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SECONDARY-RECOVERY POSSIBILITIES

OF

THE OLYMPIC FIELD

Hughes and Okfuskee Counties, Oklahoma

By

I. W. Fox, R. L. Ginter, and G. P. Alden

ABSTRACT

The Olympic field in the Seminole district of east-central Oklahoma embraces an area of 3,423 productive acres. The discovery well of the field was completed in the Cromwell sand of Pennsylvanian age July 19, 1934. The chief producing horizon in the field is the Olympic sand, a lenticular sandstone member of the Senora formation of Pennsylvanian age which is about 47 feet thick and is found at depths ranging from 1,633 to 1,920 feet. The productive area of the field is a narrow belt trending northeastward about 6-1/2 miles and ranging in width from half a mile to 1-1/4 miles. The accumulation of oil and gas occurs in a typical off-shore bar which by its structure controls distribution of the hydrocarbons. Horizons other than the Olympic sand and the Cromwell sand, such as the Calvin sand the the Gilcrease sand of Pennsylvanian age, and the Hunton limestone of Siluro-Devonian age have produced a small quantity of oil and gas.

After oil production was found in the Olympic sand, the field was rapidly defined, and development was completed by August 1937. Owing to the intense drilling activity, the field reached its peak

production from the Olympic sand in 1937, amounting to 11,564 barrels daily, and production declined rapidly thereafter.

The history of oil and gas production indicates that the Olympic reservoir produces by gas-expansion type of mechanism. Initial productivity of many oil wells ranged from 300 to 1,000 barrels of oil daily, and a few wells attained a maximum initial production of 2,000 barrels of oil per day. Oil production from wells on the flanks of the field was small, some wells producing as low as 5 barrels of oil during the first day of production. Production decline for most wells in this field was rapid and by July 1, 1946, the pr uction from all wells producing from the Olympic sand averaged 841 barrels of oil per day with about 500 barrels of salt water. The gravity of the oil ranges from 27° to 37° A.P.I., with an average gravity of about 35° A.P.I. gravity.

To July 1, 1946, the Olympic field had produced 13,202,944 barrels of oil from 347 wells producing from all the productive horizons in the field for an average recovery of 3,857 barrels of oil per productive acre. Of this volume of oil, 343 wells completed in the Olympic sand produced 12,989,817 barrels which was equivalent to a recovery of 3,795 barrels of oil per acre. Analysis of the reservoir-performance indicated that the volume of oil produced from the Olympic sand to July 1, 1946, was approximately 15.1 percent of the original 86,215,400 barrels of oil in the reservoir, or its equivalent of 25,187 barrels per acre. The 12,989,817 barrels of oil produced from the Olympic sand is equivalent to the volume of oil occupying 8.0 percent of the pore space in the reservoir. By continuation of present gas-injection methods of operation, it is estimated that the Olympic sand will produce ultimately about 14,376,000 barrels of oil. On July 1, 1946, the volume of residual oil in the Olympic sand was estimated to be 73,226,000 barrels, or 21,392 barrels of oil per acre. In equivalent terms, it may be expressed as the volume of residual oil occupying 45.3 percent of the voids in the Olympic sand.

It is estimated that gas-injection operations, embracing 870 productive acres of the Olympic sand by leaseholds, have produced 212,000 barrels of oil since the inception of these operations in August 1937. This additional volume of oil averaging 244 barrels of oil per repressured-acre resulted from the injection of 2,183,397,000 cubic feet of gas. This is equivalent to 12.0 percent of the 18,247,065,000 cubic feet of gas produced from the Olympic sand to July 1, 1946. The gross gas-oil ratio for the Olympic sand amounts to 1,405 cubic feet of gas per barrel of oil produced, whereas the net gas-oil ratio is 1,237 cubic feet of gas per barrel of produced oil.

The physical conditions of the Olympic sand body have been studied and the most favorable areas susceptible to the application of water flooding are cited together with the estimated oil reserves recoverable from these areas. The derivation of the recovery factor and its relation to the various classes of productive sand body are discussed in detail.

It is anticipated that future exploitation of the Olympic sand will entail the application of water-flooding methods of development.

The actual oil reserves and economic oil reserves of the Olympic sand, amounting to about 14,623,000 barrels of oil and 13,601,000 barrels of oil, respectively, have been computed volumetrically. Surface and subsurface water resources adaptable to the exploitation of the sand by water-flooding methods have been investigated. It is believed that future development of the field by water-flooding methods under present economic conditions will embrace about 2,775 productive acres which will yield approximately 13,601,000 barrels of oil equivalent to an estimated recovery of oil averaging 4,901 barrels per acre. The posted price of 35° A.P.I. gravity crude oil on July 1, 1946, was $1.25 per barrel. This market price was augmented by the subsidy which was paid by the Government amounting to 35 cents per barrel, making the effective price of crude oil about $1.60 per barrel in this field.

INTRODUCTION

Purpose of the Report

The application of secondary-recovery methods to oil fields producing from formations at depths heretofore usually considered to be below the range of profitable secondary exploitation by the method of water-flooding is being given the utmost consideration by many oil operators in view of the great demand for crude oil and the increasing consumption of petroleum and its products. Not only are these oil reserves of economic importance to the petroleum industry to help meet commitments for crude oil, but the profitable reclamation of such reserves is a conservation measure that will prolong the productive life of many oil producing properties.

In the past, water-flooding ventures in the Mid-Continent Region have been confined generally to formations such as the Bartlesville sand at shallow depths, though in a few fields water flooding has been profitably carried on at depths exceeding 2,000 feet utilizing spacing of 660 feet between like wells. Unquestionably, in many of the fields that have produced substantial volumes of crude oil from deeper formations by primary methods of operation and which are at present in the marginal "stripper" phase of their productive life, modern methods of secondary recovery may be successfully instituted. It is anticipated that the reclamation of these oil reserves may be accomplished profitably by utilizing the specific secondary method of operation involving either the injection of air, gas, or water into the oil reservoir. On the other hand, the successful application of these methods to oil fields producing from formations found at shallow and at moderate depths requires investigative studies of the technical problems involved in the development of the field by modern secondary practices. The technical phase of this problem is complex requiring not only investigative studies of principles of petroleum engineering, but also investigative work involving geologic and economic consideration.

The United States Geological Survey has been one of the pioneers in the publication of reports incorporating engineering and historical data pertaining to the application of secondary-recovery methods to specific oil fields. These reports were intended to stimulate interest in the practice of secondary recovery, but in essence were to aid operators in the selection of oil fields embracing Indian lands which may be exploited profitably by secondary-recovery ventures. This report on the secondary-recovery possibilities of the Olympic sand in the Olympic field, Hughes and Okfuskee Counties, Oklahoma, is one of a series of reports, 1/ 2/ 3/ on secondary-recovery program of studies on selected oil fields. It is the fourth report by the Special Studies Group of the Oil and Gas Leasing Division, Mid-Continent Region, U. S. Geological Survey concerning the application of secondary recovery to oil fields embracing restricted Indian lands over which the Department of the Interior retains jurisdiction for the benefit of the allottees.

The purpose of this report is to discuss the development-history and the relative geological and engineering data pertaining to the producing reservoir of the Olympic sand in the Olympic field, Oklahoma. Furthermore, by interpretation of the productive characteristics of the reservoir, it is the purpose to establish correlation between oil production and lithologic characteristics of the sand body as a criterion to designate areas in which secondary-recovery methods of exploitation may be feasibly and economically applied. With this in view, the commercial importance of gas-injection operations previously developed in the Olympic field and the engineering technique of the operations are discussed fully.

1/* Fox, I.W., Thigpen, C.H., Ginter, R.L., and Alden, G.P., A Study of Secondary Recovery Possibilities in the Hogshooter Field, Washington County, Oklahoma: U.S. Geological Survey, 1945.

2/* Fox, I.W., Thigpen, C.H., Ginter, R.L., and Alden, G.P., A Study of Secondary Recovery Possibilities in the Nowata-Claggett Field, Nowata County, Oklahoma: U.S. Geological Survey, 1945.

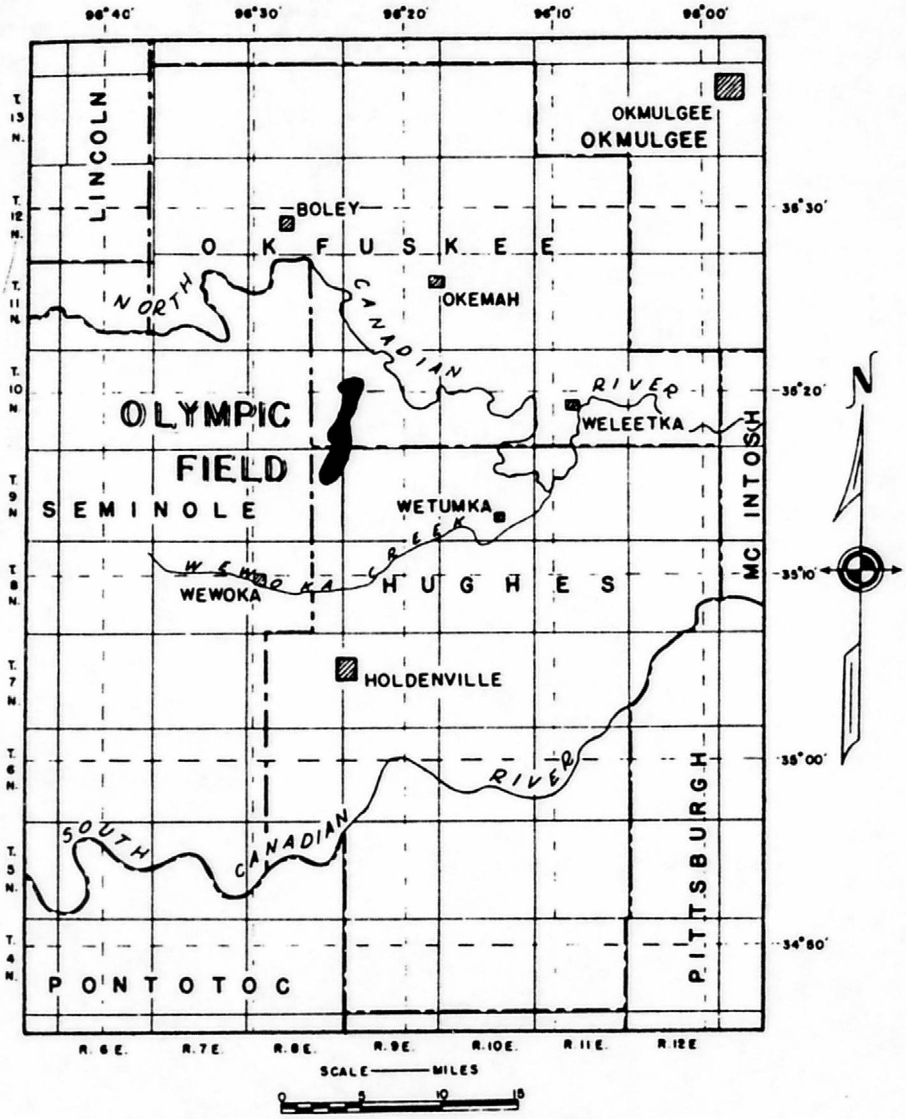
3/ Fox, I.W., Ginter, R.L., and Alden, G.P., Secondary Recovery Possibilities in the Western Part of the Delaware-Childers Field, Nowata County, Oklahoma: U.S. Geological Survey, 1948.

* Out of print.

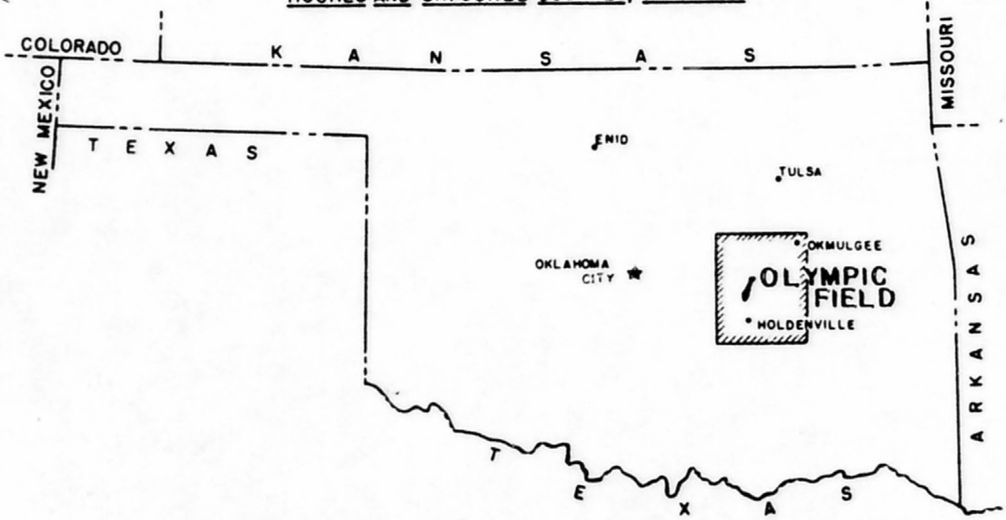
In view of the fact that future secondary exploitation of the Olympic sand in this field will probably include the application of water-flooding practices, the engineering techniques involved in this method of development and economics thereof are discussed. This report may be of particular interest to those operators who are concerned with the further development of properties by the application of secondary-recovery practices. In addition, it may be of interest to those individuals seeking some technical knowledge of a producing reservoir from which the production has declined through the "flush" production stage to the "settled" phase of production and still shows possibilities for future development by the application of secondary-recovery methods of operation.

Location and Extent of the Field

The Olympic oil field is in the southwestern part of Okfuskee County and the northwestern part of Hughes County, Oklahoma, about 50 miles east of the center of the state.(See pl. 1). The Standing Committee on Oil Field Nomenclature, Kansas-Oklahoma Division, Mid-Continent Oil and Gas Association, describes the field as embracing 9,120 acres in Tps. 9 and 10 N., Rs. 8 and 9 E. (See pl. 2). The developed part of the field, comprising 3,423 productive acres producing mainly from the Olympic sand, extends approximately N. 18° E. a distance of 6-1/2 miles. At its broadest part, the field is 1-1/4 miles wide, whereas at the narrowest part, it is about half a mile wide. The official description of the field by the Nomenclature Committee is as follows:



EXPANDED SECTION OF INDEX MAP SHOWING OLYMPIC FIELD, HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA



INDEX MAP OF OKLAHOMA SHOWING GENERAL LOCATION OF OLYMPIC FIELD

PLATE I

$S\frac{1}{2}$ sec. 7, $SW\frac{1}{4}$ sec. 8, $W\frac{1}{2}$ sec. 17, secs. 18 and 19,
$W\frac{1}{2}$ sec. 30, and $W\frac{1}{2}$ sec. 31, T. 10 N., R. 9 E.
$E\frac{1}{2}$ sec. 13, $E\frac{1}{2}$ sec. 24, secs. 25 and 36, T. 10 N., R. 8 E.
Secs. 1, 2, 11, 12, 13, and 14, T. 9 N., R. 8 E.
Sec. 6 T. 9 N., R. 9 E., Indian Meridian.

Data Examined

Because the Olympic field was developed in the latter part of the thirties at a time when operators were becoming fully aware of the technical importance of development and operational data of an oil field, more information has been recorded and been made available for analysis than for many earlier oil fields in Oklahoma. It was most opportune that complete oil production data were made available by operators and pipeline companies. These data together with complete well log records made the analysis of reservoir conditions in the Olympic sand more comprehensive. Much information concerning the gas production of the Olympic sand was available for this study. It was necessary, however, to estimate the gas production of a few leaseholds. This information and additional factual data were sufficient to show the development and operational history and geologic aspects of the field together with the behavior of the Olympic reservoir, characteristics of the sand body, present status of the Olympic field, economic aspects of oil and gas production, and oil reserves.

The analysis of reservoir conditions entailed the examination of 343 drillers' logs which disclosed pertinent data of all wells completed in the Olympic sand. Furthermore, four additional drillers' logs were obtained which pertained to wells completed in formations above or below the Olympic sand. Although 15 core analyses in addition to the aforementioned data were available, only two of these analyses presented information of the "pay" zone of Olympic sand body. The other 13 analyses presented information only for the interval from the Henryetta coal to the top of the oil "pay" zone in the Olympic sand.

The preparation of the development may (see pl. 2) included examination of many property maps of the operators and determination of the status and description of the wells in the field. Additional information for this report was acquired by interviewing operators and individuals who had been engaged in the development and operation of properties in this field.

Data Assembled

The technical data assembled for and the data included in this report conform to the requirements of modern development and operating practices. Fortunately, most of the pertinent data from which the principal conclusions were derived were readily obtainable though the preciseness of the data was often questionable. Nevertheless, a few data were not available and thus required postulation, particularly concerning the analysis of the reservoir performance. Much of these data, particularly with reference to interstitial water content, porosity, gas solubility, and shrinkage of the oil, were not determined by analytical methods and, perforce, were derived by indirect methods.

All oil produced from this field by the various leaseholds, which amounted to 13,202,944 barrels to July 1, 1946, from five producing formations, was compiled. Because a few producing zones in the field other than the Olympic sand produced some oil, estimation by decline-curves of the volume of oil produced from such zones was necessary. Of the cummulative oil production from the field, it was estimated that the Olympic sand produced 12,990,000 barrels to July 1, 1946.

The accuracy of some of the drillers' logs, especially as to the presence of the gas sand and the thickness of oil sand exposed in a few wells, is in doubt. Furthermore, many wells did not penetrate the Olympic sand completely, and for these wells the thickness of the sand was estimated from cross sections aligned through wells with recorded total thickness of sand. As the thickness of the Olympic sand has been estimated in many places by this method, it is reasonable to assume that the thickness of the sand will require determination by more precise methods, if future development of the reservoir by secondary methods is contemplated.

Many additional data concerning the development of the field and the performance of the reservoir were obtained and were incorporated in this report in the form of maps, plats, graphs, and tables supplementary to and in confirmation of the test. Included is the record of gas production from the Olympic sand and the gas-injection data. The presentation of all data concerning the performance of the Olympic sand reservoir in conjunction with the selection of areas favorable to exploitation by secondary recovery and estimates of reserves in these areas may prove to be of material aid to those operators interested in future development of this field. Reserve estimates, conclusions, and recommendations covered in this report are made as of July 1, 1946.

Acknowledgments

The investigation of secondary-recovery possibilities in the Olympic field, Oklahoma, was conducted by the U. S. Geological Survey. The work was done under the general supervision of J. R. Reeve, Supervisor, Mid-Continent Region, Oil and Gas Leasing Division, U. S. Geological Survey, Tulsa, Oklahoma, and under the direct supervision of I. W. Fox, petroleum engineer, U. S. Geological Survey, Tulsa, Oklahoma, the senior author of the report.

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Texas Company, The, Tulsa, Oklahoma

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HISTORY

Discovery and Development of Oil and Gas

The discovery well of the Olympic field, McCaslin Well 1, in the SE$\frac{1}{4}$ NW$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., was completed by the Olympic Oil Company, July 19, 1934, in the Cromwell sand at a total depth of 3,474 feet by the rotary method of drilling. Initial productivity of this well is recorded as being 25 barrels of oil hourly during a test period of 2 hours. In conjunction with the oil production the well produced 40 million cubic feet of gas daily. Although this was the discovery well of the Olympic field, it was not the discovery well of the Olympic sand. The well was drilled through and recorded the Olympic zone as micaceous sand at depths 1680-1720 feet, and showing oil saturation. The zone was not tested, however, for oil and gas production. The log of this well also recorded the Gilcrease sand between 3220-3235 feet with oil saturation in several places.

The Dixon-A Well 1, completed by the Manahan Oil Company on December 8, 1934, in the NE$\frac{1}{4}$SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., as a south-offset well to the discovery well of the field on the McCaslin leasehold, produced oil from the Cromwell sand for a time at a total depth of 3,456 feet, the producing zone being at depths between

3438-3456 feet. The Olympic zone in the Senora formation in this well was cored. The core consisted of sand at depths ranging from 1693-1700 feet; broken sand saturated with oil at depths ranging from 1700-1718 feet; and sand at depths between 1718-1751 feet. Little oil was produced from the Cromwell sand and the well was deepened by rotary-tools. Deepening started January 23, 1935, and was completed February 11, 1935, at a total depth of 4,279 feet in the Wilcox sand of Ordivician age. The Wilcox sand between depths 4277-4279 feet was proved to be barren of oil and gas production, but was found to be water bearing. The well was then plugged back to a depth of 1,737 feet and, after exposing the Olympic sand, was completed on July 17, 1935, with an initial production of 100 barrels of oil daily. It thus became the discovery well of the Olympic sand in the Olympic field.

The Olympic field might have been discovered earlier if a few of the wells that were drilled in this area to the Ordivician rocks had tested the oil and gas bearing properties of the Senora formation where the drillers' logs showed oil saturation in the sand. The most noteworthy of these wells is mentioned. John I. Cary, drilling contractor for the Independent Oil and Gas Company, drilled Carolina Well 1, in April 1924, in the SW¼ SE¼ SE¼ sec. 18, T. 10 N., R. 9 E. This well, drilled by cable-tool methods to a total depth of 3438 feet, tested the Cromwell sand at depths between 3433-3438 feet for oil and gas production. The log of this well showed that broken sand was found at depths between 1760-1836 feet, and in this section of sand, oil and gas saturation was reported at a depth of 1800 feet, presumably in the Senora formation. The productiveness of this zone was not tested, however, and the well was considered to be dry and was plugged and abandoned.

After active development of the Olympic sand had begun in the southern part of the field, a twin well to this dry hole, Fisher Well 1, was completed by the Ark Royalty Company on May 1, 1936, exposing the Olympic zone in the Senora formation at depths between 1764-1829 feet. In view of this, it is believed that the well drilled by the Independent Oil and Gas Company on the Carolina leasehold would have proved the oil and gas potentialities of the Olympic sand as early as 1924, had it been tested adequately.

An active drilling campaign followed the discovery of oil in the Olympic sand. The Olympic field was extended rapidly and the bounds of the field soon were defined either by dry holes or by wells with low initial productivity. Many wells producing from the Olympic sand were completed in 1935, but the peak of drilling activity was attained in 1936 when 178 producing oil wells were completed. During March 1937, 31 wells were completed and thereafter active development work diminished rapidly and had practically terminated by August 1937, although a few wells were completed as late as April 1938. Actually, 347 oil wells were completed in the Olympic field and of these wells 343 were completed in the Olympic sand.

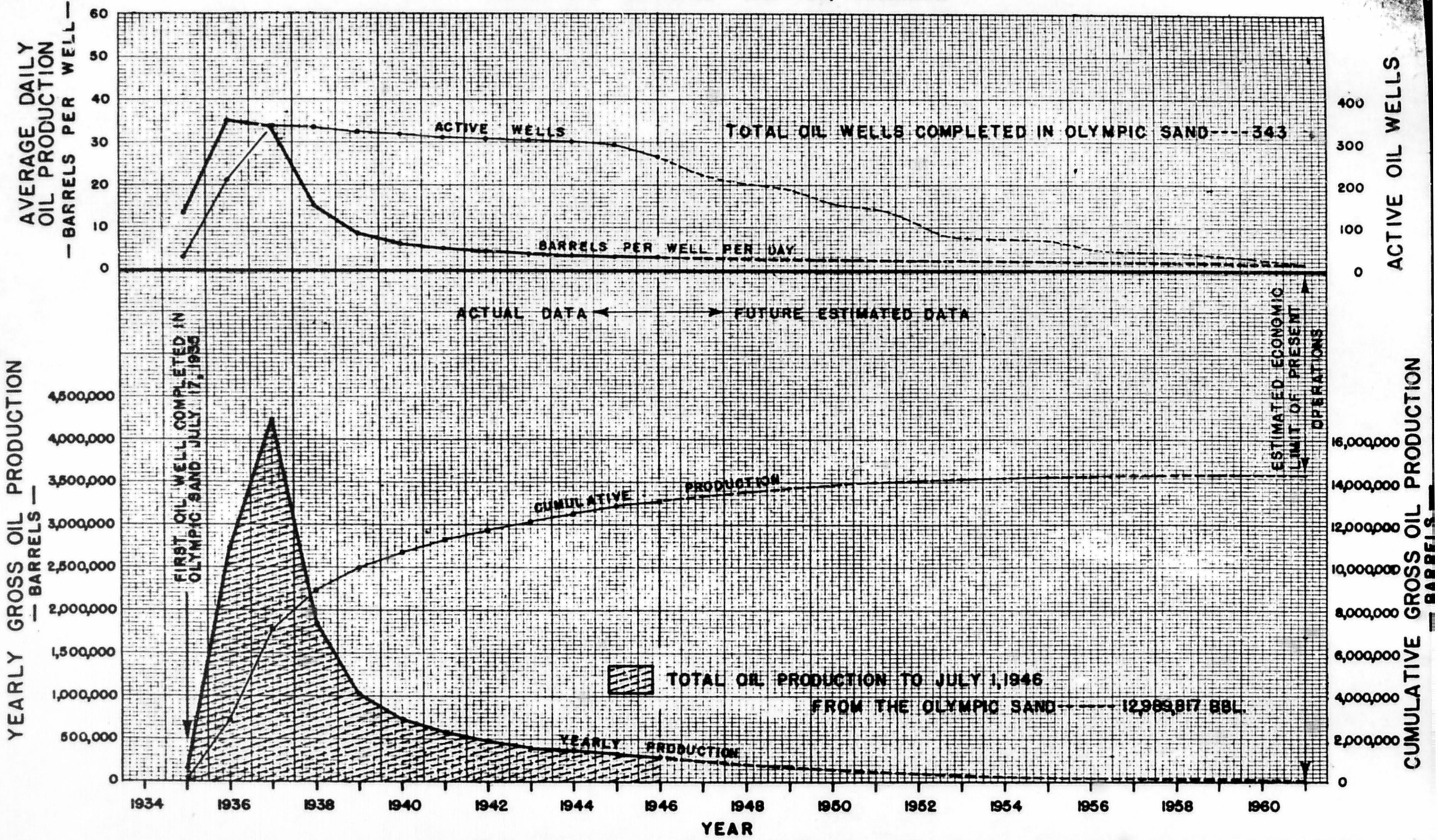
As drilling activity spread in the field, the oil production of the wells producing from the Olympic sand mounted proportionately, reaching the peak of 4,220,771 barrels for the year 1937, or an average of 11,564 barrels daily. (See pl. 3). The 1937 peak production

GRAPHS SHOWING

DEVELOPMENT, OPERATIONAL AND OIL PRODUCTION DATA OF THE OLYMPIC SAND

IN THE OLYMPIC FIELD

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA



of the field for all producing zones amounted to 4,238,505 barrels, or an average of 11,612 barrels of oil per day. (See pl. 4). Subsequently, the oil production declined rapidly and reached the period of settled production in 1942, during which year the Olympic sand produced about 1,326 barrels of oil daily, or an average of 4.3 barrels per well per day. During 1940-45, and especially in 1940-43, many old wells were deepened in the Olympic sand, and in a few of these wells the Olympic sand was exposed completely. The deepening operations were carried out on many leaseholds throughout the field.

Of the 347 oil wells completed in the Olympic field, all but four were completed in the Olympic sand; one well having been completed in the Calvin sand; one well producing from the Gilcrease sand; one well producing from the Cromwell sand and later the Hunton "lime", and one well producing from the Cromwell sand. Of further interest is the fact that a gas well in the NW¼ sec. 13, T. 10 N., R. 8 E. produces gas from the Gilcrease sand. The yield of oil from all formations other than the Olympic sand has been only a small percentage of the total production from the field to July 1, 1946, this volume being about 1.6 percent of the total oil production.

Drilling and Completion Methods

The rotary drilling method was used to develop the Olympic field almost exclusively. However, a few early wells were drilled by standard cable-tool methods. Many wells were drilled by the rotary method using light portable drilling machines and a few wells were drilled with heavier drilling equipment of the rotary type.

GRAPHS SHOWING

DEVELOPMENT, OPERATIONAL AND OIL PRODUCTION DATA

OF THE OLYMPIC FIELD

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA

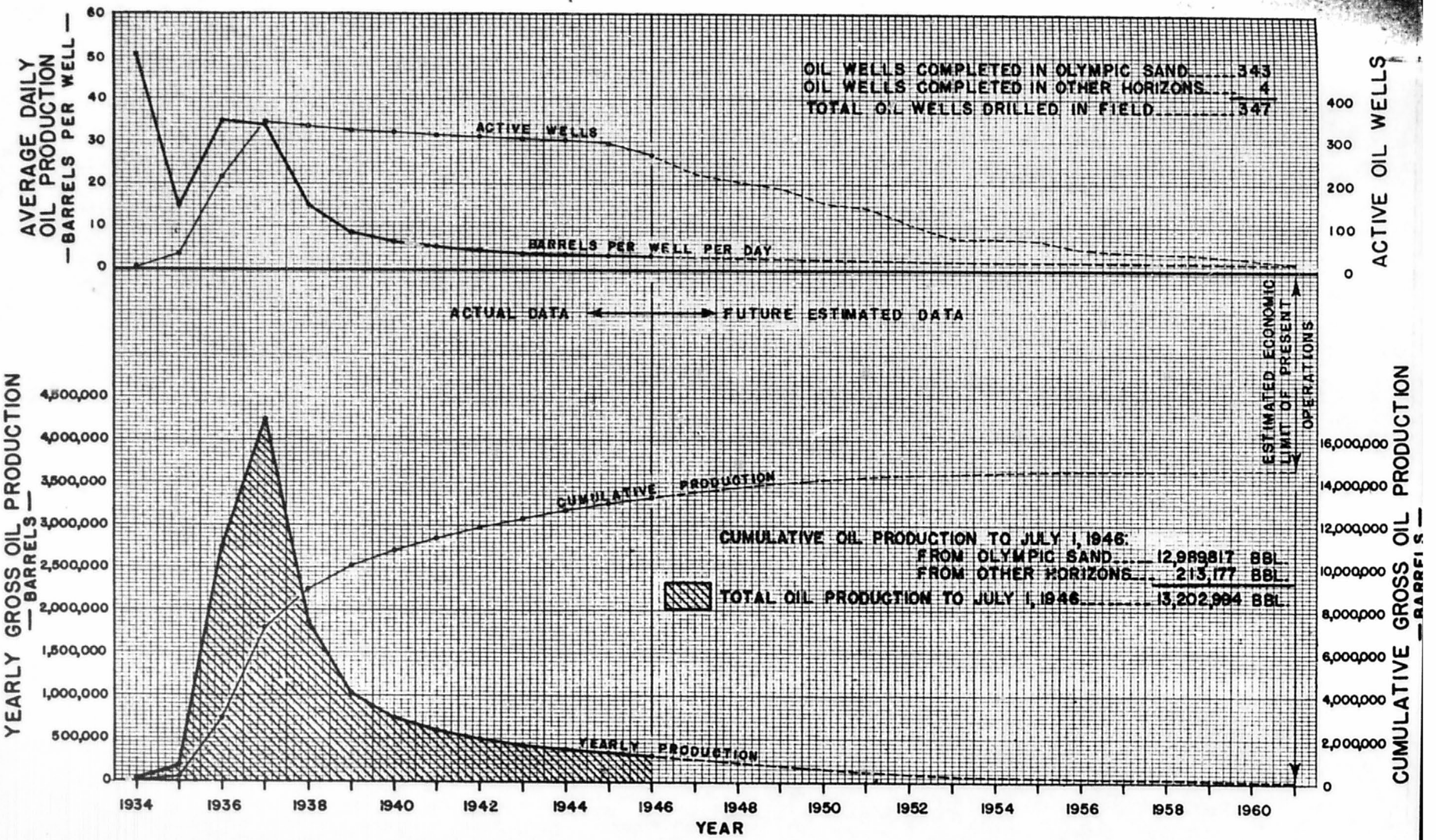


PLATE 10

The development of the Olympic field adhered to the conventional 10-acre spacing of wells except in the northern part of the field where a few small leaseholds required closer spacing of wells.

In drilling wells in this field, the usual practice was to set a conductor consisting of two or more joints of 10-inch, or 12-1/2-inch, or 15-1/2-inch casing through the surface soil, gravel, or quicksand, and to cement this casing with cement slurry amounting to 20 or 30 sacks.

In the early development of the field, it was common procedure to drill by rotary machine to a depth slightly below the Henryetta coal bed, and using this bed as a marker, to core the top of the Olympic sand or core until oil saturation was found in the sand, and then to cement 7-inch casing above the top of the Henryetta coal bed and drill the Olympic sand with cable-tool drilling machines. Owing to the continuity and uniformity of the Henryetta coal bed, it was used as a marker in all drilling operations. Furthermore, in a few wells it was used as a means to estimate the depth to the top of the Olympic oil sand, thus eliminating the necessity of coring to locate this zone. In other completion methods, 7-inch casing was cemented below the Henryetta coal in either a shale bed, in the top of the Olympic sand in the shale or gas cap zones, or at the depth where oil saturation was found to be present in the sand. The quantity of cement used in these cementing operations ranged from 75 to 200 sacks, but usually about 150 sacks were used.

In virtually all wells, the Olympic sand was shot with nitroglycerine. The charge ranged from 1 to 3 quarts per foot of sand

and aggregated about 10 to 70 quarts of explosive load. Common practice was to stem the explosive charge using 1-1/2 to 2 cubic yards of sand. The charge was exploded with either remote electrical control or by use of a clock-controlled bomb.

Initial Production

The initial production of wells producing from the Olympic sand in this field reflected the excellent productive characteristics of the Olympic sand reservoir. It indicated that in many parts of the field the Olympic sand was a very thick, highly permeable sand with a normal reservoir pressure for its depth. Initial productivity of the better wells was recorded on the drillers' logs to be as high as 2,000 barrels daily. However, most wells in the areas of thick sand produced 300 to 1,000 barrels per day initially. The initial production of most wells producing oil from the Olympic sand is shown by the initial production map. (See pl. 5). It is to be noted that the wells of large initial production lie in groups coinciding with areas of thick sand and trending usually in elongated zones with the long axis of the field. On the flanks of the Olympic sand body and in the northern part of the field, productivity rates ranged from 300 barrels daily initially to as low as 5 barrels per well per day, the average being about 150 barrels. The average initial production of all wells completed in the Olympic sand in 1935, was 394 barrels daily. In the succeeding years of development the average initial production of wells producing from the Olympic sand diminished gradually. In 1936 it was 296 barrels, and in 1937 it was 133 barrels per day.

TPS. 9 AND 10 N., RS. 8 AND 9 E.— HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA. PLATE 6

Many drillers' logs record a gas sand above the oil sand in the Olympic zone, especially those wells in T. 9 N., R. 8 E., in the southern part of the field, and those wells producing from the Olympic sand in the southern portion of T. 10 N., Rs. 8 and 9 E. Many of the wells completed in the Olympic sand in these areas produced substantial volumes of gas with the oil, the volume of gas gauging from 0.5 million to 8 million cubic feet of gas per day initially. Furthermore, in the NW$\frac{1}{4}$ NE$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 31, T. 10 N., R. 9 E., a well completed September 28, 1936, in the Olympic sand produced gas only; the volume of the gas, however, was not recorded. In the NW$\frac{1}{4}$ SW$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., a well completed in the Olympic zone produced considerable gas, and later after being deepened into the oil zone produced large volumes of gas and a small quantity of oil. The rock pressure of this well was recorded on the drillers' log as 575 pounds per square inch. In the SW$\frac{1}{4}$ SW$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., a well completed in 1935, produced 6 million cubic feet of gas and 25 barrels of oil per day initially from the Olympic sand with a recorded rock pressure of 732 pounds per square inch.

The initial production of wells producing oil or gas from formations other than the Olympic sand in this field is worthy of mention. A well in the SE$\frac{1}{4}$ NW$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., completed in the Cromwell sand at a total depth of 3474 feet, flowed initially 25 barrels of oil hourly during a 2-hour testing period. In addition this well tested 40,000,000 cubic feet of gas daily. This well was completed July 18, 1934, and on July 1, 1946 this well still was flowing at the rate of 35 to 40 barrels of oil and 500 barrels of water daily. A well in the center of the NE$\frac{1}{4}$ SW$\frac{1}{4}$ sec. 1, T. 9 N., R. 8 E., which was completed May 30, 1944, in the Gilcrease sand at a plug-back depth of 3250 feet produced initially 20 barrels of oil daily by pumping. On July 1, 1946, this well was not being produced. Of passing interest is the productivity of a well completed November 26, 1945, in the SE$\frac{1}{4}$ NE$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 13, T. 10 N., R. 8 E., which produced initially 8-1/4 million cubic feet of gas from the Gilcrease sand at depths between 3202-3250 feet. The rock pressure of this well was recorded as being 866 pounds per square inch.

Oil is produced from the Olympic sand by gas-expansion forces. Most wells completed in this sand produced initially large volumes of gas with the oil and a few flowed naturally for a short time after completion. In the early operation of the field, much gas was wasted resulting in rapid decline of both the rate of production and the pressure of the reservoir. The loss of this reservoir energy led to the early introduction of pumping operations when the wells ceased to flow. In pumping operations, the wells usually were connected to pull-rods and jack-pumped from band-wheel powers driven by gas engines. A few wells were operated by individual pumping units.

Many of the drillers' logs record the presence of salt water initially in wells that penetrated the Olympic sand on the west, south, and north flanks of the field. In the early development, the initial rate of water production usually ranged from 15 to 80 barrels daily, although one well was reported making 200 barrels of water per day initially. For this reason, many wells in the western part of the field were completed originally by penetrating only part of the Olympic sand. In the early forties, many of these wells were deepened and in a few places the wells were drilled so that they completely penetrated the sand. Generally no appreciable increase in water production was noted after exposure of the lower part of the sand in most of these deepened wells.

The wells classified as dry along the west, south, and north edges of the Olympic field usually were reported as exposing water-bearing sand in the Olympic zone. However, a few drillers' logs did not report water in the Olympic sand in wells otherwise known to be dry. On the east side of the field, water was not reported initially on the drillers' logs. As producing wells on the east side of the field have not produced salt water, it is believed not to be present here as edge water.

In the southern part of the field, but generally along the west flank of the sand body, water was found initially in many wells drilled below a depth of 926-930 feet subsea-level. Most of these wells have produced some salt water, but usually they have not shown appreciable increases in water production over the period of years in which they were produced. In the northern part of the field, the top of the Olympic sand is found in many wells below a depth of 926 feet subsea and in many of these wells with the exception of edge wells no appreciable water has been produced. In fact, the electric log of a gas well, completed in the early part of 1946 in the Gilcrease sand in the SE$\frac{1}{4}$ NE$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 13, T. 10 N., R. 8 E., records the top of the water-bearing sand at a depth of 1008 feet subsea-level. The twin well to this gas well was completed February 5, 1946, producing from the

Olympic sand initially at the rate of 36 barrels of oil and 360 barrels of water daily.

Accordingly, it is assumed that gas, oil, and water are separated gravitationally in the Olympic sand, the gas being present mainly up-dip and the water being present on the west, north, and south flanks of the field. However, there is no well-defined water level in the Olympic sand in this field.

Gasoline Extraction, Gas Injection, and Oil Production

An absorption gasoline plant, still in operation, was constructed in March 1936, to process the large quantity of available gas produced from the Olympic sand. The gasoline content of this gas on the basis of determinations made in the field by the compression method ranged from 0.4 to 2.6 gallons of gasoline per 1,000 cubic feet. The gas is absorbed in mineral seal oil at the absorption plant, and this enriched oil is transported to the distillation plant at Cromwell, Oklahoma, through a loop delivery system. The gasoline is recovered and the residue gas is returned to the Olympic field. The 8-single stage compressors at the absorption plant apply vacuum equivalent to 10 inches of mercury to the gathering system. In 1937, the gas gathering system was extended to many leaseholds in the northern part of the field in order to utilize most of the gas produced in the field. A portion of this gas is purchased by a utility company and the remaining gas is injected into the Olympic sand by means of the gas-injection system. In August 1937, two 165-horsepower compressors were added to the plant installation, and these were used to deliver gas at a pressure of 500 pounds per square inch to the gas line of a utility company and to the gas-injection system in the field.

Since the inception of gas-injection operations in August 1937 to July 1, 1946, the gas-injection system has injected 12.0 percent of the gas produced in the field from the Olympic sand. This gas was injected through a system comprising eight gas-input wells irregularly spaced throughout the field. This system of gas injection covered an area comprising 870 acres by leaseholds. Specifically, most gas has been injected into the Olympic sand in the southern part of the field. In essence, the gas-injection system acted as a disposal system for excess residue gas. The response to the injection of gas was a retarding effect on the decline of reservoir pressure and an increase in the rate of oil production. The injection of 2,183,397,000 cubic feet of gas has resulted in the reclamation of an estimated 212,000 barrels of additional oil to July 1, 1946, which is equivalent to an additional recovery over normal oil production of 244 barrels per acre. Oil production attributed to repressuring in proportion to the total oil production is nevertheless scanty, amounting to only 1.6 percent of the oil produced from the Olympic sand.

Oil production from the Olympic sand to July 1, 1946, amounted to 12,990,000 barrels, whereas, the Olympic field produced 13,202,994 barrels to July 1, 1946, from all producing horizons. The volume of oil produced from 3,423 productive acres of Olympic sand aggregated 3,795 barrels per acre to July 1, 1946. The better producing leaseholds have yielded as much as 8,782 barrels of oil per acre from the Olympic sand, and 20.5 percent of the productive acres have yielded 4,000 to 5,000 barrels of oil per acre. The best producing leaseholds are in sec. 1, T. 9 N., R. 8 E., and sec. 25, T. 10 N., R. 8 E., in areas where the Olympic sand attains its maximum thickness.

The productive life of the wells producing from the Olympic sand is influenced by the inherent conditions of the lenticular type of sand body. In areas where the sand attains its best productive characteristics, the wells on July 1, 1946, still were producing. At that time 287 oil wells were producing in the field and of these wells 286 were producing from the Olympic sand by pumping. Also, 15 leaseholds which had produced 215,187 barrels of oil from 25 oil wells had been abandoned. In areas where the sand body is thin, especially along the flanks of the Olympic sand, many wells have long been plugged and abandoned. Many of the wells in the field have produced a small volume of water, but in general the Olympic sand has not produced much water.

Oil production from the Olympic sand for the period January 1, 1946 to July 1, 1946, averaged 841 barrels of oil daily, or 2.9 barrels of oil daily per well. Estimated water production from the field during the same period was about 500 barrels daily. This water is injected into zones above the Olympic sand in this field through seven water-disposal wells.

GEOGRAPHY

Topography, Drainage, and Culture

The terrain of the Olympic field for the most part is a featureless plain with the exception of the southern part where the topography is broken by hills and gullies. From the north the surface slopes gently toward Little Wewoka Creek, a stream flowing southeastward across the southern part of the field. From Bald Mountain, a prominent feature of the hilly country in the south, the surface of the field slopes generally northeastward to the aforementioned stream. The altitudes of the field range from about 1,000 feet to 775 feet above sea level, or a maximum relief of approximately 225 feet.

Little Wewoka Creek, the principal stream draining the Olympic field, heads about 4 miles west and flows across the field southeastward to its junction with Wewoka Creek, a tributary of the North Canadian River. The North Canadian River is the principal stream in this general area and at its nearest point is about 2-3/4 miles northeast of the field.

The Olympic field is isolated from the communities and business centers of this district. The small community of Bearden on State Highway 56 is about half a mile east of the northern limits of the field. The field is not directly accessible by modern paved highways, but it can be reached from this type of highway by means of a system of graded roads. The town of Okemah on U. S. Highway 62 lies about 8 miles northeast of the field. From here the field can be reached by means of State Highway 56, via the towns of Bearden or Cromwell, and by use of branching roads.

Farming in this area is of little economic importance and this pursuit is practiced in only a small way in the lowlands.

GEOLOGY

Surface Stratigraphy

The surface rocks of the Olympic field are classified as the Francis and Seminole formations of the Missouri series of

Pennsylvanian age. Over most of the Olympic field the surface beds consist of interbedded blue and black shales, sandstones, and thin beds of limestone which constitute the Francis formation. However, in the southern part of the Olympic field, the exposed rocks are of the Seminole formation which here, in the form of conglomerate consisting of white chert in a brown matrix succeeded by sandstones and shales, constitutes the surface strata 4/. According to Dillard 5/ the Seminole formation includes members that are interpreted to be equivalent to the Jones sand and the Cleveland sand which are productive of oil near Cleveland, Oklahoma.

Subsurface Stratigraphy

Much of the information in this report concerning the subsurface stratigraphy of the Olympic field has been obtained from earlier reports in which it has been discussed in detail by Tillotson 6/, Dillard 7/, and Dott 8/.

Because most oil wells in the Olympic field were drilled with rotary tools and it was the general procedure to obtain samples of only those formations below 1,000 feet in depth, little information

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4/ Gould, Charles N., Index to the Stratigraphy of Oklahoma: Oklahoma Geol. Survey Bull. 35, p. 48, 1925.

5/ Dillard, W. Reese, Olympic Pool, Hughes and Okfuskee Counties, Oklahoma: Stratigraphic Type Oil Fields, Am. Assoc. Petroleum Geologists Symposium, p. 458, 1941.

6/ Tillotson, Allen W., Olympic Pool, Hughes and Okfuskee Counties, Oklahoma: Am. Assoc. Petroleum Geologists Bull. 11, vol. 22, pp. 1580-1581, November 1938.

7/ Idem

8/ Dott, Robert H., Regional Stratigraphy of the Mid-Continent: Am. Assoc. Petroleum Geologists Bull. 9, vol. 25, September 1941.

is available for the subsurface beds above the Wetumka formation except where such data were obtained in a few wells. A few wells that were drilled to the Olympic zone by the cable-tool method have yielded good samples and several deep wells drilled to the Wilcox sand of Ordivician age have been logged electrically. From these data Tillotson 9/ has correlated subsurface rocks in this field and special attention has been given to the correlation of horizons between the Calvin formation of Pennsylvanian age and the Wilcox sandstone of Ordivician age. So far as it can be ascertained, the thickness of the Pennsylvanian beds above the Olympic sand range from 1633 feet to 1920 feet, whereas Pennsylvanian and Ordivician rocks having a total thickness of about 4350 feet have been recorded in the deepest well so far drilled in this field. The stratigraphy of the surface and subsurface rocks of Pennsylvanian and Ordivician age which have been drilled in this field are shown on the accompanying stratigraphic section of the Olympic field. (See pl. 6).

The Senora formation is the most important of the subsurface formations in the Olympic field on account of the production of petroleum from its most prominent member, the so-called Olympic sand. Stratigraphically, the Senora formation underlies the Calvin sandstone which in this field also has produced some oil and gas from one of its two persistent beds of sandstone. The Olympic sand is about 150 feet below the top of the Senora formation which in its uppermost part is composed chiefly of shale interspersed in places with beds of

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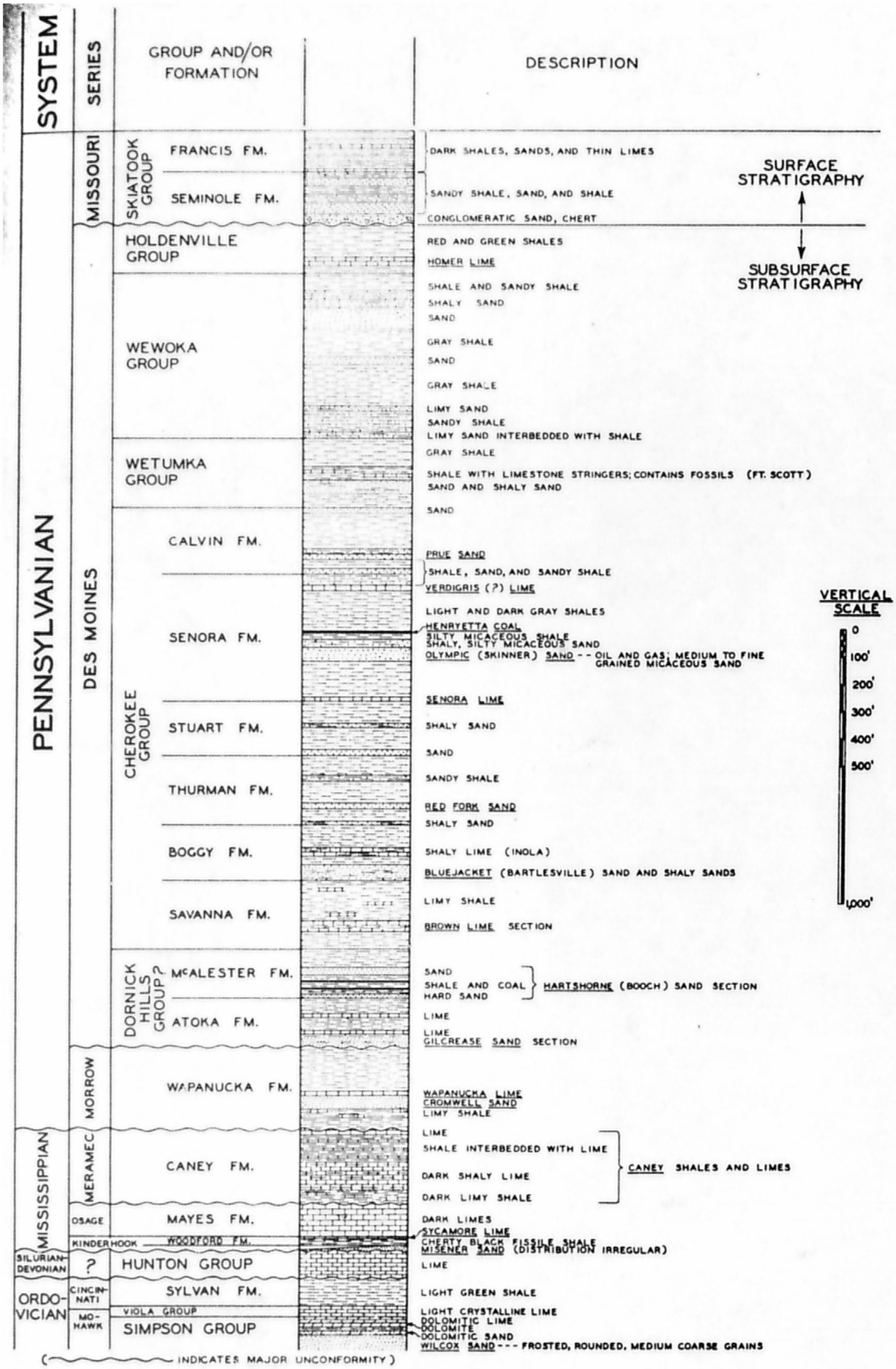
9/ Personal communication



COMPOSITE STRATIGRAPHIC SECTION

— OLYMPIC FIELD —

TPS. 9 AND 10 N., RS. 3 AND 9 E.— HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA.

PLATE

sandstone and sandy shale. A thin bed of limestone, believed to be equivalent to the Verdigris limestone, occurs in places in the upper part of the shale at the top of the Senora formation.

Stratigraphically the well known Henryetta coal, which here is about 2 feet thick, underlies the shale beds. It shows marked persistence and is recorded in most logs of wells drilled in this field. Owing to its persistence and the fact that in places where it is in contact with or is found near the Olympic zone, the coal has been used not only as a structural marker, but has been used to predict the depth of the Olympic sand in drilling operations. The Olympic sand which is found below the Henryetta coal is discussed in detail elsewhere in the text relative to the sand body study. The Olympic sand is underlain by black shale, and this shale in turn overlies the Senora limestone, a persistent bed of limestone about 10 feet thick which is an excellent regional stratigraphic marker. This limestone is oftentimes placed correlatively on the top of Stuart formation. However, it is considered herein and in the other reports as the basal member of the Senora formation.

Structure

The strike of the surface strata in the Olympic field indicates a northeast trending monocline which dips gently northwest, and the general rate of dip is about 100 feet per mile or less. The alignment of the subsurface beds of Pennsylvanian age is similar to that of the formations cropping out in this area for the strike and dip of the surface and subsurface strata are nearly equivalent. The geologic structure of the top of the Henryetta coal in the Olympic field as shown by the accompanying structure map (see pl. 7) reveals the strike of the formations to be approximately N. 25° E. and the dip of the beds to be northwest at a low angle of inclination. The general dip of 100 feet per mile is interrupted in small areas by several anticlinal noses and synclines.

Structural interruptions to the normal dip as shown by the structure of the Henryetta coal on plate 7, include two small anticlinal noses one of which trends southwest from sec. 30, T. 10 N., R. 9 E., and the other or main anticlinal nose trending south in secs. 1 and 12, T. 9 N., R. 8 E. These local structural features are depicted on the north-south cross section (see pl. 8) trending northeast with the strike of the field. Incidentally, there appears to be relation between the geologic structure of the top of the Olympic sand in places where structural anticlines are present (see pl. 9) and the thickness of the sand as shown by the Isopachous map on plate 10. In addition, the structural syncline depicted on the geologic subsurface map of the Henryetta coal is represented by a belt of thin sand extending transversely across the field in sec. 36, T. 10 N., R. 8 E., and sec. 31, T. 10 N., R. 9 E. In the northern part of the field, the structural features of the Henryetta coal in general show no relationship to variations in thickness of the underlying Olympic sand body.

Although there is striking similarity between the subsurface structure of the Henryetta coal and the structure of the top of the Olympic sand, actually the structure of the sand shows less continuity than does that of the coal, and it exhibits many irregularities which are characteristic of sand bar deposits. Stratigraphically, the Henryetta coal lies above the Olympic sand and in direct contact with it in a few places in the central part of the field. However, down-dip westward, the interval between the top of the Henryetta coal and the top of the Olympic sand becomes greater and in places this interval is as much as 25 feet. The sand is lenticular and pinches out abruptly on the east bounds of the field, but it diminishes gradually in thickness on the west margin of the field. Where the Olympic sand is thick the dip of the structure is very gentle. On the other hand, the dip is far greater on the flanks of the sand body, and it is more abrupt on the east side of the field. Depositional "highs" comprising small areas of closure on top of the Olympic sand generally are elongated parallel to the northeast strike of the subsurface strata. (See pl. 9).

The interruption of the normal northeast strike of the subsurface structure as depicted on the structure map of the Henryetta coal (see pl. 7) indicates the possible presence of a fault across the southern part of secs. 17 and 18, T. 10 N., R. 9 E., in the northern part of this field. The geologic map of Oklahoma compiled by Miser 10/ shows faulting of the surface strata at two places in the northern part of the Olympic field. One fault is in the SW¼ SW¼ sec. 17, T. 10 N., R. 9 E., trending northwest across the field to the NE¼ NW¼ sec. 18, T. 10 N., R. 9 E., and a second fault occurs in the SW¼ sec. 19, T. 10 N., R. 9 E., its fault plane trending northwest. Here, the normal strike of the subsurface structure of the Henryetta

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10/ Miser, Hugh D., Geologic Map of Oklahoma: U. S. Geol. Survey, 1926.

coal (see pl. 7) is interrupted slightly, but the evidence of faulting is not conclusive as to the presence of faulting of the Pennsylvanian strata in this part of the field. In sec. 18, T. 10 N., R. 9 E., the normal regional dip of the Henryetta coal changes from northwest to north (see pl. 7). At this place the variation in the dip of the Henryetta coal supports other evidence of the possibility of a fault in the formations of Pennsylvanian age with a plane trending northwest across the Olympic field. Generally, the subsurface structure of the top of the Henryetta coal and the subsurface structure of the top of the Olympic sand are similar. However, these structures differ in many places in the Olympic field because of the presence of small domes on the top of the Olympic sand. (See pl. 9).

Productive Horizons and Non-Productive Horizons

Oil and gas have been produced commercially from five formations in the Olympic field. The Olympic sand, which in this field is a lenticular member in the Senora formation, occurs at depths ranging from 1633 feet in the southern part of the field to 1920 feet in the northern part. It has been the most prolific producing zone of all the productive horizons which have been exploited. Other formations occurring above and below the Olympic sand have produced some oil and of these formations the Cromwell sand has been the most productive.

The Calvin formation is the shallowest of the producing formations in the Olympic field. It contains two prominent sandstone members, the lower of which is the most persistent. This member occurs about 200 feet above the top of the Olympic sand at about

1450 feet in depth. It has produced oil and gas in a few wells in the southern part of the field. Other wells in the same part of the field have found the Calvin sand to be productive of gas only. The most prolific of the gas wells produced 4,800,000 cubic feet of gas per day initially from the Calvin sand at depths of 1446 to 1483 feet.

The Gilcrease sandstone is found below the Olympic sand and it occurs at a depth of approximately 3200 feet. So far in this field, it has produced oil and gas from two wells. In sec. 13, T. 10 N., R. 8 E., a gas well produced 8,300,000 cubic feet of gas per day initially and no oil from the Gilcrease sand after the casing had been perforated between depths 3198 feet and 3217 feet. In the southern part of the field, a well in sec. 1, T. 9 N., R. 8 E., drilled to the Hunton limestone proved the formation to be barren of oil and gas. The well was plugged back to the Gilcrease sand and this zone was tested for oil production on the basis of an oil show observed during drilling operations. After completion the well produced initially 20 barrels of oil daily from the Gilcrease sand. Oil production declined rapidly thereafter and only a small quantity of oil was produced from this well during its productive life.

With the exception of the Olympic sand, the Cromwell sand, as mentioned previously, has been the most productive formation in this field. The first well that was completed in the Olympic field in July 1934, in NW$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E., found commercial oil production in the Cromwell sand at depths between 3425 feet and 3474 feet. This well, which produced by flowing at the rate of 25 barrels of oil hourly during a 2-hour testing period, also produced 40 million cubic feet of gas daily. On July 1, 1946, this well still was flowing at an estimated productivity rate of 38 to 40 barrels of oil daily.

Oil and gas were produced from the Cromwell sand for a short time by a well drilled in the SW$\frac{1}{4}$ NE$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 12, T. 9 N., R. 8 E. Its initial production was 30 million cubic feet of gas during the first 24 hours and 25 barrels of oil daily, and the initial rock pressure of the productive Cromwell sand between the depths 3448-3472 feet was 700 pounds per square inch. This well produced oil and gas in the period, December 8, 1934 to August 5, 1937. At the later date it was deepened to the Hunton limestone and drilling operations were completed in the Hunton on October 26, 1937. This well produced initially 15 million cubic feet of gas per 24 hours together with a small volume of high gravity oil from the Hunton limestone found at depths ranging from 4020-4041 feet. After producing for a short time from the Hunton limestone the well cratered and it was then plugged and abandoned.

A few wells were drilled to the Wilcox sandstone in the Olympic field to test the productiveness of this zone. It was proved to be barren of oil and gas, but produced water in all wells testing this zone. Two test wells were drilled in secs. 2 and 12, T. 9 N., R. 8 E., to total depths of 4279 feet and 4359 feet, respectively. Several wells that were drilled outside the limits of the field were reported as being "dry" in the Wilcox sandstone.

RESERVOIR PERFORMANCE

Oil and Gas Production

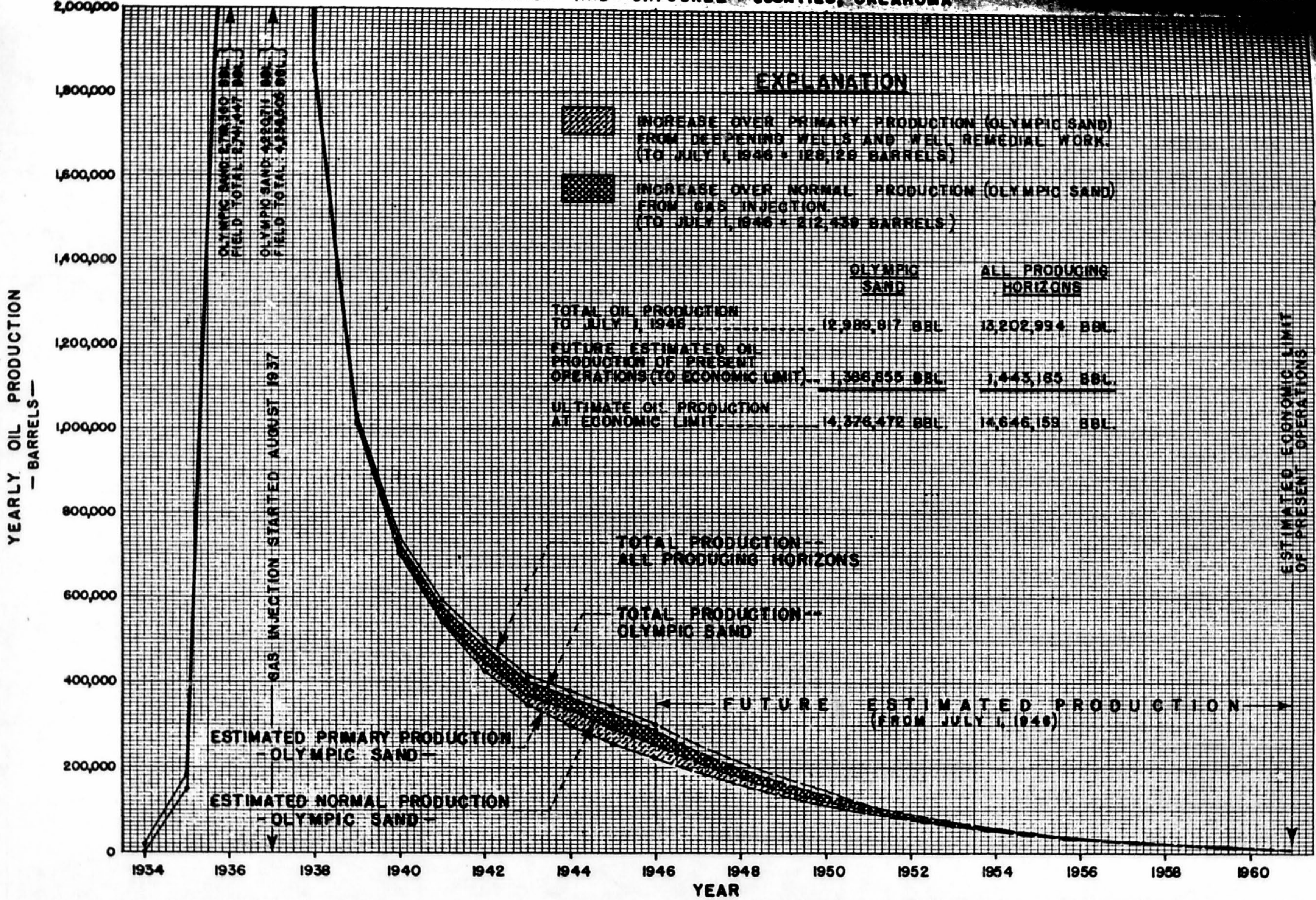
The Olympic field, by reason of the performance of its reservoir, is classified as a field producing by gas expansion forces. After discovery of commercial oil production in the Olympic sand on July 17, 1935, an intense drilling campaign was instituted and the field was developed rapidly, reaching its peak production of 4,220,711 barrels of oil in 1937. In that year the rate of production for all producing horizons in the field was 4,238,505 barrels of oil. Since 1937, the yearly oil production from the Olympic sand has declined steadily reaching a productivity rate of 328,092 barrels in 1945. (See pl. 11). The rate of decline of production ranged from 57.2 percent per year in the first year after the peak of production was attained to 10.0 percent yearly in 1945. What is more to the point is the fact that the Olympic sand has produced 12,989,817 barrels of oil since the discovery of its commercial possibilities in July 1935 to July 1, 1946. Of this volume of oil, an estimated 128,000 barrels has been produced by deepening of wells, and an estimated 212,000 barrels has been reclaimed by the application of gas-injection practices. The apportionment of this oil production attributed to deepening of wells and gas-injection practices and its rate of decline is shown on the graph (pl. 11).

Normal Oil Production.

Since the discovery of commercial oil production in the Olympic sand in July 1935 to July 1, 1946, the field has, by normal methods of operation, produced 12,777,378 barrels of oil from this main producing zone. This volume of oil is equivalent to 98.4 percent of all oil that the olympic sand has produced. As the Olympic sand comprises 3,423 productive acres in this field, the average oil

OIL PRODUCTION HISTORY AND …

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA



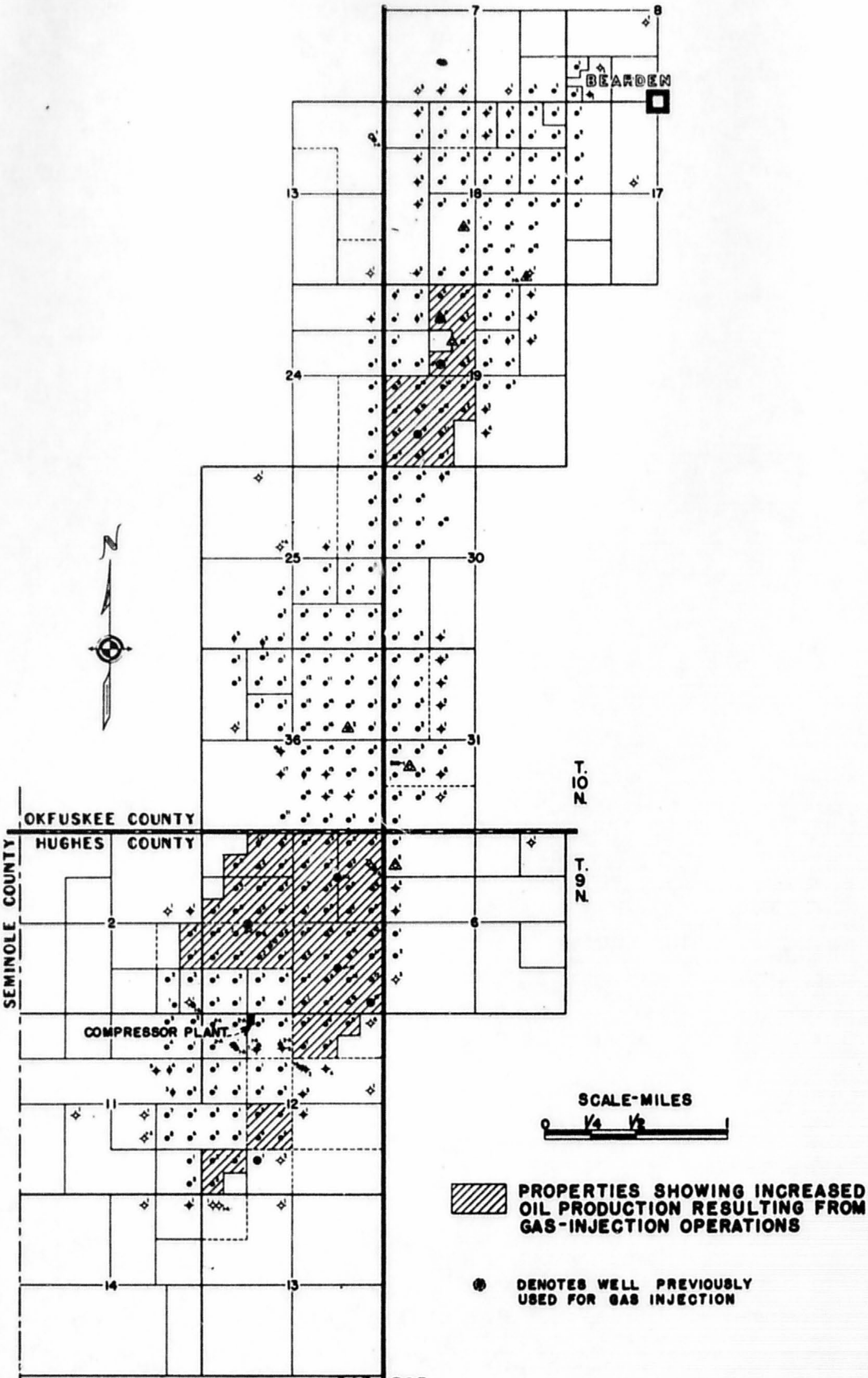
recovery from the sand by normal methods of operation to July 1, 1946, amounts to 3,733 barrels per acre. For the purpose of this report, the normal production is defined as all oil produced by primary methods of operation including also the oil produced by deepening of wells and remedial work.

The volume of oil produced per acre from the Olympic sand by normal operating methods (see pl. 12) and the distribution of the tracts yielding this oil indicate that the producing characteristics of the sand are better developed in the southern part of the field. Generally, tracts in the northern part of the Olympic field have yielded less oil than in the southern part. However, in many places in the northern part of the field, a few leaseholds have shown substantial oil production. The leaseholds having produced the most oil per acre are in sec. 1, T. 9 N., R. 8 E., and sec. 25, T. 10 N., R. 8 E., in the southern and central parts of the field. They comprise a total of 270 acres, which is 7.8 percent of all productive acreage in the field. The leaseholds comprising this area are classified in the group constituting the bracket of greatest oil production which here ranges from 7,000 to 9,000 barrels of oil per acre. The best property, however, in sec. 25, T. 10 N., R. 8 E., produced 8,787 barrels per acre to July 1, 1946, by normal operating methods. More interesting is the fact that leaseholds comprising 730 productive acres, or 21.3 percent of the total productive acreage, have produced 4,000 to 5,000 barrels per acre to July 1, 1946. Where the thickness of the Olympic sand decreases as on the flanks of the sand body the volume of oil produced per acre usually has been the least. It is to be emphasized, however, that 2,482 productive acres, or 72.5 percent of all productive Olympic sand in this field yielded over 2,500 barrels per acre by normal methods of operation to July 1, 1946.

Gas Injection and Oil Production.

In August 1937, gas was injected into the Olympic sand in an effort to stimulate the production of oil and to dispose of the residue gas remaining after extraction of the gasoline content from the gas which was produced with the oil. The residue gas returned to the reservoir has been instrumental in retarding decline of not only oil production, but also the static pressure of the reservoir. To July 1, 1946, the injection of 2,183,397,000 cubic feet of gas, which is equivalent to 12.0 percent of the cumulative gas produced from the Olympic sand, has reclaimed an additional volume of oil amounting to an estimated 212,000 barrels. As the area covering the gas-injection projects comprises 870 acres (see pl. 13), the oil recovery attributed to gas-injection operations averages 244 barrels per acre. (See pl. 14).

Gas injection operations have been concentrated mainly in the area included in T. 9 N., R. 8 E., in the southern part of the field, although some gas has been injected into the Olympic sand in sec. 19, T. 10 N., R. 9 E., in the northern part of the field. In the southern part of the field in sec. 1, T. 9 N., R. 8 E., gas injection has contributed to the reclamation of additional oil ranging from 600 to 800 barrels of oil per acre on the property showing the best response to this type of operation. On the other hand, a property in sec. 12,



INDEX MAP SHOWING

EXTENT OF GAS-INJECTION OPERATIONS IN THE OLYMPIC FIELD

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA

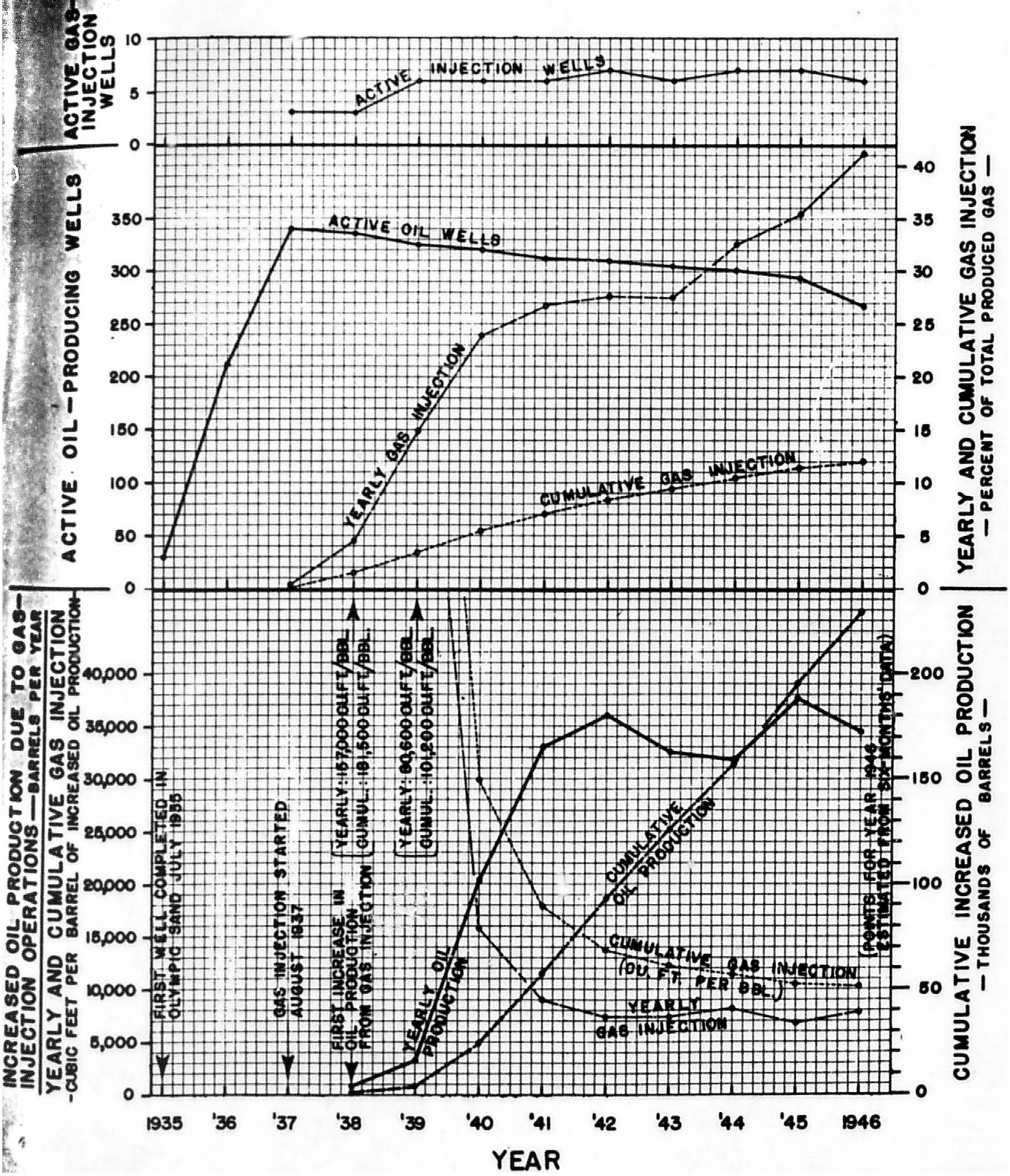
T. 9 N., R. 8 E., shows oil recovery by gas injection of less than 50 barrels per acre for the area embodying the leasehold. Unfortunately, the production record of individual wells was not available for this report and response to gas injection was attributed to the entire leasehold. Obviously, the effects of gas injection in many places, covered an area less than an entire leasehold. Consequently, the oil recovered per acre from each leasehold by the injection of gas would be necessarily greater because of smaller productive area. With the exception of the input well in the NW¼ SE¼ SW¼ sec. 12, T. 9 N., R. 8 E., all input wells have been injecting residue gas from the Olympic sand. In this well the casing has been perforated opposite the Calvin sand and the gas produced from this zone is injected into the Olympic sand at the pressure existing in the Calvin formation. The response to this gas injection operation which was started October 3, 1944, has not been great although the leaseholds north and west of the property on which the input well is located have shown some increase in rate of production.

The volume of gas injected into the Olympic sand has been a small volume of the gas produced from this formation. The volume of gas introduced into the sand in 1938 was equivalent to 4.0 percent of the gas production. The injection rate since 1938 has been increased, so that for the first six months of 1946, the gas injected into the Olympic sand was equivalent to 41.4 percent of all gas produced from that sand. The history of gas injection operations in relation to increased oil production from the Olympic sand is shown on the graph. (See pl. 15). Of particular interest is the fact that

GRAPHS SHOWING

HISTORY OF GAS-INJECTION OPERATIONS IN RELATION TO INCREASED OIL PRODUCTION FROM THE OLYMPIC SAND

OLYMPIC FIELD, HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA



since the inception of gas-injection operations in August 1937, to July 1, 1946, the volume of gas required to produce an additional barrel of oil was 10,300 cubic feet. On the other hand, 15,800 cubic feet of gas was injected in 1940, for each additional barrel of oil that was recovered. This volume was reduced to 7,900 cubic feet of gas for each barrel of additional oil recovered during the first six months of 1946. Incidentally, the quantity of oil produced during the first 6 months of 1946 by gas-injection operations was estimated to be 17,300 barrels.

Oil and Gas Production and Gas Injection in Repressured Area.

Specific data concerning the leaseholds constituting the area affected by the application of gas-injection operations reveal the efficiency of this method of operation when viewed comprehensively. These data presented on the accompanying graph (see pl. 16) show that this area has produced 4,279 barrels of oil from the Olympic sand by normal operation. Also, it has produced by gas injection an additional 244 barrels of oil per acre, making the total recovery 4,523 barrels of oil per acre to July 1, 1946, for the gas-injection project. In operations covering the first six months of 1946, these properties produced 230 barrels of oil daily by normal operations, and 96 barrels of oil daily by gas-injection operations, or a total of 326 barrels of oil daily during this period.

To July 1, 1946, cumulative gas production from the Olympic sand amounted to 6,485,160,000 cubic feet and cumulative net gas was 4,301,763,000 cubic feet of gas for the whole of the gas-repressured area. Gas injection since August 1937, at pressures ranging from 275

GRAPHS SHOWING

DEVELOPMENT AND OPERATIONAL HISTORY, OIL AND GAS PRODUCTION AND GAS INJECTION

OF PROPERTIES CONSTITUTING

GAS-INJECTION AREA

IN THE

OLYMPIC FIELD

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA

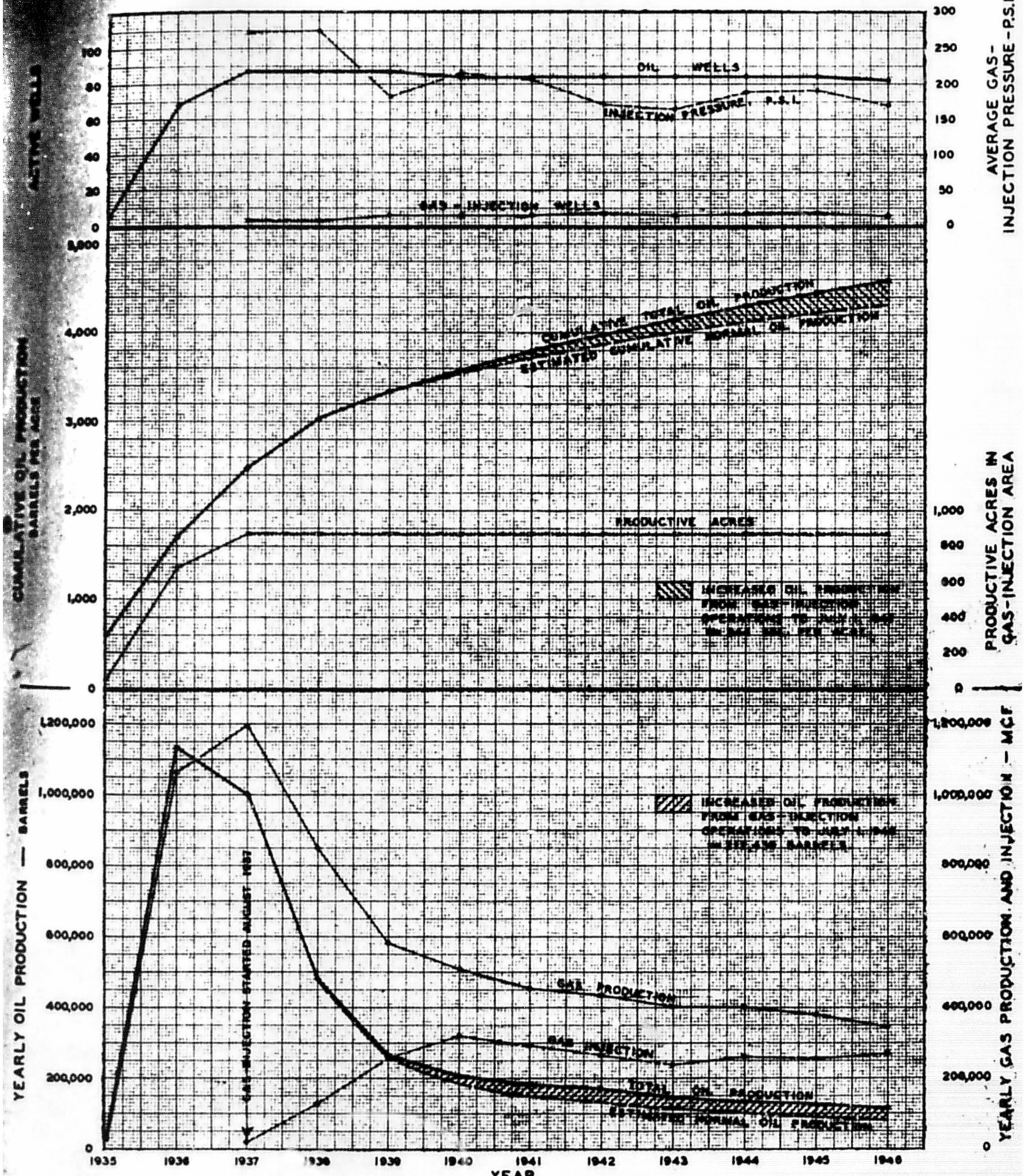


PLATE 16.

to 170 pounds per square inch, amounted to 2,183,397,000 cubic feet of gas. This volume is equivalent to 33.7 percent of all gas produced on these leaseholds. During the period January 1, 1946 to July 1, 1946, gas was being injected into the sand at the rate of about 755,448 cubic feet daily, which was equivalent to 79.1 percent of the total gas produced daily from the leaseholds. Of interest is the fact that since the inception of gas-injection operations, 10,300 cubic feet of injected gas has been required to produce each additional barrel of oil from the Olympic sand.

Generally, the ratio of gas production to oil production is used as a criterion of the operating efficiency of an oil property. Furthermore, it is often indicative of such physical characteristics of the sand as permeability, presence of gas sand, and other characteristics of the formation. For instance, the cumulative gas-oil ratio in the area of gas injection was 1,648 cubic feet of gas per barrel of oil and the net cumulative gas-oil ratio amounted to 1,093 cubic feet per barrel to July 1, 1946. It is to be assumed from these data that in general gas injection is controlled and little by-passing has occurred. However, in the first 6 months of 1946, the average gas-oil ratio in the repressured area was 2,928 cubic feet per barrel of oil, whereas, the net gas-oil ratio averaged 611 cubic feet per barrel. The large variations between gross gas-oil ratio and net gas-oil ratio for this area during the first 6 months of 1946 indicates lower operating efficiency and no doubt to some extent by-passing of gas through the gas sand in the gas-injection area. Granting that the gross gas-oil ratio has increased to a relatively high value in 1946, it has, however, shown little change since 1943. At that time the gross gas-oil ratio for wells producing from the Olympic sand in this area averaged 2,992 cubic feet of gas per barrel of oil produced.

Oil Produced by Normal and Gas-Injection Methods of Operation.

Since 1935 to July 1, 1946, the Olympic field has produced 12,989,817 barrels of oil from the Olympic sand by normal and gas-injection methods of operation from 343 oil wells draining 3,423 productive acres. This is equivalent to an average recovery of 3,795 barrels of oil per acre. The Olympic sand has produced 98.4 percent of all oil produced from the field. Formations above and below the Olympic sand have produced 213,177 barrels of which the Cromwell sand has yielded the greatest volume. A recapitulation of oil produced from the Olympic sand in the Olympic field to July 1, 1946, is given in table 1.

Table 1

Oil produced by normal and gas-injection methods of operations to July 1, 1946, in the Olympic field, Oklahoma

Operating phase	Productive acres	Oil produced to July 1, 1946, from the Olympic sand: Bbl.	Bbl. per acre	Bbl. per acre-foot	Percent of total production
Normal	3,423	12,777,378	3,733	113.5	98.4
Gas-injection	870	212,439	244	6.8	1.6
Normal and gas-injection	3,423	12,989,817	3,795	115.4	100.0

Notwithstanding the fact that most oil was produced from the Olympic sand in the southern part and the central part of the field by normal and gas-injection methods of operation, a few leaseholds in the northern part of the field also have excellent records of production. Leaseholds in sec. 1, T. 9 N., R. 8 E., and sec. 25, T. 10 N., R. 8 E., have yielded as much as 7,897 and 8,782 barrels of oil per acre, respectively, to July 1, 1946. The apportionment of the oil production and the distribution of this production by tracts in the Olympic field is shown on the map (pl. 17). Here, it is to be noted that generally the oil production in the northern part of the field has been less than that in the southern part of the field. Furthermore, that leaseholds producing on the flanks of the sand body have produced less oil per acre than have leaseholds producing from the thicker section of Olympic sand.

Oil Produced by all Horizons

The cumulative volume of oil produced in the Olympic field from all horizons since the opening of the field, July 19, 1934, to July 1, 1946, is recorded as 13,202,994 barrels. Of this volume of oil the Olympic sand has produced 98.4 percent, or 12,989,817 barrels. Other producing zones such as the Calvin sand, Gilcrease sand, Cromwell sand, and Hunton lime have produced 213,777 barrels of oil. Of this amount it is estimated that the Cromwell sand has produced 209,338 barrels to July 1, 1946.

The greatest recovery in the field is attributed to a leasehold in the NW¼ NW¼ sec. 12, T. 9 N., R. 8 E., where recovery to July 1, 1946, was 10,498 barrels per acre. This leasehold produces from the Olympic and Cromwell sands and the oil production to July 1, 1946, was 5,491 and 5,007 barrels per acre from the respective sands. Referring to the production map (see pl. 18), it will be observed that the tracts of greatest recovery, which comprise 120 acres or 3.5 percent of the total acreage, have produced from 8,000 to 10,000 barrels of oil per acre, and that 56.8 percent of all acreage has produced over 3,000 barrels of oil per acre.

Ultimate Oil Production

Ultimate oil production from the Olympic sand, including past production to July 1, 1946, and future estimated production by present operating methods, continued to an economic limit of 1.5 barrels of oil production per well per day, is estimated to be 14,380,000 barrels, or 4,200 barrels of oil per productive acre. This estimate is based on the theoretical premise that the present operating methods will be continued to the 1.5 barrel economic limit, and that all wells on specific tracts will cease to produce concurrently at this economic limit. Generally, such conditions do not occur. Actually, oil wells reach their lower limits of profitable production irregularly and are accordingly plugged and abandoned, thus reducing operating expenses of the leasehold. It may therefore reasonably be assumed that if current operating methods were continued, the ultimate oil production from the Olympic sand would exceed the aforementioned figure of estimated ultimate production. Accordingly, for the purposes of this report it is estimated that a continuation of present methods would recover, after July 1, 1946, from all producing horizons, an estimated 1,450,000 barrels, or an ultimate oil production from all horizons of about 14,650,000 barrels. Upward revisions of the posted price of crude oil will correspondingly result in larger monetary returns from production and in lower economic limits of production. This variable and others are important factors in estimating future oil production by present methods and as a result such estimates must be regarded as largely hypothetical.

By continuation of present producing methods it is estimated that an ultimate recovery from the Olympic sand of 8,000 to 10,000 barrels per acre would not be unusual on the more prolific leaseholds. It is estimated that the most productive leasehold, S½ NW¼ sec. 1, T. 9 N., R. 8 E., will recover about 9,584 barrels per acre. The distribution and magnitude of oil recovery from this tract and other tracts is shown on the map. (See pl. 19). It will be noted that 2,602 acres, or 76.0 percent of all productive acreage, will in all probability have an ultimate recovery exceeding 2,500 barrels of oil per acre from the Olympic sand.

Gas Production and Gas-Oil Ratio

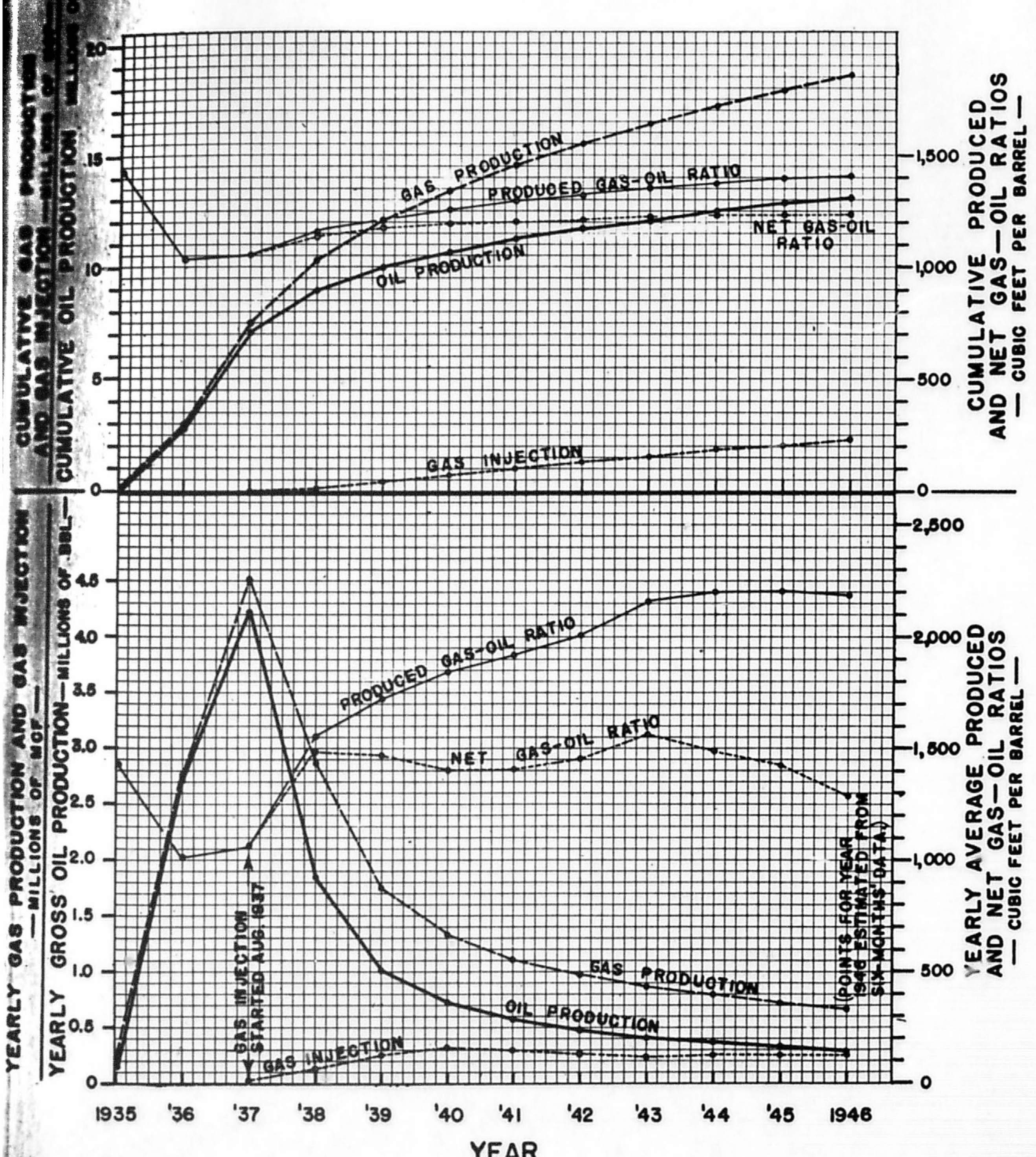
Gas produced during the period July 1935 to July 1, 1946, by wells producing from the Olympic sand is estimated to be 18,247,065,000 cubic feet. In 1937, gas production from the Olympic sand attained its peak amounting to 4,508,047,000 cubic feet. After 1937 gas production declined rapidly and in the first 6 months of 1946 gas production from the Olympic sand was 332,559,000 cubic feet. (See pl. 20). If the present production practices in the field are continued, it is estimated that the ultimate gas production from the Olympic zone will be of the order of 25,400,000,000 cubic feet.

Net gas produced in the field from the Olympic sand, or gross gas production less the volume of gas that was injected into the

GRAPHS SHOWING

OIL AND GAS PRODUCTION AND GAS INJECTION HISTORY OF THE OLYMPIC SAND

OLYMPIC FIELD, HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA



reservoir to July 1, 1946, is estimated to be 16,063,668,000 cubic feet. At the rate gas was produced in the period January 1, 1946 to July 1, 1946, it is anticipated that the net gas production from the Olympic sand for 1946 will be less than 400,000,000 cubic feet.

The cumulative gas-oil ratio, or ratio of gas production to oil production for the Olympic sand in this field to July 1, 1946, was computed to be 1,405 cubic feet of gas per barrel of oil production. (See pl. 21). In contrast to this, the gross gas-oil ratio in the first six months of 1946, averaged 2,184 cubic feet of gas per barrel of oil produced. On the other hand the gas-oil ratios of specific leaseholds were exceptionally high. For instance gas and oil were being produced at a ratio of 10,525 cubic feet of gas for each barrel of oil production on a leasehold in sec. 1, T. 9 N., R. 8 E., in the area of gas cap prior to July 1, 1946. Most of the higher gas-oil ratios are found to be in the area embracing the southern part of the field, and as to be expected generally are in the area embodying the zone of gas cap of the Olympic sand.

To July 1, 1946, the cumulative net gas-oil ratio of the Olympic sand for the field was calculated to be 1,237 cubic feet of gas per barrel of oil produced. This cumulative net gas-oil ratio is shown on the graph (pl. 20). It is noteworthy that for the first six months of operation in 1946, the net gas-oil ratio of the Olympic sand was only 1,286 cubic feet of gas per barrel of oil production.

<u>Oil Production and Reservoir Oil</u>

An analysis of the productivity of the Olympic reservoir by tracts was essential to show not only the quantity of oil that was produced by various phases of operation, but also to ascertain the productive characteristics of the sand body. It was thus possible to estimate from the basic data the original oil content of the reservoir and also the residual oil remaining in the Olympic sand after withdrawal of the oil and gas fluid. These oil production and reservoir data are given in table 2.

Here, it is shown that of the estimated 86,215,400 barrels of initial oil in the Olympic sand, 12,989,817 barrels, or 15.1 percent, was produced to July 1, 1946, or that of the average initial oil content of 25,187 barrels of oil per acre, 3,795 barrels per acre were produced to July 1, 1946. This recovery represents a quantity of oil equivalent in volume to 8.0 percent of the voids in the Olympic reservoir. There remains in the sand as of July 1, 1946, an estimated 73,226,000 barrels of oil, which is equivalent to 21,392 barrels per acre, or 650.2 barrels per acre-foot of sand. This volume of residual oil represents an oil content of the reservoir occupying 45.3 percent of the void space in the Olympic sand.

All oil withdrawn from the Olympic sand reservoir is expressed in terms of barrels of oil run by common carriers furnishing outlets from the field rather then the actual barrels of oil that were produced from the Olympic sand. Prior to February 1941, the companies operating pipe lines usually deducted from 2 to 3 percent from the volume of oil gauged at the stock-tanks to allow for evaporation and wastage of oil during transportation in the pipe line. In compiling data as to the quantity of oil withdrawn from the reservoir, no correction has been applied for the variation from the actual volume of oil that was produced in the field from the Olympic sand. In view of the tolerance permitted in estimating many of the factors pertaining to the reservoir which enter into the computation of residual reservoir oil, it was considered appropriate to use actual oil runs in appraising the residual oil content of the Olympic reservoir.

It may be well to emphasize that if the ultimate oil production from the Olympic sand, estimated on the basis of continuing present producing methods, is expressed in terms of original oil in place, this recovery will be equivalent to 16.7 percent of the initial reservoir oil, or equivalent to 8.9 percent of the total voids in the Olympic "pay" zone.

In evaluating the productive characteristics of the Olympic sand in this field it seemed advisable to classify the productive areas of the sand. Therefore, the Olympic sand body was segregated into four classes in accordance with its productive ability, and the distribution and extent of the four classes are shown on the map (see pl. 28) accompanying the text which describes the sand body. On this map the various classes of productive sand, ranging from 1 to 4, represent the respective areas of best and poorest sand body conditions as determined from a study of productivity characteristics.

Table 3 shows the oil production and reservoir data for the various classes of sand body. Here, it will be noted that the productive sand designated as class 1 and class 2 is much more productive with a yield of 7,052 and 4,281 barrels of oil per acre, respectively. The area embodying class 3 type of sand body is of less commercial value and class 4 area is of little or no commercial importance.

Table 3

Oil production and reservoir data classified by producing characteristics of the Olympic sand, to July 1, 1946, in the Olympic field, Oklahoma

	Productive Class of Sandbody 1/			
	Class 1	Class 2	Class 3	Class 4
Productive acres in developed tracts	460.0	1,772.0	911.0	280.0
Productive acres affected by repressuring	150.0	500.0	220.0	0.0
Oil wells	46	177	92	28
Oil-well density, acres per well	10.0	10.0	9.9	10.0
Formation thickness, feet	47.7	47.6	47.6	39.5
Productive sand thickness, feet	35.9	33.2	33.1	24.7
Productive sand thickness of repressured area, feet	41.9	33.7	36.5	
Porosity (weighted average), percent of bulk volume	20.8	19.1	17.1	14.7
Interstitial water content, percent of voids	35.0	35.0	35.0	35.0
Formation volume factor	1.22	1.22	1.22	1.22
Reservoir void space, bbl	26,682,200	87,160,300	40,009,900	7,903,800
Reservoir void space, bbl. per acre	58,005	49,188	43,919	28,228
Normal oil production to July 1, 1946, bbl	3,194,370	7,451,302	1,982,890	148,816
Normal oil production to July 1, 1946, bbl. per acre	6,944	4,205	2,177	531
Normal oil production to July 1, 1946, bbl. per acre-foot	193.4	126.7	65.8	21.5
Oil produced by gas injection to July 1, 1946, bbl	49,439	134,293	28,707	
Oil produced by gas injection to July 1, 1946, bbl. per acre	330	269	130	
Oil produced by gas injection to July 1, 1946, bbl. per acre-foot	7.9	8.0	3.6	
Total oil produced to July 1, 1946, bbl	3,243,809	7,585,595	2,011,597	148,816
Total oil produced to July 1, 1946, bbl. per acre	7,052	4,281	2,208	531
Total oil produced to July 1, 1946, bbl. per acre-foot	196.4	128.9	66.7	21.5
Initial reservoir oil as stock-tank oil, bbl	14,221,600	46,456,100	21,325,000	4,212,700
Initial reservoir oil as stock-tank oil, bbl. per acre	30,917	26,217	23,408	15,045
Initial reservoir oil as stock-tank oil, bbl. per acre-foot	861.2	789.7	707.2	609.1
Oil produced, percent of reservoir voids	12.2	8.7	5.0	1.9
Oil produced, percent of initial reservoir oil	22.8	16.3	9.4	3.5
Residual reservoir oil as of July 1, 1946, bbl	10,977,791	38,870,505	19,313,403	4,063,884
Residual reservoir oil as of July 1, 1946, bbl. per acre	23,865	21,936	21,200	14,514
Residual reservoir oil as of July 1, 1946, bbl. per acre-foot	664.8	660.7	640.5	587.6
Residual oil saturation as of July 1, 1946, percent of voids	41.1	44.6	48.3	51.4

1/ Represents classes of sand body depicted on plate 28

Obviously, that part of the sand body apportioned to classes 1, 2, and 3 shows the best possibility for the application of secondary methods. In these respective classes the oil content of the sand averages 23,865 barrels per acre, 21,936 barrels per acre, and 21,200 barrels per acre. Notwithstanding the fact that the sand body in class 3 appears to show reserves of oil favorable to secondary development, it would be more prudent to appraise many leaseholds in the class 3 type as marginal properties for water-flooding development at a price of oil approximating $1.60 per barrel for this field on July 1, 1946. However, a few properties in this class probably could be exploited profitably at this price, and an increase in the price of crude would make exploitation of additional class 3 properties economically feasible. The leaseholds embodying the sand body classified as type 4 have no future secondary possibilities under known procedures because in these areas such characteristics of the Olympic sand as porosity and permeability indicate poor conductivity and low recovery, even though the oil saturation is apparently high.

The estimation of the oil content of the Olympic sand involved certain data which could not be determined precisely for this reservoir. The data as used, however, appear to be consistent with reservoir conditions and to be conservative in value. For this reason, the residual oil content of the sand body which is classified as 1 and 2, and which in this report is evaluated as 41.1 percent and 44.6 percent of the pore space in the sand, should be considered as conservative.

In deriving the volume of residual oil in the sand, the computation included an estimated interstitial water content of 35 percent of the pore space, and an estimated formation volume factor of 1.22. Sufficient data based on actual determinations of these factors were not available, but the values are analogous to those of similar reservoirs and are believed to be applicable to the Olympic reservoir.

The distribution of the productive acreage of the Olympic sand relative to its specific classification and the percent of oil production attributed to these areas is summarized in table 4.

Table 4

Status of classified areas on July 1, 1946, relative to performance of the Olympic reservoir

Class 1/	Productive acres, percent of total acres	Wells, percent of total wells	Oil produced to July 1, 1946, percent of total production
1	13.4	13.4	25.0
2	51.8	51.6	58.4
3	26.6	26.3	15.5
4	8.2	8.2	1.1

1/ Class of sand body depicted on plate 28.

Reservoir Characteristics and Behavior

The oil industry is adopting the fundamental hydrodynamic and physical principles controlling the movement of hydrocarbons in reservoirs to problems of production and to problems involving estimation of oil and gas reserves. These principles can be applied to the performance of the Olympic reservoir in the Olympic field. Unfortunately, very few of the required physical data relating to these principles were recorded when the field was discovered, or were determined during the early period of production. Such characteristics of the fluid as the solubility of gas in the oil, shrinkage of the oil and gas phase, and absolute viscosity of the oil--all of which are functions of the reservoir pressure, were not measured. In addition to these items, such important features of the reservoir as interstitial water content, porosity, and relative permeability are either not available or lack sufficient detail for general usage. Fortunately, Beal 11/, also Muskat and Taylor 12/, have furnished data concerning the behavior of hydrocarbons at reservoir-temperatures and pressures which appear applicable to reservoir-conditions of the Olympic sand.

Original Reservoir Pressure

Earlier in this report it was mentioned that the Olympic field is classified as a type reservoir produced by gas expansion. In this field, no initial subsurface pressures were determined by means of subsurface pressure equipment. As the productivity of a well is a function of reservoir pressure, the high initial productivity of many wells indicates that the reservoir-pressure of the Olympic sand would be equivalent to the hydrostatic head of a well producing from a sand at approximately 1800 feet in depth. An initial rock pressure of 732 pounds per square inch taken at the casing-head was reported on an oil well in the SW¼ SW¼ SE¼ sec. 12, T. 9 N., R. 8 E. This well was

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11/ Beal, Carlton, The Viscosity of Air, Water, Natural Gas, Crude Oil and Its Associated Gases at Oil Field Temperatures and Pressures: Am. Inst. Min. Met. Eng. Trans., Tech. Pub. No. 2018, vol. 9, No. 2, pp. 1-22, March 1946.

12/ Muskat, Morris, and Taylor, M. O., Effect of the Crude Gravity on the Performance of Gas Drive Reservoirs: Petroleum Engineer, pp. 88-98, December 1946.

completed in 1935. A gas well, completed in the initial development period in the southern part of the field and producing from the Olympic sand, registered a pressure of 575 pounds per square inch by gauge at the surface. The accuracy of the gauges that registered the reported tests is unknown, but the pressures recorded are comparable with the estimated pressures in this field.

In 1936, bottom-hole pressures which were recorded by Dillard 13/ in 11 wells in sec. 1, T. 9 N., R. 8 E., at a depth of 800 feet below sea-level, ranged from 190 to 510 pounds per square inch. The maximum pressure at that depth was recorded in a well in the NW¼ SE¼ NW¼ sec. 1, T. 9 N., R. 8 E., and the minimum pressure was recorded in a well in the NE¼ NE¼ sec. 1, T. 9 N., R. 8 E.

On July 20 and September 18, 1936, subsurface pressure surveys were conducted by three companies operating in this field, and data on 12 of these pressures were used in this study. At a subsea depth of 800 feet, the static pressure of fluid in the Olympic sand ranged from a minimum of 105 pounds per square inch to a maximum of 484 pounds per square inch. The maximum pressure was recorded in a well in the SW¼ SW¼ SW¼ sec. 31, T. 10 N., R. 9 E., and the minimum pressure was recorded in a well in the NW¼ SE¼ NE¼ sec. 1, T. 9 N., R. 8 E. Many of the bottom-hole pressures recorded during this survey, especially in sec. 1, T. 9 N., R. 8 E., ranged from 355 pounds per square inch to 455 pounds per square inch at a depth of 800 feet

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13/ Dillard, R. W., Olympic Pool, Hughes and Okfuskee Counties, Oklahoma: Stratigraphic Type Oil Fields, Am. Assoc. Petroleum Geologists Symposium, p. 467, 1941.

below sea-level. From these and other pertinent data, it is estimated that the average initial reservoir-pressure of the Olympic sand was approximately 650 to 700 pounds per square inch absolute. For the purpose of this report, all computations involving the estimation of the quantity of initial oil in the reservoir are referred to a sub-surface pressure of 675 pounds per square inch absolute.

Gas Solubility and Formation-Volume Factor

So far as can be ascertained, no bottom-hole sample of oil from the Olympic sand was ever obtained in this field and analyzed in order to determine precisely the quantity of gas dissolved in the oil at the temperature and pressure of the reservoir, and the volume occupied in the reservoir by one barrel of stock-tank oil under the initial conditions of temperature and pressure. However, samples of oil with qualities similar to the oil from the Olympic sand have been obtained from other reservoirs, and these samples of oil have been analyzed for gas solubility and shrinkage data. These parameters have been used in determining the performance of the Olympic reservoir. In addition, technical data published recently by Beal 14/ and Muskat 15/ are applicable to the conditions of gas solubility, shrinkage, and viscosity of the Olympic reservoir.

The presence of associated gas in the gas cap portion of the Olympic zone indicates that the oil in the Olympic sand was saturated with gas originally at the initial pressure and temperature of the formation. Moreover, gas from the Olympic sand has a gasoline content

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14/ Op. cit., pp. 1-22.
15/ Op. cit., pp. 88-98.

ranging from 0.4 to 2.6 gallons per thousand cubic feet, indicating that the gas is soluble in the oil in the reservoir. For these reasons, it was considered reasonable to use the curves of Beal and Muskat in estimating reservoir conditions of the Olympic sand. In applying the data for the liquid phase given in the curves to conditions in the Olympic sand, it is estimated that the temperature of the reservoir averages about 85° F., and that the average gravity of the oil is about 35° A.P.I., although it actually ranges from 27° to 37° A.P.I. At the estimated reservoir-pressure of 675 pounds per square inch, it was estimated that the solubility of the gas would be 250 cubic feet per barrel of stock-tank oil. By differential liberation of the gas from this initial reservoir-pressure, the thermal and isothermal shrinkage of the liquid phase to atmospheric pressure of 14.7 pounds per square inch and temperature of 60° F. would be about 18 percent of its reservoir-volume; therefore, the formation-volume factor was estimated to be 1.22. Thus, one barrel of stock-tank oil was equivalent to 1.22 barrels of oil and gas in the liquid phase at the initial pressure and temperature of the reservoir. As the absolute viscosity of gas-free oil of 35° A.P.I. gravity is about 7 centipoises, the absolute viscosity of the reservoir-fluid containing 250 cubic feet of gas in solution is estimated to be in the range of 2.7 to 3.0 centipoises.

The liquid phase of the hydrocarbons in the Olympic sand occupied 65 percent of the net pore space in the reservoir initially; therefore, the original oil content of the Olympic reservoir amounting to 105,182,800 barrels would in the process of liberating its dissolved gas shrink to 53.3 percent of the pore space of the reservoir and it would then be equivalent to 86,215,400 barrels of oil at stock-tank conditions of temperature and pressure. This computation takes no cognizance of the volume of gas in solution at low reservoir-pressure, nor of the volume of gas remaining in the pore space establishing equilibrium.

Interstitial Water Saturation

That interstitial water exists in virtually all petroleum reservoirs associated with the hydrocarbon phase is generally accepted in the oil industry. Except where low filtrate loss drilling muds or oil-base drilling muds are used, only a portion of this water has been recovered heretofore by coring methods. In the Olympic field, only a few cores were taken. The analyses of these cores relative to the interstitial water-content is unreliable inasmuch as flushing of the cores by drilling fluid is evident. For this reason, the quantity of water in the cores which was determined by core analysis is not representative of the actual interstitial water-content of the reservoir. It was evident, however, that the percentage of water-saturation varied with the permeability, as cores of low permeability had higher percentages of water-saturation.

Several cores were analyzed for interstitial water-content by resorting to the method of restored state of the original fluid phases. This method of analysis depends on the theory that the percentage of oil and water present in the reservoir varies with the difference in pressure between the oil phase and water phase. By this method, the interstitial water-content of several samples ranged from 25 to 30 percent of the void space, perforce, being dependent on and varying inversely with the permeability of the porous medium. There is doubt, however, whether the permeability of the core samples tested represented the average permeability of the Olympic sand.

In the final analysis, the interstitial water-content of the Olympic sand was computed by means of the resistivity or long normal curve of the electric log. By this means, the percentage of water-saturation was estimated to be about 35 percent of the pore space in the sand. In lieu of more conclusive data, it was considered advisable to use 35 percent interstitial water-saturation as the original quantity of water present in the pores of the reservoir. On the other hand, it is likely that interstitial water-saturation varies throughout the field in accordance with the permeability of the sand, being at a maximum on the north, west, and south flanks of the field where edge water is present. The economic significance of interstitial water-saturation is self evident, as any deviation from its actual volume is reflected in a like deviation in the volume of the hydrocarbon phase present originally in the sand.

It is believed that interstitial water-content in the Olympic sand is within the range of 30 to 40 percent saturation, as the sand is unusually fine grained, and the grains very uniform. This feature of the sand is reflected by low permeability which in the few cores available ranges from about 5 millidarcys in the zones of tight sand to a maximum of 159 millidarcys in the more porous sections. The average permeability of these cores is about 50 millidarcys, but the permeability of one core from the western flank of the Olympic sand averaged 99 millidarcys. From these cores it is evident that the permeability is greater in the section at the top of the oil zone and that it gradually decreases in value toward the base of the Olympic zone.

Rate of Production-Decline

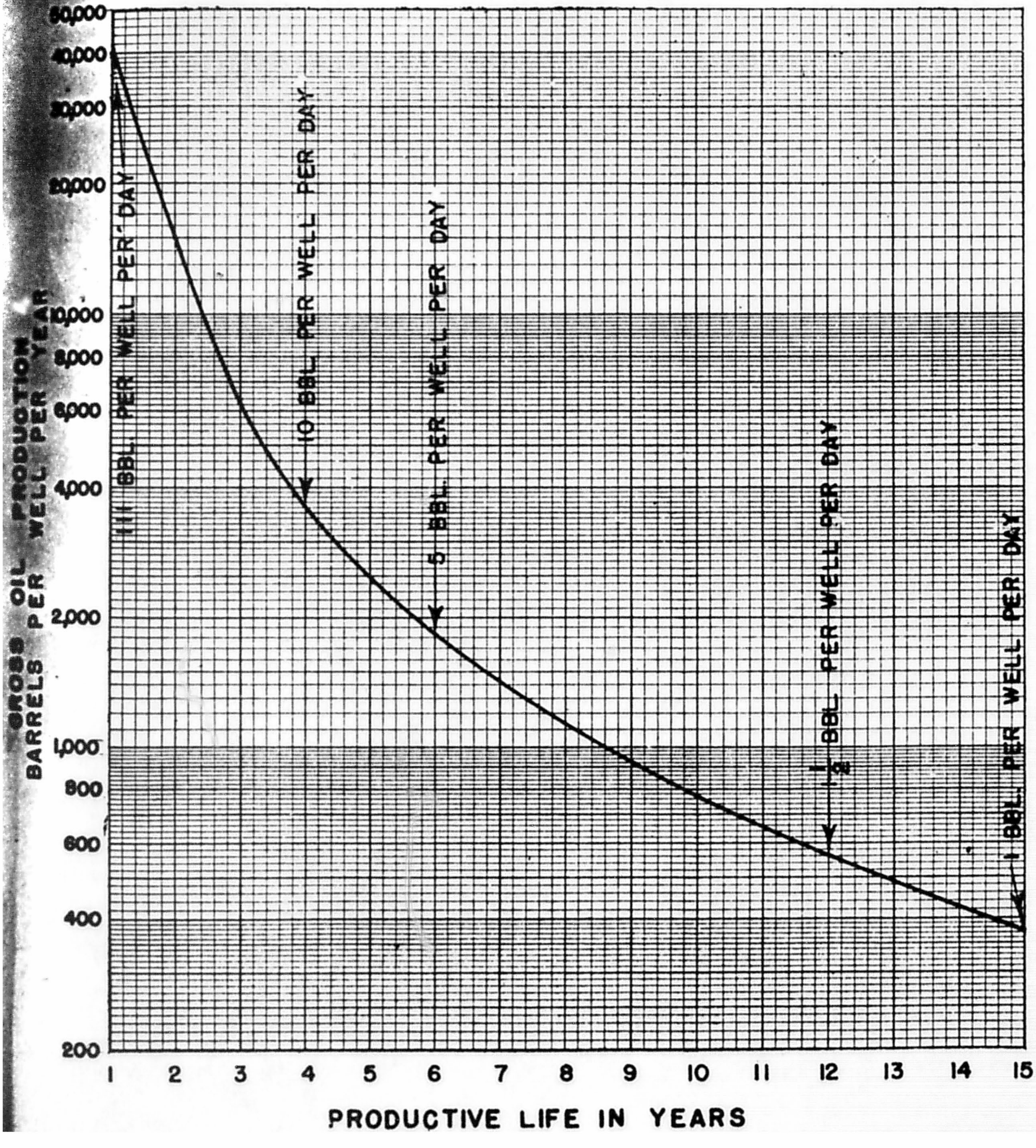
Most wells producing from the Olympic sand in the "flush" production period produced unrestricted and only a few oil wells showed producing capacity greater than their allowable productivity rate. Consequently, the rate of decline was rapid--about 62 percent yearly for the first few years of production. At the end of the 10th year the rate of decline was about 15 percent yearly. The composite curve depicting the rate of decline , plate 22, is representative of the decline of all wells producing from 30 leaseholds comprising 1,170 productive acres of Olympic sand. The curve shows that a well producing 111 barrels of oil daily by primary methods of operation at its peak of production would in the 12th year of its life be producing about 1-1/2 barrels of oil daily. In the 15th year the well would be producing about 1 barrel of oil daily, and its rate of production would be declining approximately 12 percent yearly.

Production-curves of all leaseholds in the field were prepared in order to analyze the performance of individual properties as to the rate of decline and the influence of deepening operations, remedial work, and gas injection on the performance of these wells. Individual production-curves of six leaseholds are included herewith (see pls. 23, 24, and 25) to illustrate graphically the history of oil production. These graphs also show the influence of operational

COMPOSITE CURVE
SHOWING
RATE OF DECLINE OF PRIMARY PRODUCTION
FROM THE OLYMPIC SAND
HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA

"PRIMARY" PRODUCTION EXCLUDES ALL INFLUENCE OF GAS-INJECTION OPERATIONS, DEEPENING OF WELLS AND WELL REMEDIAL WORK.

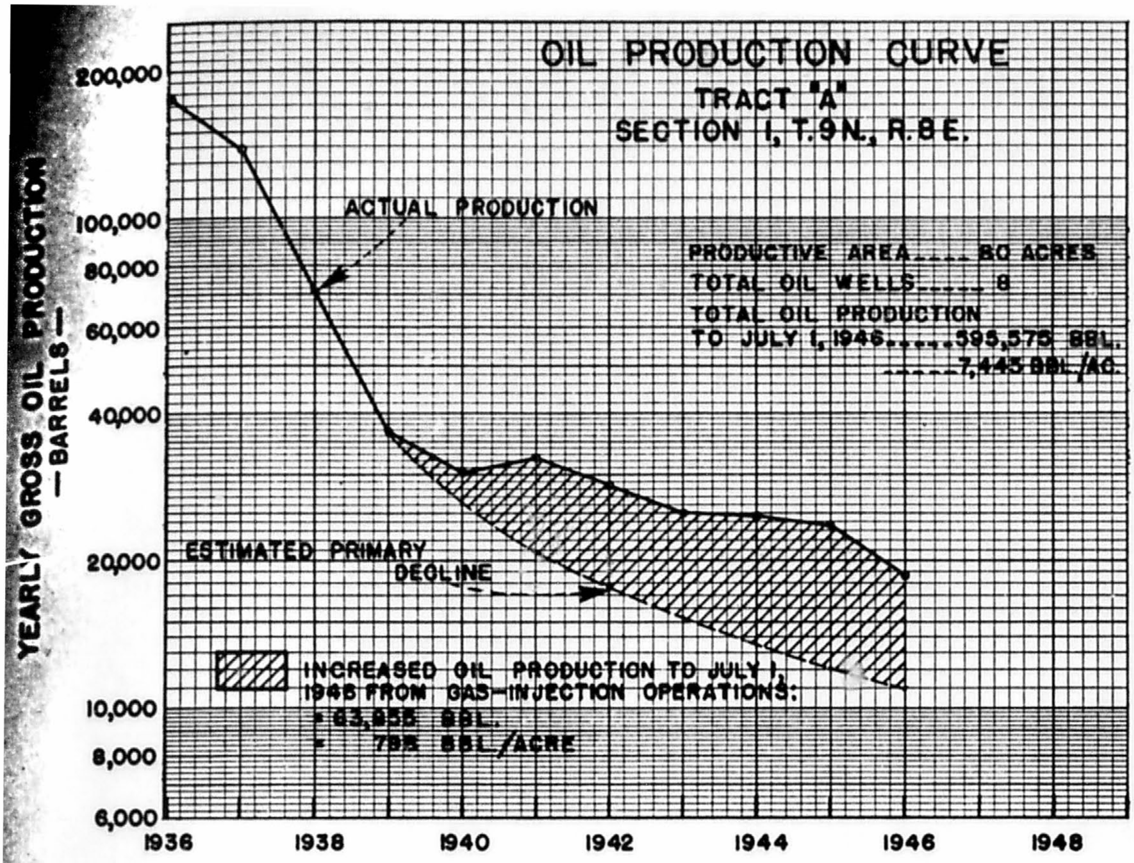
DATA REPRESENT 30 LEASEHOLDS AND 1,170 PRODUCTIVE ACRES

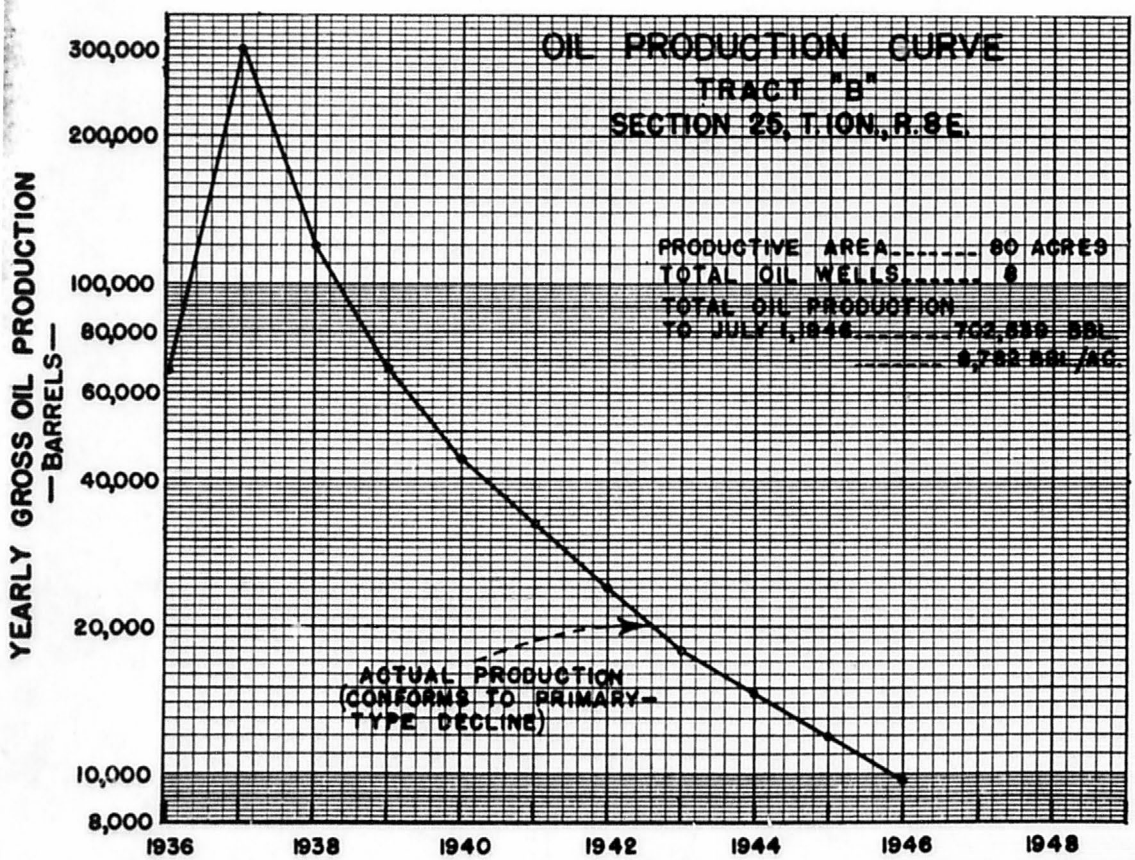


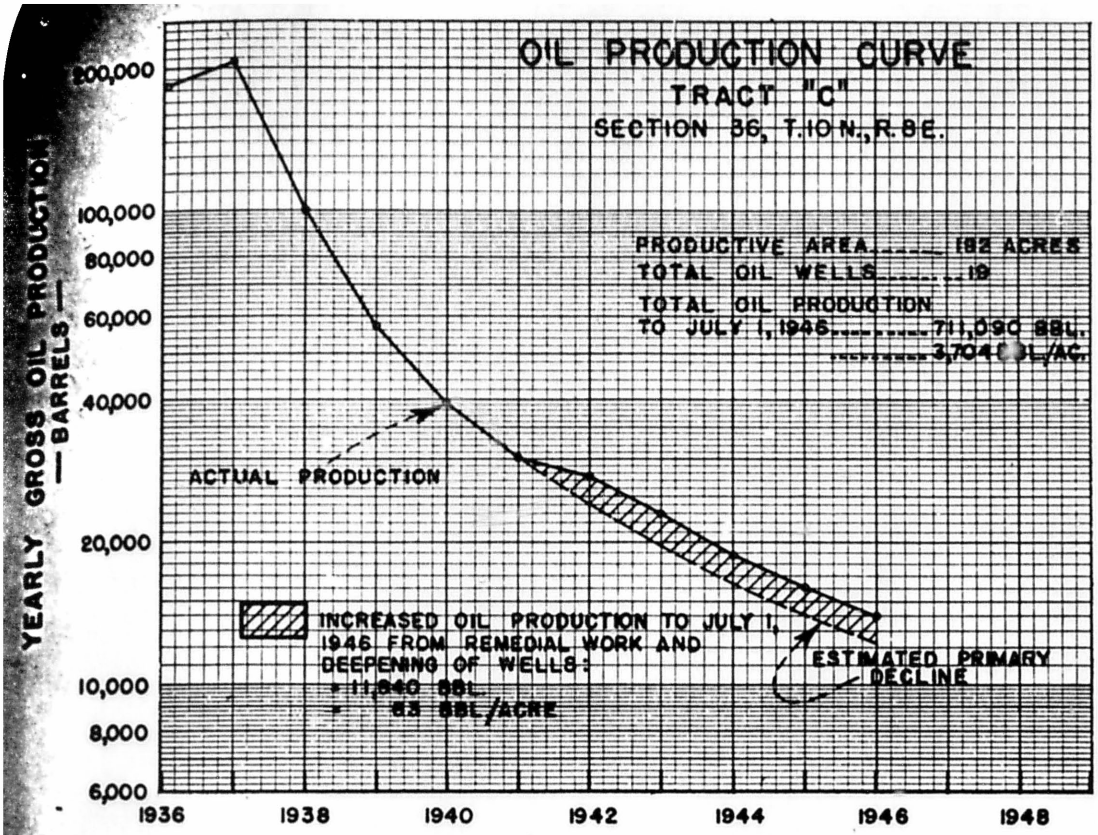
methods employed in producing these properties as well as the quantity of oil attributed to the specific phases of operation.

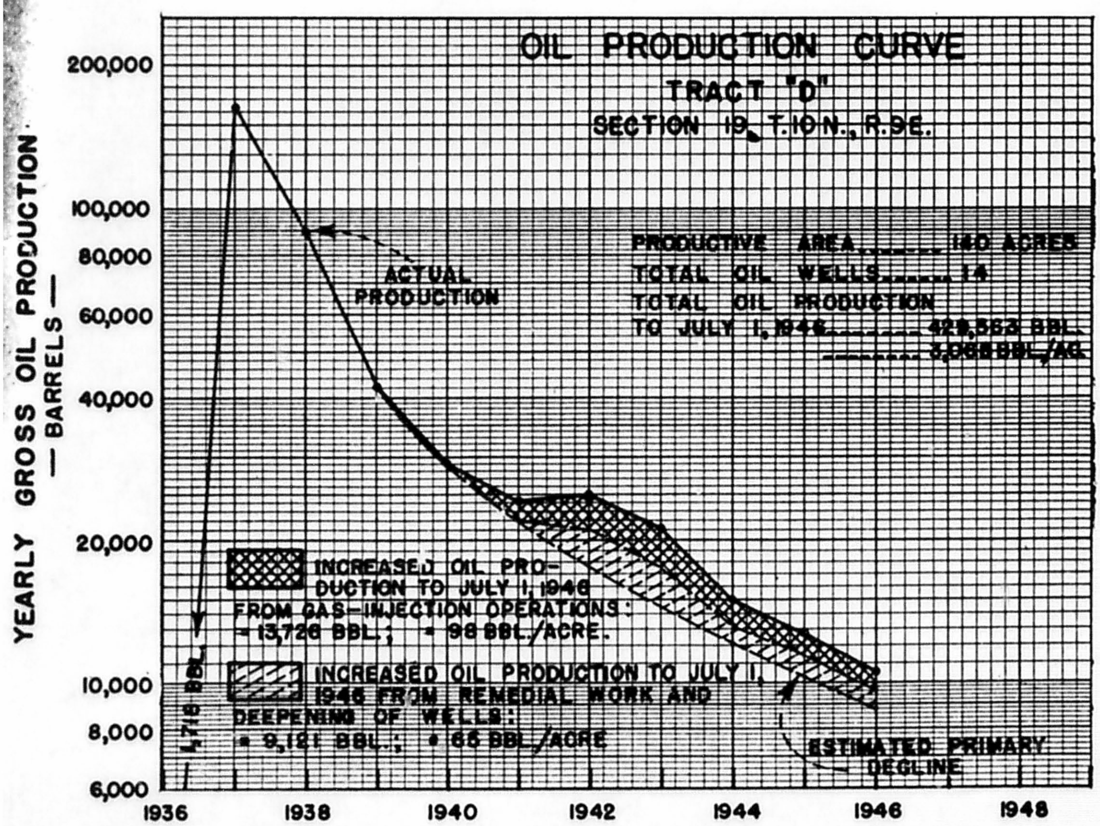
The performance of two leaseholds which represent the better producing properties of the field is portrayed by the production curves for tracts "A" and "B" shown on plate 23. Here, tract "A" is shown to have produced 6,647 barrels of oil per acre by primary methods of production, and 798 barrels of oil by gas-injection operations, for a total recovery of 7,445 barrels of oil per acre to July 1, 1946. The production-curve of tract "B" represents typical performance of a better producing property which shows no effect from gas injection. This property comprising 80 acres produced 8,782 barrels of oil per acre to July 1, 1946. In 1946, the rate of production on this leasehold was declining at the rate of 19 percent yearly. Little deviation occurred in this rate of decline during the period 1943-1946.

The manner in which deepening of wells and remedial work on wells has affected the rate of production is shown by the production-curves of tracts "C" and "D" on plate 24. Here, the decline-curve of tract "C" illustrates the effect of the deepening of producing wells--the increase in production amounting to 63 barrels of oil per acre to July 1, 1946. Although the productivity of wells on this leasehold has increased with a resultant extension of the productive life of the property, it is interesting to note that the rate of decline after deepening of the wells is comparable to the rate of primary decline. The production-curve of tract "D" shows the relative influence of the combination of deepening of wells, remedial work, and gas-injection operations.


OIL PRODUCTION CURVE
TRACT "A"
SECTION 1, T.9N., R.8E.
ACTUAL PRODUCTION
PRODUCTIVE AREA.... 80 ACRES
TOTAL OIL WELLS..... 8
TOTAL OIL PRODUCTION
TO JULY 1, 1946.....595,575 BBL.
.....7,445 BBL./AC.
ESTIMATED PRIMARY DECLINE
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM GAS-INJECTION OPERATIONS:
= 63,855 BBL.
= 798 BBL./ACRE
YEARLY GROSS OIL PRODUCTION —BARRELS—
200,000
100,000
80,000
60,000
40,000
20,000
10,000
8,000
6,000
1936
1938
1940
1942
1944
1946
1948


OIL PRODUCTION CURVE
TRACT "B"
SECTION 25, T.10N., R.8E.
PRODUCTIVE AREA...... 80 ACRES
TOTAL OIL WELLS...... 6
TOTAL OIL PRODUCTION
TO JULY 1, 1946.......702,559 BBL.
.... 8,782 BBL./AC.
ACTUAL PRODUCTION
(CONFORMS TO PRIMARY-
TYPE DECLINE)
YEARLY GROSS OIL PRODUCTION —BARRELS—
300,000
200,000
100,000
80,000
60,000
40,000
20,000
10,000
8,000
1936
1938
1940
1942
1944
1946
1948


OIL PRODUCTION CURVE
TRACT "C"
SECTION 36, T.10 N., R.8E.
YEARLY GROSS OIL PRODUCTION
— BARRELS —
200,000
100,000
80,000
60,000
40,000
20,000
10,000
8,000
6,000
1936
1938
1940
1942
1944
1946
1948
PRODUCTIVE AREA .... 192 ACRES
TOTAL OIL WELLS 19
TOTAL OIL PRODUCTION
TO JULY 1, 1946 .... 711,090 BBL.
.... 3,704
L/AC.
ACTUAL PRODUCTION
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM REMEDIAL WORK AND DEEPENING OF WELLS:
= 11,940 BBL.
= 63 BBL/ACRE
ESTIMATED PRIMARY DECLINE

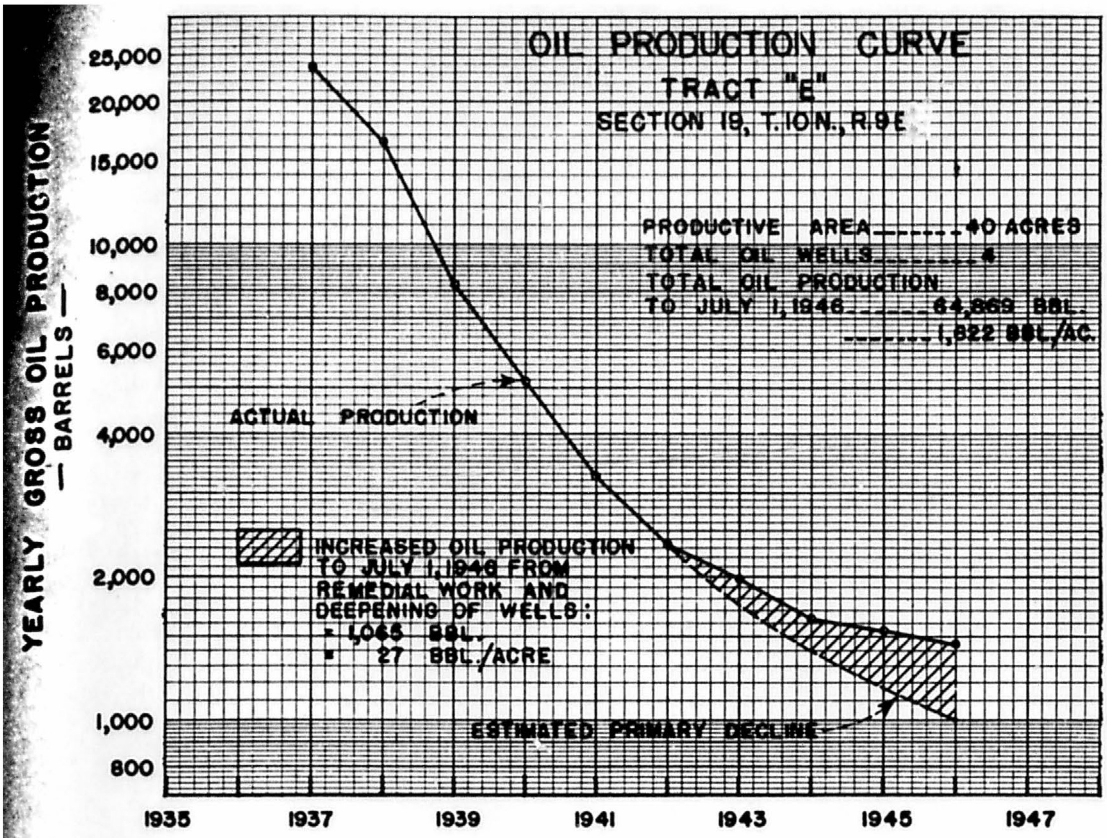

OIL PRODUCTION CURVE
TRACT "D"
SECTION 19, T.10N., R.9E.
YEARLY GROSS OIL PRODUCTION
— BARRELS —
200,000
100,000
80,000
60,000
40,000
20,000
10,000
8,000
6,000
1936
1938
1940
1942
1944
1946
1948
PRODUCTIVE AREA .... 140 ACRES
TOTAL OIL WELLS 14
TOTAL OIL PRODUCTION
TO JULY 1, 1946 .... 429,563 BBL.
.... 3,068 BBL/AC.
ACTUAL PRODUCTION
4,718 BBL.
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM GAS-INJECTION OPERATIONS:
= 13,726 BBL.; = 98 BBL./ACRE.
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM REMEDIAL WORK AND DEEPENING OF WELLS:
= 9,121 BBL.; = 65 BBL./ACRE
ESTIMATED PRIMARY DECLINE

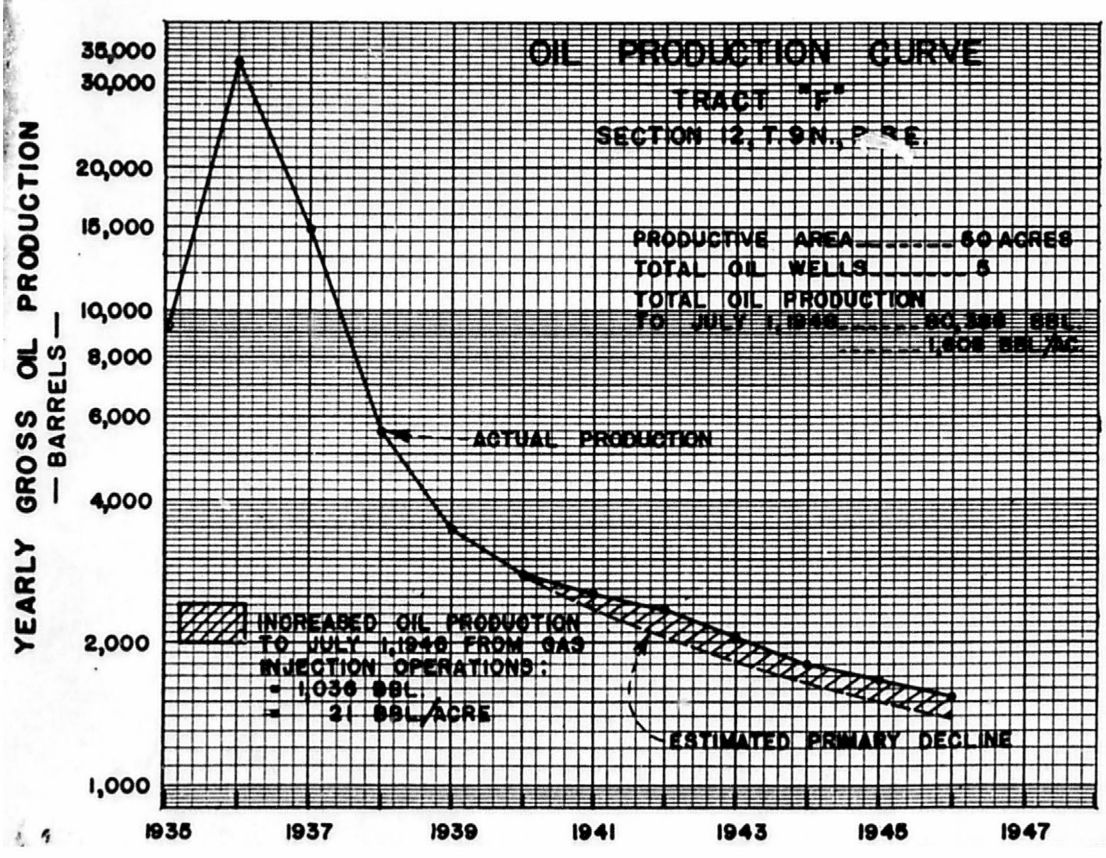
The influence of remedial work, deepening of wells, and gas-injection on properties with low primary oil production is shown on plate 25. Tract "E", which produced an estimated 1,595 barrels of oil per acre by primary production to July 1, 1946, showed an increase of 27 barrels of oil per acre by remedial work and deepening of wells. The total oil recovery is 1,622 barrels of oil per acre to July 1, 1946. Tract "F", immediately north of a leasehold on which gas-injection is practiced, has responded to these nearby gas-injection operations, although no gas has been injected on tract "F". Primary oil production from this tract to July 1, 1946 has been low--estimated as only 1,587 barrels of oil per acre. In addition, an estimated 21 barrels of oil per acre have been recovered as a result of gas-injection development on the offset lease to the north. The leasehold has yielded only 1,608 barrels of oil per acre to July 1, 1946, and it is classified as one of the less productive properties of the Olympic sand.

Characteristics of Crude Oils

Chemical and Physical Properties

The crude oil produced from the Olympic sand in this field is a brown intermediate-base oil ranging in gravity from 27° to 37° A.P.I. The initial gravity of the oil from many leaseholds was reported to be 37° A.P.I. in the early life of the field, especially on those leaseholds in the area embracing the zone of gas cap of the sand. However, as the range of gravity was considerable in this field, the average gravity of the oil produced from the Olympic sand was considered to be 35° A.P.I. The oil was sold in this field on a gravity basis in 1946


OIL PRODUCTION CURVE
TRACT "E"
SECTION 19, T.10N., R.9E
PRODUCTIVE AREA .... 40 ACRES
TOTAL OIL WELLS 4
TOTAL OIL PRODUCTION
TO JULY 1, 1946 .... 64,869 BBL.
.... 1,622 BBL./AC.
ACTUAL PRODUCTION
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM REMEDIAL WORK AND DEEPENING OF WELLS:
= 1,065 BBL.
= 27 BBL./ACRE
ESTIMATED PRIMARY DECLINE
YEARLY GROSS OIL PRODUCTION
— BARRELS —
25,000
20,000
15,000
10,000
8,000
6,000
4,000
2,000
1,000
800
1935
1937
1939
1941
1943
1945
1947


OIL PRODUCTION CURVE
TRACT "F"
SECTION 12, T.9N.,
PRODUCTIVE AREA .... 50 ACRES
TOTAL OIL WELLS 5
TOTAL OIL PRODUCTION
ACTUAL PRODUCTION
INCREASED OIL PRODUCTION TO JULY 1, 1946 FROM GAS INJECTION OPERATIONS:
= 1,036 BBL.
= 21 BBL./ACRE
ESTIMATED PRIMARY DECLINE
YEARLY GROSS OIL PRODUCTION
— BARRELS —
35,000
30,000
20,000
15,000
10,000
8,000
6,000
4,000
2,000
1,000
1935
1937
1939
1941
1943
1945
1947

at prices ranging from $1.09 per barrel for 27° to $1.29 for 37° A.P.I. gravity. In addition to the standard price schedule, a subsidy of 35¢ per barrel oil was paid by the Government. Subsidy payments started August 1, 1944, and were still in effect on July 1, 1946.

Samples of crude oil from the Olympic sand and the Cromwell sand were collected from the stock-tanks on a few leaseholds in 1946, and these oil samples were analyzed by the U. S. Geological Survey Laboratory, Casper, Wyoming. The general characteristics of the crude oils and the characteristics of the fractions of these oils as determined by the Bureau of Mines Hempel method of analysis are given in tables 5 and 6.

Table 5

Analyses of oil from the Olympic sand in the Olympic field, Oklahoma
(J. D. Clark, Analyst)

Sample 1

Location	SE$\frac{1}{4}$ sec. 1, T. 9 N., R. 8 E
Depth of Olympic sand, feet	1670
Sample collected	September 17, 1946
Sample obtained at	Stock tank

GENERAL CHARACTERISTICS

A.P.I. gravity	34.2°
Specific gravity	0.854
Sulfur, percent	0.033
Saybolt Universal viscosity at 70° F., sec.	80
Saybolt Universal viscosity at 100° F., sec.	54
Pour point, °F.	10
Color	brown
Base	intermediate

DISTILLATION, BUREAU OF MINES HEMPEL METHOD

Distillation at atmospheric pressure, 630 mm.
first drop 43° C. (109° F.)

Fraction No.	Cut at °C.	Cut at °F.	Per cent	Sum, per cent	Sp. gr., 60/60°F.	°A.P.I., 60°F.	C.I.	S. U. visc., 100°F.	Cloud test, °F.
1	50	122	1.1	1.1					
2	75	167	2.0	3.1	0.658	83.5	4.1		
3	100	212	4.1	7.2	.696	71.8	12		
4	125	257	4.7	11.9	.725	63.7	17		
5	150	302	4.4	16.3	.747	57.9	19		
6	175	347	4.9	21.2	.766	53.2	21		
7	200	392	4.0	25.2	.782	49.5	23		
8	225	437	5.2	30.4	.798	45.8	25		
9	250	482	5.1	35.5	.812	42.8	26		
10	275	527	7.0	42.5	.828	39.4	29		
Distillation continued at 40 mm.									
11	200	392							
12	225	437	3.9	46.4	0.863	32.5	36	49	30
13	250	482	5.8	52.2	.871	31.0	37	59	45
14	275	527	6.6	58.8	.883	28.8	39	94	60
15	300	572	6.6	65.4	.895	26.6	42	172	75
Residuum			30.5	95.9	0.947	17.9			

Carbon residue of residuum, 8.46 percent; carbon residue of crude 2.86 percent.

APPROXIMATE SUMMARY

	Per cent	Sp. gr., 60/60° F.	°A.P.I., 60° F.	Viscosity, sec.
Light gasoline	7.2	0.680	76.6	
Total gasoline and naphtha	30.4	0.744	58.7	
Kerosene distillate	5.1	0.812	42.8	
Gas oil	9.4	0.837	37.6	Below 50
Nonviscous lubricating distillate	11.2	.864-.884	32.3-28.6	50-100
Medium lubricating distillate	8.3	.884-.899	28.6-25.9	100-200
Viscous lubricating distillate	1.0	.899-.901	25.9-25.5	Above 200
Residuum	30.5	.947	17.9	
Distillation loss	4.1			

Sample 2

Location ....SW¼ NE¼ NW¼ sec. 12, T. 9N., R. 8E.
Depth of Olympic sand, feet 1696
Sample collected ....September 17, 1946
Sample obtained at .... Well 1-A
Status of well .... pumping

GENERAL CHARACTERISTICS

A.P.I. gravity .... 27.9°
Specific gravity 0.888
Sulfur, percent 0.033
Saybolt Universal viscosity at 70° F., sec. 419
Saybolt Universal viscosity at 100°F., sec. 133
Pour point, °F. 35
Color .... brown
Base .... Intermediate

DISTILLATION, BUREAU OF MINES HEMPEL METHOD

Distillation at atmospheric pressure, 628 mm.
First drop 92° C. (198° F.)

Fraction No.	Cut at °C.	Cut at °F.	Per cent	Sum per cent	Sp. gr., 60/60°F.	°A.P.I., 60/60°F.	C.I.	S. U. visc., 100°F.	Cloud test, °F.
1	50	122							
2	75	167							
3	100	212							
4	125	257	1.0	1.0	0.747	57.9	27		
5	150	302	2.1	3.1	.759	54.9	25		
6	175	347	2.2	5.3	.773	51.6	25		
7	200	392	3.5	8.8	.780	49.9	22		
8	225	437	4.7	13.5	.798	45.8	25		
9	250	482	7.8	21.3	.817	41.7	28		
10	275	527	5.4	26.7	.833	38.4	31		
Distillation continued at 40 mm.									
11	200	392							
12	225	437	7.3	34.0	0.860	33.0	35	49	25
13	250	482	7.4	41.4	.871	21.0	37	61	45
14	275	527	5.9	47.3	.881	29.1	38	92	60
15	300	572	7.4	54.7	.890	27.5	39	133	75
Residuum			41.9	96.6	0.948	17.8			

Carbon residue of residuum 8.13 percent; carbon residue of crude 3.55 percent.

APPROXIMATE SUMMARY

	Per cent	Sp. gr., 60/60°F.	°A.P.I., 60° F.	Viscosity, sec.
Light gasoline				
Total gasoline and naphtha	13.5	0.779	50.1	
Kerosene distillate	7.8	.817	41.7	
Gas oil	8.6	.843	36.4	Below 50
Nonviscous lubricating distillate	15.6	.861-.883	32.8-28.8	50-100
Medium lubricating distillate	9.2	.883-.895	28.8-26.6	100-200
Viscous lubricating distillate				Above 200
Residuum	41.9	0.948	17.8	
Distillation loss	3.4			

Table 6

Analysis of oil from the Cromwell sand in the Olympic field, Oklahoma
(J. D. Clark, Analyst)

Sample 1

Location .... SE¼ NW¼ NW¼ sec. 12, T. 9N., R. 8E.
Depth of Cromwell sand, feet 3425
Sample collected .... November 21, 1946
Sample obtained at .... Separator
Status of well .... flowing

GENERAL CHARACTERISTICS

A.P.I. gravity	37.4°
Specific gravity	0.838
Sulfur, percent	0.206
Saybolt Universal viscosity at 70° F., sec.	52
Saybolt Universal viscosity at 100° F., sec.	43
Pour point, °F.	25
Color	green
Base	intermediate

DISTILLATION, BUREAU OF MINES HEMPEL METHOD

Distillation at atmospheric pressure, 630 mm.
First drop, 66° C. (151° F.)

Fraction No.	°C.	°F.	Per cent	Sum, per cent	Sp. gr., 60/60°F.	°A.P.I., 60°F.	C.I.	S. U. visc., 100°F.	Cloud test, °F.
1	50	122							
2	75	167	0.7	0.7					
3	100	212	4.7	5.4	0.730	62.3	28		
4	125	257	7.2	12.6	.738	60.2	23		
5	150	302	5.1	17.7	.755	55.9	23		
6	175	347	6.5	24.2	.770	52.3	23		
7	200	392	5.5	29.7	.786	48.5	25		
8	225	437	5.9	35.6	.800	45.4	26		
9	250	482	6.3	41.9	.814	42.3	27		
10	275	527	7.3	49.2	.828	39.4	29		
Distillation continued at 40 mm.									
11	200	392							
12	225	437	6.7	55.9	0.859	33.2	34	50	25
13	250	482	6.0	61.9	.868	31.5	35	64	45
14	275	527	6.2	68.1	.881	29.1	38	105	65
15	300	572	4.2	72.3	.887	28.0	38	153	80
Residuum			24.2	96.5	0.931	20.5			

Carbon residue of residuum, 3.75 percent; carbon residue of crude 1.01 percent.

APPROXIMATE SUMMARY

	Per cent	Sp. gr., 60/60° F.	°A.P.I., 60° F.	Viscosity, sec.
Light gasoline	5.4	0.730	62.3	
Total gasoline and naphtha	29.7	.755	55.9	
Kerosene distillate	12.2	.807	43.8	
Gas oil	10.6	.837	37.6	Below 50
Nonviscous lubricating distillate	11.9	.859-.880	33.2-29.3	50-100
Medium lubricating distillate	7.9	.880-.890	29.3-27.5	100-200
Viscous lubricating distillate				Above 200
Residuum	24.2	0.931	20.5	
Distillation loss	3.5			

THE OLYMPIC SAND BODY

The Olympic sand is a typical lenticular-type sand body of Pennsylvanian age which is similar in most respects to many of the other lenticular Pennsylvanian sands in the Mid-Continent Region. It is overlain and underlain by shale beds which converge laterally as the sand pinches out to form a stratigraphic trap. There are no dry holes within the main part of the sand body. The oil is produced by gas-expansion forces. Some water is produced with the oil in a few wells.

The Olympic sand body is dissimilar to many Pennsylvanian lenticular sand-reservoirs with respect to the accumulation of gas. The examination of well records and numerous cross sections of the sand body indicates that the structural attitude of the reservoir was an important factor in the accumulation of gas. The influence of sand thickness on gas accumulation appears to have been relatively minor.

The depth to the top of the sand varies from 1,633 feet in the southern part of the field to 1,920 feet in the northern part. The weighted average thickness of the Olympic sand body is 47 feet, and the weighted average thickness of the oil-productive sand is 32.9 feet.

Type of Sand Body

The majority of the Pennsylvanian sand bodies are either the bar or channel type of deposit. The Olympic sand body is an elongated deposit that parallels the strike of the region, and the sand body cross sections taken across the strike suggest the bar type of deposit. (See pl. 26.) These cross sections further indicate that the sand was deposited upon a reasonably plane surface. The isopachous map (pl.10) shows, in general, a rapid thinning of the sand body along the east side of the field. Across the field westward, however, the thinning is more gradual. This evidence, together with the shape of the sand body as shown by the transverse cross sections, indicates that the eastern side of the sand body constituted the seaward side of the bar.

Although the cross sections of the sand body do not show appreciable differences in the interval between the base of the Henryetta coal and the base of the sand body, this aspect is changed when the field is studied in its entirety. North of the syncline in sec. 36, T. 10N., R. 8E., the average interval between the base of the sand and the base of the coal is 72 feet along the east side of the field, 60 feet through the middle of the field, and 48 feet along the west side of the field. South of the syncline, the interval is 59 feet along the east side of the field, 66 feet through the middle of the field, and 38 feet along the west side of the field. These data imply that the sand body was deposited on a surface that sloped gently eastward. The present dips of the base of the sand body are either to the north and west, or to the south and west. The regional westward dip is predominant, and the localized dips to the north or south are reasonably consistent within small areas.

The Henryetta coal, in general, is in direct contact with the top of the sand body in those areas where the sand thickens to form local depositional "highs". Eighty percent of the wells wherein the coal is in contact with the sand have sand body-thicknesses ranging from 46 feet to 81 feet, and the average thickness of the sand in these wells is 60 feet. Most wells which logged the coal in direct contact with the sand body are located south of the syncline and their locations are consistent with the thicker sand sections shown on the isopachous map.

To summarize, the Olympic sand body appears to be a bar that was deposited near the western shore of the Cherokee sea, upon a comparatively plane surface that sloped gently eastward. The irregularities of the top of the sand body were caused by depositional "highs" and intervening "sinks" which were later filled with laminated silty shale. The regression of the sea was followed by the deposition of the coal over a fairly flat surface.

Lithology

The lithology of the Olympic sand body was ascertained from inspection of the individual logs of all wells in the field, from binocular examination of well cuttings, and from the study of available sample logs and core analyses data. A number of sample logs were prepared at the time the Olympic field was developed, and 26 of these logs were available for study. Additional information was obtained by making binocular examinations of cable-tool cuttings from 30 wells, and the samples from 20 of these wells were found to be representative of the oil-productive section of the sand body. Core samples of the upper part of the sand body from 21 wells were examined. The wells from which the core samples were taken were located in sec. 1, T. 9N., R. 8E., sec. 25, T. 10N., R. 8E., and secs. 8, 18, 19, and 30, T. 10N., R. 9E. These 21 wells had an average of five core samples per well, which represented a total of about 17 feet of sand per well.

Examination of the samples and data disclosed that the Olympic sand body has pronounced gradational lithology, with the upper part usually consisting of silty, micaceous shale, interbedded with fine-grained silty, micaceous sand and grading downward to medium- and fine-grained sand with decreasing clay bond and increasing friability. In many areas, however, the lower part of the sand body contains thin sections of micaceous siltstones and thin sections of fine-grained sand that is cemented with siderite or calcite. The upper part of the sand body is generally thin-bedded, whereas the lower and oil-productive part is usually more massive and the sand-grains are better sorted. The quartz sand-grains are medium to fine in size and sub-rounded with the exception of secondary grain growth. The bonding material consists essentially of white clay, calcite, and siderite. Two sample logs of part of the Senora formation, presented in table 7, were prepared for the purpose of showing the lithology of the Olympic sand-section in greater detail.

Analysis of Sand Body

The investigation of available well records disclosed certain indefinite details relative to the amount of productive sand. These conditions are enumerated as follows: (1) many wells were drilled only partially through the sand; (2) portions of the oil-bearing section

Table 7

Detailed sample logs of part of the Senora formation, Olympic field, Oklahoma 1/

Well:	- 1 -	- 2 -
Location:	SW¼SW¼NE¼ sec. 1, T. 9N., R. 8E.	SE¼SW¼SW¼ sec. 30, T. 10N., R. 9E.
Initial oil production, barrels per day:	560	70
Estimated oil-productive sand, feet:	38	26
Estimated gas sand, feet:	4	17

Well 1

Depth, feet:	Lithology
1650-52	Coal
1652-58	Gray shale
1658-62	Medium-grained sand, inter bedded with shaly siltstone
1662-66	Micaceous, medium-grained sand, interbedded with siltstone and clay
1666-71	(No samples; driller's log shows oil sand)
1671-78	Medium-grained, micaceous sand, interbedded with silty gray shale
1678-83	Hard medium-grained sand, cemented with calcite
1683-89	Soft medium-grained sand with small amount of clay
1689-1702	Soft medium-grained sand, interbedded with fine-grained sand; clay bond
1702-10	Fine-grained sand with clay bond
1710-13	Hard sand cemented with calcite
1713-20	Light brown shale and dark shale
1720-28	Dark shale
1728 ...	Total depth

Well 2

Depth, feet:	Lithology
1715-17	Black shale
1717-19	Coal
1719-25	Dark and gray shale
1725-33	Silty micaceous gray shale
1733-42	Hard fine-grained Micaceous sand, clay
1742-48	Soft fine-grained micaceous sand
1748-52	Hard fine sideritic sand
1752-56	(No samples; driller's log shows oil sand)
1756-60	Fine-grained micaceous sand interbedded with silty shale
1760-62	Hard fine-grained sand interbedded with shale
1762-66	Soft fine-grained well-sorted sand
1766-69	Hard fine-grained sideritic sand
1769-79	Fine-grained well-sorted sand
1779-81	Hard sideritic sand
1781-87	Soft fine-grained sand
1787-88	Hard sand, cemented with calcite
1788-90	Dark gray shale
1790 ...	Total depth

1/ Samples examined represented intervals of 2 to 5 feet.

were not productive because of unfavorable sand-conditions; and (3) the productive sand was overlain with a gas cap in certain areas of the field. Consequently, estimates of the total sand and productive sand-thickness were required for many wells.

The total thickness of the sand body was not known for the many wells in the field which were not drilled through the sand. In order to obtain reasonable estimates of the total sand, oil-productive sand, and gas sand, a detailed study was made of well log data. The well logs were arranged in a series of north-south cross sections for each leasehold in the field. When the log data so arranged did not provide sufficient control on the base of the sand body, information from adjacent leaseholds was used as a guide. These cross sections, augmented by statistical analysis of the sand body, permitted reasonable estimates of the total sand-thickness, and also provided data from which to estimate the base of the gas cap and the amount of oil-productive sand.

Estimates of the amount of undrilled sand exceeded 5 feet for 99 wells in the field. Twenty-nine of these wells were edge wells, and presumably were not drilled deeper in order to avoid drilling into water. The other 70 wells were scattered throughout the field, and the samples indicated that these wells were not drilled deeper because of the unfavorable appearance of the well-cuttings. Subsequent to the initial development-period, however, a number of wells were deepened 10 to 15 feet without completely penetrating the sand.

The amount of productive sand, expressed as percent of the total sand, was estimated whenever possible from the 56 available sample logs and from the drillers' logs. If the log descriptions were considered inadequate, an average productive-sand percentage, derived from the examination of 20 sets of cable-tool samples, was applied. The distribution of the 20 sample-log wells in the field, the estimated percentages of productive sand, and the average percentage are presented in table 8.

Table 8

Summary of sample-log examinations of the Olympic sand, showing amount of oil-productive sand expressed in terms of percent of total sand, Olympic field, Oklahoma

Well location	Oil-productive sand, percent of total sand
SE¼NW¼NW¼ sec. 18, T. 10N., R. 9E	71.0
SW¼NE¼NW¼ . . . . . . do	70.0
SE¼NE¼NW¼ . . . . . . do	67.0
SW¼NW¼NE¼ . . . . . . do	63.0
SE¼NW¼NE¼ . . . . . . do	76.0
NW¼SE¼NE¼ . . . . . . do	71.0
NE¼SE¼NE¼ . . . . . . do	55.0
NW¼SW¼NW¼ sec. 17, T. 10N., R. 9E.	65.0
SE¼SE¼SE¼ sec. 25, T. 10N., R. 8E	89.0
SE¼SW¼SE¼ . . . . . . do	67.0
SW¼SW¼SE¼ . . . . . . do.	65.0
SW¼SE¼SW¼ . . . . . . do	48.0
SW¼SE¼NE¼ . . . . . . do	61.0
SE¼SW¼SW¼ sec. 30, T. 10N., R. 9E	89.0
NE¼SW¼NW¼ . . . . . . do	60.0
NW¼SW¼NW¼ . . . . . . do	80.0
SW¼SW¼NE¼ sec. 1, T. 9 N., R. 8E.	75.0
SW¼NW¼NE¼ . . . . . . do	70.0
NW¼NE¼NW¼ . . . . . . do	57.0
SW¼SE¼NW¼ . . . . . . do	91.0
AVERAGE;	69.5

Gas Cap

The gas cap of the Olympic field is of considerable importance in connection with anticipated secondary-recovery operations. The casing in the majority of the wells was set in the top of the sand body, and if the permeability of the gas cap should prove comparable to or greater than that of the oil-producing section, serious difficulty would be encountered by "thiefing" of any injected media. The available information pertaining to the gas cap consisted of gas-oil ratio records, estimates of initial gas production from many wells, and log data relative to the tops of the gas sand and oil sand.

All of the aforementioned data were used in determining the extent of the gas-cap area, but the most reliable information was found to be the 1937 gas-oil ratio records of the individual leaseholds. Complete records for any earlier year were not obtainable. The original solution gas-oil ratio in the field was approximately 250 cubic feet per barrel, but for the 16 leaseholds which were determined to constitute the gas-cap area, the average 1937 gas-oil ratio was 3,200 cubic feet per barrel. For 46 other leaseholds, however, the average 1937 gas-oil ratio was only 500 cubic feet per barrel.

The gas-cap area, shown superimposed on the isopachous map (pl.10), embraces 990 acres and consists of a 200-acre area in the central portion of the field and a 790-acre area in the southern part of the field. The average thickness of the gas sand in the central area was determined to be 11.9 feet, and the average thickness of the gas sand in the southern area was ascertained to be 13.4 feet.

Complete permeability data on the gas sand were not available.

It is therefore not possible to state definitely whether or not the gas-cap permeabilities are of sufficient magnitude to impede secondary-recovery operations. Examination of well cuttings, well logs, and core analysis data indicates that the gas-sand permeability in the central gas-cap area is not high enough to interfere with either gas- or water- injection operations. The existence of low gas-sand permeabilities in this area is substantiated by the fact that only two wells were reported as having initial gas production.

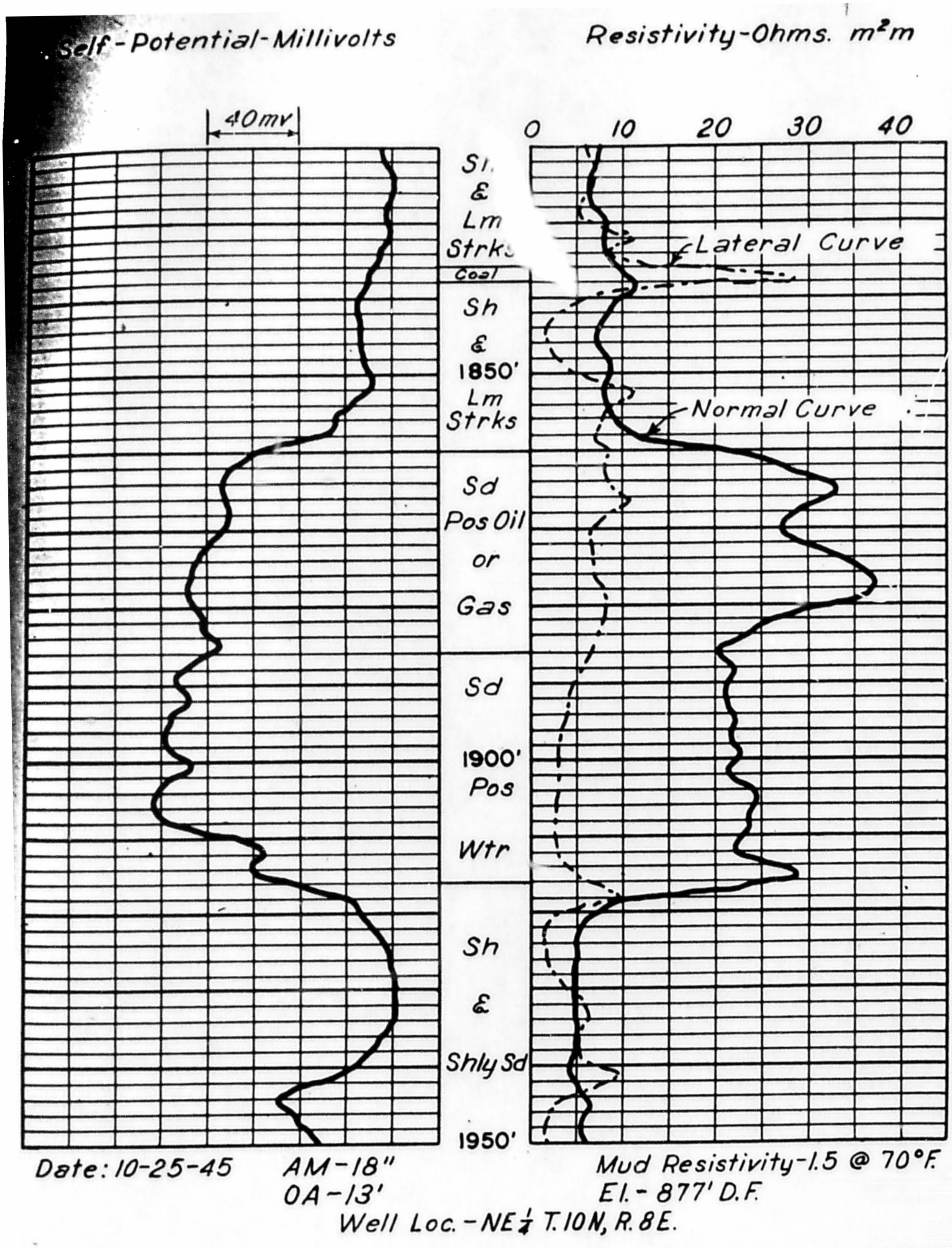
The log descriptions and core analyses of the gas sand in the southern gas-cap area indicate that approximately one-half of this area has permeabilities sufficiently high to impair gas-injection operations. These permeabilities, however, are probably not high enough to have deleterious effects on water-flood operations. Twelve core analyses were available for the gas sand in the southern area, and for five of these analyses the permeability ratios suggest the possibility of unsatisfactory gas-injection operations. In these five wells the permeability values for 74 feet of gas sand varied from 1 to 121 millidarcies, and the weighted average permeability was 42 millidarcies. In the other seven wells, however, the range in permeability for 125 feet of gas sand was from 1 to 50 millidarcies, and the weighted average permeability was only 15 millidarcies. The log descriptions for the wells within the gas-cap area show that the gas sand consists essentially of interbedded fine sand and silty shale. Consequently, further exploration by coring will be necessary for accurate determinations of gas-sand permeabilities and related effects on secondary-recovery operations.

Edge Water

Lenticular sand-reservoirs of Pennsylvanian age seldom contain bottom water, herein defined as water which underlies the oil at substantially the same sub-sea depth over the entire reservoir. The water-production history of the Olympic field does not show evidence of the presence of bottom water, but it does indicate the presence of edge water, which is found generally down-dip along the western margin of the field. Table 9 gives the location of the wells producing edge water, together with initial water- and oil-production data and the approximate sub-sea depth of the water-level in each well. An electric log of the last well in table 9 is reproduced on plate 27.

Some inside wells produced water initially, but these wells were usually found to be improperly completed and the source of the water was above the Olympic sand. Many wells are now making a small volume of water which may be interstitial water held originally in the pores of the sand. No attempt is made herein to explain the production-mechanics of interstitial water.

The analyses of six water samples, which were collected in the Olympic field, are given in table 10. The well from which sample 4 was collected produced 360 barrels of water daily at time of completion, and in June 1946, produced water at the rate of 150 barrels per day. The electric log of a well directly offsetting this well (see pl. 27) shows a distinct water-level in the Olympic sand. In view of these facts the water designated as sample 4 was presumed to be actually



ELECTRIC LOG OF OLYMPIC SAND
OLYMPIC FIELD, OKLAHOMA

Table 9

Summary of wells producing oil and water
initially from the Olympic sand,
Olympic field, Oklahoma

Well location	Initial production, barrels per day Water	Oil	Water level, approximate subsea depth, feet
NE¼NW¼NE¼ sec. 14, T. 9N., R. 8E.	-hole full of water-		938
NE¼NE¼NE¼ . . . . do.	86	23	933
NW¼SE¼NE¼ sec. 11, T. 9N., R. 8E.	10	37	943
SW¼SE¼NE¼ . . . . do.	50	10	949
SE¼SE¼NE¼ sec. 2, T. 9N., R. 8E.	86	23	926
SE¼SE¼NW¼ sec. 36, T. 10N., R. 8E.	80	35	916
SE¼SW¼NW¼ . . . . do.	-hole full of water-		935
SW¼NE¼NW¼ . . . . do.	200	40	904?
SE¼SW¼NE¼ sec. 25, T. 10N., R. 8E.	60	60	931
NE¼SE¼NE¼ sec. 24, T. 10N., R. 8E	8	47	964
NE¼NW¼SW¼ sec. 18, T. 10N., R. 9E.	30	30	977
SW¼SE¼NW¼ . . . . do.	40	100	986
NE¼NW¼NW¼ . . . . do.	22	10	997
NW¼NE¼NW¼ . . . . do.	25	30	983
SE¼SE¼SE¼ sec. 7, T. 10N., R. 9E.	36	24	985
SW¼SE¼SE¼ . . . . do.	14	42	986
SE¼SW¼SE¼ . . . . do.	-hole full of water-		983
SW¼SW¼SW¼ sec. 8, T. 10N., R. 9E.	23	45	971
SE¼NE¼NE¼ sec. 13, T. 10N., R. 8E.	360	36	1,009

produced from the Olympic sand. This conclusion assumes that no dilution by water from upper formations had occurred. The average of the total solids in samples 1, 2, and 3 was noted to be approximately 11,700 parts per million greater than the total solids in sample 4. The leaseholds from which samples 1, 2, and 3 were collected were producing, as of July 1, 1946, about 25, 1, and 12 barrels of

Table 10

Analyses of water produced from wells completed in the Olympic sand, Olympic field, Oklahoma (J. D. Clark, analyst)

Sample	- 1 -	- 2 -	- 3 -
Location	Sec. 36, T. 10N., R. 8E.	Sec. 11, T. 9N., R. 8E	Sec. 19, T. 10N., R.9E
Wells producing water	4	2	2
Average depth, feet	1,733	1,787	1,917
Date samples taken	11-21-46	9-17-46	10-15-46
	Ppm 1/	Ppm	Ppm
Calcium (Ca)	11,500	9,812	9,991
Magnesium (Mg)	1,995	1,848	1,979
Alkalis (Na)	39,526	41,739	40,008
Chloride (Cl)	87,120	87,120	85,140
Sulfate (SO_4)	-	-	-
Bicarbonate (HCO^3) . .	26	18	50
Total solids (calculated)	140,057	140,528	137,143

Sample	- 4 -	- 5 -	- 6 -
Location	Sec. 13, T. 10N., R. 8E	Sec. 12, T. 9N., R. 8E.	Sec. 1, T. 9N., R.8E
Wells producing water	1	1	14
Average depth, feet	1,881	1,756	1,715
Date samples taken . . .	10-15-46	9-17-46	9-17-46
	Ppm	Ppm	Ppm
Calcium (Ca)	9,276	7,261	409
Magnesium (Mg)	1,924	1,686	89
Alkalis (Na)	37,073	32,128	1,996
Chloride (Cl).	79,200	67,320	4,059
Sulfate (SO_4).	-	-	-
Bicarbonate (HCO^3) . .	27	-	5
Total solids (calculated) . . .	127,486	108,395	6,556

1/ Parts per million.

water per day respectively. Water sample 5 appears to have been diluted slightly by water from above the Olympic sand and sample 6 appears to have been highly diluted by water from upper formations.

Physical Conditions of the Sand Body

The essential prerequisites for the successful operation of a secondary-recovery project are: (1) adequate total reserves in terms of barrels per acre; (2) sufficient saturation in terms of percent pore space or barrels per acre-foot; and (3) suitable physical conditions with respect to permeability and porosity. These three interrelated factors are of equal importance. The significance of the physical conditions relative to uniformity merits brief comment. Experience has shown that a proper secondary-recovery survey should include the analysis of a representative number of cores from the sand-reservoir. Such a survey may indicate that both the reserves and saturation are sufficient, but that certain sections of the sand body show permeabilities deviating considerably from the weighted average permeability. Under these circumstances the sand sections having large deviations greater than the average would probably constitute "thief" sections, and those having large deviations less than the average presumably would not be responsive to the conventional application of a single injection pressure at the sand face. This aspect of continuous heterogeneity or anisotropy in the sand is possibly the most important engineering problem relating to secondary recovery.

Only two of the 15 core analyses available for study represented the oil section of the Olympic sand body. Hence, it was necessary to adopt some indirect method for studying the permeability-porosity features of the sand. Such data as sample examinations, well initial-production, and production-decline curves are often used for estimating the physical character of oil sands. Experience has shown that the production-decline curves for the majority of Pennsylvanian sand lense reservoirs are hyperbolic, in cases of unrestricted production. Further, the history of these unrestricted reservoirs usually shows that from 70 to 80 percent of the "primary" production is obtained during the first one-third of the life of the field. The term "primary" production, as used in the discussion of the sand body, includes all of the oil produced from the Olympic sand to July 1, 1946, except that attributed to gas-injection operations. The hyperbolic decline curve (pl. 22) shows that the oil production from the Olympic sand was unrestricted. The production records for the individual leaseholds disclosed that the "primary" production for the first four years constituted 62 to 89 percent of the total "primary" production to July 1, 1946. The average for the field was found to be 78 percent. These facts suggest that the "primary" production, expressed as barrels per acre-foot of productive sand, may be used as an index of the permeability-porosity conditions of the sand body.

The "primary" production, in terms of barrels per acre-foot of productive sand, was determined for all of the leaseholds in the field and used as a "sand body condition factor". The numerical value of this factor, as used in this report, is expressed as a square-root function, and the formula is as follows:

$$\text{SAND BODY FACTOR} = \sqrt{\frac{\text{Barrels/Acre/Ft. of productive sand}}{10}}$$

The basic assumption in the application of this concept is that the permeability and porosity characteristics vary directly with the magnitude of the sand body factor. The sand body factor values for the entire field were divided into four classifications and the results are presented on the sand body-condition map. (pl. 28.) The area shown on the map as class 1 represents the best sand body-conditions as to productive characteristics, and class 4 area represents the relatively poorest sand body-conditions. The areas shown as class 2 and class 3 represent sand body-conditions between these two extremes. An analysis of the sand body condition map with respect to sand body classes, factors, and acreage is gi n in table 11.

Table 11

Classification and relative distribution of Olympic sand body, Olympic field, Oklahoma

Class of sand body	Sand body factor	Area, acres 1/	Percent of total acres	Oil-productive sand thickness, feet 2/
1	4 to 5	460	13.2	36
2	3 to 4	1,790	51.6	33
3	2 to 3	931	26.8	33
4	less than 2	290	8.4	-
	Total:	3,471		

1/ Acres equal productive acres plus proved acres.
2/ Weighted average sand-thickness.

Relation of Sand Body Factor Values to Other Production Characteristics

The relation between the sand body factor and well initial-production, by leaseholds, is shown graphically on plate 29. However, the well initial-production values, expressed as

$$\sqrt{\text{Barrels/Day/Ft. Productive Sand}}$$

show a more consistent relation to the sand body factors. These data are shown graphically on plate 30, figure 1. The well initial-production data plotted on these graphs did not include leaseholds having both edge wells and inside wells because the initial production per foot was found to be consistently lower for the edge wells. An analysis of 13 leaseholds, embracing 63 inside wells and 26 edge wells, showed a weighted average initial production, in barrels per day per foot of productive sand, of 7.7 for the inside wells and 2.9 for the edge wells.

The peak yearly oil production, expressed as

$$\sqrt{\frac{\text{Barrels/Well/Ft. Productive Sand}}{10}}$$

shows a reasonably good relation when plotted, by leaseholds, against the sand body factor values. The graph of these data is presented on plate 30, figure 2.

Porosity of the Sand Body

Reserve estimates are often made by using a single porosity value for an entire reservoir. When data are available and are analyzed by leaseholds, however, the use of a single porosity figure is inappropriate. Data relative to Pennsylvanian lenticular sand

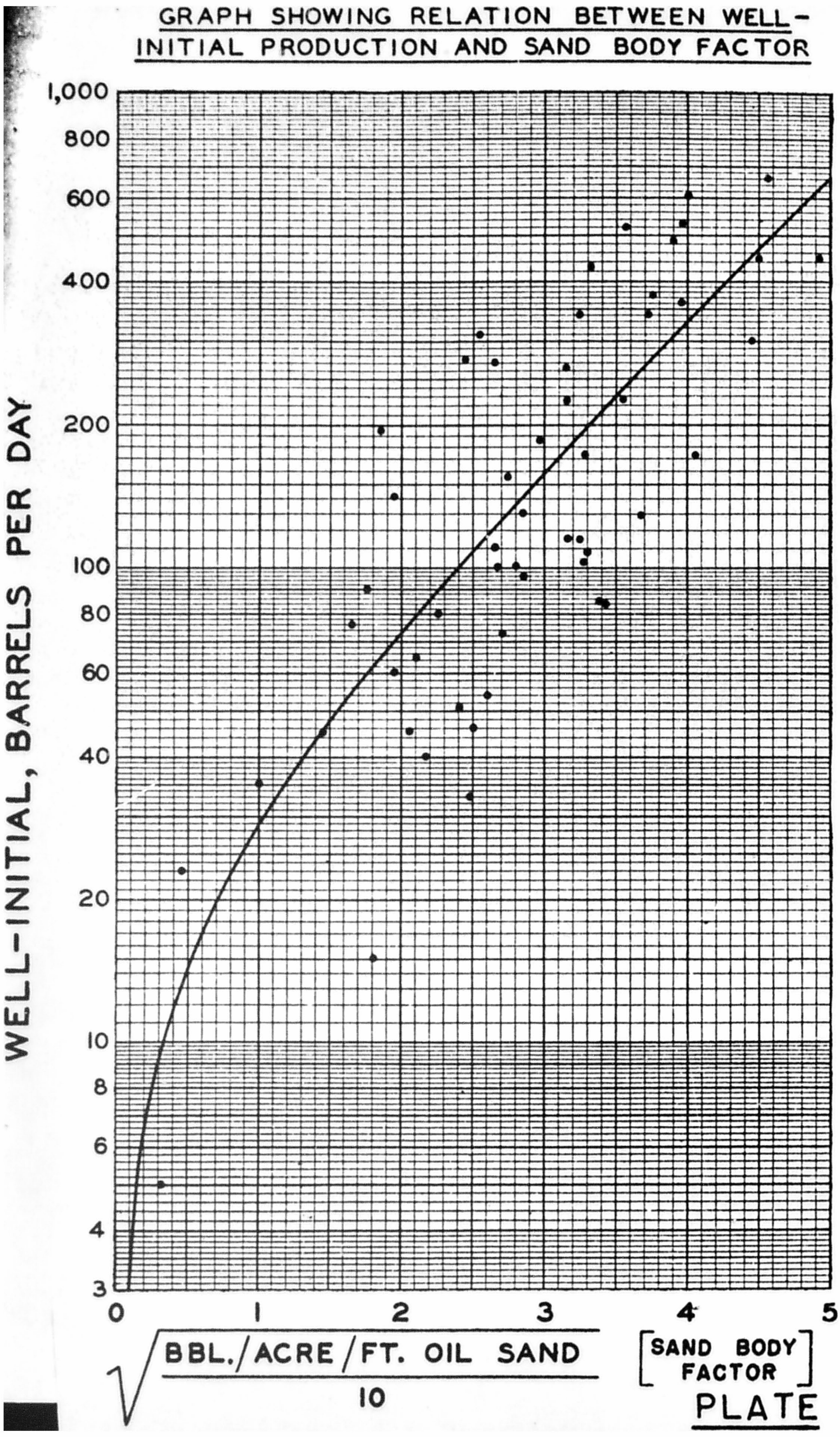

GRAPH SHOWING RELATION BETWEEN WELL-INITIAL PRODUCTION AND SAND BODY FACTOR
1,000
800
600
400
200
100
80
60
40
20
10
8
6
4
3
WELL-INITIAL, BARRELS PER DAY
0
1
2
3
4
5
√(BBL./ACRE/FT. OIL SAND / 10)
[SAND BODY FACTOR]

PLATE 29.

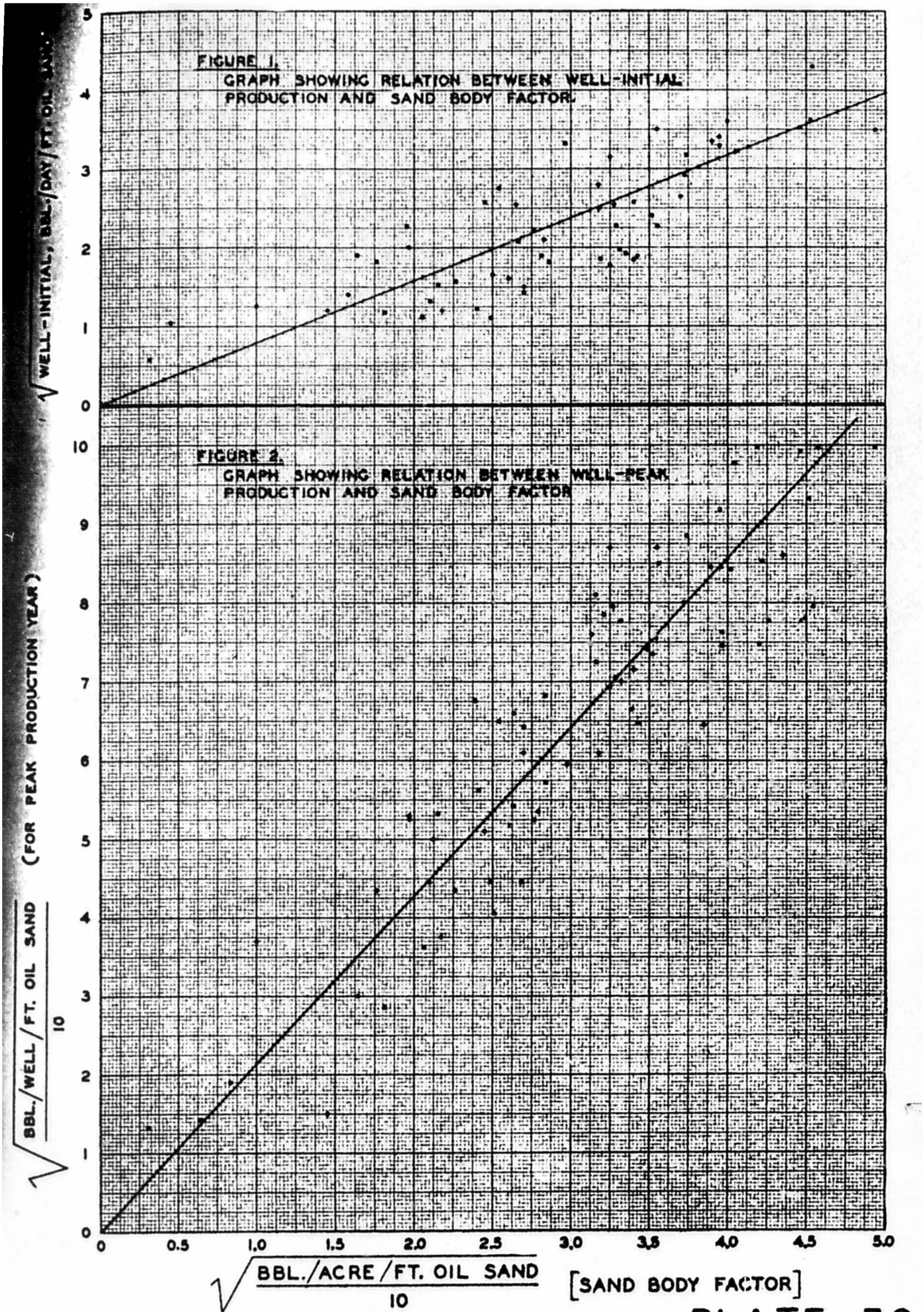


FIGURE 1.
GRAPH SHOWING RELATION BETWEEN WELL-INITIAL PRODUCTION AND SAND BODY FACTOR
FIGURE 2.
GRAPH SHOWING RELATION BETWEEN WELL-PEAK PRODUCTION AND SAND BODY FACTOR
√ WELL-INITIAL, BBL./DAY/FT. OIL SAND
√ (BBL./WELL/FT. OIL SAND)/10 (FOR PEAK PRODUCTION YEAR)
√ (BBL./ACRE/FT. OIL SAND)/10 [SAND BODY FACTOR]
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

PLATE 30.

bodies indicate that porosity of a magnitude of about 12 percent is the approximate minimum for oil-producing sections. Consequently, the sand body factor of 0 was arbitrarily assigned the value of 12 percent porosity and the sand body factor of 5 was assigned the value of 22 percent porosity. A simple linear graph was constructed from these assumed values and the porosities for all the leaseholds were estimated from this graph. A few comparisons of porosities from core analyses and those estimated by the previously described method are given in table 12.

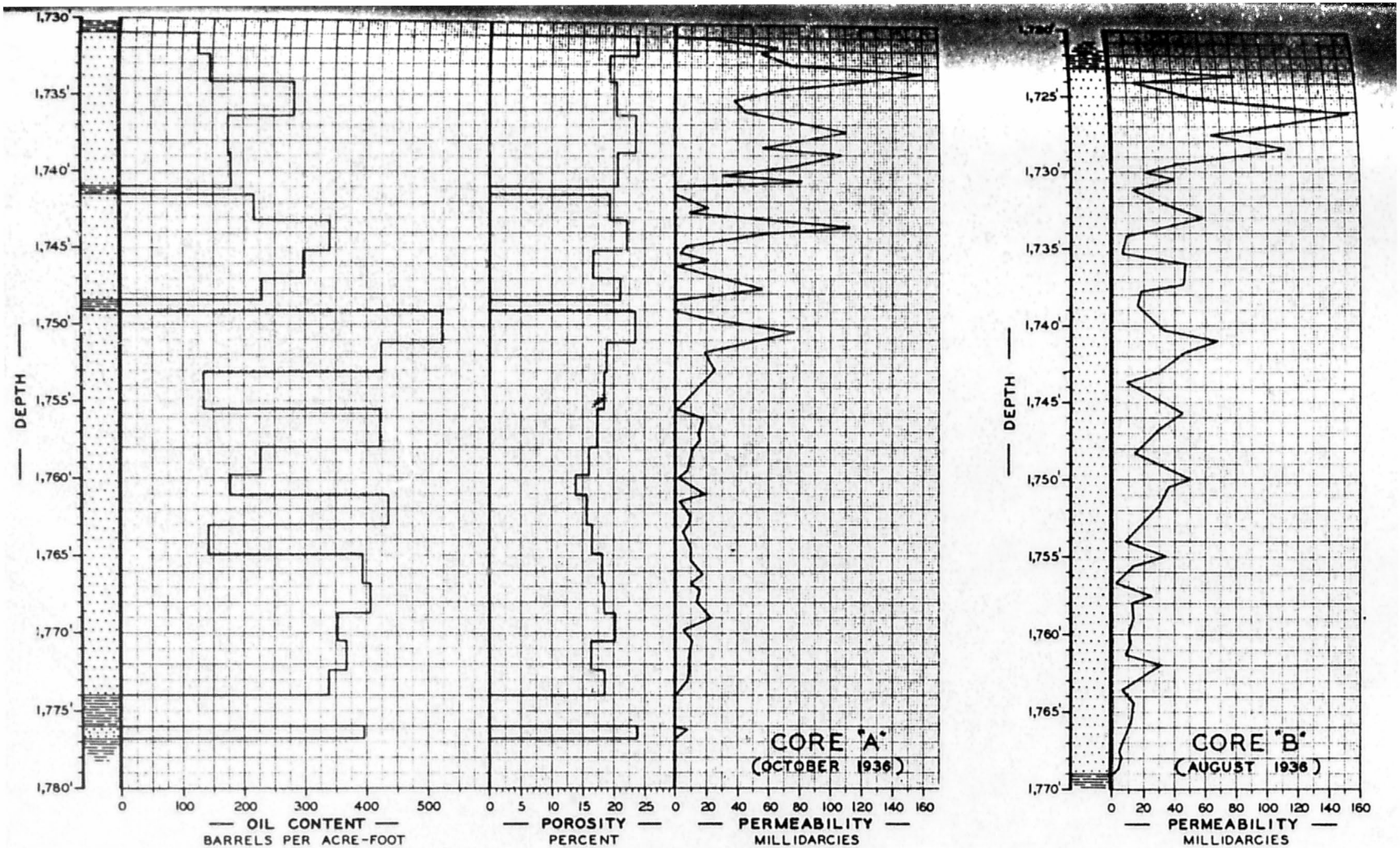
Table 12

Comparison of porosity of the Olympic sand derived from the sand body factor and specific porosity determined by core analysis, Olympic field, Oklahoma

Location of leasehold	Number of wells on leasehold	Number of cores analyzed	Total samples analyzed 1/	Porosity, percent: Determined from core analyses (average)	Porosity, percent: Estimated from sand body factor
Sec. 30, T. 10N., R.9E	12	2	6	19.0	18.4
Sec. 31, T. 10N., R.9E	8	1	23	19.0	17.3
Sec. 25, T. 10N., R.8E.	5	3	?	21.0	19.1

1/ From oil-productive section.

Table 13 is a weighted average summary of two core analyses of the Olympic sand. Both cores were taken through the entire sand section from top to bottom and the complete core profiles of the two analyses are shown on plate 31.



— "OIL CONTENT" REPRESENTS MINIMUM RESIDUAL OIL SATURATION RESULTING FROM FLUSHING AT TIME OF CORING: EQUIVALENT TO RESIDUAL OIL SATURATION AFTER LABORATORY FLOODING. —

CORE ANALYSES OF OLYMPIC SAND

SECTION 31, T.10 N., R.9 E.

OLYMPIC FIELD

HUGHES AND OKFUSKEE COUNTIES, OKLAHOMA.

PLATE 31.

Table 13

Summary of core analysis determinations
of the Olympic sand,
Olympic field, Oklahoma

Core "A"
SE¼NW¼NW¼ sec. 31,
T. 10N., R. 9E.

	Gas sand	Oil-productive sand
Sand-thickness, feet	5.4	37.2
Oil content, barrels per acre-foot .	197.0	308.0
Oil saturation, percent of voids . .	12.0	20.8
Porosity, percent	20.9	19.0
Permeability, millidarcies	76.0	26.0

Core "B"
SE¼SW¼NW¼ sec. 31,
T. 10N., R. 9E

Sand-thickness, feet	none	37.0
Permeability, millidarcies	-	41.3

SECONDARY RECOVERY MEDIA

Surface Water Resources

It appears that a considerable volume of oil can be obtained from the Olympic sand by intensive application of secondary-recovery methods of development, and it is anticipated that such exploitation will be by water-flooding methods. For this purpose, it is essential that adequate water resources be made available in view of the large volume of water that is required for injection purposes during operation of extensive water-flooding projects.

A reconnoissance of the water resources in the general district of the Olympic field indicates that the water resources of the North Canadian River could be utilized to meet the demands of extensive water-flooding operations in the Olympic field. Furthermore, the surface-water resources of the Olympic field and adjacent areas can be made available for the purpose of water-flooding by impounding this water in a reservoir by the construction of a dam across Little Wewoka creek in the SE¼ sec. 35, T. 10N., R. 8E.

It is conceded that the procurement of water and its transportation to the place of service in the Olympic field would require a large investment which would affect seriously the size of the water-flooding project to be developed. This may result in the adoption of a program of unitization because of the economies that probably would result from the development of extensive water-flooding projects covering many leaseholds. It is surmised that water-flooding ventures, even under a plan of unitization, would adopt the 5-spot pattern system of development using a spacing of 660 feet between like wells. If such a development-program would comprise 10 quarter-sections, or an area of 1,600 acres, and the rate of intake of the water-input wells would average about 200 barrels of water daily per well, the total daily consumption of water would be approximately 32,000 barrels daily for the project. This rate of consumption is equivalent to 125 acre-feet of water monthly.

Water Resources of North Canadian River

The Olympic field lies in the drainage basin of the North Canadian River and at its nearest point this stream is 2-3/4 miles northeast of the field. It is therefore to be considered as an important source of water for water-flooding operations in exploiting the field. In fact, the discharge record of the North Canadian River from April 1938 to October 1946, (see pl. 32) indicates that sufficient water has been and probably will be available for future use in operating extensive water-flooding projects. The data which are presented also in table 14, were obtained from records on file with the office of the U. S. Corps of Engineers, Tulsa, Oklahoma, and from water-supply data of the U. S. Geological Survey. The records from the office of the U. S. Corps of Engineers pertains to the period October 1944 to October 1946 only. From these water-discharge data, it can be seen that the minimum rate of discharge for this stream during the period mentioned amounting to 2,720 acre-feet of water in January 1940, is greater than the volume of water required by the water-input wells on a 1,600 acre water-flood project.

A combination water-treatment and pressure plant, including the pipe-line system, that would supply the minimum requirement of 32,000 barrels of water daily from the North Canadian River would involve a large initial capital investment. This investment would be largely contingent upon the capacity of the water-treatment plant and the size of the pipe and length of the pipe-line system from water supply to the plant. A water-plant, if constructed in the Olympic field on the leasehold near the NE$\frac{1}{4}$ NE$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 1, T. 9N., R. 8E., would be about 4.8 miles from the North Canadian River. To furnish the required supply of water at the water-plant, it is estimated that 12-inch diameter pipe would be used to connect the source of water supply with the plant. A pumping station at

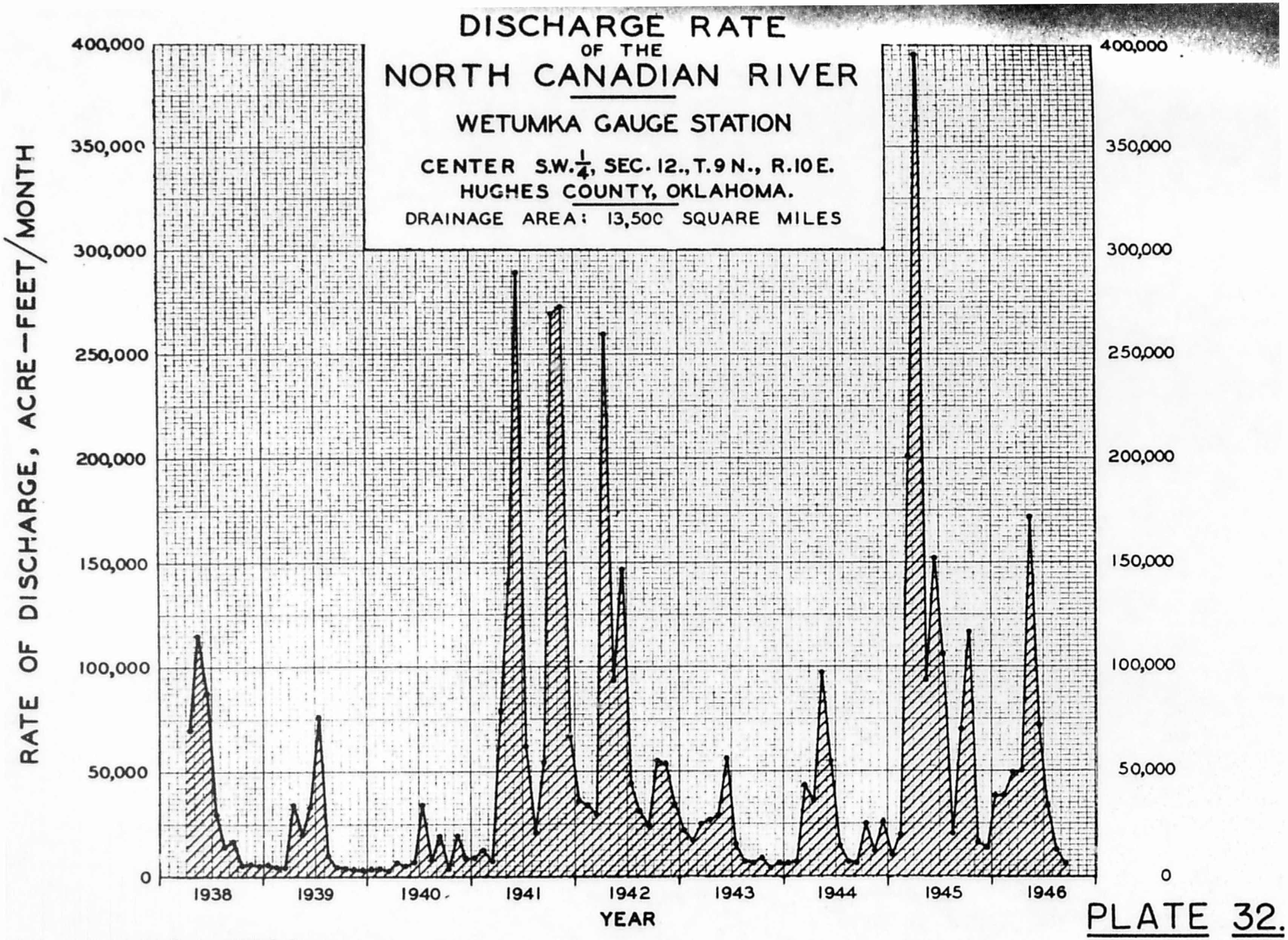

DISCHARGE RATE
OF THE
NORTH CANADIAN RIVER
WETUMKA GAUGE STATION
CENTER S.W.1/4, SEC. 12., T.9 N., R.10 E.
HUGHES COUNTY, OKLAHOMA.
DRAINAGE AREA: 13,500 SQUARE MILES
RATE OF DISCHARGE, ACRE—FEET/MONTH
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1938
1939
1940
1941
1942
1943
1944
1945
1946
YEAR

PLATE 32.

Table 14

Rate of discharge of the North Canadian River at Wetumka Station
Sec. 12, T. 9N., R. 10E., Hughes County, Oklahoma
Drainage basin: 13,500 square miles
Discharge rate in thousands of acre-feet of water per month

	1938	1939	1940	1941	1942	1943
January		5.31	2.72	8.77	35.59	22.28
February		4.26	3.58	12.49	34.15	16.52
March		4.14	2.67	7.24	29.23	24.66
April	70.43	33.91	12.37	78.22	259.00	27.48
May	115.30	19.96	5.25	139.60	93.33	286.40
June	87.05	33.44	12.27	288.90	146.90	55.89
July	29.75	75.68	34.27	62.33	43.79	14.63
August	13.70	10.45	12.48	21.45	31.38	6.78
September	17.37	3.73	19.32	54.29	24.00	5.82
October	5.46	3.53	3.21	269.20	54.62	8.07
November	5.67	2.92	18.55	272.50	52.95	4.12
December	4.73	2.87	8.27	67.01	33.79	5.72

	1944	1945	1946
January	6.41	9.84	38.45
February	6.79	19.55	38.45
March	42.90	201.20	49.05
April	36.28	395.30	49.60
May	97.20	93.62	171.80
June	55.05	151.70	71.64
July	13.59	105.90	32.81
August	6.88	20.08	12.45
September	5.93	70.29	6.40
October	24.57	116.60	
November	12.17	16.25	
December	26.13	12.92	

the North Canadian River, probably in the NE$\frac{1}{4}$ sec. 22, T. 10N., R. 9E., would be required to deliver the water through the pipe-line system to the water-plant. Because the relief here does not exceed 150 feet, it is estimated that the total head on the pump, consisting of suction head, static head, velocity head, friction head and pressure head, if any exists, would be low. Consequently low duty water-pumps of centrifugal type will suffice.

The investment in a water-transportation system and a combination treating and pressure plant having delivery capacity of about 40,000 barrels daily would be approximately $178,000. This investment would include $58,000 as the cost of constructing 4.8 miles of pipe line, and the pump-station at the North Canadian River. The investment in the water-treating plant would vary considerably in accordance with the design of the proposed plant, but would be about $3.00 per barrel for a plant having a delivery capacity of 40,000 barrels of water per day. The total cost of the combination water-plant and water-transportation system would be equivalent to about $4.45 per barrel of the plant delivery capacity daily. On account of various factors such as the cost of labor and the price of steel, it is suggested that the investment quoted may be considered as relative only.

Impounded Water Supply

An alternative water supply for the purpose of water-flooding the Olympic sand may be provided through the creation of a reservoir by the construction of a dam across Little Wewoka Creek, preferably in the SW¼ SE¼ sec. 35, T. 10N., R. 8E., slightly west of the Olympic field. This small stream enters the Olympic field from the west in sec. 36, T. 10N., R. 8E., and crosses the field flowing southeastward. A dam constructed here to a height of approximately 25 feet and having an elevation of 800 feet at the top of the dam would impound a maximum of about 15,488 acre-feet of water with an estimated average depth of 10 feet. The drainage basin for this reservoir would be about 18.4 square miles.

No records are available of the rate of discharge of Little Wewoka Creek in this area. However, records of precipitation and water run-off for the area nearest the Olympic field for which such records are available show sufficient precipitation for flooding the Olympic field. These records give the water run-off at the Dewar gauging station in sec. 25, T. 12N., R. 13E., on the Deep Fork River, about 35 miles northeast of the Olympic field. Its drainage basin covers 2,300 square miles and shows a 9-year record previous to 1946 of 819,500 acre-feet of water discharged yearly. At this rate the drainage basin of the proposed reservoir on Little Wewoka Creek embracing an area of 18.4 square miles would discharge 546 acre-feet of water per month. It is not to be construed that these records pertain to the actual water run-off in the general area of the Olympic field, but if precipitation in the Olympic field is comparable, sufficient water could be made available for water-flooding purposes on large projects in the Olympic field by impounding water on Little Wewoka Creek.

Subsurface Water

Water has been produced with the oil from subsurface formations in a few places in the Olympic field. At several places on the north and west side of the field water has been reported in some wells drilled into the Olympic sand and classified as "dry holes". In the NE$\frac{1}{4}$ sec. 13, T. 10N., R. 8E., a well completed in the Olympic sand produced initially 36 barrels of oil and 360 barrels of water daily. From these data it is believed that the Olympic sand along the margin of the field would not produce sufficient volumes of water for extensive flooding operations and that in any event the cost of drilling these wells also would be prohibitive.

A well completed on July 19, 1934 in the Cromwell sand in the NW¼ sec. 12, T. 9N., R. 8E., at a total depth of 3,474 feet, was producing on July 1, 1946, about 500 barrels of water daily with its oil production. This quantity of water would suffice for a small "pilot" water-flood project. On the other hand the Cromwell sand and deeper horizons do not appear attractive as possible sources of water in view of their low rate of discharge and the large investment required to drill and complete a well at this depth or at depths below the Cromwell horizon.

Electrical logging of shallow formations has indicated several of these strata to be water bearing, but they have not been tested for their rate of water production. It is questionable if these formations can produce at a rate sufficient to supply water for extensive water-flooding operations. On the other hand their potentialities for producing water should not be overlooked. Future tests of these zones may show that they can be used as a source of water for small water-flooding projects.

Gas Resources

A large volume of gas was produced with the oil from the Olympic sand in the early life of the field. In the phase of settled production through which the field is now passing, the gas production has become less abundant even in view of the fact that gas-injection operations still are in progress. During the first 6 months of 1946, it is estimated that the Olympic sand produced 332,559,000 cubic feet of gas. But during this period 136,736,000 cubic feet of gas was injected into the Olympic sand in the gas-injection system. In view of the fact that a large volume of gas is consumed in pumping the wells, in marketing, and in operating the gasoline plant, it is believed that the surplus gas is of small volume. This volume of gas is too small to be commercially important for extensive gas-injection operations. In addition to the gas produced from the Olympic sand, some gas is produced from the Cromwell sand by a well in the NW¼ sec. 12, T. 9N., R. 8E. The volume of gas and the reservoir pressure of this well are being used for flowing the oil production. No record is available, however, of the gas being produced from the Cromwell formation by this well.

In the early life of the field some gas was produced from the Calvin sand which is found about 200 feet above the Olympic zone. These wells have been depleted and have been plugged and abandoned. Yet, a well which produced from the Olympic sand for a time in the SW¼ sec. 12, T. 9N., R. 8E., was converted to a gas-injection well by exposing the Calvin sand for its gas production and reinjecting this gas into the Olympic sand by use of tubing set on a packer above the Olympic sand.

In a few other places in the Olympic field the Calvin sand has been found to be gas productive. In 1935, a well completed in the Calvin sand in the NE¼ sec. 12, T. 9N., R. 8E., produced about 4,800,000 cubic feet of gas initially per day. Furthermore, a well completed in the Olympic sand in the NE¼ SW¼ sec. 12, T. 9N., R. 8E., found the Calvin sand to be gas productive when this horizon was drilled. A test of this sand showed gas-producing potentialities of 3,000,000 cubic feet daily. It is anticipated that the Calvin sand should be gas productive in other parts of the Olympic field if the potentialities of the sand are tested properly.

A 4-inch gas-transmission line in the NE¼ sec. 1, T. 9N., R. 8E., is used to gather gas from the Olympic field for commercial marketing. It connects with the main 8-inch pipe line about 3 miles east of the Olympic field. As the market price of gas in this area ranged from $0.045 to $0.05 per thousand cubic feet on July 1, 1946, it is probable that repressuring ventures could not be operated profitably by injecting gas purchased at this market price.

OIL RESERVES

Non Recoverable Oil

In the appraisement of oil reserves recoverable by the application of secondary recovery methods, it is prudent to determine the terminal oil saturation of the sand at the time of depletion relative to the specific medium that is to be injected into the reservoir. Regardless of the characteristics of the injected medium, no method of injection is known that will remove all oil from the pores of a producing reservoir. Theoretically, the percentage of oil coexisting in the reservoir with the interstitial water is dependent on the difference in pressure between the two phases 16/. The injection of water into porous media is believed to be the best method by which oil saturation can be reduced to a minimum in those reservoirs adaptable to this type of operation.

Muskat and Taylor 17/ have shown by experiments in the laboratory that at about 20 percent oil saturation, the permeability of the reservoir to oil is low and at about 16 percent oil saturation the permeability to oil is zero. Furthermore, the profile of oil content of a core from a producing well drilled by the rotary method and which was described in that part of the text pertaining to characteristics of the sand body, depicted the voids of the core as being 20 percent saturated with oil. Undoubtedly this core was flushed during drilling. Accordingly, the oil content of the core has been reduced to a minimum oil saturation. It is equivalent to the terminal oil saturation derived by artificial water flooding of cores in the laboratory in flood pots. On the basis of the evidence, it was believed advisable in estimating the reserves of oil in the Olympic sand to consider the volume of oil remaining in the sand after the application of water flooding as non-recoverable oil.

16/ Bruce, W. A., and Welge, H. J., The Restored State Method for Determination of Oil in Place and Connate Water: World Oil, p.34, August 4, 1947.

17/ Muskat, M., and Taylor, M. O., Production Histories of Gas Drive Reservoirs: Am. Inst. Min. Met. Eng. Trans., vol. 8, No. 5, p. 4, September 1945.

Water-flooding projects in oil fields of Oklahoma so far have not shown the efficiency of the flooding tests performed in the laboratory on cores of the producing sands in these fields owing to anisotropic conditions of the sand, by-passing of the injected medium, and variations in water-flooding coverage. Muskat 18/, in the treatment of a 5-spot system of water flooding, which is the type of pattern adopted generally in water-flood development, has shown that in this particular type of geometric pattern the theoretical efficiency of the flood is 72.3 percent. On other geometric patterns the efficiency ranges from about 32 to 89 percent. It is anticipated that exploitation of the Olympic sand in this field by water flooding will follow the 5-spot pattern. Thus, in this field, the theoretical efficiency of the water-flood projects will be about 72.3 percent. As the efficiency of a water-flood is defined as the fraction of the total area of the network that is flooded by the time the flooding medium first reaches the producing wells, the minimum oil saturation of the sand at the time of depletion by secondary operations is therefore increased from 20 percent to 28.3 percent for the entire field. For the purpose of this report the calculated lower limit of oil saturation was further increased by 1.7 percent owing to the effect of economic conditions on the life of secondary operations, making the actual oil saturation of the Olympic sand at the economic limit of operation about 30.0 percent of the pore space in the Olympic reservoir. It is anticipated

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18/ Muskat, M., The Flow of Homogeneous Fluids Through Porous Media, pp. 596-597, New York and London, McGraw-Hill Book Co., 1937.

that a few properties in the field will not be exploited by water flooding, and on these properties the residual oil remaining in the sand as non-recoverable oil will be equivalent to the oil saturation at the point of depletion of these properties by continuation of the present operations. On the other hand, some of these leaseholds, though not directly developed by secondary methods, will no doubt offset properties exploited by water flooding, and undoubtedly these properties will show some effect from water-flooding operations. The residual oil saturation of the offset properties would be reduced accordingly, but in a less efficient manner than if the properties were embraced in a systematic water-flood plan.

Recoverable Oil

The oil reserve of the Olympic sand recoverable by the application of water-flooding methods of operation has been estimated by computing the volume of oil in place initially for each leasehold and by deducting the volumes of oil and gas withdrawn therefrom, during the several phases of production, to a minimum limit of oil saturation. This terminal oil saturation is a function of the relative permeability-oil saturation relationship. In addition, it was necessary to take full cognizance of the factor relating to the economics of oil production. Thus, as the reservoir is produced and the flow of oil in the producing sand approaches the lower limit of permeability, it may be mechanically feasible to withdraw oil from the voids, but continued operation may be unprofitable. Accordingly, the volume of oil that may be recovered from the Olympic sand by the application of water flooding during future exploitation of the various leaseholds represents the secondary-oil reserves of the Olympic sand in this field. It is the volume of oil that can be recovered by reducing the residual saturation of the reservoir on July 1, 1946, which is shown in table 2, to a terminal oil saturation equivalent to 30 percent of the pore space in the sand. An additional feature of this method includes modification of this procedure by the application of a correction factor to allow for reduced permeability-capacity of the Olympic sand relative to the specific class of sand body.

It is to be noted that the Olympic sand in many places in the field has shown variable productive characteristics during the primary phase of production. It is anticipated that in zones of equal thickness, the permeability-capacity of the sand may be the influencing factor, if all other features are comparable. It is reasonable to expect that little oil would be recovered by primary methods in zones of low permeability. Also, in places where a thin section of sand had high permeability and the ratio of maximum permeability to minimum permeability of the sand was high, the recovery of oil would be correspondingly poor.

On account of the variable conductivity characteristics of the Olympic sand, the basic method of computing oil reserves was modified to compensate for variations in permeability-capacity of the sand. For this reason, the Olympic sand was segregated into four classes of productive sand which were directly related to its productive characteristics. Furthermore, the volume of recoverable oil was computed using these producing and conductivity characteristics of the sand. In calculating the reserves of the best class (class 1) of sand body, it was estimated that the volume of oil in the sand in this area would be reduced to a minimum oil saturation whose volume would occupy 30 percent of the voids in the reservoir. For the other classes of sand body, a correction factor was applied to compensate for permeability-ratio and reduced permeability-capacity of the sand in relation to the sand body factor of the best class of sand body. Actually, the correction factor for each leasehold is derived by dividing the square of the sand body factor for the specific leasehold by the square of the average factor for the class 1 type of sand body. The average factor for class 1 sand body is 4.35. It is believed that this correction factor not only compensates for reduced permeability-capacity of the sand in zones where the productive characteristics of the sand are poor, but that it also compensates for the discrepancy entering the estimation of reserves in these areas caused by the application of a constant for interstitial water saturation in these areas.

The residual oil content of class 1 type of sand body amounts to 23,865 barrels of oil per acre as of July 1, 1946. This volume is equivalent to 664.8 barrels of oil per acre-foot of sand and represents an oil content occupying 41.1 percent of the void space of the reservoir. The succeeding classes of sand body ranging from 2 to 4, inclusive, showed residual oil content of 21,936 barrels per acre, 21,200 barrels per acre, and 14,514 barrels per acre, respectively.

In the order named, this residual oil content of the reservoir is equivalent to 660.7 barrels per acre-foot, 640.5 barrels per acre-foot, and 587.6 barrels per acre-foot, respectively. The corresponding oil content of these classes of sand body ranges from 44.6 percent of the voids in the class 2 type of sand body to 51.4 percent of the pore space in the class 4 type of sand body.

It is the opinion commonly accepted by core-analysts that the interstitial water saturation of a sand increases proportionately in zones of low permeability. However, no correction for this factor has heretofore been applied by engineers in appraising the reserves of oil for various leaseholds in accordance with the sand characteristics.

The volume of oil representing the oil reserves of the Olympic sand by tracts has been computed, as previously mentioned, in accordance with classification of sand body and its distribution is shown on the accompanying map. (See pl. 33). Here, it is to be noted that the recoverable-oil reserve of the Olympic sand estimated by the aforementioned method of computation amounts to 14,622,702 barrels of oil to be recovered from 3,471 productive acres. This is equivalent to a recovery of 4,213 barrels of oil per acre of sand. As no consideration was given to the problem of economics of recovery, it is doubtful whether this estimated volume of oil will be recovered even though the mechanics of production seemingly are feasible.

It is significant that the volume of oil which may be recovered from a reservoir varies not only with the specific type of secondary method, but also varies with the producing efficiency of the type of pattern, and the spacing of the wells in the pattern. Thus, the application of various geometric patterns may increase or decrease the reserves of oil to be recovered. It is to be expected that the Olympic field, in being developed by the application of water flooding, will be adapted to the 5-spot type of geometric pattern. For this reason, all estimates of recoverable oil by water flooding have been made with this type of pattern in view.

The estimated volume of oil that may be recovered from the Olympic sand by the application of water-flooding methods to the various classes of sand body by leaseholds is given in table 15. Here it is to be noted that on the leaseholds constituting class 1 and class 2 type of sand body the volume of recoverable oil amounts to 11,842,415 barrels, or 81.0 percent of all recoverable oil.

Table 15

Classification of recoverable oil from the Olympic sand on July 1,1946, in the Olympic field, Oklahoma

Class of sand body	Productive acres	Productive sand, ft.	Reservoir void space, thous. bbl.	Recoverable oil: Percent of voids	Recoverable oil: Total bbl.	Recoverable oil: Bbl. per acre	Recoverable oil: Bbl. per acre-foot
1	460	35.9	26,682.2	12.0	3,205,171	6,968	194.1
2	1,790	33.2	87,855.5	9.8	8,637,244	4,825	145.3
3	931	33.1	40,824.2	6.3	2,583,158	2,775	83.8
4	290	24.6	8,153.1	2.4	197,129	680	27.6
Total and aver.	3,471	32.8	163,515.0	8.9	14,622,702	4,213	128.4

However, this oil reserve represents recoverable oil by classes of sand body where the oil saturation is reduced to a minimum oil saturation which is equivalent to a volume of oil occupying 30 percent of the pore space. It is not to be construed as the actual oil reserve of the field, inasmuch as many properties whose recoverable oil is low cannot be exploited by water flooding at a crude oil price which, on July 1, 1946, ranged from $1.09 to $1.29 per barrel, and averaged $1.25 for crude of 35° A.P.I. gravity. As of July 1, 1946, however, the Government subsidy payable as a 35-cent per barrel premium increased the effective price of 35° A.P.I. gravity crude oil to $1.60 per barrel. On many leaseholds the income from the sale of crude oil is augmented by additional revenue from the sale of residue gas and gasoline; however, this additional income is small and has not been given consideration in this report.

If the factor of economics is considered in relation to the recovery of oil from the Olympic sand by the application of water-flooding methods, then all of the area embodying class 4 type of sand body can be eliminated from consideration as having potential oil reserves at this time. Also, most of the area embracing class 3 type of sand body does not warrant consideration in estimating the oil reserves of the Olympic sand. Actually, the oil reserves of the Olympic sand are to be found on classes 1 and 2 and part of class 3 type of sand body on leaseholds which can produce at least 2,500 barrels of oil per acre when the posted price of crude oil of 35° A.P.I. is $1.60 per barrel. Gross oil production of 2,500 barrels per acre herein represents the investment in developing a water-flood project, and the operating cost of the project in terms of gross oil production.

Inasmuch as many factors were considered in the computation of these oil reserves, it is suggested that the resulting estimates in essence will be considered as reconnaissance. For this reason, it is expected that some tolerance will be given to these estimates of oil reserves recoverable from the Olympic sand.

It is believed that the estimated oil reserve of the Olympic sand, as of July 1, 1946, recoverable by water-flooding methods of development and amounting to 13,601,391 barrels of oil, is a conservative estimate in view of the estimated ultimate production from the field under continuation of present practices. A summary of the economic oil reserves recoverable by the application of water-flooding methods to properties estimated to be capable of producing over 2,500 barrels of oil per acre is given in table 16.

Table 16

Estimated oil reserves of the Olympic sand on leaseholds showing oil reserves greater than 2,500 gross barrels of oil per acre

Class of sand body	Productive acres	Productive sand, ft.	Reservoir void space, thous. bbl.	Percent of voids	Recoverable oil: Total bbl.	Recoverable oil: Bbl. per acre	Recoverable oil: Bbl. per acre-foot
1	460	35.9	26,682.2	12.0	3,205,171	6,968	194.1
2	1,760	33.5	87,165.8	9.8	8,571,296	4,870	145.4
3	555	37.7	27,265.8	6.7	1,824,924	3,288	87.2
Total and aver.	2,775	34.5	141,113.8	9.6	13,601,391	4,901	142.1

The economic oil reserves of the Olympic sand and its corresponding class of sand body are shown by plate 34.

It is difficult to estimate the trend of the future price of crude oil after July 1, 1946. It is believed, however, that the increasing demand for crude oil will influence the crude-price structure. Any increase in the price of crude in the future, therefore, places water-flooding ventures in the Olympic sand in this field in a more favorable position. It is anticipated that ultimate recovery by water flooding in the Olympic sand should result in the reclamation of about 13,600,000 barrels of crude oil which, at the price of $1.60 per barrel for 35° A.P.I. gravity oil, including the Government subsidy, prevailing on July 1, 1946, would result in a gross income of $21,760,000.

ECONOMICS OF SECONDARY RECOVERY

Investigative work concerning the possibilities of exploiting properties in the Olympic field by means of the application of secondary-recovery methods so far has dealt chiefly with the behavior of the Olympic reservoir. Yet, the problem of economics of oil recovery to all operators is a vital necessity for the profitable application of the principles of secondary recovery in the development of oil producing properties. This knowledge permits the operator to follow a definitely conceived program of development and, what is more to the point, it gives the operator some conception of the tangible and intangible costs of development and the rate of return on his investment.

An evaluation of a water-flood project is subject to the influence of so many variable factors that it is difficult for the appraiser to ascertain accurately the monetary return from secondary-recovery ventures which may be applicable to specific properties and, which still may be used for comparative purposes on any property that is being considered for secondary-recovery exploitation. Factors influencing the development plans and appraisal of prospective water-flooding property are depth of producing formation and type of pattern, spacing of input wells and oil producing wells, operational practices, completion of wells, selling price of crude oil, and many other auxiliaries too numerous to mention, but of common knowledge.

..s the development spacing of the Olympic field conforms to the regular class of geometric pattern with spacing between oil wells being 660 feet for the most part, the field naturally can be readily adapted to the 5-spot type of pattern common to secondary development. In this type of geometric pattern, the spacing will be 660 feet between like wells, or one input well for each ten acres under secondary operation. In similar water-flooding projects in south-eastern Kansas, where the Bartlesville sand is water flooded at a depth of about 2,000 feet, the water-input wells are usually completed using 5-1/2 inch O.D. casing. It is logical to expect adaptation of similar type of well completion in this field as the sand here averages 1,789 feet in depth.

The volume of recoverable oil in the Olympic sand and the distribution of the leaseholds shown on plate 34 have been estimated conservatively as the oil reserves from the respective properties of this field that can be reclaimed by the application of water-flooding methods of operation. The leaseholds constituting the productive area of the oil reserves have been limited to those leaseholds that are estimated to have potentialities for recoverable oil of over 2,500 gross barrels of oil per acre. This oil recovery per acre is estimated to be equivalent to the monetary investment in development plus the cost of operation of a project under flood with a productive life of about 10 years. Actually, the tangible and intangible costs for development and operation of a water flood, including taxes, should in equivalent terms range from 2,300 to 2,500 barrels of oil per acre. In estimating the oil reserves of the Olympic sand in this field, it was believed to be prudent to use a base recovery of 2,500 gross barrels of oil per acre. This estimate appears to be reasonable in view of the probability that the oil wells in the southern part of the field in which the gas sand is exposed would require special treatment involving considerable expense before the inception of water-injection operations. On the other hand, it is indicated by core analyses of the gas sand that oil is contained in the pores of this sand in many places throughout the gas sand area. Consequently, it is believed that no remedial work will be required on these oil wells in adapting them to the water-flood pattern as the permeability ratio of the gas sand and oil zone is probably low.

Although the oil reserves of the Olympic sand have been estimated as the recoverable oil from leaseholds capable of producing over 2,500 barrels of oil per acre by water-flooding methods, actually the oil reserve of the Olympic sand may be greater on some leaseholds and the scope of the available properties in this field wider as it is estimated that the break-even oil production for a water-flood project producing from the Olympic sand could possibly be as low as 1,500 gross barrels of oil per acre. For this reason, it is possible that many leaseholds showing recoverable oil amounting to about 1,500 barrels of oil per acre can be included as tracts having oil reserves. These estimates have been made on the basis of a posted price of crude oil, including the subsidy paid by the Government, of $1.60 for an oil of 35° A.P.I. gravity on July 1, 1946. These estimates of a break-even factor of production are preliminary and in no sense are to be construed as being representative of all properties. On the other hand, the break-even production may be adapted as a criterion of recoverable oil on properties that are being considered for water-flood exploitation.

CONCLUSIONS

The history of oil and gas production of the Olympic sand is typical of the performance of a field producing from a lenticular sand by means of gas-expansion. Structurally, the Olympic sand is a monocline trending northeast but dipping slightly north of west whose general structural features are intercepted by small closed domes and anticlinal noses. The Olympic sand of the Senora formation has produced most of the oil from the field. However, other zones lying above and below the Olympic sand have produced some oil. Of these other zones the Cromwell sand has been the most productive. For the most part gas, oil, and salt water are segregated gravititionally in the sand. The salt water is downdip on the north, west, and south sides of the sand body and the associated gas is updip in the highest parts of the sand. In general, the Olympic sand has not been very water productive, and no distinct water-level exists in the sand body.

The rapid decline of the productivity of all oil wells producing from the Olympic sand is an inherent characteristic of the performance of a reservoir in which operations have been unrestricted with resultant inefficient utilization of available reservoir energy. Accordingly, only a portion of the original volume of oil in the reservoir has been withdrawn by primary and by gas injection operating practices to July 1, 1946. A large volume of oil remains in the pore space of the Olympic sand, a substantial part of which probably could be reclaimed by the application of secondary-recovery practices such as water flooding.

Initial productivity of wells producing from the Olympic sand was high in many places in the field and a few of these wells produced as much as 2,000 barrels in the first day of operation. The high productivity of the sand is indicative of the good producing characteristics of the reservoir, such as moderate permeability,and general excellent thickness of the producing zone.

The results of operations in the Olympic sand to July 1, 1946, are consistent with the expected performance of this type of reservoir. Of 13,202,994 barrels of oil produced from this field, it is estimated that the Olympic sand has produced 12,989,817 barrels of oil. This volume is equivalent to 98.4 percent of the oil produced from all horizons. Other producing formations are credited with 213,177 barrels of production of which the Cromwell sand produced the most oil. The oil produced from the 3,423 productive acres of Olympic sand in this field is equivalent to an oil recovery of 3,795 barrels of oil per acre.

Gas injection operations were started in August 1937, and it is estimated that the injection of 2,183,397,000 cubic feet of residue gas, representing 12.0 percent of all gas production, was instrumental in reclaiming an estimated 212,000 barrels of oil. This volume represents 1 barrel of oil over normal production for each 10,300 cubic feet of residue gas injected. Most oil attributed to the injection of gas was recovered in the southern part of the field.

To July 1, 1946, the gross gas production of the Olympic sand was 18,247,065,000 cubic feet, which represents a gas-oil ratio of 1,405 cubic feet. If the volume of gas injected into the Olympic sand is deducted from the total volume of produced gas, the net gas-oil ratio for the Olympic sand is 1,237 cubic feet.

As the original oil content of the Olympic sand is estimated at 86,215,400 barrels of stock-tank oil, the withdrawal of 12,989,817 barrels by normal and gas injection methods represented a recovery of 15.1 percent of the initial oil in the reservoir to July 1, 1946. This quantity of produced oil is estimated to have occupied 8.0

percent of the voids in the reservoir. By primary methods of production, the Olympic sand is estimated to have produced 12,777,000 barrels of oil, or 98.4 percent of the total oil produced from the sand to July 1, 1946. The combination of normal and gas-repressuring methods by July 1, 1946, had reduced the oil saturation of the Olympic sand in this field from the initial volume of oil occupying 53.3 percent of the pore space to a volume of residual oil occupying 45.3 percent of the pore space in the reservoir.

If the field should remain on production by continuation of the operating methods practiced on July 1, 1946, it is estimated that future oil production from the Olympic sand by these methods would approximate 1,387,000 barrels of oil. This would result in an ultimate production of about 14,377,000 barrels, or an average recovery of about 4,200 barrels of oil per acre. It is estimated that the average oil saturation of the Olympic sand after this withdrawal would not be much less than 45 percent of the voids.

It is expected that a portion of any future oil to be produced by continuation of the current operating practices will be attributed to the injection of gas. Prior to July 1, 1946, this practice had been instrumental in recovering approximately 212,000 barrels of oil from 870 acres comprising the leaseholds which is equivalent to 244 barrels of oil per acre. The efficiency of this method of operation in terms of volume of oil produced is low, yet gas injection has retarded production-decline, and it has extended the productive life of many properties. Of greater significance is that it has demonstrated the fact that much oil remains in the Olympic sand which may be recovered by the application of water-flooding practices.

Owing to the variation in the productive capabilities of the Olympic sand in many leaseholds of the field, the tracts have been classified in terms of sand body factors which denote their ability to produce oil. On the basis of the quantity of oil produced prior to July 1, 1946, and for the purposes of this report, the Olympic sand body is placed in four classes of productive sand by leaseholds. To July 1, 1946, the first three classes of sand body produced 12,841,001 barrels of oil, or 98.4 percent of all oil produced from the Olympic sand. Of these classes of sand body, class 2 has the largest total production. It has produced 7,505,595 barrels of oil, or 58.4 percent of the oil produced from the Olympic sand, and it unquestionably indicates the best possibilities for large scale water-flooding exploitation in the field. Nevertheless, the class 1 type of sand body possesses the best producing qualifications in terms of oil recovery per acre, but it is not widespread in this field.

In estimating the oil reserves of the Olympic sand, the lower limit of residual oil saturation to which the oil content could be reduced efficiently was estimated to be 30 percent of the pore space. The volume of oil recoverable to this terminal oil saturation was estimated to be 14,623,000 barrels from 2,775 acres of productive sand apportioned among four classes of sand body. It is equivalent to a recovery of 4,200 barrels of oil per acre. Economically, however, a portion of this oil could not be recovered at a crude oil price which averaged $1.60 per barrel for the field on July 1, 1946, including the 35-cent subsidy. Because of the influence of economic considerations on any estimate of the recoverable oil reserves of the Olympic sand, the actual oil reserves were estimated to be the recoverable oil on those leaseholds capable of producing 2,500 or more barrels of oil per acre. On this basis, it is estimated that the oil reserves of the Olympic sand are approximately 13,601,000 barrels of oil from 2,775 productive acres which are economically feasible for exploitation by water-flooding methods of operation. Such a recovery would amount to 4,900 barrels of oil per acre, or 142 barrels of oil per acre-foot of productive sand.

Because the operator of a water-flood project expects to make a profit on the investment required, it was considered conservative to compute the oil reserves only from those leaseholds estimated to be capable of producing 2,500 barrels of oil per acre by water-flood methods. The present spacing pattern of the field appears to be readily adaptable to the 5-spot geometric pattern common to water-flooding development. It is estimated that the actual break-even production of oil could be much less than 2,500 barrels per acre - probably in the range of 1,100 to 1,500 gross barrels of oil per acre. This represents the volume of oil required to amortize the investment in developing the properties and the total cost of operating these properties until the investment is paid out.

So far no attempt has been made to exploit the Olympic sand in Oklahoma, by the application of water-flooding methods of operation.

Nevertheless, it is believed that the sand can be feasibly water flooded, and that a considerable volume of oil can be recovered that might otherwise be lost to the oil industry.

By January 1, 1948, the posted price of 35° A.P.I. gravity crude oil in the Olympic field had increased to $2.55 per barrel. This increase over the price of $1.60 per barrel used herein for determining the economic feasibility of secondary development will increase the economic oil reserves in two ways. If continued, the increased oil price will extend the economic productive life of secondary-recovery projects, with a resultant increase in ultimate oil recovery. In addition, it will permit the profitable exploitation of many properties heretofore considered too marginal from an economic standpoint for development by secondary methods.