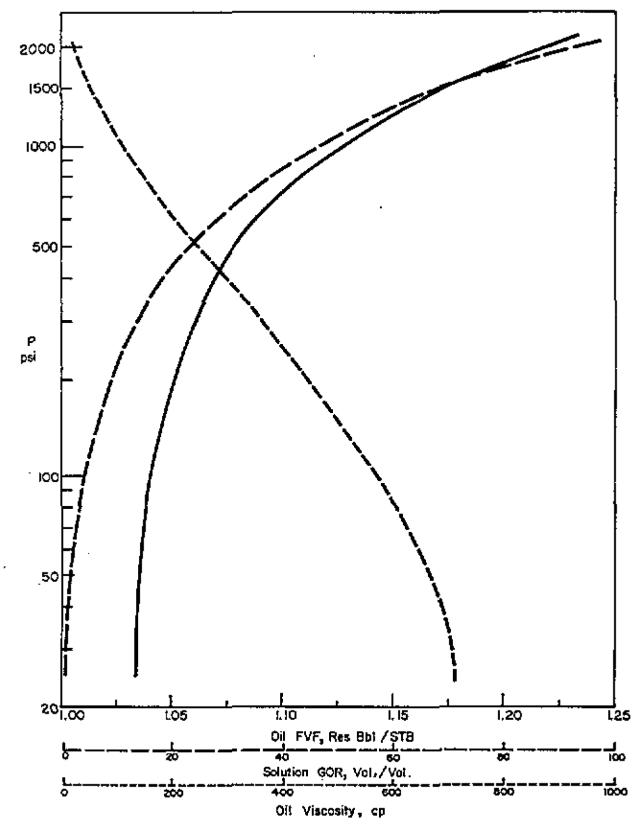

Fig. 4—Change in PVT properties of Batı Raman oil/Dodan gas mixture at saturation pressures.

multistep, could exceed many times the reservoir pressure; therefore, miscible displacement was not considered.

The highly adverse mobility ratio makes conventional displacement by CO_2 inapplicable. However, the high solubility of CO_2 in oil causes changes in oil properties, resulting in an improved mobility ratio between the oil and displacing fluid. Because of its easy accessibility and availability, water can be selected as the displacing fluid. The solution gas (highly CO_2)/oil ratio and the oil volume factor increase, and viscosity decreases, enough for good oil displacement.

On the other hand, the increase of CO_2 concentration in the reservoir water causes an alteration in carbonate-bicarbonate equilibrium. Calcium carbonate converted into the water-soluble calcium bicarbonate results in an increase of PV and permeability. Injected CO_2, reducing the surface tension between oil and connate water, helps free oil molecules from connate water more easily. As a result, a new reservoir with improved physical properties was obtained, which directly influences ultimate recovery.

Based on the previous factors, the preliminary plan consisted of the following stages.

1. CO_2 is injected into all wells in the pilot area, and the reservoir is repressured up to 20% higher than the original pressure.
2. The pilot area is produced by solution gas drive down to 600 psi [4137 kPa] or until the economical production limit is reached. This cycle is repeated once or twice.
3. Gas is injected up to the 2,100-psi [14.5-MPa] reservoir pressure and the oil is displaced by water.
4. Injection starts from 13 wells in the area on a 4-acre [16 188-m^2] per well basis.

Recent studies made by others agreed quite well with the early results with regard to performance prediction, gas injection, and well production rates.

Laboratory Studies

Both laboratory and theoretical studies comprising various phases of CO_2 application in heavy Batı Raman crude were carried out by Inst. Française du Pétrole (IFP), Intercomp Resource Development and Engineering Inc., and Williams Bros. Engineering Co. Laboratory work accomplished by IFP was classified into seven different studies.

1. In the study of Batı Raman reservoir geology, existing cores, logs, and data were examined. The study indicated that actual permeabilities measured from field tests are higher than laboratory matrix permeability measurements. This was attributed to either dual-porosity systems or loss of very permeable layers during coring.
2. Oil mobility reduction resulting from possible asphaltenes deposition during stripping was studied, and tests results showed that asphaltenes presented no risk of plugging in the formation.

3. The purpose in studying Dodan gas transfer kinetics in virgin oil in a porous medium representing a matrix block surrounded by fissures was to evaluate the amount of Dodan gas that will dissolve in Batı Raman virgin oil in the fissured zones where the gas drive mechanism occurs. The experiment consisted of bringing gas at 2,176 psi [15 MPa] in contact with virgin oil at 290 psi [2 MPa], then allowing it to diffuse into the oil at a constant gas pressure of 2,176 psi [15 MPa]. The volume of mercury injected to maintain pressure and the amount of oil extracted at the end of the experiment were reported as a function of time (Fig. 5). The observed injected and produced volumes were matched to obtain a transfer diffusion coefficient of 0.012 sq ft/D [0.0011 m^2/d].

4. In studying CO_2 liberation by depletion in a porous medium representing a matrix block surrounded by fissures, the test was designed to obtain information on the rate, amount, and composition of gas liberated with respect to time. Depletion from 2,176 psi to 1,595, 1,160, and 812 psi [15 MPa to 11, 8, and 5.6 MPa] produced 2, 16, and 20% of oil in place, respectively. The produced gas composition contained 8% methane and 9% intermediates on the average.

5. A comparison of the water/oil relative permeabilities when Batı Raman oil is saturated with Dodan gas showed that the relative permeability curve was significantly improved. Also, the residual oil saturation dropped from 46.6% when oil was not saturated to 30% when oil was saturated.

6. Three tests were conducted to study the effect of Dodan gas on gas/oil relative permeabilities. These tests were conducted at 2,176-psi [15-MPa] pressure with the presence of connate water. Gas saturated oil relative permeabilities were measured.

7. During the evaluation of Dodan gas injection in an area of the field previously waterflooded, the core samples were saturated by virgin oil in the presence of connate water. Then they were waterflooded under an average pressure of 406 psi [2.8 MPa]. Following the waterflood, the residual oil saturation was evaluated. Finally, Dodan gas was injected at the bottom of the core sample. The total amount of Dodan gas introduced into the core was evaluated. An aging time of 24 hours was allowed to ensure thermodynamic equilibrium among different phases. Then the core was waterflooded. About 5 mL [5 cm^3] pure oil was produced in the early stages of the flooding. At the end of flooding, total oil production was 12 mL [12 cm^3], which corresponds to 16.6% of oil in place before the first waterflooding.

Theoretical Studies

Collected data were evaluated by mathematical models, and more detailed evaluation results were obtained compared with the early studies. This work further displayed the effects of various parameters on the results.

Preliminary Screening. In 1980, a comparative engineering study of alternative EOR schemes to be applied in Batı Raman field was completed by the joint effort of two major U.S. companies. Six EOR schemes were considered: improved recovery by chemicals, in-situ combustion—dry and wet, steamflooding using USSR mining technology, waterflooding, steamflooding, and CO_2 or Dodan gas application.

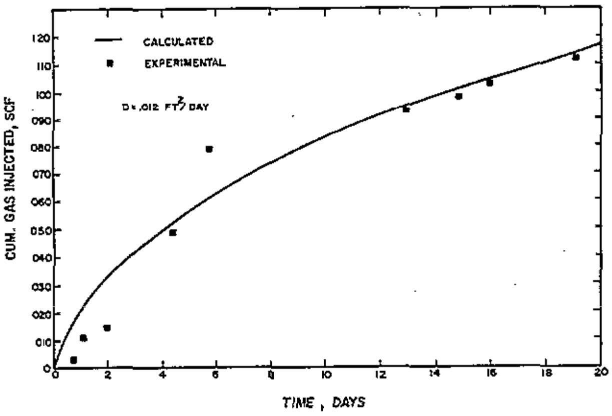

Fig. 5—Diffusion experiment simulation.

A preliminary screening eliminated some of these methods.

1. Since the salinity of formation water (100,000 to 150,000 ppm) combined with the reservoir temperature was far too high to consider any polymer or chemical flood, chemical methods were eliminated. Micellar/polymer flooding was eliminated at the outset because Batı Raman (a carbonate reservoir) oil is too heavy and viscous.

2. Dry and wet in-situ combustion methods were examined and eliminated because results of field tests in carbonate reservoirs in the U.S. were unfavorable. Also, high risks and operational problems existed.

3. Steamflooding using USSR mining technology was eliminated because of the enormous costs of sinking shafts to 4,000 ft [1219 m], drilling horizontal tunnels from this depth, and safety and environmental problems inherent in mining operations at such depth.

History Match. Reservoir data showed that Batı Raman field might be extensively fractured and that alternate reservoir descriptions could affect the performance of potential EOR processes dramatically. For this reason, and to obtain a better understanding of the reservoir, a history match of the entire field's past performance was undertaken. Intercomp's Beta II three-dimensional (3D), three-phase black-oil simulator was used in the history match. The model accounted for reservoir heterogeneity, gravity, capillary pressure, PVT data, and saturation-dependent relative permeability data. It also accounted for mixing of different fluids, thereby accurately simulating the flow of fluids of different viscosities, solution GOR's, etc.

For a better description of the reservoir, single- and dual-porosity systems were used in the simulation studies. The description was in agreement with IFP's geological interpretation of Batı Raman field. The concept of a dual-porosity system involves two distinct pore geometries that exhibit widely different permeabilities. In such a system, a network of interconnected fractures of high conductivity penetrates a tight matrix of relatively low permeability. Because of the extensively fractured matrix of the reservoir rock, the concept of a dual-porosity system was considered.

According to simulation studies, the following EOR schemes appeared attractive.

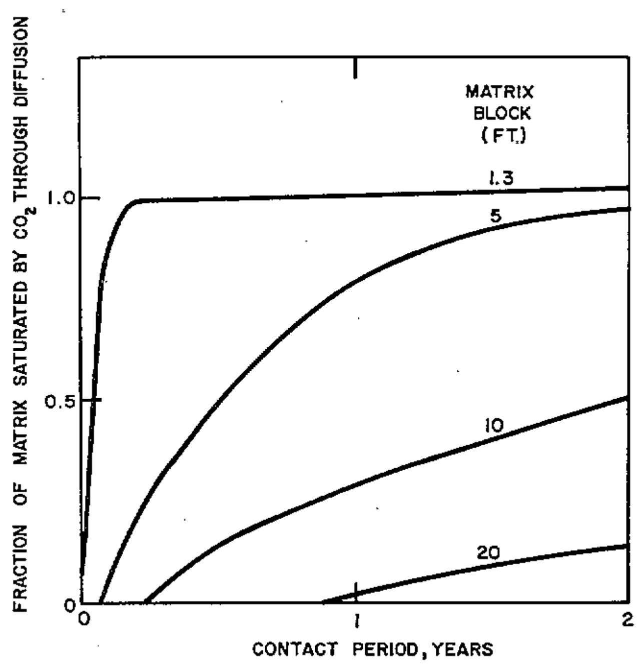

Fig. 6—Effect of matrix-block size on the extent of diffusion.

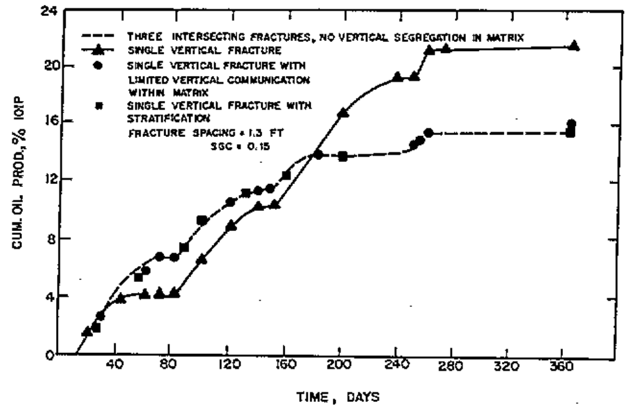

Fig. 7—Vertical fracture configuration in CO_2 cyclic stimulation.

Waterflooding. The waterflood behavior of Batı Raman field was examined by a history match using data obtained from a five-spot waterflooding pilot test conducted in the central area between 1971 and 1978. Waterflood recovery by simulation was sensitive to the rock system description. In dual-porosity simulation, the predicted recovery was less than 5% of the oil in place. This is in conformance with the field case. Data obtained by this match were used for further modeling and prediction calculations. The waterflooding method was eliminated because the final recovery figure was incomparably low.

Steamflooding. Because of the high viscosity of Batı Raman crude as well as the substantial viscosity reduction caused by increased temperature, thermal schemes appeared applicable. The steam displacement projections were based on matching the performance of a 1969 steam injection test in the central area. However, the test was prematurely terminated. As a result of a reasonable history match, the response to continued injection in the test area was simulated.

Low-quality steam was assumed to be injected at a temperature and pressure such that the fluid was all water at reservoir depth. But once the reservoir rock was heated to near the injection temperature and the fluid encountered a lower-pressure environment, the water would flash to steam and generate a steam displacement from that area forward. For the field recovery predictions, two types of injection were considered, the one described and one where the injected fluid was 50% steam quality at reservoir depth.

The study showed that the steam displacement should recover significant volumes of oil from Batı Raman reservoir—about 32 and 16% of oil in place, for single- and dual-porosity systems, respectively, after subtracting the oil needed to fuel the steam generators. The injection of 50% steam quality improves oil recovery in the eastern and western regions, but leaves the recovery essentially the same in the central region. In spite of these figures, steamflooding also was eliminated because of the high initial investment cost.

Dodan Gas Application. A promising way to improve the recovery in the Batı Raman field is by the injection of Dodan gas. The oil recovery mechanism using Dodan gas is based on the ability of gas to dissolve in oil, swell the oil, and reduce its viscosity. After a large volume of oil has been saturated, operating alternatives include continuing with cyclic Dodan gas stimulation and waterflooding the saturated oil.

The application begins by repressuring portions of the reservoir with gas, allowing it to diffuse into the oil it contacts. The injected gas will either bypass the blocks through fractures if it is a dual-porosity structure or it will displace the oil if it is a single-porosity structure. Because of the unfavorable mobility ratio, gas will have an extreme fingering tendency in the oil. But in either case, diffusion is important.

In the cyclic gas application, the reservoir pressure is built up to be 20% higher than the original and is produced back. This yields saturated oil and some injected gas. Since it is a depletion type of drive, depletion data need to be matched so that this stage of the process can be modeled. The cyclic process is repeated until a large volume of oil becomes saturated, at which point waterflooding the region is considered. Because it is likely that the reservoir rock is made up of some combination of single- and dual-porosity systems, the behavior of this recovery scheme in both systems was considered. Gas oil properties as functions of pressure and results from IFP tests were taken as basic data, and Intercomp's fully implicit compositional model was used.

Cyclic Dodan Gas Stimulation in a Dual-Porosity System. Oil recovery by cyclic stimulation relies on diffusion as the primary mechanism through which gas can dissolve in oil, causing oil swelling and viscosity reduction. But as shown in Fig. 6, diffusion requires a long time before a substantial amount of reservoir oil can be treated. It is essential that the large volume of injected gas should effectively penetrate the reservoir and provide a large areal contact. This depends on fracture spacing in the reservoir rock. Small fracture spacing will

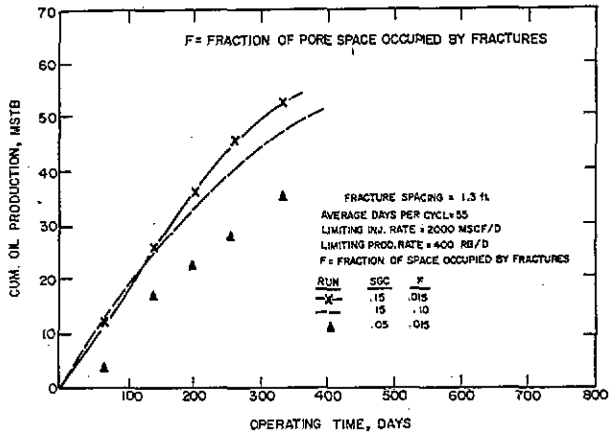

Fig. 8—Sensitivity to fracture network volume.

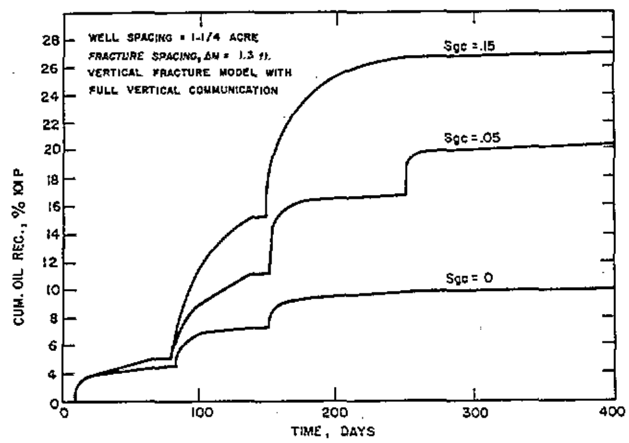

Fig. 10—Effect of critical gas saturation on oil recovery under cyclic CO_2 stimulation.

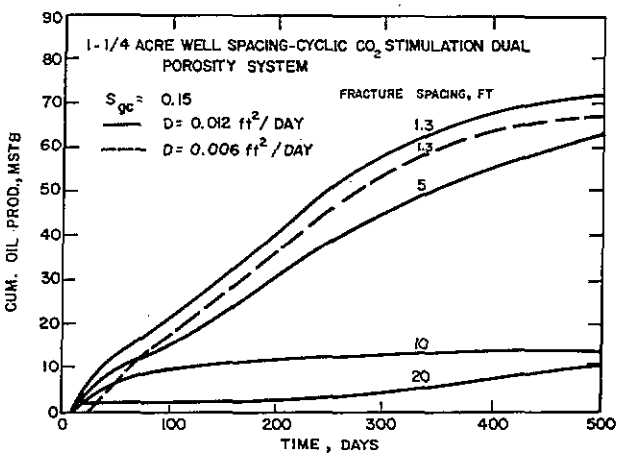

Fig. 9—Sensitivity to fracture spacing and diffusion coefficient.

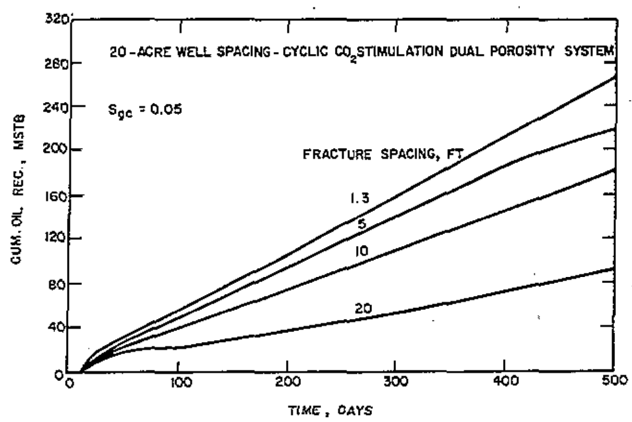

Fig. 11—Sensitivity to fracture spacing.

significantly enhance the saturation of oil by gas.

The basic dual-porosity model consists of three intersecting fractures surrounding a matrix block. Several other model configurations were tried to develop a simpler but equivalent representation. In Fig. 7, two single vertical fracture models are compared with the basic model. In all three models, fracture spacing and critical gas saturation are taken as 1.3 and 0.15 ft [0.4 and 0.05 m], respectively. Identical injection and withdrawal schedules were followed by using four injection cycles, each 10 days long, over a 1-year period.

Sensitivity to Certain Parameters. To perform the dual-porosity model simulations, reasonable values of the many unknown parameters were assigned. Therefore, it was necessary to investigate the sensitivity of the cyclic recovery process to changes in these parameters within the range of uncertainty associated with each. These sensitivity runs were subject to making three to five stimulation cycles, using a maximum injection rate of $2,000 \times 10^3$ cu ft/D [57 000 m^3/d] gas, limiting the oil production to 400 RB/D [64 res m^3/d], and employing a cross-sectional model representing 1.25-acre [5059-m^2] well spacing.

The six parameters investigated are as follows.

1. In *fracture porosity*, the fraction of a PV occupied by the fracture network is one of the parameters to which a value of 0.015 was arbitrarily assigned. This value actually could be between 0.010 and 0.015; it is obvious that the choice is not critical (Fig. 8).

2. *Fracture spacing* is an important parameter in determining oil recovery from a dual-porosity system by Dodan gas diffusion. The results presented in Fig. 9 indicate that if the fracture spacing is much less than 20 ft [6.1 m], preferably 5 ft [1.5 m] or less, cyclic gas stimulation will recover substantial quantities of oil. Field waterflood experiments indicated that fracture spacing must be smaller than 20 ft [6.1 m].

3. Another important factor that can influence oil recovery is the *critical gas saturation* in the matrix. The higher this value, the more oil will be expelled from the matrix during the depletion cycle. The value of 15% used in the simulation work is not merely an assumption but is based on two independent laboratory tests. The effect of lower critical gas saturations on oil recovery has been investigated also. Figs. 10 and 11 present the effect of gas saturation.

4. Fig. 9 also includes a comparison of oil recovery with different values of the *diffusion coefficients*. This

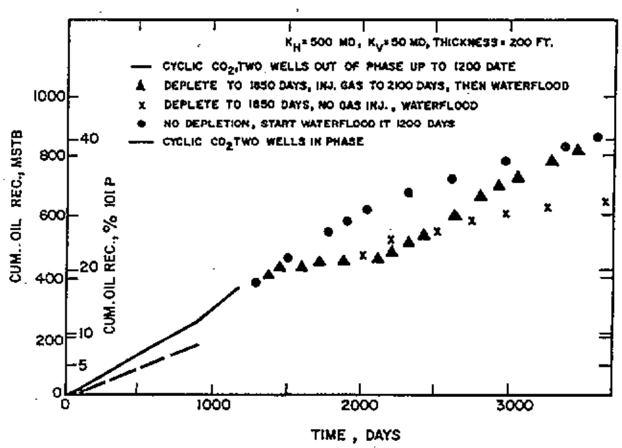

Fig. 12—Single-porosity system, 10-acre [40 000-m^2], 5-spot pattern.

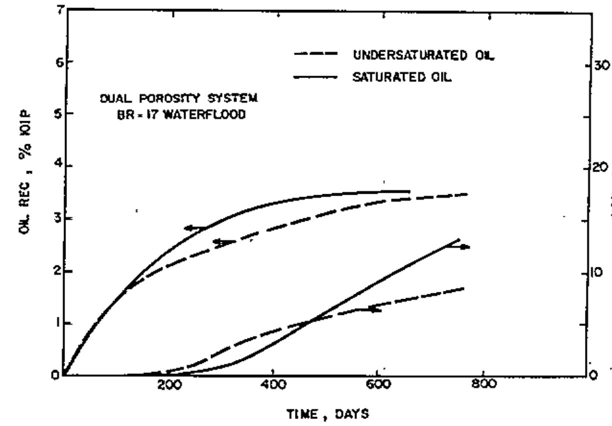

Fig. 13—Waterflood of saturated and undersaturated oil in a dual-porosity system.

figure indicates that reducing the diffusion coefficient by a factor of two has a small effect upon oil recovery.

5. Because the reservoir is assumed to be a dual-porosity system and existence of fractures is accepted, the vertical permeability is large and *gravity segregation* is expected to be a problem. However, the data in Fig. 7 indicate that this is not the case. These recoveries were calculated by assuming a single vertical fracture whose height was the entire vertical section. There was a limited vertical segregation in the matrix; however, there were no restrictions to flow in the fracture. It can be concluded that the gravity segregation will not reduce recovery in the dual-porosity system.

6. In the sensitivity runs discussed earlier, a small reservoir system representing 1.25-acre [5059-m^2] *well spacing* was used to perform the comparison quickly. In the application, the economics dictates a large well spacing. Investigations have been carried out with 2.5-, 5-, and 20-acre [10 117-, 20 234-, and 80 938-m^2] well spacings by using fracture spacing of 1.3 ft [0.4 m] and a critical gas saturation of 0.15.

Waterflooding After Gas Stimulation. It was mentioned earlier that after cyclic Dodan gas stimulation, waterflooding the resultant system should be considered. This was investigated in a symmetry element representing one-eighth of a 2.5-acre [10 117-m^2] five-spot pattern. Both wells in the symmetry element were cyclically stimulated for 1 year, resulting in the production of 30% IOIP. Then an injection period was scheduled up to 500 total days and reservoir pressure was raised to 2,150 psi [14.8 MPa]. One well was allowed to produce at 1,600-psi [11.3-MPa] backpressure. Additional recovery owing to flooding was only 2%. This low oil recovery can be attributed to the presence of free gas saturation resulting from the extensive cyclic treatment. Injected water will displace the gas, resulting in a lower waterflood oil recovery than anticipated.

If waterflooding had begun earlier, less oil would have been recovered in the cyclic stimulation and more from the waterflood.

Cyclic Dodan Gas Stimulation in a Single-Porosity System. In a single-porosity system, where the fracture network is absent, extensive fingering of Dodan gas through the oil is expected to provide the large areal contact needed for diffusion to be effective. To obtain maximum advantage from fingering phenomena, the wells surrounding the injection wells should be on production so that the gas may move out and finger readily. Fig. 12 shows the results of operating two wells out of phase for 1,200 days. Simulation results indicate that at 1,200 days the major portion of the oil has been saturated. Immediate waterflooding of saturated oil gives the best results and recovers nearly 40% IOIP after 10 years' combined cyclic and flooding operations.

Waterflooding After Dodan Gas Flooding Operations. The potential waterflood recovery of approximately 22% shown in Fig. 12 should be contrasted with a perfect dual-porosity system in which no displacement takes place in the matrix. In a system of this type, waterflooding saturated oil is not much better than waterflooding virgin oil because ultimate recovery is independent of oil viscosity and is dictated by the imbibition curve. Displacement of light saturated oil in the fracture is conducive to more severe gravity segregation (Fig. 13).

Field Demonstration Project. There was overwhelming evidence that a cyclic stimulation by Dodan gas followed by a waterflood in the western area of the field would be the best approach.

The general area chosen for this demonstration project encompasses about 1,200 acres [4 856 248 m^2] and includes 33 adjacent wells drilled in a five-spot pattern (Fig. 2).

To begin the operation, half the wells (first, third, and fifth line of wells shown in Fig. 2) will be used as injectors and the other half as producers. After conducting the gas flooding operation for about 3 months (or until gas breakthrough occurs in the producers), injectors will be converted to producers, and producers to injectors, thus reversing the direction of flooding.

This mode of operation (i.e., out-of-phase stimulation of adjacent wells) is based on the assumption of a single-porosity system. When a well is experiencing Dodan gas injection, neighboring wells will be on production so that the injected gas may readily move out from the well and finger through the oil, allowing diffusion. In this case, gas breakthrough is not expected to occur, even after 2 years' operation.

If the reservoir in all or part of the test area is closer to a dual-porosity system, then breakthrough in the producers will occur early in the scheduled 3-month injection cycle. In that case, the operation will be converted to in-phase cyclic stimulation of one half the area at a time. Thus, while the eastern half is being stimulated, the western half is produced, and vice versa.

If, on the other hand, the early breakthrough is caused by large fractures, as opposed to a dense fissure system, then the operation in that area will be halted and fracture plugging treatments then will be tried. It is important that the operation be monitored closely and appropriate decisions be made regarding any changes in the mode of operation throughout the pilot project.

As a result of the project monitoring and evaluation, an optimal field development program will be instituted. When the demonstration project is proved successful, Dodan gas injection will be expanded by infill drilling in the test area and extension to the remainder of the field. The strategy of a possible waterflood may also be determined on the basis of early performance.

It was planned that 2×10^6 scf/D [57 000 std m^3/d] Dodan gas will be injected per well and anticipated that around 300 to 400 B/D [48 to 64 m^3/d] oil will be produced from each well. The oil production from the test area is expected to reach 6,000 B/D [953 m^3/d]. This is a significant increase over the current 400 B/D [64 m^3/d] oil production of the same area.

Simulation results indicate that after 800 days' out-of-phase operation, a free gas zone will be established 500 ft [152 m] out from each well, and the reservoir oil will be saturated over an additional 200 ft [61 m]. But at no time during the 100-day injection cycles does the model predict gas breakthrough. At this point, the spacing will be reduced to 15 acres [60 703 m^2] by infill drilling, and the cyclic operation continues.

Surface facilities for both Dodan and Batı Raman fields have been designed and manufactured. After the completion of ongoing construction and erection activities, the pilot test is scheduled to start in Summer 1985.

Conclusions

1. Existence of a vast amount of heavy oil in Batı Raman field and 1.5% primary recovery have led us to investigate and screen various EOR methods.

2. Both CO_2 and steam applications were found favorable. However, immiscible CO_2 application appeared more feasible because of the nearby Dodan CO_2 gas reserve and the high initial investment cost of steam injection.

3. For immiscible CO_2 application and subsequent waterflooding, fracture spacing, critical gas saturation, and diffusion rate are the main parameters that affect the ultimate recovery significantly. Sensitivity analysis shows that the ultimate recovery range will be between 17 and 32%, depending on prevailing conditions. Full field application is to recover around 400×10^6 STB [64×10^6 stock-tank m^3] heavy oil in 25 years.

4. Economic analysis indicates that project investments will return in 2 years with the oil produced from the test area only.

5. The Batı Raman field pilot project is expected to contribute considerably to the existing technology on heavy-oil recovery using CO_2.

Acknowledgment

We thank the management of Turkish Petroleum Corp. for permission to publish this paper.

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SI Metric Conversion Factors

acre	× 4.046 873	E+03	=	m^2
bbl	× 1.589 873	E−01	=	m^3
cu ft	× 2.831 685	E−02	=	m
ft	× 3.048*	E−01	=	m
mile	× 1.609 344*	E+00	=	km
sq ft	× 9.290 304*	E−02	=	m^2

*Conversion factor is exact.

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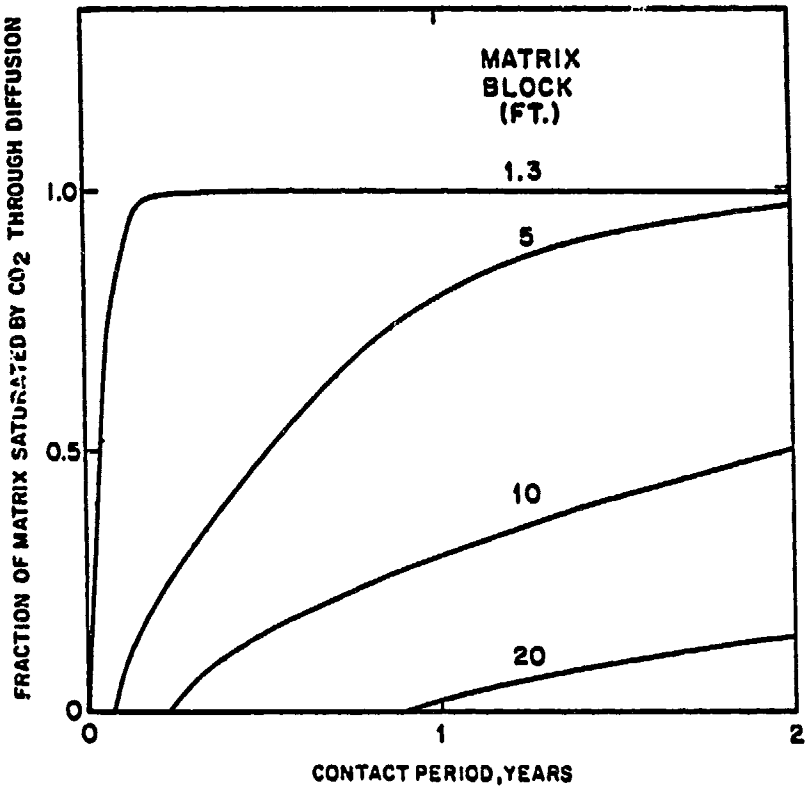

Fig. 4—Effect of matrix-block size on the extent of diffusion.

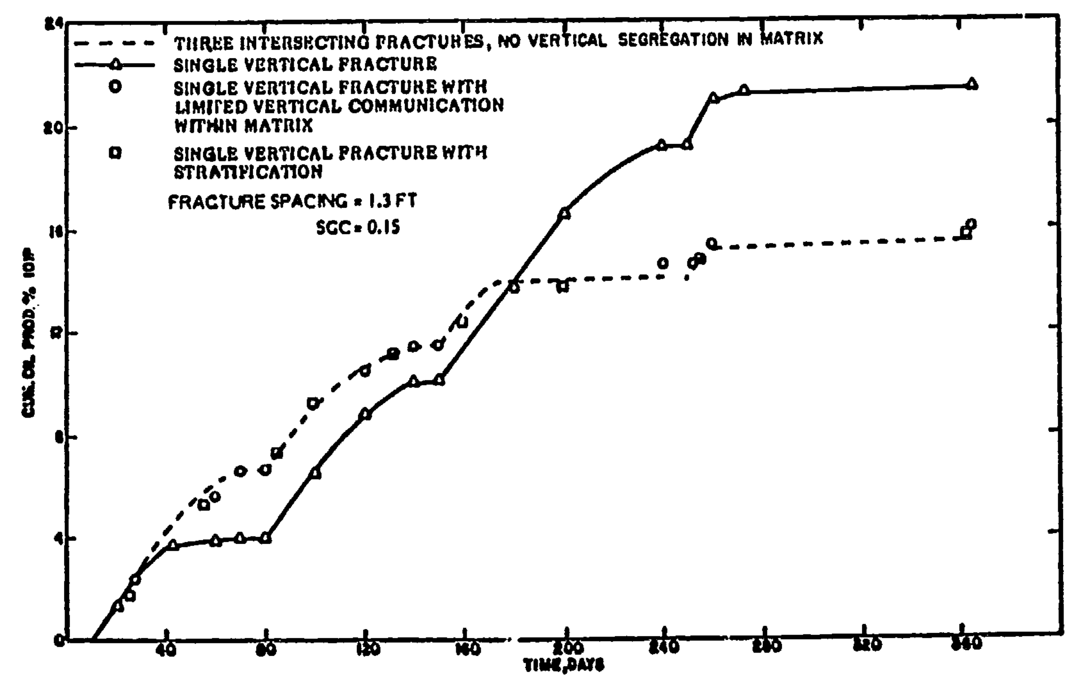

Fig. 5—Vertical fracture configuration in CO_2 cyclic stimulation.

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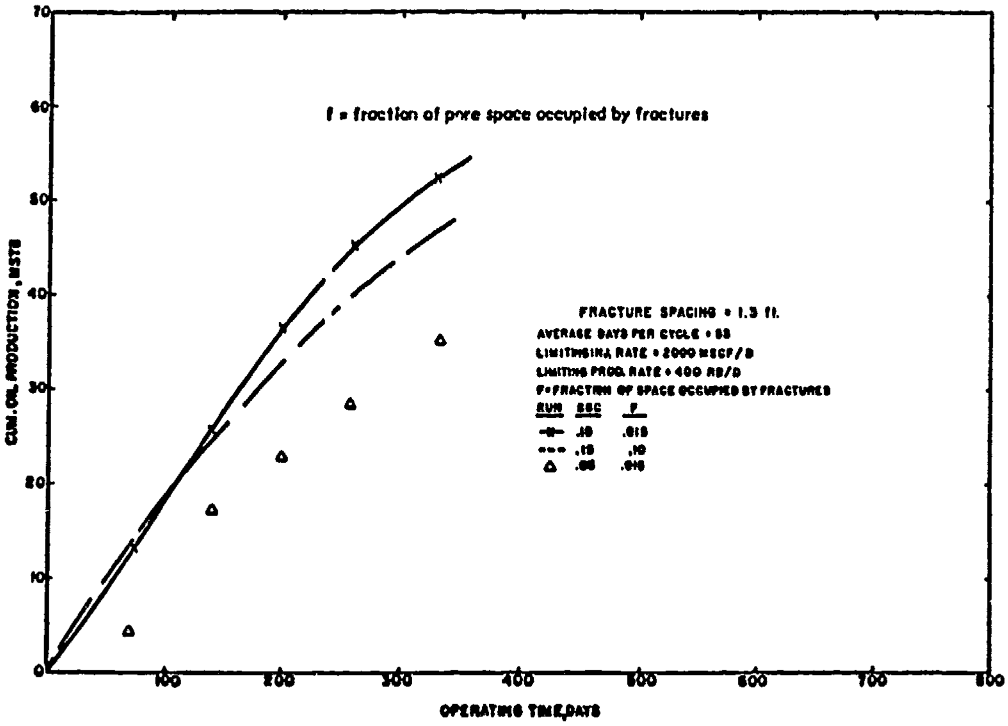

Fig. 6—Sensitivity to fracture network volume.

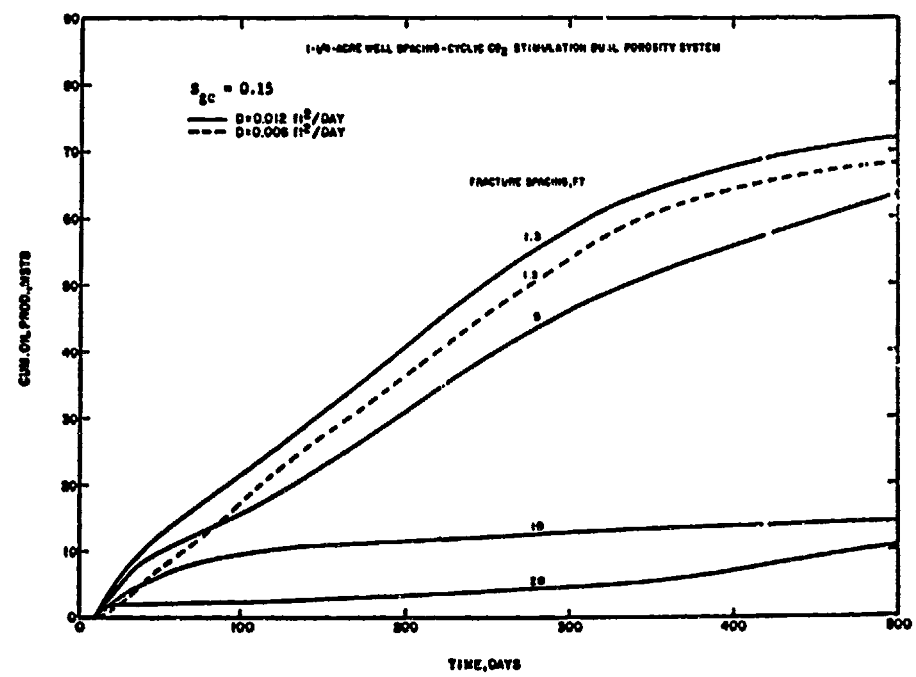

Fig. 7—Sensitivity to fracture spacing and diffusion coefficient.

SPE 11475

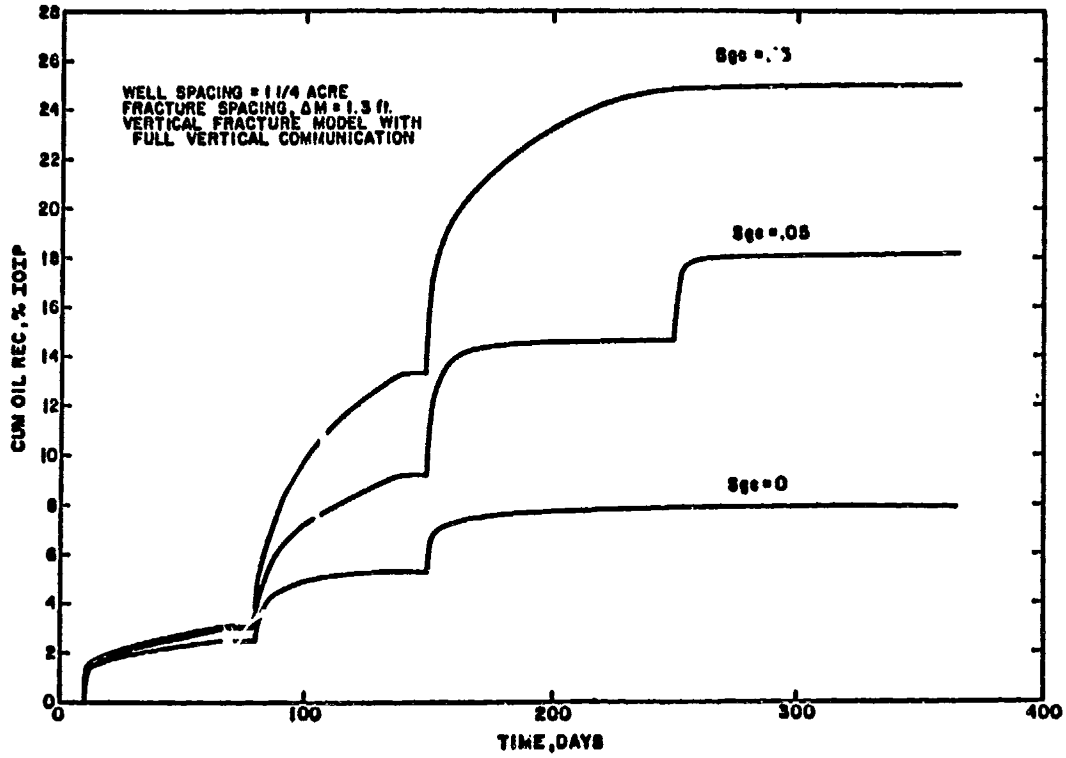

Fig. 8—Effect of critical gas saturation on oil recovery under cyclic CO_2 stimulation.

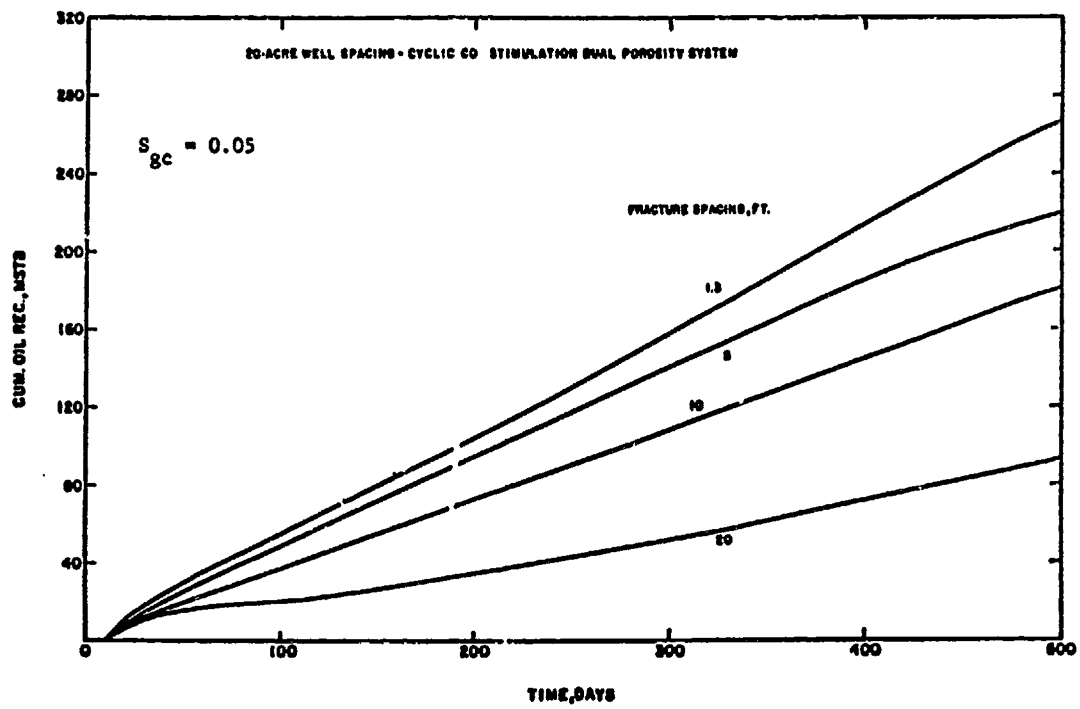

Fig. 9—Sensitivity to fracture spacing.

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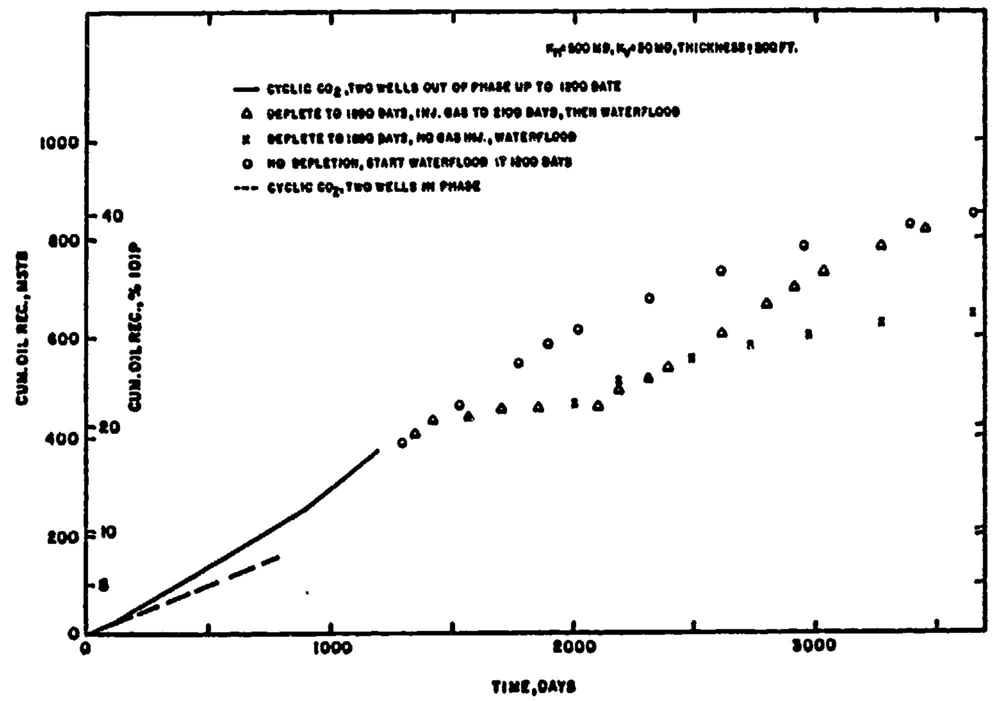

Fig. 10—Single porosity system 10-acre 5-spot pattern.

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