

LIBRARY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

ENERGY RELATIONSHIPS
IN
UNDERGROUND FLOW
OF
FLUIDS

Approved:

Byron B. Boatright
Byron B. Boatright
Professor of Petroleum
Engineering, Colorado
School of Mines
Golden, Colorado

George D. Hilding

George D. Hilding
Golden, Colorado

ProQuest Number: 10781316

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 10781316

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

28151

A THESIS
SUBMITTED
TO
THE BOARD OF TRUSTEES, PRESIDENT
AND FACULTY
OF
THE COLORADO SCHOOL OF MINES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF
MASTER OF SCIENCE

8/23/35
Dep. - \$1.50 DB Co.

By:
George D. Hilding
Golden, Colorado

28151

TABLE OF CONTENTS

<u>SUBJECT</u>	<u>PAGE</u>
Introduction	1
Physical Nature of Reservoirs Retainer and container rocks - Porosity - Saturation	1
Types of Reservoirs From Energy Viewpoint Hydraulic Control - Volumetric Control - Capillary Control	10
Sources of Energy Gravity - Fluid Head - Gas Pressure - Pressure Head	14
Energy Losses and Resistance to Flow Permeability constant - Resist- ances to flow in formation - Wall friction - Internal fluid friction - Surface tension	24
Remaining Energy Flowing wells - Heading wells - Pumping wells	36

ENERGY RELATIONSHIPS IN UNDERGROUND

FLOW OF FLUIDS

LIBRARY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

INTRODUCTION

The major purpose of this thesis shall be to apply the principles of Mechanics and Thermodynamics to an analytical study of the flow of fluids in underground reservoirs with particular reference to the drainage of oil bearing rocks. As an approach to this main function it appears natural to consider the physical nature and essentials of the container or reservoir in which this fluid flow is to occur. The source of the fluid or the manner of its migration to the reservoir is not of particular moment in this thesis.

PHYSICAL NATURE OF RESERVOIRS

The primary requisites of an underground reservoir are that it shall entrap the fluid and that the entrapped fluid may move in the reservoir to points of lower potential when equilibrium in the reservoir is disturbed. The existence of such a

reservoir is determined partly by the physical properties of the rocks themselves and partly by the attitude or inclination of the rocks. An ideal oil reservoir is a structural dome, containing a circular area of gas at the top surrounded by a belt of oil, which is in turn surrounded by an area of water. Although this structural arrangement is not the most common, nevertheless the effect, or a partial effect, of such an arrangement of fluids may be expected to obtain to some degree in any structure¹.

Rocks perform one of two functions, retaining or containing. Whether the rock is retaining or containing will depend on the size of the openings, which may be subcapillary, capillary, or supercapillary.

Subcapillary openings (less than .0002 mm. for tubular openings and less than .0001 mm. for sheet openings)² are those so small that the attraction between molecules extends across the space. Circu-

1. W. H. Osgood: Increasing the Recovery of Petroleum.
Stanley C. Herold: Analytical Principles of the Production of Oil, Gas, and Water from Wells.
2. B. B. Boatright: Lectures on Petroleum Production at the Colorado School of Mines.

lation in subcapillary openings is either very slow or non-existent. The occurrence of high temperature, with a corresponding lowering of the viscosity of the fluid, and high pressure, may appreciably increase the rate of flow of a given fluid through subcapillary openings. Since the function of retainer rocks is to prevent the escape of the fluid from the reservoir, rocks with subcapillary openings will, under the ordinary conditions of temperature and pressure encountered in underground reservoirs, act as retainer rocks. Gaseous fluid, however, will not be retained absolutely by such rocks unless the openings have been closed by liquid. Because of this retentive quality, shales containing only subcapillary openings will not be commercially productive of oil by the drainage method, even though saturated with oil.

The requirement of imperviousness imposed upon retainer rock or cap-rock is most often exhibited by clays, shales, non-porous limestone and highly cemented sandstone and one or more of these generally performs the function of retention.³ The function of

3. Ver Wiebe: Oil Fields in the United States.

retention may be augmented by cementing and faulting, though the effect of cementing is more often apparent in considering porosity and permeability of the more porous rocks.

Capillary openings (.0002 mm. to .618 mm. for tubular openings and .0001 mm. to .254 mm. for sheet openings)⁴, though permitting flow of fluid under normal conditions of temperature and pressure, are such that the laws of hydraulics are affected by capillary action. Friction near the walls prevents free circulation, but increase in pressure will force the fluid through these openings and correspondingly increase the circulation. Through such openings viscous flow only will occur. Rocks with capillary openings are essentially container rocks.

Supercapillary openings are large enough so that flow of fluid through such openings will occur in accordance with the ordinary laws of hydraulics.

The container rocks then are rocks of a

4. Prof. B. B. Beatright: Lectures on Petroleum Production at the Colorado School of Mines.

porous nature, which may hold fluid in the openings between the solid grains of material, the openings being of such nature and size that motion of the fluid through them will occur under the varying conditions of pressure and unoccupied space which shall occur in the reservoir composed of these rocks.

The capacity of a reservoir for containing oil and/or gas is a function of porosity of the container rock, percentage of saturation, other fluids present, and the cubical extent of the container rock.⁵ There are many kinds of rock, and they differ greatly in the number, size, shape and arrangement of their interstices and hence in their capacities as containers of fluid. Most rocks have numerous interstices of very small size but some are characterized by a few large openings such as joints or caverns.

The porosity of a rock is its property for containing interstices and is expressed quantitatively as the percentage of the total volume of the rock that is occupied by interstices or that is not occupied by

5. Oscar Edward Meinzer: Water Supply Paper #489.

solid rock material. Porosity depends chiefly on, (1) the shape and arrangement of the constituent particles of the deposit, (2) the degree of assortment of sizes of particles, (3) cementation and compacting to which the deposit has been subjected, (4) the removal of mineral matter through solution by percolating waters, and (5) the fracturing of the rock, resulting in joints and other openings.⁶ Well sorted deposits such as uncemented gravel or sand have high porosity whether the grains are large or small, whereas if the material is poorly sorted the small particles occupy the spaces between the large particles, greatly reducing the porosity. Furthermore, if very large particles occur they displace interstices and reduce porosity. In the case of well rounded particles the effect of arrangement may be best shown by the following diagrams.⁶

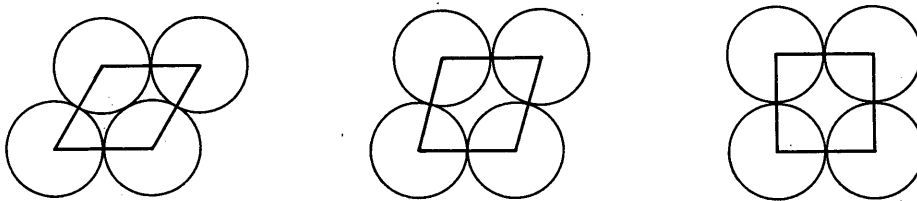


Figure I.

6. Oscar Edward Meinzer: Water Supply Paper #489.

Deposits may be made up of particles which are themselves porous, in which case high porosity exists. Limestone, which is relatively soluble, may become cavernous through the action of percolating water and have a very high porosity. Natural deposits are not made up of perfectly round particles but rather of particles of various shapes, depending on the mineral of which they are composed and shapes of the original fragments and wear to which they have been exposed. Irregularity gives a wider range of porosity and may tend to either increase or decrease porosity, although irregularities tend to counteract each other. Porosities of container rocks may range as high as 40% and of course, other things being equal, more oil may be expected from rocks of high porosity than from those of low porosity. However, it should be noted that percentage of recovery is not necessarily a direct function of porosity of the container rock, but is somewhat dependent on the nature of the rock. For example, no production may be expected from sand of porosity lower than 10% whereas with limestones and shales jointing and channeling may give

ease of movement of the fluid so that production may come from rocks in which samples show less than 10% porosity.⁷

While porosity is a measure of the space not occupied by solid material, the extent to which this space is filled with oil, that is, the percentage of saturation, is a direct influence on the capacity of the container rock in a particular reservoir. The percentage of saturation will be affected by the specific gravity of the oil, the lighter oils tending to greater degree of saturation. The gas-oil relation in the reservoir is a further influence on degree of saturation. If the openings in the rock are relatively large and continuous the ability of the fluid to saturate the sand is improved. In general, more than 90% of the pore space in the oil belt will be filled with oil, while the remainder of this space is filled with occluded gas and water. In the gas space or in formations containing gas alone 100% saturation may be assumed. In actual practice the degree of saturation of an oil sand is not

7. Prof. B. B. Boatright: Lectures on Petroleum Production at the Colorado School of Mines.

determinable with very great accuracy because of the difficulty of obtaining a section of the formation in the exact condition existing underground. High degree of saturation is an aid to production since the tendency for gas to escape without doing work is lessened.

Thus far it has been the purpose of this paper to give a general idea of the nature of reservoirs which may contain recoverable oil and/or gas and to point out the influences which are involved in governing the quantity of fluid which may be stored in such reservoirs. Of more immediate importance to the producer of oil is the percent of recoverability of the oil existing in the reservoir. This factor of recoverability will depend upon the utilization of the energy which is available for driving the oil into the well. Therefore, we now turn to the study of the energies and forces which influence the recovery of oil.

TYPES OF RESERVOIRS FROM ENERGY VIEWPOINT.⁸

Heretofore we have discussed an ideal reservoir with regard to the physical requirements necessary for a container of fluid and the passage of fluid through the reservoir. Further discussion and classification of reservoirs with regard to the utilization of energy is now necessary. Our ideal reservoir shall be one indicated in general by the following figure.

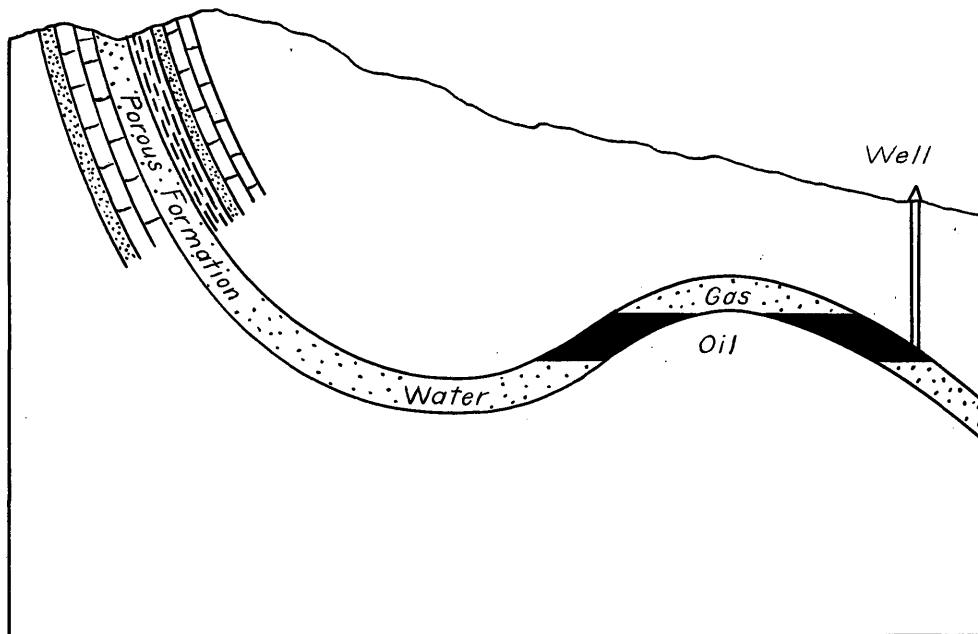


Figure II

8. Stanley C. Herold: Analytical Principles of the Production of Oil, Gas, and Water from Wells.

The stratum of porous material provides a reservoir for oil and/or gas in the folded section and extends to the surface at some point where surface water may enter the formation and provide a hydrostatic head. Or, the stratum may be in contact with other formations which furnish this supply of water. If a well is drilled into the formation as indicated in the figure, an opening is provided through which flow from the reservoir may occur in accordance with the laws of fluid mechanics as modified by the particular conditions existing while the flow is in progress.

Assuming a definite hydrostatic head existing before the orifice is opened, the factors which may affect subsequent flow are as follows:

1. The size of the orifice.
2. The location of the orifice.
3. The depth of the well.
4. Back-pressure under which production occurs.
5. Further influence on back-pressure if the fluid is not produced at atmospheric pressure.

6. The source of hydrostatic head, which may or may not be sufficient to maintain a constant head under flow conditions.

7. The nature of the porous formation with regard to resistance to flow of gas, oil, and water. (Permeability.)

8. The resistance to flow offered by gas bubbles intermingled with the liquid. (Jamin Effect.)

The conditions of flow which may result from the effect of combinations of the above factors have been classified by Herold into three types which he calls "controls".

1. Hydraulic Control: where rate of production remains constant through finite time. Such a condition can only occur when pressure head on the orifice remains constant. It may be typified by a simple tank in which the liquid level is held constant by an inflow equal to the outflow, or by the simple gas holder with a floating top of constant weight. In our ideal reservoir Hydraulic Control can only be maintained if the conditions

are such that the source of hydrostatic head is sufficient to maintain a constant pressure in the reservoir under flow conditions.

2. Volumetric Control: where rate of production declines and approaches zero in finite time. This condition, which will occur when the pressure head on the orifice declines with production, may be typified by a tank in which the outflow exceeds the inflow. In our ideal reservoir this control will occur when the Jamin Effect is not an influence and the source of hydrostatic head is insufficient to maintain constant pressure or the source of energy is solely gas pressure.

3. Capillary Control: where rate of production also declines and approaches zero in finite time, but the decline in pressure is increased by the Jamin Effect. In our ideal reservoir, if the pressure is insufficient to overcome the Jamin Effect in capillary openings, capillary control will prevail. Some students are inclined to view capillary control as a modified type of volumetric control. There is justification for this view

since the equation for the pressure-time curve is $p = kt^2$ in both instances, the difference in actual curves coming from the different values which the constant k will assume. These curves will be presented later.

SOURCES OF ENERGY.

In the broadest sense the ideal reservoir as pictured by Figure II on Page 10 might be considered as a finite part of an infinite system composed of the sun, the earth, seas, atmosphere, clouds, rain, and in fact all of the elements and factors which are involved in the carrying out of the intricate processes of Nature. Within the scope of this paper it is sufficient to take cognizance of the known facts that these elements and factors exist and that through their effect natural reservoirs occur which contain liquids and gases. In the more restricted sense, then, we are concerned with the immediate sources of energy in the finite reservoir.

The most important source of this energy has its origin in the effect of the earth's gravitational force. Less important sources of energy are: heat from the interior of the earth, chemical reactions, vapor pressure, and pressure due to folding.

The following diagramatic analysis⁹ assists in correlating these sources of energy.

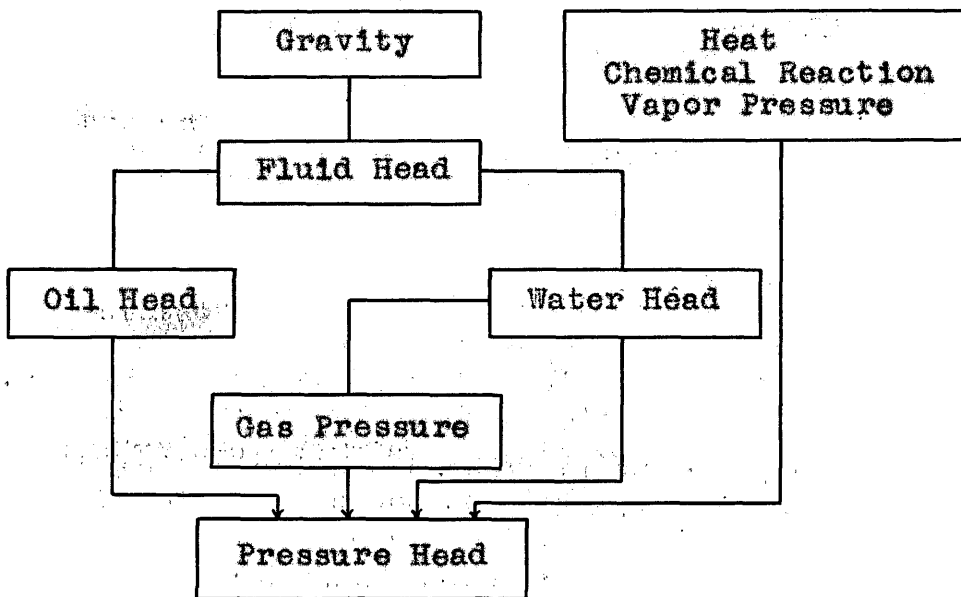


Figure III

9. Prof. B. B. Boatright: Lectures on Petroleum Production at the Colorado School of Mines.

Theoretically any mass removed a distance from the earth's center possesses potential energy equivalent to the work required to move the mass that distance against the force of gravity. It is not customary to be concerned with the absolute potential energy which a body possesses with reference to the earth's center as a datum plane, but rather to consider potential energy with reference to some convenient datum plane at or near the earth's surface. Thus in hydrostatics we arrive at the analysis of the energy possessed by a mass of liquid at rest by relating the weight (force of gravity), and the distance above a given datum plane. It follows that the energy is $W \times h$. If we consider a column of this liquid h feet high and one square foot in cross sectional area, the weight of such a column is $W \times h$, where W is the weight of one cubic foot of the liquid. The assumption is here made that the liquid is non-compressible and that, therefore, the column has a uniform density throughout its height. Such a column produces an intensity of

pressure at its base of $W \times h$ pounds per square foot. So we determine that hydrostatic head may be viewed as potential energy of a mass of water at a height h above a datum plane or as energy evidenced by intensity of pressure due to a column of liquid h feet high. It is from this analysis that we draw a conclusion that a mass of liquid in our reservoir possesses energy due to the fluid head to which it is subjected.

The fluid head acting at any given point in a reservoir may be that due to a column of a single liquid, or it may be due to a column made up of more than one liquid. In either case the total weight of the column of fluid of unit cross sectional area determines the intensity of pressure at its base and hence is the measure of the pressure energy contributed by gravitational force or fluid head.

Gas, which has the physical property of undergoing volume change when subjected to changing pressure, has the ability to store energy

when compressed. Thus the gas which may occur at the top of the ideal reservoir, or in fact any gas which is present in the reservoir exterior to the oil, being subjected to the hydrostatic pressure in the reservoir will be in a compressed state and will contain potential energy equal to PV , i.e., pressure times volume. In the diagrammatic analysis above it is intended to show that gas pressure is related to pressure head, having received its pressure from the fluid head.

Heat energy delivered to the reservoir from the earth's interior may have the effect of increasing pressure head by increasing gas pressure, though this source of energy is doubtless of relative unimportance. The release of energy by chemical reaction underground is also doubtless of little importance in relation to oil production. However, if such a release of energy does occur, the expected effect should be a prolongation of pressure head. It is hardly conceivable that such reactions would be likely to

occur at a rate rapid enough to release sufficient energy to increase the pressure head over that produced by fluid head under flow conditions. Such a source of energy might conceivably tend to build up pressure head under static conditions.

Vapor pressure, though a definite source of energy, is so directly related to gas pressure in oil reservoirs that it is hardly necessary to discuss it separately. It is of passing interest to note that vapor pressure is the primary cause of flow in such phenomena as geysers, where vapor is the medium through which heat energy of the earth's interior is released.

Pressure due to folding or shifting of the formation may be of primary importance where a reservoir has been isolated by earth movement and the entrapped fluids have been subjected to the pressure resulting from such folding. Such a reservoir would be expected to produce under falling pressure head from the start and would be a

typical example of volumetric control. In a reservoir left open to the influence of hydrostatic head in a continuous formation the pressure due to folding should not have a permanent effect on pressure head.

Before proceeding to the discussion of the energy losses encountered in production from a reservoir it seems pertinent to form a basis of analysis by examining the theoretical or maximum work possibilities involved in the two important items of energy, fluid head and gas pressure.

Let us consider for the moment that the pervious formation which was indicated in Figure II on Page 10 is a simple conduit as pictured in the following figure and that this conduit, open to the atmosphere at the upper end, is filled with water.

Under static conditions the liquid at A is under pressure due to the fluid head h . It has pressure energy evidenced by an intensity of

pressure equal to $W \times h$ pounds per square foot, where W is the weight of a cubic foot of water, and h is the height in feet. If the conduit

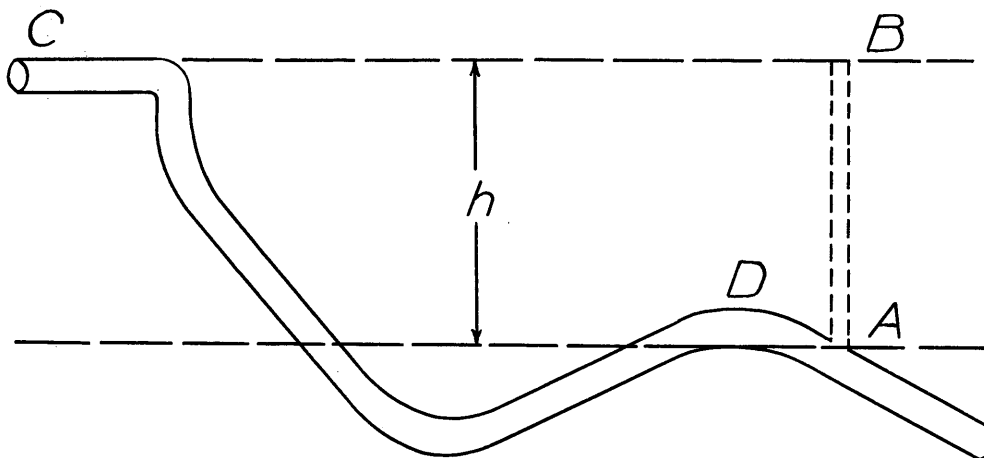


Figure IV

were tapped at A, a particle of liquid could rise the height h to B if no energy losses occurred in the conduit or from A to B. Furthermore, if the conduit were kept full by a constant supply of water at C this ideal flow could continue indefinitely. If the supply at C is any amount less than the discharge at A the pressure head or energy

possessed by a particle of fluid passing A will constantly decline. Such a complete utilization of energy as this is naturally inconceivable in any process and so is merely set up as a reference plane from which energy losses may be deducted.

When gas is entrapped in the reservoir as at the high point D in the conduit, this gas will be subjected to the pressure due to the fluid head acting. A clearer idea of the limiting effect of this compressed gas may be obtained by reference to Figure V.

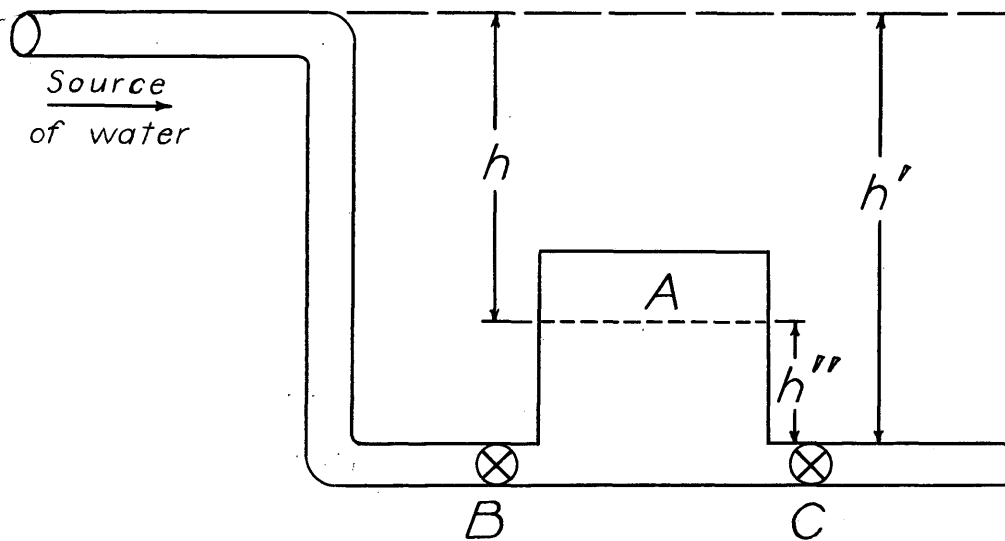


Figure V

Suppose the closed tank A is filled with a perfect gas at low pressure. When valve B is opened water will enter A and partially fill the tank to some level, such as indicated by the dotted line, until the gas is compressed to a pressure equal to the pressure produced by the fluid head h and pressure volume energy will be stored in the gas. A static condition now exists. If valve C is now opened and inflow at B continues equivalent to outflow at C the gas pressure at A will remain constant, and, again assuming no losses, the liquid at C has energy equal to the head h' . Suppose the valve B to be closed while C is open. At the first instant, liquid at C has energy equal to the head h' , but this head is supplied by the gas pressure head at A and the head h'' . Immediately, as the level of liquid in A falls, due to the outflow at C, the gas begins to do work of expansion, giving up energy, with a simultaneous drop in pressure head. Consequently the pressure head at C or the energy possessed by a particle of fluid passing C will be constantly decreasing. A similar

effect results if inflow at B is less than outflow at C but the rate of decline of energy at C will be lessened.

With modifications imposed by energy losses and restricting influences, the processes outlined above are indicative of what occurs in an underground reservoir.

ENERGY LOSSES AND RESISTANCE TO FLOW

In order to present a more definite idea of the effect of energy losses due to frictional processes and other resistances to flow it will be necessary to utilize another figure similar to Figure II on Page 10.

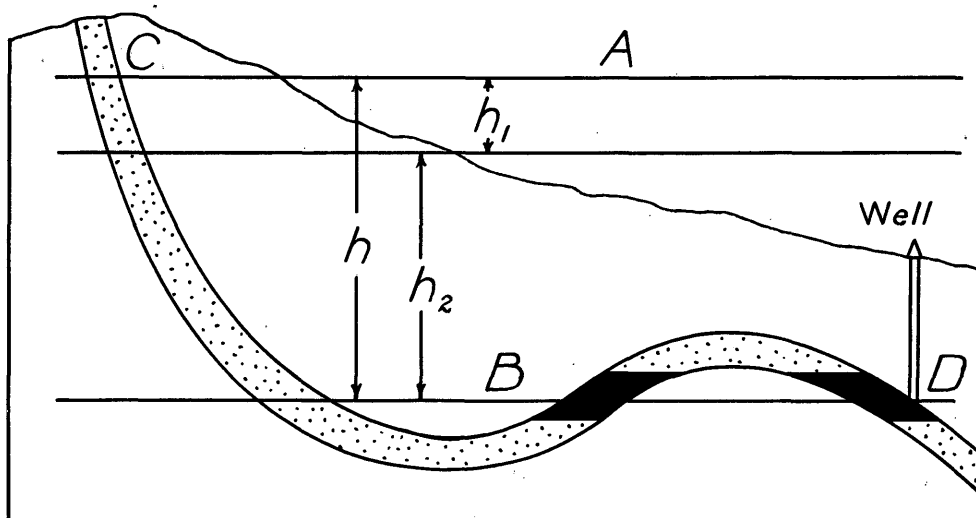


Figure VI

In this figure two datum planes, A and B, are assumed. A is at the water level in the formation and B at the level of the bottom of the well. In accordance with the previous ideal flow assumption, oil should arrive at B with energy equivalent to the head h , however, a loss of pressure head occurs between A and B which is due to the energy given up in overcoming the various resistances encountered in the formation. The general effect may be considered to be the same as if the study were applied to a filament of liquid moving from point C through the formation to point D. The resistances encountered by this filament of liquid, which require the expenditure of energy to overcome, are grouped under the general head of frictional losses. It should by no means be considered that any constant relationship of friction loss could be assigned throughout this path, as may be done in the case of a liquid flowing in an ordinary pipe line. To do so would be to neglect the fact that constantly varying conditions occur throughout the path. It is,

however, possible to determine the total lost head with some degree of accuracy by measuring the static pressure head and comparing this to the pressure head under flow conditions. A detailed study of the several influences which produce this total lost head is of importance because of the application in assisting to form an estimate of the expectancy of flow.

The most important item of energy loss is that resulting from the resistances to flow in the formation. This lost head is indicated by a height h_1 in Figure VI. At the present time the trend in petroleum production is to study this energy loss on a basis of the permeability factor of the porous medium. The following discussion of permeability is based on the "Proposed A. P. I. Code for Permeability Standardization".

The permeability of a porous medium to fluids is defined as: The rate of flow of a specified fluid through a unit cross-section of the porous medium under a unit pressure gradient and conditions of viscous flow. The unit is the darcy,

which is defined as: The rate of flow in milliliters per second, of a fluid of one centipoise viscosity through a cross-section of one square centimeter of porous medium, under a pressure gradient of one atmosphere (76.0 cm. Hg.) per centimeter and conditions of viscous flow.

The theory is based on Darcy's empirical law for viscous flow of liquids, which is expressed as:

$$V_x = \frac{K}{u} \frac{dp}{dx}$$

Where:

V_x is the velocity of the liquid measured as liquid flux across a unit area of porous medium in direction x .

u is the viscosity of the liquid.

$\frac{dp}{dx}$ is pressure gradient at the point to which V_x refers.

K is the permeability constant of the porous medium.

From this expression K is equal to:

$$u V_x / \frac{dp}{dx}$$

In the case of flow of an incompressible

liquid at constant temperature, V_x and u are evidently constant and so the pressure gradient will also be constant.

In considering the flow of gas through a porous medium, account must be taken of the fact that V_x will not remain constant but will increase with pressure drop as the volume of the gas increases. For gas flow in porous media the formula for K takes the form:

$$K = \frac{u \bar{Q}L}{A(P_1 - P_2)}$$

Where:

\bar{Q} is the mean quantity flowing, referred to the mean pressure.

A is the cross sectional area.

L is the length over which the pressure drop occurs.

The foregoing equations apply only to conditions of viscous flow. When turbulence occurs further energy is dissipated in the form of eddies. "Under such conditions the velocity will not rise as rapidly as the pressure gradient and Darcy's Law will be replaced by an equation of

this form:

$$v_x = \frac{K(dp)}{u(dx)}^n$$

where n may have any value between the limits 1.0 and 0.5, depending on the degree of turbulence." ¹⁰

Reduced to the energy analysis the permeability constant K is a measure of the energy loss as evidenced by drop in pressure head when flow is occurring in a porous medium. This energy loss is accounted for in overcoming three types of resistance, viz: the friction of the fluid against the solid material of the porous medium, the internal fluid friction and the effects of surface tension. These forces are inter-related in that they are all related to certain physical properties of the fluid. They are also, in one manner or another, related to the nature of the porous medium and to the velocity of flow. It is because of this complex relationship that the empirical permeability constant K has been devised in order to throw the total resistance into a re-

10. Quoted from the Proposed A. P. I. Code on Permeability Standardization.

relationship based on the measurable quantities velocity, viscosity and pressure drop. A better understanding of the obscure variable factors which influence the value of K will possibly result from a separate consideration of each of the three types of resisting forces mentioned above.

WALL FRICTION

If the attention is directed to viscous flow of an incompressible liquid, free from gas bubbles, wall friction may be abandoned. Gibson¹¹ says: "The streamline motion of a fluid through a pipe or channel is not accompanied by any slip at the boundary of solid and fluid and the resistance to flow is due to viscous resistance to shear of adjacent parallel planes. It follows from this that with steady motion the resistance is independent of the solid surface."

Oil is almost always accompanied by occluded gas in the form of bubbles or absorbed gas which will be released under changing conditions. Some of these bubbles will adhere to the sand face,

11. A. H. Gibson: Hydraulics and Its Applications.

setting up a force of resistance as they slip along the wall. Such wall friction is related to surface tension, which is the force tending to hold the bubble on the sand face.

INTERNAL FLUID FRICTION

This resistance to shear of adjacent parallel planes of fluid is distinctly a property of the fluid which is defined as viscosity. Viscosity varies with the other physical properties of the fluid, decreasing as temperature increases and density decreases. The absorption of gas by the fluid also decreases the viscosity, and since the amount of absorbed gas is proportional to the surrounding pressure, viscosity also decreases with increase of pressure when the fluid is in contact with gas. The amount of absorption is also dependent on the composition of the absorbed gas and the composition of the oil itself. The effect of gas absorption on viscosity clearly indicates the advantage of maintaining the reservoir pressure, as a means of conserving energy by reducing fluid friction.

SURFACE TENSION

When gas occurs with the oil the phenomenon of surface tension is responsible for an important source of resistance to flow. Surface tension is affected by change in other physical properties of the oil, decreasing with increase of temperature and pressure and with gas absorption¹². Consequently, maintaining the reservoir pressure has the desirable effect of decreasing this source of resistance. The effect of surface tension is manifested in two distinct ways in an oil reservoir. In the first instance surface tension is responsible for the adherence of a film of oil to the grain faces. Since the surface area of the grains in a cubic foot of sand amounts to several hundred square feet, the amount of oil held in the reservoir by this wetting of the grain surfaces is an important factor in so far as the percent of recoverability is concerned. The problem of removing this oil comes under the head of production methods and is not pertinent to this discussion of energy losses. Capillary at-

12. N. K. Adam: Physics and Chemistry of Surfaces.

traction, which is another manifestation of surface tension, also acts to retain oil in the sand.

The effect of capillary attraction on energy loss is most pronounced in its relation to the Jamin Effect as illustrated by the Jamin Capillary Tube. This important source of resistance occurs when the common condition exists, i.e., when the liquid contains occluded gas. Decreasing the reservoir pressure by too rapid production and thereby releasing absorbed gas has a tendency to aggravate this effect. A permeable formation containing globules and bubbles of gas may be considered as a network of capillary tubes, extending from top to bottom of the formation and spreading laterally in all directions from any well. The distortion of these bubbles as they pass from openings of one size to openings of another size sets up a considerable resistance to the motion of the fluid. The proportions which this resistance may assume are set forth in Herold's book¹³ by direct translation from the original work by the French physicist, Jules Celestin Jamin. Referring

13. Stanley C. Herold: Analytical Principles of the Production of Oil, Gas, and Water from Wells.

back to Herold's types of control it will be seen that this type of resistance must be overcome in Hydraulic and Volumetric Controls by the hydrostatic head, while in Capillary Control the hydrostatic head is overcome by the resistance set up by the Jamin effect and/or capillary attraction¹⁴.

Another effect produced by occluded gas occurs near the entrance to the well. Here the release of pressure and simultaneous expansion of the gas causes an increase in velocity of both gas and liquid. The effect on the permeability constant of this increase in velocity, which means an increase in frictional losses, is clearly indicated by the Darcy formula. Uren¹⁵ states that experiments have shown that 50% of the loss in moving oil 300 feet occurs within 10 feet of the well.

A great amount of valuable research work is evidently being done under the auspices of the A. P. I. on permeability and resistance to underground flow. The use of the Darcy formula with the empirical

14. Stanley C. Herold: Analytical Principles of the Production of Oil, Gas, and Water from Wells.
15. L. C. Uren: Paper on experimental study of the drainage characteristics of reservoir sands. University of California.

constant K would appear to be adequate when the conditions of flow approximate those under which the experimental determination of K was made. However, this writer is not satisfied that a laboratory experiment can properly simulate the conditions which may occur underground when occluded gas is influencing the resistance.

All other factors being the same, the variation of the permeability constant for different porous media will be a function of the nature of the openings in these media. The nature of these openings will depend on: the assortment of sizes and shapes and the arrangement of the grains of porous material, the degree and extent of compaction and cementation, and the degree and extent of channeling.

In summary, the factors which affect the lost head h_1 indicated in Figure VI, Page 24, are:

1. Physical properties of the fluid. Related to u and K in the Darcy formula.
2. Nature of the porous medium. Related to K in the Darcy formula.
3. Rate of production. Related to V in the Darcy formula.
4. Distribution of wells. Related to X in the Darcy formula.

REMAINING ENERGY

The remaining energy which the fluid possesses when it reaches the well bore is the factor which determines the kind of production the well will have. If we could confine our attention to a situation where only oil, with little or no gas associated with it reached the well bore, the conditions would be rather simple. In such a case, if the remaining energy represented by the pressure head h_2 in Figure VI were sufficient to sustain a column of liquid of height equal to the well depth and in addition supply some velocity head and overcome the resulting flow friction in the well casing, the well would flow naturally. With a source of hydrostatic head sufficient to maintain constant conditions Hydraulic Control would prevail and the production curve would be a straight line parallel to the time axis. Producing oil from the well would then be like drawing water from a faucet.

As a matter of fact, a condition such as the above may occur when the first wells are

drilled into the oil belt and before the gas reaches the well. When the initial pressure in the formation is very high the conversion of pressure energy to velocity energy results in tremendous flow if the well is allowed to flow open. However, even if such an initial condition occurred it would not continue long as production were made and additional wells were drilled in. This desirable condition may be prolonged by restricting production so that the source of hydrostatic head and the expansion of fluids in the formation¹⁶ will be able to compensate the pressure drop tending to result from the withdrawal of oil. By thus maintaining the formation pressure the resistances to flow will also be minimized as indicated in the chapter on energy losses.

At an early stage, for those wells drilled near the border of the gas belt, and eventually for those drilled further down the oil belt, a considerable volume of gas will come into the well and become an influence on flow. As the gas enters the region of lower pressure it will expand and do work

16. T. V. Moore: The Oil and Gas Journal, March 14, 1935

on the oil. It will also associate with the oil and lower the density of the fluid column in the well. Natural flow of this oil-gas mixture will continue and if the volume of gas coming to the well is constant and sufficient, constant production as defined by Hydraulic Control can occur. Again, by restricting production and maintaining back pressure this condition may be prolonged. But since the volume of gas in the reservoir is finite the condition cannot be prolonged indefinitely unless production is so slow as to allow gas energy to be replaced by hydraulic head.

Production will eventually reach a state where hydrostatic head and volume of gas are insufficient to maintain a constant rate of production, though sufficient to produce continuous flow. This condition may even prevail initially. In such event the well will produce under falling head, i.e., Volumetric Control, where rate of production decreases in finite time. As the volume of gas coming to the well becomes less and less, a state will eventually be reached where the energy available is

insufficient to produce a continuous flow and the well ceases to be a flowing well.

When the condition stated above is reached the well may become a heading well. In this case some gas is coming in with the oil. A head of oil accumulates in the well and gas builds up under this column of oil. When sufficient volume of gas has accumulated it will discharge the column of oil above it. The process will then be repeated. Volumetric Control is still in effect though production is intermittent. If the gas pressure is insufficient to discharge the oil column, the gas will slip through the oil and the production will be in the nature of a gas and oil spray. Production may be improved under these conditions by agitating the oil column. This agitation releases some of the absorbed gas in the oil and hastens the process of heading. Another method, commonly called "gas lift", may be employed. This process involves conveying energy from the surface to the bottom of the well in the form of compressed air or gas. By this artificial means a heading well may be again

converted to a flowing well. The time during which natural flow will take place may sometimes be prolonged by reducing the size of the flow tubing. This tends to give a denser column of oil with less slipping of the gas, and hence a more efficient performance.

When little or no gas remains and hydrostatic head is insufficient to raise the oil to the surface, pumping or the gas lift must be resorted to. If the quantity of oil entering the well is relatively small, even the gas lift will not be practical from an economic standpoint. In this state of production the oil is usually entering the well under the direct influence of the force of gravity acting on the oil in the immediate vicinity of the well. The final steps that can be taken to increase recovery under these conditions are either repressuring the formation with gas, or resorting to water drive. A few cases exist where oil sands have been mined and the oil removed by treatment on the surface. Such an operation is only practical under special and unusual conditions of occurrence of the oil bearing sand.

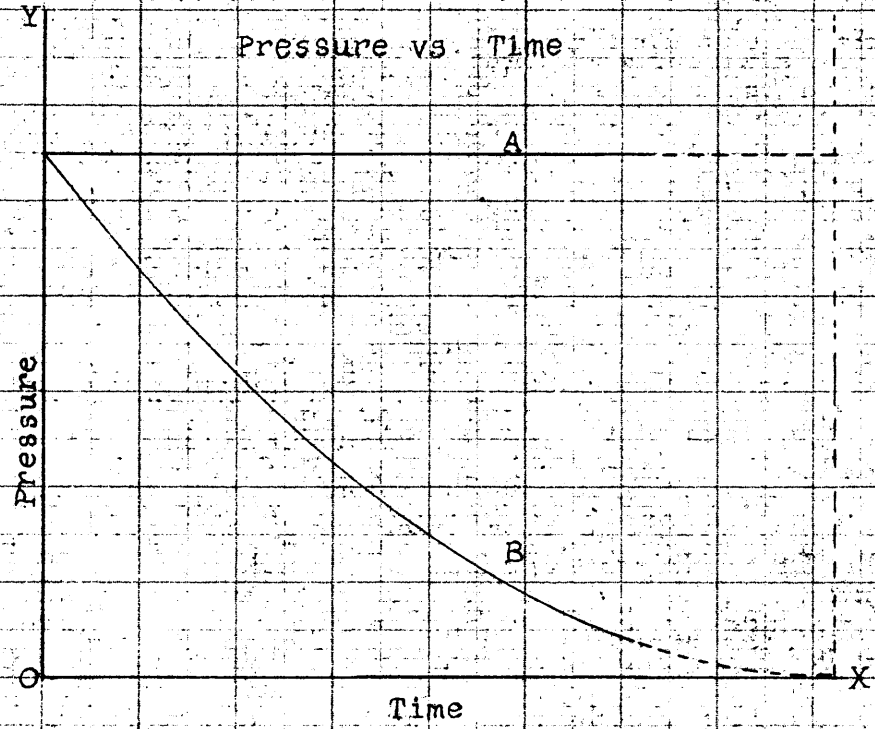
LIBRARY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

The common conditions in important oil pools which are carefully developed is a succession of Hydraulic Control, Volumetric Control, and Capillary Control. The application of repressuring or water drive as a means of obtaining the ultimate in production has been resorted to where conditions are favorable. All oil pools do not have the initial characteristics tending to this succession of production stages. Some may produce under Volumetric Control at the outset or even under Capillary Control.

As an Appendix several curves are here presented which are characteristic of the conditions under which production occurs. These curves are taken from "Analytical Principles of the Production of Oil, Gas and Water from Wells", by Stanley C. Herold.

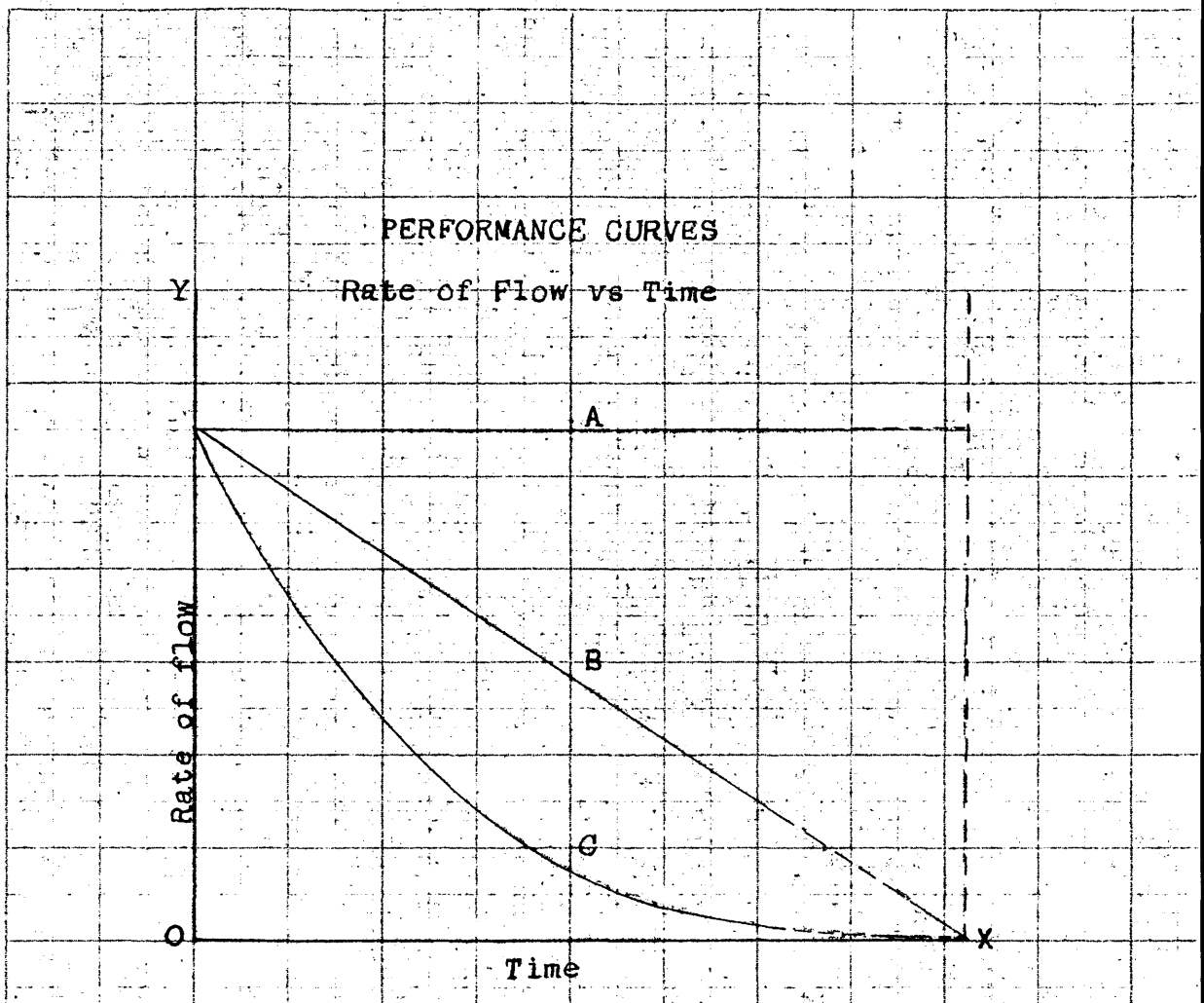
PERFORMANCE CURVES

Pressure vs. Time



Curve A --- Hydraulic Control
 $P = a \text{ constant}$

Curve B --- Volumetric or Capillary Control
 $P = KT^2$ the equation of a parabola



Curve A --- Hydraulic Control

$$Y = a \text{ constant}$$

Curve B --- Volumetric Control

$$Y = K X$$

Curve C --- Capillary Control

$$Y = K_1 X^3$$

BIBLIOGRAPHY

The Geology of Petroleum and Natural Gas - E. R. Lilley

Geology of Petroleum - W. H. Emmons

The Occurrence of Ground Water in the United States - Water Supply Paper 489 - Oscar Edward Meinzer

The Effect of Pressure on the Migration and Accumulation of Petroleum - F. H. Van Tuyl and R. C. Beckstrom - Bulletin of the American Association of Petroleum Geologists - Vol. 10, No. 10.

Oil Fields of the United States - Walter A. Ver Wiebe

Analytical Principles of the Production of Oil, Gas, and Water from Wells - Stanley C. Herold

Increasing the Recovery of Petroleum - W. H. Osgood

Fluid-Energy Relations in Production of Petroleum and Natural Gas - R. A. Cattell and H. C. Bowler - Mineral Yearbook 1934

Hydraulics - Horace W. King and Chester O. Wisler

Principles of Thermodynamics - G. A. Goodenough

Thermodynamics - G. N. Lewis

Principles of Chemical Engineering - W. H. Walker, W. K. Lewis and W. H. McAdams

Hydraulics and Its Applications - A. H. Gibson

Proposed A. P. I. Code on Permeability Standardization

Physics and Chemistry of Surfaces - N. K. Adam

LIBRARY
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO