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SOME PRINCIPLES GOVERNING THE PRODUCTION OF OIL WELLS

BY

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SOME PRINCIPLES GOVERNING THE PRODUCTION OF OIL WELLS.

By Carl H. Beal and J. O. Lewis.

INTRODUCTION.

The material for this paper was collected for the most part by C. H. Beal during the years 1916, 1917, and 1918. Many of the conclusions reached in regard to the life of oil wells have already been published by the Bureau of Mines[1] but those presented in this paper deal particularly with the theoretical aspects of oil production.

The report discusses some of the fundamental factors governing oil production, taking up first the conditions affecting the amount of oil in the oil sand, then those factors that control the rate of production of oil wells, and then discusses several related problems, most of which deal particularly with the effect of the production of one well on that of another.

ACKNOWLEDGMENTS.

The authors gratefully acknowledge their indebtedness to Roy E. Collom, Clarence G. Smith, E. D. Nolan, and R. V. Mills, of the Bureau of Mines, for suggestions and criticisms of the manuscript, and to the many oil operators in the United States, who courteously furnished the material upon which the paper is based.

FACTORS CONTROLLING THE PRODUCTION OF OIL.

The factors governing the production of oil are extremely variable. Many of them can be studied and their influence on production can be determined, but the effect of others can only be estimated. Most of the factors are interrelated, and practically all are affected in some way by each other. Seldom can the effect of one be isolated completely and studied. In studying these factors, therefore, it is necessary to arrive at many conclusions by observing the action of oil properties or wells where one factor is stronger than the others. Some of the factors that control the oil content in a porous reservoir influence also the amount of oil that can be recovered from the reservoir and the rate at which it may be obtained. Therefore, the study

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[1] Beal, C. H., The decline and ultimate production of oil wells with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 1919, 215 pp.

of oil production includes the investigation of those factors (1) that control the total amount of oil in the reservoir, (2) that influence the amount of recoverable oil or the ultimate production, and (3) that control the rate at which the oil may be obtained—that is, the size of the wells and their rates of decline.

The main influences in the production of a well may be classed as natural and artificial. The chief natural influences are the oil content of the reservoir rock; the resistance to the movement of oil through the reservoir rock; the expulsive forces; and the effectiveness of these forces in expelling the oil from the reservoir rock. The chief artificial factors are the spacing of the wells, the operation of the wells, and the application of stimulative processes.

Oil content is determined by the thickness, porosity, extent, and, sometimes, the saturation of the oil sand. The factor of resistance depends chiefly upon the porosity, size of the sand grains, and the viscosity of the oil. The expulsive forces are the dissolved and the associated compressed gases, the direct water pressure, and gravity. All these factors are interrelated as regards their influence on the ultimate production of a well, and they control the manner and rate of the flow of oil to the well. This paper discusses these factors and their influence on oil content, ultimate production and decline in production.

OIL CONTENT.

The amount of oil contained in a porous reservoir depends upon several variable factors, as follows:

1. The pore space in the oil-containing medium.
2. The percentage of the voids filled with oil, sometimes called saturation.
3. The thickness of the reservoir.
4. The extent of, or the area occupied by, the reservoir.

POROSITIES OF OIL SANDS.

The porosity of a sand depends on the shape and uniformity of the grains making up the sand body and the amount the pore space has been reduced by cementation. Reduction in porosity has frequently been said to be due in part to compression. Although the porosities of argillaceous and very fine sediments seem to have been largely affected by compression subsequent to deposition, the authors doubt whether it has played an appreciable part in sands, because once a sand has been deposited in moving water, observation shows that the grains can not be further compressed without shifting their positions one to another. In this paper the discussion of porosity is confined entirely to oil sands—that is, to sands and sandstones impregnated with oil—and does not cover porous limestones, the porosity of which depends upon the number and size of the caverns in the limestone. In a sandstone the porosity is highest when the sand grains are of uniform size. Theoretically, the mean pore space for spherical grains of a uniform size is 36.795 per cent. Sands of uniform grain, however, are uncommon, and usually the voids of the larger grains are partly filled by smaller, regular, or irregular sand grain or silt. Pore space is reduced by the cementation of the sand grains by mineral matter deposited from aqueous solutions. Minor reduction of porosity may possibly result from compacting under the weight of the overlying formations and through lateral pressure.

Very few sandstones are uniformly porous from top to bottom. Ordinarily small "breaks," or thin layers of relatively impervious material, lie parallel to the sandstone bedding, and cause beds of sandstone to show considerable differences in porosity on account of the varying characteristics of the sand grains and the degree of cementation. Nor is the porosity of an ordinary sandstone uniform laterally because the conditions of sedimentation vary, as do the later secondary changes resulting from cementation.

So different in porosity are the members of some sandstone beds that in many oil fields most of the production comes from a "pay" or "pay streak" that forms only a small proportion of the total thickness of sand. In many sands varying in thickness from 50 to 100 feet the "pay" may be 10 feet thick or even less. The "pay streaks" are usually the more porous or coarser layers of the sand and may or may not be separated from the other layers by "breaks" or shales.

Lewis has collected a mass of data on the porosities of oil sands. The table following is taken from a recent report:[2]

TABLE 1.—*The porosities of sandstone.*

Locality.	Number of tests.	Porosity.		Character of rock.
		Limits.	Average.	
Mexia, Tex.[a]		16.60 to 34.20	25.40	Gas sand.
Petrolia, Tex.[b]		18.50 to 27.00	[h] 22.75	Do.
Ohio[c]	6	15.87 to 17.83	16.63	Berea grit (building stone).
Missouri[d]	6	7.01 to 23.77	17.74	Building stone.
Wisconsin[e]	32	4.81 to 28.28	15.89	Do.
Washington[f]	3	10.61 to 18.00	13.17	Do.
Europe[g]	7	6.90 to 25.50	[h] 16.20	Do.

[a] Matson, G. C., Gas prospects south and southeast of Dallas, Tex.: U. S. Geol. Survey, Bull. 629, 1916, p. 92.

[b] Shaw, E. W., Gas in the area north and west of Fort Worth, Tex.: U. S. Geol. Survey, Bull. 629, 1916, p. 36.

[c] Bownocker, J. A., Building stones of Ohio: State Geol. Survey, Bull. 18, 4th ser., 1915, p. 77.

[d] Buckley, E. R., The quarrying industry of Missouri: Missouri Bureau of Geology and Mines, vol. 2, 2d ser., 1904, p. 317.

[e] Buckley, E. R., Building and ornamental stones of Wisconsin: State Geol. and Natural Hist. Survey, Bull. 4, econ. ser. No. 2, 1898, p. 402.

[f] Shedd, S., Building and ornamental stones of Washington: Washington State Geol. Survey, Annual Rep. for 1902, vol. 2, 1903, pp. 134-136.

[g] Foester, —, Baumaterialenkunde, vol. 1, p. 13.

[h] Mean.

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[2] Lewis, J. O., Methods for increasing the recovery from oil sands: Bull. 148, Bureau of Mines, 1917, pp. 16–18.

TABLE 1.—*The porosities of sandstone*—Continued.

Locality.	Number of tests.	Average ratio of absorption.	Computed porosity.[j]	Character of rock.
Northeastern States [i]	25	2.66	5.98	Building stone.
Ohio and Indiana [i]	29	5.22	11.75	Do.
Wisconsin, Minnesota, Iowa, Missouri, and Michigan [i]	34	7.93	17.84	Do.
Colorado, Utah [i]	27	9.85	22.20	Do.
Other localities [i]	10	5.89	13.25	Do.
Total or average	134	6.50	14.60	

[i] Compiled from Merrill, G. P., Stones for building and decoration, 1891, pp. 504–507; Hopkins, T. C., Carboniferous sandstones of western Indiana, 20th Annual Report, Dept. Geol. and Nat. Resources of Indiana, 1895, p. 323; Buckley, E. R., Building and ornamental stones of Wisconsin, Bull. 4, econ. ser. No. 2; Wisconsin Geol. and Nat. Hist. Survey, 1898, p. 414; Smock, J. C., Building stone in New York, Bull. New York Museum, vol. 2, No. 10, Sept. 1890, pp. 195–395; Bain, H. F., Properties and tests of Iowa building stones, Iowa Geol. Survey Annual Report, vol. 8, 1898, p. 410.

[j] Porosity computed by multiplying the ratio of absorption by a factor of 2¼, as justified by Buckley, E. R., The quarrying industry of Missouri, Missouri Bureau Geol. and Mines, vol. 2, 2d ser., 1904, p. 303.

White[3] estimated from tests that the porosities of West Virginia oil sands range from 10 to 20 per cent. Carll[4] from crudely made tests of Pennsylvania oil sands estimated the porosity to be from one-fifteenth to one-tenth.

A recent article by Melcher[5] gives the most reliable data (see Table 2) yet published on the porosities of oil and gas sands in this country, and also gives a simple and accurate method of determination. These tests were made with pieces of sandstones blasted from oil and gas wells, though not all were from sands actually productive. The clear relation between the porosities and the size of the pores of sands and the productivities of the wells has been demonstrated by Mills and Wells.[6] Further investigations will disclose the essential relationship between the character of the reservoir rocks and the yields of the wells drawing on them.

TABLE 2.—*Porosities of oil and gas sands as determined by Melcher.*

Locality.	Number of tests.	Porosity.	
		Limits, per cent.	Average, per cent.
North Texas fields	11	13.2–37.7	23.5
Appalachian fields [a]	49	4.5–22.2	13.0
Wyoming fields [b]	10	3.4–30.1	17.1
Bartlesville field, Oklahoma	4	16.1–17.7	16.7

[a] Includes several samples of cap rock and unproductive sands. Average of actually productive sands would be over 15 per cent.

[b] Include several samples of cap rock. Average of productive sands would probably be 25 per cent.

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[3] White, I. C., Petroleum and natural gas: West Virginia Geol. Survey, Vol. 1A, 1904, p. 45.

[4] Carll, J. F., The geology of the oil regions of Warren, Venango, Clarion, and Butler Counties: Second Geol. Survey Pennsylvania, vol. 3, 1880, p. 251.

[5] Melcher, A. F., Determination of pore space of oil land gas sands: Am. Inst. of Min. and Met. Eng., April, 1920.

[6] Mills, R. Van A., and Wells, Roger C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geol. Survey Bull. 693, 1919, pp. 20–21.

No determinations of porosity have been made by the author of this paper, although considerable information has been collected from persons interested in that subject. Many geologists and engineers engaged in estimating, by the use of porosity, the oil content of sands in the Mid-Continent field ordinarily use a factor of 17½ per cent, and it has been said that the porosity of oil sands in the Augusta field, Kansas, averages about 18 per cent. The porosity of the ordinary oil sand of California is usually taken as about 25 per cent, undoubtedly a low figure, since sands as loose as those generally average 36 per cent or more in porosity. Porosity in the Appalachian field is estimated as 10 to 12½ per cent, but the actually productive portions of the sands probably average at least 15 per cent.

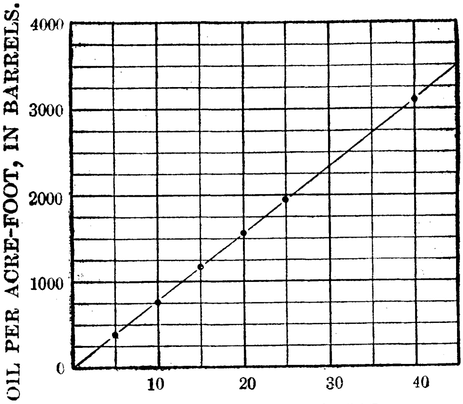

FIGURE 1.—Chart showing the barrels of oil contained in each acre-foot of sands of different porosity.

Figure 1 shows graphically the barrels of oil contained in each acre of pay sands 1 foot thick but of different porosities. To use the chart the porosity must be estimated and the thickness of pay sand multiplied by the barrels of oil per acre-foot, as indicated on the left side of the figure.

Although porosity determines the possible oil content of a cubic foot of sand, a careful distinction must be made relative to the productive capacity. In a sand of high porosity the grains may be so minute that the yield of oil to a well will not be at a commercial rate. On the other hand, a very coarse sandstone highly cemented and of low porosity may be very productive. The productivity of an oil sand, for reasons given hereafter, is not solely dependent upon porosity or capacity.

SATURATION.

One of the elusive factors that may influence the oil content and yield of a sand is the extent to which the voids in the oil-bearing part of the sand body are filled with oil. The term "saturation" has been used loosely and often as synonymous with "oil content" or "oil yield"; thus "highly saturated" is often used to denote a prolific oil sand, and sands of low yield are referred to as "partly saturated". Low yield or low recovery is thus explained by an assumed "low saturation," although the voids of the oil sand may be completely filled with oil; but the low porosity or small size of the pores or the lack of expulsive force may prohibit the recovery of the oil.

It may be taken as axiomatic that no vacuum exists in a sand but each void is filled with water, gas, or oil. Some sands are known to be filled only with water or gas. In a field where there is more gas than can be held in solution in the oil under the pressure and temperature of the oil-bearing sand, the gas will collect alone in the upper part of the sand body, which will be solely gas bearing; whereas at a lower level the sand will be oil yielding. It is this oil-yielding part of the sand that is being considered here with respect to "saturation." In an exact sense, all parts of the sand are saturated—but the question is whether that part of the sand that contains oil contains only oil and gas dissolved in the oil, or whether it is partly filled with water and free gas.

A full consideration of the subject would be too long for this paper. Lewis has devoted much study to the question, and has concluded that except in special cases the oil-bearing sands in a virgin field are probably approximately saturated with oil and that under the general conditions of occurrence partial saturation in the popular sense is hardly compatible with physical laws. Both authors believe that ordinarily, at least, the yield of oil sands are governed more by factors influencing the efficiency of recovery than by an assumed partial saturation.

THICKNESS.

The thicker the oil-containing medium the greater the oil content. The total thickness of the sand, commonly spoken of as the oil-producing formation, is not always productive, for, as stated above, the "pay" may form only a small part of the sand. The thickness of sands and of "pay" in different fields shows wide differences. In some fields the productive part of the sand is less than 5 feet thick, yet wells drilled into this "pay" have produced commercial quantities of oil for many years.

Some good examples of thin pay are in the Clinton sand in southeastern Ohio, where the pay often averages not more than 10 feet in thickness; also in the Berea Grit in some parts of West Virginia. Although the Berea Grit formation itself is often thick, the pay constitutes only a small part of the total thickness. The Big Injun sand in some parts of West Virginia is also a thick formation, but usually the pay is only a few feet thick. These thin sands, however, show in general less recoverable oil per acre than the thicker sands, as is indicated in the recovery curves published by the Bureau of Internal Revenue.[7]

In the Cushing field in Oklahoma the Bartlesville sand, which in some places has a total thickness of nearly 200 feet, furnishes an excellent example of a complex oil sand. Its members are lenticular and of varying porosity. In some places in the northern part of this field the top part of the sand may be "dry"—at least, it is so recorded in the logs—or it may contain gas. Underneath the few feet of seemingly barren sand a productive streak of oil sand a few feet thick may be encountered, beneath which gas may be reported under high pressure in a more porous part of the sand. Underneath the gas there is, in certain places, a strong flow of salt water, directly under which more gas or an extremely prolific oil "pay" may be reported. In some wells in that part of the Cushing field the whole Bartlesville sand is composed of these individual members, which seem to be separated from each other by small "breaks"—whose existence can be detected only by careful observation in drilling—by bedding planes, or by differences in porosity.

The thickness of the productive sand in this part of the Cushing pool is very difficult to determine, and a knowledge of the thickness of the sand itself is of comparatively little value for estimating oil content, unless the aggregate thickness of the individual "pay streaks" can be determined.

Pay streaks 30 or 40 feet thick are by no means uncommon, and in some parts of the California fields the "pay" comprises a much greater thickness of the productive formation. In Oklahoma the thickness of the oil sands usually ranges between 15 and 100 feet. It is, of course, practically impossible to determine in a great thickness of oil sand just what part produces oil and what part is either barren or possessed of a porosity so small or a grain so fine as to give up no appreciable quantity of oil. Therefore estimates on the oil content of a district based on the voids in a sand and on the thickness of the sand are subject to much error. A sand like the Bradford sand in northwestern Pennsylvania, the uniformity of which is well known, may not offer such difficulties in estimating the oil content, as the sand is presumably regular in porosity and its voids seemingly filled completely with oil at time of discovery.

The interpretations of conditions in the oil-bearing horizons are subject to much uncertainty from the fact that the evidence comes from drillers' reports. These records are personal opinions as well

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[7] Bureau of Internal Revenue: Manual for the oil and gas industry, 1919, fig. 4, p. 80.

as observations made by men technically untrained; even the experienced technical man may derive from the same observations diverse conclusions as to underground conditions. One must constantly be on guard, therefore, lest deductions based on reports of drillers are made from premises that are open to question.

Reliable estimates of the recoverable oil content can not yet be made from the thickness or porosity of sands, but there is a striking general relation between these factors and the productivity of wells, as is shown by the curves and tables of the Bureau of Internal Revenue. The thin and comparatively light Clinton sand of southeastern Ohio, for example, shows an average future of 2,100 barrels for a well that produced 1,500 barrels the preceding year, whereas the average Bradford sand well can expect 6,600 barrels, and the average well in Kern River, Calif., where the sands are thick, coarse, and very porous, can expect 12,000 barrels.

AREAL EXTENT.

The oil content of a pool or field, of course, depends largely upon the areal extent of the productive sands. The areal extent of oil-yielding sands is limited by nonpersistence of the sand, by lack of porosity, by water, or by segregated gas. Some productive sands in the fields of the United States are lenticular, and in such cases the size of the field is not determined altogether by geologic structure. The Bartlesville sand is an example of a sand that is locally lenticular, although in the Cushing field the pools of oil are also limited by the geologic structure. The sand in some cases thins perceptibly on the northeastern side of the Cushing field to a "broken," nonproductive sand. Many of the productive oil "zones" in the California fields are made up of discontinuous overlapping lenticular sands.

Examples of a sand uniformly deposited are the Clinton sand in Ohio, which contains oil over large areas, and the Bradford sand of northwestern Pennsylvania. The Berea Grit and Big Injun sands in West Virginia and parts of Pennsylvania are also persistent. In these sands oil in paying quantities is not always present even when favorable structural conditions exist because of variations in porosity. The productive sands of the Illinois field are good examples of nonpersistent sands; evidently they were deposited under varying conditions.

Geologic structure is commonly the principal factor governing the areal extent of an oil pool. Oil accumulates up the slopes of the oil-bearing formations against either structural or formational barriers that restrict further upward movement. Of the many types of structures that are oil bearing, the most common structure is anticlinal, the extent of the anticlinal structure being usually the most important factor in the extent of the pool.

The oil content of a horizontal acre of ground depends partly on the dip of the formation beneath it. Obviously as the dip increases the amount of oil in a porous, dipping bed under an acre of horizontal surface increases. Figure 2 has been prepared to show the increase of oil content with the increase in dip. The curve marked *b* gives the percentage to be added to the oil content of a horizontal acre for the different degrees of the dip of the oil reservoir. The other curve gives the actual cubic feet per acre.

This curve may be further explained as follows: In a horizontal bed an acre in extent and 1 foot thick are 43,560 cubic feet. If this bed is inclined, the number of cubic feet included within the limits of the acre, as measured on the surface of the oil sand, will increase. This increase will vary with the degree of dip of the oil sand; for example: As shown by the curve, an oil sand a foot thick with a dip of 20°, underlying an acre of ground, will contain 46,600 cubic feet instead of 43,560 cubic feet, or an increase of 6.98 per cent. As the thickness of oil sands is most likely to be measured in a drilling well which automatically allows for the inclination, it is not necessary to consider this factor unless the inclination is materially different from that of the place of measurement and is to be estimated before wells are drilled.

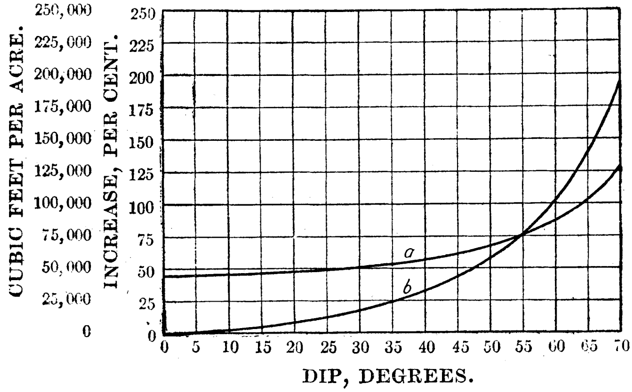

FIGURE 2.—Chart showing the difference in oil content of beds of different dip, but of the same porosity and bedded thickness. Curve *a* shows the increase per acre-foot of oil sand with the change in dip; curve *b* shows the increase in per cent.

The area underlain by oil already developed in this country is by no means as great as the layman ordinarily believes; in fact, it is much smaller than many geologists and operators are aware. In the Mid-Continent the fields differ in size from a few acres to several thousand. In the Gulf Coast region productive fields occupy relatively much smaller areas because of the oil and gas occurring in connection with salt domes. Many of these domes occupy less than 1 square mile, but are extremely productive. In Illinois the total productive area lies chiefly in one locality and covers approximately 230 square miles. In this area, of course, are several distinct pools. The fields in the Appalachian district cover much larger area, though ordinarily they are not as prolific as some smaller pools elsewhere. In California the largest field covers from 40,000 to 50,000 acres. This figure, however, does not include prospective acreage near by that may prove productive. The total productive area in the United States has been estimated by Lewis at about 2,000,000 acres.[8]

ULTIMATE PRODUCTION (RECOVERABLE OIL).

GENERAL CONSIDERATIONS.

The difference between oil content and the amount of oil that may be recovered, or the ultimate production, is important. The recoverable oil of a sand underlying an area is the quantity that may actually be taken from the sand rather than the amount present in it. This recoverable oil is a percentage of the total oil content, and it varies with the conditions under which the oil occurs in the sand and under which it is produced. The proportion recovered, using only the natural forces, from a certain area depends mainly upon the porosity and size of the pores, upon the available energy within the sand for expelling the oil from the pores of the sand, and upon the efficiency of this energy. The last, in turn, is controlled largely by the external artificial conditions affecting the well or property.

The main force that expels oil from a formation is the gas compressed and dissolved in or associated with the oil. Gravitation and direct water pressure occasionally play an important part in expulsion, but by no means as important a part as gas. Artificial forces are now being employed more and more to increase oil recovery, such as vacuum pumps, by the use of which suction is placed on the productive sands; water flooding, by which the oil is driven to oil wells by water flowing through the sand from strategically located wells; and compressed air or gas forced into the sand to simulate the original conditions of absorbed and compressed gas in the oil and oil sand.

The efficiency with which these forces can be employed governs the ultimate amount of recoverable oil. The friction of the oil passing through the porous formation retards the expulsion forces to a degree depending on the viscosity of the oil but principally on the character of the porous medium containing the oil. Other factors governing the efficiency of expulsion are the distance the oil must flow through the sand to the well outlet, and the mechanical conditions

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[8] Lewis, J. O., Methods for increasing the recovery from oil sands: Bull. 148, Bureau of Mines, 1919, p. 29.

obtaining at the well. In some cases the expulsive forces are wasted and the recovery is reduced. These wastes may be due to improper casing, which allows the gas to escape through a barren or partly depleted oil sand above; to inefficient operating; and sometimes the expulsive force is wasted, because of the nature of the sand or because of the infiltration of water.

The term "exhaustion of a well," therefore, pertains more to the forces available for expelling the oil than to the actual depletion of the oil contained in the sand. These points have been discussed in general by Lewis and Beal,[9] and in some detail by Lewis.[10]

THE PERCENTAGE OF OIL RECOVERED FROM OIL SANDS (RECOVERY FACTOR).

The determination of the percentage of oil recoverable from a sand is of great importance as it makes possible an estimate of the comparative effectiveness of methods of production; it aids in ascertaining whether or not there would be profit in developing and installing new processes for recovering a further part of the unrecovered oil after the wells draining the territory were practically exhausted by the usual methods, and also permits more accurate estimates of future production. In considering recovery a distinction must be made between recovery by natural forces and by artificial forces.

The percentage of oil remaining underground differs with conditions in the different districts. In fact, the amount recovered may not be the same for different properties in the same pool or for different parts of the same property. The recovery depends upon the conditions both natural and artificial that influence production, and it may differ as much as they. For instance, the recovery factor of a small area on the crest of a dome may be much greater than that of another area a few hundred feet nearer the edge of the pool. Likewise, the first wells will obtain more oil and will more completely drain the sand than later wells.

Lewis[11] gives estimates, made by various persons, of the amount of oil left underground, and describes methods of estimating the recovery factor. These estimates of unrecovered oil range from 25 to 90 per cent. The same publication cites statistics which lead him to the opinion that only 10 to 20 per cent of the oil is commonly extracted. This is much lower than the usual estimate of approximately 50 per cent.

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[9] Lewis, J. O., and Beal, C. H. Some new methods for estimating the future production of oil wells. Bull. 134, Am. Inst. Min. Eng., Feb., 1918, pp. 478–80.

[10] Lewis, J. O. Methods for increasing the recovery from oil sands. Bull. 148, Bureau of Mines, 1917, p. 20.

[11] Lewis, J. O., work cited pp. 25–32.

HOW ULTIMATE PRODUCTION IS MEASURED.

The best method of computing, for purposes of comparison, the amount of oil that various properties will produce ultimately is by determining the average production per acre. This average is obtained by dividing the number of acres on which oil wells are producing into the amount of oil that will be produced ultimately from the area. Much has been written on the production per acre-foot; that is, the amount of oil obtained from each foot of thickness of the oil sand. In other words, the amount of oil per acre is divided by the average thickness of the sand from which the oil is produced. Estimates of the actual productive thickness of sand are difficult to make and often are liable to be erroneous. Statistics on production per acre-foot therefore are believed to be of limited value unless the sand is one of which the productive thickness can be reliably determined.

OTHER FACTORS CONTROLLING ULTIMATE PRODUCTION.

GEOLOGIC STRUCTURE.

The intimate relation existing between geologic structure and oil production is evident, for the wells of higher initial production, as a general rule, will be found toward the crest of the geologic structure. Areas that furnish such wells of high initial production will generally produce more oil per acre than those containing smaller wells.

ROCK PRESSURE AND DEPTH.

In Oklahoma and in many other fields the "rock" pressure, or the closed pressure, of the oil and gas in an oil sand, is usually proportionate to the depth of the sand below the surface. As a general rule, the number of pounds of rock pressure per square inch that is to be expected previous to drilling into a new sand may be approximately estimated by the weight of a column of water of a height equal to the difference between the elevation of the lowest outcrop of the oil sand and that of the sand where penetrated by the drill.

In the Cushing field the average rock pressures of the Layton, Wheeler, and Bartlesville sands were in very close agreement with the theoretical pressure of a head of water measured vertically from the points where the sands were penetrated to the elevation of the supposed outcrop of the sands. Whatever may have been the original cause of the rock pressure in newly developed oil and gas fields this pressure shows a tendency to balance the hydrostatic pressure of the water in the same formation adjacent to the pool.

In any district, especially in one like Oklahoma where the productive pools become progressively deeper as drilling proceeds westward, the ultimate production depends largely on the rock pressure, which in turn varies approximately with the depth of the pool.

ABSORBED GASES AS AN EXPULSIVE FORCE.

Generally the compressed gas in the oil sand is the principal force in expelling the oil from the reservoir rock. The recovery of the oil therefore largely depends on the amount and the pressure of the gas associated with the oil. Under the preceding discussion on saturation, it is stated that in the writers' opinions most of the gas intimately associated with the oil is absorbed in the oil. In accordance with Henry's law of gases, the quantity of a fixed gas that can be held in solution in the oil is proportional to the pressure; thus, if a cubic foot of oil holds one-fourth cubic foot of gas in solution at one atmosphere pressure, it could hold one-half cubic foot at two atmospheres, and 5 cubic feet at 20 atmospheres. Doubling the pressure, therefore, doubles the quantity of dissolved gas, and hence, the energy, being the pressure multiplied by the gas volume, is quadrupled. The expulsive energy thus increases as the square of the pressure, provided there is enough gas associated with the oil to saturate the oil at the existing pressure. Some of the gases present (propane and butane) are condensable at the higher pressures and thus go into solution as liquids. The effect in the field is that the expulsive energy may increase at even a greater ratio than the square of the pressure.

The reasons for the larger wells and greater recoveries at the deeper horizons are evident when the fact is borne in mind that the gas pressures are generally proportionate to the depth of the sands.

The amount of oil recovered is influenced as much by the rock pressure and the amount of gas absorbed in the oil as by almost any other factor. The decline in production of a well represents a decline of the pressure and of the volume of gas in the oil reservoir. There are, of course, exceptions, the most conspicuous present example being the production of oil in the Butler County, Kans., field. Here in many of the wells the initial production is large although very little gas accompanies the oil. Gas therefore is not the chief expulsive force. The lack of gas and the fact that water under pressure closely underlies the oil and that many of the wells quickly show water, indicate that direct water pressure and not gas is probably the predominant impelling force in that field.

Every person who has worked in an oil field is familiar with the volume of gas that usually accompanies the oil in a new well, especially if the well is among the first in the field. As more and more oil is extracted from the field and the pressures are reduced, less gas accompanies the oil. Because of this fact it is suggested that data on the reduction in volume of gas produced with each barrel of oil may be used to estimate the future production of a well, for not only does the volume of gas initially produced with each barrel in each new well decrease with the age of the field, but as the production of a well decreases the volume of gas produced per barrel of oil decreases also. The authors have made an effort to obtain such data, but without notable success, because such records are not kept by the oil companies of the United States.

Plate I, *A*, shows the greatest oil gusher ever drilled. The tremendous quantities of oil that issued from it could not have been produced without an enormous expulsive force behind the oil; this force was probably due both to the absorbed and compressed gas and to the direct water pressure behind the oil in a cavernous or creviced reservoir.

Plate I, *B*, shows a well producing in a region where the gas pressure and the absorbed gases are practically exhausted. The production of this well is only a few gallons a day, and the initial production of new wells drilled near by is little in excess of this amount. The production of wells from sands where the gas is so nearly exhausted is perhaps due as much to the gravitational flow of the oil into the well as to any expulsive force of contained gas.

In some fields the compressed gas from a formation a few feet above the productive oil formation is utilized as an expulsive force. This is questionable practice and should be avoided not only because of the waste of gas but because there is likely to be later a waste of oil into the gas sand. The pressure in the gas sand will decline much more quickly both in the well and in adjoining wells than the pressure in the oil sand, so that later in the life of the well the oil may flow into the gas sand. Such a case is reported in the Cushing field, Oklahoma.[12]

INITIAL PRODUCTION.

The writers use the term "initial production" in a broader sense than that used in some oil districts where the term has acquired a restricted meaning and refers only to the first 24 hours' production or the daily rate at the end of the first month or some other period. As used in this paper the term refers to the first part of the productive life of the well without restriction to a specific period, though in most of the investigations the initial period has been taken as the average daily production during the first year.

The ultimate or total production of a well is as a rule proportionate to its initial production. Wells of small initial output have a correspondingly small total production. This statement is true, how-

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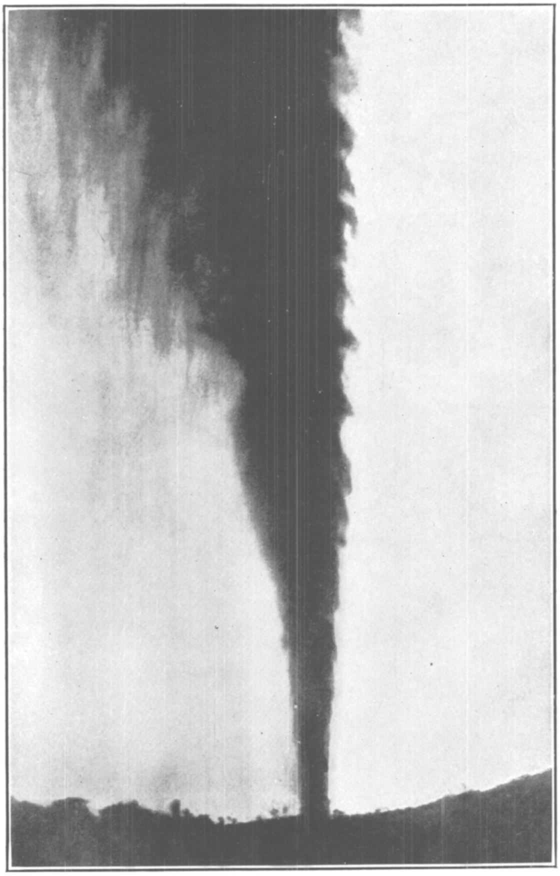
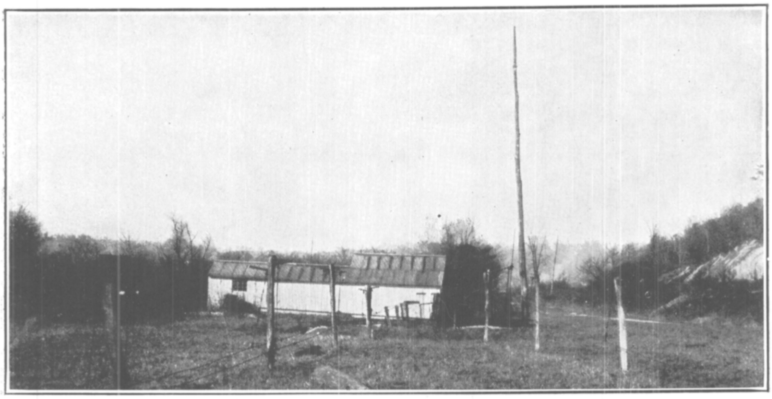
[12] McMurray, William, and Lewis, J. O., Underground waste in oil and gas fields and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, p. 18.



(By courtesy of the Mexican Petroleum Co.)

A. CERRO AZUL NO. 4, NEAR TAMPICO, MEXICO, THE WORLD'S GREATEST OIL GUSHER; BROUGHT IN FEBRUARY 10, 1916. THE MEASURED FLOW WAS 260,000 BARRELS DAILY, AND THE COLUMN REACHED A HEIGHT OF 500 TO 600 FEET.



B. OLD WELL, A FEW HUNDRED FEET FROM THE ORIGINAL DRAKE WELL, THAT HAS BEEN PUMPED FOR SEVERAL DECADES.

ever, only in a general sense, for sometimes the total production of small wells in one field may be much greater than that of wells of much larger initial output in other fields. But when comparisons are made of many wells within one field it is found that in spite of variations there is an unmistakable relation between initial and ultimate production. This relation is the basis of the method advocated by Lewis and Beal[13] for estimating the future production of wells—a method that has been adopted by the Bureau of Internal Revenue in making allowances for depletion.[14]

As their initial and ultimate production are related, the same factors influence one as the other, and therefore the tendencies are the same. The following table shows these tendencies:[15]

TABLE 3.—*General tendencies of wells producing under specific conditions.*[a]

Conditions.	Rate of decline.	General tendency of ultimate cumulative percentage.	General tendency of ultimate production.	Initial production.
Deep wells	Rapid	Small	Large	Large.
Shallow wells	Slow	Large	Small	Small.
High rock pressure	Rapid	Small	Large	Large.
Low rock pressure	Slow	Large	Small	Small.
Large gas volume	do	do	Large	Large.
Small gas volume	Rapid	Small	Small	Small.
Large initial production	do	do	Large	
Small initial production	Slow	Large	Small	
Close spacing	Rapid	Small	do.[b]	Do.
Wide spacing	Slow	Large	Large[c]	Large.
Thick sand	do	do	Large	Do.
Thin sand	Rapid	Small	Small	Small.
Large pore space	do	do	Large	Large.
Small pore space	Slow	Large	Small	Small.
High-gravity oil, Baumé scale	Rapid	Small	Large	Large.
Low-gravity oil, Baumé scale	Slow	Large	Small	Small.
With water trouble	Rapid	Small	do.[d]	Do.
No water trouble	Slow	Large	Large	Large.
Properly operated	do	do	do	Do.
Poorly operated	Rapid	Small	Small	Small.

[a] In this table the influence of any one factor is given on the assumption that all other factors are of minor influence.

[b] Small per well but large per acre.

[c] Large per well but small per acre.

[d] In some cases, when water floods in, the ultimate production will be greatly increased.

In considering these tendencies the reader should note that the statements are made on the assumption that all factors are constant each time, except that each factor is varied in rotation. In every well each factor will have a different value, therefore there are possibilities for numerous combinations of values, and the initial produc-

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[13] Lewis, J. O., and Beal, C. H., Some new methods for estimating future production of oil properties: Am. Inst. Min. Eng., Bull. 134, Feb., 1918, pp. 477–504.

Beal, C. H., The decline and ultimate production of oil wells with notes on the valuation of oil properties. Bull. 177, Bureau of Mines, 1919, 214 pp.

[14] Manual for oil and gas taxation, 1918, Bureau of Internal Revenue, 136 pp.

[15] Adapted from Table 14, p. 204, Bull. 177, Bureau of Mines, 1919. Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties.

tion for the well is the product of the additive and subtractive factors involved.

METHOD OF OPERATION.

One of the most variable factors influencing ultimate production is the method by which the wells are drilled and by which they are operated after completion. An incompetent drilling superintendent will leave the wells in such condition that the production man who takes over the completed wells will find the ultimate production greatly decreased by faulty casing, poor cementing, incursions of water, collapsing of casing, or faulty shooting. On the other hand, the well may be turned over to the production department in good shape, but inadequate knowledge of methods of production, which include proper utilization of gas pressure, will greatly decrease the amount of oil ultimately obtainable. Good operation is therefore the keynote to obtaining the maximum ultimate production, for the natural conditions on the property are not under the operator's control and can not themselves be changed. Wells should be carefully drilled, for the method of drilling and the condition of the well after completion form the foundation on which are based long life and maximum ultimate production.

GEOLOGIC STRUCTURE.

In addition to the factors mentioned the geologic structure influences initial and ultimate production. It has been pointed out that the occurrence of oil is not always in accordance with the principles of the anticlinal theory. Such an exception may be seen in Plate II, which shows that wells of higher initial production in one part of the Cushing field, Oklahoma, were found not on the crests of the anticlines and domes, but on the west side of the folds where oil and gas were intimately associated. In this part of the field gas alone occupied the higher structural positions of the sand on the east, and oil not overlaid by gas-sand was found by drilling wells farther down the westward dipping beds. Intermediate between the two areas, both oil and gas were found. The geologic structure of the Layton sand was determined from well logs. The variation in the initial production of the wells in the most prolific part of the field is shown by the red stippling.[16]

DRILLING AND WELL SPACING.

In operating a property to get maximum recovery one of the important questions is whether to drill up the property slowly or

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[16] Beal, C. H., Geologic structure of the Cushing oil and gas field, Oklahoma, and its relation to oil, gas, and water. Plate VII, U. S. Geol. Survey Bull. 658, 1917.

quickly. Theoretically, the best results will be obtained by drilling up quickly. The principle may be illustrated by assuming that one well was drilled in the center of a quarter section and that no other wells were drilled for 10 years thereafter. During these 10 years the well would be draining the whole 160 acres (unless the sand was noncontinuous), and some of the oil would be moving more than a quarter mile to reach the well. The greater the distance oil must be moved through the sand the greater the energy required; therefore the gas in the property could not expel as much of the oil as if there were more wells. The wells drilled 10 years later on the same property would find the gas pressure low and the energy in the sand dissipated, and their initial and ultimate production would be low. In general recovery will, in the writer's opinion, be greater when all wells are completed at approximately the same time. This principle is considered further under the discussion of well spacing.

When two wells are drilled near each other, the gas in the sand surrounding each well starts to force the oil toward the nearest well. This area of influence keeps extending from each well until the two areas touch, then interference sets in. The time elapsing before interference begins is governed by the factors of distance, pressure, and resistance to movement within the sand. With enough time one well might affect a whole field if the sand were continuous throughout. The greater the pressure, the sooner will interference begin between wells of a given spacing, because the oil and gas will move with greater velocity. In an open sand containing light fluid oil the resistance to movements will be slight and interference will set in rapidly. Except for the thickness of the sand, the factors that make for large initial productions make likewise for rapid interference between wells.

These problems of development and well spacing are very important and their thorough study will undoubtedly result in worth-while financial returns to the operator. The method of development on the ordinary lease is, of course, more or less influenced by the method of development on adjoining leases, so that the aggressiveness of a neighbor may prohibit proper development. Moreover, the price an operator receives for his output is an important factor. The problem at best is complicated, but promises reward for an adequate solution.

An excellent example of the many elements to be considered in plans for development is provided by the Shamrock dome, in the south part of the Cushing field, Oklahoma. When the Cushing field was being rapidly developed, in 1914 and 1915, the Hill Oil & Gas Co. selected large tracts of land covering the maximum part of the south side of the Shamrock dome. The north side of this dome was leased by other oil companies. The discovery of oil in the Cushing field had been made a few miles north of the crest of this dome, and development gradually spread southward to the properties on the north side of the dome. The policy of the Hill Oil & Gas Co. seemed to be to drill only the necessary offsets and to conserve its oil resources.

To the minds of many geologists working in that territory at the time occurred the question whether or not the policy of the Hill Oil & Gas Co. in postponing drilling, at least to a greater extent than the needed offsets, was a mistaken one. Some argued that the ultimate production obtained from these properties when finally drilled would be very much smaller than if the company joined the rush and drilled its properties at the same time that the development was carried on north of the Shamrock dome. During the rapid drilling a paper delivered in July, 1915, before the Engineer Society of Western Pennsylvania by R. H. Johnson and L. G. Huntley, entitled "The influence of the Cushing pool on the oil industry," questioned the policy of the Hill Oil & Gas Co.

Several months elapsed and a discovery of oil was made a few miles south of the crest of the dome on land not owned by the company. Development immediately proceeded from this point northward. About this time the properties belonging to the Hill Oil & Gas Co. were purchased by another corporation whose policy was to develop the territory. The heaviest drilling of these tracts was carried on two or three years after the heavy development on the north side of the Shamrock dome. The final result of the drilling on these lands suggests that the original policy of the Hill Oil & Gas Co. was at fault so far as the recovery of oil was concerned. The initial production of nearly every well was small, which meant that the ultimate amount of oil recovered from the district would also be small. Many of the wells drilled to the Bartlesville sand—the most prolific in that district—did not flow more than a few days, whereas the wells drilled to the same sand on the north side of the dome came in with much higher initial production and flowed for months.

There is a possibility, however, that the small initial productions obtained from the wells on these properties were not due to the delayed drilling policy of the Hill Oil & Gas Co., but to the fact that the sand conditions were not as favorable as on the north side of the dome, that there was not as much oil in the Bartlesville horizon, or that the sand was tighter and would not yield oil so readily. A careful study of the conditions, made by the writers in 1916, indicated that although the sand may have been not quite so prolific the smaller ultimate production on the south side of the dome was the direct result of reduced gas pressure due to the heavy drawing on the oil sand and the consequent reduction of gas pressure by the many wells on the north side of the dome.

As an oil company's primary object is to make money rather than to produce oil, the whole story of the policy of the Hill Oil & Gas Co. is not told until the financial side is considered. In 1915, when development near the Hill company's properties was most active, oil was selling at a posted price of 40 cents a barrel at Cushing. Much of it sold for less, and several companies invested large sums of money in building storage to hold their oil until a market could be found. But by January, 1916, the posted price of oil jumped to $1.20 a barrel, and by September, 1917, the posted price was $2 a barrel, while Cushing crude carried premiums of 30 cents to 50 cents a barrel. In two years' time, therefore, the price of oil increased five or six times and the net profits a barrel produced increased, possibly, ten times. Under these circumstances, doubtless, the company profited greatly by its policy of delayed drilling, even though the total recovery from the property fell much below what it might have been.

CONDITIONS OF THE WELL.

Ultimate production is influenced strongly by the conditions of the well. In many cases the maximum is not obtained from a well on account of inadequate cleaning or on account of wax being formed on the tubing or on the face of the oil sand, thereby preventing the oil from flowing or being forced into the well. The authors have seen wells in Pennsylvania, pulled after several years' pumping without cleaning, the lower part of whose tubing was almost closed by masses of paraffin wax.

In some fields chemical reactions may take place between the water associated with the oil and the water foreign to it, with enough resultant precipitation and crystallization of salts not only to retard production but to prevent it entirely. Further information on this subject has been published by Mills and Wells.[17]

PROPER UTILIZATION OF GAS.

The proper utilization of gas as an expelling agent has already been discussed; but no mention has yet been made of the device of partly "closing in" the well that is occasionally employed at large wells of high initial pressure. Producing in this manner through a "bean," or flow nipple, would appear to the layman to prevent production; as a matter of fact, however, the ultimate production can often be thus increased. If such wells are permitted to flow to their utmost, the pressure in the sand around the well is so greatly reduced that not only is the valuable expelling agent wasted, but

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[17] Mills, R. Van A. and Wells, R. C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geological Survey Bull. 693, 1919, 104 pp.

the reduction of pressure in the sand allows rapid incursions of water and thereby cuts off bodies of oil which may never be recovered. The principles of "stop-cocking" wells, used in early days in Pennsylvania, can probably be used with profit as advocated by Miles Quick and others.

WATER CONDITIONS.

Water, generally considered the oil man's worst enemy, does the greatest damage when it enters the oil sand from the surface or from other sands above or below. Unless the pressure in the oil sand is high and undepleted the water, having greater weight, will build up greater pressure and force the oil back from the well so that it can not produce. Water also corrodes the casing, tubing, and pumping equipment. At many wells the influx of water from other sands precipitates mineral matter in the pores of the oil-producing sand and seals in the oil. Water from near the surface being cooler than that in the deeper oil-producing sands, chills the oil, causing the deposition of paraffin wax or an increase of the viscosity of the oil. Large quantities of water make production costs excessive, cause emulsions, and B. S., and necessitate increased expense in handling the oil and in preparing it for shipment.

The difference in the surface tension of water and oil, especially in fields like the Mid-Continent, has an important bearing on this question. Water flows much more easily through a sand than does oil, for it is less viscous. After production begins from many wells, variable pressures exist in all parts of the sand, and an area of lower pressure undoubtedly exists in the richest part of the sand from which the most wells are drawing oil. This area is usually on the crest or on the sides of the fold containing the oil. Under such conditions, the forces in the internal reservoir are not in equilibrium, and movements to restore this equilibrium will be comparatively rapid. Because of the greater rapidity with which water flows through a sand, the richer parts of the sand—which usually coincide with those from which oil is being rapidly extracted—may show water first. If the maximum ultimate production is to be obtained, such underground conditions must be carefully studied and the operations carried on to minimize any sudden unbalancing of the equilibrium of the underground forces.

It can hardly be said without qualification, because of the present limited knowledge of the conditions affecting production, that water is invariably harmful. Warm salt water flowing through a practically exhausted oil sand flushes oil with it; otherwise many wells in the light oil pools of the eastern fields would probably not be profitable to operate. It is also a fact that in some fields, notably Bradford, Pa., water flooding through the depleted oil sands has forced out more oil than could have been recovered by natural means. Nevertheless it remains open to question whether the use of other methods could not have accomplished more profitable results. The writers are of the opinion that the "favorable" influences of water are questionable and represent the last forlorn hopes in the oil field.

Where water enters the oil sand from the same well, it can ordinarily be controlled by "casing off" upper waters or "plugging off" bottom waters. When water enters through the productive oil sand, it is either let in by adjacent wells or it is encroaching edgewater. The repair of the offending adjacent wells will prevent the first, but there is seldom any protection against the second. The edgewater gradually encroaches on the field because of the extraction of oil and gas. In some fields this encroachment is fairly regular, but there are many districts in the United States where it is extremely irregular, owing in part to differences in the character of the oil sand, and to poor methods of operation. In several fields great lateral differences in porosity have permitted irregular encroachment of edgewater to such an extent that the water passed through a long sinuous area from low down on the flank of a dome or anticline to the top of the fold, where it spread out into a large fan-shaped area, destroying many wells that were originally excellent producers.

CHARACTER OF THE OIL.

The viscosity and capillarity[18] of the oil influences the total amount recovered. A highly viscous oil will not flow readily through the pores of the sand, and a larger proportion of the oil will remain in the sand after the pressure is exhausted than if the oil had been less viscous and of lower capillarity. Temperature often has an important influence on ultimate production, as an increase in temperature reduces viscosity and capillarity.

SPACING OF WELLS.

The gross effect of spacing on ultimate production has been mentioned (p. 18) and will be discussed at some length on a later page (p. 25).

VALUE OF THE OIL.

The value of the output of the well is the quantity times the sales price per barrel of oil. If this value does not exceed the operating costs, the well will be abandoned as unprofitable, even though it may be yielding daily several barrels of oil. A rise in the price of

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[18] Lewis, J. O., Methods for increasing the recovery from oil sands: Bull. 148, Bureau of Mines, 1919, p. 21.

oil may allow the well to be operated again at a profit, thus increasing the amount of oil finally taken from the well.

STIMULATING PROCESSES TO INCREASE PRODUCTION.

The employment of stimulative processes to increase production affects ultimate production directly, although the results from such common methods as "shooting" and vacuum pumping are not as great as is commonly believed. But the ultimate production of many properties has been greatly increased by forcing compressed air into the sand, and in more exceptional cases by the "water drive."[19]

THE RATE AT WHICH THE OIL IS OBTAINED.

Even when it is possible to foretell with accuracy the future production of a property, a very important point still remains to be determined if the information is to be of maximum benefit to the oil operator. This is the rate at which the oil is to be obtained, or the decline in the production of the oil wells. The rate largely governs the rapidity with which net earnings are to be obtained. It is therefore necessary to determine this factor for the calculation of the amount of discount which should be placed on future income to reduce it to present value.

Future annual production depends (1) upon the rate at which new wells are to be drilled, and (2) upon the future rate of production of each well. The normal rate of decline in the production of each well will be affected by a number of conditions the effect of which can not always be predicted with accuracy. Furthermore, the average rate of decline of wells may change materially during the life of the property on account of the decrease in the size of newly drilled wells, through interference by the older wells or through drainage. In other words, a curve showing the decline in production of a well or a property can not be constructed that will fit each well on the property, because the rate at which the production declines is controlled to a great extent by the output of the initial well, and other things being equal the later wells on a property will produce smaller totals than the first wells.

FACTORS GOVERNING THE DECLINE OF OIL WELLS.

The rate at which oil is obtained depends primarily on the same factors that control the oil content of the sand and the total amount of oil that may be recovered from the sand. The greatest and most influential variables affecting the rate at which oil may be obtained from a well are: (1) "Rock" (gas) pressure; (2) initial production;

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[19] Lewis, J. O., Methods for increasing the recovery from oil sands: Bull. 148, Bureau of Mines, 1917, p. 54.

(3) character of the oil; (4) depth of the productive sand; (5) character of the sand; (6) thickness of the sand; (7) spacing of the wells; (8) method of operation; (9) geologic structure.

Many of these factors have already been discussed. All are interrelated. For example, initial production is influenced by "rock" pressure, and the latter factor in many fields is controlled by depth.

The effects of "rock" pressure, depth, character, and thickness of the sand, character of the oil and of geologic structure, have already been discussed in some detail under the heading of "Principal factors controlling ultimate production," and as their influence on the decline of oil production is exerted in much the same manner, they will not be considered again. The effect of well spacing, initial production, and method of operation will be discussed, however, in connection with the decline of oil wells.

In general, it may be said that the higher the initial or current production of the well the more rapid will be the decline. Slow declines, comparatively speaking, mean large ultimate productions, and conversely large ultimate productions are apt to be from wells that decline slowly, as compared to other wells of equal initial output. The significant feature of declining production is not the actual rate of decline, but the rate of decline compared to wells of equal daily production. On this basis of comparison, the factors that make for large ultimate production likewise tend toward slow decline.

INITIAL PRODUCTION.

The initial production of wells is influenced by such factors as depth, pressure, volume of associated gas, thickness, porosity, coarseness of the sand, and character of the oil. Wells of large initial production, under ordinary conditions, decline more rapidly than wells of small initial production. The rate of decline is, however, more of a function of the present output of the well than of its initial production. Figure 3 shows the difference in the rate of decline of three different classes of wells in the Blue Creek field, West Virginia. The curves showing the rate of decline of these wells have been drawn on logarithmic coordinate paper in order to reduce the curves more nearly to straight lines.

SPACING OF WELLS.

One of the most important factors controlling the rate at which oil is obtained from a well is the area from which the oil is drawn. Interference will not set in so quickly between widely spaced wells as between wells drilled more closely, and, accordingly, the decline of the wells will be slower. Figure 4 shows the difference in the rates of decline of differently spaced wells in an Oklahoma field. In constructing these curves all the properties in the Bartlesville field, the wells on which produced 11 to 20 barrels daily the first year, were divided into three groups in accordance with the average area drained by each well. The composite decline was then computed for all the properties in each group.

The sand thickness, the initial production, and the depth in each group were the same; the acreage was the only important factor that varied, so that the difference in the rates of decline shown may be attributed entirely to the influence of different spacing.

Proper spacing is largely an economic problem which depends mostly upon the ratio between the price obtained for the oil and the cost of producing the oil. Spacing is not so much a problem of how many acres a well will drain as it is a problem of obtaining the

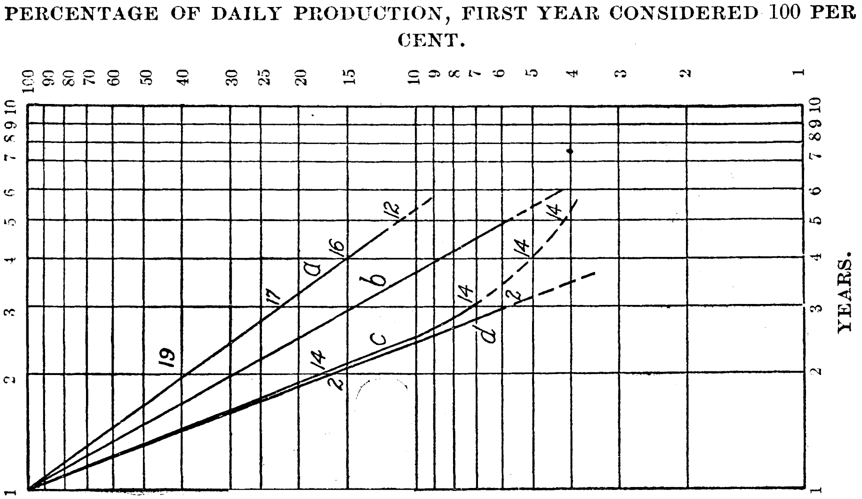

FIGURE 3.—Decline curves of large and small wells in the Blue Creek field, W. Va., plotted on logarithmic coordinate paper. Curve *a*, properties averaging 15 barrels daily; curve *b*, average decline for all properties; curve *c*, 16 to 10 barrels daily; curve *d*, over 100 barrels daily.

greatest possible production in the minimum time and at a minimum expense. The amount of oil sand that a well will drain under ordinary conditions depends largely upon the time that draining is continued. Theoretically, given ideal conditions and unlimited time, one well would drain hundreds of acres of a continuous porous oil sand, though this would be neither economical nor practical.

Draining, however, is a relative term. What the word "drained" ordinarily means is that the oil sand will no longer yield oil in profitable amounts, and has little to do with actual exhaustion of the sand; in all cases much more oil is probably left in the sand than was brought to the surface. After the sand has been drained the usual motive force—compressed gas—that forces the oil to the well has been depleted so much that, at the price of oil and the cost of pumping, the production is no longer profitable. One well in the course of time may drain out all the gas from the sand almost as completely as a hundred wells, yet the amount of oil drained from the sand will be far less than if the hundred wells had been drilled.

The spacing problem would be given a different aspect if it were desired, for the public good, so to drill a large area that a certain production would be obtained yearly through a long term. In this case the law of economics would rule, and the wells would be spaced in accordance with the amount of sand area that could be drained with comparative efficiency by a single well during the term specified. The problem in its true aspects, however, becomes one of expediency rather than one of the greatest possible recovery.

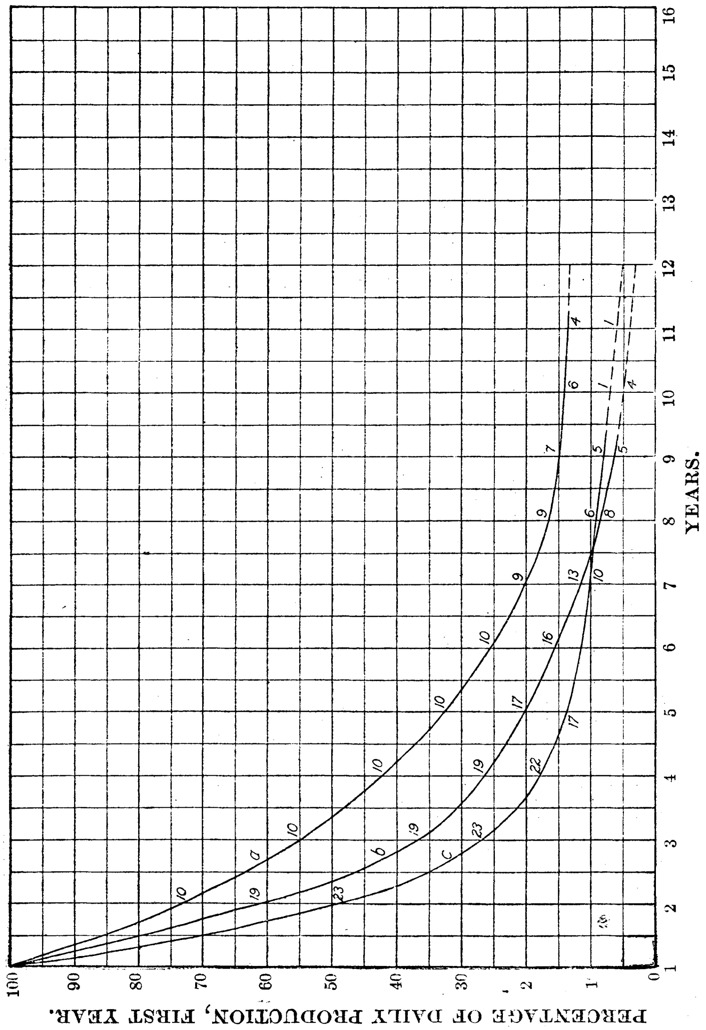

FIGURE 4.—Curves showing the difference in the rates of decline of differently spaced wells in the Bartlesville field, Oklahoma. Curve *a*, 6 to 8 acres per well; curve *b*, 5 acres per well; curve *c*, 2 to 4 acres per well.

The spacing practice to be followed depends essentially therefore on the total cost of producing the oil, which includes drilling and other costs, balanced against the total amount for which the oil produced can be sold, allowance being made also for the present value of deferred incomes. As set forth above, it is possible to obtain a greater quantity of oil from an area, in a shorter time, by close drilling, yet it may not be profitable to do so. A larger amount of oil per well can be obtained at lower drilling and operating costs by wider spacing. The value per acre of the additional oil gained by drilling wells closer together must be balanced against the cost of drilling and operating the larger number of wells necessary to obtain the increase.

Ultimate production bears a relation to initial production that may be controlled by thickness and character of sand, rock pressure, and character of oil. These factors influence well spacing in so far as they affect estimates of the ultimate amount of oil that may be obtained from a property, the rate at which it is obtained, the value of the oil, and costs of production. With high ultimate production per acre, wells often can be spaced more closely, even with a low price for oil, than with low ultimate production per acre and a higher price for oil. The depth at which the productive horizon lies below the surface is one of the determining factors in well spacing, because the cost of deep wells is greater than that of shallow wells. On the other hand, depth in many places controls the rock pressure and the absorbed gases upon which ultimate production may depend, and as a general rule more oil is recovered from deep than from shallow sands.

The most feasible way to study the proper spacing of wells in an oil field would seem to be to consider carefully the effect of various factors on the spacing of wells on developed properties of the same field or in similar fields. The conditions that influence production in oil fields are manifold; and identical conditions of depth, sand thickness, rock pressure, initial production, and geologic structure do not occur in two different fields. Furthermore, the future net profit per barrel of oil is uncertain on account of the difficulty of even approximating the future price of oil and future drilling and productive costs, so that if all other variables were known the economic factor would still cause difficulty.

As regards commercial considerations, the desired end is to get the most profit from the property. This profit will be the present value of the oil less the cost of acquiring, developing, and producing the oil. So far as spacing is concerned there is a balance to be reached between the quicker and more complete recovery by close spacing, and the cost of the additional wells involved; thus the question whether it were better to drill 16 or 25 wells on 160 acres would be answered by another query whether the additional recovered oil and the quicker returns would compensate for the additional wells and their cost of operation. The cost of the wells and the operating costs per well can be assumed as constant; but there must be determined also the amount of the oil to be obtained from the wells, the additional length of life of the wells, and the price for oil during the life of the wells. The additional oil is capable of theoretic approximation as is the time value; but the fluctuations in the future price of oil remain uncertain. This uncertainty makes too fine calculations of other factors absurd, for what is the best spacing for one price for oil will not be most profitable for another price; therefore the spacing for one period in the well's life may not be the best in another period.

A study has been made of the productivity of different groups of properties in the Bartlesville field and in the Glenn pool, Oklahoma, the spacing upon which is different, in order to determine what spacing has been the most profitable.

The properties in these fields were classified according to their average daily production per well during the first year and according to the average area allotted each well. For instance, all properties in the Bartlesville field on which the production per well the first year was 11 to 20 barrels daily were separated from those on which the production was 21 to 30 barrels daily. Each class was then divided into subclasses according to the approximate area allowed each well. Those properties on which the production per well the first year was 11 to 20 barrels daily were subdivided into three groups: (1) Those properties on which the wells were allowed 2 to 4 acres each; (2) those on which the wells were allowed 5 acres each; and (3) those on which the wells were allowed from 6 to 8 acres each.

The properties were tabulated according to the chief factors influencing production on each property, as follows: (1) The average daily production per well the first year; (2) the average thickness of the sand underlying the property; (3) the average age of production of the property; (4) the rate of development of the property; and (5) the depth of the producing sand. The identity of the producing sand was the same on each property, and the depth was practically the same, so that the effect of these two factors was approximately constant. The same classification with certain variations was also made of properties of certain productivity in the Glenn pool, Oklahoma.

Results of these tabulations are shown in Table 4, column A, which shows the principal classes into which the properties were divided. Column C shows the actual average daily production per well the first year for all the properties considered. Column G is the number of properties considered in arriving at the respective average given. It should be noted that in each general class the average daily production per well the first year is practically identical for each subclass. This is also true for the average thickness of the sand producing, D, and the average age, E, so that the effect of these three factors on the properties in each subclass may be considered constant and hence may be eliminated from consideration.

TABLE 4.—*Variation in production per acre with different spacing of wells in two Oklahoma oil fields.*

BARTLESVILLE FIELD, OKLA.[a]

A Daily production per well, first year, barrels.	B Average acreage per well.	C Average daily production per well, first year, barrels.	D Average thickness of sand, feet.	E Average age of productiod, years.	F Average total production of oil per acre, barrels.[b]	G Number of properties used in obtaining average.
11-20...	2-4	14	26	8	2,930	28
	5	14	27	9	2,550	20
	6-8	15	26	9	2,090	10
21-30...	3-4	24	27	9	6,500	5
	5	26	30	9	5,650	7
	6-8	25	28	9	3,000	4

GLENN POOL, OKLA.

A	B	C	D	E	F	G
0-10....	5	6	35	5	1,000	5
	6-10	7	36	4	880	6
21-30...	6- 7	24	28	5	2,320	4
	8-10	23	46	7	2,070	5

[a] The sand was identical under each property and the depths differed little.
[b] These total production figures, for all practical purposes, may be taken as representing ultimate production, for the production of most of the properties had declined to one or two barrels per well daily.

Inasmuch as the method of development, within certain limits, and the depth and identity of the sand and the quality of oil were the same, their effects may also be eliminated. There remains, therefore, only one important variable factor influencing ultimate production, and that is the acreage drained by each well, B. The amounts in column F represent the true effect on total production per acre.

Take, for example, the first class of the table, which includes the average production per acre of 58 properties, subdivided according to the acreage drained per well. It is to be noted that the closer the well the greater the amount of oil that will be taken from each acre in the same time. Although this fact should be self-evident, such a demonstration of the rate of increase in total production per acre with the decrease in acreage drained per well is valuable. The effect of each factor on the properties in each subclass has been eliminated by equalizing them, so that one can definitely say that 10 properties in the Bartlesville field, the wells on which averaged 15 barrels daily the first year, produce an average of 2,090 barrels per acre in 9 years when the wells drain 6 to 8 acres each, whereas, under pratically identical conditions, the production per acre of 28 other properties, on which the wells drain 2 to 4 acres each, will be 2,930 barrels. This gives a working basis for determining the net profit derived from each acre of ground under certain stipulated prices of oil and assumed drilling and production costs.

Table 5 shows the result in tabular form of an analysis of the first class of properties given in Table 4. Columns A, B, and C in Table 5 are identical with columns B, F, and G, respectively, in Table 4. The cost of drilling wells throughout the area covered by these properties is practically the same, and has been assumed at $5,000 per well. The number of wells per acre is shown in column E, and the cost of drilling on each acre, shown in column F, is determined by multiplying the respective amounts in the two preceding columns. Three different prices of oil were then assumed, and the income, exclusive of drilling cost but deducting 10 cents per barrel for production cost at these different prices, was computed and is shown in columns G, I, and K, for oil at $0.60, $1.10, and $2.10, respectively. The net income derived from each acre obtained by subtracting the drilling cost from the total income is shown for oil at these different prices in columns H, J, and L.

When oil sells at 60 cents per barrel, if wells are drilled so that they drain 3 acres each, the total loss per acre to the producer after operating 8 years will be $185; for wells draining 5 and 7 acres each, the profit per acre at the same price will be $275 and $345, respectively. This indicates that wells should not be drilled closer than 7 acres in the Bartlesville pool with oil at 60 cents and other conditions as specified. On the other hand, if the price of oil is $1.10 per barrel, the greatest profit derived per acre is from those wells which drain 5 acres each, so that with this price of oil, seemingly the most economical spacing is 5 acres per well. But if the price of oil is $2.10 per barrel, none of the wells should be drilled farther apart than 3 acres each, for with this close spacing the maximum net income is obtained.

A factor not considered in Table 5 is the time element in production. The oil will be obtained more quickly by close spacing and hence its present value will be greater. One must, however, balance two practical considerations against this theoretical advantage. If the price of oil goes up the rise may more than compensate for deferred profits caused by wider spacing and hence slower recovery. The closer spacing also calls for a larger original investment risk.

TABLE 5.—*Net profit derived from each acre*[a] *of oil land on several properties in the Bartlesville field, Oklahoma, with different acreages per well, variable price of oil, and wells producing 11 to 20 barrels daily the first year.*

						Price of oil, $0.60 per barrel.		Price of oil, $1.10 per barrel.		Price of oil, $2.10 per barrel.	
A Average acreage per well.	B Average production of oil per acre, barrels.	C Number of properties used in obtaining average.	D Drilling costs per well,[b] dollars.	E Number of wells per acre.	F Drilling cost per acre,[c] dollars.	G Total income per acre after deducting production cost of 10 cents per barrel, dollars.	H Net income from each acre,[d] dollars.	I Total income per acre after deducting cost of 10 cents per barrel, dollars.	J Net income from each acre, dollars.	K Total income per acre after deducting production cost of 10 cents per barrel, dollars.	L Net income from each acre, dollars.
2-4.....	2,930	28	5,000	0.33[e]	1,650	1,465	−185	2,930	1,280	5,860	4,210
5.......	2,550	20	5,000	.20	1,000	1,275	275	2,550	1,550	5,100	4,100
6-8.....	2,090	10	5,000	.14[f]	700	1,045	345	2,090	1,390	4,180	3,480

[a] Land value and mineral rights excluded for sake of simplicity.
[b] Assumed to be approximately the same because wells on all properties were about the same depth.
[c] Obtained by multiplying amounts in column D by respective amounts in column E.
[d] Obtained by subtracting amounts in column F from respective amounts in column G.
[e] Assuming 3 acres per well.
[f] Assuming 7 acres per well.

The costs given are assumed and may not hold even approximately, but the case illustrates the commercial principles involved in spacing. As a general rule, production costs per barrel increase as the production of a well declines. In the present case, however, the production cost has been assumed as 10 cents per barrel for the period under consideration. The material has not been prepared to determine the proper spacing of wells in the Bartlesville field, but to demonstrate a feasible method by which an operator in any field, if he can make an estimate of the amount of oil he will ultimately produce from a property, can determine approximately what spacing practice he should follow.

Operators in such a district desiring to utilize this information can substitute their estimates of drilling and production costs for those used above, and obtain similar results that will demonstrate the approximate acreage that should be allowed under any estimated price of oil.

Table 6 gives similar information for the second class of wells shown in Table 4. This class includes 16 properties on which the wells during the first year averaged 21 to 30 barrels daily. The table has been prepared to show that with higher initial productions the ultimate production is higher, and with the same price of oil as assumed in Table 2 the spacing will necessarily differ considerably. For instance, in Table 2 the most profitable spacing per well, with oil at 60 cents, $1.10, and $2.10, is 7 acres, 5 acres, and 3 acres, respectively. In Table 3, which includes properties with higher total production per acre, the proper spacing with oil at 60 cents per barrel will be 5 acres instead of 7 acres per well; with oil at $1.10 per barrel, it will be between 3 and 4 acres per well instead of 5 acres per well; and with oil at $2.10 per barrel, it will be less than 3 acres per well.

TABLE 6.—*Net profit derived from each acre*[a] *of oil land on several properties in the Bartlesville field, Oklahoma, with different acreage per well, variable price of oil, and wells producing 21 to 30 barrels daily the first year.*

						Price of oil $0.60 per barrel.		Price of oil $1.10 per barrel.		Price of oil $2.10 per barrel	
A	B	C	D	E	F	G	H	I	J	K	L
Average acreage per well.	Average total production of oil per acre, barrels.	Number of properties used in obtaining average.	Drilling costs per well,[b] dollars.	Number of wells per acre.[c]	Drilling cost per acre,[c] dollars.	Total income per acre after deducting production cost of 10 cents per barrel, dollars.	Net income from each acre,[d] dollars.	Total income per acre after deducting production cost of 10 cents per barrel, dollars.	Net income from each acre, dollars.	Total income per acre after deducting production cost of 10 cents per barrel, dollars.	Net income from each acre, dollars.
3-4.....	6,500	5	5,000	0.29[e]	1,450	3,250	1,800	6,500	5,050	13,000	11,550
5.......	5,650	7	5,000	.20	1,000	2,825	1,825	5,650	4,650	11,300	10,300
6-8.....	3,000	4	5,000	.14[f]	730	1,500	770	3,000	2,270	6,000	5,270

[a] Land value and mineral rights excluded for sake of simplicity.
[b] Assumed to be approximately the same because wells on all properties are about the same depth.
[c] Obtained by multiplying amounts in column D by respective amounts in column E.
[d] Obtained by multiplying amounts in column F by respective amounts in column G.
[e] Assuming three acres per well.
[f] Assuming seven acres per well.

The spacing problem is essentially a balance between the increased cost of recovering the oil and the increased value obtained by increasing the number of wells. Where reasonable estimates of future productions can be made, the most uncertain factor in the problem of spacing will be the future price of oil, and the best spacing will vary greatly with this factor. However, the greater proportion of the production will be obtained as a rule early in the development, therefore the spacing should be gaged on the immediate prospects of the oil market with a tendency toward better prices in future, as it has been the history of nearly every field that the price of oil increases as the field ages and the wells produce less.

Much criticism has been made of the economic waste in spacing wells too closely in different Oklahoma oil fields, especially in the Glenn pool. The price of oil, however, at the time of the inception of the Glenn pool was very low, and, according to the principle shown above, when low prices prevail wells should be spaced far apart. The price of oil at present is very much higher, and the authors believe that these wells are not now too close for economical development.

In the fields of the United States practically the universal custom in spacing wells is to follow the "square set" system, every four wells forming a square. This custom has grown partly from the necessity of drilling offset wells along property lines. Where a large block of land is owned by one company and spacing is not unduly influenced by neighbors it is sometimes practicable to space the wells in accordance with the "staggered" system; that is, every four wells forming a rhombus. By this method the area very often can be drained somewhat more thoroughly by the same number of wells. The actual advantages of this system, however, have probably been exaggerated. The general adoption of such a system is impracticable, because of the small holdings in most oil fields and because of the necessity of concerted action among the operators in drilling their leases under such a system.

EFFECT OF METHODS OF OPERATION ON RATE OF DECLINE.

Methods of operating the wells greatly influence their rate of decline in the same way that it does ultimate production. The relation between ultimate production and rate of decline has been discussed previously (p. 15): Anything that causes a more rapid decline of the wells affects unfavorably the total amount of oil that may be obtained from the wells, and vice versa. Improper finishing of the well, improper pumping, failure to clean out the well, infiltration of water, and numerous other factors that interfere with the recovery of oil likewise hasten the decline of the well. Conversely, those things that tend to increase the total recovery will lengthen production and cause a slower decline.

DECLINING PRODUCTION OF AN OIL PROPERTY.

The decline in production of an oil property is the composite decline of the wells producing the oil. The decline in production of a single well is fairly simple to analyze, for after the first "flush" production the well produces less and less oil on account of the reduction in gas pressure and the partial depletion of the supply. The decrease in production of a property, however, is complicated by the "bringing in" of new wells, which probably will vary in output and rate decline, as the different factors affect them differently.

If all the wells on a property are drilled at approximately the same time the decline in production will be the average of the decline of the wells, and the curve showing the average will usually fall at a uniform rate. If the wells on a property are drilled at different times, however, the curves showing the decline of successive wells will in reality be a family of curves which, on account of interference and consequent reduced initial production, will show slower rates of decline for the more recent wells.

When a well is first brought in, the production fluctuates from day to day, particularly if the oil sand is soft and unconsolidated. This period of extreme fluctuation varies in accordance with the local conditions; if the sand is tight it does not last long. If the sand is loose, the period may extend over two or three years, as in the McKittrick field, California, where the production of some wells has been greater at the end of such periods than during the first weeks. The general tendency of the curve of production, however, is steadily downward from the first day the well has been put into shape for production to the end of the well's life, unless the trend is modified by changes in methods of operation.

A typical curve of production by monthly periods on ordinary cross-section paper will show rapid and uneven decline during the first part of the well's history, and slower and apparently more even decline in later life. It has been customary to call the first part the period of flush production, and the latter part the period of settled production, the point of separation being largely a matter of individual opinion. This seeming evenness of settled production is largely illusory, however, as is shown when the same curve is plotted on semilogarithmic paper which shows the true variations in rates. There is likely to be greater fluctuations in the rate of decline during the latter stages of the life of the well, as production is more apt to be influenced by manner of operation.

THE DECREASE IN INITIAL PRODUCTION.

The initial production of wells on a property or in a field, as a rule, decreases progressively from the first wells drilled. In the Cushing field, for example, the first wells had initial production averaging in some parts of the field thousands of barrels daily, whereas a few years later wells in the same sand and in the same district had initial productions averaging in the tens of barrels. This decrease or decline of initial production is caused by interference from the early wells on the sites of the wells drilled later, and the interference is probably exerted chiefly through the extraction of the high-pressured gas from the sand. It is thus affected by the same factors as were discussed under the spacing of wells. The effect that a well will have on an area and on the wells subsequently drilled within that area will depend upon the time between the drilling of the two wells, the distance between them, and the rapidity of movement of the gas and oil through the sand. The latter is a matter of the gas pressure, the coarseness and porosity of the sand, and the viscosity of the oil.

In fields where the sands are fairly regular this rule generally holds true, but where the sands are not uniform there are likely to be many exceptions. The first wells drilled may have been in unfavorable parts of the sand and the later wells in more productive parts of the sand. Moreover, the sand may not have been continuous between the wells, and thus the later wells may not be affected by the early ones.

Often a group of properties developed under usual conditions in a new pool will start the first year with rather small initial production, but within the next two or three years the average daily production the first year will increase because the more prolific parts of the pool have been found. From this time, however, the initial yearly production decreases on account of the drilling of inside locations and the setting up of interference between wells. It is safe to assume that after the peak of the curve showing the initial production for several years has been reached it will not be so high in future years unless a new subsidiary pool or a new sand is drilled into.

In the Robinson pool, Illinois, wells drilled on the inside locations of a 40-acre tract, with which the authors are familiar, usually " come in " at about 10 to 15 barrels the first 24 hours. The production then usually drops in a few days to 8 or 10 barrels a day. The initial production of the outside locations was originally much higher, showing that drainage has affected the whole 40-acre tract. The example of the questionable policy of the Hill Oil & Gas Co. in the South Cushing field has already been mentioned (pp. 19 to 21). The reduction in gas pressure caused by the drilling of wells on the north side of the Shamrock dome probably greatly lessened the initial production of all the wells on a large tract of land.

Because of interference several properties drilled in the Healdton field, Oklahoma, showed a rapid decline in average daily production the first year as well as a rapid decline in actual output. An excellent example was a property on sec. 31, T. 3 S., R. 3 W. During the first year one well only was producing which showed an average daily production of 150 barrels. The second year an average of 1¼ wells produced an average daily production of 270 barrels. The next year there were 24 wells producing, but the average daily production, even though it included much " flush " production, was only 122 barrels. This record shows the rapid effect of interference in the Healdton district. The rapidity with which one well influenced another on this property was undoubtedly due to the porous sand and to the close spacing of the wells.

On another property 5 wells were producing during the first 2 years with an average daily production of 42 and 62 barrels per well, respectively. The third year 14 wells were producing and the average daily production was about 40 barrels; that is, with 9 new wells and their "flush" production the average daily production dropped below that of the 5 wells for the preceding year.

Another large property in the Healdton field had initial production the first day ranging from 60 to 2,700 barrels. The depth of the sand was 800 to 1,000 feet and the average thickness of the sand was 170 feet, although this probably was not all "pay." During the 9 months of 1914, 4 wells averaged 114 barrels per well a day. During 1915, 13 wells (9 new ones) averaged 344 barrels per well a day. During 1916 including the new wells drilled there was an average of 53 wells producing. The average daily production, however, was 148 barrels per well, or 43 per cent of the average daily production of the 13 wells the preceding year.

DRILLING TO MAINTAIN PRODUCTION.

A company frequently desires to drill a property until a certain daily or monthly production is attained, and thereafter to drill just enough wells to maintain this production until the available territory is completely drilled. It is not as simple a procedure as it may seem. The mistake is frequently made of assuming that a definite production can be maintained by drilling an equal number of wells each month or each year. This assumption is not sound, as interference between wells usually begins after several wells have been drilled, and later wells then produce less oil at their beginning than the earlier wells. This factor is most important, but its importance or even its existence is seldom recognized; its effect is difficult to determine as it is greatly influenced by both the rate and the method of development.

The ultimate production of a property depends somewhat on the method of drilling. If two properties situated side by side, under the same conditions of sand, depth, etc., are drilled differently, they will very likely produce different quantities of oil, for the simple reason that ultimate production depends primarily on the proper utilization of every ounce of gas pressure in forcing from the sand the maximum amount of oil. Even if the same two properties are drilled in the same manner, location for location, but at different rates, the property drilled the more rapidly will probably produce more oil. The method of development and the rate of development therefore are factors that must be considered in determining the number of wells to be drilled to maintain production, inasmuch as they influence the initial production of new wells.

A large company in West Virginia has been striving to maintain a production of a little more than 1,000,000 barrels a year since 1911. During that year, 1,865 wells produced a little more than 1,000,000 barrels. In 1916 the production had declined to about 700,000 barrels, for it had become almost impossible to drill enough new wells to offset the normal decline in production of the old ones.

Referring to the rapid decline of initial production in the Healdton field, Oklahoma, the drilling of enough new wells to maintain production over any considerable period of time would have been practically impossible. In the Osage Nation, Oklahoma, a large oil company attempted to maintain a given production and produced during the year 1911 nearly 800,000 barrels of oil from 156 wells. Of those wells, 45 were completed and 4 abandoned during that year. During 1912, 791,000 barrels were produced from 193 wells, of which 42 were completed (about 30 per cent of the old wells) and 5 abandoned that year. Thus by drilling three wells less during 1912 the production fell off only about 9,000 barrels. During the following year oil was produced at the rate of about 600,000 barrels, and only 12 new wells were completed and 2 abandoned. In this case the company found it possible to drill in several proved localities where little drilling had been carried on before.

Another company operating a large tract of land in the Osage Reservation endeavored to maintain a production of 7,000 barrels daily. During December, 1912, the daily production was 7,010 barrels, and in December, 1913, 7,004 barrels. During 1913, 297 wells were drilled, and 657 wells were producing at the beginning of the period. This number of new wells is an increase of about 45 per cent.

The number of wells to be drilled to maintain production is not constant, but it increases rapidly under ordinary conditions because of the decline in initial production. On account of the discovery of new pools, the production of the whole United States has not only been maintained but it has very rapidly increased almost since the drilling of the first oil well in 1859. But after the last new field has been discovered in this country it will be utterly impossible to prevent a gradual decline in production.

There are two general problems connected with drilling to maintain production: (1) The problem of determining the wells to be drilled to maintain production on lands belonging to a single company, and (2) the problem of determining the wells to be drilled to maintain the production of a field. In the former case there is the disadvantage of not having accurate knowledge of the probable future of the field soon enough for use in making estimates, even although detailed information is at hand on the probable acreage that will prove productive. In the second case, information is usually available as to the action of producing properties for several years, as well as accurate statistics on the total production of the field and wells drilled during several periods of time; there is an advantage, therefore, in obtaining the percentage increase over the preceding year in the wells drilled to maintain a certain daily production for the field. If such information can be obtained, it can be applied with proper modifications as an average to any property in the field.

DRILLING TO MAINTAIN PRODUCTION ON A GIVEN PROPERTY.

Lombardi[20] has outlined a method for estimating the wells to be drilled to maintain production on one property, or on a series of properties. A period on the monthly production curves of the properties is selected when production remained at a fairly constant level; the number of wells producing at the beginning and end of the period is determined; and the percentage increase of wells is computed. Lombardi's estimates for the percentage increase of new wells for the Coaling field, California, was 9.33; for the Midway-Sunset field, 14.8; and for all California fields, 8.22. Inasmuch as the percentages are based on the actual performance of wells, such a method is preferable to any other when the necessary information is available.

Lombardi's method involves an assumption that must be carefully considered before a program of development is evolved from it. Should the area from which the basic data was gathered prove to be naturally either more or less productive than the average of the area developed later, all calculations would be thrown off; thus a deeper and more productive sand might cause an overestimate, and a thinning out of the sand, an underestimate in the drilling program.

There are times, moreover, when such information is not accessible, and because estimates must be made it becomes necessary to compare the district for which the estimate is desired with some district where the percentage increase of new wells over old wells is known, or to use some method which will permit the use of such information as may be available.

It is practicable to arrive at a fair idea of the number of wells to be drilled by determining the average rate of decline of the producing wells on the property and by expressing in a curve this decline in production. In addition a gradual and sometimes a rapid decrease in the initial production of new wells drilled must be estimated or assumed. In drilling to maintain production, therefore, the actual decline in the production of the old wells and the reduced initial production of new wells must be counteracted. To overcome this double factor it is necessary to drill an increasing number of wells if a specified daily production is to be maintained.

The problem is complex, particularly because of the difficulty in forecasting the initial production of the newer wells, of which only

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[20] Lombardi, M. E., The cost of maintaining production in California oil fields: Am. Inst. Min. Eng., Bull. 105, 1915, pp. 2109–2114.

an estimate can be made. The older wells decline more slowly than the new ones, and the rate of decline of each new crop of wells will be less as they will probably come in at lower initial production. After the rate of drilling has been determined, the index may be expressed in cents per barrel of oil produced, or even in the number of feet to be drilled during each time-period.

DRILLING TO MAINTAIN PRODUCTION OVER A LARGE AREA.

One method of estimating the number of wells to be drilled in order to maintain production over a large area is to select certain periods in the life of a field during which production has been maintained, and to compute the percentage increase in the number of wells that are producing at the end of the period over those producing at the beginning of the period. This method is especially applicable to large areas where much undrilled territory is available, and to districts like the California fields where it takes many years to drill a field completely, drilling being difficult and costly.

The percentage increase in drilling in the Osage Nation as a whole has been computed in this manner. The computed percentages are approximations and are not fair indices of individual properties in the Osage, for the reason that the development is scattered over a wide area and covers different fields. In the following table the statistics showing yearly production and the producing wells have been divided into three groups. The production during the time represented by each group was practically maintained. The last column shows in percentages the number of new wells required to maintain the production.

It should be noted that the increase in new wells varies from 10 per cent to 20 per cent. During 1909 an increase of only 10 per cent was necessary and the production was identical with that of 1908; but the production for 1907 was greater than that for 1908, so that fewer wells would be necessary during 1909 to maintain production at the smaller amount produced in 1908.

The reverse is true for the years 1910, 1911, and 1912. During 1911 the production was greatly increased over that of 1910, and to maintain during 1912 the 1911 production, which included much "flush" oil, a greater number of new wells had to be drilled. The increase in this case was 20 per cent. The same variation caused the large percentage in 1907 when it was necessary to increase the new wells by 17 per cent. The output of 4,500,000 barrels in 1906 was largely "flush" production, for it was increased from 1,900,000 barrels in 1905.

Thus the effect of the variation in production may be felt over two or three succeeding years, and percentages arrived at by this method should be modified in accordance with the decrease or increase in production preceding the period for which the estimate is to be made. In the present case 12 per cent for 1908 is probably a little too low, for production was not entirely sustained; on the other hand, 14 per cent for 1910 may be a little too high. A safe estimate of the average increase in new wells needed to maintain production in the Osage Nation is probably about 13 per cent.

TABLE 7.—*Oil production and development in the Osage Nation, Okla.*

Group.	Year ending June 30—	Approximate gross production, barrels.	Number of wells producing.	Percentage increase of new wells over preceding years.
I	1906	4,500,000	716	....
	1907	5,500,000	837	17
	1908	4,800,000	936	12
	1909	4,800,000	1,027	10
	1910	5,100,000	1,175	14
II	1911	9,400,000	1,562	....
	1912	9,400,000	1,887	20
III	1916	9,800,000	2,838	....
	1917	9,900,000	3,244	14

No specific amount can be computed that will represent the actual percentage of new wells because of constantly changing conditions, such as the development of richer territory and the discovery of deeper sands. With sufficient information available, however, one can arrive at a fair average of percentage that may be of value.

RELATION BETWEEN FUTURE PRODUCTION OF WELLS OF EQUAL OUTPUT.

In a preliminary paper[21] the conclusion has been advanced that on the average wells of equal output within the same pool will decline approximately along the same curves, and thus, on an average, will have the same future production and equal lives, regardless of the relative ages of the wells. This law, which may be called the law of equal expectations, has since been restated by Beal[22] and Lewis:[23]

> "*If two wells under similar conditions produce equal amounts during any given year, the amounts they will produce thereafter, on the average, will be approximately equal, regardless of their relative ages.*"

Lewis and Beal reached this conclusion independently. Lewis arrived at the fact by comparing the amounts which wells of equal

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[21] Lewis, J. O., and Beal, C. H., Some new methods for estimating the future production of oil wells. Amer. Inst. Min. Eng., Bull. 134, Feb., 1918, pp. 495–498.

[22] Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 1919, p. 36.

[23] Manual for the Oil and Gas Industry under the Revenue Act of 1918. U. S. Treasury Dept., 1919, p. 72.

output would ultimately produce, regardless of their ages, and Beal by comparing the rates of decline of wells of different output. At the time they advanced this conclusion the authors realized that it was unorthodox, contrary to the general belief of oil men, and opposed to prevalent ideas on "settled production." Nevertheless the proof seemed adequate. Subsequent investigations by the authors and by others in all the oil fields of the country have demonstrated its general correctness. The law was first based on averages of wells in certain Oklahoma districts only, and did not mean that the future production must necessarily be the same for any two groups of wells of the same current output, as there is much possibility of variations within certain limits among individuals or groups. There was no doubt, however, that as an average rule the statement was conclusive. If no evidence existed as to individual characteristics of two wells of equal output in the same district their expectations for future production and decline, regardless of their comparative ages, were assuredly equal.

The law operates by constructing, from observed production data, average curves for a prescribed district. It is essential that the data be extensive and representative enough to work out the laws of average. From the same data may be constructed maxima and minima curves. If these curves have been prepared properly, any well or group of wells within the prescribed district may be expected to fall within the two extremes. A well may approach one extreme or the other, but unless there is sufficient information on the particular well or group of wells to place it, its chances are as good for being above as for being below the average; hence until other data may be obtained its expectation is the average for its district. Provided the well or group of wells is compared with the average curve of another district wherein conditions affecting production are different, the expectation of the well or group need not be the same as the average for the district.

The average curve may portray any one of a number of relations among the wells of the district. If it is a decline curve for average production, then the average type of well within that district will follow the average curve regardless of its initial or current output. A well with an initial production of 1,000 barrels will start high on the type curve, but at the end of five years may have declined to 10 barrels. This well may follow the same curve, have the same remaining length of life and the same future production as a new well with an initial production of 10 barrels if both wells have the same average type of curve. On the other hand, two wells of different initial production may follow the same extreme type of curve or any type of curve within these extremes.[24] In other words, the important considerations are the type of curve and the size of the well, not, as was thought in the past, the age of the well.

Since the law of equal expectations, deduced only from observed facts within three districts in Oklahoma, was first set forth by the authors, a wealth of material collected by the Bureau of Internal Revenue has been analyzed by the authors and by many others. The results of these analyses have fully corroborated the law in practically every field in the United States.

Heretofore in some fields the age of the well has been made practically the sole determining factor as to the actual worth of the production from that well. If the law of equal expectations is true, the age of the well has little or nothing to do with the amount of its future production; its present output will be the determining factor.

The law of equal expectations uses comparisons of equal output, either initial, current, or other of the two wells, or uses an average of the groups of wells being compared. The period of time may be a year or the daily average of a year. The writers used primarily yearly periods and daily averages of yearly periods per well, because they could obtain data in this form. Individual records of wells are much to be preferred, but are not obtainable in Oklahoma. Because of the daily fluctuations in the production of wells or groups of wells, the period of comparison must be long enough to gain a fair average of daily or periodic production. Thus a two-year period would doubtless be somewhat more accurate than a yearly period, a semi-yearly period would be less accurate, and in many cases monthly, weekly, or daily periods would be unreliable.

The purchaser of a property would not be satisfied, however, with an estimate in averages or with a general statement if more specific information could be obtained. First of all, it is possible to determine whether the average future production in one pool is greater or less than in another, in which event the purchaser would be willing to pay a higher cost per barrel of daily production in the more promising pool than in the other. Furthermore, there may be great deviation from the average within the same pool. If the property is old and has a good record of previous production, the purchaser may estimate the future by projecting the production curve, and may determine whether and how far the property is above or below the average. If the wells are new, he can hardly do more than assume them to be average and to purchase on that basis. In the sense, then, that with old properties with well-kept records one can estimate the future with more certainty, and therefore buy more wisely

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[24] Lewis, J. O., and Beal, C. H., Some new methods for estimating the future production of oil wells: Am. Inst. Min. Eng., Bull. 134, Feb., 1918, pp. 495–49, fig. 9.

the purchase of old wells entails less risk and is more attractive than the purchase of newer wells of the same size.

The authors have stressed the relation between the output of a well and its future and total productions, although many factors influence the productivity of wells; they have taken into account these many factors, which have been discussed in preceding pages. Some of the factors, like spacing and manner of operation, are changeable by man. The production of each well is the resultant of the combination of factors at the well. The average curve of a district is the resultant of the average combination of the conditions therein; the maxima and minima are the resultant of the combinations of extreme conditions. The production curve of a well is the resultant of the combination of conditions at that well to date, and if these conditions are not changed the future production will follow the projection of the curve, as this curve is the graphic solution of the mathematical equation into which all the conditions at the well enter.

The production of the well is, therefore, in itself the solution of the complex variables that may exist between the many factors influencing it. As the values of these factors may be largely undeterminable or largely uncertain, it follows that the easiest and most accurate way to solve the future of a well's production is to solve the past production by graphic plotting and projection. However, where there is no past record, by judicious analysis of the factors at the well, such as the character of oil, gas pressure, sand thickness and characteristics, and well spacing, one can estimate whether the well will be average in production, or will tend toward either extreme and how much.

Inasmuch as the factors influencing output of which the well's production curve is a resultant, are partly changeable by man, the production curve is changeable to the same extent, and if such conditions are changed in future operations, the projection of the production curve and estimates of future production will be made inaccurate to the same degree. These are the causes for the irregularities in production curves and constitute the main practical difficulties in estimating future output. The changes that can or are likely to be wrought are in general rather small, but they make precise forecasts out of the question. Influx of water may abruptly terminate production; cleaning out may increase production; the use of vacuum is like adding an additional 10 or 12 pounds' pressure to the pool; the application of the Smith-Dunn compressed-air process may add hundreds of pounds pressure and an indefinite supply of energy, and so on. As the symmetrical production curve is the result in total of the expenditure of a definite quantity of energy with the forces that oppose or aid it, anything that adds to or takes away from these forces and energy changes the values in the mathematical equation underlying the symmetry of the curve which, therefore, limits its usefulness for estimating future production by projection. Fortunately such changes are not often of such magnitude as to render production curves useless; on the other hand, in spite of their limitations, graphic curves are proving to be of the utmost value in estimating future production.

This discussion explains some of the underlying principles back of the law of equal expectations and some of the limitations in applying the law. To demonstrate the truths of the law three different methods have been adopted. Figure 5 shows one method of demonstrating that the future production of wells of equal output is, on the average, approximately the same, regardless of the relative ages of the wells.

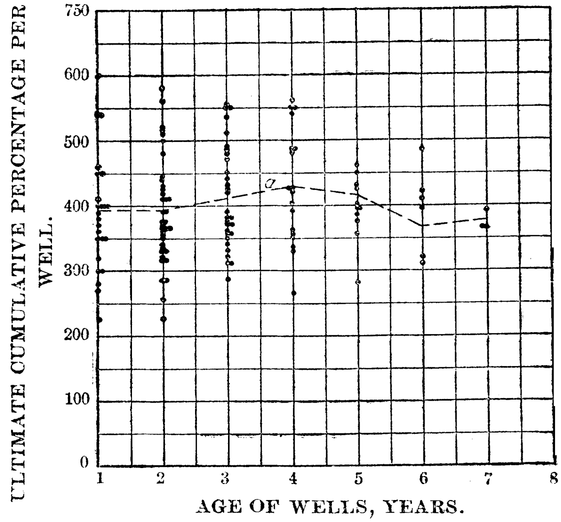

FIGURE 5.—Method of demonstrating that the future oil production of wells of equal output, on the average, is approximately the same, regardless of the relative ages of the wells.

This figure was constructed by plotting the outputs of wells which average 2 to 7 barrels daily in the Robinson pool, Illinois, against their ultimate cumulative percentages along vertical lines, representing the ages of the wells. Thus the ultimate cumulative percentages of wells that made 2 to 7 barrels daily during their initial year were plotted along the first line and the ultimate cumulative percentages of wells making the same amount the second year were plotted along the second line, and so on. It will be seen that the dots representing the different wells form in groups not far from the average line, which is approximately horizontal. If the same data for several hundred properties were plotted in the same manner the minor irregularities in the average line would probably disappear and the line would approach nearer and nearer horizontality.

Figure 6 shows the results of several such computations for different fields plotted as curves. It is to be noted that nearly all of these curves are as nearly horizontal as could be expected from the limited number of points used.

The second method of proving the conclusion was to prepare a generalized decline curve of the largest well in different pools and the maximum and minimum limits which bound the rate of decline of this well.[25] The actual decline of various properties was plotted on these generalized decline curves as a basis. In plotting these production curves the initial point—the first year—was determined by the size of the well and not by plotting the point on the time scale. The average daily production for subsequent years was plotted at intervals of one year from the first point. The several properties plotted on these generalized decline curves may zigzag from one limit to another, depending on the manner of operation and on the other factors that control the rate of decline of oil wells.

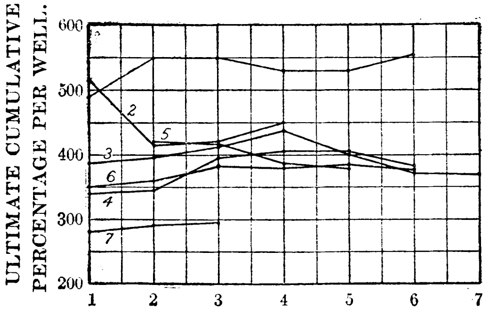

FIGURE 6.—Relation for several oil fields in the United States: *1*, Osage Indian Reservation, Oklahoma, 2 to 7 barrels daily; *2*, same district, 8 to 12 barrels daily; *3*, Crawford County field, Illinois, 2 to 7 barrels daily; *4*, Glenn pool, Oklahoma, 5 to 10 barrels daily; *5*, New Straitsville field, Oklahoma 22 barrels daily; *6*, Nowata field, Oklahoma, 2 to 5 barrels daily; and *7*, Nowata field, Oklahoma, 6 to 10 barrels daily.

Similar decline curves were prepared for the Bartlesville field, Oklahoma; the Nowata field, Oklahoma; the Crawford County field, Illinois; the Caddo field, Louisiana; and the New Straitsville field, Ohio. These curves were published by Beal.[26]

A third method for showing that wells of equal output will, on the average, produce the same amounts of oil in the future is shown in figure 7. In this figure two average properties, which showed the largest daily production per well, were selected in the Nowata field, Oklahoma. Their declines were averaged, and the actual average

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[25] Lewis, J. O., and Beal, C. H., Some new methods for estimating the future production of oil wells: Am. Inst. Min. Eng., Bull. 134, Feb., 1918, fig. 9, p. 497.

[26] Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 1919, pp. 114, 132, 159, 168, 182.

daily production per well was plotted for each year. Their decline is shown by the solid curve in figure 7.

The available production records of the properties in this field were then examined, and the record for the next largest property, a, was selected. This property produced 40 barrels daily per well the first year. Its decline was plotted on the average decline curve, the initial point being located at the proper point on the average curve. After the first point was located, the other points were plotted at intervals of one year each. The decline, which is shown by black dots, follows closely the average decline of the two largest properties. The decline of another property, b, which made 37.5 barrels daily per well the first year, is shown in a similar manner.

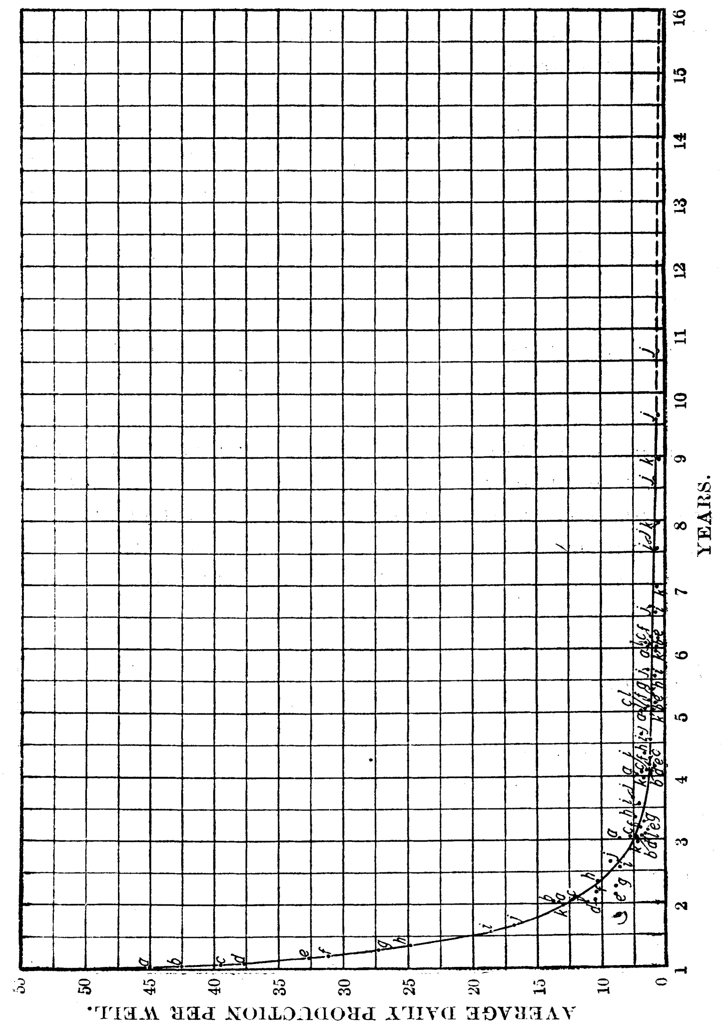

FIGURE 7.—Another method of showing that wells of equal output will have approximately the same future production regardless of the relative ages of the wells.

Several properties were then selected at random and their actual declines plotted in the same way. The letters on figure 7 represent declines of these properties and follow with remarkable regularity the average decline curve. Take, for example, the decline of property k, which made 8 barrels daily the first year. The second year this property made 2.1 barrels daily. During the third year it made 1.6 barrels daily, and during the fourth year it made 1 barrel daily, and so on. In practically every case the average daily production for each year coincides with the average decline of the two large properties selected at random, but these properties had produced a year prior to the inception of property k. In other words property k, although a year younger than the other two properties, produced practically the same amount of oil from that time on, for wells decline along the same curve, and, therefore, must have the same future output, as well as the same future life. It must be remembered that these are actual production records, and the variation above and below the average curve probably is due to the variable conditions of production.

The records of about 70 different properties in the Nowata field were available for study. Practically all of these properties were plotted roughly on figure 7, and approximately 75 per cent of them fit this figure with as great accuracy as those shown by the different letters, although it was impracticable to show them on the figure. Some of the properties varied widely from the declines shown, as would be expected from the variability of some of the factors considered in the discussion of general decline curves, but the majority of the properties in this field fitted the average curve with surprising accuracy.

The method illustrated in figure 7 for building up a generalized decline curve for a district has been still further developed by Beal,[27] who has given it the name "Family curve," in recognition of the fact that there are a series of curve types for each pool. Lewis has used the same principle, employing, however, logarithmic instead of rectilinear coordinate paper. Darnell's method also is based upon the same law. Average curves derived by these several methods from the same data in most cases coincide almost exactly.

CONSIDERATIONS ON "FLUSH" AND "SETTLED" PRODUCTION.

"Flush" and "settled" production are terms commonly used to distinguish between two supposed periods in the life of a well. "Flush" production is commonly understood to refer to the first few months or years of a well's life during which the production fluctu-

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[27] Beal, C. H., and Nolan, E. D., Application of law of equal expectations to oil production in California: Am. Inst. of Min. and Eng. Bull. 152, p. 1297.

ates irregularly from day to day. "Settled" production begins when the well produces at a fairly uniform rate. "Settled" production is a relative term which has been further defined by Smith[28] as indicating that the sharp and irregular decline in the early life of the well has been passed and that production is declining more slowly and regularly. The two terms are indefinite and variously applied; in fact, whether or not the production is "flush" or "settled" is mostly a matter of personal opinion or local custom. Flush production may be considered in some instances as lasting only a few months, whereas, in other cases it may be considered as lasting two or three years before settled production begins.

The differences between flush and settled production are more apparent than real. The decline curves of wells, aside from minor irregularities, do not indicate any critical periods denoting the passage from one to the other. This is shown by the fact that various opinions on this point will be expressed by the oil men who pass judgment on a well's production. The production of a well except for cases out of the ordinary, is a continuous decrease that usually follows, except for minor or explainable irregularities, a symmetrical curve of decline. The distinction between flush and settled production is mostly arbitrary and the latter term means, more than anything else, a slower rate of decline than at first. The law of equal expectations, as stated on page 41, shows that the rates of decline of wells of equal output, one new and the other several years old, may be the same, although popularly one will be considered flush production and the other settled. The curve, figure 7, sufficiently shows that the "flush production" of a small well may be the same as the settled production for a larger well. When the production curve is "straightened out" on logarithmic paper it shows as a straight line, hence, there can be no such distinction between flush and settled production as has been commonly made.

In practically all the oil fields east of the Rocky Mountains the price paid for producing oil properties is based on "settled" production—that is, a certain amount is given per barrel of net daily production of the property. This amount varies with the age of production and with future prospects of drilling new wells.

THE LIFE OF OIL WELLS.

A knowledge of the length of time a well will produce oil is of importance to the oil operator. Not only does such knowledge make it possible to charge off on a sounder basis the depreciation on capital

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[28] Smith, C. G., Cost accounting for oil producers: Bull. 158, Bureau of Mines, 1917, p. 115.

invested in physical property but it also provides information for making depletion deductions on account of the progressive exhaustion of the oil resources, if such a method of amortization is used, and gives the operator a working basis for the proper management of his property.

The life of an oil well may range from a few months of very high or very low productivity to many years. In some of the Appalachian fields the average daily production amounts to only a few gallons and the well is pumped not oftener than once a week. This period between the times of pumping is usually allowed for the oil to flow by gravity into the well, for the expulsive forces have long since been exhausted. Plate I, *B*, shows a well still producing within a few hundred feet of the first well drilled in this country, near Titusville, Pa. Many wells in this district are 40 or 50 years old and make only a few gallons a day.

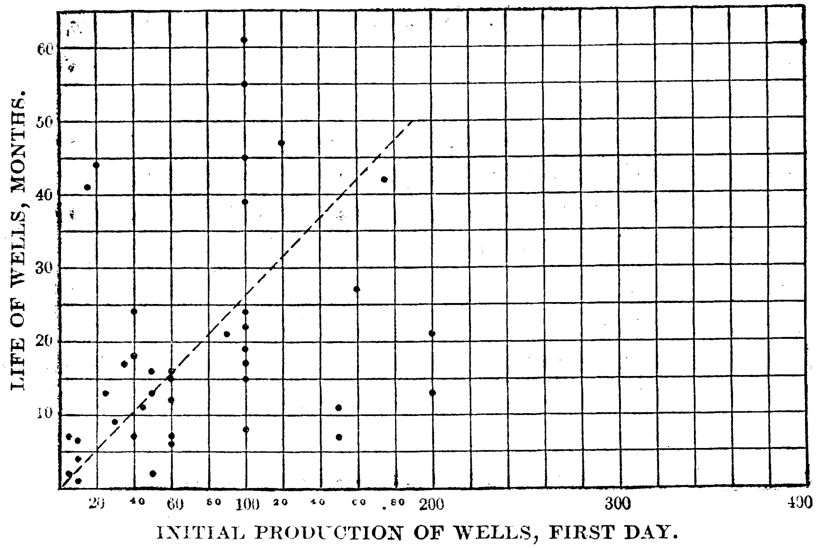

FIGURE 8.—Sketch showing the relation of the initial daily production to the life of several Gulf Coast salt-dome wells. The wells represented were selected at random from six Texas domes, Spindletop and Saratoga being better represented than the others.

In the Gulf Coast field the lives of oil wells associated with the salt domes are, as a general rule, very short. Figure 8 shows the relation of the initial daily production of 40 oil wells to their life in several Gulf Coast salt domes. The wells are represented by dots and were selected at random from six Texas salt domes, Spindletop and Saratoga being better represented than the other four. The dashed line shows the approximate average of the dots on the sketch, so that, judged from these 40 wells, the average life of a well whose production the first day was 100 barrels would be about 27 months. This line is, of course, only approximate and is based on a comparatively small number of wells. It seems to be the consensus of opinion among the oil operators in that district, however, that the average salt-dome well has a productive life of not to exceed two and one-half or three years.

FACTORS CONTROLLING THE LIVES OF OIL WELLS.

The life of an oil well is indefinite and is controlled by many factors. It is, of course, intimately related to the rate of decline of the well. All factors influencing the decline in the production of an oil well, therefore, influence the life of the well. Small holdings in an oil field are a potent factor in shortening the lives of the wells in that field, for the reason that line drilling is forced and operations are not carried on in the most workmanlike manner, thereby permitting incursions of water and the waste of gas pressure.

An example of the influence of close spacing on the flowing life of wells may be shown by statistics gathered in the Healdton field, Oklahoma. Of 60 wells drilled on 8 leases in this field, all but 6 were put on a pump a few days after having been brought in. Practically all these wells were completed before the field was drilled up and the gas pressure reduced. One well brought in during February, 1914, with an initial production of 25 barrels was producing the same amount 30 days later, and again the same amount on September 30, 1916. This well was put on the pump after flowing for 2½ years, and is an example of what might be expected with wider spacing. One well came in at 75 barrels per day and was put on the pump about one month after completion. The Healdton wells, as a rule, were rather prolific and all had fairly high initial production. The great fault in this field, however, was the close spacing, owing to small holdings, which caused a very rapid reduction of gas pressure.

Probably the most important of the factors that tend to cut off or to prolong the life of an old well is the net value of the oil to the producer. When the well declines to a small daily production and this margin becomes very narrow, a slight increase in price will cause a corresponding increase in the margin, and the life of the small well will be greatly extended thereby.

Because of the flattening out of the decline curve, a change in the profitable minimum production has a great effect on the well's life. Thus, a well that declines from 100 barrels daily average to 10 barrels daily average in 3 years may decline to 1 barrel daily in 7 years more, and to one-tenth barrel daily in an additional 20 years. Thus, a reduction from 1 barrel to one-tenth barrel daily in the profitable minimum may treble the life of the well.

An increase in the price of oil may make possible the cleaning out of the well, the extraction of thousands of barrels of oil from it, and add many years to its life. The exhaustion of a property or a well does not necessarily mean that all of the oil has been withdrawn from the productive sand, but rather that the property can no longer be operated at a profit. Absolute exhaustion of the oil in a sand is impossible, and the life of a well is, therefore, mostly a relative term.

The question has been asked, "Do wells of large initial output have a shorter life than wells of a smaller initial output?" According to figure 8, this is not true in the Gulf Coast field, for the larger the initial production the longer the well produces. It is evident also from figure 7, which proves that wells of the same output have the same average future expectation regardless of their ages, and that, on the average, wells of higher initial production have longer lives. In general, the larger the well in a district the longer the life, but there will always be many exceptions.

The life of a well may be computed by projecting the decline curve to the assumed minimum profitable production. For instance, the average production per well the first year on more than 200 properties in the Bartlesville field, Oklahoma, was 17 barrels. If the decline curve of this average well is projected to a point where the production is 6 per cent of the average daily production the first year, the well will be producing one barrel daily. This gives a life of from 13 to 15 years for the average well in the Bartlesville field.

The objection to this method of determining the average life is the necessary assumption of a minimum production to which the well can be profitably pumped. As explained above, the minimum profitable production depends on the net profit derived from each barrel of oil, and an increase in price received will considerably extend the life of the well. In 1915, when the price of oil in Oklahoma was 40 cents per barrel, wells were abandoned before they reached one barrel daily, but at the present high price (January, 1920, $3 per barrel) many of the wells can be pumped to a few gallons daily before abandonment. Many production records in the Bartlesville and Nowata fields, Oklahoma, show wells that have produced for 13 years and are still averaging two or three barrels daily.

Assuming, however, that all wells are abandoned at the time they reach a production of one barrel daily, the wells in the fields of Oklahoma have an average life of 2 to 20 years. It is true that the wells in some localities will be abandoned much earlier. Many of the wells drilled to the Wheeler sand in the Cushing field, for example, were abandoned a few months after their completion. The lives of the shallow wells in southeastern Kansas would be very short if cut off at one barrel daily, but on account of the low operating cost the wells are being pumped to much smaller amounts. As a general rule, the wells in the fields of north Texas and Louisiana, except Ranger district, will produce for 15 or 20 years before they reach one barrel daily. In Illinois and in southeastern Ohio the average life is 10 to 15 years. In California the productive horizons are thick and the gas pressure is usually high, so that the wells producing under these conditions probably will not reach the minimum production for 20 or 25 years.

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