PETROLEUM-ENGINEERING STUDY OF GAS INJECTION IN FAULT BLOCKS VB AND VI, WILMINGTON FIELD, CALIFORNIA

BY R. V. HIGGINS AND R. L. PIERCE
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Report of Investigations 5338

UNITED STATES DEPARTMENT OF THE INTERIOR
Fred A. Seaton, Secretary
BUREAU OF MINES
Marling J. Ankeny, Director

Work on manuscript completed February 1957. The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is made: "Reprinted from Bureau of Mines Report of Investigations 5338."

May 1957
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by

R. V. Higgins\(^1\) and R. L. Pierce\(^2\)

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2/ Petroleum engineer, Long Beach Harbor Department, Long Beach, Calif.

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SUMMARY AND INTRODUCTION

This report presents the results of a study of gas injection in the Upper and Lower Terminal zones in fault block VB and in the Upper Terminal zone in fault block VI, Wilmington field, California. This report is based on data obtained to January 1956.

Earlier studies of gas injection in other California fields have been reported.3/

The Upper and Lower Terminal zones, fault block VB, have been producing oil since 1945 and the Upper Terminal zone, fault block VI, since 1948. Before starting the gas-injection project, the expansion of dissolved gas was the principal mechanism moving the oil to the wells. Gravity drainage and an edgewater drive also have contributed to the movement of the oil to the wells. When the gas injection was begun, the reservoir pressure and the oil production had declined appreciably. Gas injection was started in the Upper and Lower Terminal zones, fault block VB, in May 1953 and in the Upper Terminal zone, fault block VI, in October 1953.

Oil is being produced from all zones during gas injection without any appreciable loss in reservoir pressure as of January 1956. In the Upper and Lower Terminal zones, fault block VB, the rate of decline per well has been arrested. In the Upper Terminal zone, fault block VI, interpretation of the decline rate has been complicated by the completion of many additional wells. In all the Upper and Lower Terminal zones, fault block VB, and the Upper Terminal zone, fault block VI, the net gas-oil ratio has dropped since gas injection and has remained lower than the gas-oil ratio before gas injection. Thus, the volume of gas required to produce 1 barrel of oil has been reduced. This is one of the criteria for the success of the gas-injection project.

The zones contain thick sands (minimum net, 188 ft.) with widely varying permeability. The gravity of the oil is 20°-24° API, and the viscosity of the reservoir oil is relatively high compared to oils in many gas-injection projects. These conditions presented serious problems of bypassing of the gas, and the experiences gained from this project and techniques used to prevent bypassing may be used as helpful guides to operators of properties that have comparable reservoir conditions.

ACKNOWLEDGMENTS

The authors take this opportunity to express their deep appreciation and many thanks to Frank J. Hardesty, chief petroleum engineer, Long Beach Harbor Department, Petroleum Division, Long Beach, Calif., for his permission to publish the data.

Grateful acknowledgments are made to M. N. Mayuga, geologist, Petroleum Division, Long Beach Harbor Department, for his careful review and additions to the geologic description contained in the report.

Thanks are due to employees of the Long Beach Harbor Department who prepared many of the figures used in the report.

GENERAL DESCRIPTION OF FIELD

The Wilmington oilfield is in the Wilmington area and harbor district of the City of Los Angeles and the harbor district of the City of Long Beach, Los Angeles County. The location of the Wilmington field with respect to other oilfields in the Los Angeles Basin is shown in figure 1.

The oil-producing structure is an anticlinal fold with its main axis in a northwesterly and southeasterly direction. The axis is cut by a series of transverse faults, and some of these faults branch into minor ones. Although the faulting may have begun during late Upper Miocene time, probably most of it occurred during the Lower Pliocene time. The strike of the faults is about north and south, and most of the faults hade to the east. The vertical displacement of the major faults varies from a maximum of 350 feet at the top of the Terminal zone on the Wilmington fault to about 100 feet on the Allied fault. The subsurface structure is not reflected on the surface owing to the existence of an unconformity at a depth of about 2,000 feet. Consequently, subsurface studies have guided the exploration of the field.

The apex of the structure extends to the southeast from beneath the northeastern portion of Terminal Island to an unknown distance beneath the ocean. The southeasterly plunge extends to some point offshore from Seal Beach.

In January 1932 the Ranger Petroleum Corp. completed well No. "Watson" 2, sec. 29, T. 4 S., R 13 W., in the extreme north-central end of the field in the Ranger zone at an initial production by pump of 150 barrels of 14.1° API clean oil per day. The completion of the well aroused no interest because of the low gravity of the oil, the low demand because of a world depression, and the belief that the well was an extension of the Torrance field. On June 12, 1936, the Harbor Drilling Co. well No. 1 at Coil and Mauretania Streets was completed in the Ranger zone, pumping at the rate of 130 barrels of oil per day. Gravity of the oil was 16.8° API. The top of the zone in this well was 200 feet higher than in well "Watson" No. 2. The increased structural height and the higher gravity of the oil indicated a new field.

Figure 1. - Location of fault blocks VB and VI, Wilmington oilfield, California.
but interest was still lacking until November 1936, when General Petroleum Corp. of California completed Terminal well No. 1 in the Upper Terminal zone at a depth of 3,122 to 3,625 feet. Daily production was 1,500 barrels of 20° API oil per day. Before this well was completed, it was drilled to the schist basement, which was encountered at 6,787 feet. The cores taken from the well resulted in locating the Tar, Terminal, and Ford zones. Following completion of the well the drilling boom started. In November 1937 the Long Beach Harbor Department area was opened for drilling. On June 20, 1938, the Superior Oil Co. obtained the first Terminal-zone oil in well "1960 Community" No. 1, at Amor Place and El Dorado Street. The initial production from this zone was 3,280 barrels of oil per day.

The yearly rate of withdrawal from the Wilmington field is the highest in California. In 1955 the production of oil was 31,136,000 barrels. The cumulative withdrawal to January 1, 1956, was 730,542,000 barrels of oil. The areal extent of the proved area is 6,910 acres. In the development of the field from 1932 to 1956, 3,280 wells have been completed, and of these 467 have been abandoned. The number of active wells is 2,813. In the production of oil, its nearest competitor in the State is the Ventura field.

The Wilmington field is badly faulted. The six main fault blocks have been designated by Roman numerals I to VI and the large subfault blocks by the suffix A, B, and D. The fault blocks of most interest are: I, II, II-A, III, IV, IV-A, IV-B, IV-AB, IV-D, V, V-A, V-B, VI. The east boundary of block I and the west boundary of block II is the Wilmington fault, which has east; the east and west boundary of II and III is the Ford fault, which has east; III and IV, Power Line fault, which has west; IV and V, the Harbor Entrance; V-A and V-B, the Allied, which has east; and V-B and VI, the Daisy Avenue, which has east to the west. The north and south boundaries of the oil reservoir are the oil-water contacts.

The seven separate oil-producing zones in the Wilmington field, in order of depth, are: Tar, Ranger, Upper Terminal, Lower Terminal, Union Pacific, Ford, and "237." The Annual Review, 1955, Conservation Committee of California Oil Producers, lists the production of Tar-zone oil from all but block VI; the Ranger and Upper and Lower Terminal all blocks; Union Pacific all but block I; Ford all but block III (because block III is not deep enough); "237" all but block III (because block III is not deep enough), block V, and block VI. The API gravities of the oil from the zones are as follows:

<table>
<thead>
<tr>
<th>Zone</th>
<th>API gravity</th>
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<tbody>
<tr>
<td>Tar</td>
<td>12° - 18°</td>
</tr>
<tr>
<td>Ranger</td>
<td>13° - 24°</td>
</tr>
<tr>
<td>Upper Terminal</td>
<td>15° - 27°</td>
</tr>
<tr>
<td>Lower Terminal</td>
<td>18° - 29°</td>
</tr>
<tr>
<td>Union Pacific</td>
<td>25° - 30°</td>
</tr>
<tr>
<td>Ford</td>
<td>28° - 31°</td>
</tr>
<tr>
<td>&quot;237&quot;</td>
<td>28° - 30°</td>
</tr>
</tbody>
</table>

The general trend of the API gravity of the oil decreases from block to block in the direction of the apex of the structure and increases with depth.

Geology

The upper formation from the surface to a depth of 800 feet is the Quaternary and Pleistocene (San Pedro), and the next 900 feet is the Upper Pico-Pliocene. Following, in order of depth, are: Middle Pico (Pliocene); Repetto (Pliocene); and Puente (Miocene).
The thickness of the Repetto beds increases downdip and on the downthrow side of all the faults. The thickness of the Puente beds is fairly uniform throughout the field. The variable thickness of the Repetto section to the structural features suggests that progressive folding and faulting occurred during the deposition of the Repetto beds. The folding and faulting of the Repetto and the Puente are not found in younger sediments. The Quaternary and the Pleistocene (San Pedro) consist of fresh-water sand, gravel, and clay; alternate siltstones and sands in the Upper and Middle Pico; siltstone, sands, and green and gray shale at the top grading to brownish-gray shale and fine-grain sand at the bottom in the Repetto; and unconsolidated fine sands and friable siltstone at the top of the Puente, grades into firm, coarse-grained sands and hard brown shale at the bottom.

The Middle Pico lies unconformably on the Repetto, and the Puente lies unconformably to the basement - a schist of probably Jurassic age. The deposition of the sediments over an existing ridge of the basement schist and a subsequent uplift of the area have resulted in the Wilmington and Torrance anticlines. The Tar and upper part of the Ranger zones are in the Repetto (Pliocene) and the lower part of the Ranger zone, the Upper and Lower Terminal, Union Pacific, Ford and "237" zones are in the Puente (Miocene).

The sediments have been laid so prominent markers for the zones and the subzones are present and can be located readily throughout the field by electric logs. The marker for the top of the Tar zone is identified by T; Ranger, F; Upper Terminal, HX; Lower Terminal, AA; Union Pacific, AE; Ford, AO; and "237", BA.

An electric log typical of that measured in blocks V and VI is shown in figure 2. The log shows the 7 major sand beds in the Upper Terminal and the 4 sand bodies in the Lower Terminal. The seven sand bodies in the Upper Terminal are: HX-J, J-Y, Y-K, K-Z, Z-W, W-A, and A-AA; and those for the Lower Terminal are: AA-AB, AB-AC, AC-AD, AD-AE. The edgewater location for each sand body is different. The upper and lower sediments are in the Puente series of Miocene age. The sediments of the Upper Terminal are poorly sorted, loosely consolidated, silty to medium grained sand interbedded with layers of brown silty shales. The degree of consolidation increases with depth.

HISTORY OF GAS INJECTION

By 1951 several pools in the Terminal zones had secondary gas caps. When the production from the high gas-oil ratio wells in the gas caps was curtailed the recovery efficiency improved. This was shown by a unit of the Union Pacific Railroad Co. and the General Petroleum Corp. in the Terminal zone block II and a unit of the Harbor Department in the Terminal zone VB and VI.

Because of the favorable results in conserving gas, petroleum engineers of the Harbor Department recommended that a study be made to determine if the injection of gas into pools VB and VI would be advantageous. Subsequently the Board of Harbor Commissioners of Long Beach retained a petroleum consultant to make an independent study. Following his affirmative recommendation, a detailed petroleum-engineering study of the technical details was made. The result was a plan to inject gas into Lower Terminal zones and the subpools HX, J and Y, and K, Z, W, and A of the Upper Terminal zone; all in fault Block VB. Six million cubic feet of gas per day was to be injected in the lease of the Long Beach Oil Development Co. Initially the gas was to be injected proportionate to the oil volume of the three Upper Terminal subpools and Lower Terminal zones. Later an expansion to the Richfield Oil Corp. "Parcel A" in fault block VI was planned. The Harbor Board of the City of Long
Figure 2. - Typical electric log.
Beach approved the gas-injection program by resolution HD 465 on May 19, 1952, and the project was begun. In the early part of May 1953 the compression plant was ready for use. Meanwhile several high gas-oil-ratio wells, which previously were shut in to conserve gas, had received the necessary remedial work to convert them into gas-injection wells.

On May 6, 1953, injection of gas was begun in the Long Beach Harbor Department Well J-45 in the Upper Terminal MX sand and the Long Beach Harbor Department Well J-5 in the Upper Terminal K sand. By the end of May a total of 6-million cubic feet of gas was being injected into 7 wells daily. Three million cubic feet was distributed to the Upper Terminal through 4 injection wells and 3 million cubic feet to the Lower Terminal through 3 injection wells.

In October 1953 the program was expanded by injecting gas in the Upper Terminal zone, block VI, using the Long Beach Harbor Department well A-170 for an input well. Later, Well A-168 also was used to inject gas into Upper Terminal zone block VI and Well A-88 into the Upper Terminal block VB. The injection rate was expanded to 9.5 million feet in August 1954. This rate is being maintained currently.

Bypassing

Owing to the difference in the ability of the several sand bodies in the various pools to transmit fluids, unbalanced injectivity resulted soon after gas injection was begun. Also, the highly permeable streaks in some sand bodies permitted gas to flow through the reservoir sands to the producing wells without recovering oil efficiently. The degree of bypassing was found to vary widely in the subpools of the injection project, ranging from 0 to 80 percent. In the pools where the bypassing was excessive, a committee composed of the engineering representative from the Long Beach Oil Development Co., Richfield Oil Corp., and the Long Beach Harbor Department, recommended and instituted remedial measures. These consisted of:

1. Injecting the gas through a "stinger," that is, extending the tubing to the bottom of the well - in some wells the stinger is immersed in oil;
2. Injecting oil to selectively plug the more permeable sands;
3. Curtailing the oil production from the output wells, to which gas was bypassing, to create a back pressure in the more permeable sands;
4. Sealing the highly permeable sands with plastic and cement;
5. Increasing the gas-injection rate in sands having the smallest degree of cycling; and
6. Using Camco valves in the tubing and packers between the casing and the tubing to control the injection rate into the separate sands. The latter was the last method to be tried and proved to have the most merit.

Wells J-4 and J-16 were redrilled and completed as injection wells, using Camco valves. Selective injectivity had been complicated by the use of old oil wells instead of new wells which would have been drilled and completed specifically for use as gas-injection wells.

Plugging Injection Wells

After a sustained shutdown, serious loss of injectivity occurred in some wells when the rate of injecting gas into the pools was reduced. Because the gas is very dry, probably the oil is stripped of the lighter fraction leaving a tarry residue that is held aside during the gas injection but flows to the well bore and plugs the sand when gas injection ceases for any length of time.
UPPER TERMINAL ZONE, FAULT BLOCK VB

As gas was injected into 3 different zones, which are nearly equivalent to 3 different fields, each zone will be treated separately.

The first zone to be discussed - the Upper Terminal zone fault block VB - lies at the eastern section of the Wilmington field. Figure 1 shows the location of fault block VB with respect to the rest of the field. The zone lies mostly under piers A and B and the ocean east of pier A. (See fig. 3.) The west boundary of the zone is the Allied fault, which lies under piers C and A; and the east boundary of the zone, the Daisy Avenue fault, which lies parallel to the Allied fault and passes under the east tip of pier A. The faults are about 4,000 feet apart. The original north and south boundaries of the top of the HX sand are the edgewater contacts near the 3,000-foot contour. These boundaries are about 3,200 feet apart. The north and south original edgewater boundaries of the J, Y, K, Z, and W sands of the Upper Terminal all differ from that of the HX. The original edgewaters of the K sand are the farthest north and south, and the edgewater contacts are about 5,000 feet apart; the Z sand is next, 4,800 feet apart; J sand, 4,200 feet apart; W sand, 3,900 feet; Y sand, 3,300 feet; and A sand, 3,200 feet. The position of the original edgewater contacts are shown in Figure 4, the north-south section of the Upper and Lower Terminal zones, fault block VB.

The amount of closure between the apex of the upper HX sand and the edgewater is about 100 feet. For the K sand the closure is 300 feet; for the other sands the closure is within this range. The slope between the 2,900- and 3,000-foot contours is about 10 feet per 100 feet or 10 percent. This amount of slope is an aid to gravity drainage and probably has contributed to formation of a secondary gas cap.

Completion Practice

Before 1950 water-base mud was used in drilling through the oil zone. The wells were completed by gravel packing. The mud was thinned with water and surged through the perforations to remove the plugging material from the perforations and the gravel pack. After 1950 oil-base mud was used in drilling through the oil zones, and oil was used to wash the plugging material from the perforations and the gravel pack.

Reservoir Data

There are 423 acres between the fault blocks and the edgewater of the oil-saturated sand of the Upper Terminal zone fault block VB. The normal thickness of the zone is 400 feet, and the average thickness of the "pay" sand is 276 feet. The sand volume is 423 acres times 276 feet or 116,700 acre-feet. The average porosity of the sand is 33 percent, and the pore volume is therefore 0.33 times 116,700 or 38,510 acre-feet. The average percentage of the pore space filled with interstitial water is 29, leaving 38,510 times (1.00 - .29) or 27,342 acre-feet of void space containing originally an oil having a bubble-point formation-volume factor of 1.086 at an estimated original pressure of 1,350 p.s.i.g. at a datum depth of 3,300 feet. This results in a calculated 196 million barrels of tank oil originally in place. The original gas in solution was 33 billion cu. ft. or 170 cubic feet per barrel. The average API gravity of the stock-tank oil is 20.3°. The viscosity of the oil in place containing 170 cubic feet per barrel of gas at a reservoir temperature of 151° F, is 10.6 centipoises. The oil sample for the pressure-volume-temperature and viscosity measurements was taken from well Zl-32.
Figure 3. Contours on marker HX, Upper Terminal zone, fault blocks VB and VI, Wilmington field, California.
Figure 4. - North-south section along Z, Z-1 boundary line, Upper and Lower Terminal zones, fault block VB, Wilmington field, California.
The arithmetical average permeability to air of the pay sand is about 510 millidarcys, which is much more conductive than the average oil-producing sand. A permeability of this order would be favorable to gravity drainage.

The average initial productivity index was 3.5 barrels per day per p.s.i. pressure drop.

The edgewater has not been active enough to prevent the loss in pressure of 1,450 to 480 p.s.i. and formation of a secondary gas cap.

Reservoir Performance and Gas Injection

The first well was completed in the Upper Terminal zone, fault block VB, on July 13, 1945, and the initial production was 320 barrels of clean oil per day with gas-oil ratio 800 through a 28/64-inch choke. Thirteen additional wells were completed from August 1947 to February 1948, as shown in figure 5. Oil production from the 14 wells was 2,400 barrels per day or 170 barrels per day per well. Drilling was suspended until May 1950. From May 1950 to February 1951, 78 wells were completed, and in February 1951, 94 wells were producing oil at a rate of 15,500 barrels per day or 165 barrels per day per well, which was about the highest rate of production obtained from the zone. At the start of gas injection in April 1953, the rate from 100 wells had dropped to 8,800 barrels per day or 88 barrels per day per well. The rate continued to drop until 5 months after gas injection was begun, when the rate " leveled out" at about 6,600 barrels per day. The decline in the number of barrels of oil produced per well ceased and leveled out 4 months after gas injection. Four months after gas injection the number of barrels per day per well remained in the range of 60 to 70 barrels per day per well until January 1, 1956, the last date data were obtained. Thus the benefits of gas injection are shown because the decline in oil production per well per day was arrested.

The percentage of water withdrawn with the oil remained low (2 to 3 percent) until January 1950, then the "cut" steadily and continually increased. At the start of gas injection (May 1953) the cut was 41 percent, and 3 months later it was 50 percent. The rate of increase in the water cut has slackened because of gas injection. As of January 1, 1956, the water cut was 62 percent. The source of a considerable volume of the water is the north flank of the K sand.

The initial reservoir pressure in the zone at 3,300 feet was 1,350 p.s.i., and it decreased gradually with the withdrawal of oil. At the start of gas injection the pressure in the HX sand was 630 p.s.i., J-Y sand 530 p.s.i., and K-Z sand 410 p.s.i. The injection of gas into the HX subpool was discontinued August 1954. Large percentages of gas had to be recycled through this sand, and the subpool may have been aided by the injected floodwater coming around the end of the adjoining minor fault. If this were the situation, the gas injection of the HX sand would be unduly credited. As of January 1, 1956, or 2-3/4 years after gas injection had been undertaken, the pressure in the J-Y sand was 510 p.s.i.g. and K-Z sand 410. The composite pressure was 480 p.s.i. This shows that the withdrawal of 6,430,000 barrels of oil from the HX-AA sand members and 3,680,000 barrels of oil from J-AA did not change the pressure appreciably after gas injection. The trend of the weighted average pressure, as shown in figure 6, is about the same.

The current gas-oil ratio has the general characteristics in that the peaks in the rate of oil production are followed by peaks in gas-oil ratio. The initial gas-oil ratio of 800 cubic feet per barrel increased gradually, except for a peak of 3,000 in August 1947; it increased to 2,500 in September 1948, then dropped and
Figure 5. - Pool performance curves, Upper Terminal zone, fault block VB, Wilmington field, California.
Figure 6. - Curves showing the effect of gas injection on pressure and gas-oil ratio, Upper Terminal zone, fault block VB, Wilmington field, California.
varied between 800 to 2,000 during the following 4 years. Before gas injection, the decreasing trend of the gas-oil ratio, due in part to shutting in high gas-oil-ratio wells, and the increasing trend of water production with the oil suggests that gravity drainage and the movement of the edgewater have aided recovery.

After gas injection the current gas-oil ratio increased to about 1,200, and the net gas-oil ratio averaged about 600 cubic feet per barrel, showing that the gas injection had decreased the quantity of net gas required to produce a barrel of oil and therefore was a material aid in recovering oil.

LOWER TERMINAL ZONE, FAULT BLOCK VB

The Lower Terminal zone, fault block VB, is at the eastern end of the Wilmington field and lies directly under the Upper Terminal zone. Figure 1 shows the location of the zone with respect to the rest of the field. The east and west boundaries - Daisy Avenue and Allied faults - of the Lower Terminal, fault block VB, are closer in the Lower Terminal zone than in the Upper Terminal zone, because the Daisy Avenue fault hades to the west and the Allied fault hades to the east. The faults are about 3,250 feet apart at the top of the Lower Terminal (AA marker, see fig. 7). At the HK marker, the top of Upper Terminal zone, they are 4,000 feet apart. The original north and south boundaries of the Lower Terminal, fault block VB, are the edgewater contacts, which are different for each sand member and vary widely within the same sand member. The original north and south edgewater boundaries of the upper AA sand member were about 3,300 feet apart. The corresponding boundaries for the lower AA sand member were about 1,700 feet apart. The original edgewater contacts for the remaining AB, AC, AE, and AD sand members were about 1,700 to 3,300 feet apart. The approximate position of the original edgewater contacts is shown in figure 4.

The amount of closure between the apex of the upper AA sand and the edgewater is about 100 feet, and for the lower AA the closure is about 50 feet. The closure of other sand members varies between 50 and 100 feet. The slope near the apex is less than down the flanks. The average slope on the AA marker is about 8 percent. This amount of slope could aid gravity drainage.

Completion Practice

The wells in the Lower Terminal zone were completed similarly to those in the Upper Terminal zone.

Reservoir Data

The area between the fault blocks and the edgewater of the oil-saturated sand for the Lower Terminal, fault block VB, is 381 acres. The normal thickness of the zone is 520 feet, and the average thickness of the "pay zone" is 187 feet. The sand volume is 187 feet times 381 acres or 71,200 acre-feet. The average porosity of the sand is 30 percent, and the pore space is therefore 0.3 times 71,200 acre-feet or 21,400 acre-feet. The average percentage of the pore space filled with oil is 63 percent of 21,400, or 13,480 acre-feet of oil having a bubble-point formation-volume factor of 1.123 at an estimated initial pressure of 1,670 p.s.i.g. at a datum depth (vertical subsea) of 3,800 feet. Based on these reservoir data, the calculated tank oil originally in place was 93 million barrels. The original gas in solution was 21,850,000 M cu. ft. or 235 cubic feet per barrel of oil. The average API gravity of the tank oil is 26.1°. At a temperature of 163° F, the viscosity of the oil in place, containing 235 cubic feet of gas per barrel, according to the data on a sample of oil taken from well Z-41, is 4.0 centipoises.
Figure 7. - Contours on marker AA, Lower Terminal zone, fault blocks VB and VI, Wilmington field, California.
The arithmetical average permeability to air of the pay sand is about 266 millidarcies, which is conductive enough to aid gravity drainage.

The edgewater has not been active enough to prevent the loss in pressure from 1,670 p.s.i. at the time of discovery to 550 p.s.i. just before gas injection.

The average initial productivity index was 3.0 barrels of oil per p.s.i. pressure drop.

**Reservoir Performance and Gas Injection**

The first city well was completed in October 1939, and the initial production was 600 barrels of oil per day, with a gas-oil ratio of 1,120 cubic feet per barrel producing through an 18/64-inch choke. The general development of the zone started December 5, 1944, with completion of well 21-07. By November 1951, 33 wells had been completed, and the combined production was 5,950 barrels per day, the peak rate of oil production from the zone. At that time the daily rate of oil production per well was 180 barrels. By May 1953, the start of gas injection, the production from 32 wells had dropped to 4,450 barrels of oil per day - a daily production of 139 barrels per well, as is shown in figure 8. Four months after gas injection the rate of decline in production established before gas injection had decreased, and the oil production per well leveled out to 90 to 110 barrels per day and remained within this range until January 1, 1956, the last date for which data were obtained. Thus the benefits of gas injection are indicated by arresting the decline in the daily oil production per well.

The percentage of water produced with the oil remained low (0.5 to about 5 percent) until August 1949, after which the "cut" was between 6 to 10 percent until November 1951. After November the "cut" increased steadily to 42 percent until October 1954, 18 months after gas injection. It remained near that level, thus showing the delayed influence of gas injection.

The initial pressure in the zone at the datum depth of 3,800 feet was 1,670 p.s.i., and the pressure decreased gradually with the withdrawal of oil. At the start of gas injection the pressure was 600 p.s.i. The pressure, as of January 1, 1956, 2-3/4 years after gas injection, was 550 p.s.i. Thus, the withdrawal of 3,515,000 barrels of oil did not materially change the pressure after gas injection.

The weighted average pressure, as is shown in figure 9, dropped 50 p.s.i. during the withdrawal of the 3,515,000 barrels of oil. This is a small pressure loss compared to the pressure loss prior to gas injection.

The initial gas-oil ratio was 1,900 cubic feet per barrel as of January 1, 1945, and had increased to 3,300 cubic feet per barrel by January 1, 1947. The rate then began to decline and within 11 months it was approximately 1,500 cubic feet per barrel. For 5 years it remained between 1,500 and 1,000 until gas injection was begun, when the net gas-oil ratio decreased and remained at an average of about 750 cubic feet per barrel for the remainder of the 2-3/4 years after gas injection, the end of the period for which data have been obtained. The decrease, after gas injection, in the net gas-oil ratio required to produce 1 barrel of oil shows the material aid to the recovery of oil as a result of gas injection.
Figure 8. - Pool performance curves, Lower Terminal zone, fault block VB, Wilmington field, California.
Figure 9. - Curves showing the effect of gas injection on pressure and gas-oil ratio, Lower Terminal zone, fault block VB, Wilmington field, California.
UPPER TERMINAL ZONE, FAULT BLOCK VI

The Upper Terminal zone, fault block VI, is in the extreme eastern end of the Wilmington field. As of October 1956 the eastern and southern limits of Upper Terminal fault block VI had not been completely determined by drilling. The boundary between fault block VI and the adjoining fault block VB on the west (fig. 3) is the Daisy Avenue fault. On a northeasterly radial line from the apex of the zone and at right angles to the contour line (fig. 3), the distance to the original edgewater contact for the K sand member is 2,800 feet; for the Z and Upper HX sands, 2,650 feet; for the J, W, and Upper Y sands, 2,000 feet; and 1,900 feet for the Middle HX, and Lower Y sands.

The contour lines show that the zone has the shape of a half dome, with the apex at the middle of the Daisy Avenue fault (fig. 3). The amount of closure between the apex and the original edgewater contact, as measured on the northeasterly radial line, for the Upper HX and Z sands is 250 feet and for the J, Y, W, A, and Middle HX sands, about 150 feet. The slope of the productive sands is less near the apex than down the flanks.

The slope along the northeasterly radial line between the 2,850- and the 2,900-foot contours is 7 percent and between the 2,900- and 2,950-foot contours it is 12 percent. Between the 3,000 and 3,050-foot contours the slope of the sands is 17 percent. This amount of slope is an aid to gravity drainage.

Completion Practice

The Upper Terminal zone, fault block VI, is under the floor of the ocean and a considerable distance from Pier A. The wells were drilled directionally into the zone from Pier A at an appreciable angle. The bottoms of many wells measured horizontally are 2,700 to 3,000 feet from the wellheads.

Reservoir Data

The estimated area of the oil sand in the Upper Terminal zone, fault block VI, from which oil is being produced is 404 acres. The normal thickness of the zone is 540 feet, and the average thickness of the pay sand is 260 feet. Sand volume is 260 feet times 404 acres or 105,000 acre-feet. The average porosity of the sand is 38 percent, and the pore space is 38 percent of 105,000 acre-feet or 40,000 acre-feet. The average percent of the pore space filled with interstitial water is 40 percent, leaving 40,000 times 0.60 or 24,000 acre-feet of pore space containing originally an oil having at the bubble point a formation volume factor of 1.09 at an estimated initial pressure of 1,450 p.s.i.g. at a datum depth (vertical subsea) of 3,300 feet. Based on the reservoir data, the calculated tank oil originally in place was 170 million barrels. The original gas in solution was 27.5 billion cu. ft. or 165 cubic feet per barrel of oil. The average API gravity of the tank oil is 21°. At a temperature of 151° F., the viscosity of oil in place, containing 165 cubic feet of gas a barrel, is 15.0 centipoises. The arithmetical average permeability of the pay sand is about 1,400 millidarcies which is more conductive than many reservoir sands. For such a conductive sand, gravity drainage should be effective.

The edgewater has not been active enough to prevent the loss of pressure from 1,450 p.s.i. at the time the first well was drilled to 850, 750, and 600 p.s.i. for the sand members HX, J-Y and K-Z-W-A, respectively, just before gas injection.
The average initial productivity index was 3.0 barrels of oil per p.s.i. pressure drop.

Reservoir Performance and Gas Injection

Since the first well was drilled, the number of completions averaged about 4 wells per year, and by the time gas injection was begun (November 1953) about 6 years later, the production from 24 wells was 3,600 barrels of oil per day - daily production of 155 barrels of oil per well, as shown in figure 10. This rate of production was only 660 barrels per day less than the peak daily production of 4,260 barrels per day - a daily production of 162 barrels of oil per well. The peak of 4,260 barrels was exceeded after gas injection in June 1955, when the daily production of oil was 4,500 barrels per day from 34 wells or a daily production of 135 barrels of oil per well.

Six months after gas injection was begun the declining trend in the daily rate per well "levelled out." This could be due in part to the increased number of producing wells besides the gas injected.

The percentage of water produced with the oil varied, but the general trend of the percentage of water withdrawn with the oil was upward. After completion of additional wells the trend was slowed or decreased for a short time. At the end of the second year the "water cut" was 3 percent, at the end of the fourth year 9 percent, and at the end of the sixth year (2 months after the start of gas injection) 18 percent. Between the 11th and 15th month after gas injection, the "water cut" dropped to about 13 percent, owing to the effect of gas injection and new completions.

Initial pressure in the zone at the datum depth of 3,300 feet was 1,450 p.s.i., and the pressure decreased until the time of gas injection when the pressure was 850 p.s.i. in the HX sand; 750 p.s.i. in the J and Y sands; and 600 p.s.i. in the combined K, Z, W, and A sands.

The initial gas-oil ratio was 1,000 cubic feet per barrel, and a peak gas-oil ratio of 1,700 cubic feet per barrel was reached in July 1949, 16 months later. It remained between 1,500 to 1,000 until July 1952, when it dipped to 800 and then increased to about 900 to 1,000 range. At the start of gas injection the gas-oil ratio was 1,000 cubic feet per barrel and the net gas-oil ratio immediately dropped to and remained less than 1,000, thus showing the benefits of gas injection by the production of oil with less net gas per barrel of oil.

CONCLUSIONS

The reservoir performance of the three zones (Upper and Lower Terminal in fault block VB, and Upper Terminal, in fault block VI) showed that the gas injection has aided in the recovery of oil. Owing to gas injection, the long-term decline in the reservoir pressure has either leveled off, or the pressure has increased. Since gas injection was initiated, large quantities of oil have been produced from the zones. The small or negative pressure drop per barrel of oil required to produce the large quantity of oil after gas injection shows the benefits of gas injection.

The gas-oil ratio has followed a similar pattern. The net gas-oil ratio remained less than the current gas-oil ratio established before gas injection.

The production curves showing barrels per day per well indicated the benefits of gas injection. The decline in these curves was arrested by gas injection.
Figure 10. - Pool performance curves, Upper Terminal zone, fault block VI, Wilmington field, California.