BRIDGER LAKE FIELD
RESERVOIR STUDY

By

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ER-1375

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ABSTRACT

A reservoir study was made to determine the technological floodability of the Bridger Lake Field (Utah). The initial oil-in-place was calculated to be 60 MM stock-tank barrels with the use of the material balance equation. Recovery above the bubble point was determined to be 5.226 MM stock-tank barrels. Recovery below the bubble point was found to be 14.298 MM stock-tank barrels when a limit of 100 psi was assumed. Secondary recovery calculations were performed with the Dyes-Caudle-Erickson, Buckley-Leverett, and Dykstra-Parsons methods.

It is concluded that a waterflooding project is a great risk for the Bridger Lake Field, since the values of recovery by primary and secondary recovery calculations are approximately the same. It is therefore recommended to carry out a pilot waterflood in order to obtain a better evaluation of secondary performance by waterflooding.

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INTRODUCTION

Secondary recovery has been defined by Smith (1966, p. 1) as the oil, gas, or the combination of both, recovered by artificial flowing or pumping means, through the joint use of two or more wellbores. Primary recovery has been defined by the same author as the oil, gas, or the combination of both, recovered by any method, either natural flow or artificial lift, through a single wellbore.

The present reservoir study considers the possible engineering floodability of the Bridger Lake Field. Primary recovery calculations were carried out above the bubble point by considering fluid and rock expansion. Recovery below the bubble point was calculated by means of the Tarner's modification of the material balance.

Secondary recovery by waterflooding was obtained by multiplying displacement efficiency (Buckley-Leverett), areal sweep efficiency (Dyes-Caudle-Erickson), vertical sweep efficiency (Dykstra-Parsons), and initial oil-in-place (Schilthuis Material Balance).

Required data for this study was obtained from fluid and core analysis made by commercial laboratories, well logs, and production history from each well. A complete record of pressure history permitted calculations using the material balance equation.

LOCATION AND GEOLOGY

The Bridger Lake Field is located about 95 miles east of Salt Lake City (Utah) at the northern foot of the Uinta Mountains on the extreme south flank of the Green River Basin. The legal location according to Utah regulations is Range 14 East, Township 3 North. Figure 1 shows the location of the Field.

The sand of interest (Sand A) is located in the lowest part of the Cretaceous Dakota formation. The Dakota formation lies between the Mowry formation and the Morrison formation at depths between 6305 feet (Fork A Well No. 10) and 6746 feet (Fork A Well No. 7) below mean sea level. Core analysis of this zone indicated good oil show with very erratic values of permeability. The sand grains are basically light brown, and their size varies from fine to medium.

A consistent correlation of Dakota formation, Sand A, and adjacent formations was made with the use of SP-Resistivity logs and the construction of two subsurface cross sections. Cross section A-A' extends from South-West to North-East across the Bridger Lake Field, and cross section B-B' extends from North-West to South-East (Plates 1 and 2).

An examination of the structural map of the A Sand indicates that the Dakota is an anticline even though no closure is shown in the map. It would be, however, more accurate to define this structure as a south-dipping plunging structural nose. Well 43X-28 (Shell Company) in the south-west of the field is dry because this well is structurally lower than all the other wells in the area. Fork A Well No. 11 in the northeast part of the field is dry too. This well, however, is structurally higher than many of the wells producing in this field. This fact can be explained by either a fault or an impermeable barrier which isolates the well. The first possibility, i.e., a fault, was discarded because a very detailed log correlation of Fork A Wells No.'s 10, 11, and 12 indicated the absence of any possible fault. Consequently, it was concluded that Fork A Well No. 11 was dry due to an impermeable barrier isolating the well. This conclusion was verified by calculations of permeability based on electric log correlations.

An important fact obtained from log correlations was the determination of the possible water-oil contact which is shown in Figure 2. A careful analysis of resistivity logs in the zone of interest indicated a characterized slope in Fork A Well No. 7, which can be an indication of the water-oil contact.

The structure, sand thickness, and depth of this reservoir provide favorable characteristics for waterflooding. High injection pressures are possible without the danger of fracturing of the formation since the formation is very deep.

The stratigraphic column for the Bridger Lake Field is shown in Table I. This column includes all the formations penetrated in this region so far.

HISTORY OF FIELD

The first well (Fork A Well No. 1) was spudded on July 4, 1966. The original test indicated an initial rate of 2753 BOPD, 2415 MSCFD and 125 BWPD through a 3/4-in. choke. The corrected API gravity was 40.3. Nine wells have been drilled since then with a success rate of 90 %. Initial rates varied from 284 to 881 BOPD with very low water cuts. Corrected API gravities varied from 39.7 to 40.9.

All the wells were drilled as far as the Morrison Formation (greater than 15,500 feet) except Fork A Well No. 10 which was drilled to the Nugget Formation (17,910 feet).

The reservoir was initially highly undersaturated. At present the reservoir is still above the bubble point with the primary reservoir energy being fluid and rock expansion.

Figures 3 to 11 show the production of the wells individually since their completion date. Figure 12 shows the composite production curve for the field.

RESERVOIR PARAMETERS

Porosity, permeability, water saturation, and pay thickness were statistically determined for Bridger Lake Field as follows:

Porosity

Values of arithmetic average porosity, median porosity, and arithmetic mean porosity were calculated from cores taken in the Dakota formation in the Fork A Wells No.'s 1, 2, and 3.

The arithmetic mean porosity was calculated from the equation:

$$\phi_a = \sum_{i=1}^{n} \phi_i F_i$$

where ϕ_a = arithmetic mean porosity, fractional

ϕ_i = class mark (value of porosity at midpoint) of i-th class interval or range

n = number of class intervals

F_i = frequency for i-th class interval, fractional

Table II shows the classification of porosity data and the determination of the arithmetic mean porosity which was found to be equal to 12.6 %. A porosity histogram and distribution for all samples from the Sand A is shown in Figure 13. The value of median porosity, i.e., the value of the variable corresponding to the 50 % point on the cumulative frequency curve, was found from this Figure to be 12.8%. The arithmetic average porosity was found to be 12.4 %.

The median porosity was used for all the calculations in the present study.

Permeability

Values of arithmetic average permeability and geometric mean permeability were calculated from the same cores used for evaluation of porosity.

The geometric mean permeability was calculated from the equation:

$$\log k_g = \sum_{j=1}^{n} F_j \log (k_a)_j$$

where k_g = geometric mean permeability, millidarcies

F_j = cumulative frequency of j interval, fractional

$(k_a)_j$ = arithmetic average permeability of logarithmic class interval j

n = total number of classified intervals

Table III shows the calculation of geometric mean permeability which was found to be 77 md. The arithmetic average permeability was 112 md.

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Water Saturation

For the calculation of the average water saturation, capillary-pressure measurements were made on 13 samples for different water saturations as shown in Figures 14, 15, 16, and 17. Table IV summarizes the properties of the samples. The logarithm of permeability was plotted against water saturation holding capillary pressures constant. This plot yielded approximate straight lines as shown in Figure 18. With the use of geometric mean permeability (77 md.), values of water saturation were found for different capillary pressures and plotted as shown in Figure 19. The resulting curve represents the average capillary pressure of the reservoir.

The height above the water - oil contact to the volumetric center of the reservoir was determined to be 80.5 feet. This distance was converted to capillary pressure by the equation:

$$P_c = \frac{h\ (\rho_w - \rho_o)}{144}$$

where P_c = capillary pressure, psi

h = distance from lowest point to midpoint, ft

ρ_w = water density, lbs/ft^3

ρ_o = oil density, lbs/ft^3

The capillary pressure was calculated to be

5.65 psi. On inclusion of this value in Figure 19, the average water saturation was determined to be 31 %. This value was corroborated by means of core analyses.

Effective Pay Thickness

This parameter was determined from electrical logs. The pay thickness for each well was determined from induction, lateral, gamma-ray, and spontaneous potential logs. The thickness varied from 18 feet in Fork A Well No. 12 to 60 feet in Fork A Well No. 3. The arithmetic average pay thickness for the Sand A of the Bridger Lake Field was determined to be 40.4 feet. Table V summarizes the net thickness for each well.

RESERVOIR FLUID STUDY

Reservoir fluid information was obtained from bottom-hole samples collected 6 days after Fork A Well No. 1 was completed. The following is a discussion of these data.

The saturation pressure of the fluid was found to be 2692 psig at the reservoir temperature of 225° F. This indicates the fluid in the reservoir was highly under-saturated since the initial reservoir pressure was 7226 psig. The solution gas-oil ratio was found to be 859 standard cubic feet of gas per barrel of residual oil (Figure 20). The formation volume factor was 1.575 barrels of saturated fluid per barrel of residual oil (Figure 21). The oil viscosity varied from 0.358 centipoise at the saturation pressure to 1.219 centipoises at atmospheric pressure. The gas viscosity varied from 0.0198 centipoise at the saturation pressure to 0.0120 centipoise at 200 psig (Figure 22). The gas deviation factors for various pressures were calculated and are shown in Figure 23. The gas formation volume factors were evaluated from the equation:

$$B_g = \frac{0.00515\ Z\ T}{P}$$

where B_g = gas formation volume factor, Bbl/SCF

Z = deviation factor

T = reservoir temperature, °R

P = reservoir pressure, psia

Figure 24 shows a plot of gas formation volume factor.

RELATIVE PERMEABILITY DATA

Representative relative permeability curves were obtained for the Bridger Lake Field as follows:

Gas-Oil Relative Permeability

Laboratory gas-oil relative permeability data were obtained from seven cores taken in Fork A Well No. 3. These data were classified in four different ranges of effective permeability to oil by considering less than 10 md., 10-50 md., 50-100 md., and 100-300 md. (Table VI and Figure 25). The four curves within a permeability range were averaged, as explained by Guerrero (1968, p. 39), with the use of the equation:

$$S_{gav} = \sum_{i=1}^{i=4} S_g F_i$$

where S_{gav} = average reservoir gas saturation corresponding to a selected k_g/k_o, fractional

S_g = average gas saturation of range corresponding to a selected k_g/k_o, fractional

F_i = thickness represented by a permeability range (frequency), fractional

The results of the above equation are shown in Table VII.

The average gas-oil relative permeability curve for the Bridger Lake Field is shown in Figure 26.

Water-Oil Relative Permeability

A representative field curve was determined by averaging the data of seven samples taken in Fork A Well No. 3 as follows:

1. The water saturation of each sample was plotted against the initial water saturation of the samples for different values of water-oil relative permeabilities, as shown in Figure 27. For constant relative permeabilities, straight lines were drawn through all the points; the lines were thus forced to converge through the value of one minus residual oil saturation.

2. Values of water saturation and relative permeabilities were determined by entering Figure 27 with the initial water saturation (31 %) of the Field.

3. A Field curve for an initial water saturation of 31 % was plotted in Figure 28.

The above method to average water-oil relative permeabilities was suggested by Dykstra-Parsons. The method, however, has not been published (class notes).

WATER INFLUX

The possibility of water influx in the reservoir was considered for the Bridger Lake Field with the use of the equation developed by Van Everdingen and Hurst (1949, p. 305):

$$W_{e_n} = B \sum_{j=1}^{n} \Delta P \; Q(t_D)_j$$

where W_e = water influx, bbls
B = water influx constant, bbls/psi
ΔP = pressure decrement, psi
$Q(t_D)$ = dimensionless water influx (function of dimensionless time)

On application of the above equation, when $B = 2000$ bbls/psi and $\Delta t_D = 0.00327$, a value of cumulative water influx was determined to be 3.2 MM bbls at 788 days. This water influx value far exceeds the cumulative voidage at 788 days, hence it must be assumed that the volume of any water aquifer is very limited. As a consequence, the reservoir will be treated as volumetric for all the following calculations.

DETERMINATION OF INITIAL OIL-IN-PLACE

The initial oil-in-place was calculated with the use of the material balance equation for the conditions in which the reservoir pressure is above the bubble point. The equation for slightly compressible fluids, as expressed by Amyx, Bass, and Whiting (1960, p. 572), was used. This equation can be written as:

$$N = \frac{N_p (D + E P) - (W_e - W_p) (F + B_{wb} C_w P)}{(P_i - P) A}$$

or when the reservoir has no water influx:

$$N = \frac{N_p (D + E P) + W_p (F + B_{wb} C_w P)}{(P_i - P) A}$$

where N = initial oil-in-place, stock-tank bbl

N_p = cumulative oil produced, stock-tank bbl

$D = B_{ob} (1 - C_o P_b)$

B_{ob} = oil formation volume factor at bubble point, reservoir bbl per stock-tank bbl

C_o = oil compressibility, vol/vol/psi

P_b = reservoir pressure at bubble point, psi

$E = B_{ob} C_o$

P = reservoir pressure, psi

W_p = cumulative water produced, bbls at standard conditions

$F = B_{wb} (1 - C_w P_b)$

B_{wb} = water formation volume factor at bubble point, reservoir bbl per stock-tank bbl

C_w = water compressibility, vol/vol/psi

Pi = initial reservoir pressure, psi

$$A = B_{oi} \frac{1}{1 - S_{wi}} (C_f - S_{wi} C_w) - C_o \frac{B_{ob}}{B_{oi}}$$

B_{oi} = oil formation volume factor at initial pressure, reservoir bbl per stock-tank bbl

S_{wi} = initial water saturation, fractional

C_f = formation (rock) compressibility, vol/vol/psi

The above equation was used to calculate initial oil-in-place by considering all the pressure history available as shown in Table VIII. Then a plot of the estimates of oil-in-place versus the cumulative oil production was prepared (Figure 29). This plot resulted in an approximate horizontal line, which indicates that the reservoir has no water influx as calculated before. From Figure 29 it was found that the initial oil-in-place was 60 million stock-tank barrel.

PRIMARY PERFORMANCE

Calculations to evaluate the primary performance above and below the bubble point were carried out for the Bridger Lake Field. The following is a discussion of such calculations.

Above the Bubble Point

Oil recovery above the bubble point including formation and water compressibilities was calculated by the following equation:

$$N_p/N = \left[\frac{\Delta P(C_f + (1 - S_{wi})\ C_o + S_{wi}\ C_w)}{(1 - S_{wi})\ (B_o/B_{oi})}\right]\left[\frac{1}{(1 + WOR(B_w/B_o))}\right]$$

where N_p/N = recovery, fractional

ΔP = pressure drop from initial pressure to bubble point pressure, psig

C_f = rock compressibility, vol/vol/psi

S_{wi} = initial water saturation, fractional

C_o = oil compressibility, vol/vol/psi

C_w = water compressibility, vol/vol/psi

B_o = oil formation volume factor, bbl/STB

B_{oi} = initial oil formation volume factor, bbl/STB

WOR = water-oil ratio, STB/STB

The rock compressibility was obtained from Hall's (1953, p. 309) chart. The water compressibility was obtained from Dodson and Standings' (1944, p. 173) charts in relation to the known salinity, temperature, and reservoir pressures. The oil compressibility was found from reservoir fluid analysis. The following is a summary of these values:

Rock compressibility, C_f	4.3×10^{-6}
Water compressibility, C_w	3.74×10^{-6}
Oil compressibility, C_o	12.4×10^{-6}

Recovery above the bubble point was calculated to be 8.20 % of the initial oil-in-place or 4.920 MM STB.

For the confirmation of the above results, the same method was applied to determine recovery at 5745 psig. The value found for recovery at the above pressure was 2.69 % of the initial oil-in-place or 1,614,000 STB, which matches very well with the actual cumulative at the same pressure or 1,581,953 STB. The minor difference is probably due to the assumption of 10 per cent water - oil ratio for all calculations.

Below the Bubble Point

Tarner's material balance for predicting reservoir performance by internal gas drive was used in a form proposed by Schilthuis (1936, p. 33). The calculations were carried out by choosing an initial content of one stock-tank barrel and assuming a producing gas-oil ratio at pressure decrements which satisfy the material balance equation, the producing gas-oil ratio equation, and the oil saturation equation to an accuracy of 0.5 %. The calculations, as explained by Elliot (1970, p. 18) were performed by the computer. The three basic equations used were:

$$N = \frac{N_p (B_t + B_g (R_p - R_{si}))}{B_t - B_{ti}}$$

$$R = R_s + \frac{B_o \mu_o}{B_g \mu_g} \frac{k_{rg}}{k_{ro}}$$

$$S_o = \left[1 - \frac{N_p}{N}\right] \frac{B_o}{B_{oi}} (1 - S_{wi})$$

where N = oil-in place (Assume $N = 1$ STB)

N_p = cumulative oil production, fractional

B_t = total formation volume factor, res bbl/STB

B_g = gas volume factor, res bbl/SCF

B_o = oil volume factor, res bbl/STB

μ_o = oil viscosity, centipoise

R_p = cumulative GOR, SCF/STB

μ_g = gas viscosity, centipoise

R_s = solution gas-oil ratio, SCF/STB

R_{si} = initial solution gas-oil ratio, SCF/STB

$\frac{k_{rg}}{k_{ro}}$ = gas-oil relative permeability, fractional

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R = instantaneous gas-oil ratio, SCF/STB
S_o = oil saturation, fractional
B_{ti} = initial total formation volume factor, res bbl/STB
B_{oi} = initial oil formation volume factor, res bbl/STB
S_{wi} = initial water saturation, fractional

The recovery at an assumed abandonment pressure of 100 psi was calculated to be 23.83 % of the stock-tank oil at the bubble point or 13,125,564 STB. The gas-oil ratio increased to a maximum of 6888 SCF/STB, which is 8.0186 times the initial value. Table IX shows the output of the computer program with calculations every 100 psi. Figure 30 shows a plot using the results of the computer program.

Total Primary Recovery

The total primary recovery above and below the bubble point was determined to be 18,045,564 STB.

LABORATORY STUDIES

The possibility of carrying out a miscible fluid project on the Bridger Lake Field was investigated from fluid samples taken in Fork A Well No. 1. Waterflooding was evaluated based on data obtained on cores taken in Fork A Wells No.'s 2 and 3. The following is a discussion of each type of flooding.

Laboratory Miscible Flooding Tests

Miscible displacement studies were carried out with the use of samples of separator and liquid from the Fork A Well No. 1. The samples were recombined to yield a fluid with a saturation pressure of 2692 psig at 225° F. This fluid was charged in a sand-packed stainless steel column whose properties are shown in Table X, and displaced with synthesized gas whose composition is similar to that of the gas available for injection. Composition of the synthesized gas is shown in Table XI. The results of this displacement indicated that the gas and reservoir fluid were miscible at 5600 psig and not fully miscible at 5200 psig. Even though the values of oil recovery with the use of this test were found to be very high, it is believed that these figures are not representative for the Bridger Lake Field. The sand-packed stainless steel column was forming a 90 degrees angle with the horizontal which permits beneficial displacement of the oil. The Sand A, however, is essentially a horizontal strata and displacement of oil with gas can result in serious over-riding problems due to the effect of gravity. Another reason, as mentioned by Smith (1966, p. 319) is that "the presence of continuous strata of differing permeability will usually have an adverse effect on the displacement, in both steeply dipping and horizontal beds that comprise an oil reservoir." This is basically the case of the Bridger Lake Field.

Laboratory Waterflood Tests

Laboratory waterflood experiments were conducted on eight core samples from the Dakota formation taken in Fork A Wells No.'s 2 and 3. Distilled water was used to flood the samples since the water available for flooding the Bridger Lake Field would be fresh. The results showed that the average remaining oil saturation in the four samples from the Fork A Well No. 2 after floods with water-oil ratios of 30:1 was 57.5 %. (Oil saturation prior to waterflooding the core sample was 87 %). When the water oil ratio was in excess of 100:1 during the same floods, the average residual oil saturation was 55 %. These results indicated 29.5 % and 32 % of oil recovered (per cent of pore space), respectively.

The average remaining oil saturation in the three samples from the Fork A Well No. 3 after floods with water-oil ratios of 30:1 was 53.7 %. (Oil saturation prior to waterflooding the core sample was 86.7 %). When the water-oil ratio was in excess of 100:1 during the same floods, the average residual oil saturation was 50.2 %. These results indicated 33 % and 36.5 % of oil recovered (per cent of pore space), respectively. These results together with those of the tests on samples taken from Fork A Well No. 2 showed that good oil recovery can be obtained by waterflooding the Sand A. The results of these tests are summarized in Table XII.

All the following studies and calculations will be carried out for the case of secondary recovery by waterflooding.

SECONDARY PERFORMANCE

Oil recovery from waterflooding the Bridger Lake Field was determined by calculating displacement efficiency, sweep efficiency, vertical sweep efficiency, and the application of the values found in the equation:

$$N_p = N E_s E_d E_v$$

where N_p = oil recovery, barrels

N = oil-in-place, barrels

E_s = sweep efficiency, fractional

E_d = displacement efficiency, fractional

E_v = vertical sweep efficiency, fractional

The following is a discussion of how these parameters were determined.

Displacement Efficiency

Buckley-Leverett's method (1942, p. 107) was used to calculate displacement efficiency for the Bridger Lake Field. The following are some basic assumptions which are made in order to apply Buckley-Leverett's method:

1. The reservoir has constant initial saturation.

2. The fluids are incompressible and immiscible.
3. Only two phases are flowing.
4. The reservoir can be represented by a linear system.

All the information required to use Buckley-Leverett's equations has been calculated in the preceding sections.

Fractional Flow Calculations: Without the inclusion of capillary pressure and gravity effects, the Buckley-Leverett's fractional flow equation can be written as:

$$f_w = \frac{1}{1 + \frac{k_{ro}}{k_{rw}} \frac{\mu_w}{\mu_o}}$$

where f_w = water cut, fractional
k_{ro} = oil relative permeability, fractional
k_{rw} = water relative permeability, fractional
μ_o = oil viscosity, centipoise
μ_w = water viscosity, centipoise

Complete results of fractional water cuts for water saturations between 31 % and 60 % obtained with the use of the above equation are shown in Table XIII. A fractional flow curve versus water saturation was drawn with these results (Figure 31).

Frontal Advance Calculations: The average saturation behind the front was calculated as a function of the saturation at the efflux side of the system. Graphically, the average saturation was obtained by drawing a tangent to the fractional water cut curve at the value of initial water saturation (31 %) and extending it to $f_w = 1.00$ (Figure 31). The following values were found for the Bridger Lake Field water flooding project:

Saturation at the front (Efflux), S_{we}	59.0 %
Average saturation behind the front, S_{wav}	61.5 %
Fractional water cut, f_{we}	92.0 %

The displacement efficiency was calculated, when $S_{gi}=0$, by the following equation:

$$E_d = S_{wav} - S_{wi} - S_{gi} + S_{gr}$$

where E_d = displacement efficiency, fractional

S_{wav} = average water saturation behind the front, fractional

S_{wi} = initial water saturation, fractional

S_{gi} = initial gas saturation, fractional

S_{gr} = residual gas saturation, fractional

The calculated displacement efficiency indicated that 30.5 % of the oil-in-place would be recovered by waterflooding.

Areal Sweep Efficiency

Calculations of areal sweep efficiencies were carried out for the Bridger Lake Field for the cases of "Direct Line-

Drive," "Staggered Line-Drive," and "Five-Spot" patterns. Each pattern was evaluated through these steps, as explained by Dyes, Caudle, and Erickson (1954, p. 81):

1. Determination of mobility ratio with the use of the equation:

$$M = \frac{k_{rw}/\mu_w}{k_{ro}/\mu_o}$$

where M = mobility ratio
k_{rw} = relative permeability to water, fractional
k_{ro} = relative permeability to oil, fractional
μ_w = water viscosity, centipoise
μ_o = oil viscosity, centipoise

2. Determination of sweep efficiency at breakthrough for each pattern using the graphs prepared by Dyes, Caudle, and Erickson.

The values k_{rw} and k_{ro} were determined at the saturation behind the front and initial water saturation, respectively. The water viscosity was determined to be 0.3 centipoise at 225° F from a graph prepared by Craft and Hawkins (1959, p. 264) on the basis of the known salinity of the water (7200 ppm). The oil viscosity was found from the reservoir fluid laboratory study. With the use of these parameters, the mobility ratio was determined to be 2.95.

In the second step the value equivalent to the inverse of the mobility ratio was entered on the abscissa of the appropiate graph and extended to the known value of fractional water cut (92 %). The sweep efficiencies were then read on the ordinate.

The following sweep efficiencies were found for each pattern:

Five-Spot	90 %
Direct Line-Drive	94 %
Staggered Line-Drive	93 %

The above values suggest the "Direct Line-Drive" as the most advisible pattern for waterflooding the Bridger Lake Field.

Vertical Sweep Efficiency

Vertical sweep efficiency was determined by the application of the Dykstra-Parsons' (1950, p. 160) method. The method consists basically of a correlation of four fundamental variables: permeability variation, mobility ratio, initial water saturation, and vertical sweep efficiency at a given producing water oil ratio. The following is a discussion of how each one of these parameters was determined.

Permeability Variation: Calculations were carried out to determine permeability variation as explained by Dykstra and Parsons (1950, p. 171) according to the following steps:

1. Permeabilities in a distribution were tabulated in descending order with their corresponding cumulative frequencies (Table XIV).

2. Permeabilities were plotted on the log scale, and cumulative frequencies were plotted on the probability scale of log-probability graph paper (Figure 32).

3. The best straight line was drawn through the central points.

4. The following equation was used to determine the permeability variation:

$$V = \frac{k_{50} - k_{84.1}}{k_{50}}$$

where V = permeability variation, fractional

k_{50} = permeability at 50 % of cumulative frequency, md. (on straight line)

$k_{84.1}$ = permeability at 84.1 % of cumulative frequency, md. (on straight line)

With the use of the above equation, the permeability variation was found to be 75 %.

<u>Mobility Ratio</u>: It was determined to be 2.95 in the discussion of "Areal Sweep Efficiency."

Initial Water Saturation: It was determined to be 31 % in the section "Reservoir Parameters."

Water-Oil Ratio: This parameter was calculated to be 17 on application of the equation:

$$WOR = \frac{B_o}{B_w} \times \frac{f_w}{1 - f_w}$$

where WOR = producing water-oil ratio, STB/STB

B_o = oil formation volume factor, 1.486 res bbl/STB

B_w = water formation volume factor, 1.04 res bbl/STB

f_w = fractional water cut at the front (0.92)

Vertical sweep efficiencies were determined to be 42 % and 72 % from graphs prepared by California Research Corporation for the cases of producing water-oil ratios equal to 5 and 25, respectively. The interpolated value of the sweep efficiencies was 57 %.

Result

The product of displacement efficiency, areal sweep efficiency, and vertical sweep efficiency indicated that total applicable sweep efficiency is 16.5 %. Consequently, the ultimate recovery by waterflooding the Bridger Lake Field with the use of a "Direct Line-Drive" pattern would be 13,200,000 STB.

The above figures indicated that waterflooding is not advisable for the Bridger Lake Field at the present time, since primary recovery was calculated to be 19,524,000 STB. The same set of calculations were carried out for other stages of depletion at pressures of 2000, 1000, and 500 psi, in order to determine the most ideal time to start waterflooding. The following ultimate recoveries were determined for each case:

2000 psi	18,300,000 STB
1000 psi	20,800,000 STB
500 psi	21,600,000 STB

It is evident from the above results that a waterflooding project is a great risk for the Bridger Lake Field. In addition, an examination of the location of the present wells indicates that all the area of the field will not be contacted by water. As a result the values of recovery indicated above are optimistic and waterflooding is not feasible for the purpose of increasing oil recovery.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to determine the advisability of waterflooding the "A" sand in the Bridger Lake Field. Calculations indicated that a waterflooding project is not feasible. The values of recovery indicated below are optimistic, since the displacing water does not contact the total area calculated in the section "Areal Sweep Efficiency." The following are conclusions and recommendations based on primary and secondary recovery computations:

1. Ultimate recovery by primary depletion would be 18,045,564 STB.

2. Ultimate recovery by primary depletion and waterflooding would be 18,350,000 STB if the waterflood were initiated at a reservoir pressure of 2000 psi.

3. Ultimate recovery by primary depletion and waterflooding would be 20,840,000 STB if the waterflood were initiated at a reservoir pressure of 1000 psi.

4. Ultimate recovery by primary depletion and waterflooding would be 21,620,000 STB if the waterflood were initiated at a reservoir pressure of

500 psi.

5. It is recommended to examine the reduction of lifting costs that are associated with the injection of water and compare this to lifting costs expected under primary operations.

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APPENDIX

APPENDIX

APPENDIX

Table I - Stratigraphic Section of the Bridger Lake Field

TIME	PERIOD	FORMATION
CENOZOIC	TERTIARY	BRIDGER FORT UNION
MESOZOIC	CRETACEOUS	MESAVERDE HILLIARD FRONTIER MOWRY DAKOTA
	JURASSIC	MORRISON STUMP PREUSS TWIN CREEK
	TRIASSIC	NUGGET

Table II - Classification of Porosity Data

Porosity Range %	Mid-value of Range, % ϕ_i	Number of Samples	Frequency Fraction F_i	$\phi_i F_i$
Less than 10	9	8	0.1454	1.3036
10 - 12	11	10	0.1818	1.9998
12 - 14	13	24	0.4364	5.6732
14 - 16	15	11	0.2000	3.0000
16 - 18	17	2	0.0364	0.6188

Arithmetic mean porosity = $\phi_i F_i$ = 12.6004

Table III - Geometric Mean Permeability of the Bridger Lake Field

Permeability Range (Millidarcies)	Average Permeability of Range $(k_a)_j$	Number of Samples	Frequency Fraction	Cumulative Frequency F_j	F_j x $\log(k_a)_j$
1.3 - 2.5	1.9	0	0.0000	0.0000	0.0000
2.6 - 5.0	3.8	4	0.0952	0.0952	0.0552
5.1 - 10.0	7.5	3	0.0714	0.1666	0.0625
10.1 - 20.0	15.0	2	0.0476	0.2142	0.0560
20.1 - 40.0	30.0	1	0.0238	0.2380	0.0352
40.1 - 80.0	60.0	8	0.1906	0.4286	0.3390
80.1 - 160.0	120.0	6	0.1429	0.5778	0.2971
160.1 - 320.0	240.0	15	0.3571	0.9349	0.8500
320.1 - 640.0	480.0	3	0.0714	1.0063	0.1914
		42			1.8864

Geometric mean permeability = antilog 1.8864 = 77 millidarcies

Table IV - Properties of Samples in Which Capillary Pressure Measurements Were Made

Sample No.	Depth, Feet From	To	Permeability Millidarcies	Porosity Per Cent
160A	15559	15560	0.45	8.9
162A	15561	15562	73.20	13.3
165A	15564	15565	267.00	13.5
169A	15568	15569	148.00	13.2
170A	15569	15570	220.00	13.2
175A	15574	15575	0.97	5.7
176A	15575	15576	29.70	11.2
164A	15563	15564	209.00	12.6
173A	15572	15573	182.00	12.1
177A	15576	15577	18.70	8.3
171A	15570	15571	258.00	12.8
172A	15571	15572	223.00	14.6
179A	15578	15579	25.50	13.1

Table V - Effective Pay Thickness

Well	Net Thickness Feet
Fork A No. 1	36
Fork A No. 2	27
Fork A No. 3	60
Fork A No. 4	38
Fork A No. 5	38
Fork A No. 6	54
Fork A No. 7	36
Fork A No. 8	42
Fork A No. 10	55
Fork A No. 12	18

Average Thickness = 40.4 feet

Table VI - Ranges of Effective Permeability to Oil for the Bridger Lake Field

Range	Permeability Range Millidarcies	Number of Samples	Frequency Fraction F_i
1	Less than 10	1	14.69
2	10.1 - 50.0	2	28.57
3	50.1 - 100.0	1	14.29
4	100.1 - 300.0	3	42.85
		7	100.00

Table VII - Weighted Average Permeability-Ratio Data

k_g/k_o from Figure 25	S_g x F_i Range 1	S_g x F_i Range 2	S_g x F_i Range 3	S_g x F_i Range 4	Weighted Gas Saturation Fractional
0.005	0.400	0.857	0.429	1.286	2.972
0.010	0.704	1.285	0.557	2.143	4.689
0.030	1.144	2.286	1.415	3.856	8.701
0.050	1.438	3.000	1.843	4.713	10.994
0.070	1.584	3.286	1.986	5.571	12.427
0.100	1.878	3.714	2.558	6.427	14.577
0.300	2.465	5.428	3.415	8.699	20.007
0.500	2.905	6.143	3.844	9.984	22.876
0.700	3.051	6.571	4.130	10.841	24.593
1.000	3.345	7.142	4.559	11.869	26.915
3.000	4.225	9.142	5.487	14.869	33.723
5.000	4.665	10.000	5.987	15.983	36.635

Table VIII - Calculation of Oil-in-Place by Material Balance for the Bridger Lake Field

(1) N_p (STB)	(2) P (psi)	(3) ΔP (psi)	(4) $A \times \Delta P \times 10^{-4}$	(5) E x P	(6) $B_o =$ EP + D	(7) N_p(EP+D)	(8) $B_{wb}C_wP$	(9) F + (8)	(10) W_p Bbls	(11) W_p x (9)	(12) $N = \frac{(7)+(11)}{(4)}$ (STB)
0	7226	0	0.00	.1411	1.4869	0	.028376	1.06838	0	0	
27661	7202	24	6.31	.1406	1.4874	41143	.028282	1.06828	1100	1175	67.064
60886	7167	59	15.51	.1400	1.4880	90598	.028145	1.06815	5125	5474	61.942
90312	7128	98	25.76	.1392	1.4888	134457	.027992	1.06799	9060	9676	55.952
201323	7023	203	53.37	.1372	1.4908	300132	.027579	1.06757	15441	16484	59.324
318889	6821	405	106.47	.1332	1.4948	476675	.026786	1.06679	22015	23485	46.977
846615	6395	831	218.47	.1249	1.5031	1272547	.025113	1.06511	79650	84836	62.131
1215000	5910	1316	345.98	.1154	1.5126	1837809	.023209	1.06321	120000	127585	56.806
1,581,953	5745	1481	389.35	.1122	1.5158	2397924	.022561	1.06226	175400	186320	66.373

Table IX - Schilthuis Material Balance Computer Output for the Bridger Lake Field

PRESS	RECOVERY	DELTA RECOVERY	INST GOR	AVG GOR	DIFF GAS	TOTAL GAS
2692.	.0000	.0000	859.	0.	.000	.000
2600.	.0128	.0128	829.	844.	10.803	10.803
2500.	.0270	.0142	927.	878.	12.468	23.271
2400.	.0408	.0138	1007.	967.	13.342	36.614
2300.	.0570	.0162	1124.	1065.	17.255	53.868
2200.	.0709	.0139	1297.	1211.	16.826	70.695
2100.	.0850	.0141	1523.	1410.	19.886	90.581
2000.	.0991	.0141	1749.	1636.	23.070	113.650
1900.	.1077	.0086	2013.	1881.	16.179	129.829
1800.	.1192	.0115	2397.	2205.	25.358	155.187
1700.	.1294	.0102	3024.	2710.	27.644	182.831
1600.	.1365	.0071	4171.	3597.	25.541	208.371
1500.	.1436	.0071	3475.	3823.	27.144	235.516
1400.	.1520	.0084	3972.	3724.	31.279	266.795
1300.	.1590	.0070	4398.	4185.	29.295	296.090
1200.	.1656	.0066	4883.	4641.	30.629	326.719
1100.	.1708	.0052	5350.	5117.	26.606	353.325
1000.	.1773	.0065	5808.	5579.	36.262	389.587
900.	.1828	.0055	6241.	6025.	33.135	422.722
800.	.1880	.0052	6682.	6461.	33.600	456.322
700.	.1925	.0045	6828.	6755.	30.397	486.719
600.	.1976	.0051	6888.	6858.	34.976	521.695
500.	.2028	.0052	6834.	6861.	35.675	557.370
400.	.2089	.0061	6491.	6662.	40.639	598.008
300.	.2153	.0064	6081.	6286.	40.230	638.238
200.	.2235	.0082	5041.	5561.	45.603	683.841
100.	.2383	.0148	3406.	4224.	62.511	746.352

Table X - Packed Column Displacement Study for the Bridger Lake Field - Summary of Basic Data

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Sand-Packed Column Properties

Length, feet:	41
Internal diameter, inches:	0.277
Porosity, per cent:	30.7
Hydrocarbon pore volume, cc:	151

Operating Conditions

Column temperature, °F.:	225
Separator pressure, psig:	0
Separator temperature, °F.:	75

Reservoir Fluid Properties

Saturation pressure, psig:	2692
Surface gas-oil ratio, SCF/STB:	778
Stock tank oil gravity, °API @ 60° F.:	38.8
Formation volume factor at 5600 psig, Bbls/STB	1.442
Formation volume factor at 5200 psig, Bbls/STB	1.449

Table XI - Composition of Synthesized Gas

Component	Composition, Mol Per Cent Desired	 Measured
Carbon dioxide	1.06	1.08
Nitrogen	1.76	1.83
Methane	88.00	87.58
Ethane	7.40	7.65
Propane	1.41	1.48
n-Butane	0.37	0.38
	100.00	100.00
Calculated gas gravity:	0.626	0.629

Table XII - Laboratory Waterflood Study

Fork A Well No. 2

Sample No. And Permeability	Oil Saturation Before Flood Per Cent	Oil* Saturation After Flood Per Cent	Oil Saturation at 30:1 Water-Oil Ratio Per Cent	Sand
61 A (560 md)	90.2	45.3	47.0	A
63 A (224 md)	85.2	62.7	65.0	A
64 A (850 md)	86.0	48.2	52.0	A
67 A (116 md)	86.5	63.7	66.0	A
Average	87.0	55.0	57.5	

* Water-Oil Ratio in excess of 100:1

Fork A Well No. 3

Sample No.	Oil Saturation Before Flood Per Cent	Oil* Saturation After Flood Per Cent	Oil Saturation at 30:1 Water-Oil Ratio Per Cent	Sand
66 A (156 md)	87.7	50.2	56.0	A
76 A (84 md)	86.7	49.7	52.0	A
79 A (114 md)	85.7	50.7	53.0	A
Average	86.7	50.2	53.7	

* Water-Oil Ratio in excess of 100:1

Table XIII - Fractional Flow Calculations for the Bridger Lake Field

Water Saturation Fractional	k_{rw}/k_{ro} Fractional	Fractional Flow f_w
.31		.000
.39	.011	.013
.40	.014	.016
.41	.019	.022
.42	.025	.029
.43	.035	.040
.44	.047	.053
.45	.063	.071
.46	.085	.092
.47	.110	.116
.48	.155	.156
.49	.215	.204
.50	.300	.263
.51	.440	.345
.52	.600	.417
.53	.850	.503
.54	1.200	.565
.55	1.750	.676
.56	2.600	.758
.57	4.000	.826
.58	6.400	.885
.59	10.000	.923
.60	18.500	.957

Table XIV - Vertical Distribution of Permeability

Average Permeability of Range Millidarcies	Thickness Feet	Frequency Fraction	Cumulative Frequency
480.0	3	0.0714	0.0714
240.0	15	0.3571	0.4285
120.0	6	0.1429	0.5714
60.0	8	0.1906	0.7620
30.0	1	0.0238	0.7858
15.0	2	0.0476	0.8334
7.5	3	0.0714	0.9048
3.8	4	0.0952	1.0000
	42	1.0000	

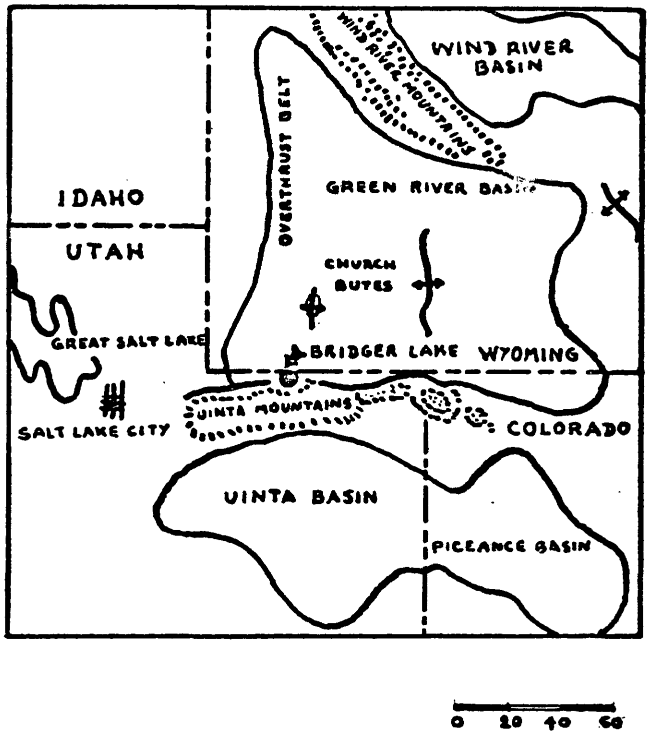


Figure 1: Location Map of the Bridger Lake Field

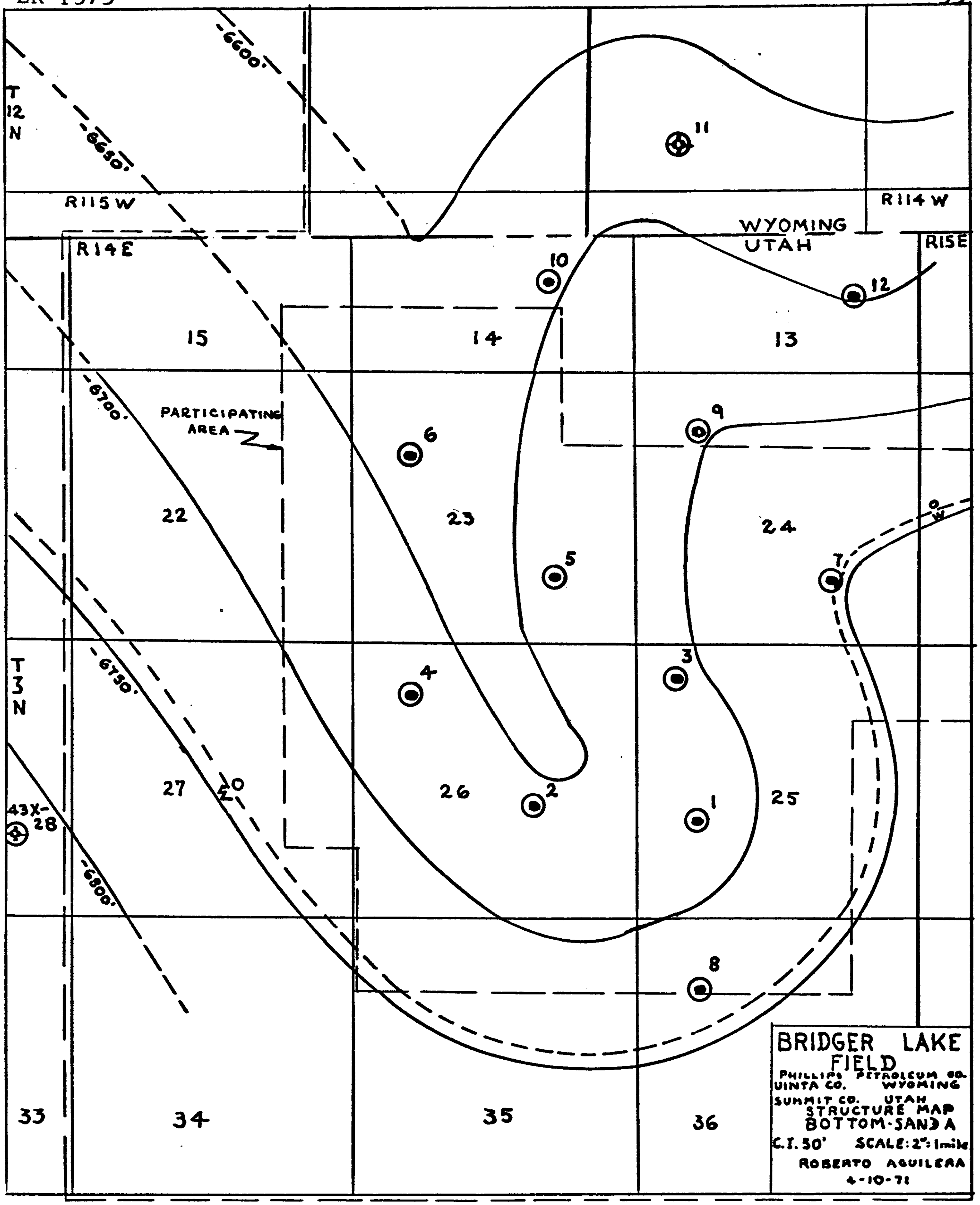


Figure 2: Bridger Lake Structure Map, Bottom Sand A Pay

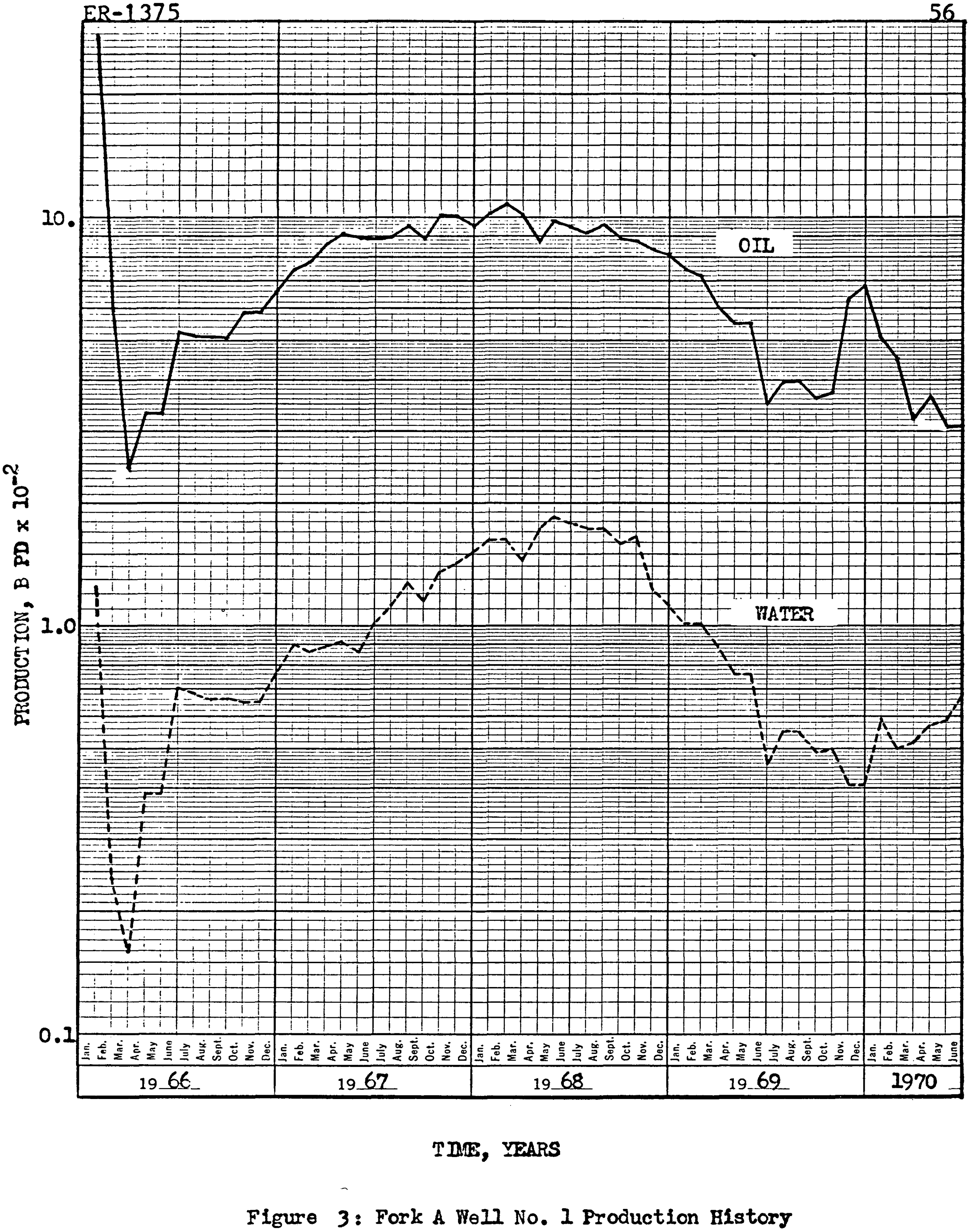


Figure 3: Fork A Well No. 1 Production History

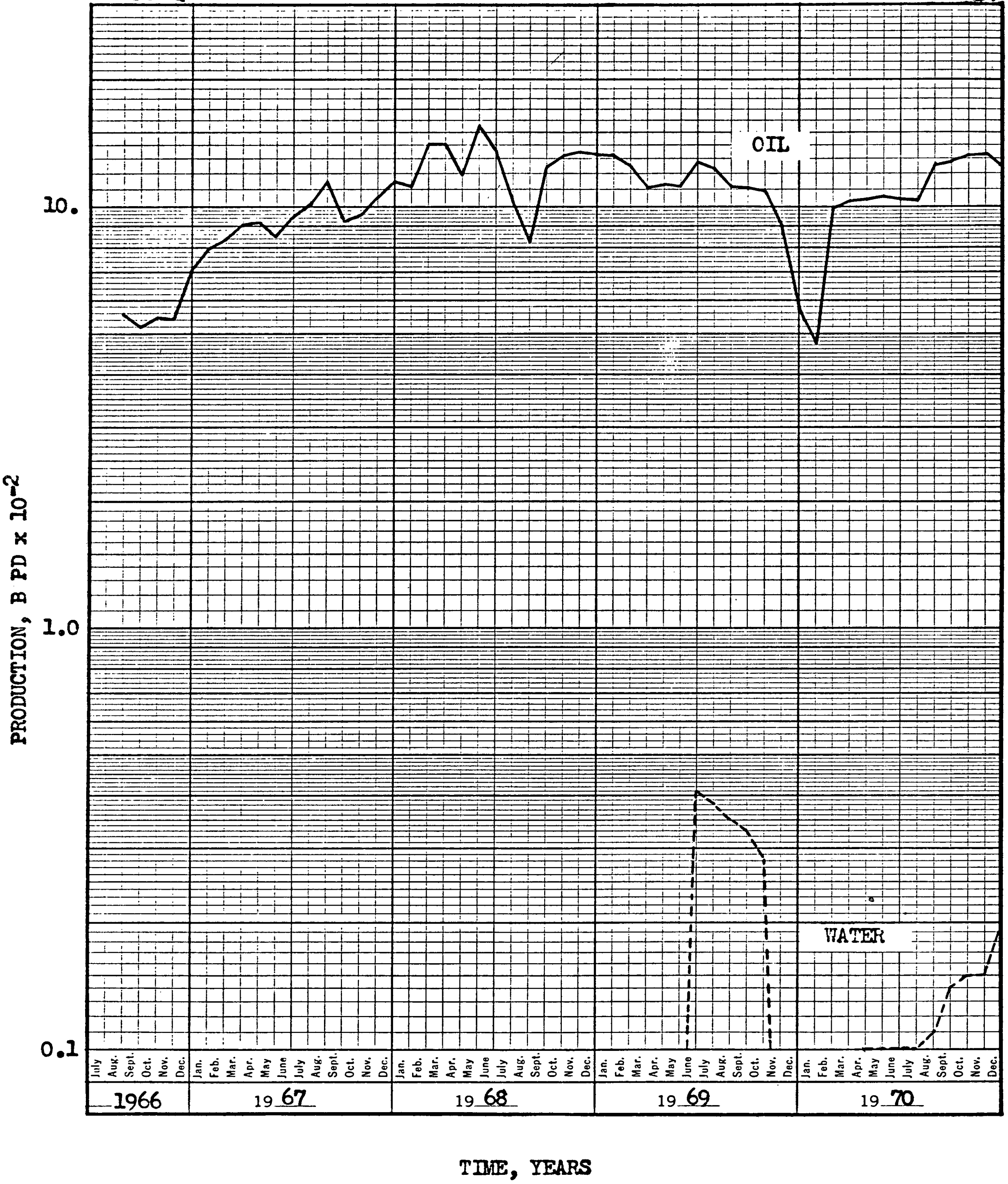


Figure 4: Fork A Well No. 2 Production History

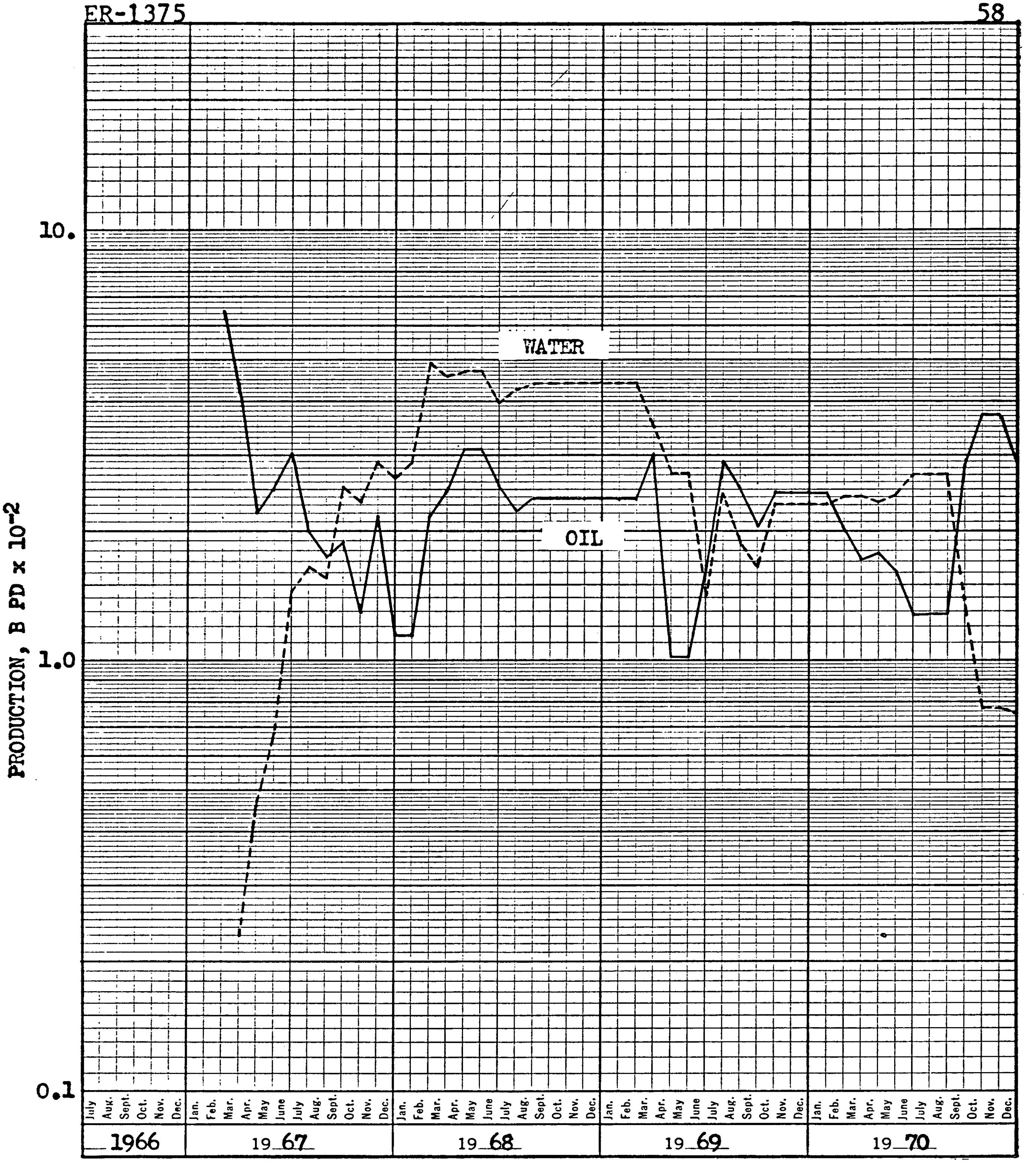


Figure 5 : Fork A Well No. 3 Production History

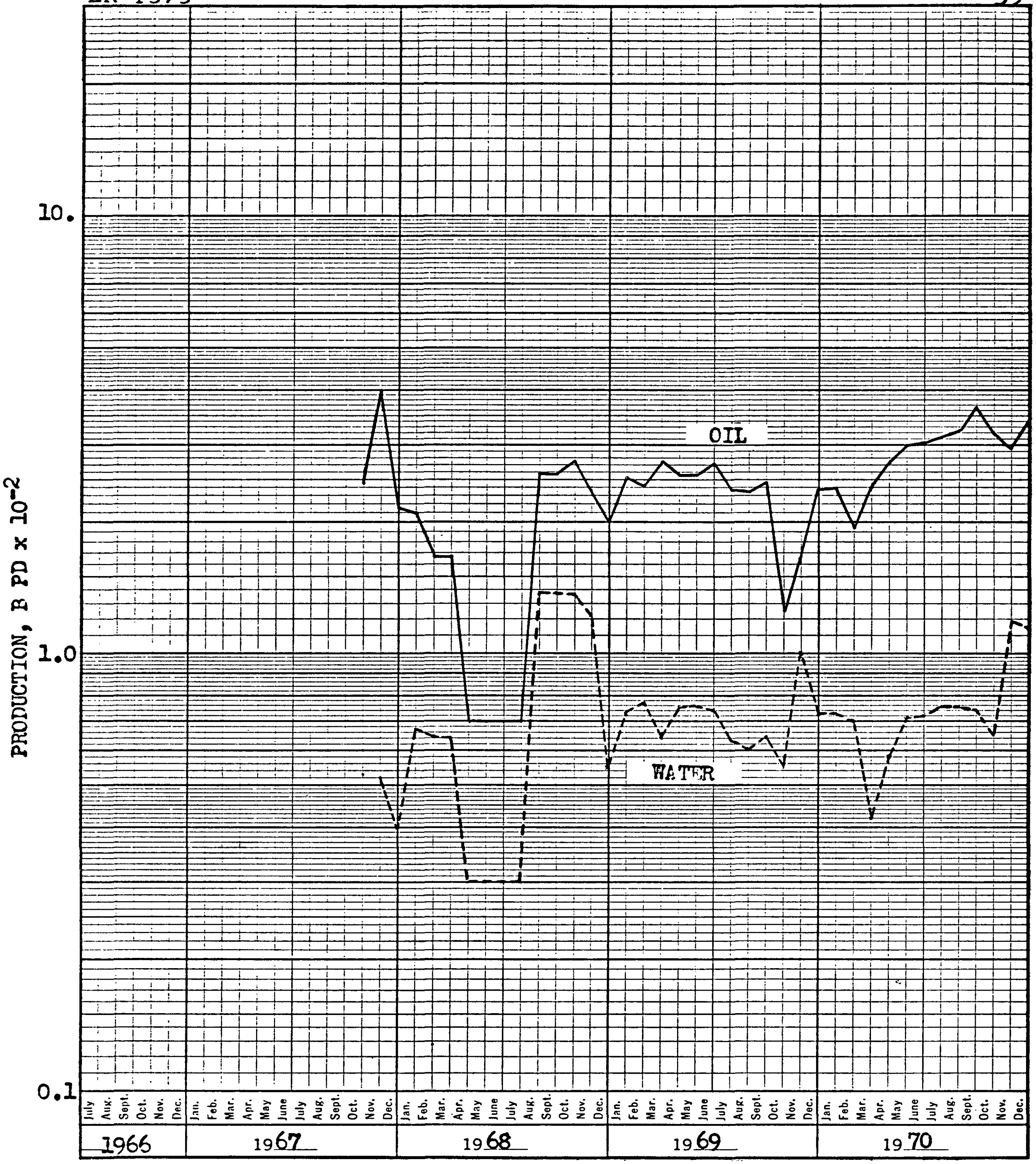


Figure 6: Fork A Well No. 4 Production History

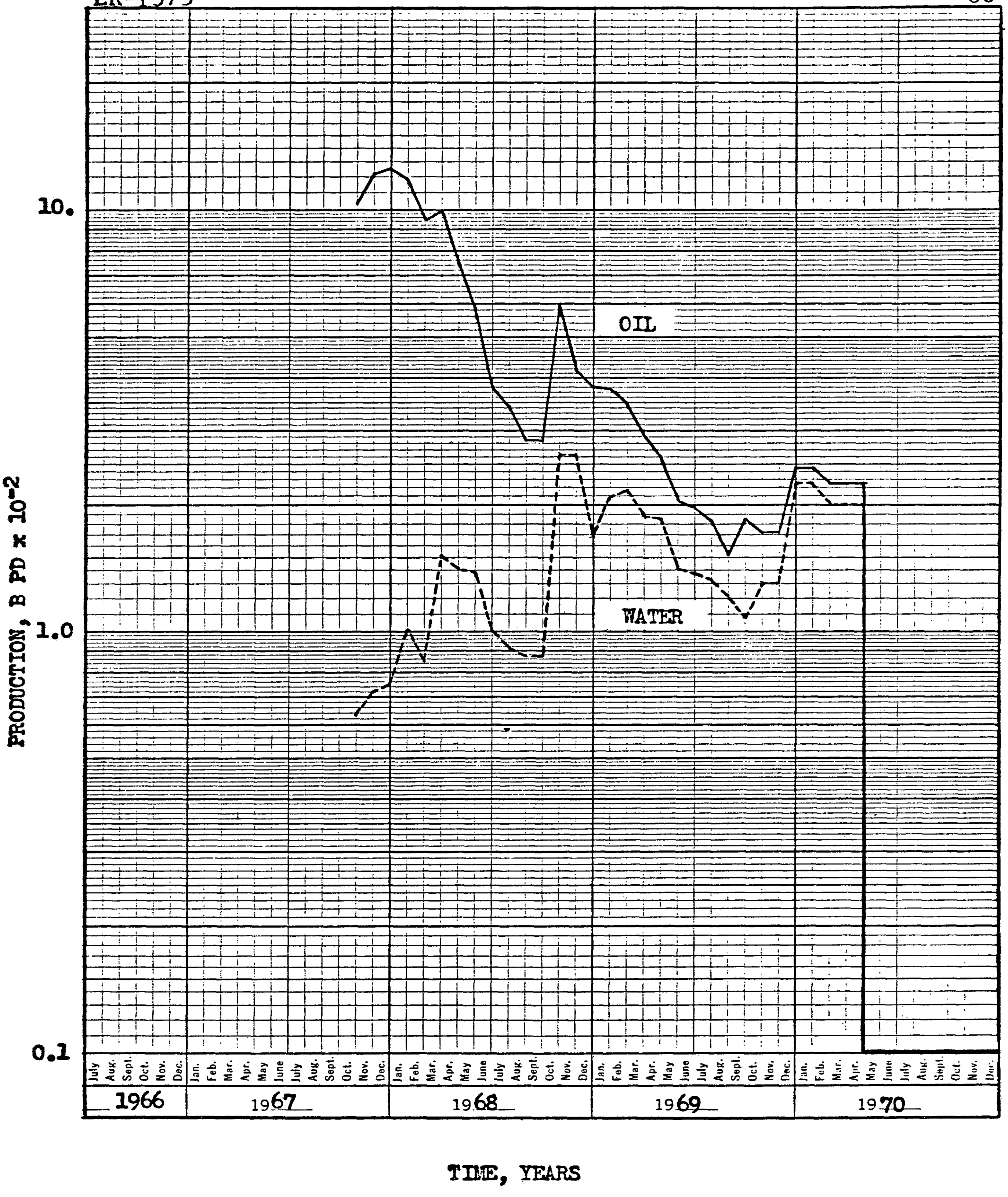


Figure 7: Fork A Well No. 5 Production History

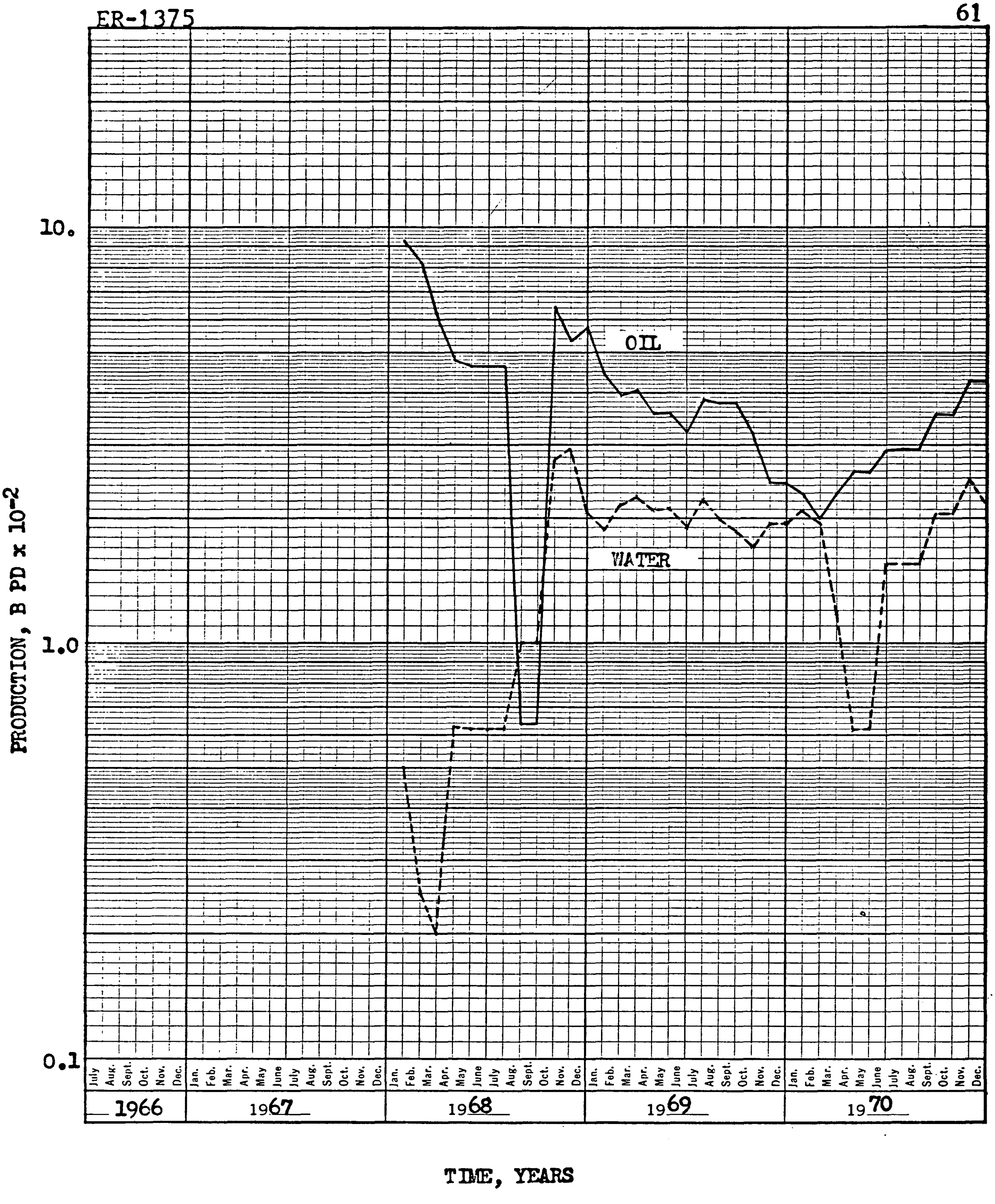


Figure 8 : Fork A Well No. 6 Production History

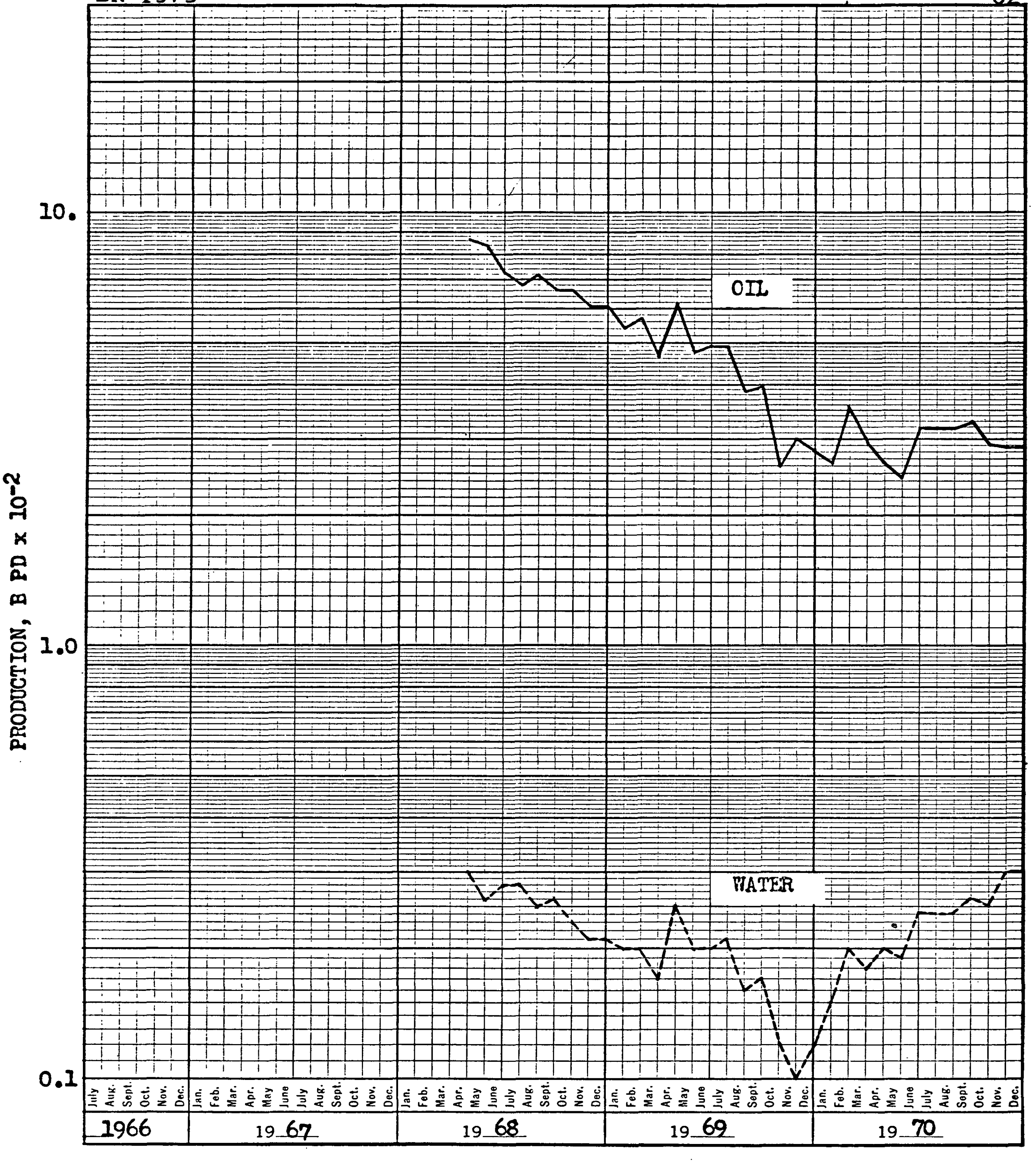


Figure 9 : Fork A Well No. 7 Production History

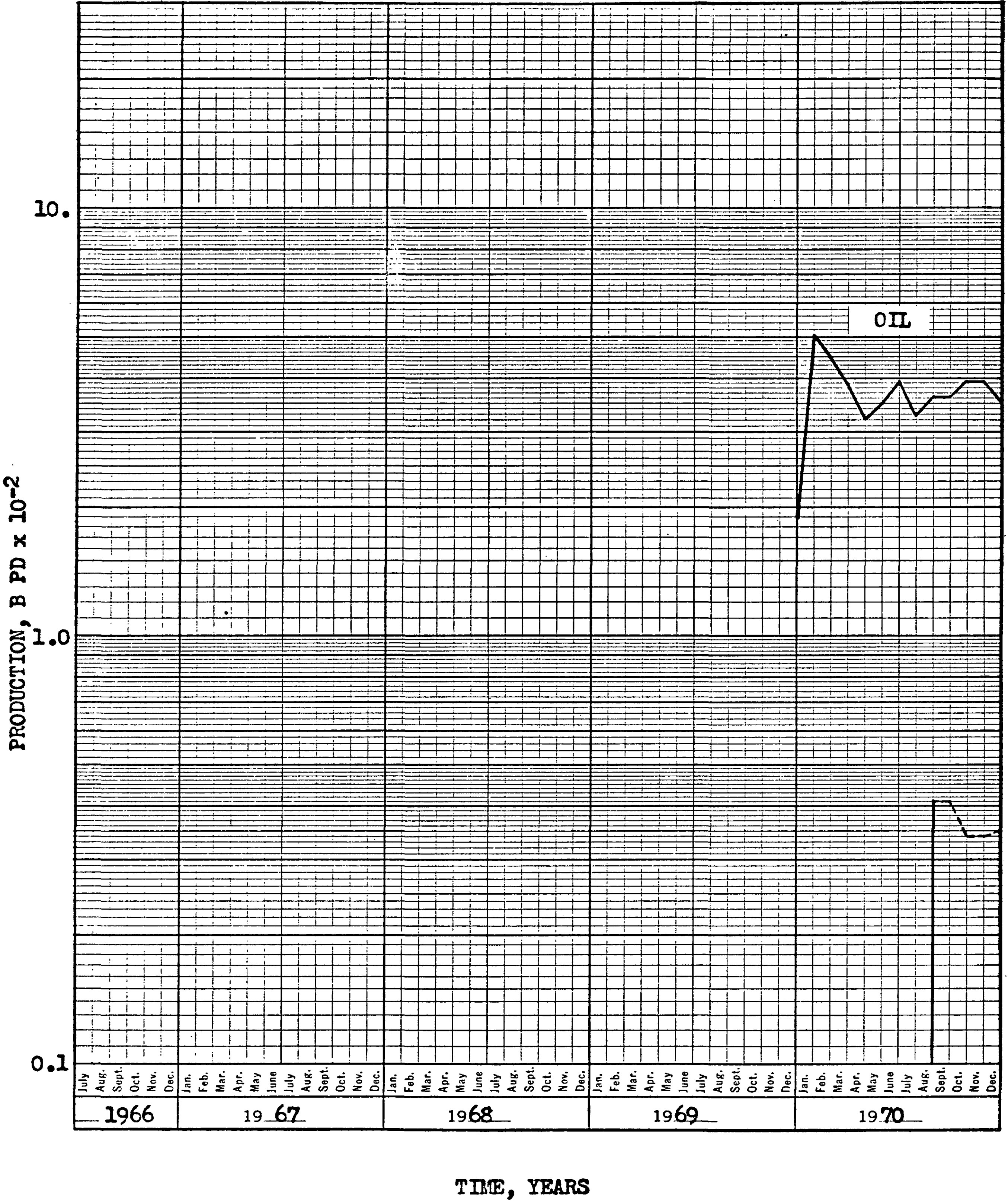


Figure 10: Fork A Well No. 8 Production History

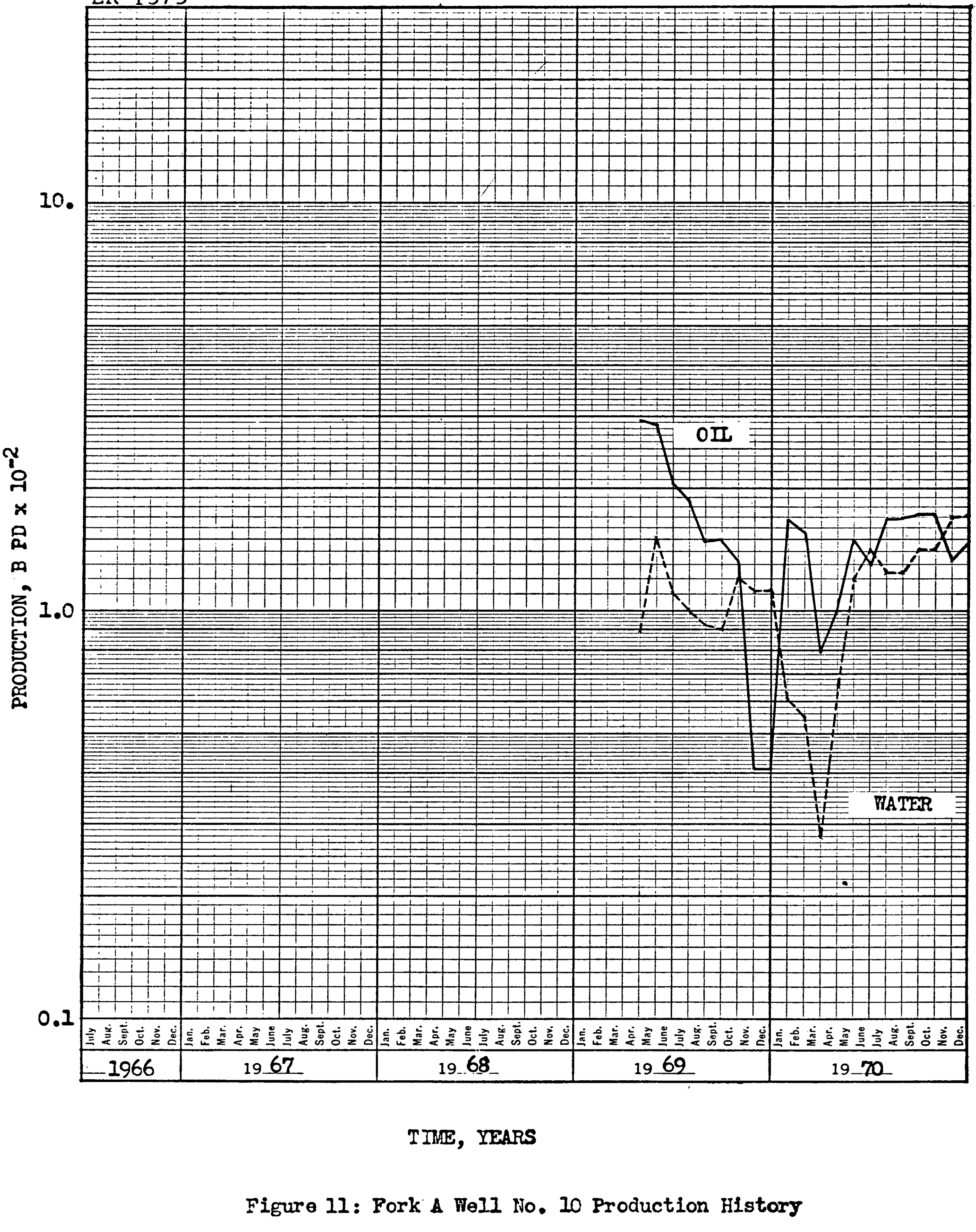


Figure 11: Fork A Well No. 10 Production History

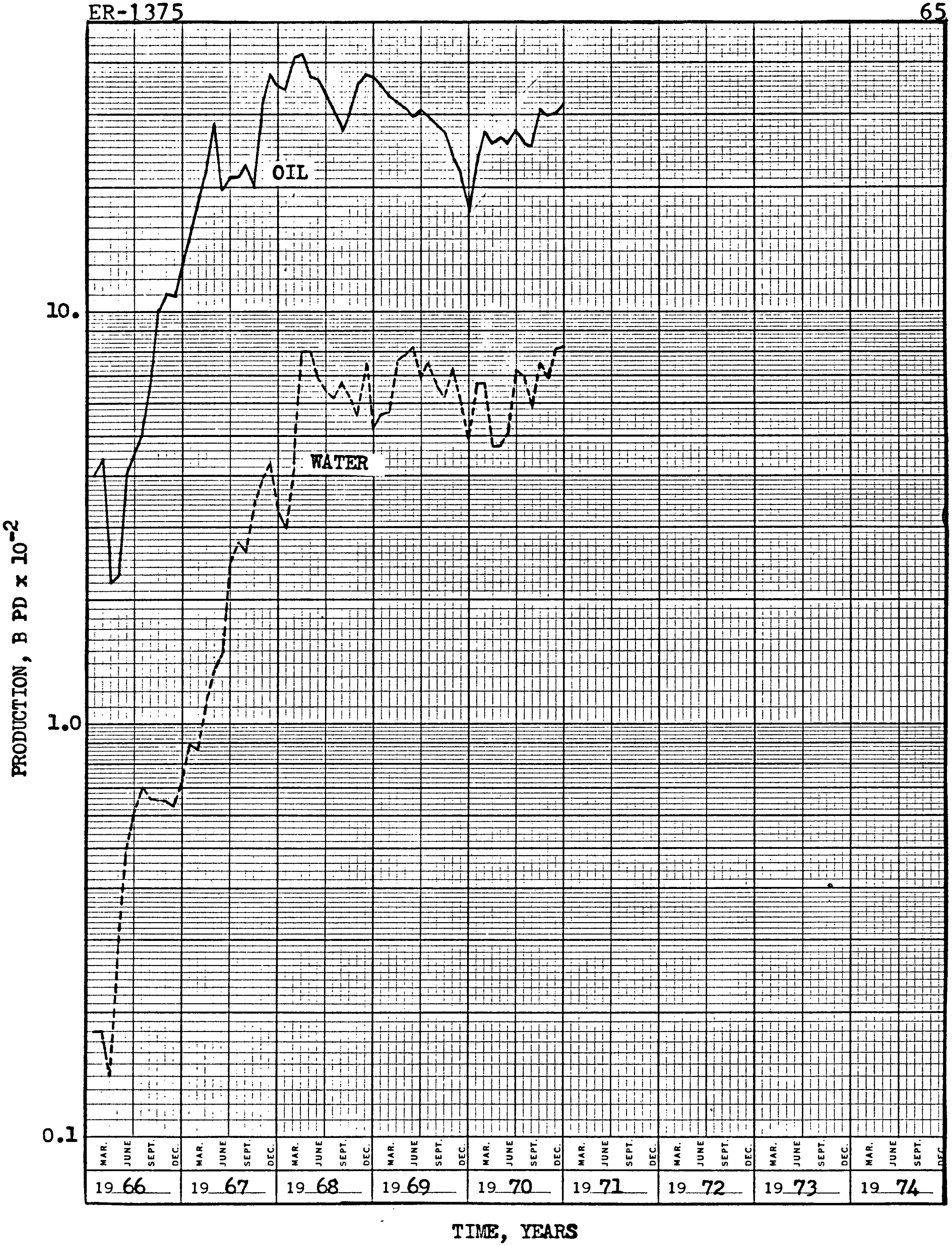


Figure 12: Bridger Lake Field Composite

Production History

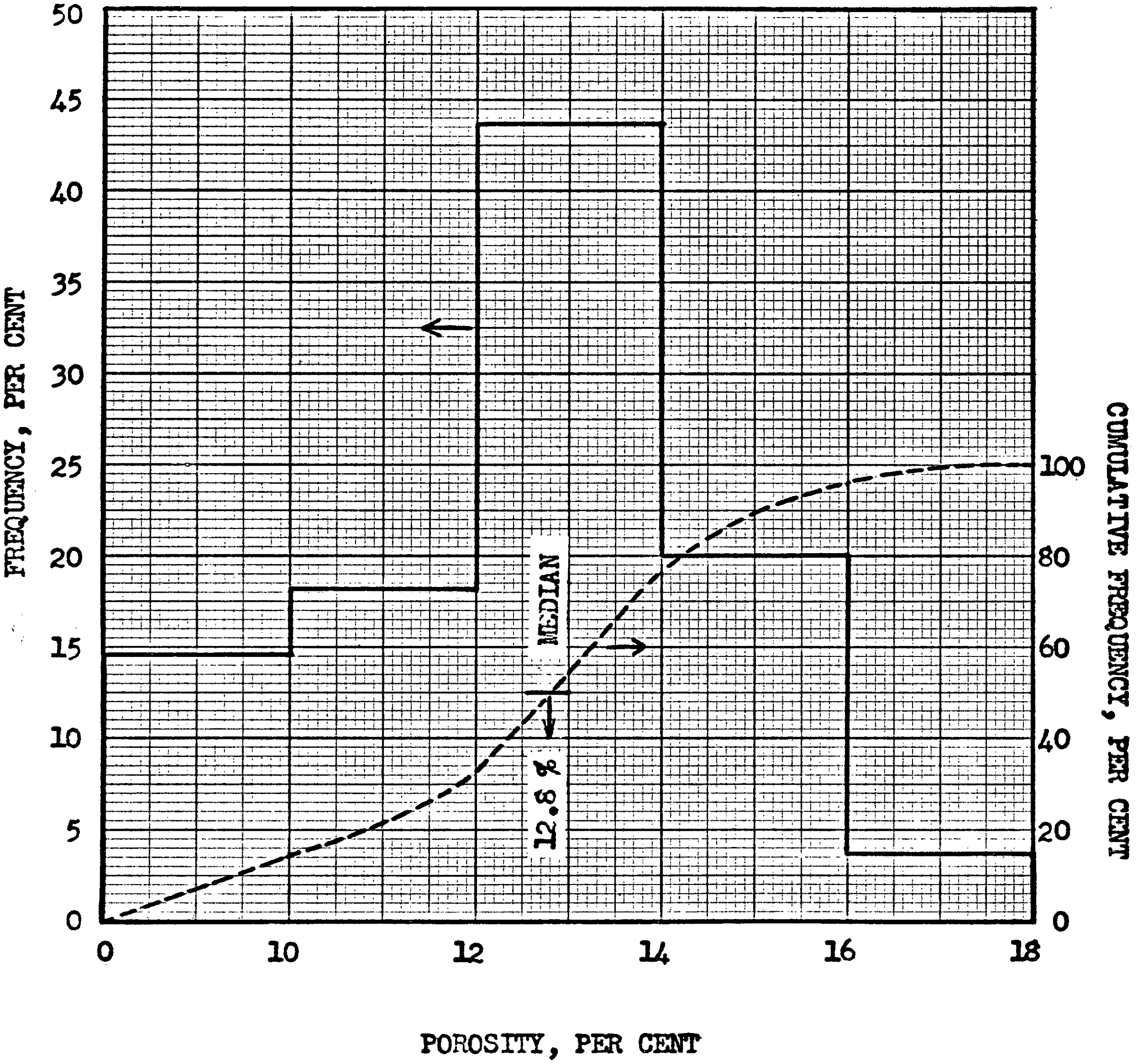


Figure 13 : Porosity Histogram and Distribution for all Samples from Sand A

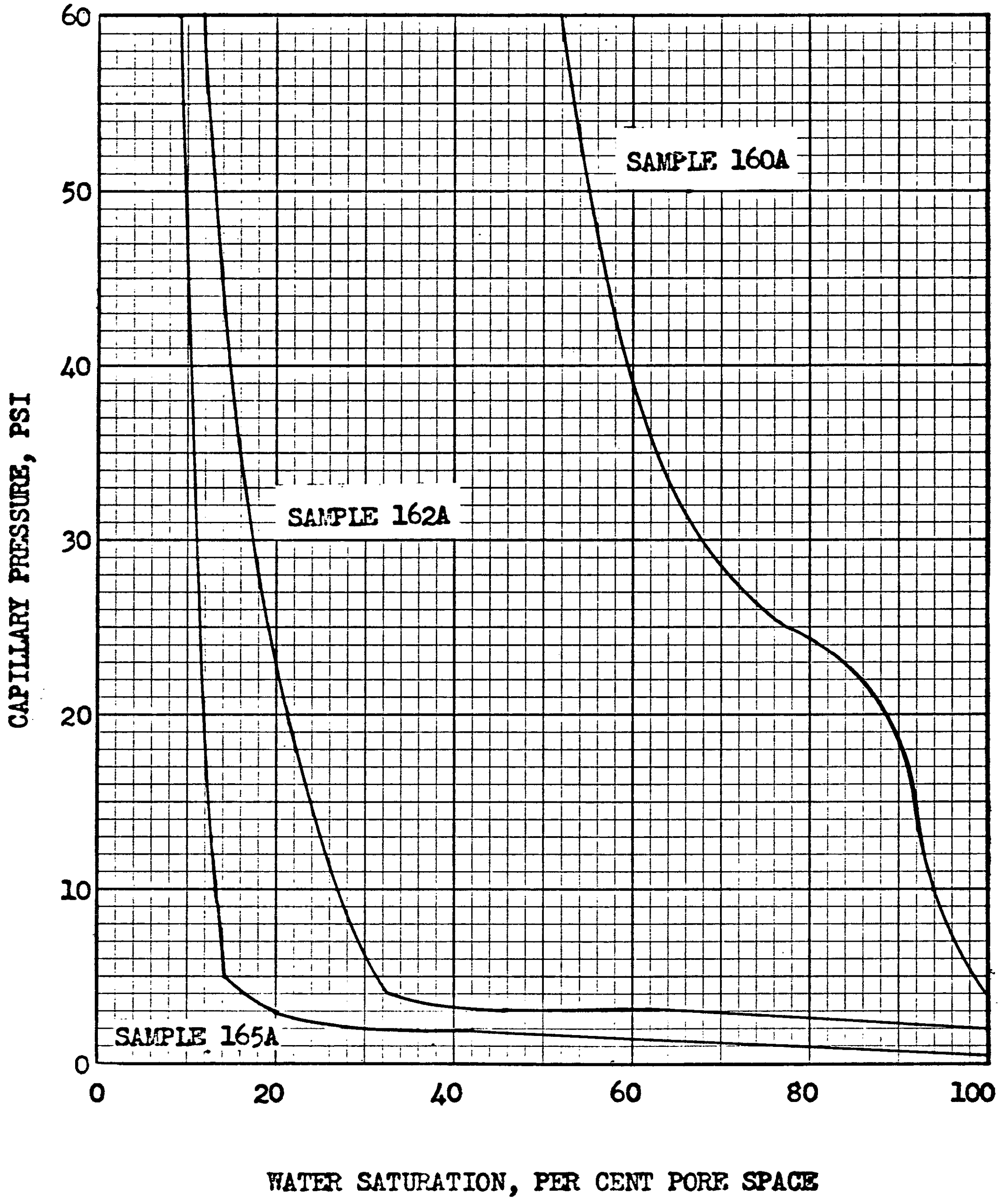


Figure 14: Capillary Pressure Curve

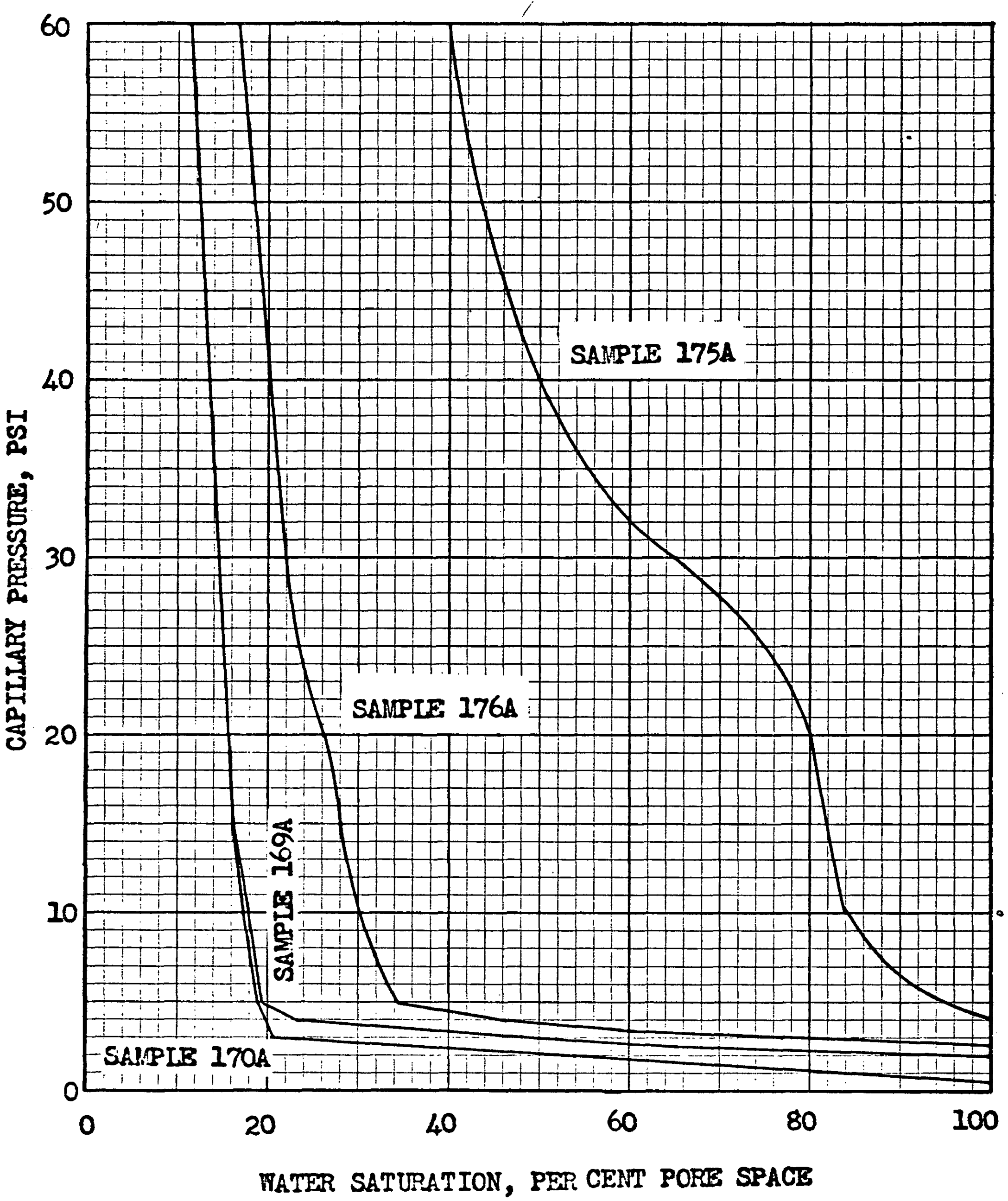
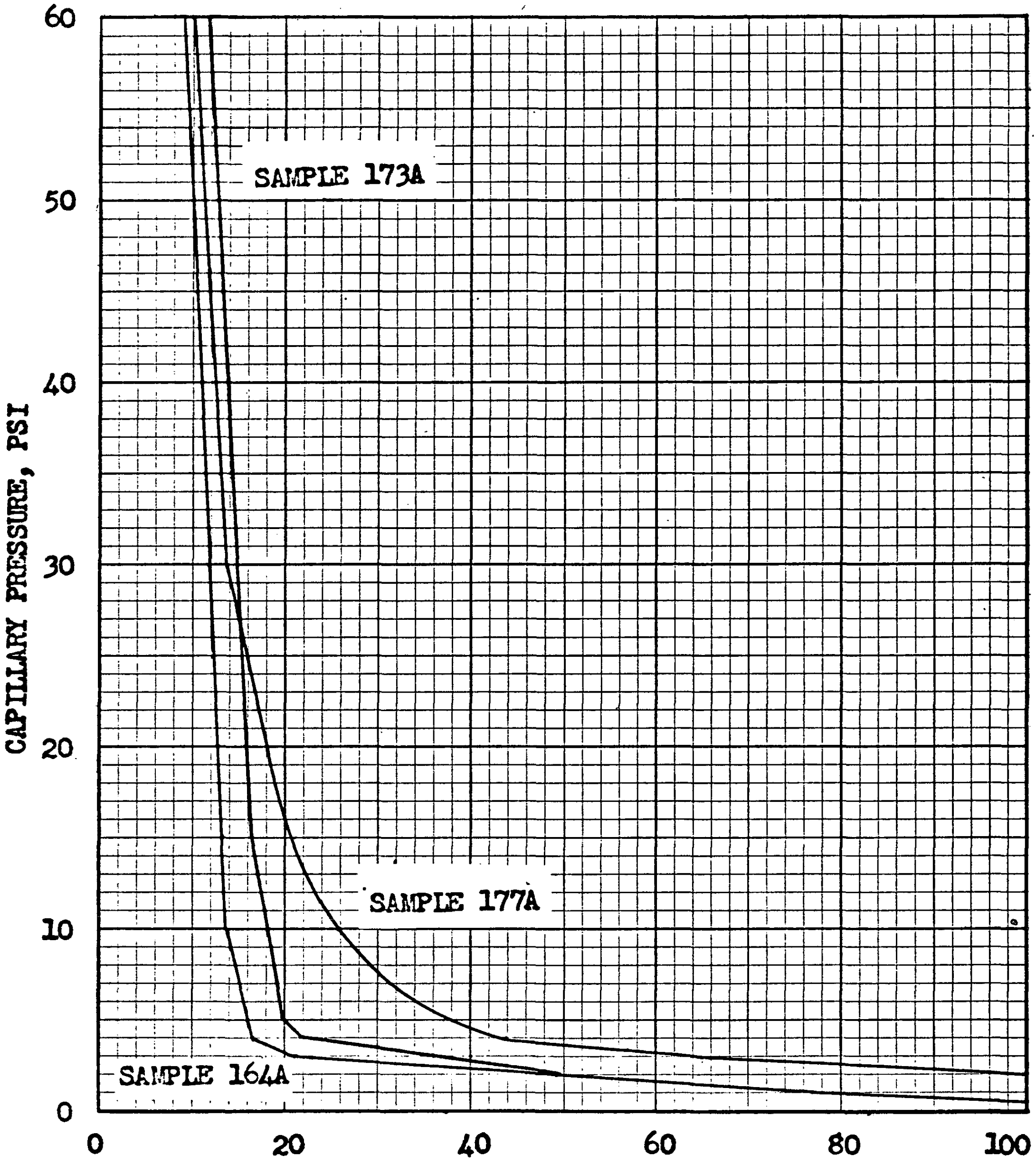


Figure 15: Capillary Pressure Curve



WATER SATURATION, PER CENT PORE SPACE

Figure 16: Capillary Pressure Curve

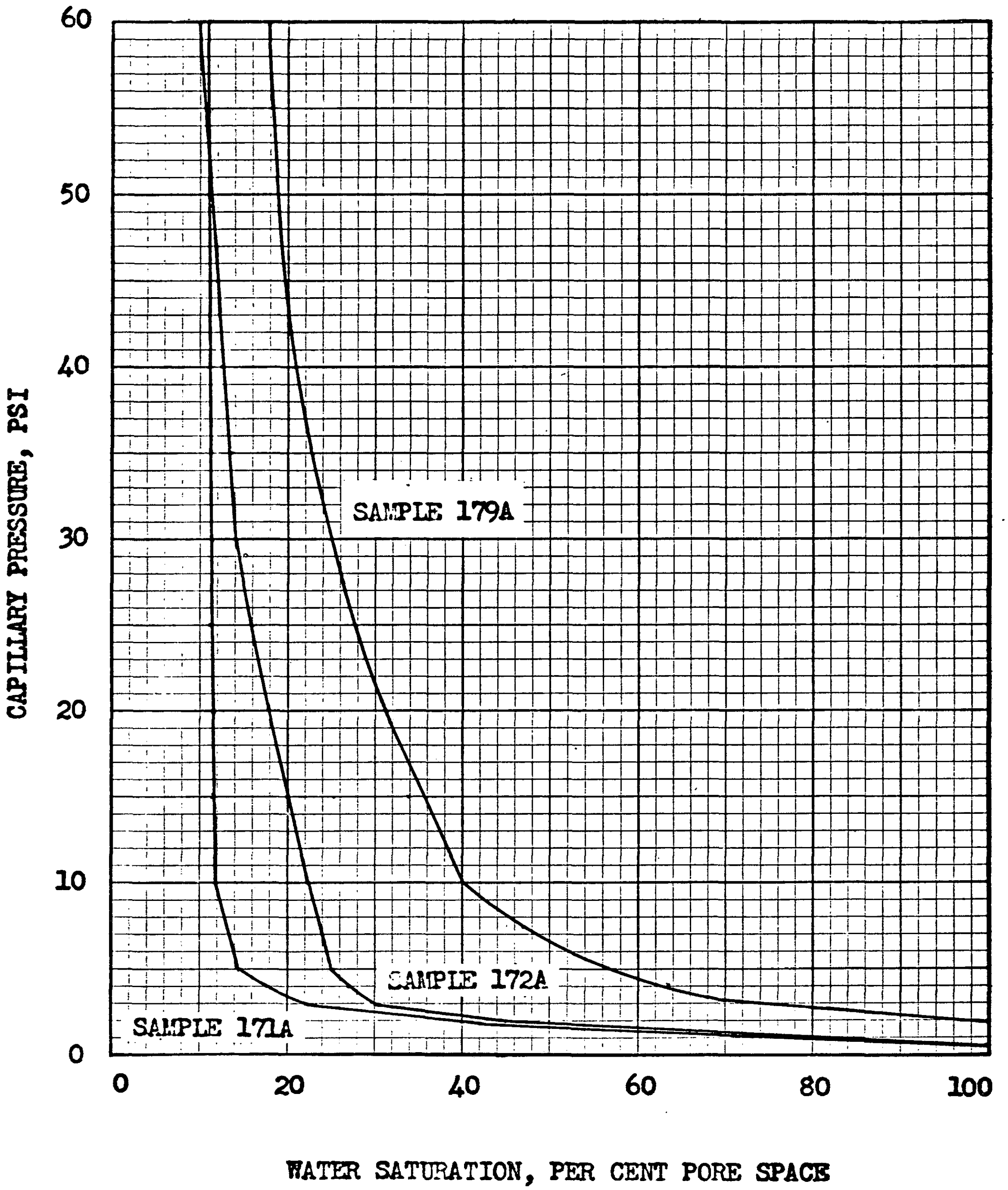


Figure 17: Capillary Pressure Curve

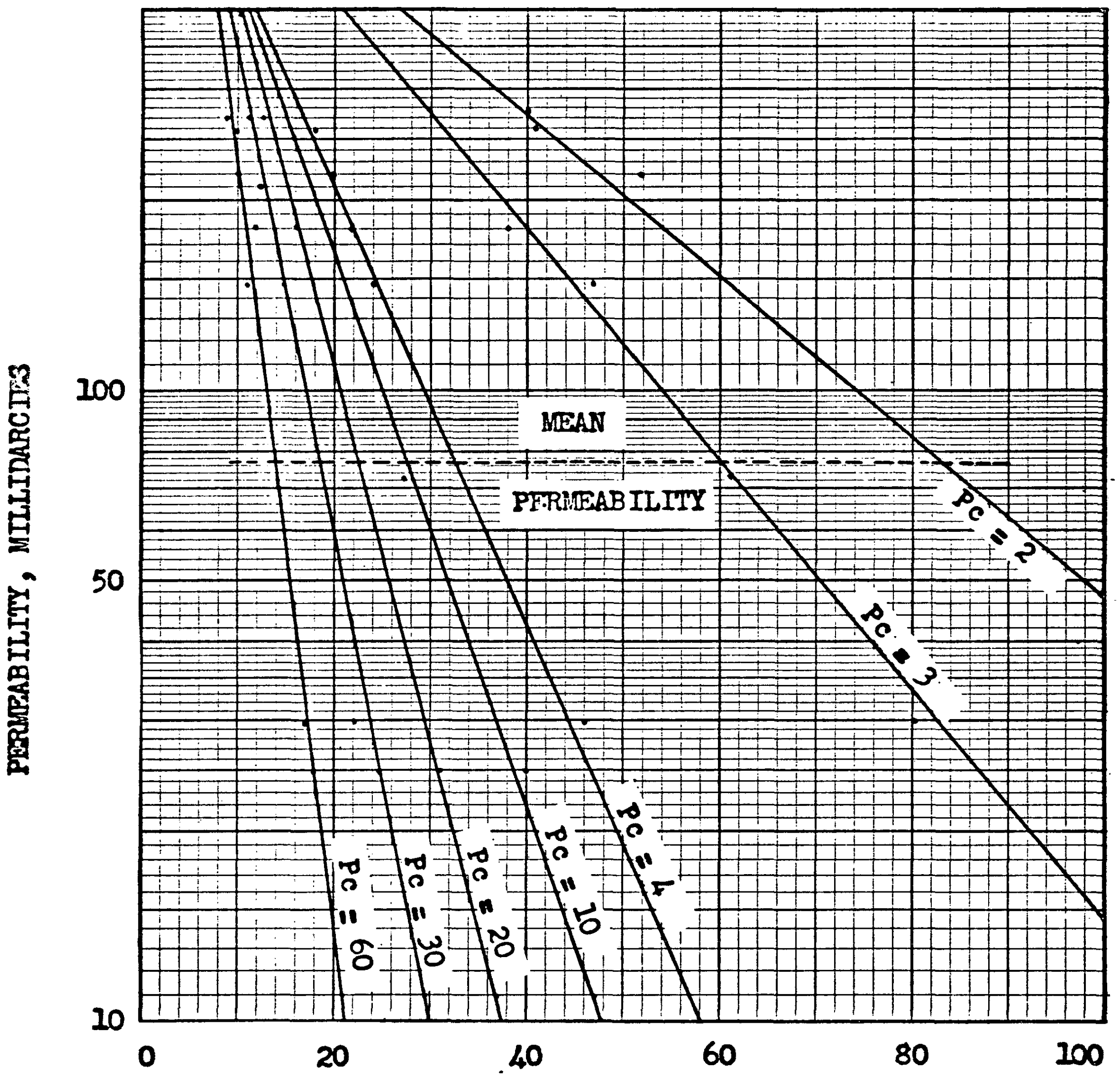


Figure 18: Correlation of Water Saturation With Permeability For Various Capillary Pressures

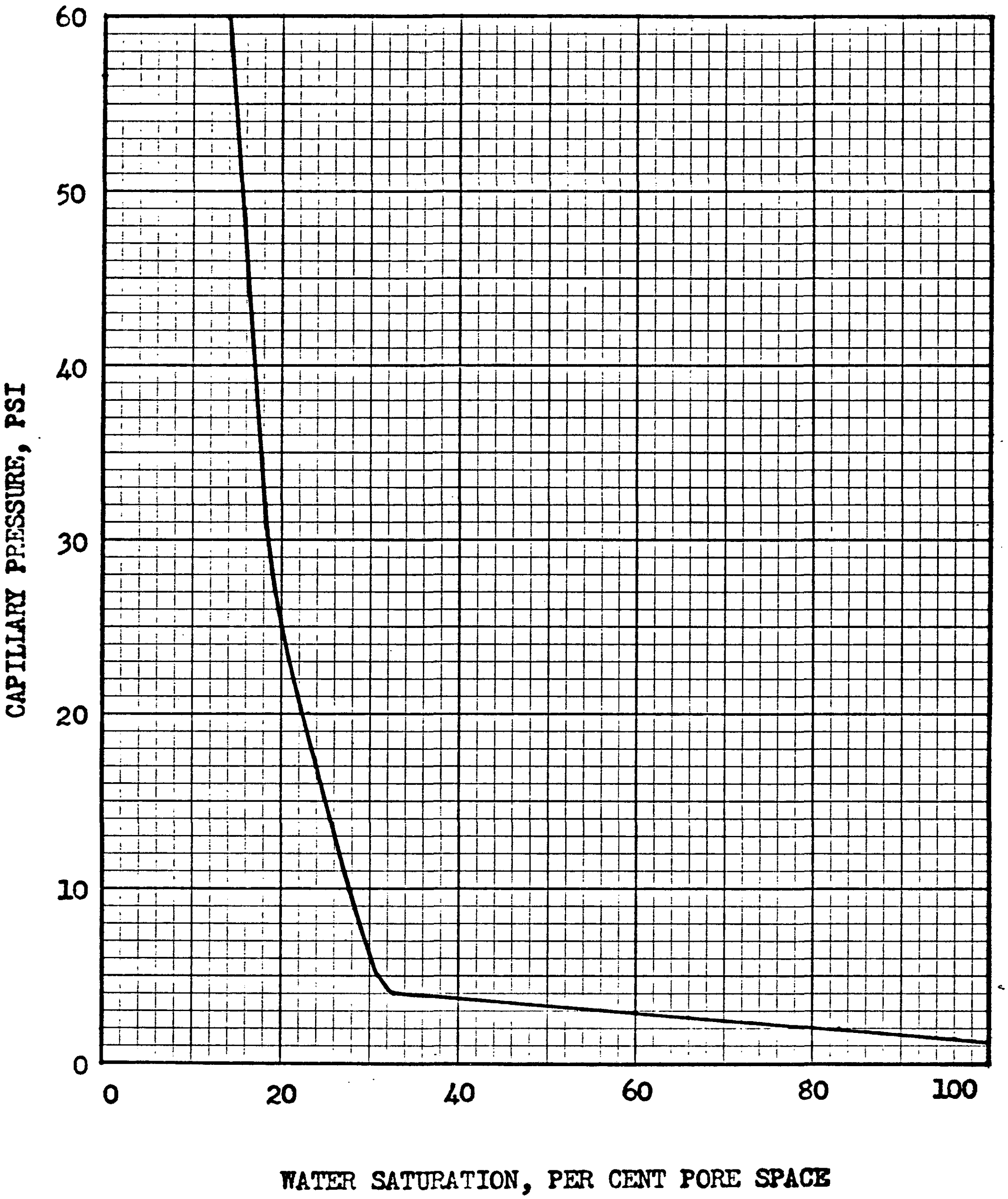


Figure 19: Bridger Lake Average Capillary Pressure

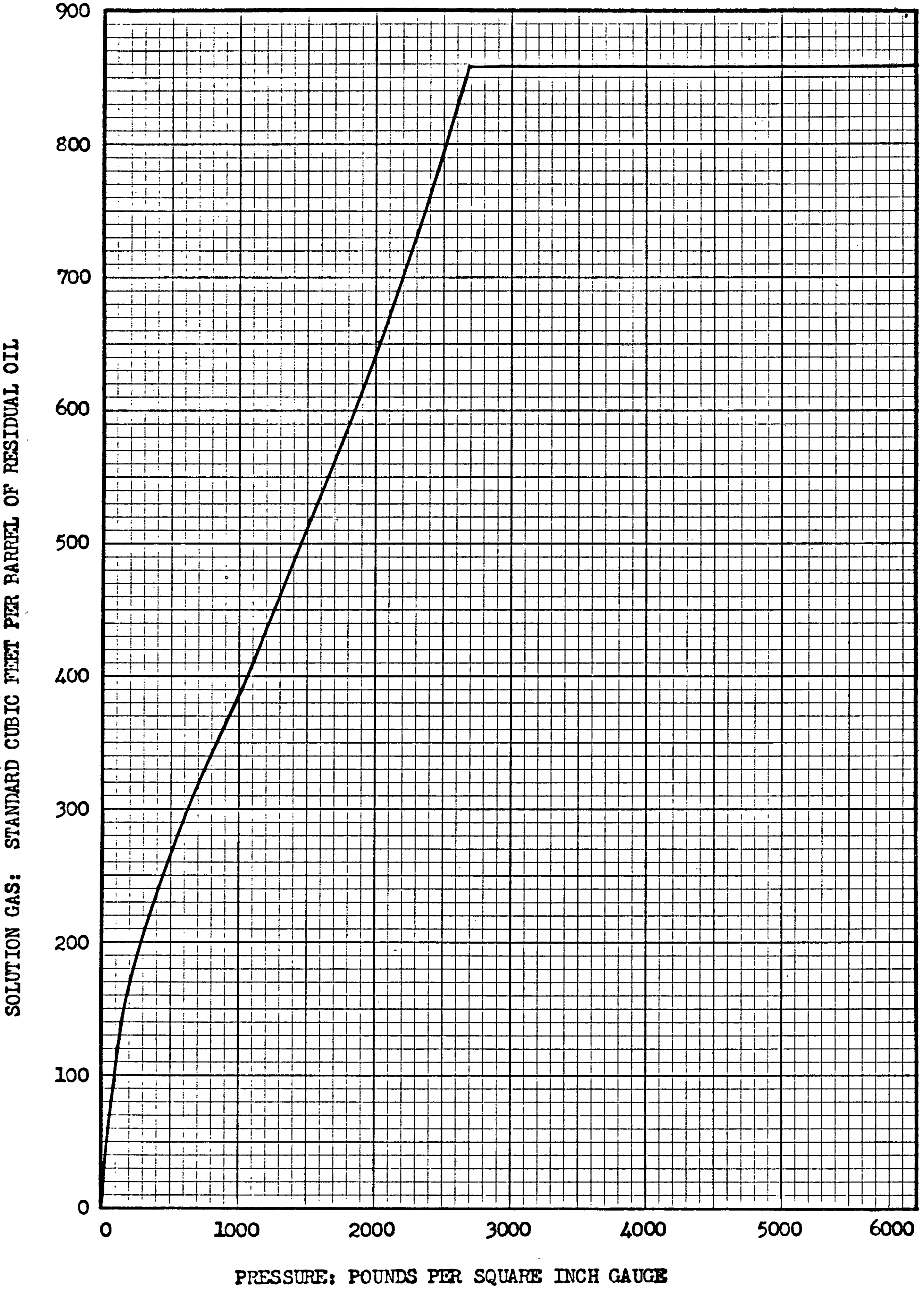


Figure 20: Bridger Lake Differential Gas Liberation

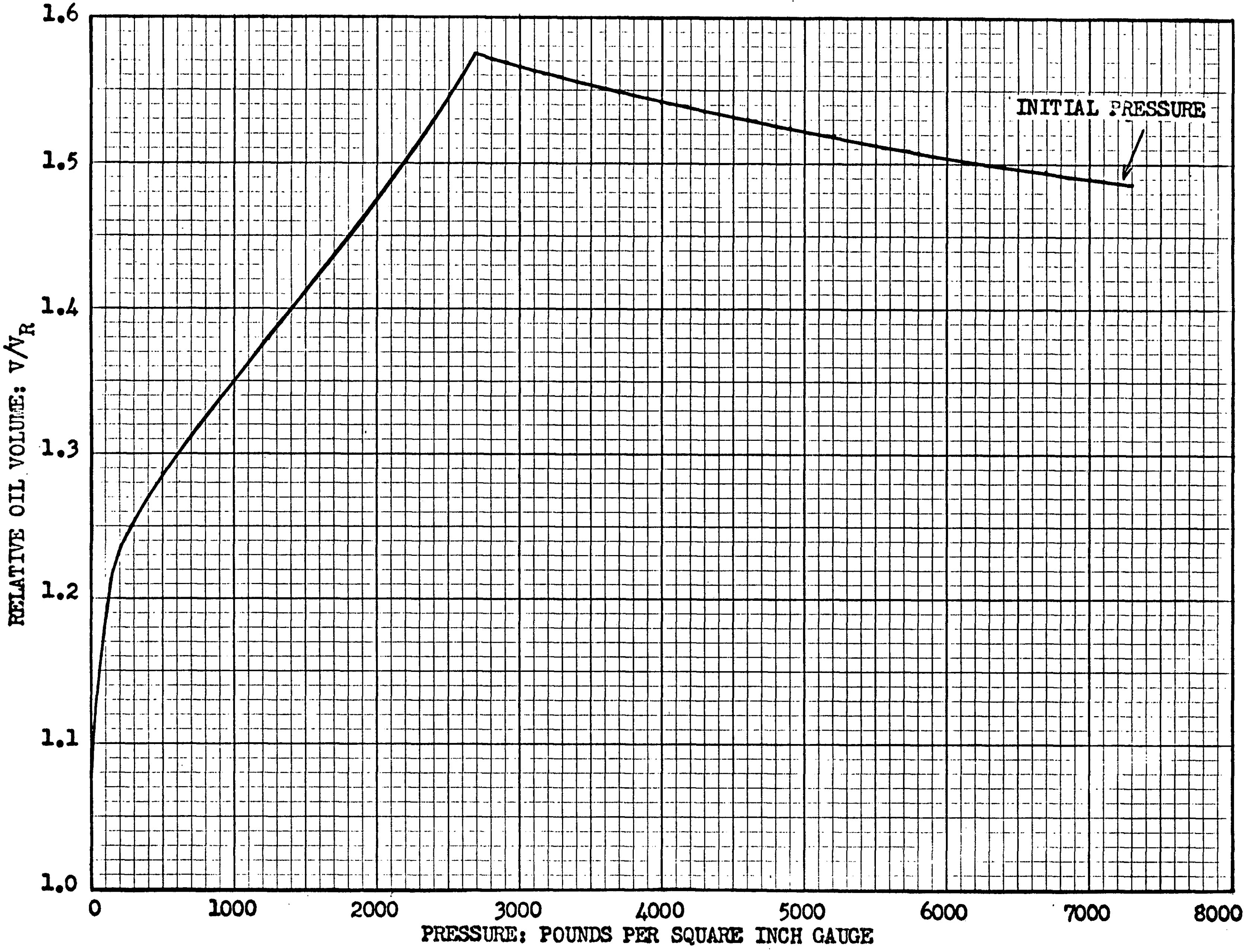


Figure 21: Bridger Lake Reservoir Oil Pressure - Volume Relationship

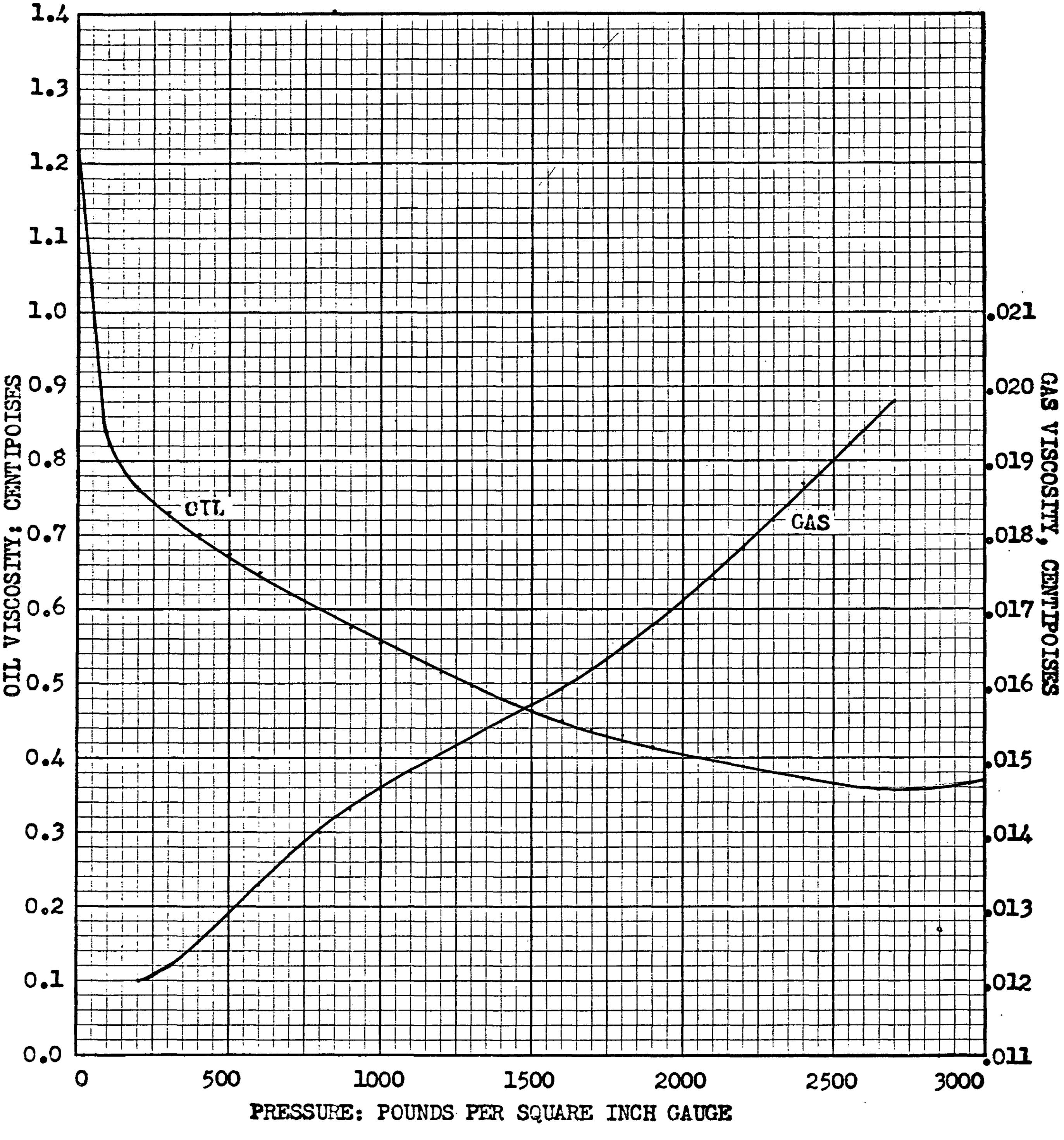


Figure 22: Bridger Lake Viscosity Data

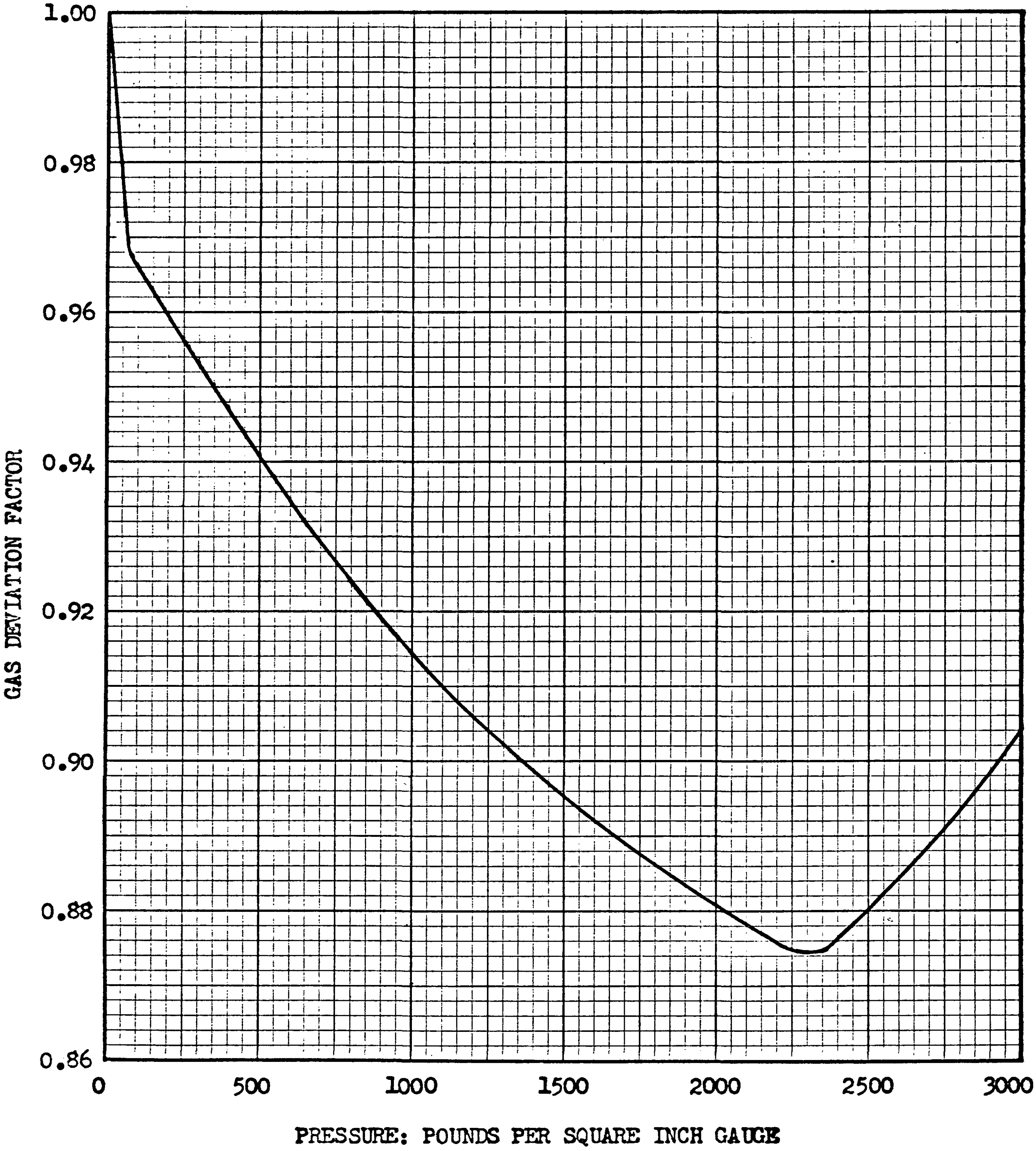


Figure 23: Bridger Lake Reservoir Oil Pressure - Gas Deviation Factor Relationship

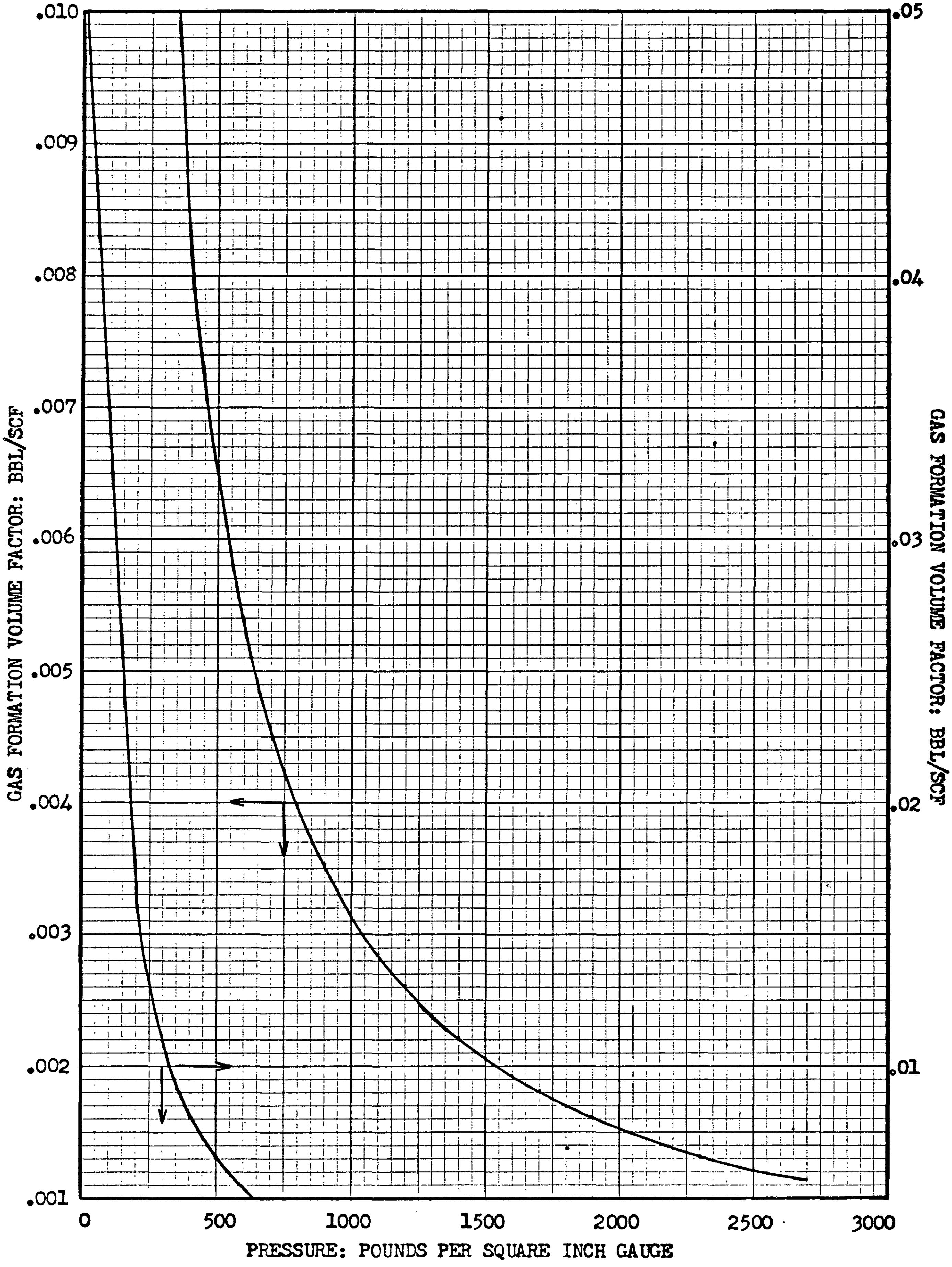


Figure 24: Bridger Lake Gas Formation Volume Factors

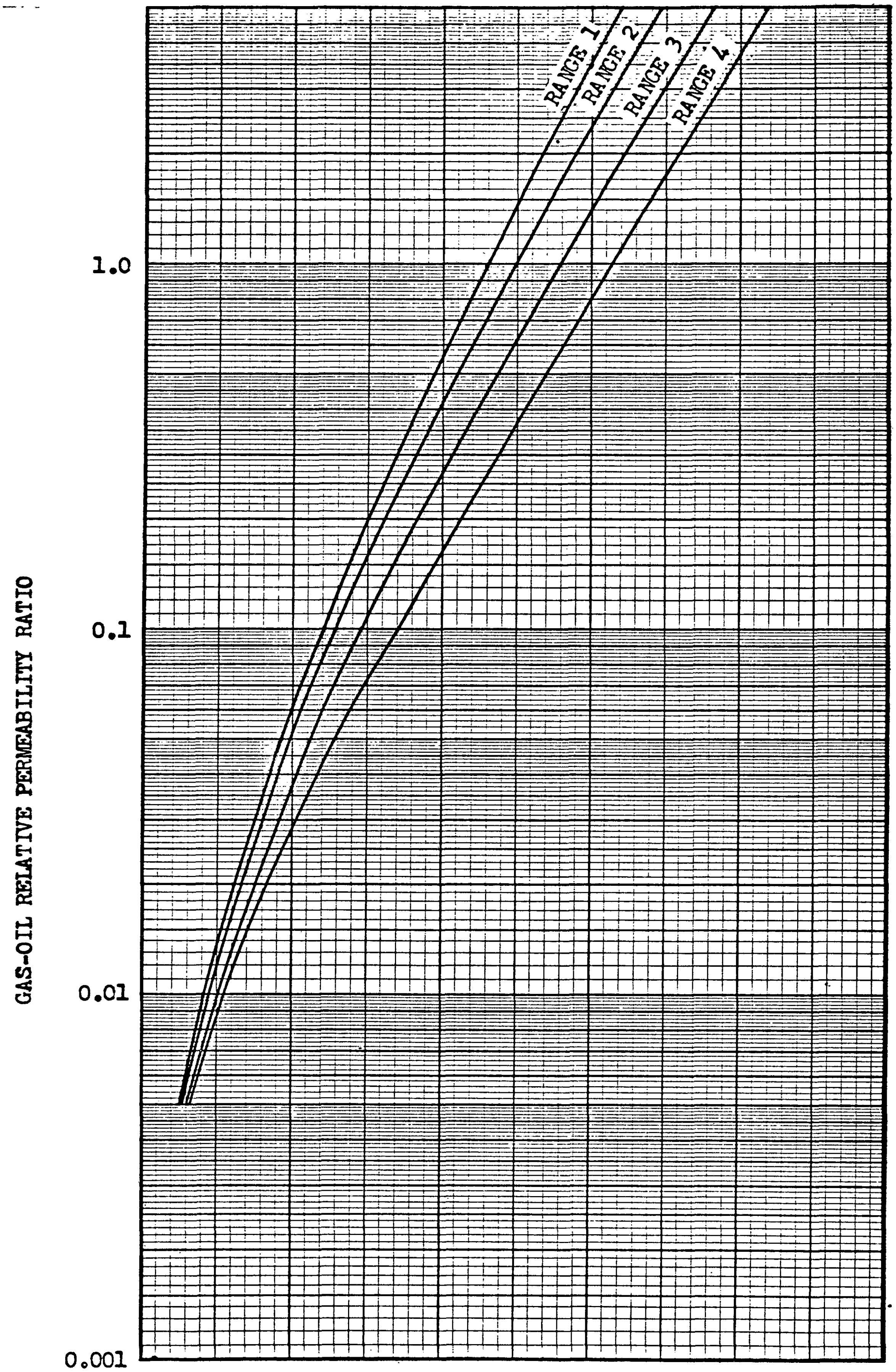


Figure 25: Individual Average Range Curves

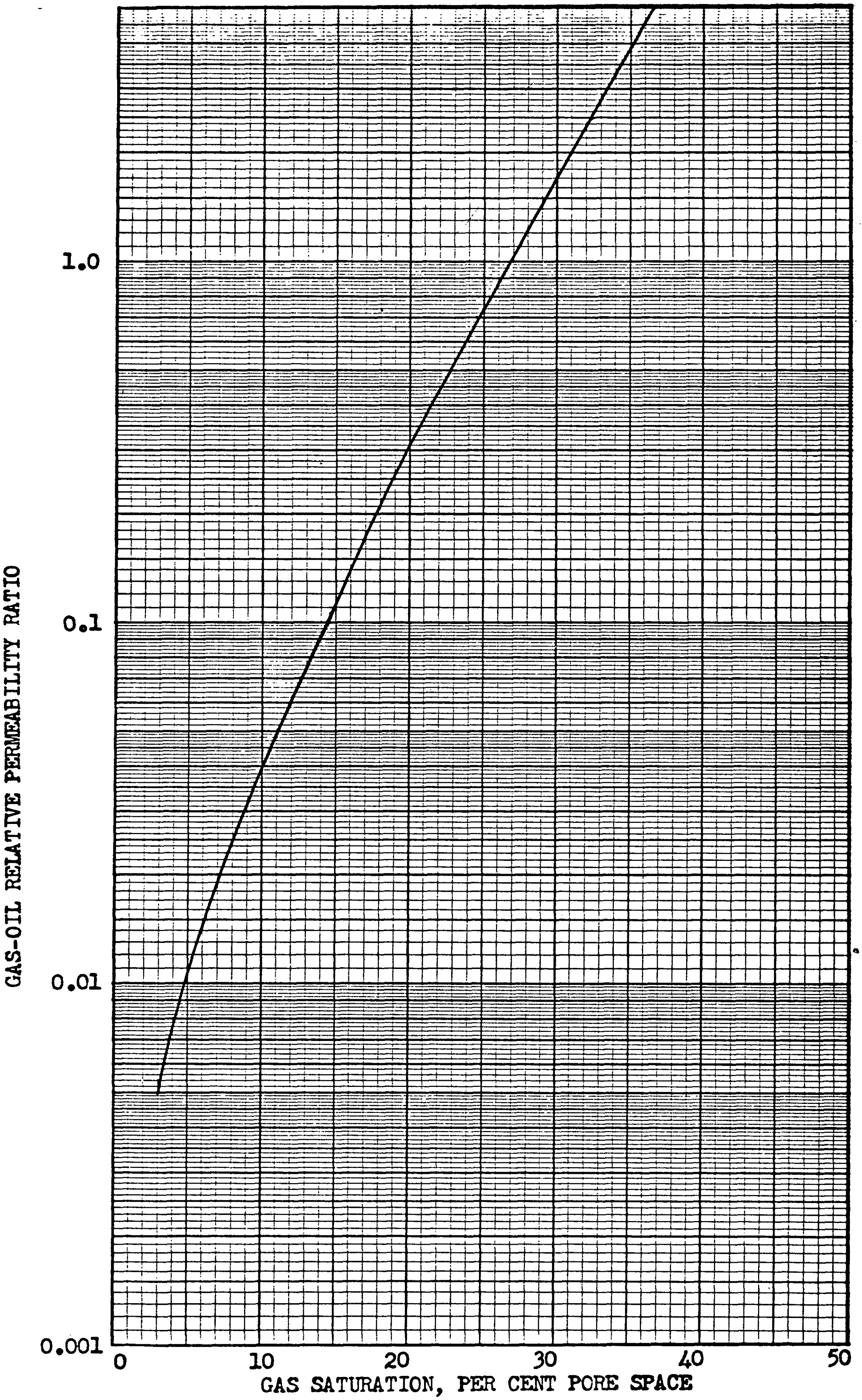


Figure 26: Bridger Lake Average Gas-Oil Relative Permeability

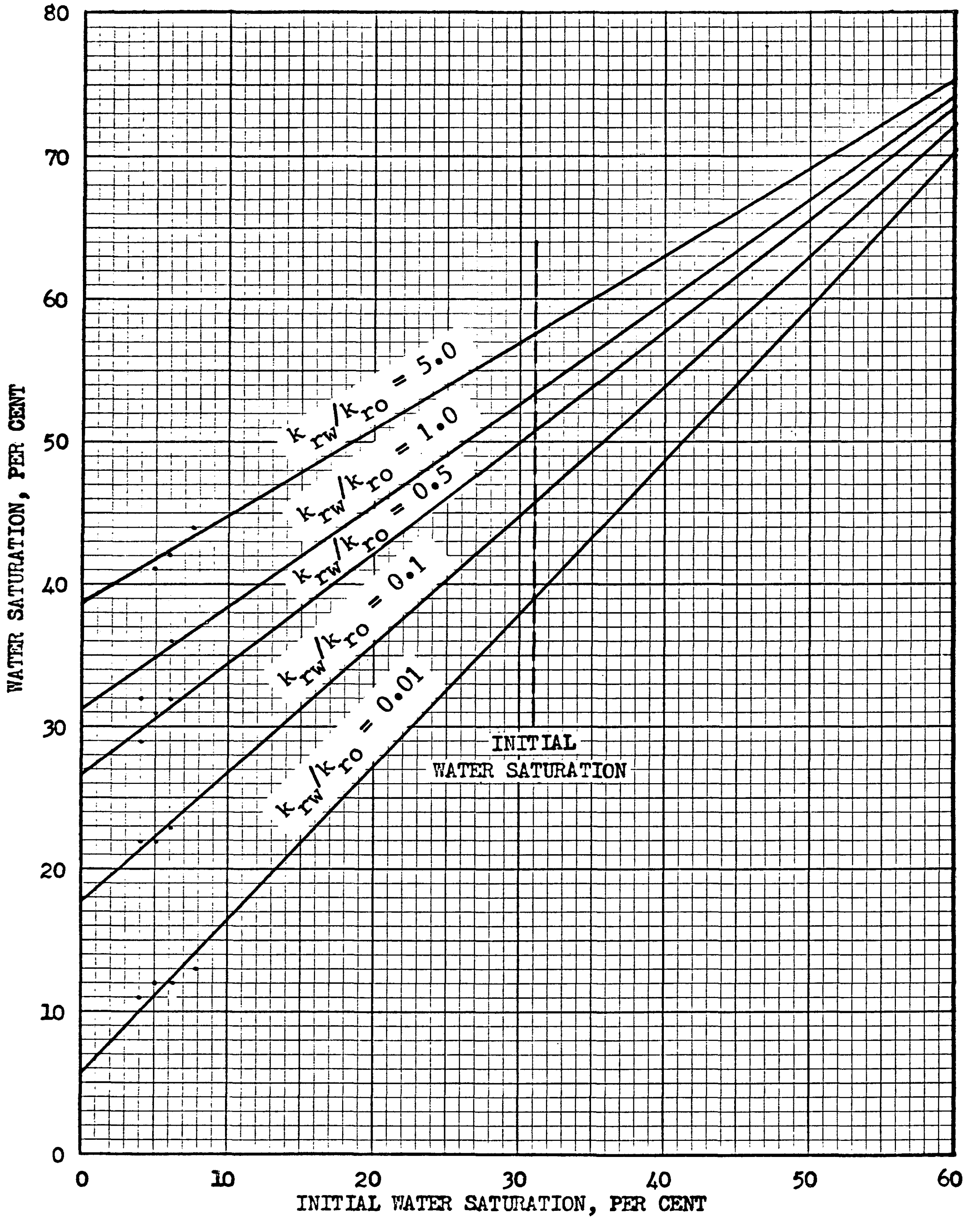


Figure 27: Smoothing Water-Oil Relative Permeability Data

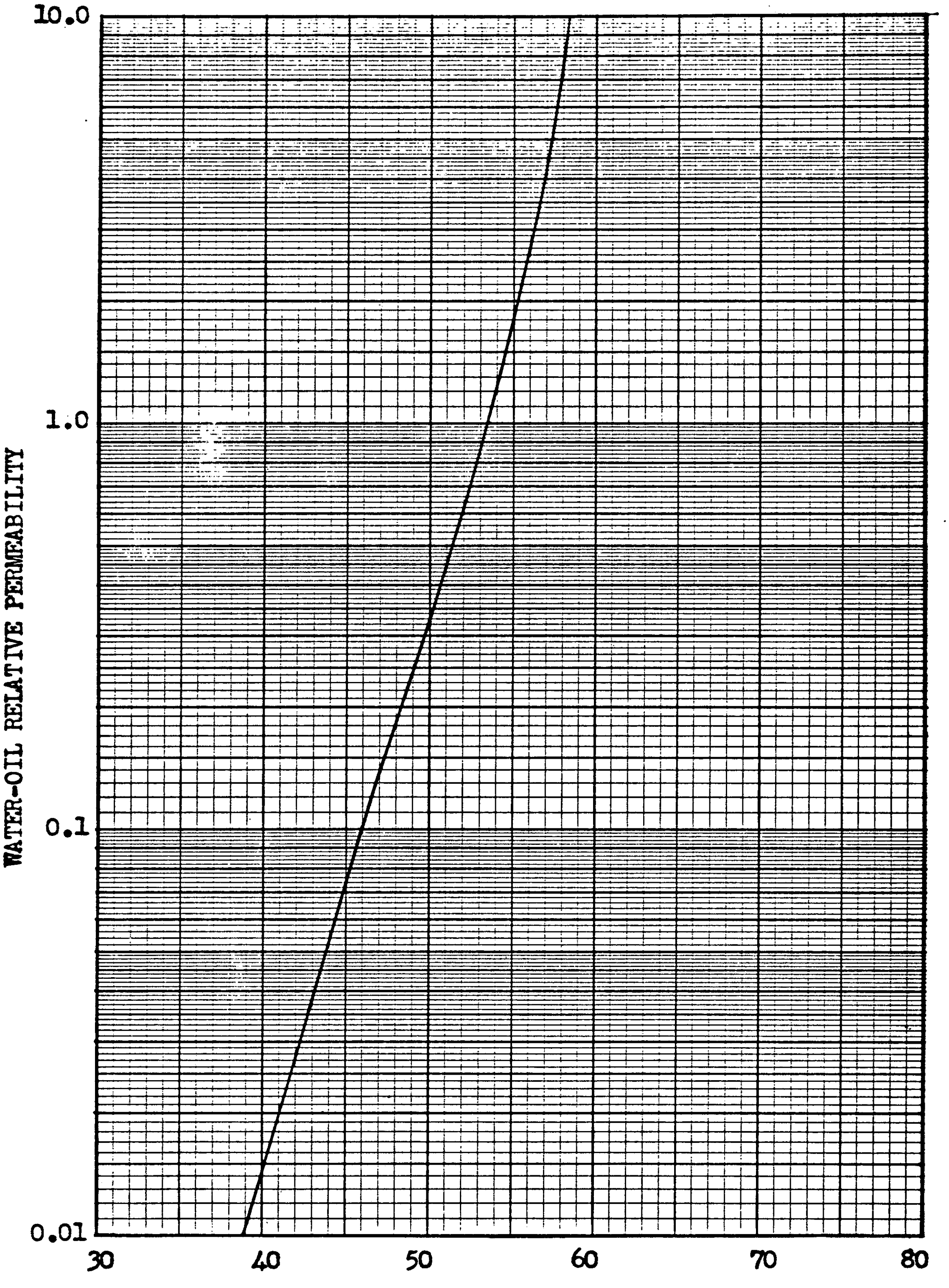


Figure 28: Bridger Lake Average Water-Oil Relative Permeability

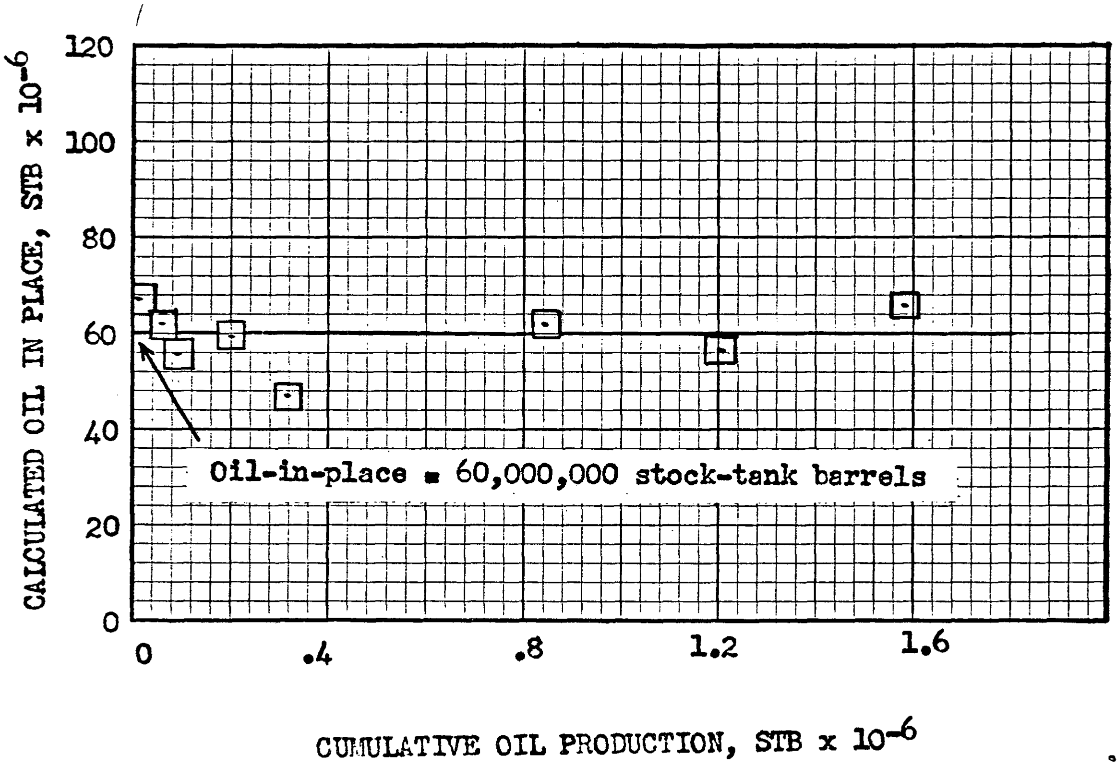


Figure 29: Material-Balance Calculation of Oil-in-Place

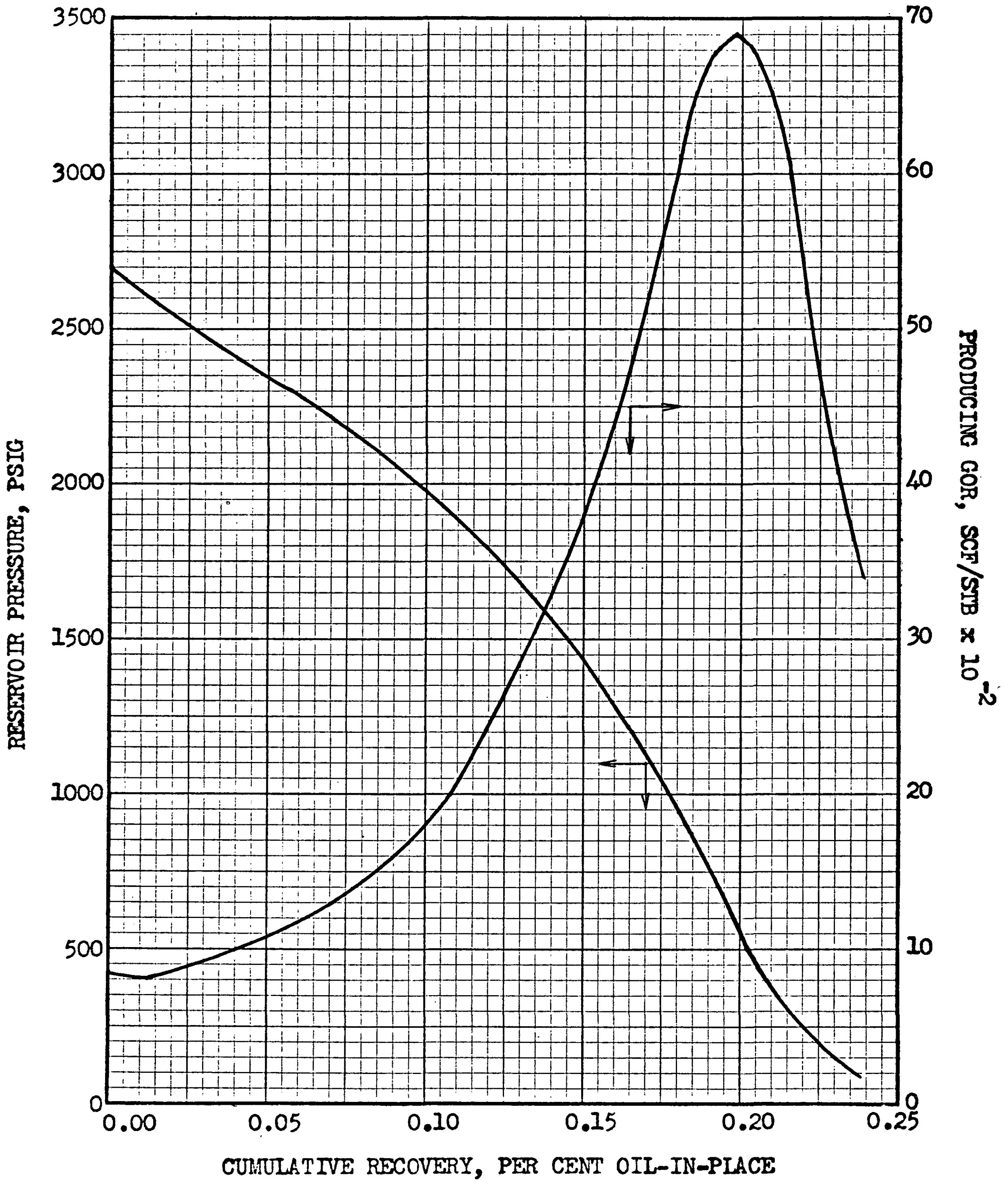


Figure 30: Bridger Lake Reservoir Schilthuis Material Balance

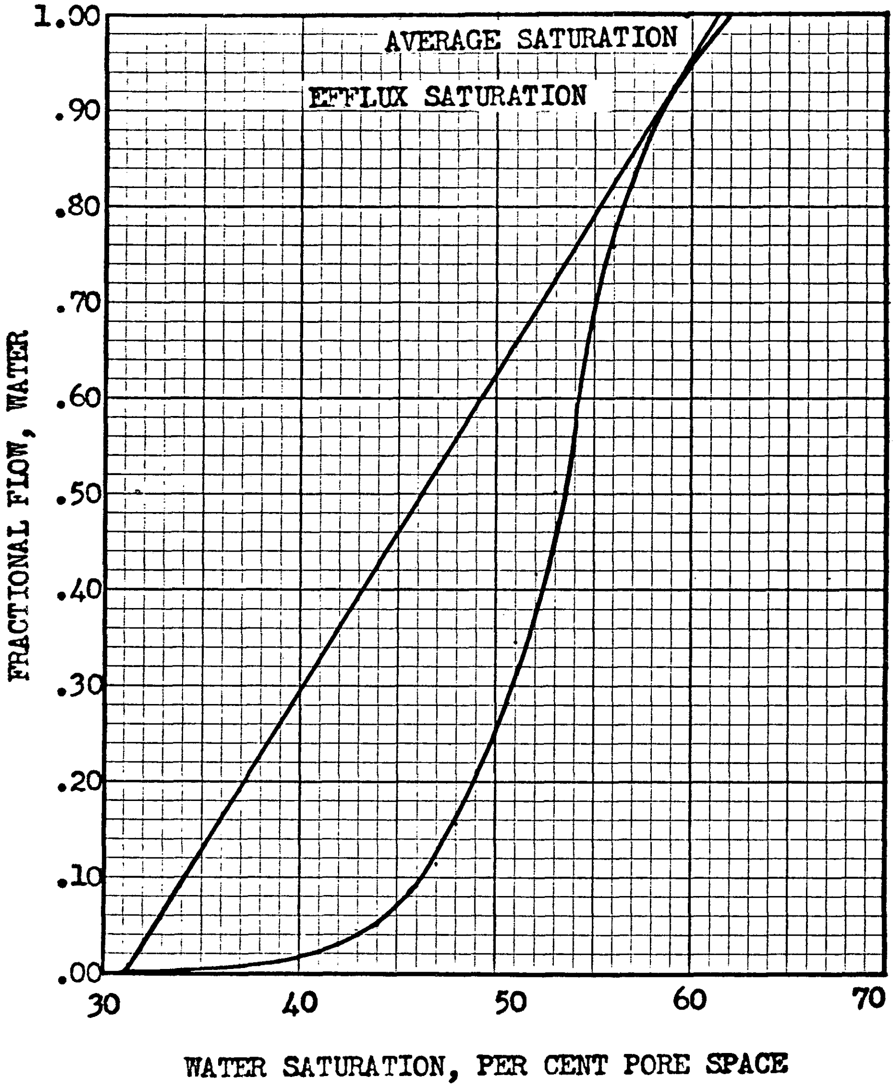


Figure 31: Bridger Lake Water Fractional Flow Relationship

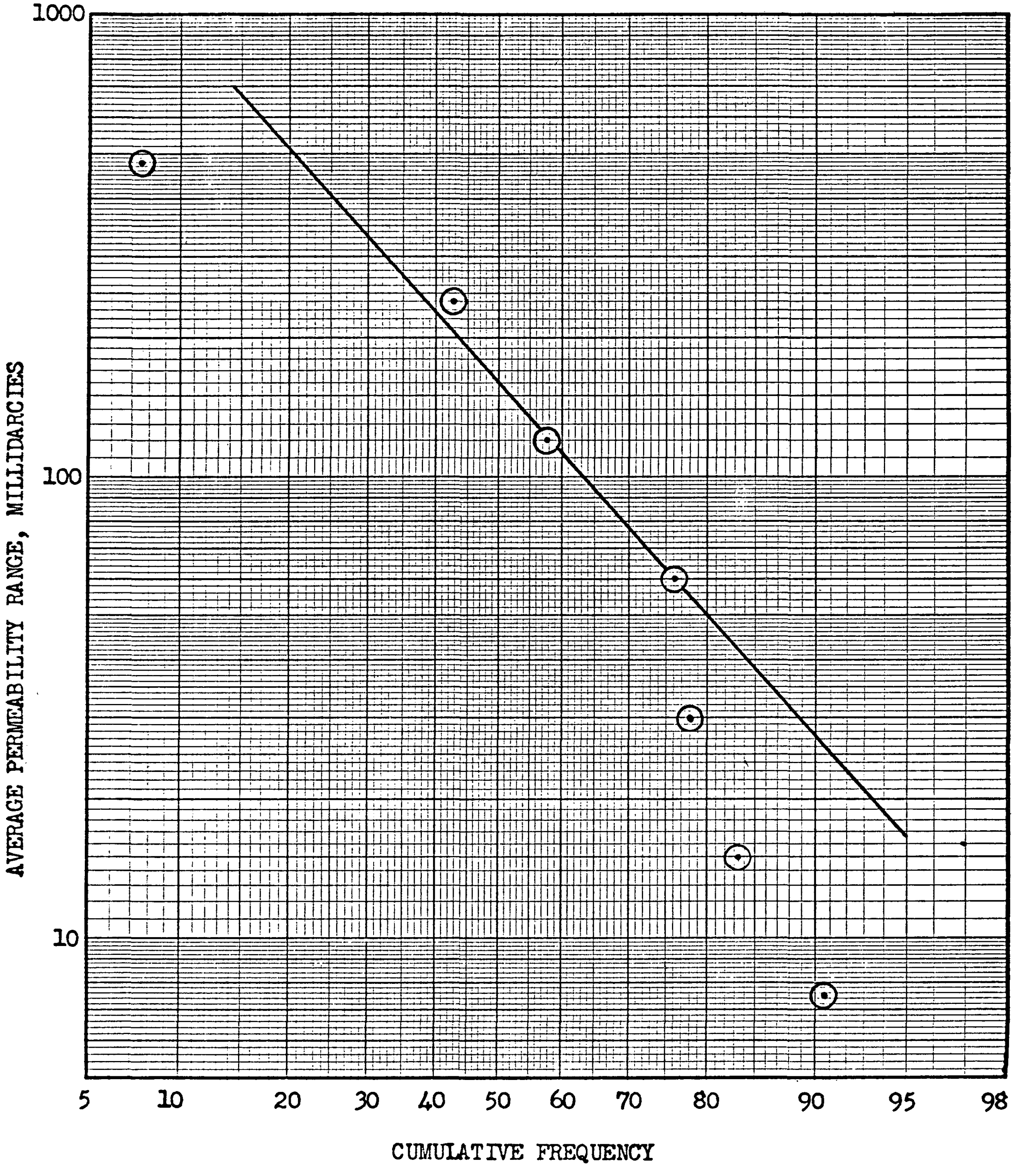
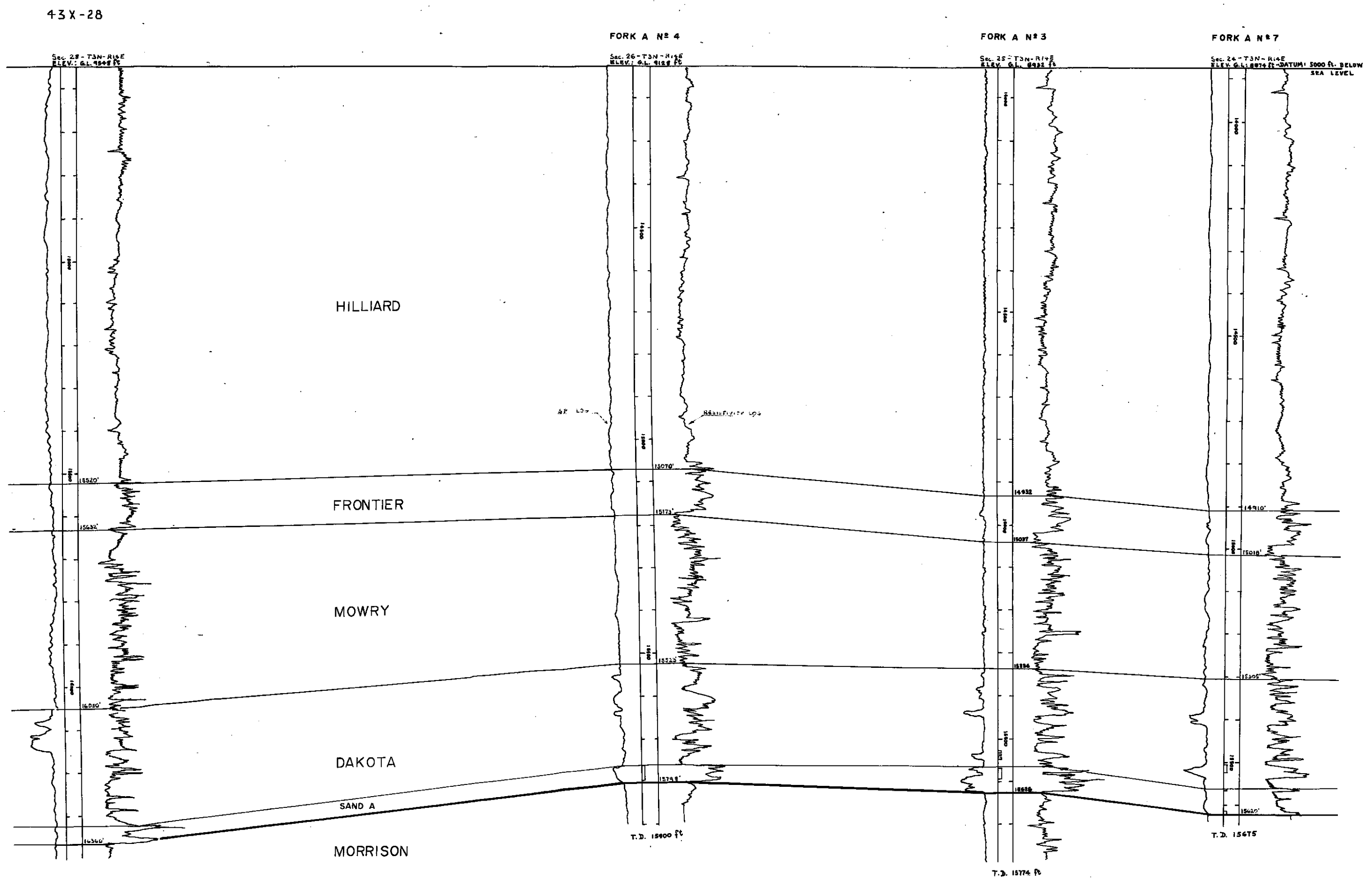
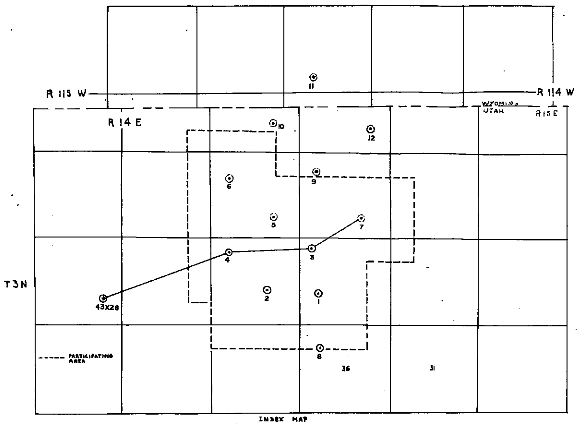


Figure 32: Bridger Lake Permeability Variation





PHILLIPS PETROLEUM COMPANY

BRIDGER LAKE FIELD

SUMMIT CO., UTAH & UINTA CO., WYOMING

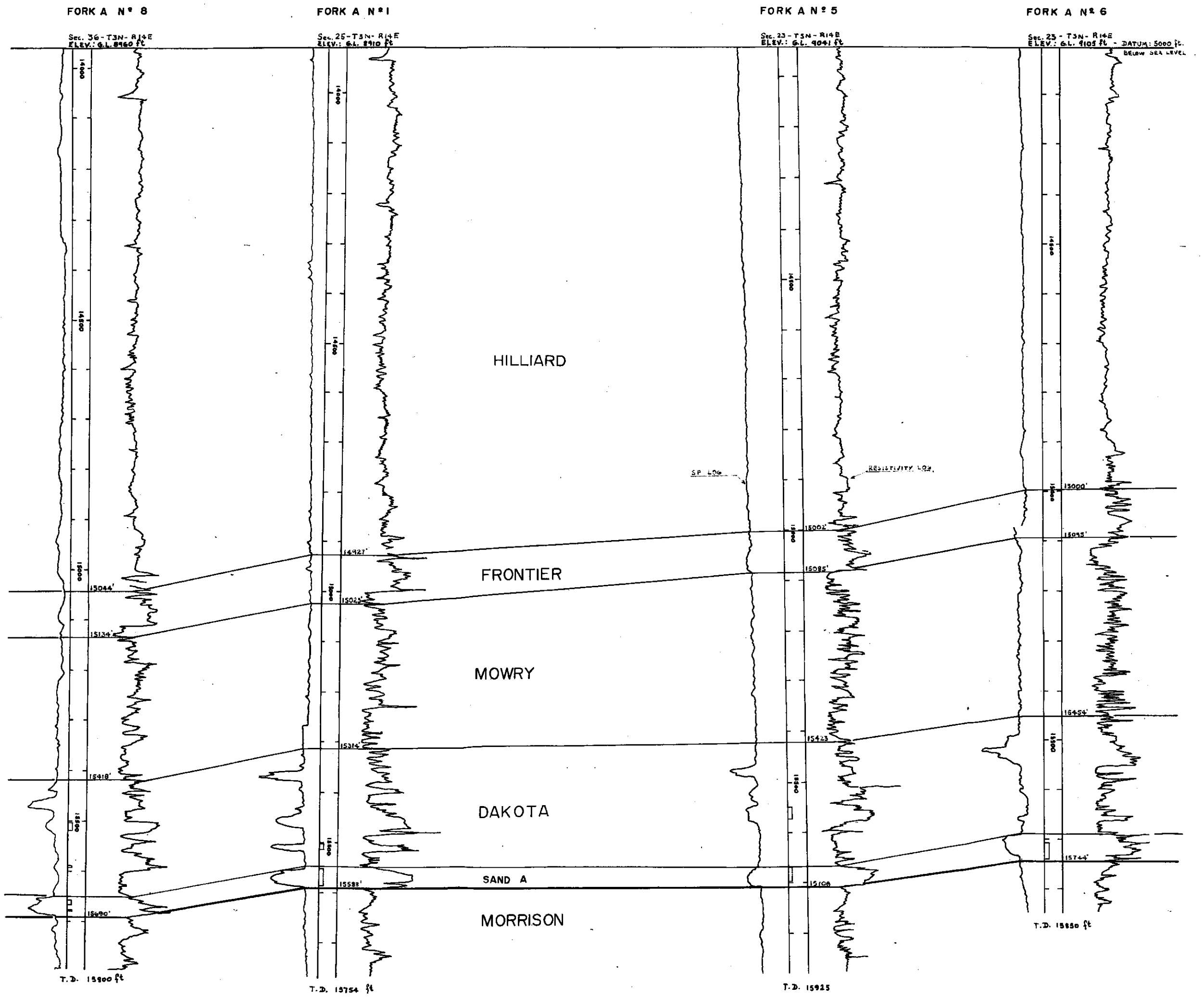
CROSS SECTION A-A'

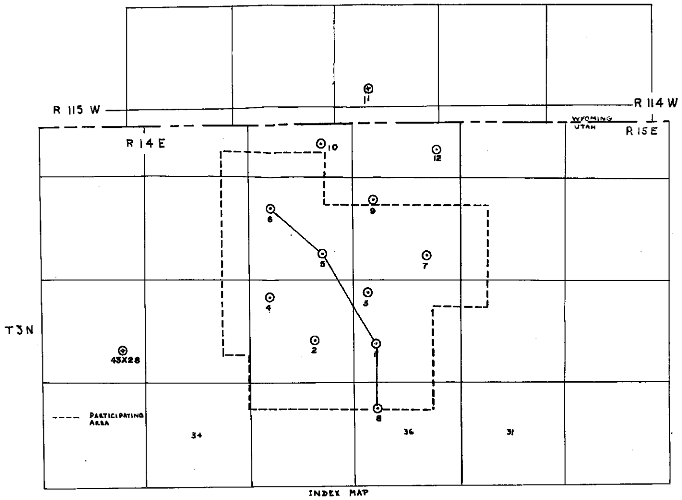
HORIZONTAL SCALE 0 586.5 ft 1173.0 ft

VERTICAL SCALE 0 100 ft 200 ft

ROBERTO AGUILERA
4-10-71

PLATE I





INDEX MAP

PHILLIPS PETROLEUM COMPANY

BRIDGER LAKE FIELD

SUMMIT CO., UTAH & UINTA CO., WYOMING

CROSS SECTION B-B'

HORIZONTAL SCALE 0 586.5 ft 1173.0 ft

VERTICAL SCALE 0 100 ft 200 ft

ROBERTO AGUILERA
4-10-71

PLATE 2