

**CALCULATION OF DECLINE CURVES
FOR
GAS DRIVE RESERVOIRS**

by

Felipe Eduardo Baldo

ProQuest Number: 10781360

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10781360

Published by ProQuest LLC (2018). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

44277

A Thesis Submitted to the
Faculty and the Board of Trustees
of the Colorado School of Mines
In Partial Fulfillment of the Requirements
For the Degree of
Master of Petroleum Engineering

Approved:



Clark F. Barb
Professor of Petroleum
Engineering
Colorado School of Mines
Golden, Colorado



Felipe Eduardo Baldo
Golden, Colorado
May 23, 1947

LIBRARY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

44277

ACKNOWLEDGMENT

The author is greatly indebted to Professor Clark F. Barb, Head of the Petroleum-Production Department, Colorado School of Mines, for the valuable advice on the subject and for allowing the use of his personal library.

TABLE OF CONTENTS

Introduction	1
Reservoir Energy	1
Energy from Natural Gas	2
Energy from Encroaching Edge Water	4
Effect of Gravity	5
Expulsive Force by Compaction of the Reservoir Rock	5
Expulsive Force by Expansion of Liquids Within the Reservoir	6
Retentive Force of Capillarity and Adhesion	8
Frictional Resistance	8
Relative Permeability	10
Oil Recovery by Dissolved Gas Drive Mechanism	11
Mathematical Relationships for Dissolved Gas Drive Reservoirs	
Reservoir Pressure Decline Equation	12
The Radial Flow Equation	13
Decline Curve Equation	16
Instantaneous Gas-Oil Ratio Equation	18
Use of Equations	19
Example of Calculation	21
Summary	33

Introduction

During the last ten years the broad problem of general reservoir performance has been analyzed by several authors from both the qualitative and quantitative points of view. The present work represents an approach to the same problem from the analytical point of view, using as a starting point the radial flow equation based on D'Arcy's law of viscous flow of homogeneous fluids.

The author's choice of writing the present paper on this subject was due to personal interest in it, and to the great importance of the study of reservoir performance for establishing the optimum methods of primary and secondary oil recovery.

A brief discussion of the reservoir energy and the different forms under which it may be available in a reservoir, is believed to have its place here for the better understanding of the main subject of this thesis.

Reservoir Energy

In a reservoir, the energy available for the production of oil is called reservoir energy. This energy is the source of the natural forces which result in the flow of underground fluids from the porous rocks into the penetrating wells.

The sources of this energy are:*

*Prof. C. F. Barb; Lectures on Petroleum Production at the Colorado School of Mines.

1. Gas pressure, which might be produced by the expanding forces of natural gas in solution, in a free gas cap, or both;
2. Water pressure, either static or dynamic;
3. The force of gravity, usually so small that it can be neglected;
4. The expulsive force due to the compaction of poorly consolidated reservoir rocks on release of pressure; and,
5. The expansion of the liquids within the reservoir.

By this classification it is not implied that only one of the above forces will be effective in a reservoir, since the driving force can be a combination of two or more of them.

Energy from Natural Gas

Before an oil reservoir is drilled in, the expulsive and retentive forces are in equilibrium. When a well penetrates the deposit, an area of low pressure is created at the well and, if maintained, will cause the oil and gas to flow toward and into the well. If it is not shut in and a pressure differential is maintained between the reservoir and the well, flow will continue, the fluids always moving toward the low pressure region about the well. The energy contained in the gas in its compressed state is the primary force responsible for this movement.

Production of the oil will bring, as a consequence, reduction of the reservoir pressure. When the saturation pressure, or "bubble point," is reached, gas will start to come out of solution in the form of minute bubbles, since they are still under pressure. Further reduction of pressure will cause these small bubbles to expand. As a result, the fluids in the reservoir expand to a new volume that is several times the original, and this expansion will displace a quantity of oil and gas equivalent to the volume of gas formed.

This type of oil production can be compared with the effect obtained when the cap of a warm gaseous beverage is removed. The invisible gas under pressure will start to come out of solution as soon as the pressure is reduced. The small bubbles of gas will increase their size and force part of the liquid up the neck of the bottle; in the same form the oil is forced up the well to the surface.

If the gas in the deposit is in the form of a large body of free gas under pressure at the crest of the structure (gas cap), it will operate in a quite different way in expelling the oil from the reservoir rock. This gas, at high pressure, will exert a force downward against the surface of the oil, pushing it down the flanks of the structure from where it can be

recovered by wells penetrating only the flanks.

In all the gas expansion reservoirs, the gas has the function of reducing the surface tension and viscosity of the oil, besides supplying the energy for the recovery of the fluids within the reservoir.

Energy from Encroaching Edge Water

Fields operated by hydrostatic pressures usually are of the type called "open fields;" that is, the type in which the producing formation outcrops in the surroundings of the structure. However, this is not the only condition, since continuity of the formation from the outcrop to the place where the oil is accumulated, as well as a high permeability throughout the formation, is required. With these three conditions available, the water which enters the formation at the outcrop will flow, without much resistance, from the outcrop to the oil reservoir, tending to concentrate and displace much of that oil held in the reservoir rock by capillarity, toward and into the penetrating wells.

It is generally recognized that the additional oil recovered in this way may be an important part of the total production from the field.

In a "water Drive" field, if the rate of oil production is made equal to the rate at which the water moves through the producing bed, the pressure of

the reservoir will remain practically constant. This is a well-known characteristic of fields in which the energy comes from hydrostatic pressure.

Effect of Gravity

The gravitational force is always effective in a reservoir, modifying to a certain extent the effect of other expulsive forces. However, in reservoirs operated by gas expansion or water drive the force of gravitation is so small compared with the main expulsive forces, that for practical purposes it is usually neglected.

It should be mentioned, however, that in closed structures in which there is not enough gas present to supply the energy required to move the oil into the wells, the effect of gravity drainage will be of primary importance. In such cases, the pay zone thickness, the dip of the formation, and the permeability of the reservoir rock will be, of course, directly proportional to the amount of oil recovered by gravity alone.

Drainage of the reservoir by this force will probably continue until the slope of the oil in the sand is just enough to overcome the resistance to flow offered by the reservoir rock.

Expulsive Force by Compaction of the Reservoir Rock

In a reservoir in which the producing

formation is composed of poorly consolidated sands, there is the possibility that the weight of the overlying sediments will produce, upon the release of pressure, a further compaction of the loose sands, therefore decreasing the volume of the pore spaces and forcing part of the oil out of the reservoir rocks. There are several instances in which surface subsidence has followed the release of gas pressure with oil production in fields.

Expulsive Force by Expansion of Liquids within the Reservoir

At the existing high pressures in oil reservoirs, the liquids within the pores of the producing formation have suffered a small decrease in volume due to the slight compressibility of liquids. Upon reduction of pressure these liquids will tend to expand, this new volume tending to move toward the wells. Experiments have shown that as much as 1% of the original oil and water in a reservoir rock can be recovered for each 3,000 pounds per square inch pressure drop. It is obvious that the larger the original volume of liquids in the reservoir, the greater the oil recovery by this force only. If edge water is present in the deposit, the expansion of this water will cause it to encroach at the beginning of production, therefore acting as a natural water drive.

Consideration must be given to the main retentive forces inherent in the reservoir rock that will tend to oppose the movement of the reservoir fluids to the areas of relatively low pressure in the vicinity of the recovery wells. Uren* defines these forces as: capillarity, adhesion, and pore friction. The expulsive energy available in the reservoir is largely consumed in overcoming the resisting forces, and the oil recovery will depend on the magnitude of the expulsive and retentive forces. The engineering side lies in the way in which the natural forces are conserved and utilized.

The capillary and adhesive forces are responsible for a large part of the original oil not recovered from the reservoir rock, while the other part of the unrecoverable oil is accounted for by the frictional resistance offered by the rock pores to the expulsive forces which tend to drive the oil to the recovery wells.

The detailed discussion of each of these forces is beyond the scope of this work, but a general consideration of them will be given at this point in order to set the basis for a clearer understanding of the relative permeability concepts which will follow.

*Uren, L. C., Petroleum Production Engineering - Oil Field Exploitation, McGraw-Hill Book Company, Inc. 1939. P 756.

Retentive Force of Capillarity and Adhesion

Capillarity is the result of the operation of surface tension of the oil in a reservoir, which tends to absorb and retain the liquids inside the capillary openings of the reservoir rock.

The retentive force of capillarity will be greater in a deposit which contains oil of a high surface tension.

As mentioned before, gas in solution in the oil, as well as an increase in temperature, will reduce surface tension, therefore decreasing the amount of original oil left unrecovered because of capillarity.

The adhesion of an oil film to the reservoir rock by intermolecular attraction leaves in the producing bed a large portion of the original oil. Due to the loose crystalline structure of most of the common rock-forming minerals and to the influence of pressure, the oil is driven into all crevices and cleavage planes to such extent that the subsurface pores will retain the liquid even when the surface is apparently free of it. This action will make the rock preferentially wetted by oil and subsequently will increase the retentive force of adhesion.

Frictional Resistance

The various frictional forces which oppose the movement of fluids through the pore channels

toward a well have been listed as;† (1) internal friction of the oil in overcoming its own viscosity and inertia; (2) friction of the oil and gas on the rocky surfaces forming the walls of the flow channels; (3) resistance offered by the gas bubbles to deformation or partition in passing through the constrictions of the flow channel; and (4) the capillary drag of the minute openings through which the oil must pass.

The frictional force listed under (3) is more commonly known as the "Jamin effect," named after Jamin, an early French physicist, who conducted a series of experiments in which chains of alternating gas bubbles and separating liquid filaments were forced under pressure through capillary tubes with several constrictions. Due to the similarity between these experimental capillary tubes and the actual flow channels in a reservoir rock, it has been suggested that the conclusions reached by Jamin have significance in the production of oil by gas expansion.

A variation†† in the apparent permeability of the reservoir rock to gas and oil has been attributed to the Jamin effect and will be discussed in the following pages.

†Uren, L. C., loc. cit.

††R. D. Wyckoff and H. G. Botset; The Flow of Gas-Liquid Mixtures Through Unconsolidated Sands, Physics 7, 1936; p. 325-345.

Relative Permeability

D'Arcy's law for the viscous flow of homogeneous fluids through sand states that the rate of flow is proportional to the pressure drop and to the permeability of the medium, and inversely proportional to the viscosity of the fluid. He expressed this rate of flow by the equation:

$$Q = \frac{KA}{u} \cdot \frac{dp}{dr}$$

Q is the rate of flow; K is the permeability of the medium; A is the cross-sectional area; u is the viscosity of the fluid; and dp is the pressure drop across the length dr. In this way, $\frac{dp}{dr}$ represents the pressure gradient.

In the case of non-homogeneous fluids, such as gas-liquid mixtures, a variation of D'Arcy's law was found to occur, this variation being in the apparent permeability of the medium to the gas and liquid components, and dependent in a complex manner upon the relative concentration of the two fluid components present. As mentioned before, this is attributed to the Jamin effect. The apparent permeability of the medium to any of the components is more generally referred to as relative permeability.

Experimental work conducted by several investigators in unconsolidated sands on the variation

of the relative permeability of the medium to liquid (K_1) and to gas (K_g) with the percentage liquid saturation, indicates that it is reasonable to represent that variation as the average curve shown in Figure 1. These curves are for no connate water in the sand since it has been found* that the relative permeability to oil and gas is changed when interstitial water is present. On the other hand, it was found out that moderate variations in the viscosity and surface tension of the oil appear to have negligible effect on the permeability-saturation relation for a sand.

As it will be shown later, the ratio of the relative permeability of gas to the relative permeability of oil (K_g/K_1) is a direct indication of the gas-oil ratio, showing its direct relationship with the liquid saturation of the sand.

Oil Recovery by Dissolved Gas Drive Mechanism

The conditions required for a dissolved gas drive to act as the expulsive force in a reservoir have been listed as follows:**

1. The existence of a flat structure with a low vertical permeability which would prevent the gravitational segregation of gas released from solution in the oil;

*M.C. Leverett and W.B. Lewis, Steady Flow of Gas-Oil-Water Mixtures Through Unconsolidated Sands; A.I.M.E. Pet. Dev. and Tech. 1941, Vol. 142, p. 107-116.

**Joint Progress Report on Reservoir Efficiency and Well Spacing, by the Comms. on Reservoir Development and Operation of Standard Oil Co. (N.J.) Affiliated Cos. and of the Humble Oil and Refining Co., 1943.

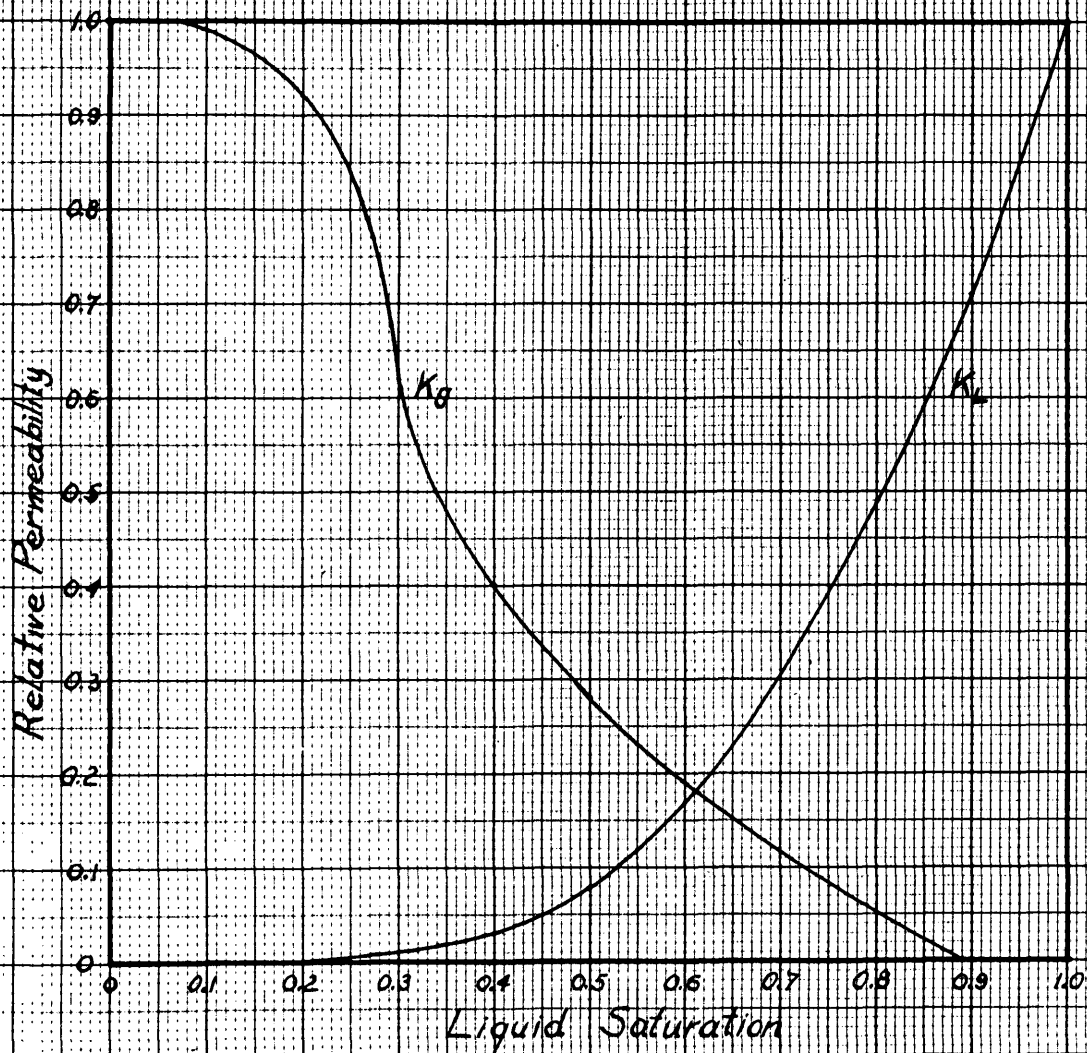


Figure 1
Relative Permeability
to Gas (K_g) and to Oil (K_o)
vs. Liquid Saturation

2. The absence of a free gas cap or of a water body which could move into the reservoir; and,
3. A high rate of oil production that would exceed the ability of any water present to advance into the reservoir; or the efficient expansion of a free gas cap, if present.

The most important attribute of this recovery mechanism is the horizontal flow of oil and gas within the reservoir rock which, in the absence of a flat structure, may be brought about by low vertical permeability or by high flowing pressure differentials occasioned by high producing rates and a tight sand.

Mathematical Relationships for Dissolved Gas Drive Reservoirs

Reservoir Pressure Decline Equation

Following the conditions for the existence of dissolved gas drive in an oil reservoir, let us assume a structure in which the producing formation is a tight sand with very low specific permeability. The oil in this reservoir contains gas in solution at a high pressure and it is going to be produced with the maximum flowing pressure differential; that is, with a well pressure equal to atmospheric pressure.

Under the above conditions, if we assume a uniform decline of the reservoir pressure P_e , with time t , we will have the following relationship:*

*M. Muskat, "Flow of Homogeneous Fluids" Equation (13) p. 711, McGraw-Hill, 1937.

$$P_e = \frac{1}{\frac{K K_1 t}{f u_o r_e^2 \ln \frac{r_e}{r_w}} + \frac{1}{P_1}}$$

P_e is the reservoir gauge pressure, in atmospheres.

K is the specific permeability, in darcys.

K_1 is the relative permeability, as a fraction of the specific permeability.

t is the time in seconds after production has started.

f is the porosity of the reservoir rock, as a fraction of the total volume of reservoir rock.

u_o is the oil viscosity in centipoises.

r_e is the radius of drainage affected by the well, and usually taken as one half of the well spacing in centimeters.

r_w is the radius of the well in the pay zone of the reservoir, in centimeters.

P_1 is the initial reservoir gauge pressure, in atmospheres.

For convenience, equation (1) will be written as:

$$P_e = \frac{1}{\frac{0.93 K K_1 t}{f u_o r_e^2 \ln \frac{r_e}{r_w}} + \frac{1}{P_1}} \quad (2)$$

u_o is in poises; t is in days; r_e and r_w are in feet.

The 0.93 introduced in equation (2) accounts for the conversion of units of u_o , t , and r_e .

The Radial Flow Equation Based on D'Arcy's Law

In a preceding section of this work D'Arcy's relation for the rate of flow of an homogeneous fluid

through a porous medium has been expressed by the equation:

$$Q = \frac{KA}{u} \cdot \frac{dp}{dr} \quad (3)$$

The radial flow concept implies that the flow of fluids from the reservoir rock to the well occurs along channels radiating in all directions from the well. In any section of thickness h , since the fluids are flowing from a distance r (the drainage radius) toward the well, the cross-sectional area through which this flow is occurring can be written as follows:

$$A = 2\pi r h$$

Substituting this value of A in equation (3), we obtain:

$$Q = \frac{2\pi K r h}{u} \cdot \frac{dp}{dr}$$

Rearranging this equation for integration between the limits of p_e and p_w , and r_e and r_w , we have:

$$Q \int_{r_w}^{r_e} \frac{dr}{r} = \frac{2\pi K h}{u} \int_{p_w}^{p_e} dp$$

and integrating, we obtain:

$$Q \ln \frac{r_e}{r_w} = \frac{2\pi K h (p_e - p_w)}{u}$$

or:

$$Q = \frac{2\pi Kh(p_e - p_w)}{u \ln r_e/r_w}$$

Q is the fluid rate of flow in cubic centimeters per second.

K is the specific permeability in darcys.

h is the pay zone thickness, in centimeters.

p_e is the reservoir gauge pressure, in atmospheres.

p_w is the well gauge pressure, in atmospheres.

u is the viscosity of the fluid in centipoises.

r_e is the reservoir drainage radius, in feet.

r_w is the well radius in the pay zone, in feet.

These are the units used in the original D'Arcy's Law equation for homogeneous fluids. By changing the units and introducing the term K_1 to account for the non-homogeneous character of the oil flow, we obtain:

$$Q = \frac{1.05 KK_1 h (p_e - p_w)}{u_o \ln \frac{r_e}{r_w}} \quad (4)$$

The symbols have the following meanings and units:

Q is the oil volume rate of flow in barrels per day.

K is the specific permeability in darcys.

K_1 is the relative permeability of the oil, a fraction of the specific permeability.

h is the pay zone thickness, in feet.

p_e and p_w , the reservoir and well gauge pressures, respectively, in atmospheres.

u_o is the viscosity of the oil, in poises.

\ln is for natural logarithm; logarithm to the base e .

r_e and r_w , are the drainage and well radii, respectively, in feet.

Equation (4) is the radial flow equation for oil based on D'Arcy's law.

Decline Curve Equation

If in equation (4) we make $p_w = 0$, or, assuming the well pressure as atmospheric, it can be solved for the reservoir pressure, therefore obtaining:

$$p_e = \frac{Q u_o \ln \frac{r_e}{r_w}}{1.05 KK_1 h} \quad (5)$$

Since the conditions under which this relation was obtained are the same used for deriving equation (2), these two expressions for p_e can be made equal to each other, giving the following relation:

$$\frac{Q u_o \ln \frac{r_e}{r_w}}{1.05 KK_1 h} = \frac{1}{f u_o r_e^2 \ln \frac{r_e}{r_w} + \frac{1}{P_i}} \quad (6)$$

The symbols and units of this relation are defined under equations (2) and (4).

With the aid of equation (6) the daily oil production decline, with time, can be obtained by

plotting the values of Q against the corresponding values of t .

However, for solving this last equation, additional information is required on the value of K_1 , the relative permeability to the oil. For this purpose a relation will be obtained for the initial oil saturation of the area to be drained by the well. This can be done by the sand-volume porosity method. The result is the equation:

$$S_1 = \frac{\pi r_e^2 f h (1-I)}{5.61} \quad (7)$$

S_1 is the quantity of reservoir oil present, in barrels.

r_e , f and h have the same meanings and units as those in equation (6).

I is the interstitial water saturation, expressed as a fraction of the porosity.

For the purpose of finding the relative permeability to oil and to gas, equation (7) will represent the quantity of oil equivalent to 100% oil saturation. In this way the residual oil saturation at any moment can be calculated by:

$$S = 1 - \frac{Q_e}{S_1} \quad (8)$$

S is the residual oil saturation as a fraction.

Q_e is the cumulative reservoir oil recovered, in barrels.

S_1 is the initial reservoir oil saturation as obtained from equation (7).

The Instantaneous Gas-Oil Ratio Equation

In the early part of this work it has been mentioned that the ratio of the relative permeability of the gas to the relative permeability of the oil (K_g/K_l) is a direct indication of the flowing gas-oil ratio.*

Fundamentally, the instantaneous gas-oil ratio will be given by the following relation:

$$R = \frac{Q_g}{Q} + M$$

R is the instantaneous gas-oil ratio in cubic feet of gas per barrel of reservoir oil.

Q_g is the gas volume rate of flow in cubic feet per day.

Q is the oil volume rate of flow in barrels per day.

M is the gas dissolved in the oil, in cubic feet per barrel.

The gas volume rate of flow can be expressed by the radial flow equation as:

$$Q_g = \frac{(5.61)(1.05) K K_g h (p_e - p_w)(p_e + p_w) T_a}{u_g \ln \frac{r_e}{r_w} 2p_a T} \quad (9)$$

K_g is the relative permeability to gas, a fraction of the specific permeability.

u_g is the viscosity of the gas in poises.

T_a is the atmospheric temperature, degrees Rankine (Fahrenheit absolute).

T is the reservoir temperature, degrees Rankine.

p_a is the atmospheric absolute pressure, in atmospheres.

*R. D. Wyckoff and H. G. Botset, loc. cit.

Since Q is given by equation (4), the final expression for the instantaneous gas-oil ratio is:

$$R = \frac{5.61 K_g u_o (p_e + p_w) T a}{K_o u_g 2p_a T} + M \quad (10)$$

The value of M can be secured from laboratory tests with field bottom-hole samples.

Use of Equations

With the aid of equations (5), (6), (7), and (10) and Figure 1, the production histories for dissolved gas drive oil wells can be calculated.

The following procedure should be used when working with those equations:

1. The first step is to introduce into equation (6) the numerical values of u_o , r_e , r_w , K , h , and P_1 , and then solve for Q in terms of t and K_1 .
2. Since the relation obtained in the above step represents the decline curve of the well, if it is integrated between zero and t , it will give the cumulative production Q_o up to the time t . The fact that K_1 is a direct function of Q_o and not a function of t , makes possible the integration in which K_1 is treated as a constant.
3. With the known data solve equation (7) obtaining the reservoir oil present within the drainage

area of the well, and representing unit liquid saturation.

4. Assume of value of Q_c and with the aid of equation (8), the present liquid saturation of the sand can be obtained as a fraction of the initial oil saturation. Using this value in Figure 1, the relative permeability to the liquid (K_1) is obtained. With the values of Q_c and K_1 , the equation obtained in step 2 can be solved for t .
5. With these values of t and K_1 , the equation obtained in step 1 can be solved for Q .
6. Substituting the known values into equation (5), the reservoir pressure p_e can be obtained.
7. The last step is to find the instantaneous gas-oil ratio, and this can be done by using equation (10), and the data on the solubility of gas in oil obtained from laboratory tests.

As it can be readily observed, no consideration has been given to the amount of gas present in the reservoir, and therefore the results obtained from the use of these equations will be under the assumption that 100% of the gas produced with the oil is returned to the pay zone of the reservoir as fast as it is produced.

With the purpose of illustrating this method of calculation and to give an idea of the magnitude of

the numerical results, an example using imaginary data will be worked out in the following pages.

Example of Calculation

The following imaginary data on a field is assumed to be available:

Specific permeability of the sand, K : 0.01 darcys.

Pay zone thickness, h : 60 feet.

Porosity, fraction of total sand volume, f : 0.15.

Initial reservoir pressure, P_1 : 183 atmospheres gauge.

Well pressure, p_w : 0 atmospheres gauge.

Oil viscosity, μ_o : 0.01 poises.

Gas viscosity, μ_g : 0.00016 poises.

Radius of drainage, r_e : 660 feet.

Atmospheric temperature, T_a : 520° Rankine.

Reservoir temperature, T : 600° Rankine.

Assuming no interstitial water present ($I=0$), Figure 1 can be used for obtaining the relative permeabilities. Also, in Figure 2, the solubility of the reservoir gas in the oil is shown.

The calculation by steps follows:

Step 1: By introducing the values of μ_o , r_e , r_w , K , h , and P_1 in equation (6) and solving for Q , the following expression is obtained:

$$Q = \frac{877,000}{0.198t + \frac{545}{K_1}} \quad (11)$$

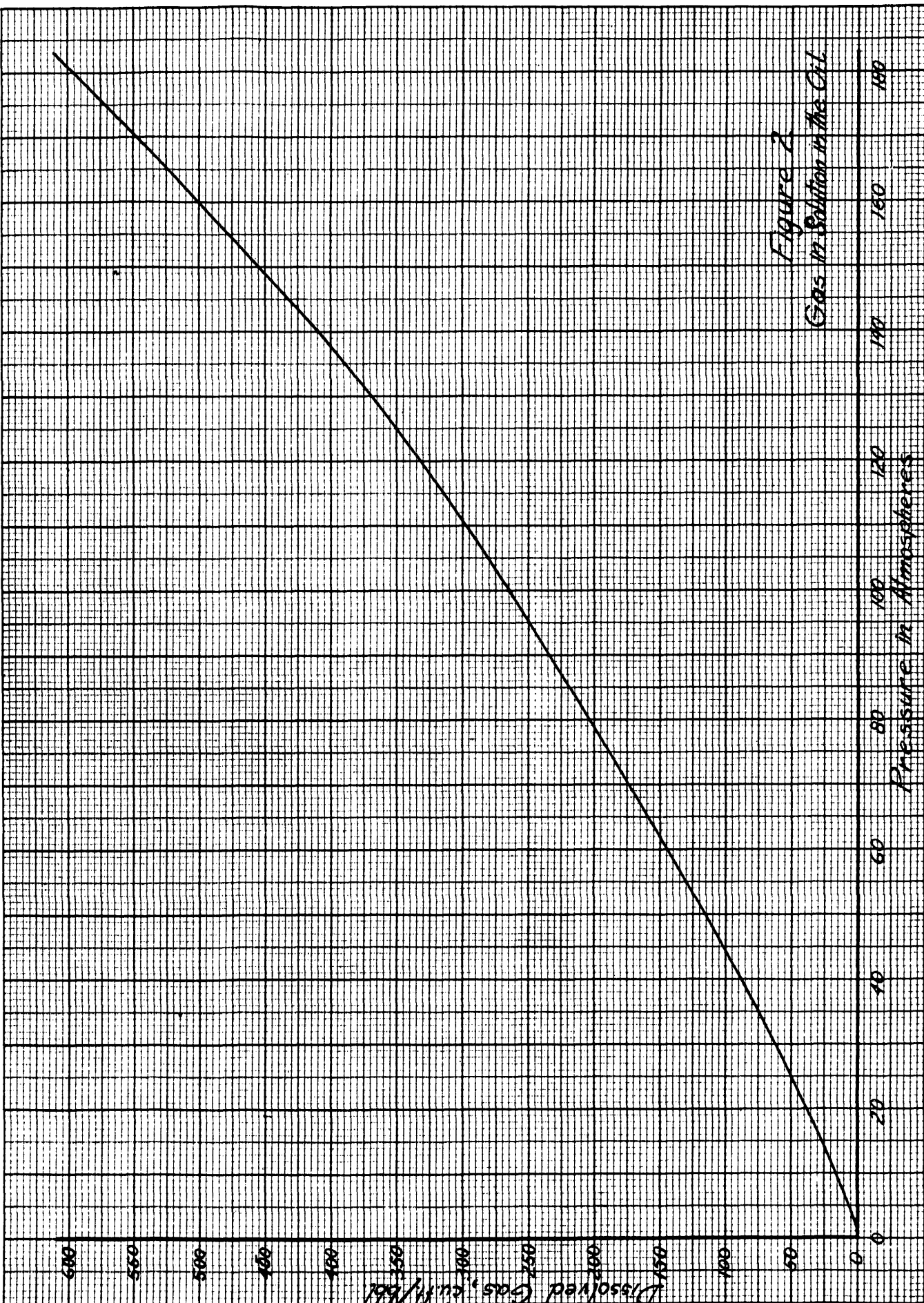


Figure 2
Gas in Solution in the Oil

Step 2: Integration of equation (11) between 0 and t will give the cumulative production Q_c .

Therefore:

$$Q_c = \int_0^t Q dt$$

$$Q_c = \int_0^t \frac{877,000}{0.198t + \frac{545}{K_1}}$$

Integrating and simplifying:

$$Q_c = 4,430,000 \ln \left[\frac{(0.198K_1 t)}{545} + 1 \right] \quad (12)$$

Step 3: Solving equation (7) the liquid saturation within the area to be drained by the well is found to be:

$$S_1 = 2,196,000 \text{ barrels}$$

Step 4: Assuming Q_c to be 219,600 barrels, the liquid saturation is found by equation (8):

$$S = 1 - \frac{219,600}{2,196,000} = 0.90$$

Referring back to Figure 1, for a saturation value of 0.90, K_1 is found to be 0.71. Now equation (12) can be solved for t, obtaining $t = 197$ days.

Step 5: With this value of t, equation (11) developed in Step 1 can be solved for Q, giving:

$$Q = 1087 \text{ barrels per day}$$

which is the daily oil production 197 days after the production of the well has started.

Step 6: The reservoir pressure is now obtained from equation (5), giving:

$$p_e = 174.4 \text{ atmospheres}$$

Step 7: With the aid of Figures 1 and 2 and equation (10) the gas oil ratio can be computed knowing the reservoir pressure. From Figure 1, the relative permeability to gas at 0.9 liquid saturation is zero, and therefore the flowing gas-oil ratio is equal to the gas in solution at 174.4 atmospheres, or:

$$R = 572 \text{ cubic feet per barrel}$$

Steps 4 to 7 are repeated assuming different cumulative oil recoveries. The results are given in Table I, and plotted in Figures 3 to 9.

TABLE I

t, Time In Days	Q _c , Cumulative Production		Q, Oil Produc- tion Barrels Per Day	P _e , Reservoir Pressure Atmospheres	R, Gas-Oil Ratio, Cubic Ft. per Barrel
	Barrels	Percentage of Original Oil			
1	1,608	0.73	1,608	183	610
197	219,600	10.0	1,087	174.4	572
585	439,200	20.0	714	166.2	3,145
1,400	658,800	30.0	437	158.1	9,375
3,450	878,400	40.0	231	150.4	25,607
9,680	1,098,000	50.0	100	143.1	77,875

Daily Oil Production Decline Curve

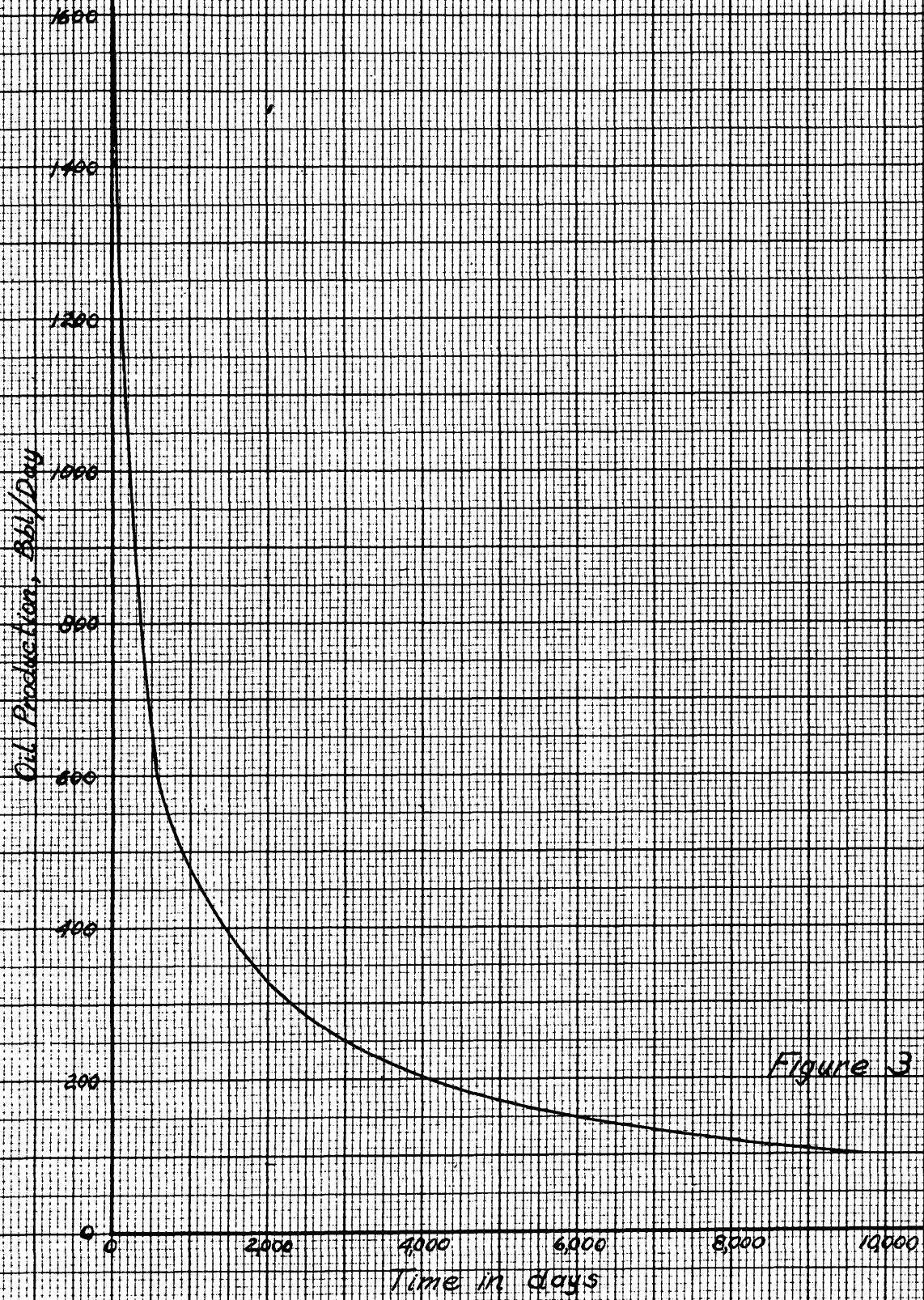


Figure 3

Reservoir Pressure Decline Curve

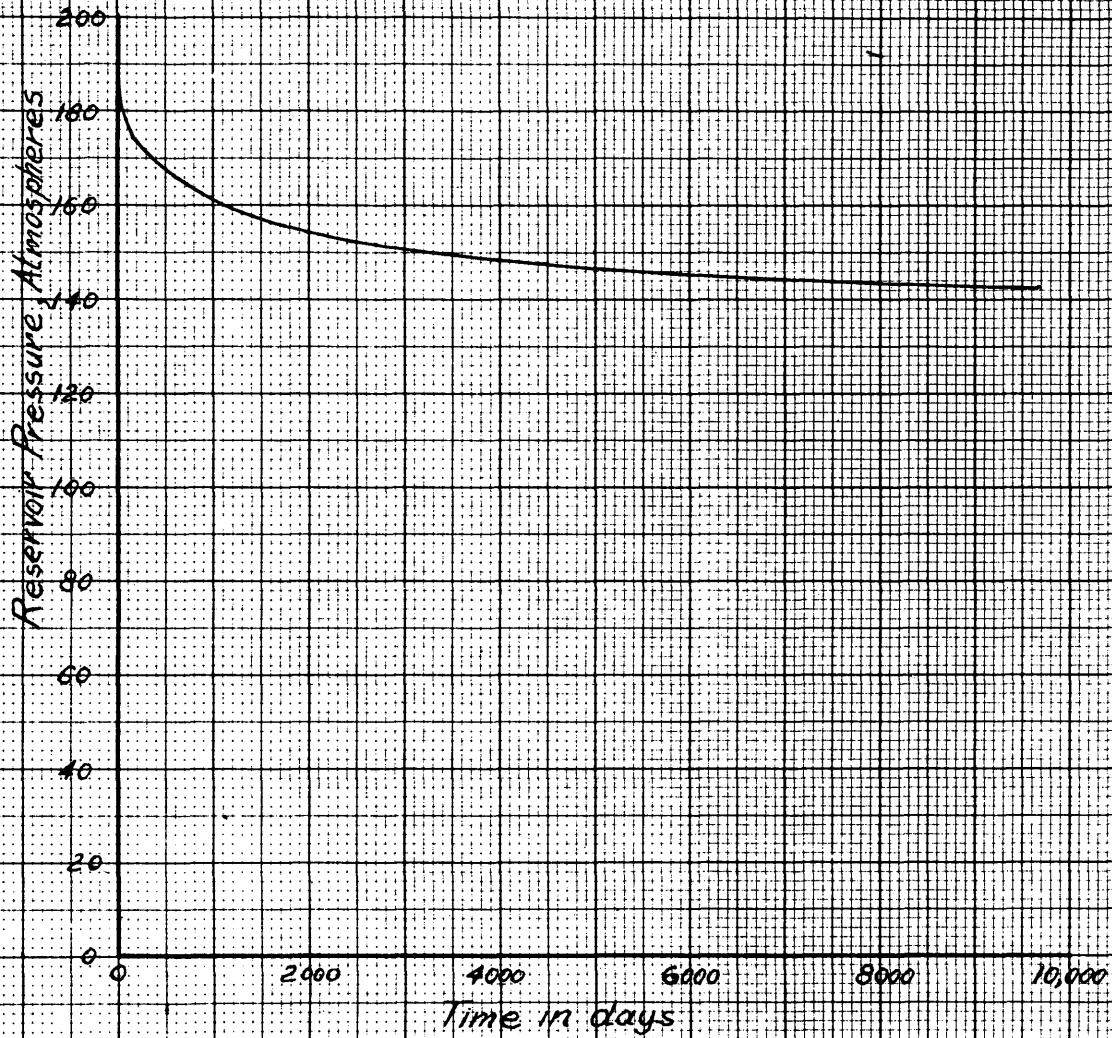


Figure 4

Cummulative Production vs. Time in days

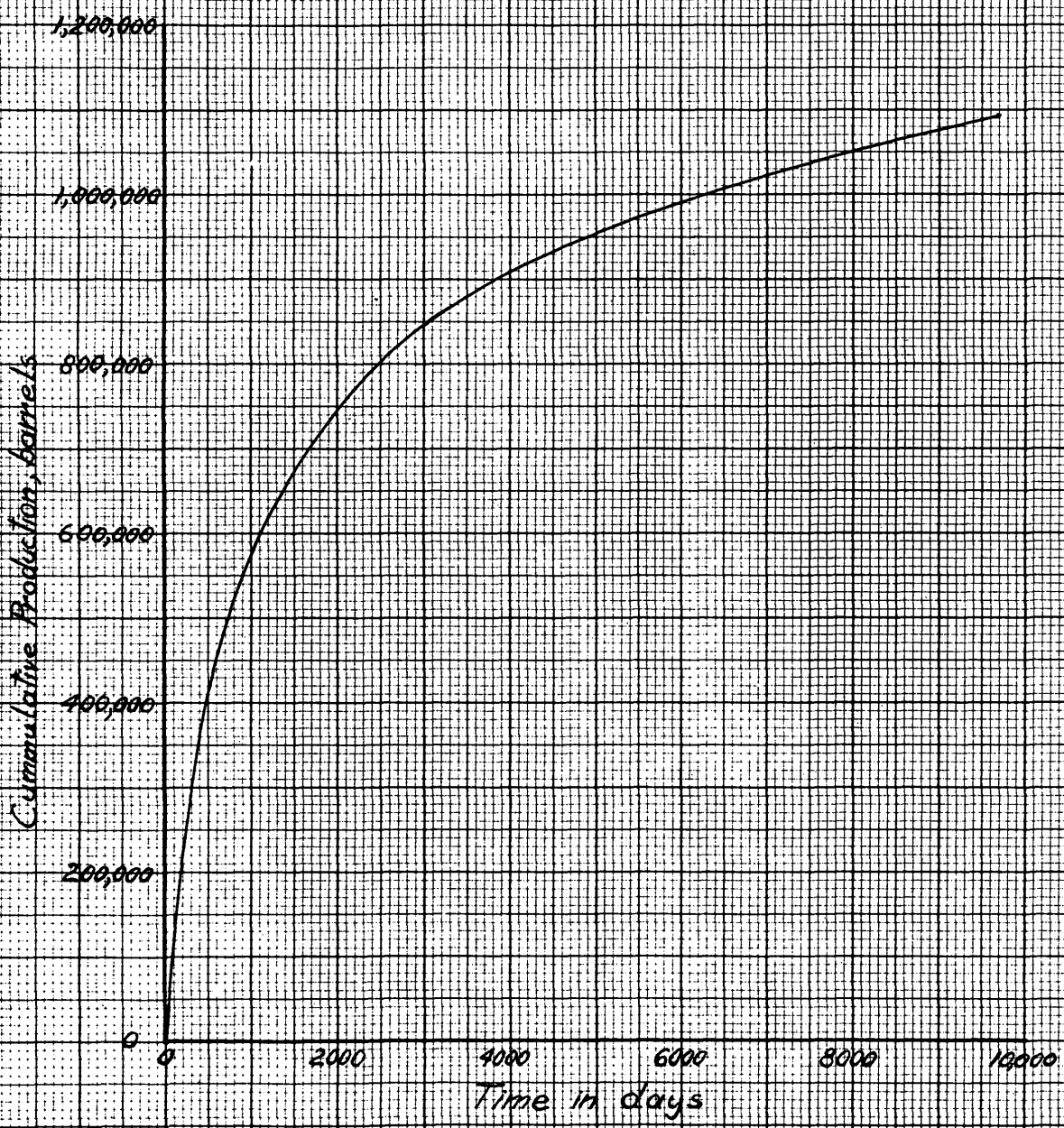


Figure 5

Gas-Oil Ratio vs. Time in days

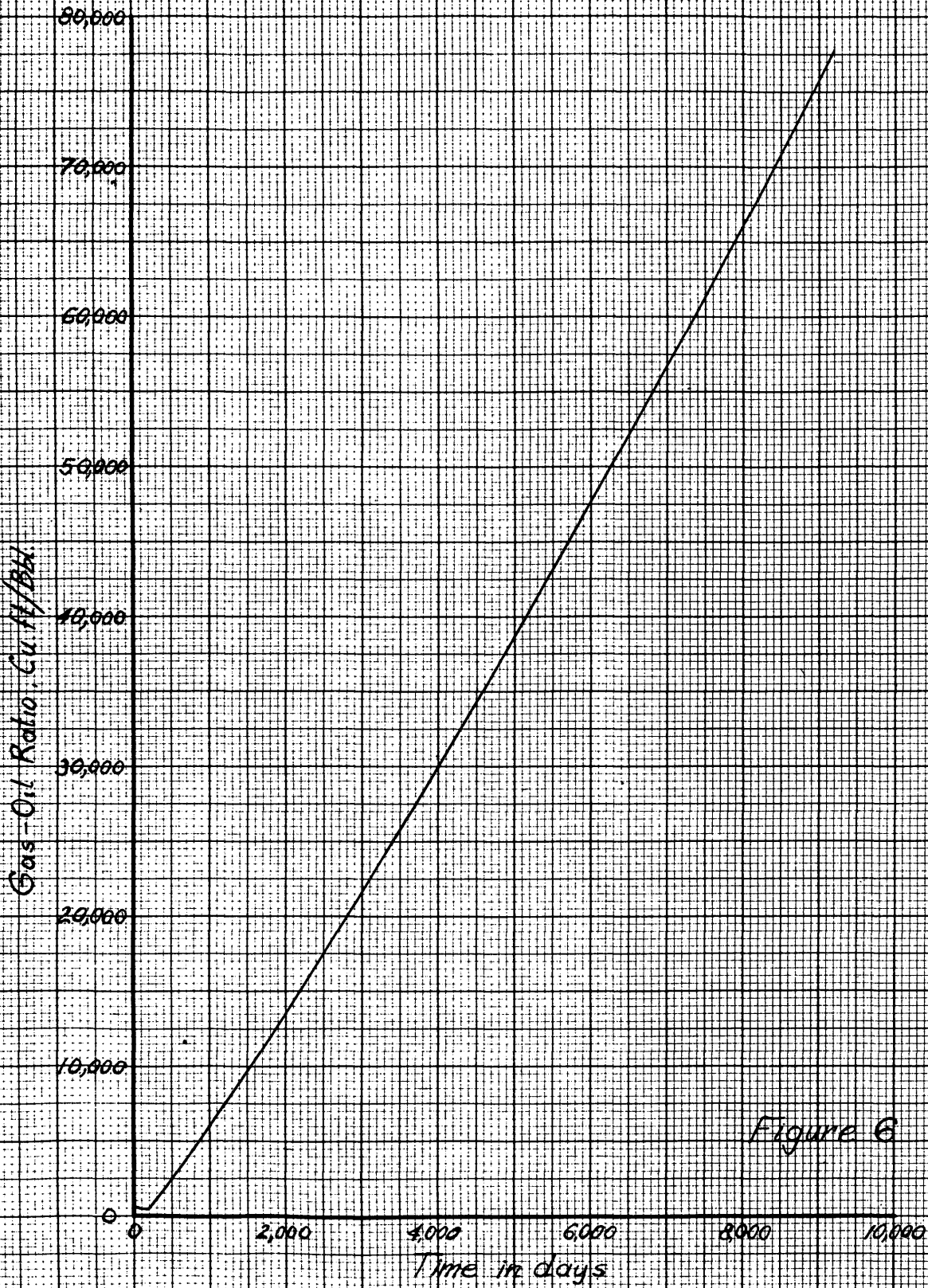
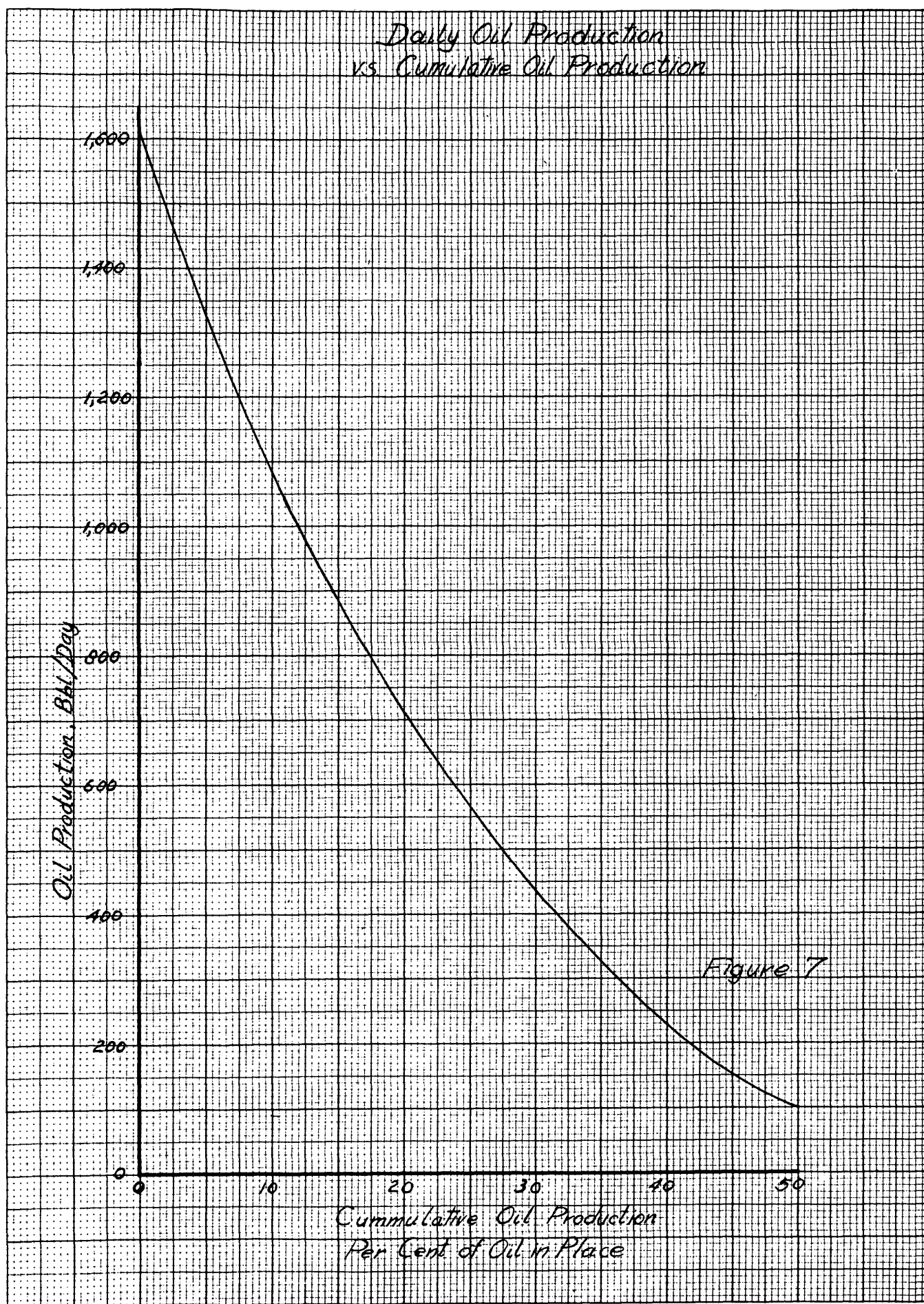


Figure 6

*Daily Oil Production
vs. Cumulative Oil Production*



Reservoir Pressure vs. Cumulative Oil Production

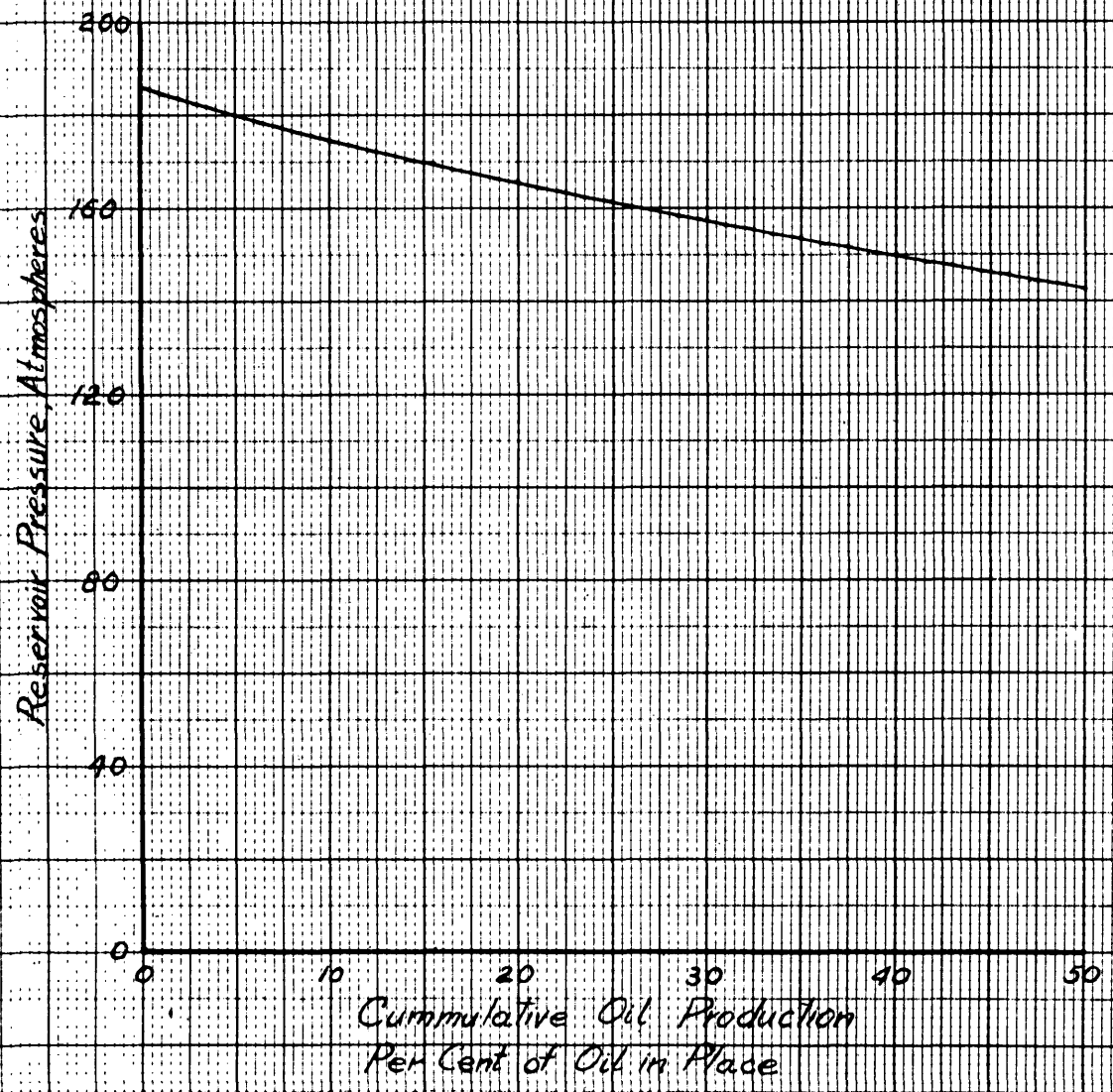


Figure B

Gas-Oil Ratio
vs. Cumulative Oil Production

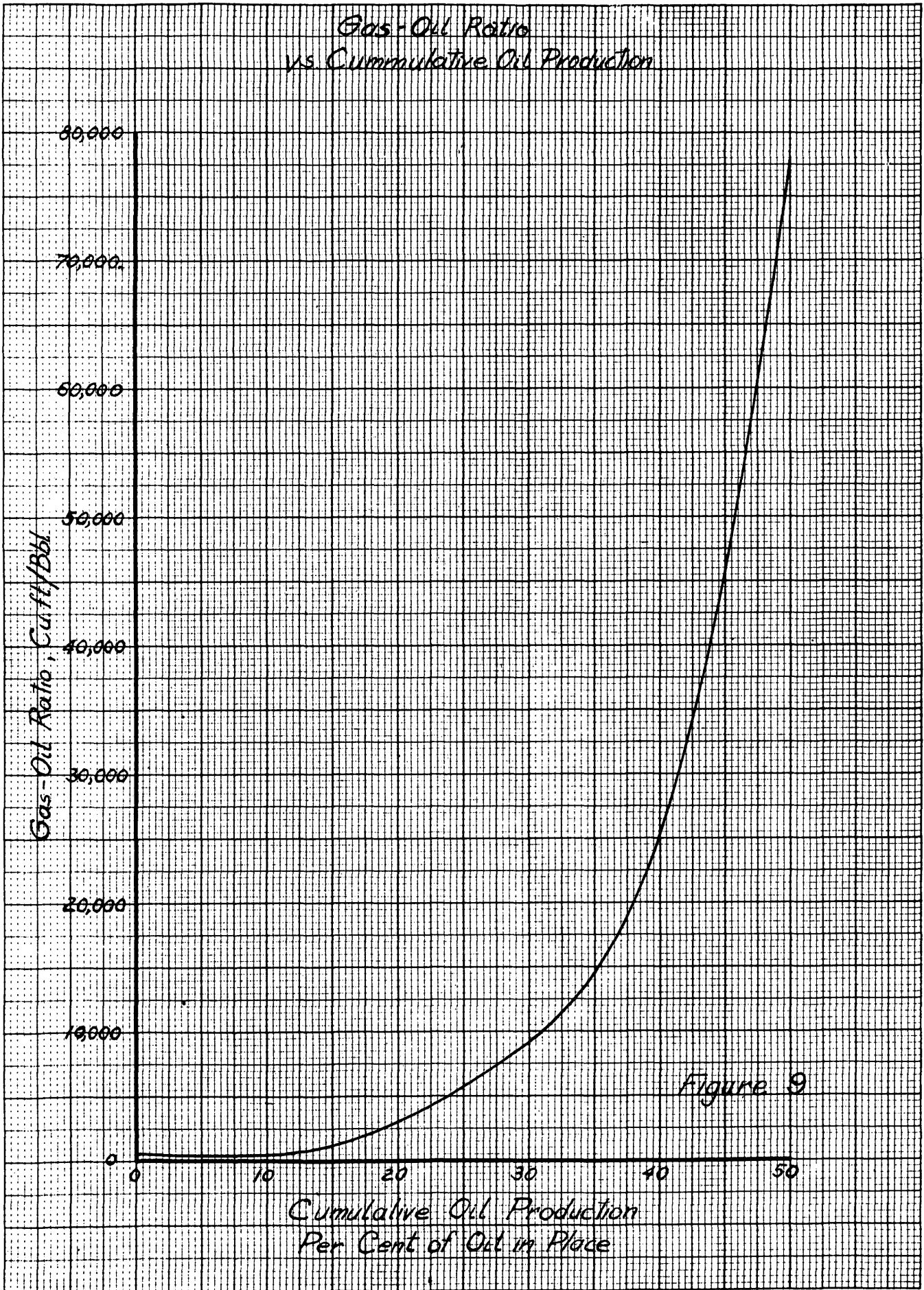


Figure 9

Summary

As outlined, this work is concerned with the problem of finding the decline curve of a well in an oil reservoir producing by the expansive force of gas in solution.

This procedure presents the advantage of requiring considerably less time and a smaller amount of laboratory data than most of the methods developed up to the present. On the other hand, the conditions for which these equations can be used are very restricted and will limit their use to a few cases only in actual practice. Many attempts were made to relate these equations to a material balance expression in order to account for the amount of gas present at any time, but the introduction of several variables which could not be accounted for made these trials unsuccessful.

The information obtained on the cumulative oil recovery, the reservoir pressure, and gas-oil ratio gives the production history of the well. All the curves follow the characteristic trend that is observed in actual practice.

By reinjecting all of the gas produced, a high percentage of the original oil would be recovered but this is not feasible as the gas-oil ratio will reach infinite values. Also, the cost of compressing and injecting the gas will be far greater than the value of the oil recovered.

Bibliography

1. M. Muskat, Flow of Homogeneous Fluids, McGraw-Hill Book Company, Inc., 1937.
2. H. G. Botset, Flow of Gas-Liquid Mixtures Through Consolidated Sand; Pet. Dev. and Tech. (1940) p. 91-103.
3. R. D. Wyckoff and H.G. Botset, Flow of Gas-Liquid Mixtures Through Unconsolidated Sand, Physics (1936) 7, pp. 325-345.
4. L. C. Uren, Petroleum Production Engineering - Oil Field Exploitation, McGraw-Hill Book Company, Inc. 1939.
5. W. F. Cloud, Petroleum Production; University of Oklahoma Press, 1939.
6. P. J. Jones, Petroleum Production, Volumes I and II, Reinhold Publishing Corporation, 1946.
7. L. S. Reid and R. L. Huntington, Flow of Oil-Gas Mixture Through Unconsolidated Sands. Pet. Dev. and Tech. (1938) p. 226-239.
8. H. H. Evinger and M. Muskat, Calculation of Theoretical Productivity Factor; Pet. Dev. and Tech. (1942) p. 126-139.
9. S. E. Buckley and M. C. Leverett, Mechanism of Fluid Displacement in Sands; Pet. Dev. and Tech. (1942) p. 107-116.
10. E. G. Babson, Prediction of Reservoir Behavior from Laboratory Data; Pet. Dev. and Tech. (1944) p. 120-132.
11. M. Muskat and M. W. Meres, Flow of Heterogeneous Fluids Through Porous Media, Physics (1936) 7, p. 346-365.
12. M. Muskat, Production Histories of Oil Producing Gas-Drive Reservoirs; Physics (1945) 16, p. 147-159.
13. J. Turner, How Different Size Gas Caps and Pressure Maintenance Programs Affect Amount of Recoverable Oil; The Oil Weekly (June 12, 1944) p. 32-44.

14. D. L. Katz, A Method of Estimating Oil and Gas Reserves, Pet. Dev. and Tech. (1936) p. 18-31
15. R. E. Old, Jr., Analysis of Reservoir Performance, Pet. Dev. and Tech. (1943) p. 86-98.
16. M. C. Leverett and W. B. Lewis, Steady Flow of Gas-Oil-Water Mixtures Through Unconsolidated Sands, Pet. Dev. and Tech. (1941) p. 107-116.
17. Joint Progress Report on Reservoir Efficiency and Well Spacing, by the Committees on Reservoir Development and Operation of the Standard Oil Company (New Jersey) Affiliated Companies and of the Humble Oil and Refining Company (1943).

