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ESTIMATION OF UNDERGROUND OIL RESERVES BY OIL-WELL PRODUCTION CURVES

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ESTIMATION OF UNDERGROUND OIL RESERVES BY OIL-WELL PRODUCTION CURVES.

By WILLARD W. CUTLER, JR.

PREFATORY STATEMENT.

SCOPE OF BULLETIN.

This bulletin reviews, in the light of recent experience, the use of production-decline curves in estimating the future production of oil from wells. It deals with the estimation of the reserves of recoverable oil in properties already producing or in those adjacent to them, takes cognizance of the physical laws governing expulsion of oil from oil sands, and shows how the production-decline curve can be made to utilize these laws in estimating reserves and rates of production. The valuation of oil properties should be based on the total amount of oil recoverable from a property by the methods in use, the rate of recovery, the cost of production, and the selling price. Numerous other curves besides those for reserves and rates of production may be formed from the production-decline curve and will present desired information in a convenient time-saving form. These curves also are described.

Methods developed before the production-decline curve method was used are briefly discussed in order that the principles on which estimations of oil reserves are based may be made plain. The construction of curves and tables for estimating future production of individual wells and of average wells in most of the important oil districts of the United States is described and operating problems that may be solved by the use of production-decline curves are discussed. The bulletin does not deal with costs, oil prices, or the methods of evaluating oil properties.

Many engineers have amply demonstrated the value of the production-decline curve method by forecasting within reasonable limits the production of many thousands of wells and tracts. The value of similar estimates depends however, on (1) the application of trustworthy methods; (2) the care and judgment of the estimator; and (3) the length and reliability of the records and the accuracy of other information used in estimating future production. When adequate records and information are available, experience has shown that a qualified engineer can forecast production far more accurately than has been deemed possible, except where the usual conditions governing the expulsion of oil from a sand have been radically changed by applying compressed air or by flooding with water, or, to a less degree, by using vacuum. In general, the production-decline curve method, though there are limits to its accuracy, is far more trustworthy than any other.

CLASSES OF OIL PROPERTIES.

In the evaluation of oil properties at least five distinct classes have to be considered:

(1) Properties from which oil is obtained through wells drilled into oil-filled sands or other porous formations containing gas under pressure. The properties in most of the fields in the United States belong in this class.

(2) Properties yielding oil through wells drilled into sands or other formations, in which the natural gas pressure is augmented, or replaced if absent, by artificial means—such as gas pumping (vacuum), compressed air or gas, and flooding with water.

(3) Properties yielding oil through wells tapping fissures or very porous zones where either hydrostatic pressure or gas, or both, are the expellant forces. The so-called " Southern fields " of Mexico are generally thought to be of this class.

(4) Properties that will yield oil by mining and treatment of oil sands.

(5) Properties from which oil will be obtained by mining and retorting oil shales.

This bulletin deals with the estimation of oil reserves in properties of the first and second classes only.

DEVELOPMENT OF PRESENT METHOD.

Engineers of the Bureau of Mines have been instrumental in developing the production-decline curve method for estimating oil reserves, In 1918, J. O. Lewis and Carl H. Beal,[1] then petroleum technologists of the bureau, advanced the " law of equal expectations," which has since been adopted as the basis of the production-decline curve method. The ideas advanced by Lewis and Beal in 1918 were later discussed at length by Beal[2] and published in bulletin 177 of the Bureau of Mines.

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[1] Lewis, J. O., and Beal, Carl H., Some new methods for establishing the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 477–504.

[2] Beal, Carl 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.

Prior to the publication of these papers, valuable contributions relating to methods of estimating future production were made by Thompson,[3] Requa,[4] Washburne,[5] Lombardi,[6] Arnold,[7] Johnson and Huntley,[8] Bacon and Hamor,[9] and Pack.[10]

On the enactment of the revenue act of 1918, the office of the Commissioner of Internal Revenue, Treasury Department, undertook an investigation—conducted by Ralph Arnold, then chief of the subdivision of natural resources of that office—to determine the best methods for evaluating oil properties. The ideas presented by J. O. Lewis, of the Bureau of Mines, were used as a basis of the investigation, and the results were published by the Treasury Department in 1919 in the "Manual for the oil and gas industry." Great credit is due the men who assisted in this work. Among them were J. O. Lewis, C. H. Beal, and A. W. Ambrose, of the Bureau of Mines; G. B. Richardson and E. W. Shaw, of the United States Geological Survey; Cassius A. Fisher, J. L. Darnell, W. A. Williams, Tom Cox, C. F. Powell, Roswell Johnson, E. deGolyer, V. R. Garfias, A. D. Brokaw, L. G. Donnelly, Norval White, Thomas E. Savage, James H. Hance, Arthur Eaton, E. D. Nolan, L. C. Glenn, Barnum Brown, Calvin T. Moore, W. E. Wrather, Abner F. Dixon, M. W. Mattison, C. W. Comstock, and others.

In August, 1921, a revised edition of the manual was published under the supervision of C. F. Powell and Albert H. Fay, former chiefs of the natural resources subdivision, assisted by Norval White, Roger White, Lyon Terry, Walker S. Clute, Oscar Rheinhold, Burr MacQuirt, and other members of the oil and gas section of the office of the Commissioner of Internal Revenue. The section of the manual (revised edition, August, 1921, pp. 72 to 185) dealing with the estimations of underground recoverable reserves of oil and the curves and tables for different pools and districts was prepared by the writer of this bulletin and by Roger White, of that office.

Other engineers have made many other valuable contributions in papers and publications during late years. Reference to some of this

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[3] Thompson, A. B., Petroleum mining and oil-field development. 1910. 362 pp.

[4] Requa, M. L., Present conditions in the California oil fields: Am. Inst. Min. Eng. Bull. 64, April, 1912, pp. 377–386; Methods of valuing oil lands: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 409–428.

[5] Washburne, C. W., The estimation of oil reserves: Am. Inst. Min. Eng. Bull. 98, February, 1915, pp. 469–471.

[6] Lombardi, M. E., The valuation of oil lands and properties: Internat. Eng. Cong., San Francisco, September, 1915; also published in Western Eng., vol. 6, October, 1915, pp. 153–159.

[7] Arnold, Ralph, The petroleum resources of the United States: Econ. Geol., December, 1915, pp. 695–712.

[8] Johnson, R. H., and Huntley, L. G., Principles of oil and gas production, 1916. 371 pp.

[9] Bacon, R. F., and Hamor, W. A., The American petroleum industry. 1916. 963 pp.

[10] Pack, R. W., The estimation of petroleum reserves: Am. Inst. Min. Eng., Bull. 128, August, 1917, pp. 1121–1134.

literature is made in other parts of this bulletin and in the bibliography at the end.

ACKNOWLEDGMENTS.

The preparation of this bulletin was begun under the guidance and direction of J. O. Lewis, formerly chief petroleum technologist of the Bureau of Mines, who has been instrumental in the development of the production-decline curve method. His suggestions and criticisms were exceedingly helpful.

A. W. Ambrose, formerly chief petroleum technologist of the Bureau of Mines, offered many valuable ideas and suggestions.

Roger White, of the oil and gas section of the office of the Commissioner of Internal Revenue, assisted in preparing the curves of the various fields, as presented in Table 16 on page 64.

Lyon F. Terry, formerly of the oil and gas section of the office of the Commissioner of Internal Revenue, assisted in the development of the rate of production curve. Walker S. Clute, formerly of the same section of that office, assisted in determining the effect on production of spacing and delay in drilling. R. van A. Mills, petroleum technologist of the Bureau of Mines, gave valuable suggestions regarding the effect of natural conditions on production.

Bulletin 177, Bureau of Mines, by Carl H. Beal, has been of much aid in the study of methods employed.

Especial thanks for records of pressure in oil wells in Buena Vista Hills, Calif., are due E. C. Gaylord, geologist of the Pacific Oil Co.

The author also acknowledges courtesies shown by J. T. Darnell and C. L. Powell, former chiefs of the natural resources subdivision of the office of the Commissioner of Internal Revenue; Norval White, former chief of the oil and gas section of that office; Ralph Wardwell, D. D. Riddle, and Burr MacQuirt, formerly of the same section; Prof. Roswell Johnson, of the University of Pittsburgh; and T. E. Swigart, of the Bureau of Mines.

The manuscript was read and criticized by A. W. Ambrose, Carl H. Beal, J. O. Lewis, T. E. Swigart, and E. P. Campbell. H. B. Cooke did the preliminary drafting and J. G. Shumate prepared the final illustrations.

DEFINITIONS.

Some of the terms used in this bulletin are defined below:

Production records.—In this bulletin production records refer to the records—by days, months, years, or other units of time—of the yield of oil, not of the total fluid that a well or tract has produced.

Future production, unless otherwise stated, is the estimated amount of oil that a well, tract, or field is expected to produce in the future under natural conditions.

Ultimate production is the total amount of oil that an area or well will ultimately produce. The ultimate production per acre is the sum of the past and the estimated future production of the wells in a given area, divided by the number of acres in that area.

Natural conditions.—Conditions that govern the production of oil and are not controlled or caused by the operator are defined as natural conditions. They include the porosity, texture, depth, thickness, and productive extent or area of the reservoir rock; the oil, gas, and water contents of the producing formation; the gas pressure; and the geological conditions determining the accumulation of the oil and gas.

Artificial conditions.—Those conditions governing the production of oil that are controllable or caused by the operator are defined as artificial conditions. They include the time and rate of drilling wells; the spacing of wells; and the use of artificial means—such as gas pumping (vacuum), compressed air, and flooding—to stimulate production.

Flush production.—In this bulletin the term "flush production" denotes the erratic production of a well during the first period of its life, before the regular decline of production sets in. Flush production can seldom be used in constructing curves for estimating underground reserves of oil.

Settled production is the production of a well after a fairly regular decline has started. Production records during this period may be used in constructing curves for estimating underground reserves of oil. The terms flush and settled production can not be defined and interpreted strictly, but they are so commonly used by oil operators that they are here given as definite meanings as possible in order to avoid confusion.

Economic limits.—The economic limit of production is here defined as the smallest production per unit of time at which a well may be operated profitably. It differs greatly for different wells, and depends on two factors, (1) the cost of production and (2) the price of oil. As the future price of oil can not be foretold, the economic limit assumed must be based on reasonable estimates of future costs and prices.

NOMENCLATURE OF CURVES.

A study of the literature dealing with production curves shows great confusion of nomenclature. In the spring of 1920 a list of the various terms that had been used to describe curves was compiled and submitted to about 60 petroleum engineers with a request for suggestions and criticisms. The nomenclature used in this bulletin was compiled in accordance with the replies to these requests.

The footnotes (Nos. 11 to 16) refer to publications in which this nomenclature has been used.

Production-decline curve.[11]—A curve based on the past performance of a well or wells; it shows the amounts of oil produced by the well or average of a group of wells during equal successive periods of time. (See Fig. 2, p. 17.) The abscissas of this curve are time and the ordinates are barrels of production.

Percentage-decline curve.[12]—A curve showing the decline in the production of a well or average well of a property or field, the productions during the successive units of time being expressed as percentages of the production during the first unit of time, which is taken as 100 per cent. (See Fig. 1, p. 14.) The abscissas of this curve are time and the ordinates are the percentage production of the first unit of time. This curve is not used in the production-decline curve method.

Future-production curve.[13]—A curve based on the extension of a production-decline curve; it shows the estimated average future production carried to a stated economic limit for wells in the same tract, pool, or field, with relation to the amount of oil that they produced during the past year or other time unit. (See Fig. 19, p. 72.) The abscissas of this curve are barrels produced during the past year or other time unit and the ordinates are the estimated future production in barrels.

Appraisal curve.[14]—A curve based on the past performance of wells; it shows the estimated average ultimate production to a stated economic limit of the wells in the same tract, pool, or field, with relation to the amount of oil that they produced during the initial year. (See Fig. 16, p. 59.) The abscissas of this curve are barrels produced during the initial year and the ordinates are the estimated ultimate production.

Future curve.[15]—A curve that shows the future production carried to an economic limit of a well or average well of a property or field with reference to the remaining life of the well; it is used as an auxiliary curve to the production-decline curve. (See Fig. 21, p. 75.) The abscissas of this curve are time and the ordinates are barrels of production.

Rate-of-production curve.[16]—A curve auxiliary to the production-decline curve; it shows the daily rate of production of wells whose

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[11] Manual for the Oil and Gas Industry, Treasury Department, U. S. Internal Revenue (under Revenue Act of 1918). 1919.

[12] Lewis, J. O., and Beal, Carl H. Some new methods for establishing the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 477–504.

[13] Manual for Oil and Gas Industry (1919).

[14] Manual for Oil and Gas Industry (1919).

[15] Beal, Carl H., and Nolan, E. D., Application of law of equal expectations to oil production in California: Am. Inst. Min. Eng. Bull., August, 1919.

[16] Manual for the Oil and Gas Industry. (Rev. ed., August, 1921.)

yearly production is shown by the production-decline curve. (See Fig. 22, p. 77.) The abscissas of this curve are time and the ordinates are barrels of production.

The curves defined are all closely related, and the production-decline curve gives the information necessary to form the others.

TERMS.

The word "average" should always be used before the main description of a curve, if the curve represents the average of a number of wells, tracts, or fields. The word "estimated" should always be used before the main description of a curve unless the whole curve is formed from records of actual production.

To the main description of a curve may be appended any descriptive remarks which are deemed necessary to identify the curve further. These remarks may include a description of the form of records used, such as tract production or individual well productions; the method used in forming the curve, such as the "family curve" method, whether plotted on coordinate or logarithmic paper; segmental method, or appraisal-curve method; and any other comments the writer deems necessary. The remarks may be added or omitted as desired. Where added, it serves to establish the reliability of the curve. Below are examples:

"Estimated average future-production curve for Cushing field, made from tract production records by appraisal-curve method."

"Average production-decline curve for 'Jones lease,' made from individual well records by segmental method."

In practice the designation of the type of curve may be abbreviated Thus curves of individual wells are referred to as well curves, curves of tracts as tract curves, and curves of fields as field curves.

CHAPTER I.—PREVIOUS METHODS OF ESTIMATING RESERVES OF OIL.

LIST OF METHODS.

In the early days of the oil industry, estimates of future productions were based merely on the judgment of the operators and usually were very unreliable. As the principles underlying the production of oil became recognized, methods for estimating future output were advanced. Four methods were used before the production-decline curve method was developed. These were: (1) The barrels-per-acre method, (2) saturation method, (3) constant percentage-decline method, and (4) percentage-decline curve method.

BARRELS-PER-ACRE METHOD.

In the barrels-per-acre method, the ultimate production per acre of a producing or exhausted area is employed as a unit measure for estimating the ultimate production per acre of another area. Thus if an exhausted tract had produced 5,000 barrels to the acre, and it is considered that a near-by undrilled tract should be equally productive per acre, an ultimate production of 5,000 barrels per acre is estimated for the undrilled tract. Such a comparison is usually applied only to adjacent or near-by tracts, though sometimes it is applied to distant tracts in the same pool, or to tracts in other pools where the geological conditions and other conditions affecting production are thought to be similar.

The ultimate production per acre of the area, used as a unit of measure, must be multiplied by a hazard factor such as 1, ¾, ⅔, ½, ¼, etc. This factor should be based on the relative original productivities of the areas considered (these productivities being dependent on geological location, condition of sands, and oil content); the percentage loss in recoverable oil due to the exhaustion of gas pressure and the draining of oil content by wells already producing; the hazard of dry holes and the probability of a smaller recovery, because of water troubles and mechanical difficulties, than was estimated. The determination of this factor involves a study of the geology and other conditions in the pool, as well as the history and production of the wells already drilled. On account of the indefinite nature of its components, the correct factor is difficult even to approximate.

The barrels-per-acre method only gives the ultimate production that may be expected. It does not estimate the rate of recovery, which is extremely important with respect to both production and evaluation.

When areas not yet exhausted are used as a unit of comparison, the barrels-per-acre method necessitates an estimation of the future production of the area in order to state the ultimate production per acre. This requires the use of some other method, preferably the production-decline curve, as a means of estimating the ultimate production per acre of any but exhausted or nearly exhausted areas. The future production thus estimated represents a large or a small percentage of the estimated ultimate production, depending on the stage of exhaustion of the area. A reliable estimate of future production is an important factor in determining the ultimate production of such areas with a long remaining life, but may be negligible for areas almost exhausted.

The varying productivity of different areas in a pool makes estimations based on the production per acre of even near-by properties decidedly unreliable.

Plate II (p. 94) shows the irregularity in productivity existing throughout the Hewitt field, Carter County, Oklahoma. Such irregularities exist in many pools and fields. Even where natural conditions are similar, the number of wells drilled, the time of drilling, and the manner of operation may cause material differences in the recovery per acre from two properties.

The barrels-per-acre method should be employed only for estimating oil reserves in undrilled but proved properties, and for checking results obtained by the production-decline curve method. If information on the thickness of the producing sands is available, the ultimate number of barrels per acre-foot of drilled-up territory may be used as a check on less-drilled areas. Thus the estimates will contain an allowance for the thicknesses of the oil sands.

SATURATION METHOD.

The saturation method[17] consists in first estimating the total oil content of a property by multiplying the volume (area times thickness) of the oil measures by the percentage of porosity and percentage of estimated saturation of the reservoir rock. The probable percentage that may be recovered of the total amount of oil in the property is then estimated and multiplied by the total amount of oil, in order to determine the amount that eventually will be produced.

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[17] Washburne, C. W., The estimation of oil reserves. Am. Inst. Min. Eng. Bull. 198, February, 1915, pp. 469–471.

As knowledge of underground conditions is usually meager, the factors of porosity and saturation are for most wells impossible even to approximate[18]; also, the amount of recoverable oil varies with both natural and artificial conditions, and the percentage of the total oil that will be recovered can not be determined without a thorough knowledge of all these conditions. The porosity of producing sands is usually estimated as 12½ to 25 per cent of the volume,[19] and the recoverable oil may be reasonably estimated as 10 to 30 per cent of the total oil, hence the estimated recoverable oil by this method will be about 1.25 per cent (12½×10÷100) to 7.5 per cent (25×30÷100) of the total volume of the sand underlying the property, if drainage of oil from neighboring areas is not considered. Actually in many pools in the United States, the ultimate recovery obtained is 2 to 4 per cent of the total volume of the producing sand contributing to a well.

The results obtained by the saturation method are obviously unreliable, and the method should be used only for making rough preliminary estimates of the recoverable underground reserves of oil in undrilled areas of new pools.

CONSTANT PERCENTAGE-DECLINE METHOD.

The constant percentage-decline method, formerly used in California, was based on the assumption that after the period of flush production had passed the production of a well would show a constant percentage decline each year. When this method was applied, for example, to a well whose production was 1,000 barrels for the first year considered and 800 barrels during the second year, a decline of 20 per cent per year, the productions for succeeding years were estimated as 80 per cent of 800, or 640 barrels for the third year, 80 per cent of 640, or 512 barrels for the fourth year, and similarly a 20 per cent decline for each succeeding year. This method was far in advance of any other that had been presented before. The constant-percentage decline curve is a straight line when plotted on semilogarithmic paper and a curve concave to the left when plotted on logarithmic paper. It is not a hyperbolic curve, which is the true curve for oil wells with gas as the principal expelling agent.

Arnold and Anderson[20] in referring to the production for the Oil City area in the Coalinga district, California, say: "The average normal rate of decrease per well for the field, disregarding the rapid decrease from the initial production, has been between 15 and 20 per cent per year since 1900." Estimations thus made were not as

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[18] King, F. H., Conditions and movements of underground waters: U. S. Geol. Survey, 19th Ann. Report, Pt. II, 1899, pp. 209–215. Lewis, J. O., Methods for increasing the recovery of oil from wells: Bull. 148, Bureau of Mines, 1917, pp. 15–19.

[19] Lewis, J. O., work cited, pp. 16–32.

[20] Arnold, Ralph, and Anderson, Robert, Preliminary report on Coalinga oil district: U. S. Geol. Survey Bull. 357, 1908, p. 79.

reliable as estimations made by the production-decline curve method because few fields have a constant yearly percentage decline.

Figure 11 (p. 34) shows the danger of estimating future productions by this method. Semilogarithmic paper was used for plotting the curves. The broken line represents the production-decline curve of the average well in the East Side Coalinga field California, as obtained from actual production records. The full line represents the production-decline curve of the same average well, based on the first eight years of production and the same percentage decline in production in future years. The area between the full and dashed lines shows the error that this method would introduce in estimating reserves in this field. The error may not be much for a short future period, but increases tremendously with estimates extended over long periods. In general, the method underestimates the recoverable reserves, is now obsolete, and should not be used.

PERCENTAGE-DECLINE CURVE METHOD.[1]

The percentage-decline curve method was based on the percentage-decline curve, which showed the production during successive units of time, expressed as percentages of the production during the first unit of time which was taken as 100 per cent. Future production is estimated by extending the curve.

For estimating the future production of individual wells from their own records, or of tracts from their own records, this method was reliable and gave results similar to those obtained by the production-decline curve, which is described in this bulletin. The method was unnecessarily laborious because it required the conversion of production into percentages and then percentages back again into production.

Percentage-decline curves were used also to estimate the future production of wells and tracts other than those from whose records the curves were formed. It was believed that wells of the same age, regardless of size, if producing under similar conditions, would have the same percentage declines. Thus the future productions of wells and tracts whose production records were not available were esti-

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[1] Lombardi, M. E., The valuation of oil lands and properties: Internat. Eng. Cong., San Francisco, September, 1915; also published with a few changes in Western Eng., vol. 6, October, 1915, pp. 153–159. Johnson, R. H., and Huntley, L. G., Principles of oil and gas production, 1916, p. 154. Pack, R. W., The estimation of petroleum reserves: Am. Inst. Min. Eng. Bull. 128, August, 1917, pp. 1121–1134. Beal, Carl H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, p. 108. Requa, M. L., Method of valuing oil lands: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 409–428. Johnson, Roswell, Amer. Ass. Pet. Geol., vol. 3, 1919, p. 422. Hager, Dorsey, Oil field practice, 1921, p. 235.

mated according to the percentage-decline curves of similar wells or tracts, the age of the wells determining the corresponding percentage decline.

Average percentage-decline curves were constructed for properties or fields by averaging the first year's production of all the wells or tracts, calling that average production 100 per cent, then averaging each succeeding year's production of the wells and expressing these average productions in terms of percentages of the first year's production.

The future production of wells or tracts was estimated from the average curve by using the age of the wells to determine what percentage decline to employ. If tracts were under consideration a large amount of labor was involved in determining the age of the average well on the tract.

The error in applying a percentage-decline curve to wells other than the well from which the curve was made, and in estimating future productions thereby, lies in the fact that the percentage of decline relates more to the relative sizes of the wells than to their relative ages. A careful study of numerous production records has shown that wells of large and small daily production in the same pool, even if they are of the same age, usually have different percentage declines, the percentage decline of large wells being usually much greater than that of the small wells.

An example is given here to illustrate the fallacy in the percentage-decline curve method. Table 1 shows the production records of a tract in the Avant-Ramona district, Oklahoma. From columns 1 and 4 of the table the average production-decline curve (A) in Figure 1 was plotted.

TABLE 1.—*Production record of a tract in the Avant-Ramona district, Oklahoma.*

1 Year.	2 Production, barrels.	3 Number of wells.	4 Production of average well, barrels.	5 Percentage of yearly production to first year year's production.
1	104,246	15	6,947	100
2	70,928	16	4,433	63.8
3	48,902	17	2,873	41.4
4	37,373	17	2,196	31.7
5	29,323	17	1,729	24.9
6	24,939	17	1,467	21.2

Table 2 following shows the error introduced into estimations of future production for a well of initial yearly production of 2,873 barrels in this tract, if the same percentage production for each year is used as for the average well of an initial yearly production of 6,947 barrels.

TABLE 2.—*Example of error in estimation of future production made by percentage-decline curve.*

Year.	Acutal production decline of average wells, barrels produced per year.	Percentage-decline curve.		Error, per cent.
		Calculated from Table 1, per cent.	Estimated production, barrels.	
1	2,873	100.0	2,873	0.0
2	2,196	63.8	1,835	−16.5
3	1,729	41.4	1,190	−31.2
4	1,467	31.7	908	−38.0
Total	8,265		6,806	−17.6

This table shows that during the three years subsequent to the initial production of 2,873 barrels the estimated production of the well by the percentage-decline curve method will differ 17.6 per cent (8,265—6,806=1,459 barrels) from the actual production of the average well of this tract.

Figure 1 illustrates graphically the error involved by the use of the percentage-decline curve in this example. Curve A, plotted from scales 2 and 4 (shown at the left of the chart), represents the average percentage-decline curve, based on an initial production of 6,947 barrels a year, and for that particular initial production is identical with the average production-decline curve plotted from scales 3 and 4 for this tract, as shown in Table 1. Curve B, plotted from scales 1 and 5, represents the percentage-decline curve for an average well, in this tract, with an initial yearly production of 2,873 barrels, when its yearly productions for each subsequent year are figured on the basis of the percentages of the yearly productions of a well with an initial production of 6,947 barrels. The difference between the two curves A and B (hatched area) represents the error involved by applying the percentage-decline curve to wells of these different initial productions.

If an average percentage-decline curve is constructed from many well or tract records, the percentage-decline of many wells of different sizes is averaged, and in the percentage-decline curve obtained the yearly percentage decline tends to be the same regardless of either the size or age of the wells. Such a curve would be correct only for wells whose percentage decline was constant throughout their lives. Past production records show, however, that only a few fields have wells of this type.

The cumulative percentage curve and other types of percentage curves based on the percentage-decline curve involve the same or similar errors when applied to wells or tracts other than the wells or tracts from whose records they have been derived. It is being recognized that the percentage-decline method furnishes unreliable estimations and is also unnecessarily laborious. For these reasons its use is being abandoned.

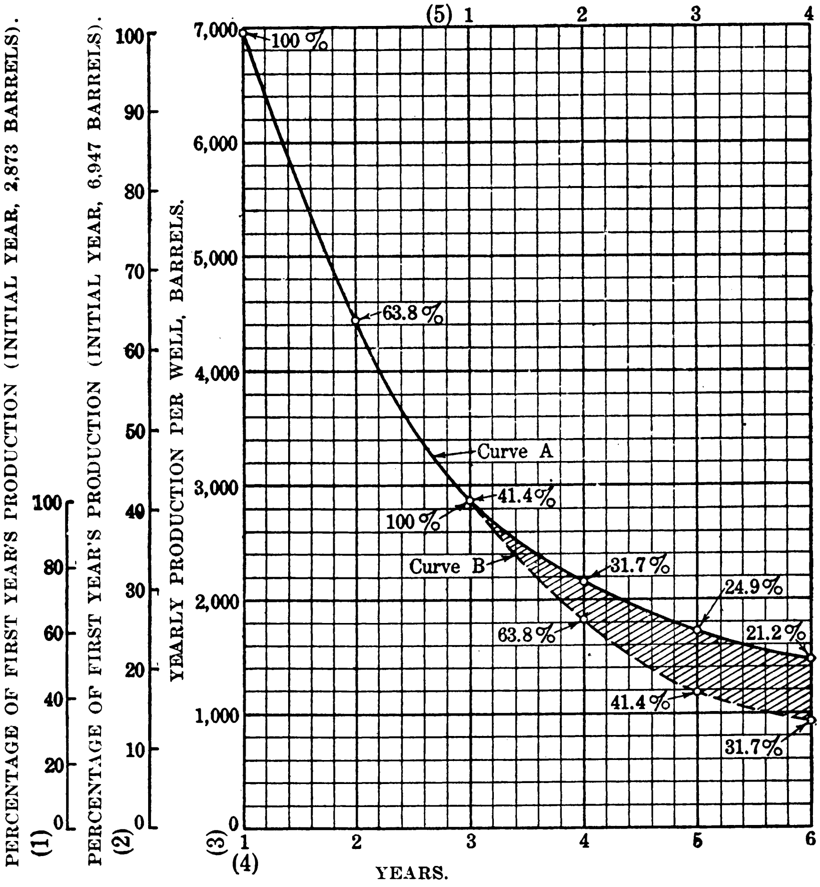

FIG. 1.—Diagram showing the error of the percentage-decline curve. Curve A is average percentage-decline curve of a tract with an initial average yearly production of 6,947 barrels, scales 2 and 4. This is also the average production-decline curve of the tract, scales 3 and 4. Curve B is percentage-decline curve for wells of initial yearly production of 2,873 barrels, based on the same yearly percentage of production as wells with an initial production of 6,947 barrels per year, scales 1 and 5. Hatched area between curves A and B represents error in the use of the same percentage-decline curve for wells of initial yearly production of 6,947 and 2,873 barrels.

RÉSUMÉ OF OLD METHODS.

The barrels-per-acre or barrels-per-acre foot method and the saturation method are useful for making preliminary and rough estimates of reserves in undrilled areas, and also for checking results obtained by the production-decline curve method.

The constant-percentage decline method and the percentage-decline curve method are liable to introduce serious errors into estimates of future output. Therefore they should not be used.

CHAPTER II.—THE PRODUCTION-DECLINE CURVE.

GRADUAL DEVELOPMENT.

A production-decline curve is a graphic record usually plotted on coordinate paper of the production of a well or average well of a group of wells. The vertical scale is used to represent production per unit of time, usually taken in old fields as barrels a year. The horizontal scale is used to represent time. Figure 2 (see p. 17) shows a production-decline curve for a well in the Glenn pool.

The production-decline curve has been generally used for many years by various engineers and oil companies. At first it was used to show graphically the production decline of wells or properties. During the last 10 years, its value as a means of estimating future production has become recognized and it is now generally used for that purpose. As its development and use has been gradual, credit can not be given to the engineer or group of engineers that first employed it for estimating the future production of individual wells or tracts.

J. O. Lewis, formerly chief petroleum technologist of the Bureau of Mines, and Carl H. Beal, formerly petroleum technologist of this bureau, are entitled to the credit of enlarging the scope of the production-decline curve by the introduction of average curves based on the law of equal expectation.[22]

FUNDAMENTAL PRINCIPLE OF THE PRODUCTION-DECLINE CURVE.

The fundamental principle underlying the estimation of underground reserves of oil by the production-decline curve method is that the decline of well production is on the average symmetrical enough to permit projecting the production-decline curve to indicate the estimated production of a well in future years. This symmetry is not evident in the records of those wells whose behavior is erratic. Any production record will show variations from symmetry because of minor changes in the conditions of operation, or the drilling of offset wells, etc.; and therefore the longer the record of actual production, the more accurately can the curve be extended and the future production estimated. If production is recorded by

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[22] Lewis, J. O., and Beal, Carl H., Some new methods for establishing the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 477–504. Beal, Carl H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 215 pp.

yearly periods, records for at least three years are necessary, and in order to establish a curve definitely, records for four or more years should be available. If production is recorded for periods shorter than years, such as weeks or months, a tentative production-decline curve can be constructed for many wells from only a few months' productions.

The production-decline curve should be used only for estimating the future production of wells that will continue to be operated in practically the same manner as they have been. Minor changes that affect production are those in methods of operation—such as raising or lowering the working barrel, changing the rapidity and length of stroke, period and intermission of pumping, cleaning and shooting, repairs and minor manipulations within reasonable limits. These changes, though they greatly influence production, are not considered because it may be assumed that producers will regulate such details of operation so as to recover as nearly as possible the maximum amounts of oil.

Major changes include the conditions of the sands, the spacing of the wells, the introduction of pumps—vacuum, water drive, or compressed air. Variation in these conditions materially affects the decline of oil wells.

The need of careful, thoughtful work and a thorough study of the conditions of the field can not be too strongly emphasized. Especial care must be taken in using production records of either large wells or very small wells. Large wells are usually situated in areas partly developed. Later drilling may lessen the area drained by the early wells and thus affect the declines of their production. Large wells usually produce by flow, and some of them may be partly choked in. The effect of pumping and of relieving the back pressure must be considered in estimating the future production, and failure to allow for these factors may introduce serious errors. Small wells are greatly affected by minor changes of method, and through poor operation may reach an economic limit prematurely. Careful and efficient management may extend their life for many years and may permit their operation to a lower economic limit.

WELL CURVES.

Production-decline curves are sometimes made for individual wells, although there are many wells whose declines in productions are so irregular that extensions of their curves do not reliably indicate future productions.

The construction and use of a production-decline curve for an individual well is illustrated here. Actual production records were available from a well in the Glenn pool, Oklahoma, from the years

1910 and 1916, inclusive, as shown by columns 1 and 2 of Table 3. The production-decline curve for this well is shown in Figure 2.

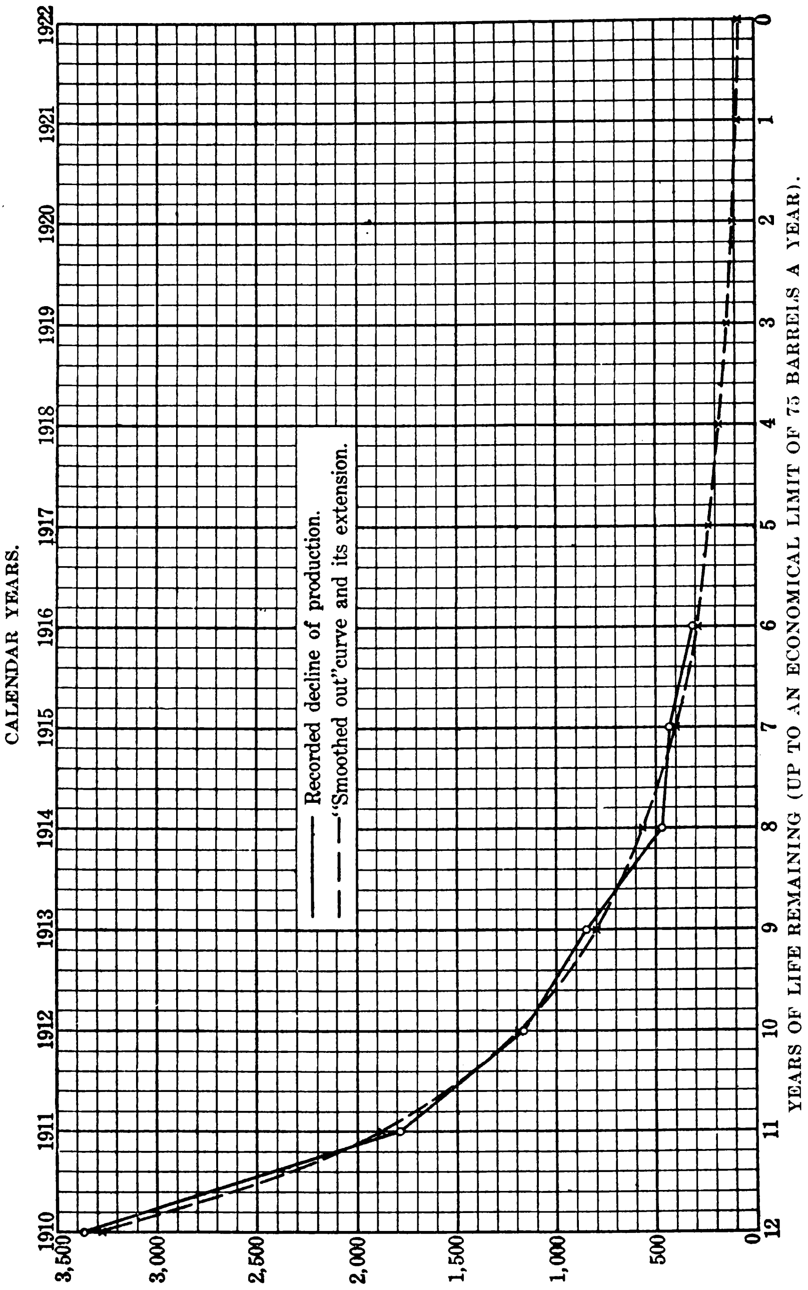

FIG. 2.—Production-decline curve for an individual well in the Glenn pool, Oklahoma. Full line represents recorded decline of production; dashed line represents "smoothed-out" curve and its extention.

Each heavy horizontal spacing denotes one year, and each heavy vertical spacing represents a production of 500 barrels a year. The successive yearly productions, beginning with 3,361 barrels in the first year, 1910, were plotted and the points were connected by lines to make the graph shown by the full lines. Thus plotted the record makes a fairly regular and symmetrical curve. By extending the curve as the dotted line beyond the last recorded production, that for 1916, the yearly productions of the well, provided it produces under the same conditions, may be estimated through any desired period or to what is considered the economic limit.

The sum of the estimated yearly future productions, including the year of economic limit, as shown by the extended production-decline curve, will be the estimated future production of a well at the end of any year. Thus in Figure 2, if an economic limit of 75 barrels a year has been assumed, the estimated future production of the well, which in 1916 produced 309 barrels, will be the sum of the estimated future productions of the years 1917 to 1922, inclusive, which is 230+180+145+115+93+75, or 838 barrels.

With the same scale in time as before the horizontal scale may be numbered back from the point of economic limit. By reading this horizontal scale (remaining life in years) for any point on the production-decline curve, the estimated remaining life of the well in years may be obtained. The estimation of remaining life is subject to a greater relative error than the estimation of ultimate production because the time of abandonment is subject to price fluctuations, and also the production during the last stage of a well's life is an almost negligible percentage of the ultimate production.

From the production-decline curve may be formed a table (Table 3) showing the estimated future productions at the end of any year to an assumed economic limit.

TABLE 3.—*Past and estimated future production of a well in the Glenn pool, Oklahoma.*

PAST PRODUCTION.

[Assumed economic limit, 75 barrels a year.]

Year.	Production per year, barrels.	Estimated total remaining future production, barrels.	Estimated remaining life, years.
1910	3,361	5,871	12
1911	1,787	4,084	11
1912	1,175	2,909	10
1913	854	2,055	9
1914	478	1,577	8
1915	430	1,147	7
1916	309	838	6

ESTIMATED FUTURE PRODUCTION.

Year.	Production per year, barrels.	Estimated total remaining future production, barrels.	Estimated remaining life, years.
1917	230	608	5
1918	180	428	4
1919	145	283	3
1920	115	168	2
1921	93	75	1
1922	75	0	0

For the well used for compiling Table 3 the production through 1916 was obtained by pumping without vacuum and the estimated future production would apply to this well only if the same methods of operation were continued.

TRACT CURVES.

Production records are more often kept by properties than by individual wells. In order to form a basis for the estimation of future production where only records of total yearly tract productions are available, the average yearly production per well is used instead of the production of an individual well. The production-decline curve of the average well on a tract may be extended for estimating future productions in the same manner as are the curves of an individual well. (See Fig. 21, p. 75.)

Several important factors have to be considered in obtaining the average yearly production per well.

COMPUTATION OF NUMBER OF WELLS PRODUCING.

If some wells have long shutdowns caused by unusual circumstances that will probably not happen again in the future, they should not be considered as producing during the periods of shutdown. Customary shutdowns, such as those for pulling and cleaning, which probably will occur as often in the future as they have in the past, should be ignored, however, and the total time of all wells producing during the period should be used.

Table 4 illustrates the method of obtaining the yearly productions of an average well of a tract. The figures are from the records of a tract in the Bartlesville-Dewey field, Oklahoma.

There were two wells producing on this tract January 1, 1911. A third well was put on production September 1, 1911, and a fourth well November 1, 1911. In 1911 two wells produced 12 months each, one well produced from September 1 through December 31, or 4 months, and another produced from November 1 through December 31, or 2 months, making a total of 30 well months, or the equivalent of 2.5 wells producing an entire year. During 1912 to 1915, inclusive, all four wells produced continuously.

TABLE 4.—*Estimation of yearly average production per well for a tract in the Bartlesville-Dewey field, Oklahoma*

Past production.		Number of wells producing during year in tract.	Average production per well during year, barrels.
Year.	Total yearly production of tract, barrels.		
1911	1,965	2.5	787
1912	6,600	4	1,650
1913	4,029	4	1,007
1914	2,150	4	538
1915	1,610	4	402

INCREASING NUMBER OF WELLS.

In using tract records particular care must be taken if the number of wells producing varies. During the early life of a tract the number of wells producing each year usually increases. Where new wells have a greater or less initial production than the production of the older wells for the same time, the average production per well of the tract during following years does not represent the decline of the old wells and should not be so considered.

Table 4 shows that the average production per well increased in 1912 through the bringing in of wells of high initial production during the later part of 1911; therefore the production before 1912 can not be used to form a production-decline curve for the average well.

DECREASING NUMBER OF WELLS.

During the late life of a tract old wells may be abandoned because their production has declined so much that they are no longer profitable to operate. For estimating the average production per well, those periods during which a large number of wells have been abandoned should not be used, as the average yield for the remaining wells would be unduly sustained.

Table 5 illustrates how the average well production of a tract is sustained by the abandonment of a small producer.

TABLE 5.—*Example of the effect of abandonment of well on the average production of a tract in Cumberland County, Ill.*

Past production.		Number of wells producing during year in tract.	Average production per well during year, barrels.
Year.	Total yearly production of tract, barrels.		
1908	1,188	4	297
1909	1,100	4	275
1910	996	4	249
1911	864	4	216
1912	800	4	200
1913	736	4	184
1914	684	4	171
1915	700	4	175
1916	600	3½	[a] 172
1917	618	3	206
1918	531	3	177
1919	525	3	175

[a] Well abandoned July 1, 1916.

Here the abandonment of a well on July 1, 1916, increased the average production of the wells in the tract. In order to draw and extend the true production-decline curve to the assumed economic limit for this tract the average yearly productions per well for the tract from the year 1908 through 1915 should be used and the records for 1916 to 1919, inclusive, discarded. The average production of

1919 (175 barrels) then should be used to determine the position of the average well in 1919 on the production-decline curve so constructed, and future productions should be estimated. See Figure 3 below.

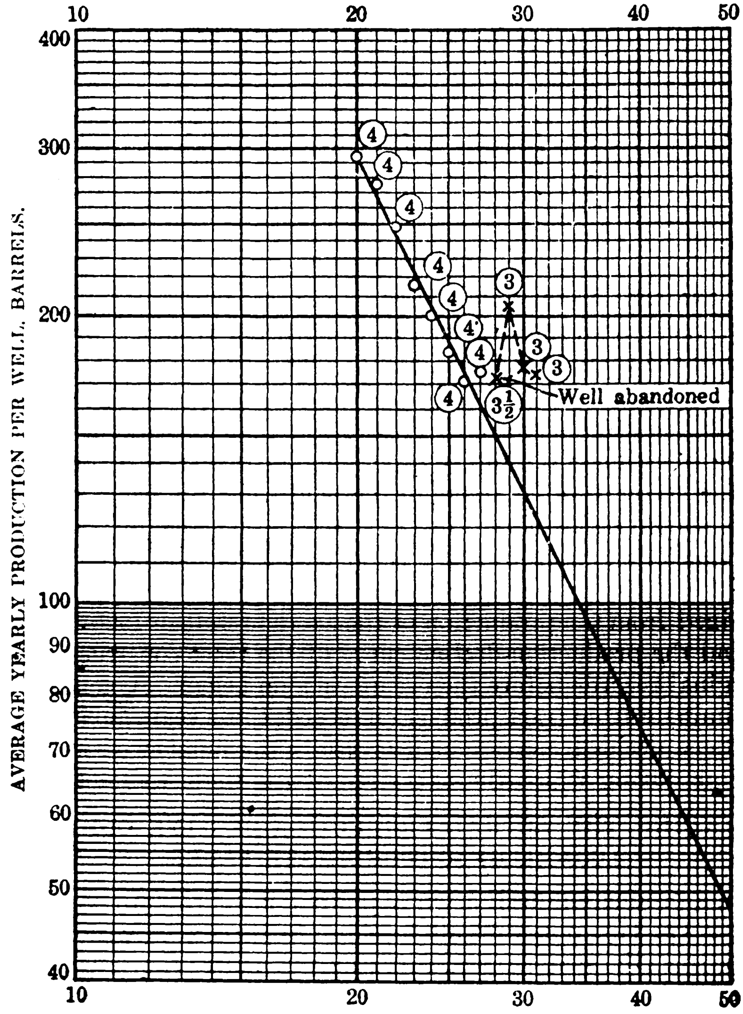

FIG. 3.—Effect of abandonment of well on the production-decline curve of a tract. Production-decline curve of a tract in Cumberland County, Ill., illustrating elimination of parts of production records due to abandonment of wells. Full line represents extension of production-decline curve unaffected by abandonment of wells. Crosses indicate average well production as sustained by abandonment of wells. Figures (4) indicate number of wells producing during year.

NEW METHOD OF OPERATION.

Table 6 shows the production record of a tract on which vacuum (gas pumping) began in 1918.

TABLE 6.—*Effect of installation of vacuum on the average production of a tract in the Glenn pool, Oklahoma.*

Past production.		Number of wells producing during year in tract.	Average production per well during year, barrels.
Year.	Total yearly production of tract, barrels.		
1913	15,657	9	1,740
1914	7,561	9	840
1915	3,636	9	404
1916	2,164	9	240
1917	1,720	9	191
1918	1,719	9	[a] 191
1919	7,461	9	829
1920	4,835	9	537

[a] Vacuum installed.

The average production-decline curve of this tract producing without vacuum on the well may be constructed from the production records of the years 1913 through 1917. This curve could be used for estimating the future production of the tract if pumping were continued in the same manner as previously; that is, without vacuum. In order to estimate the future production of this tract after vacuum is used, a study of other tracts in the field when the wells are under vacuum should be made in order to ascertain the effect of vacuum on production (Fig. 23, page 91). If no such information could be obtained, the future production of the average well on the tract might be determined from the production of the average well in 1920 (537 barrels) and the production-decline curve of the tract constructed from the original records before the use of vacuum began. A general rule is to eliminate from tract production records those years during which there was a decided increase or decrease in the number of wells producing or during which the operation of the wells was not normal.

EXTENDING THE ACTUAL PRODUCTION-DECLINE CURVE BY LOGARITHMIC COORDINATE PAPER.

From a production-decline curve plotted on coordinate paper as in Figure 2 (p. 17), it is difficult to obtain a correct extension of the curve because the symmetry of curvature can not be continued by eye. A striking feature observed in connection with the study of production-decline curves is that many such curves, either for individual wells, tracts, or pools assume approximately the shape of an hyperbola, whose type formula is $yx^n = K$. A curve of this type when plotted on logarithmic coordinate paper may be moved to such a position on the paper that it is represented by a straight line, and a straight line may be extended to estimate future production without the sources of error that accompany the use of a curve on coordinate paper.

The curve shown in Figure 2 (p. 17) was replotted on logarithmic paper as Figure 4. This figure shows the same curve in three different positions on logarithmic paper. If the curve is plotted any-where on the paper ecept in a certain position, it retains the form of a curve, with its convex side pointing in the direction to which it should be moved in order to be represented by a straight line. In order to plot a curve on logarithmic paper the same procedure as previously explained for plotting on coordinate paper is followed.

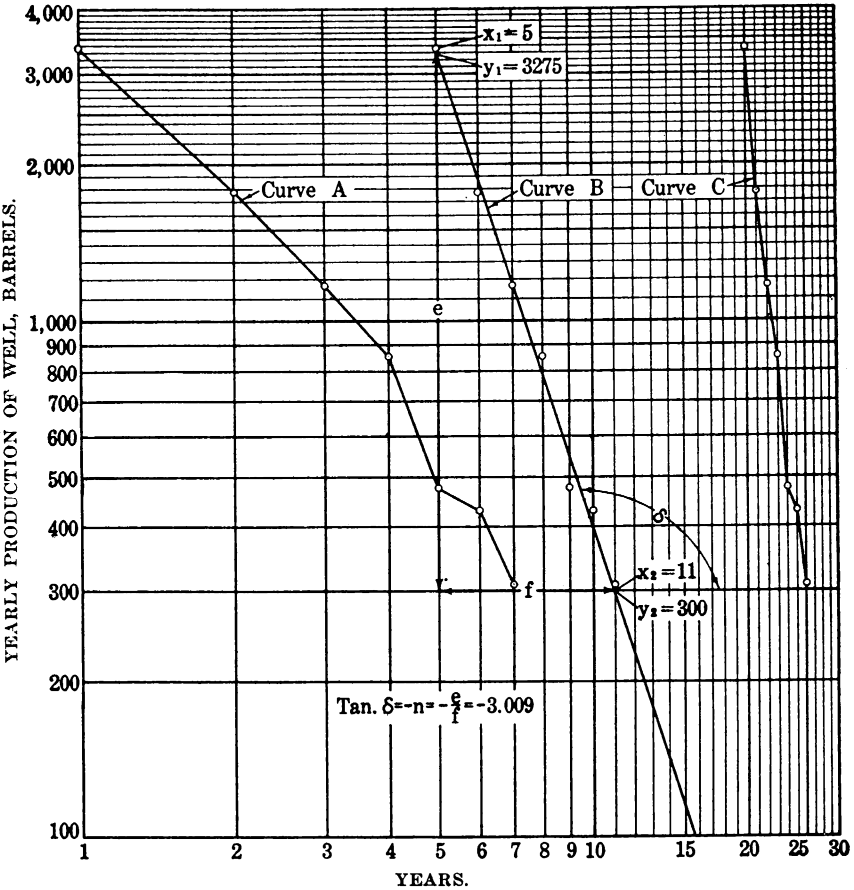

FIG. 4.—Production-decline curve in Figure 2, plotted on logarithmic paper. Illustrates method of shifting a production-decline curve into the position of a straight line on logarithmic paper. In position A the curve is too far to the left; move all points to the right 4 spaces or year units. In position C the curve is too far to the right; move all points to the left 15 spaces or year units. In position B the curve falls approximately into the straight line, which may be extended downward to estimate the future yearly productions of the well.

On logarithmic paper the vertical and horizontal lines are not spaced uniformly but according to a logarithmic scale. In order to straighten a curve that has been plotted on logarithmic paper, move all points on the curve the same number of units to the right or left, as indicated by the direction of convexity, until the curve is represented by a straight line which passes through or lies between all points of the curve and represents the mean average of the curve.

As a check, it is best to shift a convex curve past what is thought to be a straight line until it begins to show convexity in the other direction.

Care must be taken that the curve, when placed on logarithmic paper, is not too far to the right, as the convexity of curves is more difficult to determine on the right side of logarithmic paper than on the left side.

DETERMINATION OF AVERAGE CURVE.

After the segment of the curve that represents the normal decline of the well or average of the wells has been constructed the straight line should be passed through the points in that segment, so that it represents a true average of all the points. The sum of the period productions of the straight line should approximate the sum of the period productions of the points on the segment.

Thus in Figure 4 the production of all the years 1910–1916, inclusive, as shown by Table 3 (p. 18), represents the normal decline in production of the well. These productions were plotted on logarithmic paper so that they would be as nearly as possible in a straight line. Then a straight line was passed through these points of production. The straight line represents an average of the productions during the recorded period, because the sum of the productions for the unit periods on the straight line equals approximately the sum of the actual recorded productions.

TABLE 7.—*Method for determining whether straight line is an average of production decline.*

Year.	Recorded productions, barrels.	Points on straight line, barrels.
1910	3,361	3,275
1911	1,787	1,875
1912	1,175	1,160
1913	854	800
1914	478	560
1915	430	406
1916	309	300
Total	8,394	8,376

The straight line may be extended downward and the future productions (Table 3) read from it, thus avoiding the chances of error that attend estimating the extension of curves by symmetry on coordinate paper. Likewise the straight line may be extended upward to estimate past productions, when records are lacking and an approximate figure for the past production of a property is desired, or to estimate the future production of a well of greater initial production than any drilled on the property.

Figure 5 illustrates both good and poor interpretations of the extension of a curve on logarithmic paper. It shows the necessity for plotting on logarithmic paper the production-decline curve in the correct position, in order that an extension of the curve will estimate productions for future years. Curves A, B, C, and D, are all average curves drawn through points representing the same five years' productions of a well in Hocking County, Ohio; each curve is placed in a different location on the logarithmic paper. All four of these curves are average curves, the sum of the intercepts of each average curve practically equaling the sum of the five years' productions, but only one is the correct average production-decline curve.

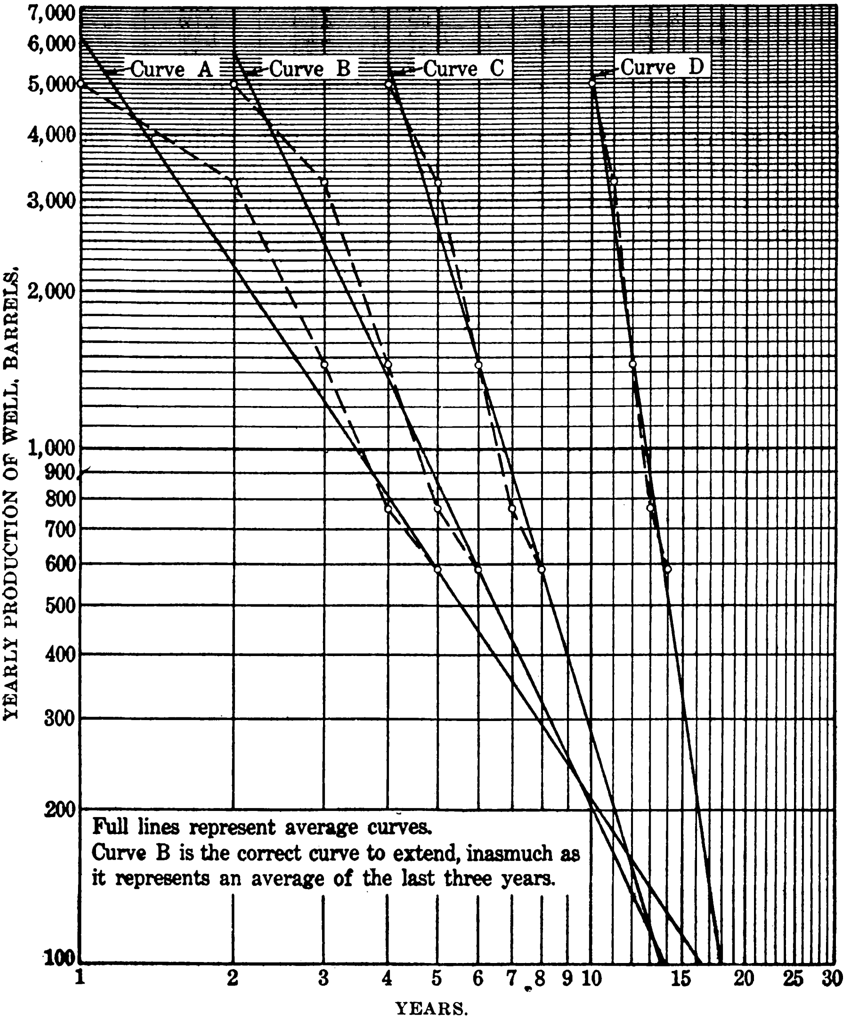

FIG. 5.—Good and poor extensions of a production-decline curve (well in Hocking County Ohio). Full lines represent average curves. Curve B is the correct curve to extend inasmuch as it represents an average of the last three years, which in this well represent normal operations such as may be expected in future.

TABLE 8.—*Method of determining the correct average curve.*

Sum of five years' productions, barrels.	Sum of intercepts.			
	Curve A.	Curve B.	Curve C.	Curve D.
5,008	6,200	5,775	5,500	5,300
3,250	2,240	2,480	2,620	2,750
1,450	1,230	1,360	1,450	1,550
765	810	855	900	900
585	585	585	585	550
11,058	11,065	11,055	11,055	11,050

The extensions of these four curves are very different, and the selection of the proper one of these four would be essential to a reliable estimation of the future production of this well. The extensions of curves A, B, C, and D between yearly productions of 585 and 100 barrels give the following figures:

Time of decline, years:	
Curve A	11½
Curve B	8
Curve C	5¾
Curve D	4

Production during decline, barrels:	
Curve A	2,420
Curve B	1,170
Curve C	1,250
Curve D	860

In order to determine which of these curves should be selected the history of the well must be studied and those yearly productions selected which represent normal operation or what may be expected in the future. Such a study shows that the last three years represent normal operation of the well, or what may be expected in the future. Curve B is the only curve that is an average of the last three yearly productions. The other curves, although average curves for all the five yearly productions, are not average curves for the last three yearly productions. Curve B is therefore the production-decline curve on which estimates of the future production of this well should be based.

This examination emphasizes the need of accuracy in constructing logarithmic curves and in interpreting them. No matter how sound a method may be, poor execution will give untrustworthy results. Poor estimations of future production because of poor construction of basic curves or because of faulty application of the curves from lack of information on field conditions may discredit the production-decline curve method.

FRACTIONAL ABSCISSAS.

Occasionally a production-decline curve straightens out on logarithmic paper in a position where the recorded productions fall on fractional abscissas. The highest production may fall to the left of abscissa 1. Figure 6, showing the production-decline curve of the average well of a tract in Ventura County, Calif., illustrates such a curve. Unit spaces to the left of abscissa 1 represent one-tenth of a year. The highest production is plotted at 0.2, and successive yearly productions would therefore be plotted at abscissas 1.2, 2.2, 3.2, and so on.

RECORDING PRODUCTION-DECLINE CURVES.

Logarithmic paper also offers a convenient method of recording curves. Two coordinates of a production-decline curve as located by a straight line on logarithmic paper definitely establish the smoothed-out curve. Thus in Figure 4 the following record establishes the curve: $x_1=5$, $y_1=3{,}275$; $x_2=11$, $y_2=300$.

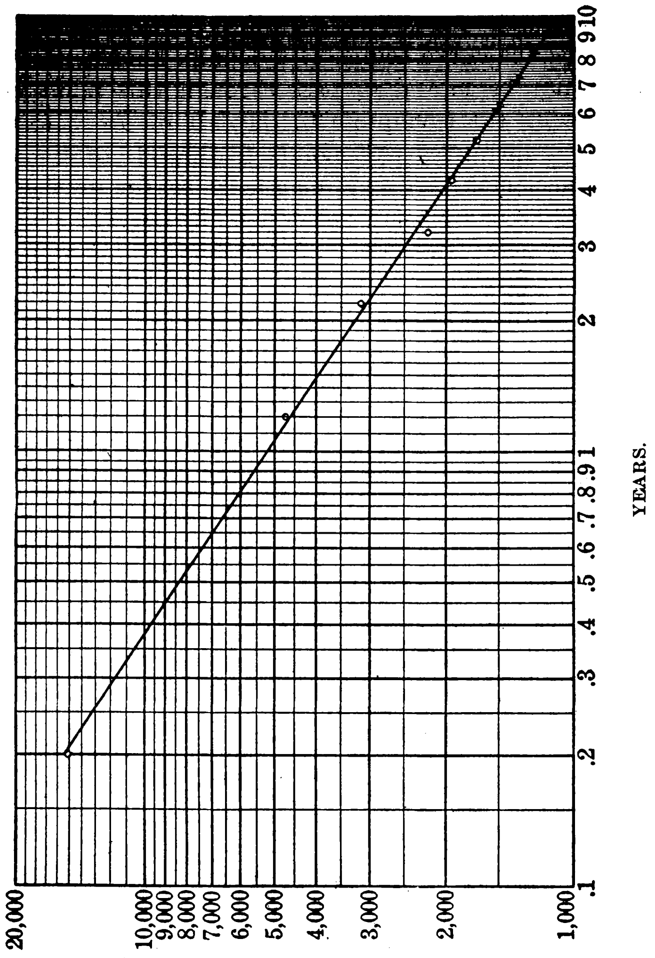

FIG. 6.—Chart illustrating the method of plotting a production-decline curve with fractional abscissas. This is the actual production-decline curve of the average well of a tract in Ventura County, Calif. Yearly productions are plotted on abscissas 1 unit apart—0.2, 1.2, 2.2, 3.2, etc. Future yearly productions should be read on abscisas 6.2, 7.2, etc.

Thus curves for hundreds of properties may be recorded in a limited space (Table 16, p. 64) and the curves will still be available for reconstruction by plotting the two points on logarithmic paper and connecting them by a straight line. To record the curve on coordinate paper requires the coordinates of three points. If preferred, production-decline curves may be recorded by equations.

EQUATION OF A PRODUCTION-DECLINE CURVE.

Figure 7 shows the type of hyperbola which the production-decline curve approaches. The equation for this curve is $y - A = K(x' - B)^{-n}$, where A and B are the distances of the asymptotes from the x and y axes, respectively, $^{-n}$ is the slope of the curve and K is a constant, y the distance of a point from the x axis and x' the distance of a point from the y axis, and $x' - B$, the distance of a point from the y asymptote.

A production-decline curve begins at a definite known production and the y axis may be moved to pass through this point on the curve, thus throwing the asymptote to the left of the y axis and making B a minus quantity. All points to the left of the y axis thus become minus quantities and imaginary so far as the curve for the particular well or wells are concerned. As the y axis has been passed through the point of highest production, x' at that point is zero and B becomes —B. The expression $x' - B$ then becomes $0 - (-B) = B$. As the y asymptote lies on zero on the logarithmic paper, the value of B may be determined for any production-decline curve by plotting the curve as a straight line on logarithmic paper and reading the abscissa of the highest production. The value of $x' - B$ for any point may be denoted as x and will be the abscissa as read from the logarithmic paper.

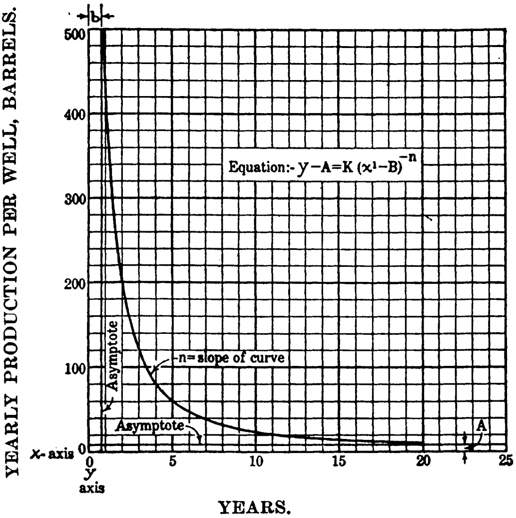

FIG. 7.—Hyperbola (general type of production-decline curve).

The production-decline curve may be theoretically considered as ending at zero production and infinite time. Thus A is zero and the asymptote coincides with the x axis, although actually production ceases when a well has reached an unprofitable stage.

The factor —n, the slope of the curve, may be determined by plotting the production-decline curve as a straight line on logarithmic paper and then scaling the tangent of the slope by actual arithmetical measurement, and not by reading from the logarithmetic scale. (See Fig. 4, p. 23, where $\tan \delta = -\frac{e}{f} = -3.009$.)

K is a constant and may be determined graphically from the straightened logarithmic curve, as it is the value of y where the curve crosses the left side of the logarithmic paper at 1 on the abscissa from the asymptote. It may be determined mathematically by substituting the already determined values of $^{-n}$, x, and y for any point in the equation [28] below:

$y - A = K(x' - B)^{-n}$ where $A = 0$ and $(x' - B) = x$
Then $y = Kx^{-n}$ or $yx^{n} = K$

EXAMPLE.

In Figure 4 (p. 23), $^{-n}$ was determined by scaling e and f as $-\frac{e}{f} = -3.009$. The highest recorded production was 3,275, which lies on the straightened logarithmic curve where the abscissa equals 5. B, therefore, for this curve is —5 and K, which equals the value of y where the curve lies at abscissa 1, equals 415,000. Assume it is desired to determine the value of y when x equals 5. Substituting the known values for one point in the formula $yx^{n} = K$. Then $y\ (5)^{3.009} = 415{,}000$ or $y = 3{,}275$ if $x = 5$. If $x = 10$ then $y\ 10^{(3.009)} = 415{,}000$ or $y = 406$ if $x = 10$.

When the value of n is high (for some curves it approaches 20), the determination of n must be very exact. Under these conditions it is difficult to obtain. A small error in the value of n introduces a large error into the calculations. Therefore it is preferable and easier to record the coordinates of two points of the curve $(x_1) = 5$, $y_1 = 3{,}275$; $x_2 = 11$, $y_2 = 300$) instead of the equation.

If preferred, the general curve may be recorded by the coordinates of one point on the logarithmic paper and the value of n. Thus in Figure 4 (p. 23), the curve could be recorded as $x = 5$, $y = 3.275$, $n = -3.009$.

This type of hyperbolic curve is the curve for expanding gases and is what might be expected, for the production of an oil well generally represents the work accomplished by the expansion of the compressed natural gas associated with the oil in the sand.

INTERPRETATION OF CURVES BY LOCATION ON LOGARITHMIC PAPER.

That position on logarithmic paper where a production-decline curve may be plotted as a straight line is indicative of the relative rate of decline in production throughout the curve.

A curve that is plotted with small abscissas has a rapid decline for the period of large production as compared with its decline during the period of small production, whereas a curve that is plotted with large abscissas has a fairly uniform decline throughout. For instance Figure 8 shows two production-decline curves (A and B), both of which indicate a decline from 1,000 barrels a year to 100 bar-

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[28] Lewis, J. O., and Cutler, W. W., A numerical expression for production-decline curves: Eng. and Min. Jour., Sept. 4, 1920, p. 479.

rels a year in four years. The highest yearly production, 1,000 barrels, of curve A is plotted at abscissa 2, and the highest yearly production, 1,000 barrels, of curve B is plotted at abscissa 20. Both curves (A and B) show the same decline in four years; but curve A declined from 100 barrels a year to 10 barrels a year in 12 years, and curve B in only 5 years.

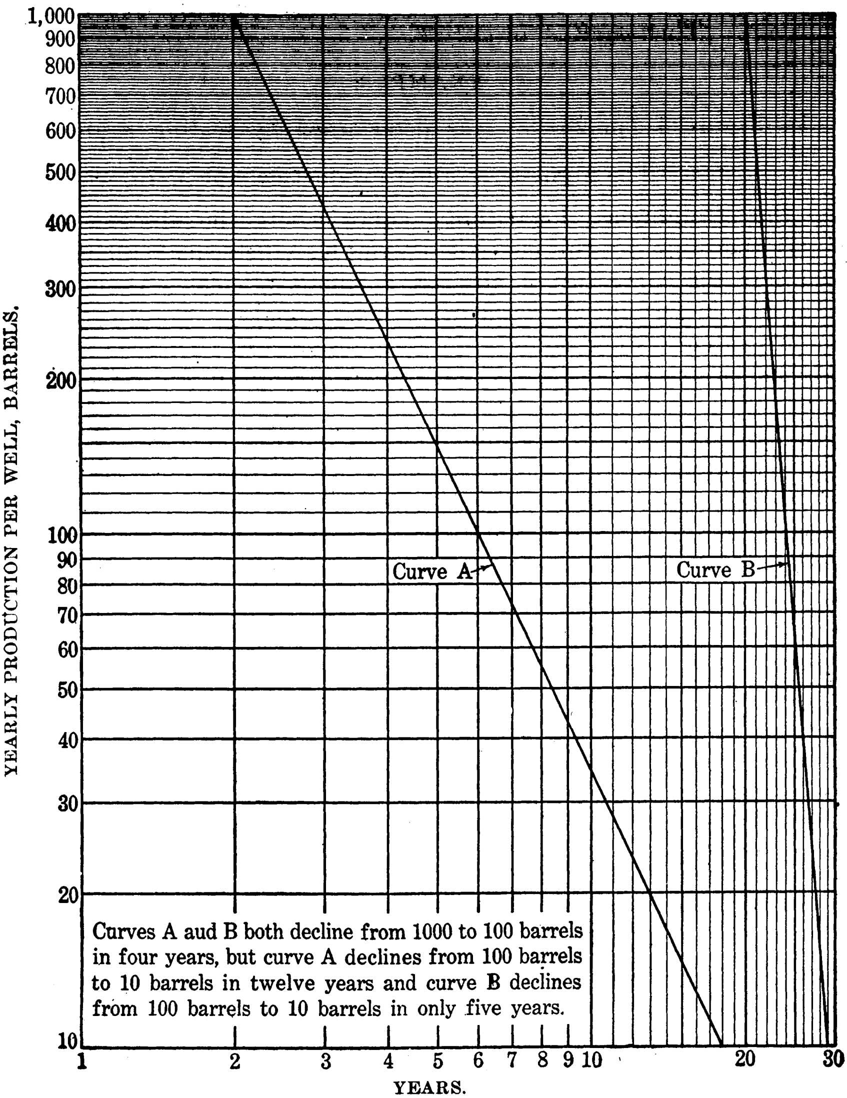

FIG. 8.—Chart to illustrate the relation between position of a curve on logarithmic paper and relative decline.

Figure 9 gives these same two curves (A and B) plotted on coordinate paper to show the varying declines in production of curves A and B. Curve B shows a greater total production in declining from 1,000 to 100 barrels but a less total production in declining from 100 to 10 barrels than curve A shows.

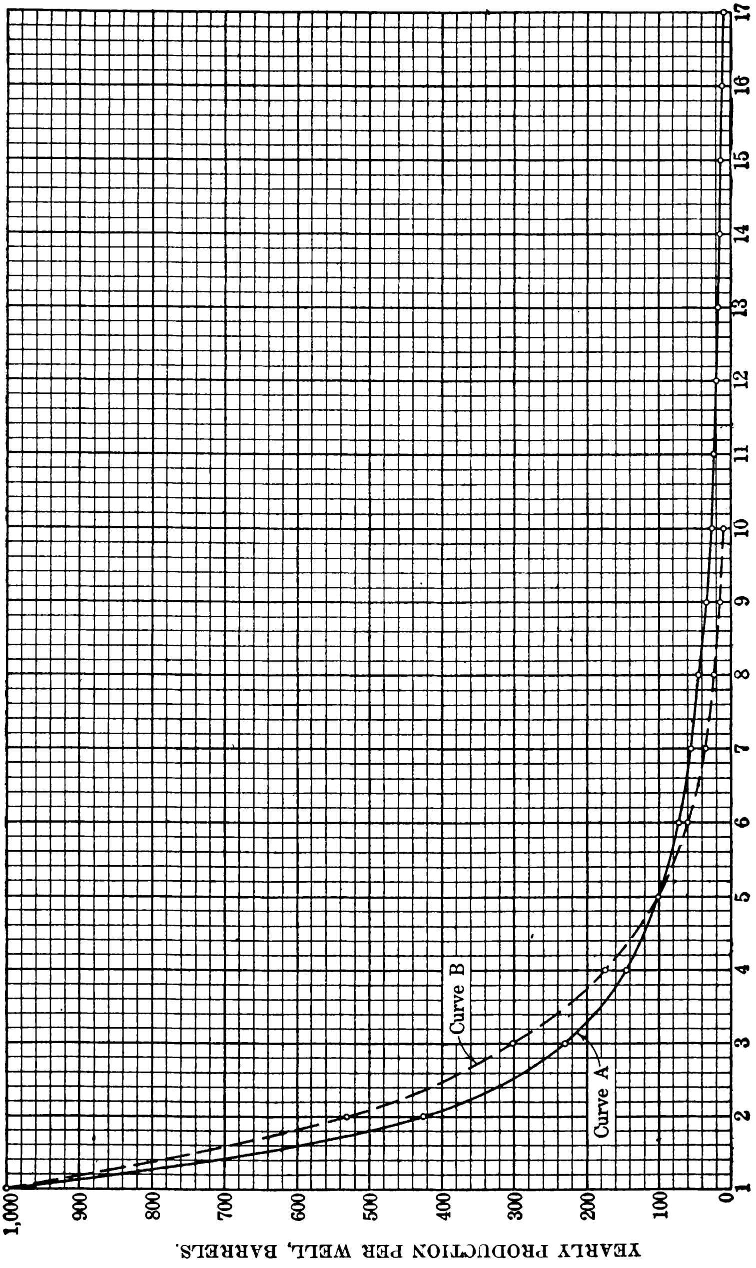

FIG. 9.—Curves of Figure 8 plotted on coordinate paper.

Table 9 was formed from Figure 8 to illustrate how the position on logarithmic paper of curves plotted as straight lines is related to the relative declines.

TABLE 9.—*Comparison of the relative rates of decline in production of two wells, one with small and the other with large abscissas.*

Curve A.	*Curve B.*
$x_1=2$; $y_1=1,000$	$x_1=20$; $y_1=1,000$
$x_2=6$; $y_2=100$	$x_2=24$; $y_2=100$

Yearly productions.	Percentage decline from previous year.	Yearly productions.	Percentage decline from previous year.
Barrels.	*Per cent.*	*Barrels.*	*Per cent.*
1,000		1,000	
430	57	530	47
235	45	300	43
150	36	175	42
100	33	100	43
74	26	60	40
56	25	37	38
44	21	23	38
35	20	15	35
29	17	10	33
24	17		
20	17		
17	15		
15	12		
13	13		
11.5	12		
10	13		

Note that curve A, with small abscissas, shows a percentage decline from the previous year, ranging from 57 to 13 per cent, and curve B, with large abscissas, only from 47 to 33 per cent.

SEMILOGARITHMIC PAPER.

Figure 10 illustrates the use of semilogarithmic paper. The vertical scale is logarithmic and increases with smaller ordinates, but the horizontal scale is arithmetical; that is, uniform scale.

Any straight line on semilogarithmic paper represents a curve with a constant percentage increase or decline. Semilogarithmic paper is therefore adapted especially for showing relative percentage changes from period to period. As with logarithmic paper, small amounts may be plotted with more accuracy on semilogarithmic paper than with ordinary coordinate paper.

USES OF SEMILOGARITHMIC PAPER.

Semilogarithmic paper is adapted to plotting the price changes of commodities over long periods of time in order to show the average percentage change. The curves may be used to show the value of money at compound interest in future years, or the present discount value of money to be received in the future.

Figure 10 shows the present worth of $1.00, due in future years, discounted at 10 per cent. This graph is plotted by determining the present worth of $1.00 due in any future year, and joining by straight line the value as plotted at that date to the point $1.00 at the present time. This straight line may be extended to future years as desired.

Thus \$1.00 at 10 per cent would be worth \$1.10 a year later. If x represents the present values, \$1.00 due in one year at 10 per cent would have a present value of $\frac{x}{\$1.00}=\frac{\$1.00}{\$1.10}$ or $x=\$0.909$. This \$0.909 due in one year at 10 per cent would have a present value of $\frac{x}{\$0.909}=\frac{\$1.00}{\$1.10}$ or $x=\$0.826$. If \$0.826 at two years is joined to \$1.00 at zero years by a straight line, this line extended may be used to read the present value of \$1.00 due at any future date discounted at 10 per cent. Thus the present worth of \$1.00 due in 11 years discounted at 10 per cent is shown by Figure 10 to be \$0.35.

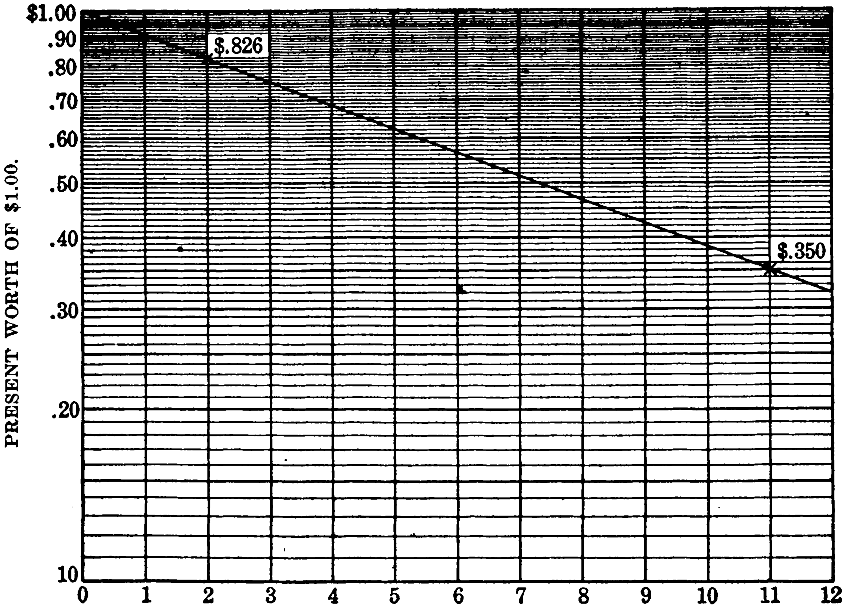

FIG. 10.—Use of semilogarithmic paper for estimating the present worth of money. A straight line on logarithmic paper represents a constant percentage increase or decrease. Straight line shown above represents present value of \$1.00 receivable in future years, discounted at 10 per cent.

Such a graph is useful, in the evaluation of oil properties, for estimating the present net value of oil that will be produced in the future.

ERROR IN USING SEMILOGARITHMIC PAPER FOR ESTIMATING THE FUTURE PRODUCTIONS OF OIL WELLS.

Semilogarithmic paper has been used by some petroleum engineers to plot production-decline curves of oil wells. If the production of wells showed a constant yearly percentage decline, as was formerly believed, the production-decline curve would best be represented on semilogarithmic paper, as it could then be plotted as a straight line and extended to estimate future production.

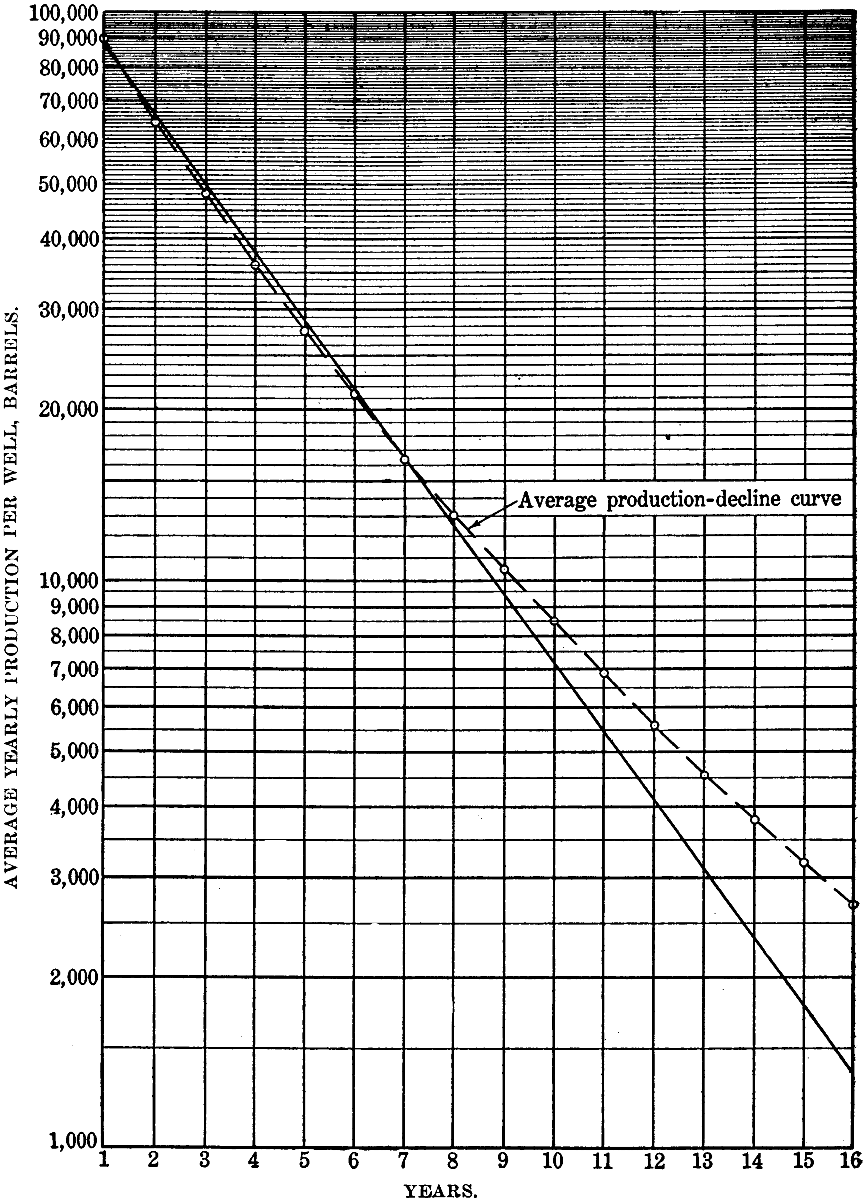

FIG. 11.—Chart to illustrate inapplicability of semilogarithmic paper to production-decline curves. Broken line represents the average production-decline curve for the East Side, Coalinga pool, Fresno County, Calif. Full line represents a straight line extension of the years of large production by semilogarithmic paper. Area between broken and full lines shows error introduced by using semilogarithmic paper.

However, there are only a few pools in the United States in which the production of wells shows a constant yearly percentage decline under present methods of operation. Most wells have a higher yearly percentage decline during their early life than later. As a general rule, production-decline curves can not be plotted as straight lines on semilogarithmic paper, therefore their extension when so plotted to estimate future production is incorrect.

Figure 11 shows an average production-decline curve for the East Side Coalinga field, Fresno County, Calif., plotted on semilogarithmic paper. The curve is based on data taken from the table on page 172 of the "Manual for the oil and gas industry," revised edition, August, 1921, published by the Treasury Department.

This curve has an almost constant yearly percentage decline during eight years of high production, as shown by the straight line. An extension of this straight line would indicate a faster decline than more recent production records of wells in that field have shown. If estimations of future production were based on the extension of the average production-decline curve during the early life of the wells as plotted on semilogarithmic paper the estimates would be too small. A production-decline curve is best plotted on logarithmic paper, for the entire curve may be then represented as a straight line and its projection for estimating future production may be relied on. The logarithmic curve fits the fundamental conception of the production-decline curve, being a hyperbola, whereas the semilogarithmic curve does not.

CHAPTER III.—AVERAGE CURVES.

LAW OF EQUAL EXPECTATIONS.

In 1918 Lewis and Beal advanced the law of equal expectations,[24] which states " 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." For example, if two groups of wells producing under similar conditions from the same pay sand in the same pool have averaged the same production per well during the past year, they will on the average produce the same amount per well in the future, even though the wells of one group may be new producers whereas the wells of the other group may have been producing for many years. The importance of this law lies in the fact that if nothing is known of the past histories of wells or tracts, the past production records of other wells that formerly had the same rate of production as the wells under consideration and produced under approximately similar conditions may be used as a basis on which to estimate the future productions of the wells or tracts in question. Both the natural and artificial conditions vary greatly in different fields, but many of these conditions are approximately similar for wells in the same pool and often for wells that produce from the same horizon in different fields in the same general district. The gas pressure almost always falls as an area becomes drained, but this is reflected more in the initial productions of the wells than in their rates of decline.

The " law of equal expectations " when first expounded received much criticism, but since its later presentation, with methods based on it for estimating future productions, in the " Manual for the oil and gas industry " published by the Treasury Department in 1919, it has attracted wide attention from petroleum engineers in the United States. The results obtained from its use are believed to have fully verified it and it is now generally accepted.

This law does not apply to wells producing under hydrostatic pressure, such as the wells in the Tampico-Texpam district in Mexico. Such wells produce under a pressure that is almost constant and their rate of production is correspondingly constant until they are drowned by water.

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[24] Lewis, J. O., and Beal, Carl H., Some new methods for estimating the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 477–504.

AGE-SIZE LAW.

Johnson and Roth, in calling attention to the effect of the age of wells, say:

> Wells in one pool, having the same size and age, counting either from the date the well was drilled or the date the first well was drilled in the pool, will have a production in the following year which varies with a central tendency sufficiently reliably determinable that it may be used successfully in the construction of composite curves.[25]

This substitute to the law of equal expectations introduced the element of age in connection with the size of the wells. The element of age would add a refinement to the law of equal expectations if it could be shown that pressures under which wells produce oil vary consistently with either the age of the wells or the age of the field. Production-decline curves of wells, grouped according to both age and rate of production, would then represent the decline of wells with equal pressures. But as this is not so, nothing is gained by considering the age of the wells.

Information available concerning the pressures of oil wells shows that during the early development period of a pool pressures vary greatly. New wells near old wells are brought in with pressures greater than those of the old wells at the time, but less than the original pressures of the first wells in the neighborhood. As the field becomes completely drilled, the pressures of all wells tend to decrease and tend to become uniform. Thus a grouping of wells based on either the age of the wells or the age of the field does not group the wells even approximately according to pressure, until the field is completely drilled and has been producing many years.

The age-size law is impractical for general use because the segregation of the records necessary and the construction of many curves for each group of wells are usually impossible through the lack of enough detailed records. It is simpler to use for a tract or pool an average production-decline curve formed by methods based on the law of equal expectations than to construct curves according to the age-size law.

The law of equal expectations was established and has been supported by the behavior of wells in hundreds of pools. The age-size law as presented was based on the records of only a few wells in a few pools, which would seem insufficient as compared to the thousands of wells and the many properties to which curves based on the law of equal expectations have been applied and found satisfactory.

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[25] Johnson, R. H., and Roth, E. E., The effect of age and size on oil-well decline curves. Paper read before Tulsa meeting of Am. Ass. Petroleum Geol., March, 1921.

AVERAGE PRODUCTION-DECLINE CURVES.

Where production records for a particular well or tract are not available it may become necessary to estimate underground reserves by using the average production-decline curve for the pool or field in which the property is situated. Such a curve should be made by combining the production records of enough wells or tracts to form an average production-decline curve for the area covered. Then the producing conditions for all the wells that make up this average curve should be similar, and the use of the resulting average curve should be restricted to other wells producing under like conditions; that is, wells whose productions are from the same sand in the same field with substantially the same methods of operation.

An average curve represents only a true curve for the average well. Variations from this average by individual wells or tracts must be expected. Therefore, the use of the average curve of the field for calculating the future production for a particular well or tract may introduce considerable error at times, and such a curve should never be used where enough production records are available to form curves for the wells or tracts themselves. The use of the average curve is justified by the fact that a well or tract, unless there is other evidence to the contrary, is as likely to be above as below the average, hence the average curve stands the best chance of approaching the true decline curve for the particular well or lease. This curve, however, should be used only when there are not enough production records to construct a curve for the property or well under consideration.

There may be places where, for lack of other information, the average curve of a district may be used for other districts, in order to make a rough preliminary estimate of their future production.

USES OF AVERAGE CURVES.

The average curve has a number of uses; some of them are as follows:

NEW FIELDS.

(*a*) On the discovery of a new field, average curves of other fields producing under similar conditions assist the engineer to estimate the probable life and production of wells and properties pending the assembling of sufficient production data of the individual wells or tracts to form production-decline curves.

(*b*) For the valuation of new properties whose own records are not long enough to form a basis for appraisal, the average curve of the pool or field may be used. From study of the various parts of a field to determine whether the records tend above or below the average, a closer estimate of a particular property may be made by noting whether its position is near to or similar to wells above or below the average curve.

OLD FIELDS.

(*a*) Where past records of old properties are meager, estimates of future production may be made from recent production records and an average curve of the field. This method is especially adapted to estimating total future productions of several tracts scattered throughout the field, as the average decline of all these wells should approach closely the average decline of the field.

(*b*) Where records are too short lived to use.

(*c*) For estimating production of undrilled acreage.

(*d*) For comparing the average curve of a field with the curve of a specific property on which a special method of operation has been employed, in order to determine the value of that method.

(*e*) For determining the proper spacing of wells. The operator, having the average curve for the field and knowing his operating costs, is better able to decide how he should space his wells.

GENERAL USES.

(*a*) In furnishing the basis of estimating the ultimate production of various fields for statistical information.

(*b*) For comparing the productivity of different fields for investment purposes. An engineer preparing a report on the purchase of widely scattered properties finds average curves of the fields in which these properties are located of great aid in making preliminary comparison of the relative merits of these properties.

(*c*) For analyzing the effects of different factors in the decline of production, average curves furnish the technologist a method of comparing the effects of porosity, gravity, depth, thickness, and pressure, thus enabling him better to understand and solve production problems.

METHODS OF RECORDING PRODUCTION.

A few remarks on the methods of recording production are in place here, as the operator should endeavor to have his production records in such a form that they may be used most advantageously for the purpose of estimating future output. This is one of the important uses of production records.

The yield of properties may be recorded either by tract records or by the records of individual wells. A tract record should show the oil production of the tract for equal consecutive periods of time and the average number of wells producing during each period. Records for individual wells should show their oil production for equal consecutive periods of time.

Where possible, records of the production of individual wells should always be kept; they are more valuable than tract records for the following reasons: Tract records often include records of wells that had widely differing rates of production for the same period. The use of such records for determining the future production introduces the same elements of error as are inherent to the percentage-decline curve, namely, wells with different rates of production are averaged together to obtain the average decline.

Nearly every well has at first a period of flush production when its behavior is erratic. The period of symmetrical decline sets in later. Tract records necessarily include these irregularities. Also, the average well production of tract records usually shows either a sustained production or an abnormal decline through the bringing in of new wells with initial productions above or below the contemporary production of the old wells. Application of such a production-decline curve to the estimation of future reserves for a definite number of wells already producing may introduce an error that would make the estimate valueless. A longer segment of an average production-decline curve may be obtained with individual well records than with tract records that cover the same period because the range of production is usually much greater. If records of individual wells are available, irregularities in the production of individual wells may be accounted for, and if thought advisable, the records of irregular producers may be omitted. Also the production from different sands can be better segregated.

Records of individual wells are especially necessary in the early life of a property, while the wells are large; their productions vary greatly, and new wells are being drilled in; they are not so necessary for old settled production, as the wells are then small and their productions more uniform. Sometimes it is impracticable to have individual tanks for each well; then an extra tank ("gun-barrel" tank) may be provided. On consecutive days the oil from the different wells may be run into this tank and the tract productions apportioned among the several wells. The accuracy of this method of gaging as used in the Hewitt field, Oklahoma, is shown by Swigart and Schwarzenbek.[26] Plate I, *A*, represents two tanks arranged for gaging wells in this manner; the smaller tank (gun-barrel tank) is used for measuring the runs of individual wells.

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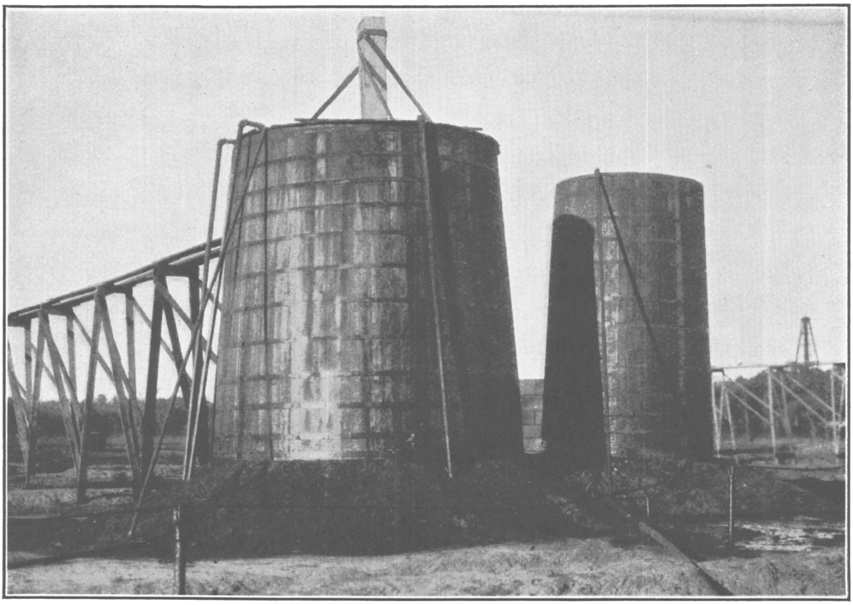
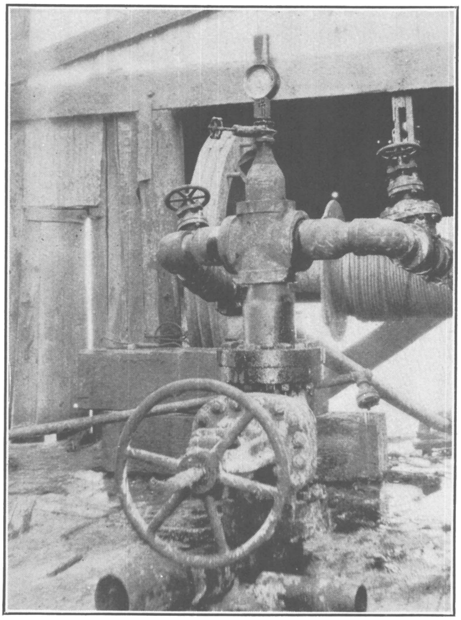
[26] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil Field, Oklahoma. Cooperative bulletin of Bureau of Mines and the Ardmore, Okla., Chamber of Commerce, Jan., 1921, p. 129.



A. GUN-BARREL TANK FOR INDIVIDUAL GAGING (AFTER T. E. SWIGART).



B. METHOD OF ATTACHING A PRESSURE GAGE TO THE OUTLET OF A FLOWING WELL IN ORDER TO MEASURE THE PRESSURE OF THE WELL.

Methods of gaging that will provide records of production which can be used satisfactorily in estimating future output have been further discussed by Ambrose,[27] and by Kirwin and Schwarzenbek.[28]

The unit periods by which production records should be kept must be determined by the length of time for which records are available. Although it is true that the longer the period covered by production records the more accurate will be the production-decline curves formed from them, nevertheless for new fields or new tracts with records covering only a few months valuable and fairly reliable curves may be formed for estimations of future reserves, provided the production records of individual wells have been kept carefully by short unit periods of time, such as months or even weeks. Records of new wells that are still in the erratic period of flush production should not be used. For old tracts, records showing the yearly production of wells or tracts are satisfactory. With the record of production should be kept a chronological record of important operating conditions, such as completion of offset wells, changing from flowing to pumping, changes in back pressures and all changes in equipment and methods of pumping, appearance of water, application of vacuum, and degree of vacuum. By recording these dates the engineer may not only make more dependable estimates but may also help the producer to solve production problems and to choose the best producing methods.

CONSTRUCTION OF AVERAGE CURVES.

In order to conform with the law of equal expectations an average curve should show the average behavior of wells of the same size. Some method of combining individual well records to form an average curve for a tract or some method of combining a number of tract records to form an average curve for a pool or field must be employed.

Numerous methods have been devised for constructing average curves, as follows:

(*a*) The family-curve method, with curves plotted on either coordinate paper or logarithmic coordinate paper.[29]

(*b*) The mathematical method.[30]

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[27] Ambrose, A. W., Underground conditions in oil fields: Bull. 195, Bureau of Mines, 1921, pp. 182–192.

[28] Kirwin, M. J., and Schwarzenbek, F. X., Petroleum engineering in the Deaner oil field, Okfuskee County, Okla. Cooperative bulletin of Bureau of Mines, State of Oklahoma and the Bartlesville, Okla., Chamber of Commerce, July, 1921, pp. 25–27.

[29] Lewis, J. O., and Beal, C. H., Some new methods for establishing the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, February, 1918, pp. 477–504. Beal, C. H., and Nolan, E. D., Application of law of equal expectations to oil production in California: Am. Inst. Min. Eng. Bull. 152, August, 1919, pp. 1237–1245. 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. 198.

[30] Cutler, W. W., jr., A mathematical method of constructing average oil-well production curves: Reports of Investigations, Bureau of Mines, July, 1920.

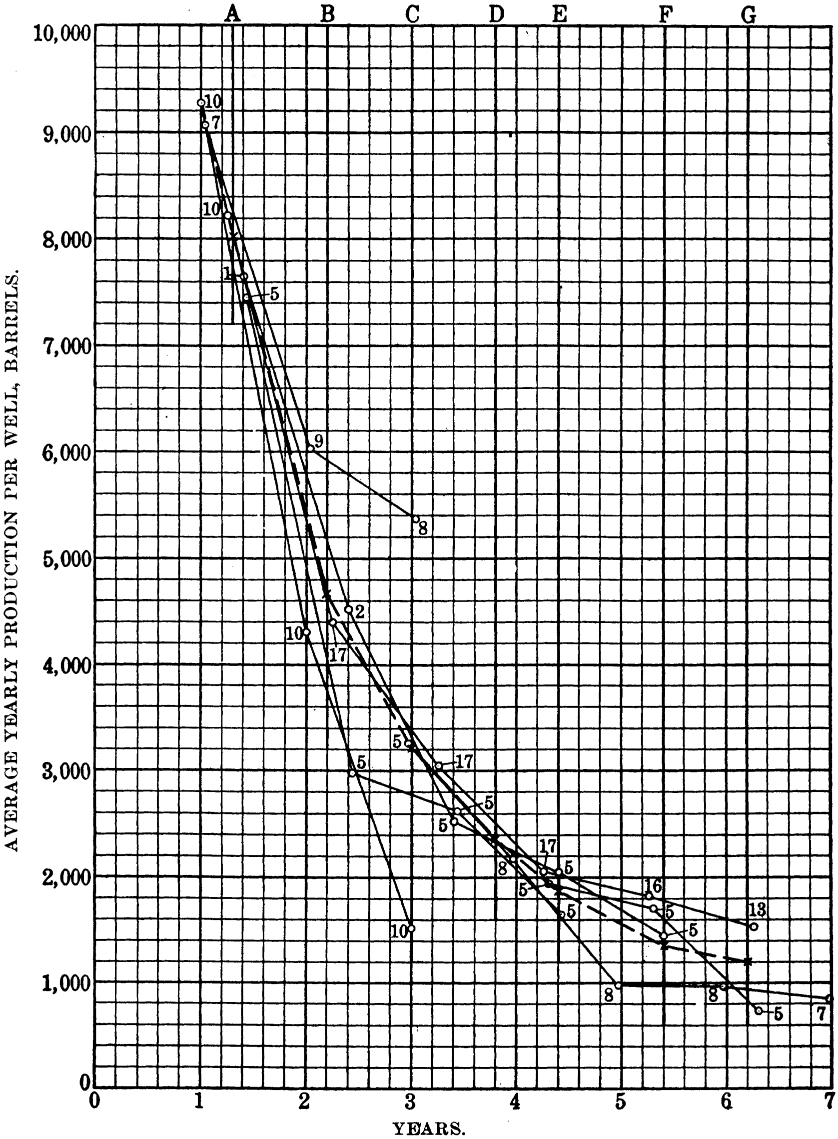

FIG. 12.—Family-curve method of constructing an average production-decline curve on coordinate paper.

(*c*) The segmental method.[31]

(*d*) The appraisal-curve method, sometimes termed the "fly-speck" method.[32]

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[31] Manual for the Oil and Gas Industry. 1st ed., Treasury Department, 1919, p. 67, second par. Method introduced by J. L. Darnell.

[32] Manual for the Oil and Gas Industry, 1st ed., Treasury Department, 1919, pp. 70–72. 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. 30–36.

FAMILY-CURVE METHOD ON COORDINATE PAPER.

Briefly, the family-curve method consists of tying wells to an average curve at the point of their greatest production and then averaging the subsequent productions.

Figure 12 shows how production-decline curves for separate tracts producing under similar conditions in the same field may be combined to construct an average production-decline curve for the average well of all the tracts. In this example records of seven tracts were available, showing the yearly productions and the average number of wells producing each year from each tract as given in Table 10. In order to obtain the yearly productions of the average well of each tract the successive yearly productions of each tract were divided by the number of wells producing each year.

TABLE 10.—*Production records of seven tracts in the Salt Creek field, Wyoming.*

Tract No.		Calendar Year.					
		1915	1916	1917	1918	1919	1920
1	Total yearly tract production, barrels	....	....	....	92,760	43,000	15,200
	Number of producing wells	....	....	....	10	10	10
	Average yearly production per well, barrels	....	....	....	9,276	4,300	1,520
2	Total yearly tract production, barrels	....	....	....	63,532	54,180	42,960
	Number of producing wells	....	....	....	7	9	8
	Average yearly production per well, barrels	....	....	....	9,076	6,020	5,370
3	Total yearly tract production, barrels	82,200	74,800	51,850	34,952	29,200	19,890
	Number of producing wells	10	17	17	17	16	13
	Average yearly production per well, barrels	8,220	4,400	3,050	2,056	1,825	1,530
4	Total yearly tract production, barrels	....	7,650	13,545	12,625	10,200	7,250
	Number of producing wells	....	1	3	5	5	5
	Average yearly production per well, barrels	....	7,650	4,515	2,525	2,040	1,450
5	Total yearly tract production, barrels	....	15,060	37,750	14,900	13,100	8,250
	Number of producing wells	....	3	5	5	5	5
	Average yearly production per well, barrels	....	5,020	7,550	2,980	2,620	1,650
6	Total yearly tract production, barrels	....	16,250	17,400	7,840	7,760	5,880
	Number of producing wells	....	5	8	8	8	7
	Average yearly production per well, barrels	....	3,250	2,175	980	970	840
7	Total yearly tract production, barrels	....	....	....	9,700	8,500	3,650
	Number of producing wells	....	....	....	5	5	5
	Average yearly production per well, barrels	....	....	....	1,940	1,700	730

The records to be combined must first be carefully examined and the abnormal irregularities eliminated. The latter include, particularly, records of fluctuations preceding the period of symmetrical decline, and parts of tract records where the number of producing wells changes rapidly, or where wells are deepened to other sands, or are unduly affected by water encroachment, cleaning out, or other factors. The production for 1916 of the average well on tract 5 is obviously low; it represents production before the beginning of the period of average symmetrical decline for the tract and should not be used in constructing the average production-decline curve.

The next step is to plot the average productions per well on the various tracts. The consecutive yearly productions of the average well of that tract whose average well shows the highest initial year's production (tract 1, 9,276 barrels) are plotted on a piece of coordinate paper, with the vertical scale representing barrels of production per annum and the horizontal scale representing years. (See Fig. 12.) The rest of the records are later plotted in a descending order based on the amount of the first year's production of the average well on each tract, but the calendar of that production is disregarded. In order to weight the tracts according to the number of producing wells, the number producing each year is written above the recorded graphical production. The average well of the tract whose average initial production is second highest (tract 2) is then plotted, its first year's production (9,076 barrels) being placed on the graph of that tract which is already plotted and its subsequent yearly productions spaced at yearly intervals.

A vertical line, A, is drawn through these two graphs at any place below that point where the next tract will be tied on the average curve. The points of intersection of this vertical line with the two graphs already plotted are now averaged vertically, proper allowance being made for the number of wells on each tract. In order to obtain this average, the points cut off on the graph of the first tract (7,800 barrels) and the graph of the second tract (8,300 barrels) by the vertical line A are multiplied by the number of wells as follows:

10×7,800= 78,000
8×8,300= 66,400
— ———
Total 18 144,000

The quotient of 144,400 divided by 18 is 8,022, which is the average production for the two tracts at the line A. A broken line drawn from the point in common of the two graphs (9,076 barrels) to the average point on line A (8,022 barrels) gives the average production-decline curve to the line A. On this average line are tied any other graphs whose initial productions lie above 8,022 barrels. In this example tract 3, which had an initial average yearly production of 8,220, is tied on.

In Figure 12, seven vertical lines—A, B, C, D, E, F, and G—were used to obtain points on the average curve, thus consecutively prolonging the curve to permit the tying on of other wells. When all of the records have been used the average production-decline curve has been constructed, as represented by the broken line in Figure 12. Irregularities may be smoothed out and the curves extended by passing a curve through the various segments, either on coordinate paper or, better still, by transferring the points to logarithmic paper according to the method illustrated in Figures 4 and 5. The resulting average production-decline curve before it is smoothed out and extended for future years is as follows: 9,276, 5,360, 3,200, 2,200, 1,550, and 1,250 barrels.

FAMILY-CURVE METHOD ON LOGARITHMIC PAPER.

The method just outlined may be used with logarithmic coordinate paper. The procedure is identical, and when correctly used the family-curve method on logarithmic paper gives approximately the same average curve as the family-curve method on coordinate paper. Logarithmic paper is more convenient because the same accuracy may be obtained with a smaller sheet of paper. In addition the symmetry of the curves is more obvious. The individual curves as plotted on logarithmic paper approach more closely segments of curves than those plotted on coordinate paper, and hence the resulting average curve is more nearly a true average curve than that made on coordinate paper. One can also detect errors due to too few records at either the start or the end of a group of curves. The middle portion may straighten out but bend at the ends. This can be less readily detected on coordinate paper.

Figure 13 is an example of the construction of an average curve by the family-curve method on logarithmic paper with the production records shown in Table 10 (p. 43). The yearly points of the resulting average production-decline curve before it is smoothed out and extended is as follows: 9,260, 4,800, 3,125, 2,100, 1,600, and 1,275.

LIMITATION OF FAMILY-CURVE METHOD.

Usually the production-decline curves of many tracts in the same pool bear a striking similarity; however, there are always some tracts or wells with relatively sustained productions and others with relatively rapid declines.

In the family-curve method, individual production-decline curves that are unduly sustained or decline too rapidly tend to depart more and more from the average curve with each succeeding year's production. The tracts with fast declines reach their economic limit and the curves are ended, but the normal tracts and those with

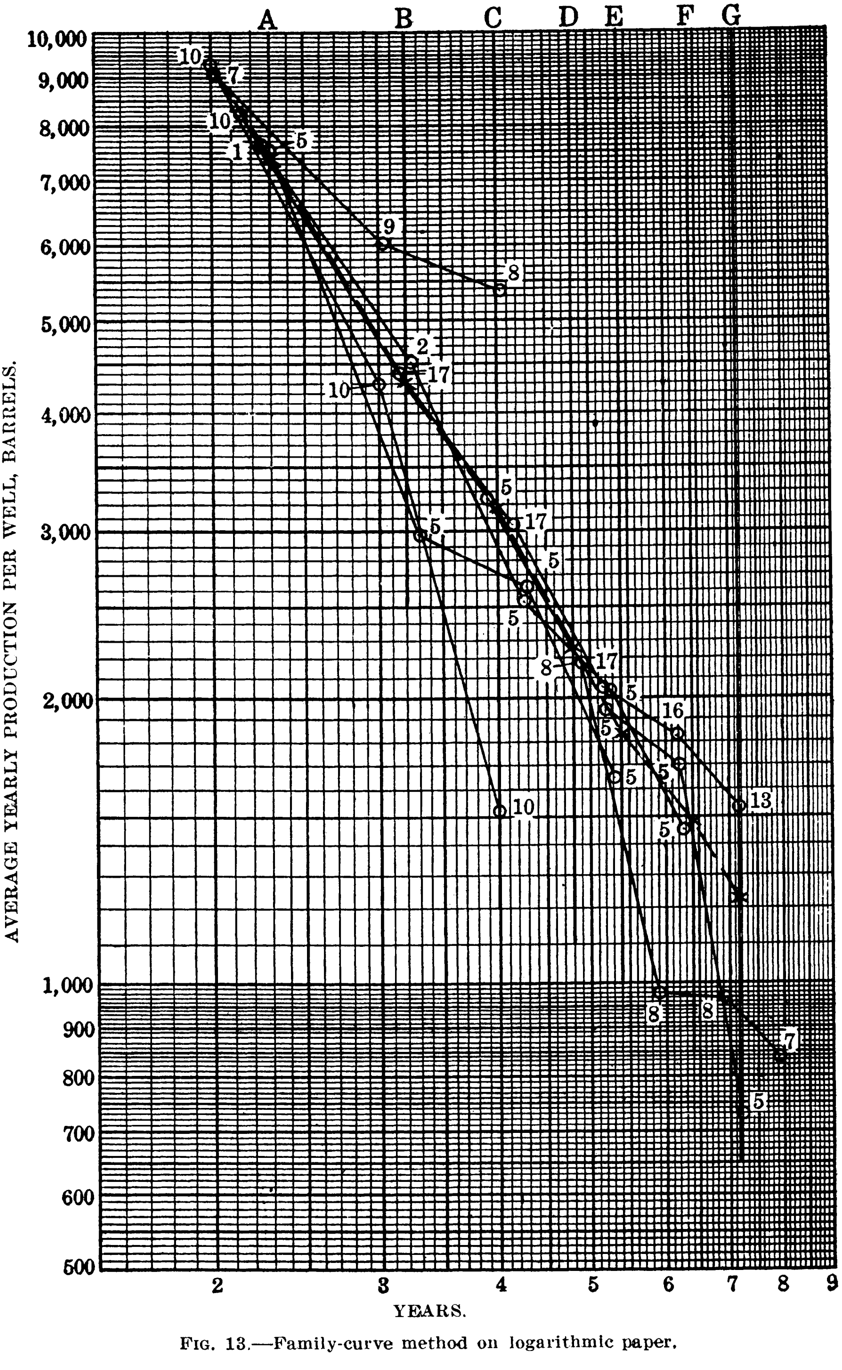

FIG. 13.—Family-curve method on logarithmic paper.

sustained production are still plotted to form the average curve. This results in a sustaining of the average curve as each curve of accelerated decline is dropped. The average curve no longer represents the average production decline of all of the wells of the field, but the average decline of production of the normal and sustained tracts.

For this reason the average curve as constructed by the family-curve method by tying the initial productions to the average production-decline curve is not a true average curve beyond the point where curves of accelerated decline have reached their economic limit unless these curves are projected and their projections beyond the economic limit are averaged in. The lower part of the curve can be checked for probable accuracy by noting wether the curve straightens out on logarithmic paper or whether the lower part deviates to the right. In new fields a curve sustained at the bottom may be a true average, the lower part being sustained by the installation of pumps. Such factors, of course, must be considered.

The average curve beyond such a point of deviation may be extended on logarithmic paper, or if it is a field in which all wells have reached a low production another average-production curve may be constructed for wells of small production by tying all wells together at a common low point on the average curve. A regrouping of all the wells at a low production is conformable with the law of equal expectation, which states that the future of wells of the same size producing under similar conditions will be approximately the same. As the conditions of production during the late life of a pool are apt to be more similar as regards pressure, spacing, and operation than in the early life of a pool, such a regrouping is the best method of estimating the average future production of wells of small production, provided, however, that all of the wells have reached the production at which the wells are tied together.

Assume, for example, that it is desired to form an average production-decline curve by the family-curve method for the wells in a tract where the production of the largest well is at present 1,000 barrels a year and many wells have reached an economic limit and have been abandoned. An average production-decline curve for the tract is constructed from old records by the graphical family-curve method. It is found that the average curve below 2,000 barrels a year is not an average of all of the wells, as the average curve beyond this point is only an average of the more sustained and normal wells because some of the wells of fast decline have been abandoned. All of the wells may therefore be tied together on the average curve at or above 2,000 barrels a year and the curve extended downward by this regrouping to 1,000 barrels a year, at which point the curve must be extended by logarithmic paper, as there are then some wells that have been abandoned and the curve no longer represents the average of all of the wells.

That segment of the average production-decline curve which represents an average of a relatively large number of wells should be considered as a true average curve. Thus in Figure 12 (p. 42), the average curve represents a true average of the tracts through six yearly periods to the point whose ordinate is 1,250 barrels. None of the tracts has yet reached an economic limit, and the accelerated productions offset the sustained. The sixth year represents an average of 26 wells out of a total recorded of 63 wells, but the seventh year represents the average of only 7 of the 63 wells and therefore should not be used in determining the true production-decline curve.

The family-curve method is especially adapted for constructing average curves for pools in which no tracts have yet been abandoned and for tracts in which no wells have yet been abandoned. This method is particularly useful where there are relatively few records and can not be used so well where there are a great many records.

MATHEMATICAL METHOD.

A modification of the family-curve method of constructing average-decline curves is the mathematical family-curve method, which may be used where there are numerous records available. The production records are listed in columns instead of being plotted on coordinate paper. The same principles are embodied in both the graphical and mathematical family-curve methods except that in the mathematical method it is seldom possible to tie a well to the average curve at the exact point of its initial production. In the mathematical method a well is tied to the average curve at that yearly, quarterly, or monthly period which is closest to the well's initial production. Experience has shown that with a large number of records the errors thereby resulting will compensate, and the smoothed-out average curve will be practically identical with that obtained by the graphical method.

The mathematical method avoids the confusion that accompanies the plotting of many records on a single sheet of coordinate or logarithmic paper and thus permits the use of a greater number as well as shorter records than the graphical method. Moreover, it is simple and rapid.

DESCRIPTION OF METHOD.

In the use of the mathematical method it is necessary first to carefully examine the production records in the same manner as for the graphical method. To clarify the explanation of this method the production-decline curve of the average well for the seven tracts shown in Table 10 (p. 43) will be computed. The tract whose average well showed the highest initial year's production (9,276 barrels) was used to start the curve as in the graphic method. On suitably ruled paper (Table 11, p. 50) the successive yearly productions of the average well of this tract were tabulated in horizontal order in succeeding columns, with the number of producing wells each year in parenthesis below, and the total production of the tract for the year to the right of the figure for each yearly production of the average well. For convenience, the main columns have been subdivided into two subcolumns called A and B; A contains the yearly production of the average well of the tract, with the number of wells producing during each year in parentheses below, and B the total yearly tract productions. The tract whose initial year's production for the average well was next highest (9,076) was then selected and the average production of the initial year placed in that column (A) which contained the figure nearest this initial production. Thus, 9,076 is nearer 9,276 than 4,300, and therefore was placed in column 1. The succeeding years' productions of the average well of this tract were then placed in successive columns with the corresponding yearly tract productions in the B column. This same procedure was followed until all the production figures were utilized. In the columns to the right there may appear the first year's production for a small well and the third or fourth year's productions for some larger wells. The position of the production figures in the columns for any tract does not depend in any way upon the calendar years or the life years of the other tracts, but is based entirely on the size of the initial year's production of the average well of the tract.

TABLE 11.—*Illustration of mathematical method of constructing average curves.*

[Tentative average of columns written vertically.]

Tract No.	Column 1.		Column 2.		Column 3.		Column 4.		Column 5.		Column 6.		Column 7.	
	[a] A	[a] B	A	B	A	B	A	B	A	B	A	B	A	B
1........	9,276 (10)	92,760	4,300 (10)	43,000	1,520 (10)	15,200	....	....	....	....	....	....	....	....
2........	9,076 (7)	63,532	6,020 (9)	54,180	5,370 (8)	42,960	....	....	....	....	....	....	....	....
3........	8,220 (10)	82,200	4,400 (17)	74,800	3,050 (17)	51,850	2,056 (17)	34,952	1,825 (16)	29,200	1,530 (13)	19,890	....	....
4........	7,650 (1)	7,650	4,515 (3)	13,545	2,525 (5)	12,625	2,040 (5)	10,200	1,450 (5)	7,250	....	....	....	....
5........	7,550 (5)	37,750	2,980 (5)	14,900	2,620 (5)	13,100	1,650 (5)	8,250	....	....	....	....	....	....
6........	....	....	....	....	3,250 (5)	16,250	2,175 (8)	17,400	980 (8)	7,840	970 (8)	7,760 -	840 (7)	5,880
	9,276		4,535		3,016		2,023							
7........	....	....	....	....	....	....	1,940 (5)	9,700	1,700 (5)	8,500	730 (5)	3,650	....	....
Average yearly production......	(33)	$\frac{283,892}{8,603}$	(44)	$\frac{200,425}{4,555}$	(50)	$\frac{151,985}{3,039}$	(40)	$\frac{80,502}{2,013}$	(34)	$\frac{52,790}{1,553}$	(26)	$\frac{31,300}{1,204}$	(7)	$\frac{5,880}{840}$

[a] A indicates yearly production (barrels) of average well of tract, and number of wells producing. B indicates total yearly production.

In order to determine in which column to place the initial production of a tract of low average initial production, the average of subcolumns B were taken and only the production figures which were not initial productions were used. Thus, in order to determine in which column to place 1,940, the average initial production of tract 7 the average of column 3 was taken through 13,100 and the average of column 4 through 17,400. As the average of column 3 was 3,016 and the average of column 4 was 2,023, the initial production of tract 7 (1,940) was placed in column 4. If the average initial production of a tract lies halfway between two columns it is placed according to the relation of the second year's production of the tract and the succeeding column.

To obtain a curve of the average well of the tracts due consideration must be given the number of wells producing each year on each lease. This is called "weighing" the tracts, and is done as follows: The production figures having been placed in the correct columns the total tract productions under B are added and then divided by the total number of producing wells shown under A. The result gives the successive years productions of the weighed average well for the field. The yearly average well production shown under A is used only to place the records in their proper columns.

Thus, for subcolumn B of column 1, Table 11, the total of the tract productions was 283,892 barrels, which, when divided by the total number of wells in the column, as represented by the sum of the figures in parenthesis (33), gave the weighed average production of the average well of all of the tracts during that year as $\frac{283{,}892}{33}=8{,}603$ barrels. The average of the successive subcolumns B furnishes the production of the average well of all of the tracts for successive years. These yearly average productions may be plotted on coordinate or logarithmic paper to form a production-decline curve in the same manner as that of an individual well. Thus, in the accompanying illustration, the curve will be plotted from the following data (Table 11):

Year.	Production, barrels.
1	8, 603
2	4, 555
3	3, 039
4	2, 013
5	1, 553
6	1, 204

The resulting curve may be smoothed out, its irregularities of curvature eliminated, and then extended downward to estimate future production. If individual well records are used instead of tract production records only one figure occurs in each line of the column and no weighing is necessary, for the total of each column is divided by the number of figures in the column to obtain the average well's production.

ANALYSIS OF THE MATHEMATICAL METHOD.

To judge the reliability of this method, the resulting decline curve may be compared with the curve obtained by the "family-curve" graphical method. The same production records were used in constructing a curve by each of the two methods, and both curves were plotted on the same sheet of coordinate paper. (Fig. 14.) These curves when smoothed almost coincide, as shown by the following table:

TABLE 12.—*Comparison of average curves formed by family-curve and mathematical methods.*

Year.	Actual plotting points.		Productions (barrels) for corresponding yearly periods from curves.	
	By graphical curve.	By mathematical method.	Family curve.	Mathematical method.
1	9,276	8,603		
2	5,360	4,555	5,360	5,200
3	3,200	3,039	3,200	3,300
4	2,200	2,013	2,200	2,200
5	1,550	1,553	1,550	1,600
6	1,250	1,204	1,250	1,270
Total			13,560	13,570

If a large number of records are used to make an average production-decline curve by this method, the resulting curve will be almost identical with one made with the same records by the "family-curve" method. When only a small number of records are used, the resulting curves will not check so closely, because in the "family-curve" method the wells are tied to the average curve at the exact position on the curve where their production equals that of the average curve, whereas in the mathematical method the wells are tied to the average curve at the nearest yearly point.

The mathematical method has the same limitations as the family-curve method. It does not furnish a true average curve below the point where wells or tracts have been abandoned. However, the wells may be regrouped at a common point of low production, as in the family-curve method, by placing low productions of about the same amount of each of the individual wells in the first column, and later successive productions for the unit periods in succeeding columns. The true average production curve may thus be extended.

SEGMENTAL METHOD.

The time during which each well or average well of a tract produced between definite rates of production, such as 9,000 barrels a year to 8,000 barrels a year; 8,000 to 7,500; 7,500 to 5,400; 5,400 to 3,250, and so on, is recorded and a numerical average of the time of fall of all wells between each set of limits is calculated. The selection of the sets of limits is arbitrary. The records to be aver-

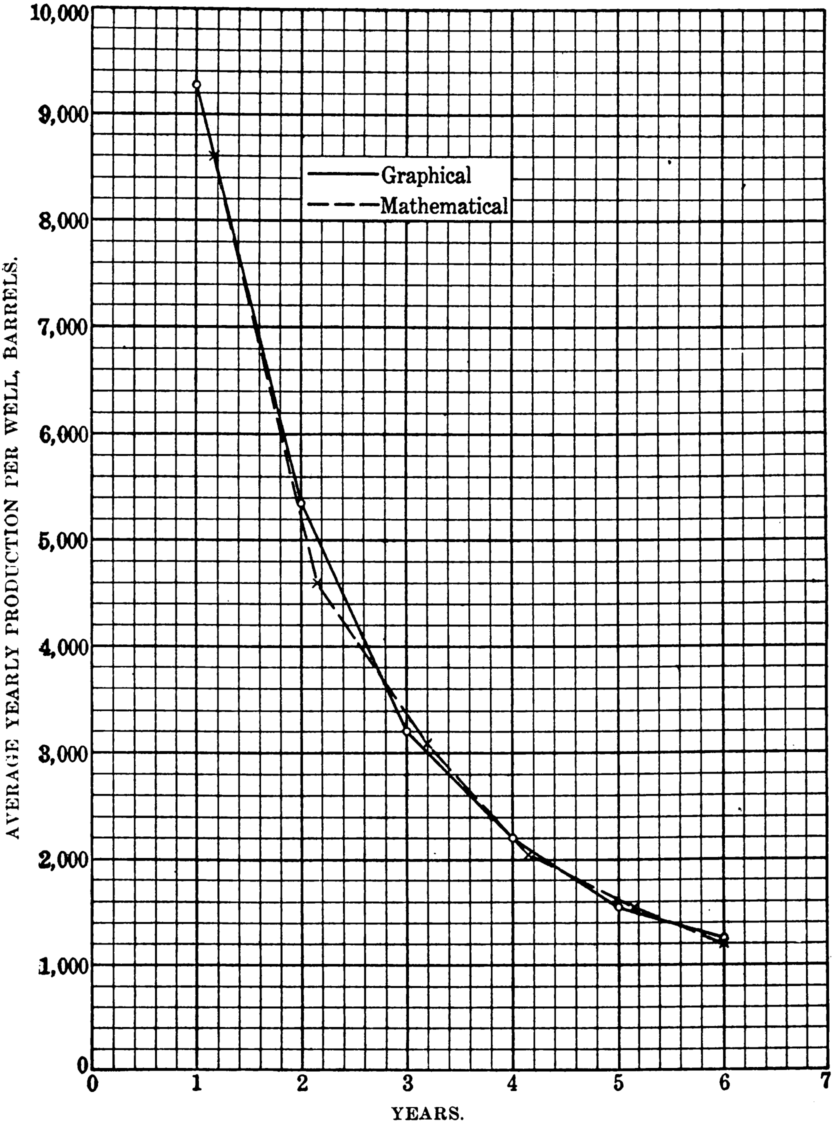

FIG. 14.—Comparison of average production-decline curves formed by family-curve and mathematical methods.

aged should be examined, enough limits chosen to establish a curve, and those limits selected which will make the calculations as simple as possible. The average time of decline between these limits may be plotted to form the resulting average production-decline curve.

The time during which the production of the average well of each tract fell between each set of limits may be read directly from the plotted production-decline curves of the individual tracts or may be calculated directly from the production records.

The mathematical calculation of the average time of decline from 9,000 to 8,000 barrels a year for tract 1, as shown in Table 10 (p. 43), is as follows:

$$
\begin{array}{rrrl}
 & 9,276 & 9,000 & \\
1\text{ year} & & & ?\text{ year.} \\
 & \underline{4,300} & \underline{8,000} & \\
 & 4,976 & \dfrac{1,000}{4,976} & =0.201\text{ year.}
\end{array}
$$

The average well fell from 9,000 to 8,000 barrels a year in 0.201 year.

The mathematical calculation of the time of decline from 7,500 to 5,400 barrels a year for tract 2, as shown in Table 10, is a follows:

$$
\begin{array}{rrrl}
 & 9,076 & 7,500 & \\
1\text{ year} & & & \\
 & \underline{6,020} & \underline{6,020} & \\
 & 3,056 & \dfrac{1,480}{3,056} & =0.484 \\
 & 6,020 & 6,020 & \\
1\text{ year} & & & \\
 & \underline{5,370} & \underline{5,400} & \\
 & 650 & \dfrac{620}{650} & =0.955 \\
 & & & 1.439\text{ years.}
\end{array}
$$

Table 13 shows how information from the production records of Table 10 is assembled to form an average production-decline curve by the segmental method.

TABLE 13.—*Assemblage of information to construct an average curve by segmental method.*

LIMIT, 9,000 TO 8,000 BARRELS A YEAR.

Tract.	Time, years.	Wells.	Well years.	Average time, years.
1	0.20	10	2.01	
2	.33	8	2.64	
Total	....	18	4.65	0.26

TABLE 13.—*Assemblage of information to construct an average curve by segmental method.*—Continued.

LIMIT, 8,000 TO 7,500 BARRELS A YEAR.

Tract.	Time, years.	Wells.	Well years.	Average time, years.
1	0.10	10	1.00	
2	.16	8	1.28	
3	.13	10	1.30	
Total		28	3.58	0.13

LIMIT, 7,500 TO 5,400 BARRELS A YEAR.

1	0.42	10	4.20	
2	1.44	8	11.52	
3	.54	14	7.56	
4	.66	2	1.32	
5	.45	5	2.25	
Total		39	26.85	0.69

LIMIT, 5,400 TO 3,250 BARRELS A YEAR.

1	0.59	10	5.90	
3	1.12	16	17.92	
4	.93	3	2.79	
5	.47	5	2.35	
Total		34	28.96	0.85

LIMIT, 3,250 TO 2,400 BARRELS A YEAR.

1	0.31	10	3.10	
3	.80	17	13.60	
4	.63	5	3.15	
5	1.28	5	6.40	
6	.80	6	4.80	
Total		43	31.05	0.72

LIMIT, 2,400 TO 1,900 BARRELS A YEAR.

1	0.18	12	2.16	
3	1.02	17	17.34	
4	.98	5	4.90	
5	.53	5	2.65	
6	.44	7	3.08	
Total		46	30.13	0.67

LIMIT, 1,900 TO 1,650 BARRELS A YEAR.

1	0.14	10	1.40	
3	.89	15	13.55	
4	.41	5	2.05	
5	.25	5	1.25	
6	.21	8	1.68	
7	.91	5	4.55	
Total		48	24.28	0.51

LIMIT, 1,650 TO 1,000 BARRELS A YEAR.

6	0.53	8	4.24	
7	.66	5	3.30	
Total		13	7.54	0.58

TABLE 13.—*Assemblage of information to construct an average curve by segmental method.*—Continued.

LIMIT, 1,000 TO 850 BARRELS A YEAR.

Tract.	Time, years.	Wells.	Well years.	Average time, years.
6	1.92	8	15.36	
7	.16	5	.80	
Total	....	13	16.16	1.24

TABLE 14.—*Average time of decline between the limits of production given in Table 13.*

Limits of production, barrels a year.	Average time, years.	Average cumulative time, years.
9,000 to 8,000	0.26	0.26
8,000 to 7,500	.13	.39
7,500 to 5,400	.69	1.08
5,400 to 3,250	.85	1.93
3,250 to 2,400	.72	2.65
2,400 to 1,900	.67	3.32
1,900 to 1,650	.51	3.83
1,650 to 1,000	.58	4.41
1,000 to 850	1.24	5.65

From this table may be plotted the average production-decline curve as shown in Figure 15.

ANALYSIS OF THE SEGMENTAL METHOD.

The segmental method regroups wells of the same rate of production at various points on the average curve and averages their time of declines between the same rates of production. Graphically the average would be taken horizontally on the time scale instead of vertically on the production scale as in the family-curve method. This method is conformable to the law of equal expectations, inasmuch as a regrouping of wells of equal production enables an average to be made of the production declines of wells of equal size.

The segmental method should not be used in the construction of an average curve for a young field. In such a field the most favorably situated areas and those tracts the least drilled have a more sustained production than tracts less favorably situated and more completely drilled. Hence in a partly drilled field, on any stated day, the tracts with large average wells are those with the most sustained production, and the tracts with small average wells are those with fast-declining production. The upper part of an average curve constructed by the segmental method for a young field is formed from practically all of the production records of the wells with sustained production and only the early records of the wells with fast declines. The lower part of the curve is formed almost entirely from the recent records of the wells of fast declines. Therefore the upper part of such an average curve does not show as fast a decline as the average well in the field, and the

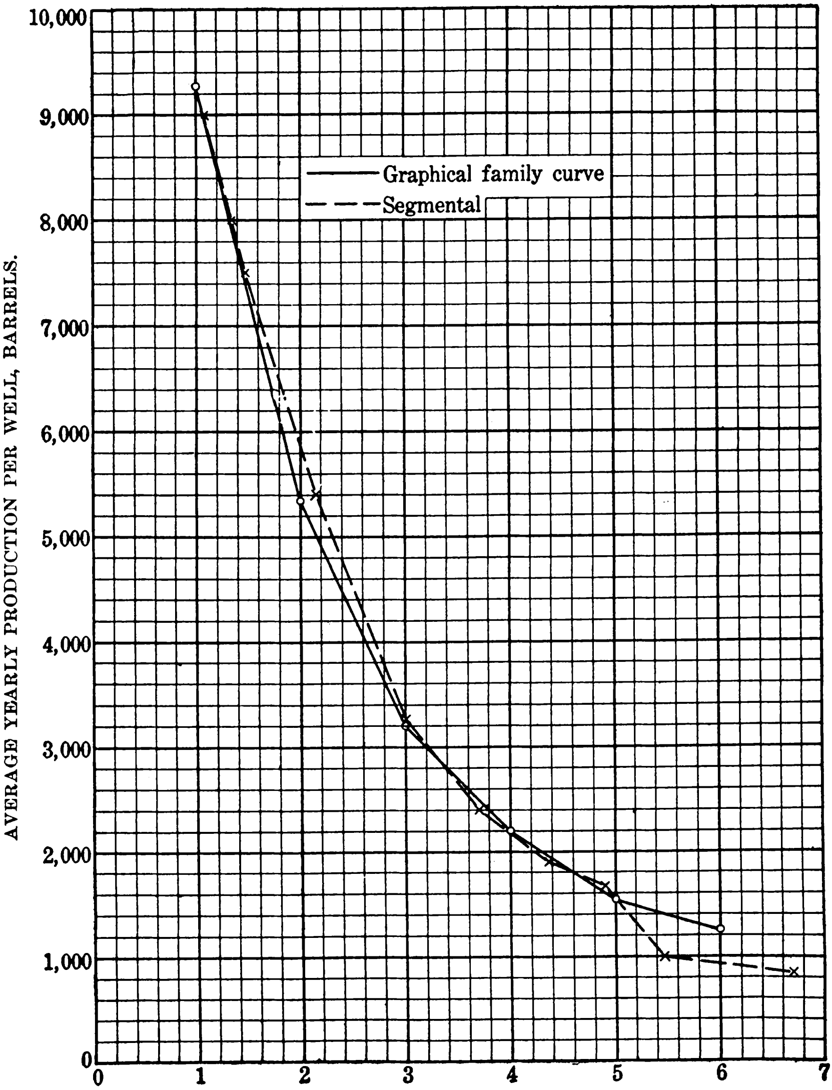

FIG. 15.—Comparison of curves formed by family-curve and segmental methods.

lower part has a more rapid decline than the average well in the field.

Figure 15 compares the average production-decline curves formed from the records of the tracts in Table 10 (p. 43) by the family-curve and the segmental methods. It illustrates the inadvisability of using the segmental method in the construction of an average curve for a young field. The average curve formed by the segmental method has a smaller decline in the upper portion, is about the same in the central portion, and has a more rapid decline in its lower portion than the average curve formed by the family-curve method.

The segmental method may be used in constructing average curves for old fields that have been completely drilled for several years. The upper part of the resulting curve will not have as fast a decline as the average well of the field, but as the period of wells of high production is already past, this part of the curve is not needed in the estimation of future yield. The lower part of the average curve will show the average decline of wells of small production.

APPRAISAL-CURVE METHOD.

The appraisal-curve method is radically different from the three methods already discussed; it is used to form an appraisal curve and not a production-decline curve. An appraisal curve is a curve showing the relation between the first year's production of wells of different sizes and their ultimate productions. Figure 16 illustrates this method of constructing an average appraisal curve. The horizontal scale for such a curve represents the first year's production of the wells and the vertical scale represents the ultimate production to an assumed economic limit.

To construct an appraisal curve from production records it is first necessary to plot the yearly production of each well or average well of a tract and then extend these curves to the assumed economic limit. The ultimate production of each well is then estimated and a dot placed upon the coordinate paper for each well. The dot represents the first year's production plotted with reference to the ultimate production. After the dots are all plotted an average curve drawn through the points will represent the average appraisal curve for the area under consideration. This average curve should be drawn as a median line; that is, so that it will have as many dots on one side as the other.

This method involves a large amount of work and it can not be used where records are short because it requires the estimating of future productions for every record of the wells or tracts used, nor can it be used where records are few. However, the method if correctly used with enough records provides a reliable average appraisal curve from which may be derived an average production-decline curve for a tract or field. (See Fig. 17, p. 61.) It furnishes a maximum and minimum estimate of future production obtainable by no other method as yet advanced. In Figure 16 a minimum and a maximum appraisal curve may be passed through the points representing respectively the wells of fastest decline and those of most sustained production. The maximum and minimum ultimate production that may be expected for wells of any initial yearly production may thus be determined.

For example, a well of a yearly production of 1,000 barrels in Wood County, Ohio, may have an ultimate production as small as 2,550 barrels or as large as 5,800 barrels, the probability being, if the well is producing under the average conditions for that area, that the ultimate production will be 4,450 barrels.

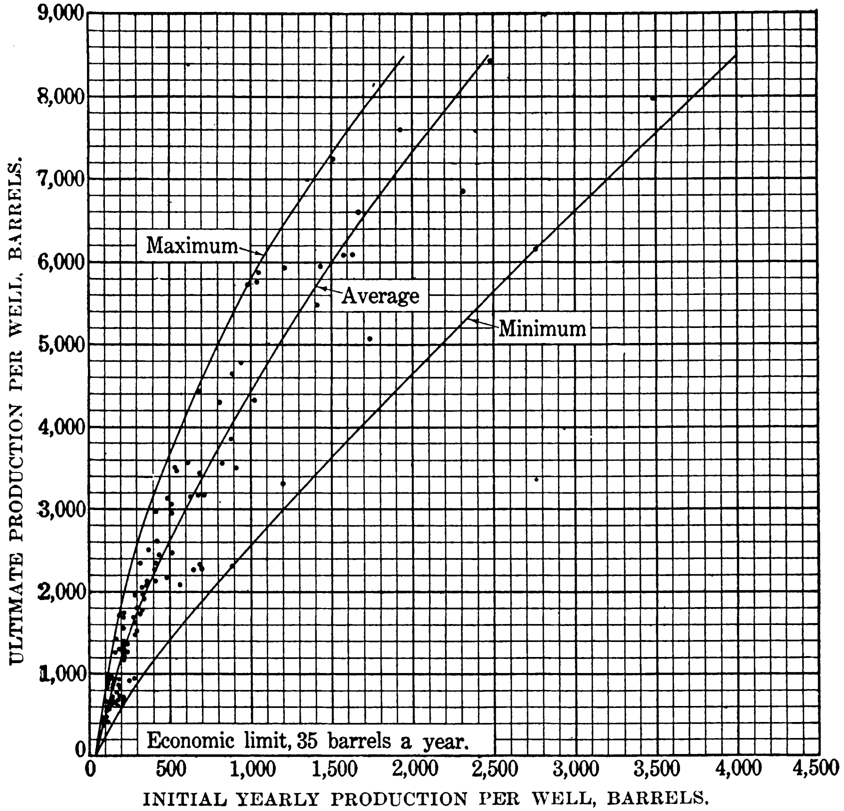

FIG. 16.—Appraisal-curve method.

The use of maximum, average, and minimum curves is described on page 62 of this paper. These maximum, average, and minimum curves are useful in buying a producing property because they assist in determining a reasonable price for it.

The appraisal curve may be used to estimate the ultimate productions of wells according to the initial year's production or the future plus the last year's production referred to the last year's production.

Estimates are best made by the last year's production, thus basing estimations of future production on the latest performance of the wells.

RÉSUMÉ OF METHODS.

Each method which has been described is applicable to certain conditions. Table 15 classifies the methods.

TABLE 15.—*Guide for selection of method of forming average curves.*

	Young pools.	Medium-aged pools.	Old pools.
Few records	Family curve	Family curve	Segmental or family curve.
Many records	Mathematical	Mathematical	Segmental, appraisal, or mathematical.

The appraisal-curve method involves more labor than the family-curve, segmental, or mathematical methods, but should be used when the establishing of maximum, average, and minimum curves for a tract or pool is desired. It is best to check any resulting average curve by comparison with an average curve formed by another method, in order to insure that the curve is representative of the average production-decline of the wells under consideration.

APPLICATION OF AVERAGE CURVES TO ESTIMATION OF RESERVES.

As before stated, only the records of wells and tracts that produce under similar conditions in the same pool, field, or tract should be used in the construction of an average curve. These wells and tracts may vary greatly in their initial productions and also in their rates of decline. However, if the individual curves of these wells and tracts are plotted as straight lines on logarithmic paper the highest production of each of these curves will be found to lie near the average production-decline curve on the logarithmic paper. As has been shown (p. 29 and Fig. 5, p. 25), the location on logarithmic paper of a curve greatly affects its extension downward for estimating future production. It has also been shown (p. 26) that the location of two points on logarithmic paper establishes a production-decline curve. The location on logarithmic paper of the average curve therefore assists greatly in the construction of tentative curves for properties in the early stages of development, before enough production records are available for plotting and establishing production-decline curves for the properties themselves.

Figure 17 shows the maximum, average, and minimum production-decline curves for Wood County, Ohio. These curves were derived from the maximum, average, and minimum appraisal curves shown in Figure 16, by the method described on page 58. All three of these production-decline curves shown in Figure 17 may be plotted

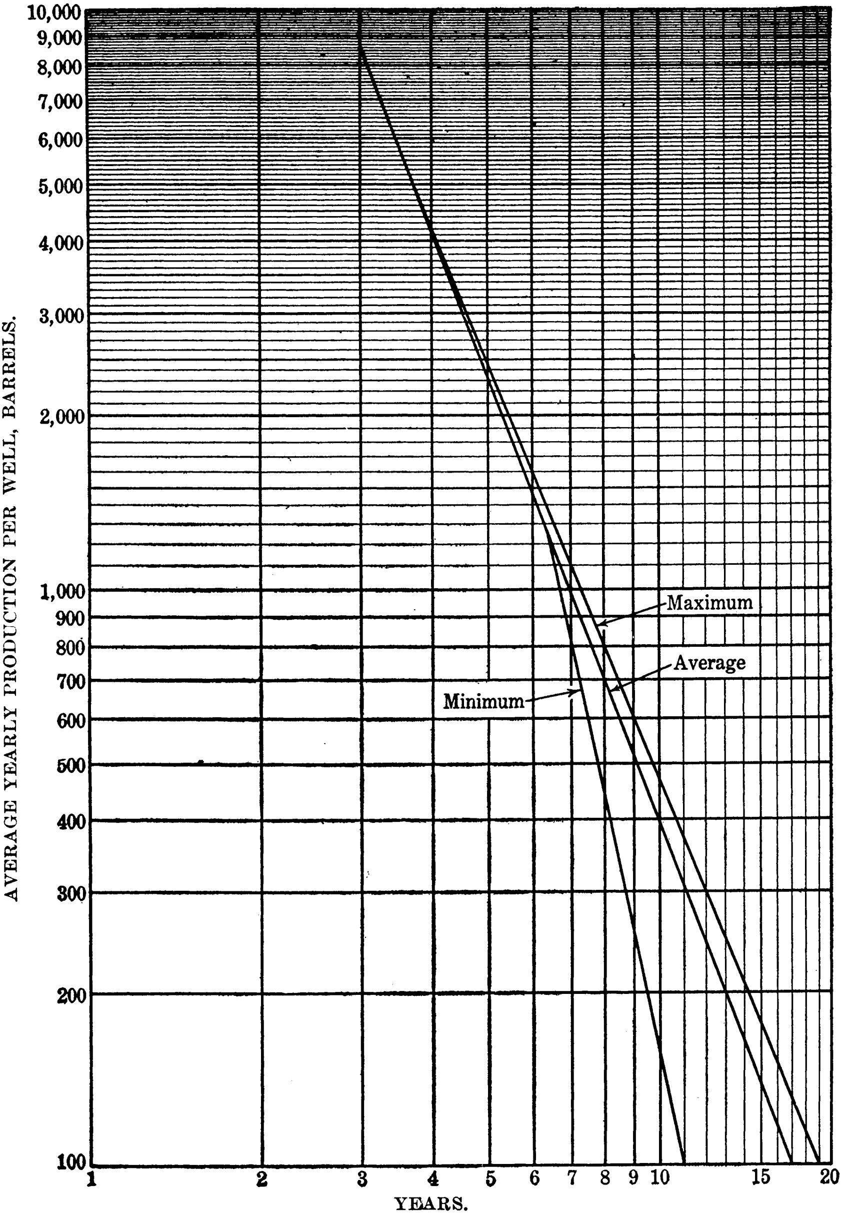

FIGURE 17.—Maximum, average, and minimum production-decline curves for Wood County, Ohio.

as straight lines on logarithmic paper. The reader will note that the maximum and minimum production-decline curves join the average curve at their points of greatest production.

If only one year's period production of a tract is known, the average curve, or some curve lying between the maximum and minimum curves, can be used for estimating the reserves of the tract. The behavior of the wells and the natural and artificial conditions affecting production should determine the selection of the curve to be used. A conservative buyer, knowing little of the past history of a property, might use a curve that lies between the minimum and the average curves, the probability being that the production decline of the wells will follow the average curve. The difference between such a curve and the average curve represents the margin of safety that this buyer would allow himself in his estimates of reserves.

If the productions of two yearly periods of a tract are known, the first year's production may be plotted on the average production-decline curve on logarithmic paper and the next year's production plotted with reference to that point. The two points may then be joined and the straight line may be assumed to indicate the production-decline curve for that tract if its decline of production from the first year to the second was normal. The history of the tract, including all operations on the wells, water conditions, and mechanical difficulties, should indicate whether the past decline was normal. The production-decline curve of the tract will probably lie near the average curve for the field, and there is little chance of its lying outside of the range between the maximum and minimum curves of the field. The relation of the curve to the maximum, average, and minimum curves of the field, as established by the two years' production records, aids in determining whether the curve can be relied upon. In any case, a curve based on two years' period productions can only be tentative, for the decline in production as represented by the two production figures may not be normal and the location on logarithmic paper of these two productions is only approximate.

When the point representing the third year of production is plotted, the production-decline curve as plotted after the second year may be modified, and each future year's production used as a check or means of modifying the tentative production-decline curve previously formed.

The production-decline curve may be considered as fairly established after the fourth year. If production records have been recorded for short periods, such as months, a reliable production-decline curve may be constructed from the records of the wells, or the property under consideration, over a much shorter time than four years. In no case should the average curve for a field be used after enough production records are available to form production-decline curves for the wells on a property.

COORDINATES FOR AVERAGE PRODUCTION-DECLINE CURVES.

The use of average curves is so general that coordinates for most of the pools and fields of the United States are given in Table 16. The method of recording curves by means of two coordinates has been discussed on page 26. These average curves were made in 1921 by the mathematical method from the latest production records available from many thousands of individual wells and properties. Many of them have been checked against curves made by the family-curve method.

The third column in Table 16 names the sand or sands on which the curves were based. (These tables should not be used to estimate reserves for other sands than those given in this column, as the production decline of different sands even in the same field may vary materially.) Columns 4 to 7 give the x and y coordinates used to establish two points for each production-decline curve, which is to be plotted as a straight line on logarithmic paper. Unless noted under " remarks," all coordinates are for yearly production-decline curves.

TABLE 16.[a]—*Table showing x and y values of production-decline curves for various pools and districts.*

County.	Pool and district.	Sand or formation to which curve is applicable.	x_1	y_1	x_2	y_2	Remarks.
ARKANSAS.							
Union	Eldorado	Nacatoch	8	70,000	16	3,150	Monthly production-decline curve.
CALIFORNIA.							
Fresno	East side Coalinga pool	First, second, or both zones	18	90,000	38	1,200	
Do	West side Coalinga pool	Any or all zones	18	95,000	42	1,000	
Kern	Belridge pool	Upper zone	10	28,000	24	1,000	
Do	East side Elk Hills district, secs. 35, 36, T. 30 S., R. 24 E.; sec. 31, T. 30 S., R. 25 E.	First zone	2	1,000,000	6	10,500	Does not apply to Westside Elk Hills.
Do	Kern River pool	Thick zone	15	42,400	38	1,250	Sustained curve due to use of sustained tract production.
Do	Lost Hills pool	First or second zone	12	52,000	26	1,000	For spacing of 4 to 5 acres per well.
Do	McKittrick pool	Wells producing from different and several zones.	4	49,500	37	1,000	Sustained curve due to complex structure and great difference in number of productive sands at different wells; also to use of sustained tract production.
Do	Midway-Sunset district, Buena Vista Hills area.	Either or both zones	7	800,000	14	14,500	Applies to drilled-up area only.
Do	Midway-Sunset district, Fellows area.	Any or all zones	20	100,000	34	1,200	
Do	Midway-Sunset district, Maricopa Flat area.	First zone	10	27,500	29	1,000	
Do	Midway-Sunset district, sec. 15, T. 31 S., R. 22 E.	do	9	30,000	33	1,000	
Do	Midway-Sunset district, Twenty-five Hill area.	Either or both zones	4	37,000	26	1,000	
Los Angeles	Montebello pool	Upper zone (first)	4	62,800	22	1,000	
Do	do	Lower zone (second)	5	700,000	11	10,000	
Do	Salt Lake pool	Puente formation	39	90,000	56	1,000	
Los Angeles and Orange.	West Coyote pool	Any or all sands	9	530,000	16	10,500	
Los Angeles	Whittier pool	do	50	78,000	66	1,200	
Orange	Brea Canyon pool	Any sand	13	400,000	24	11,000	
Do	Fullerton, La Habra pool	Any or all sands	8	72,000	25	1,000	
Do	Olinda pool	do	38	75,000	58	1,100	
Orange and Los Angeles.	West Coyote pool	do	9	530,000	16	10,500	
Santa Barbara	Santa Maria pool	Deep zones only	28	75,000	41	1,100	
Ventura	Shields Canyon pool	Upper sand	1	20,000	9	1,000	

ILLINOIS.							
Clark	Johnson pool	Either of two pay sands in Casey sand.	6	10,000	19	125	
Do	Westfield pool	....do	2	2,200	10	129	
Clinton and Marion	Carlyle and Sandoval pools	Stein, Benoist, or Carlyle sand	51	3,200	64	100	
Crawford	Birds-Flatrock district	Robinson sand	7	7,900	19	115	
Do	Robinson and other pools	Robinson and Kirkwood sands	20	10,000	31	125	
Cumberland	Siggins pool	Either of two pay sands in Casey sand.	4	4,300	27	100	
Lawrence	Dennison pool	Bridgeport, Ridgely, Kirkwood, Tracey, or McClosky sands.	11	6,100	24	110	
Do	Kirkwood pool	Kirkwood, Tracey, or McClosky sands.	51	8,000	63	100	
Do	Upper Lawrence district	Bridgeport, Kirkwood, Tracey, or McClosky sands.	26	10,000	40	110	
Marion and Clinton	Sandoval and Carlyle pools	Either Stein, Benoist, or Carlyle sands.	51	3,200	64	100	
McDonough	Plymouth or Colmar pool	Hoing sand	13	900	17	50	
INDIANA.							
Adams, Blackford, and Jay.	Blackford and other pools	Trenton limestone	8	835	21	35	
Blackford, Jay, and Adams.	....do	....do	8	835	21	35	
Gibson	Princeton	Princeton sand	21	835	32	50	
Grant	Northeast quarter of Grant County	Trenton limestone	50	1,500	58	100	
Huntington	Southern part of Huntington County	....do	31	760	42	35	
Jay, Adams, and Blackford.	Blackford and other pools	....do	8	835	21	35	
Pike	Petersburg, Gladish, Bowman, Rumble, and Oakland City.	Rumble, Gladish, and Oakland City	10	5,500	16	180	
Sullivan	Sullivan	Two sands in Huron formation	8	6,000	16	100	
KANSAS.							
Butler	Augusta district	Either of several sands	3	100,000	8	1,200	
Do	Eldorado district	....do	4	83,000	9	1,100	
Butler and Marion	Peabody-Elbing district	Sands of Mississippian age	19	100,000	24	1,050	Quarterly production curve.
Chautauqua and Montgomery.	Chautauqua-Sedan district	Bartlesville, Peru, and Red Fork sands.	4	2,150	15	125	
Marion and Butler	Peabody-Elbing district	Sands of Mississippian age	19	100,000	24	1,050	Do.
Montgomery and Chautauqua.	Chautauqua-Sedan district	Bartlesville, Peru, and Red Fork sands.	4	2,150	15	125	
Wilson	Neodesha district	Cherokee shale	5	520	31	75	
KENTUCKY.							
Bath	Ragland district	"Corniferous"	7	3,700	23	100	
Estill	Irvine pool	....do	25	5,200	33	100	
Floyd	Beaver pool	Any of several Carboniferous sands	10	2,750	25	160	
Wayne	Mount Pisgah, Sinking, Slickford, and Parnell pools.	Beaver Creek sand	3	2,600	11	150	

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[a] Table prepared by Willard W. Cutler, Jr., and Roger White, Office of Commissioner of Internal Revenue, Treasury Department, from revised edition, August, 1921, of the Manual for the Oil and Gas Industry.

TABLE 16.[a]—*Table showing x and y values of production-decline curves for various pools and districts*—Continued.

County.	Pool and district.	Sand or formation to which curve is applicable.	x_1	y_1	x_2	y_2	Remarks.
LOUISIANA.							
Acadia	Evangeline-Jennings pool	Salt dome	6	41,000	18	1,000	
Caddo	Mooringsport pool	Woodbine sand	9	35,000	19	1,000	
Do	Pine Island pool	do	3	100,000	5	2,000	
Do	Vivian pool	do	4	27,000	7	1,050	
Calcasieu	Edgerly pool	Salt dome	2	37,000	8	1,000	
Do	Vinton pool	do	2	37,500	10	1,000	
De Soto	De Soto district	Woodbine sand	4	65,000	11	1,250	
Red River	Red River district	do	2	75,000	9	1,125	
NEW YORK.							
Allegany and Cattaraugus, N. Y., and McKean, Pa.	Several pools	Bradford	9	7,880	32	100	
OHIO.							
Allen	Lima district	Trenton limestone	5	920	20	35	
Belmont, Jefferson, and Monroe.	Several pools	Berea	9	700	23	40	
Jefferson, Monroe, and Belmont.	do	do	9	700	23	40	
Hancock	Lima district	Trenton limestone	9	940	30	35	
Hocking and Perry	Gore pool	Clinton	2	6,300	10	200	
Lucas and Ottawa	Lima district	Trenton limestone	3	730	21	35	
Mercer	do	do	3	640	20	35	
Monroe, Belmont, and Jefferson.	Several pools	Berea	9	700	23	40	
Monroe	Jackson Ridge pool	Keener	10	1,500	28	102	
Ottawa and Lucas	Lima district	Trenton limestone	3	730	21	35	
Perry and Hocking	Gore pool	Clinton	2	6,300	10	200	
Sandusky	Lima district	Trenton limestone	2	4,200	14	110	
Seneca	do	do	21	780	35	35	
Van Wert	do	do	3	690	20	35	
Washington	St. Marys pool	Keener	10	1,120	18	100	
Wayne	Several pools	Clinton	9	7,500	15	200	
Wood	Lima district	Trenton limestone	3	8,600	17	100	
OKLAHOMA.							
Carter	Healdton district	Healdton or deeper sand	40	53,000	49	1,000	
Do	Hewitt pool	Upper Hewitt sand	15	58,000	20	1,550	Quarterly production curve. Applies only to upper sand.
Creek	Cushing pool	Bartlesville sand	3	100,000	9	1,200	

Do	.....do	Layton sand	2	22, 500	6	1, 025
Do	.....do	Tucker sand	2	100, 000	7	2, 000
Do	.....do	Wheeler sand	11	41, 000	15	1, 100
Creek and Tulsa	Glenn pool	Glenn sand	10	54, 000	18	1, 100
Do	.....do	Red Fork sand	2	9, 300	17	103
Do	.....do	Taneha sand	10	9, 700	21	100
Garfield	Garber pool	Any of a number of sands	3	75, 000	6	1, 000
Kay	Blackwell district	Any of several deep sands	2	8, 900	9	103
Muskogee	Muskogee-Boynton district	Any of a number of sands	5	5, 600	12	105
Nowata	Adair pool	Bartlesville sand	2	3, 000	10	110
Nowata and Rogers	Nowata district	.....do	4	4, 550	13	140
Okmulgee	Okmulgee district	Any of a number of sands	3	40, 000	9	1, 080
Osage and Washington.	Avant-Ramona district	Bartlesville sand	11	60, 000	20	1, 250
Osage	Hominy district	Either Peru, Oswego, or Bartlesville sand.	8	85, 000	16	1, 250
Do	Okesa district	Bartlesville sand	5	9, 000	26	120
Do	Pawhuska-Wynona district	Either Peru or Bartlesville sand	5	82, 000	13	1, 150
Osage and Tulsa	Bird Creek-Skiatook district	Bartlesville sand	9	9, 800	23	150
Pawnee	Cleveland district	Cleveland, Bartlesville, or Tucker sand.	6	9, 100	21	200
Rogers and Nowata	Nowata	Bartlesville sand	4	4, 550	13	140
Tulsa and Osage	Bird Creek-Skiatook district	.....do	9	9, 800	23	150
Tulsa and Creek	Glenn	Glenn sand	10	54, 000	18	1, 100
Do	.....do	Red Fork Sand	2	9, 300	17	103
Do	.....do	Taneha sand	10	9, 700	21	100
Washington and Osage.	Avant-Ramona district	Bartlesville sand	11	60, 000	20	1, 250
Washington	Bartlesville-Dewey district	.....do	3	100, 000	11	1, 000
Do	.....do	Peru	3	10, 000	12	175
PENNSYLVANIA.						
Allegheny	Dorseyville, Grafton, and Chartiers pool.	Thirty-foot sand	2	5, 000	13	115
Do	Fort Pitt, Grafton, and Chartiers	Gordon sand	10	1, 200	28	100
Allegheny and Butler.	Brush Creek, Milltown, Glade Run, Slippery Rock, and other pools.	One hundred-foot sand	10	2, 000	28	103
Allegheny and Washington.	McDonald, Venice, Grafton, Washington, and other pools.	Fifth sand	3	2, 700	20	100
Butler	Speechly pool	Speechly sand	10	1, 700	25	150
Butler and Allegheny.	Glade Run, Slippery Rock, Brush Creek, Milltown, and other pools.	One hundred-foot sand	10	2, 000	28	103
Greene	Ninevah and Cameron	Gordon sand	3	8, 600	21	130
McKean, Pa., and Cattaraugus and Allegany, N. Y.	Several pools	Bradford sand	9	7, 880	32	100
Washington and Allegheny.	McDonald, Venice, Grafton, Washington, and other pools.	Fifth sand	3	2, 700	20	100

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[a] Table prepared by Willard W. Cutler, Jr., and Roger White, Office of Commissioner of Internal Revenue, Treasury Department, from revised edition, August, 1921, of the Manual for the Oil and Gas Industry.

TABLE 16.[a]—*Table showing x and y values of production-decline curves for various pools and districts*—Continued.

County.	Pool and district.	Sand or formation to which curve is applicable.	x_1	y_1	x_2	y_2	Remarks.
TEXAS.							
Eastland	Desdemona pool	Ranger sand	10	58,000	12	1,900	Quarterly production curve.
Do	Ranger district	do	5	66,000	10	1,000	Do.
Hardin	Batson pool	Salt dome	6	33,000	16	1,000	
Do	Sour Lake pool	do	11	50,000	17	1,000	
Do	Saratoga pool	do	10	62,000	20	1,000	
Harris	Goose Creek pool	do	3	68,000	7	1,000	
Do	Humble pool	do	3	57,000	6	1,000	
Jefferson	Spindle Top pool	do	3	40,000	12	1,000	
Marion	Western extension, Caddo, La., district.	Woodbine sand	3	52,000	11	1,200	
Navarro	Corsicana pool (light oil)	Powell sand	10	4,800	30	130	
Do	Corsicana pool (heavy oil)	Nacatosh sand	10	4,700	23	112	
Palo Pinto	Old Strawn (shallow pool)	Strawn formation	2	1,900	6	110	
Stephens	Caddo-La Casa district	Caddo limestone	43	70,000	49	1,000	Do.
Do	Parks-Breckenridge district	do	36	94,800	50	1,100	Do.
Wichita	Burkburnett Old Field pool	Wichita sand	3	35,000	10	1,440	
Do	Burkburnett northwestern extension pool.	do	4	40,000	8	1,450	Do.
Do	Burkburnett town-site pool	do	2	3,850	6	500	Do.
Wichita and Wilbarger.	Electra district	Wichita formation	11	37,000	17	1,300	
Wilbarger and Wichita.	do	do	11	37,000	17	1,300	
WEST VIRGINIA.							
Dodridge	Shiveley and Salem pools	Gordon sand	20	2,100	34	100	
Gilmer and Lewis	Maxon, Buffalo, Fink, and Carter pools	Gordon, Fifth, and Fifty-foot sand	5	2,820	16	115	
Harrison	Eagle, Clay, and Salem pools	Gordon sand	18	1,900	30	125	
Do	Shinnston pool	Fifty-foot sand	3	6,200	12	110	
Lewis and Gilmer	Maxon, Buffalo, Fink, and Carter pools	Gordon, Fifth, and Fifty-foot sand	5	2,820	16	115	
Lincoln	Duval pool	Berea sand	5	9,700	17	150	
Roane	Spencer, Rock Creek, Harper, and others.	Big Injun sand	25	3,200	38	105	
Wetzel	Four Mile, Wetzel, and Folsom pools	Gordon sand	20	4,100	31	110	
WYOMING.							
Converse	Big Muddy pool	First Wall Creek sand	10	85,000	17	1,400	
Hot Springs	Grass Creek pool	Frontier formation	40	24,900	44	1,200	
Natrona	Salt Creek pool	First Wall Creek sand	13	96,000	24	1,400	
Park	Elk Basin pool	Frontier sand	20	77,000	26	1,000	

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[a] Table prepared by Williard W. Cutler, Jr., and Roger White, Office of Commissioner of Internal Revenue, Treasury Department, from revised edition, August, 1921, of the Manuel for the Oil and Gas Industry.

Table 16 includes a group of curves for wells that decline very rapidly and the curves for them have been based on quarterly productions in order to show in more detail the rate of future production and the remaining lives of wells of varying sizes.

All of the curves are based on the assumption that the wells will have normal lives. In the use of these tables allowance must be made for wells that will have their lives shortened through encroachment of water, collapse of casing, or other causes.

METHOD OF USING COORDINATES OF TABLE.

An example of the use of Table 16 for constructing an average production-decline curve appears below. The coordinates for the Goose Creek pool, Harris County, Tex., as given in this table are:

$$x_1=3, y_1=68{,}000, x_2=7;\ y_2=1{,}000.$$

The two points designated by x_1, y_1 and x_2, y_2 are first plotted on logarithmic paper and are then joined by a straight line as shown by Figure 18. Yearly intervals represent the successive yearly productions of the average well. Thus the successive yearly productions of the average well in Goose Creek, Harris County, Tex., may be read from the curve in Figure 18 as 68,000; 16,000; 5,200; 2,150; and 1,000 barrels.

VARIOUS CURVES USED IN ESTIMATING RESERVES.

BASIC CURVE—PRODUCTION-DECLINE CURVE.

The production-decline curve shows period production. Though embodying all the information regarding decline in production, it does not present directly the information regarding the total future production of wells. Other curves, which present in a convenient and suitable form the information desired for estimating future production, may be constructed from the production-decline curve.

FUTURE-PRODUCTION CURVE.

For general use a curve that shows the future production of wells of known period production, is called a future-production curve.

A table may be constructed from a production-decline curve showing the production decline by periods and the estimated future production of wells of varying sizes, such as Table 17.

TABLE 17.—*Future-production table, Goose Creek pool, Harris County, Tex.*

[Economic limit, 1,000 barrels a year.]

1 Production per well during year, barrels.	2 Estimated average recoverable underground reserves, barrels.	3 Estimated average remaining life of well to economic limit, years.
68,000	24,350	4
16,000	8,350	3
5,200	3,150	2
2,150	1,000	1
1,000	0	0

Columns 1 and 2 of Table 17 may be used to form an average future-production curve, as in Figures 19 and 20. The curves are used

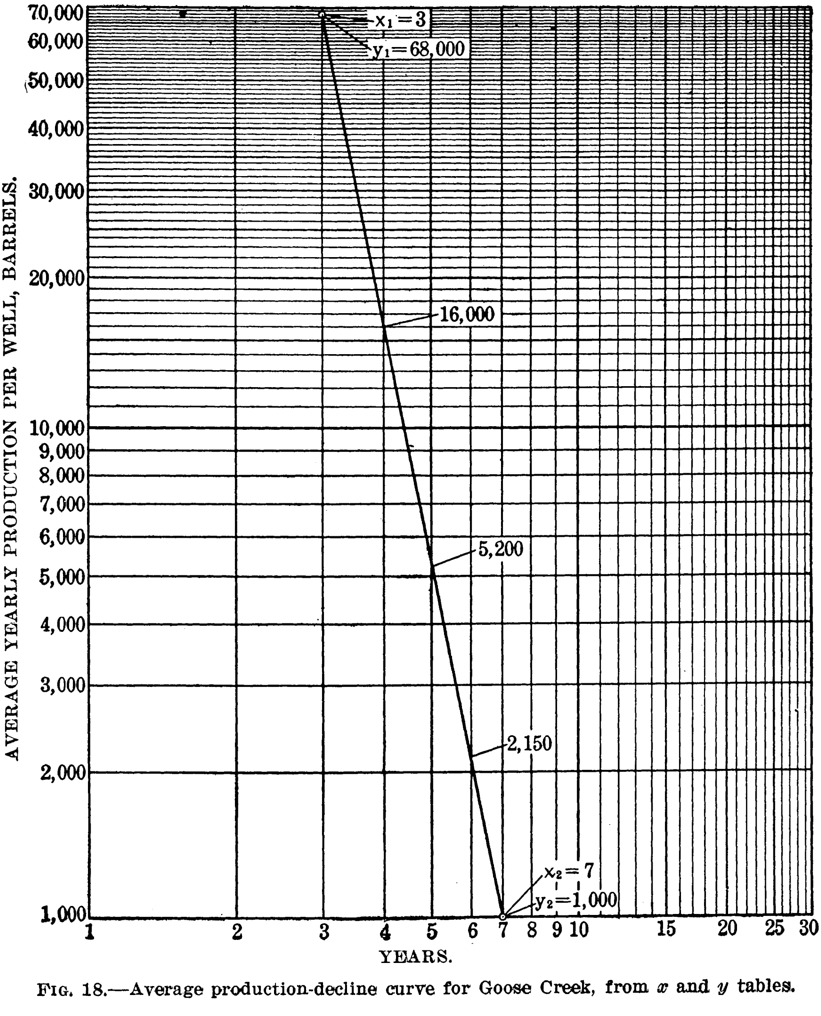

FIG. 18.—Average production-decline curve for Goose Creek, from *x* and *y* tables.

in estimating the future productions of wells with yearly productions not shown in Table 17.

An example of the use of a future-production curve or table follows: A completely drilled tract with five producing wells of about equal size in the Goose Creek pool, Harris County, Tex., produced 70,000 barrels of oil in 1920. It is desired to estimate the amount of oil that may be recovered from these wells in the future and the average estimated remaining life of the wells. No records of past production are available, and the spacing and other conditions are normal for the field. The economic limit has been arbitrarily determined as 1,000 barrels per year. Dividing the total production for 1920 (70,000 barrels) by the number of wells producing during the year (5 wells) gives the average production per well for 1920 (14,000 barrels). Reference to the average future-production curve in Figure 19 for the Goose Creek field shows that the estimated average future production of a well that produced 14,000 barrels during a year is 7,500 barrels and the estimated remaining life is about three years for the assumed economic limit of 1,000 barrels a year. The total estimated average future production for the five wells producing to an economic limit of 1,000 barrels a year from the same zone will be 5×7,500=37,500 barrels. The estimated average remaining life per well will be about three years.

In using average future-production curves, if the rates of production of the wells differ much in the same tract the estimating of future production should be for individual wells, if possible, and the sum of these should be used for the tract.

CONSTRUCTION OF A PRODUCTION-DECLINE CURVE FROM A FUTURE-PRODUCTION CURVE.[33]

Average curves are sometimes presented in the form of future-production curves, and they were so presented in the first edition of the Manual for the Oil and Gas Industry, published by the Treasury Department.

A future-production curve gives only the total estimated future production and does not furnish information on the rate of recovery of the oil. To determine this from a future-production curve it is necessary to construct a production-decline curve from the future-production curve. The following procedure may be used: Figure 19 shows an average future-production curve for Goose Creek, Harris County, Tex., from which it is desired to construct an average production-decline curve.

The economic limit of future production is given as 1,000 barrels a year. On this basis the future production of an average well in

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[33] Cutler, W. W., Jr., Extended life of wells due to rise in price of oil: Min. and Met. September, 1920.

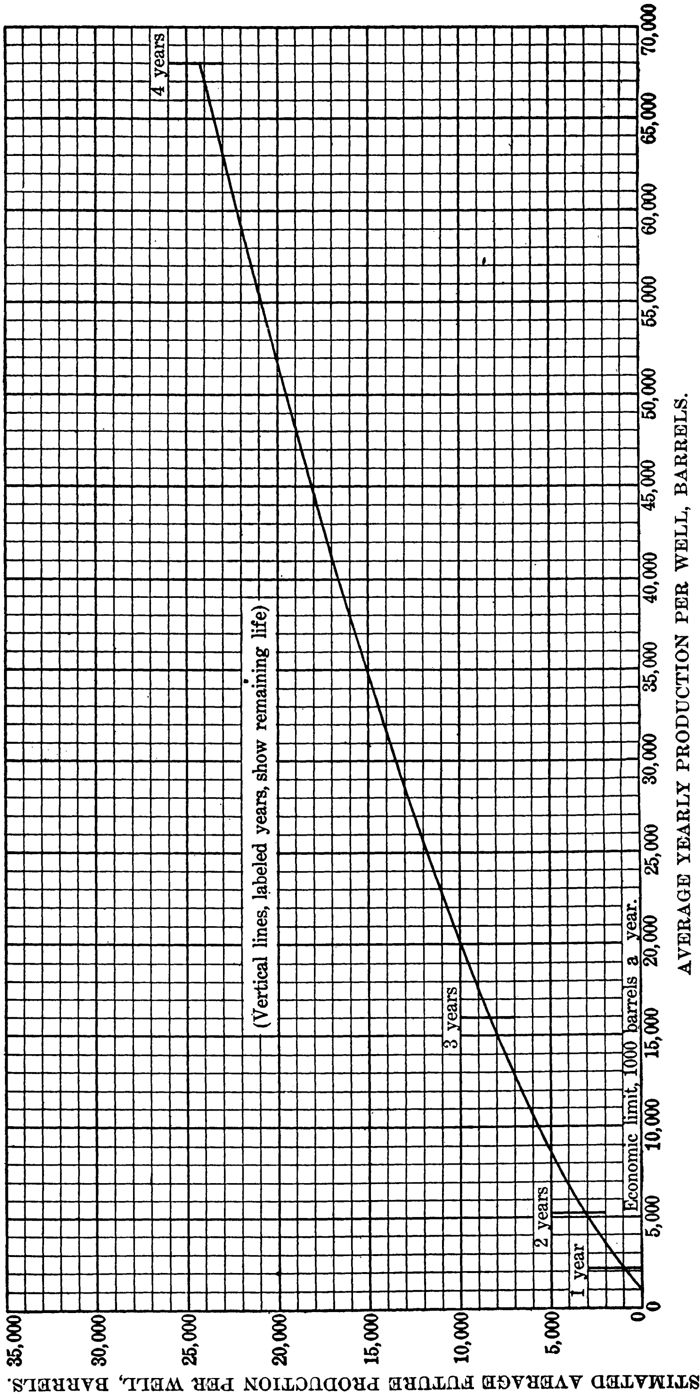

FIG. 19.—Average future-production curve for Goose Creek, on coordinate paper.

that field one year previous to exhaustion would be 1,000 barrels. On the future-production curve read the production of the past year of a well whose future production is 1,000 barrels. This is seen to be 2,150 barrels and is therefore the production of the well the year before its year of economic limit. The sum of the yearly and future productions for any year is the future production for the previous year. Thus 2,150+1,000=3,150, which is the future production of the average well with a remaining life of two years. Reference to the future-production curve shows that the past year's production of a well with a future of 3,150 barrels was 5,200 barrels. Continue this procedure throughout the future-production curve. The resulting table (see Table 18) will furnish the material necessary for a production-decline curve.

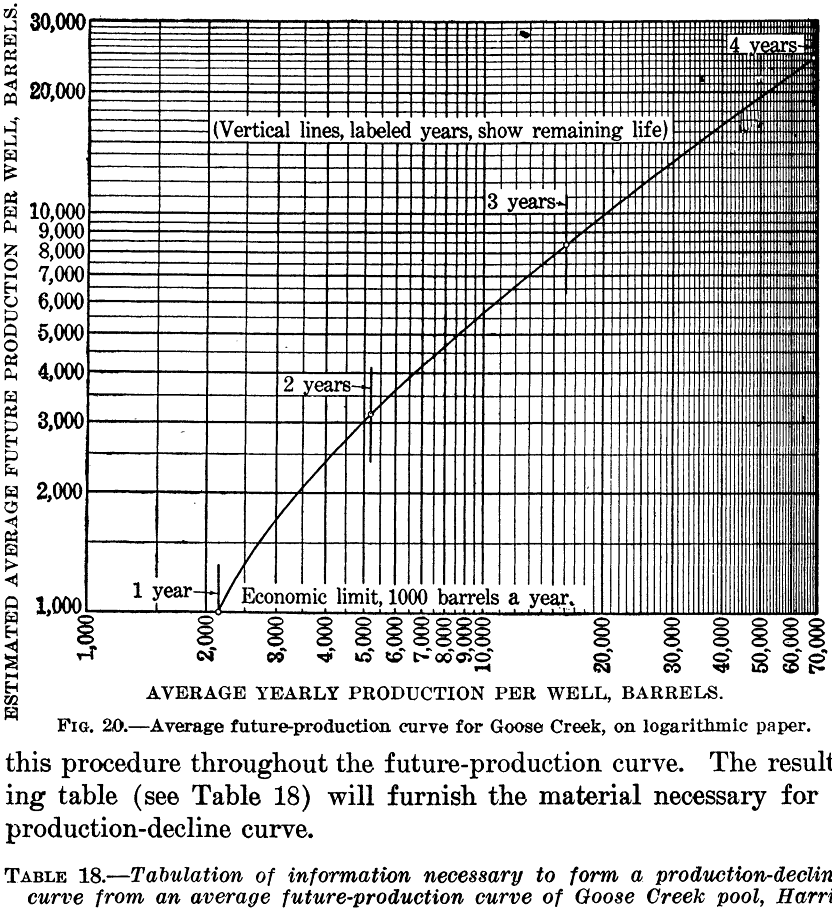

FIG. 20.—Average future-production curve for Goose Creek, on logarithmic paper.

TABLE 18.—*Tabulation of information necessary to form a production-decline curve from an average future-production curve of Goose Creek pool, Harris County, Tex.*

Past year's production, barrels.	Estimated future production, barrels.	Past year's plus estimated future production, barrels.	Remaining life of well, years.
1,000 (economic limit)	0	1,000	0
2,150	1,000	3,150	1
5,200	3,150	8,350	2
16,000	8,350	24,350	3
68,000	24,350	92,350	4

PRODUCTION-DECLINE AND FUTURE CURVES.[34]

Future curves which are in general use, show the future production of wells of known period productions; they are auxiliary to the production-decline curve and can not be presented except with it. By showing the rate of future production the future curve has the advantage over the future-production curve. However, if the rate of future production is not desired, the future-production curve is simpler and is easier to use than the future curve used with the production-decline curve. The future curve is constructed by plotting the future production of wells of various period productions vertically above or below their locations on the production-decline curve.

Figure 21 (p. 75) shows the future curve plotted with the production-decline curve for an average well in the Goose Creek pool, Harris County, Tex. The production-decline curve was plotted from column 1 and the future curve from column 2 of Table 17.

CONSTRUCTION OF A PRODUCTION-DECLINE CURVE FROM AN APPRAISAL CURVE.[35]

Average curves are sometimes constructed in the form of an appraisal curve, but the latter does not show the rate at which the total production will be obtained.

It may be desired to construct a production-decline curve from an appraisal curve. Figure 16 (p. 59) shows an appraisal curve formed from the production records of wells and tracts.

Inasmuch as the ultimate production is the sum of the initial year's production plus the future production as of the end of the first year, the future production for the first year is obtained by subtracting that year's production from the ultimate production. For example, in Figure 16 (p. 59) the highest point on the average appraisal curve shows an ultimate production of 8,500 barrels for an average well of 2,475 barrels initial yearly production: 8,500 (ultimate production) less 2,475 (yearly production) equals 6,025 (future production at end of first year).

Hence 6,025, the future production at the end of the first year, may be assumed to be equal to the ultimate production of another average well. Reference to Figure 16 shows 1,490 barrels to be the yearly production for a well whose ultimate production is 6,025 barrels. This procedure may be followed to the economic limit of the appraisal curve and a table like Table 19 may be formed from which a production-decline curve may be constructed.

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[34] Beal, C. H., and Nolan, E. D., Application of the law of equal expectation to oil production in California: Am. Inst. Min. Eng. Bull., 152, August, 1919, pp. 1237–1245.

[35] 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. 41.

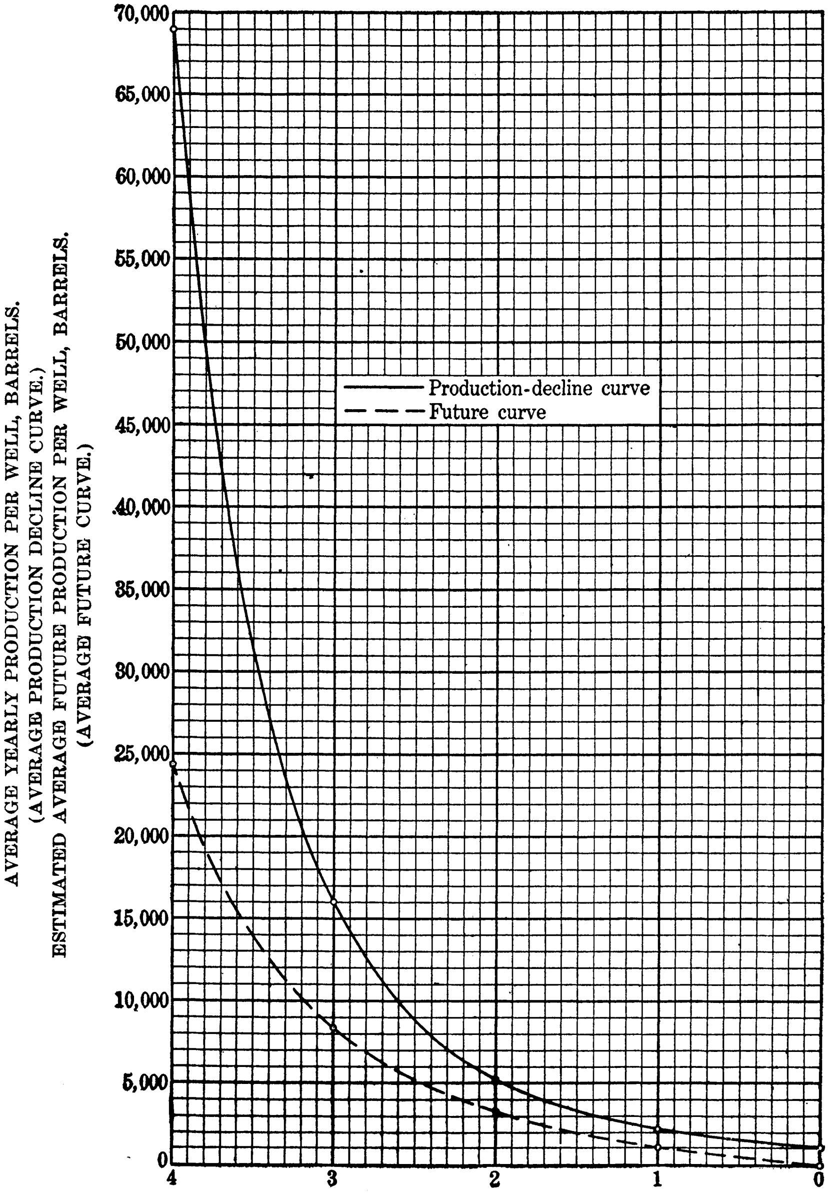

FIG. 21.—Production-decline and future curves for an average well in the Goose Creek pool, Harris County, Tex.

TABLE 19.—*Tabulation of data necessary to form a production-decline curve from an appraisal curve for Wood County, Ohio.*

Average yearly production per well, barrels.	Average future production per well, barrels.	Average ultimate production per well, barrels.	Life of well, years.
2,475	6,025	8,500	1
1,490	4,535	6,025	2
1,025	3,510	4,535	3
740	2,770	3,510	4
540	2,230	2,770	5
415	1,815	2,230	6
315	1,500	1,815	7
250	1,250	1,500	8
205	1,045	1,250	9
170	875	1,045	10
145	730	875	11
125	605	730	12
105	500	605	13

The average production-decline curve may be formed from column 1 and extended to the economic limit of 35 barrels a year, which was used in constructing the appraisal curve in Figure 16.

RATE-OF-PRODUCTION CURVE.

A "rate-of-production curve" is auxiliary to the production-decline curve and shows the daily rate of production of wells whose yearly production is shown by the production-decline curve. This curve was devised by the author in May, 1920, and since that time has been used by the oil and gas valuation section of the Treasury Department[37] in determining the rate of production of wells for purposes of taxation. The curve is useful for estimating the future production of a well, or group of wells, of known daily settled production, where future-production curves and tables based on yearly production records are available. It also provides a means for determining the past year's production of a well of known daily settled production, or, conversely, the estimated production on any day for a well of known yearly production.

The rate-of-production curve is auxiliary to the production-decline curve and is derived from it. In estimating the future production of a tract, a production-decline curve formed from the records of the tract itself should be used. If such records are not available, and there is no information leading to the belief that the average production decline of the wells in this tract differs appreciably from the average for the pool or district, an average curve for the pool or district may be used.

Figure 22 shows a typical rate-of-production curve and the yearly production-decline curve from which it is derived. The

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[37] Manual for the Oil and Gas Industry. Treasury Department. Rev. ed., 1921.

latter is for an average well in the Augusta district, Butler County, Kans., and has been constructed from the tables given on page 128 of the revised edition of the Treasury Department manual.

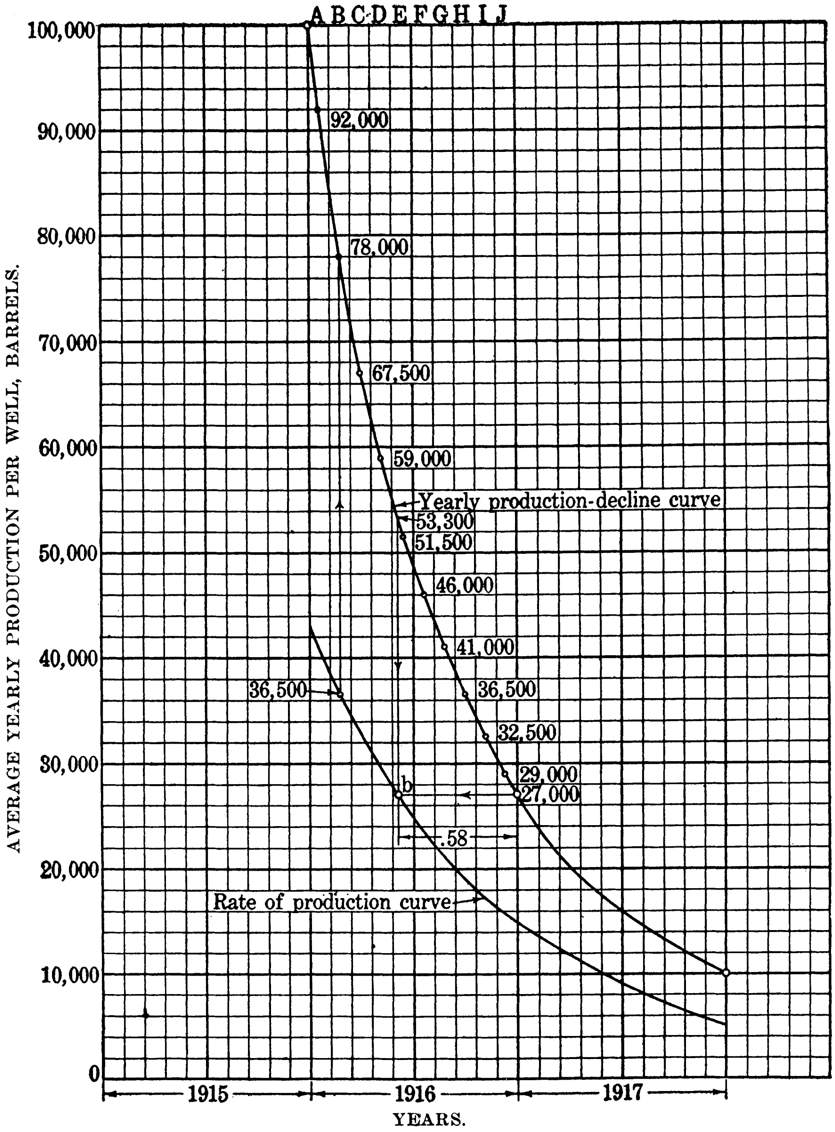

FIG. 22.—Rate-of-production curve.

The ordinate (vertical scale) of any point on a yearly production-decline curve represents the production of the well during the year previous to the date shown by the abscissa (horizontal scale). For example, Figure 22 shows that an average well which produced

100,000 barrels of oil in 1915 produced 92,000 barrels in the year preceding January 19, 1916; produced 53,300 barrels in the year preceding June 1, 1916; produced 49,000 barrels in the year preceding July 1, 1916; 27,000 barrels in 1916; and 10,000 barrels in 1917.

In other words, the ordinate of any point on the yearly production-decline curve does not indicate the rate at which the well was producing on the date shown by the abscissa, but indicates the total yearly production, or the average yearly rate of production, of the well during the previous year. For a well with a symmetrically declining production there is theoretically but one day in any year when the well is producing at the average rate for that year. This day of average production is some time before the middle of the year. Thus in Figure 22, the total production of the well during the year 1916 was 27,000 barrels, but the day when the well was actually producing at the rate of 27,000 barrels a year, or 74 barrels (27,000÷365) a day, was not December 31, 1916, but some time before July 1 of that year.

Any segment of a production-decline curve represents the decline in the production of the well during a definite period of time. This period, however, is not for the time shown by the abscissas, but for the time when the well was producing at the yearly rates shown by the ordinates. For example, in the chart (Fig. 22) the yearly segment of the production-decline curve, which lies between the ordinates representing 100,000 and 27,000 barrels, and with abscissas representing the year 1916, does not signify that the rate of production of this well fell from 100,000÷365 or 274 barrels a day on January 1, 1916, to 27,000÷365 or 74 barrels a day on December 31, 1916. It does, however, signify that the rate of production of this well declined from 100,000 barrels a year to 27,000 barrels a year in one year's time, or that there was an interval of one year between the daily production of 274 barrels and 74 barrels, the interval extending from some time before July 1, 1915, to some time before July 1, 1916, and not from January 1, 1916, to January 1, 1917.

By dividing a yearly segment of a production-decline curve into equal time periods, by lines perpendicular to the base of the diagram and averaging the ordinates for the middle points (relative to the horizontal spacing, or the abscissa) of these periods, an average ordinate is obtained, which, when plotted on the yearly segment, represents the time of the year (for a well of that yearly production) when the day of average production for the year occurred.

In Figure 22 (p. 77) a yearly segment (as represented by abscissas for 1916) of the production-decline curve was divided into 10 equal time periods, A, B, C, D, E, F, G, H, I, and J. The middle ordinates for these periods were read and recorded as follows: 92,000, 78,000, and so on, as noted on the curve. These ordinates were averaged, and the average ordinate (53,300) was obtained, as shown below:

TABLE 20.—*Method of determining day of average production for a year.*

92, 000	A
78, 000	B
67, 500	C
59, 000	D
51, 500	E
46, 000	F
41, 000	G
36, 500	H
32, 500	I
29, 000	J
10)533, 000	
53, 300	(average ordinate).

The average ordinate (53,300) represents the yearly production in barrels of a well that produced at the rate of 100,000 barrels a year or 100,000÷365=274 barrels a day on the first day of the year, at the average rate of 53,300 barrels a year or 53,300÷365=146 barrels a day during the year and at the rate of 27,000 barrels a year or 27,000÷365=74 barrels per day on the last day of the year. If the point 53,300 is plotted on this yearly segment of the curve it will be seen that the day of average production for the year occurred 0.58 (fifty-eight hundredths) of a year before the end of the year.

As previously stated, however, the well produced 53,300 barrels during the year previous to June 1, 1916. Also, as shown in the preceding paragraph, when the well produced 53,300 barrels a year it produced at the rate of 274 barrels a day on the first day of the year and at the rate of 74 barrels on the last day of the year; that is, May 31, 1916.

The time when the day of average production occurs for any year varies with the degree of curvature of the production-decline curve. The degree of curvature is affected chiefly by the percentage decline in production from the previous year. By the method illustrated above, the day in the year when the well produced at the average rate for the year was determined for about 50 different well years, involving a number of average production-decline curves for different fields. On a sheet of coordinate paper a point was plotted representing this day for each well year under consideration, as against the percentage decline of production from the previous year. A curve was drawn through these points, and the table following was derived from this curve.

TABLE 21.—*Day when average production of year occurred for any well or tract.*

Decline of yearly production from previous year, per cent	Time before the end of year when the day of average production occurs, per cent of year.	Calendar date.
0	50	July 1
10	51	June 26
20	52	June 23
30	53	June 19
40	54	June 16
50	55	June 12
60	57	June 4
70	58	June 1
80	60	May 24
90	63	May 14
95	66	May 3
97	69	Apr. 22
99	73	Apr. 7

From this table the day of average production of any well or tract for any year can be determined within a reasonable error; that is, the production on that day will not vary more than 5 per cent from the correct average daily production for the year. This table can be applied to any production-decline curve.

CONSTRUCTION OF A RATE-OF-PRODUCTION CURVE.

In order to form a rate-of-production curve from any yearly production-decline curve, refer to Table 21 to find for each year the time before the end of the year when the day of average production for that year occurred. Plot a point for each year, with the ordinate representing the production for that year and the abscissa the day when the production was equal to the average production for that year. Join these yearly points together and the result will be a rate-of-production curve lying to the left and below the yearly production-decline curve. For example, the production of the well shown on the chart (Fig. 22) fell from 100,000 barrels in 1915 to 27,000 in 1916, or the percentage decline was $\frac{100,000-27,000}{100,000}=\frac{73,000}{100,000}=73$ per cent. The first column of Table 21 shows that the day of average production for a well with a 73 per cent decline of yearly production is June 1, or 58 per cent of a year before the end of the year. A point (*b*) plotted fifty-eight hundredths of a year's space to the left of the point on the production-decline curve whose ordinate is equal to the production for 1916 (27,000 barrels) will lie on the rate-of-production curve.

Similar points may be plotted for each year and intermediate points between the years. These may be joined to form a rate-of-production curve.

USE OF THE RATE-OF-PRODUCTION CURVE.

By construction, any point on the rate-of-production curve represents the rate at which the well was producing on the last day of that year whose production is shown by the point vertically above on the yearly production-decline curve. Conversely, any point on the yearly production-decline curve represents the production for the year previous to or ending on the day when the well produced at the rate shown by the point vertically below on the rate-of-production curve. As future-production curves and tables are usually based on the past year's production of a well, the rate-of-production curve permits the use of such curves and tables if the daily settled production on any date is known.

Thus in Figure 22 (p. 77), if an average well in the Augusta district produced 78,000 barrels in a year, its rate of production at the end of the year may be determined by drawing a line vertically downward through the point 78,000 and reading the point where this line intersects the rate-of-production curve, which is 36,500 barrels. The well that produced 78,000 barrels in one year is therefore producing at the end of that year at the rate of 36,500 barrels a year, or 36,500÷365=100 barrels a day.

Conversely, if an average well in the Augusta district is producing at the rate of 100 barrels a day of settled production, its place on the yearly production-decline curve—that is, its past year's production, if it produced, and its estimated future production—can be determined as follows: One hundred barrels a day is at the yearly rate of 100 times 365, or 36,500 barrels a year. Determine the point on the rate-of-production curve which has the ordinate 36,500, and from this point draw a line vertically upward to intersect the yearly production-decline curve. The ordinate of this point is 78,000 barrels, which is the past year's production of a well that is now producing 100 barrels per day.

Table 22, which is taken from the revised edition of the Treasury Manual (p. 128), gives the estimated average future production of wells of different yearly productions in the Augusta district, Butler County, Kans.

TABLE 22.—*Estimated future-production table, Augusta district, Butler County, Kans. (one of several sands).*

Average production per well during year past, barrels.	Estimated average future production per well, barrels.	Estimated remaining life of average well, years.
100,000	46,260	8
90,000	42,800	....
80,000	39,500	....
70,000	36,000	....
60,000	32,500	....
50,000	28,900	....
40,000	25,000	....
27,000	19,260	7
10,000	9,260	6
4,400	4,860	5
2,200	2,660	4
1,200	1,460	3
710	750	2
450	300	1
300	0	0

Assumed economic limit, 300 barrels a year.

The total future production of an average well in the Augusta district, Kans., that yielded 78,000 barrels during the past year, or is now yielding 100 barrels a day, is found by interpolation to be 38,800 barrels. The rate of this future recovery can be determined by reading the ordinates for successive years on the production-decline curve.

The rate-of-production curve may be used with monthly, quarter yearly, or other production-decline curves in the same manner as is here described for the yearly production-decline curve.

APPLICATION TO EVALUATION OF OIL PROPERTIES.

In the Mid-Continent and eastern fields it is common practice to appraise producing properties with settled production on the basis of so many dollars a barrel. Obviously the most important factor in relation to the value per barrel of present production is the amount of recoverable oil represented by the barrel purchased. Thus for one property the future recovery for each barrel of present production might be 1,000 barrels, whereas for another it might be 3,000 or 4,000 barrels.

Inasmuch as sale is made on the basis of recent gages or on official run tickets it is important that the estimate of future production be related to the present rate of production rather than to the average for a year previous, such as the future-production curves give. The rate-of-production curve is particularly adapted to the appraisal of "settled" properties.

APPLICATION OF CURVES TO ESTIMATING UNDERGROUND RESERVES OF OIL.

OBJECT AND VALUE OF ESTIMATION.

An estimation is an opinion or judgment of the worth, extent, or quantity of anything (Webster). If derived by a logical reasoning from a large number of past and present events or circumstances, an estimation may be considered reliable. An estimation of the future production of an oil property should be based not only on all of the information available for the property itself but also on general information regarding adjacent properties. Inferences as to what may be expected from a specific property can be substantiated from what has already occurred on similar properties.

Estimations of the future productions of oil properties are the bases of many important decisions affecting income tax, the purchase and sale of land, the program of development, and the disposal of the oil. A reliable estimation is therefore of great value in shaping a sound financial policy—an unreliable estimation may lead to financial disaster. The expense involved in making a reliable estimation is slight in comparison with its importance, and this expense is justified amply by the resulting security of action.

WORK PREPARATORY TO MAKING AN ESTIMATION.

In estimating future production the actual construction of curves is an important but a relatively small part. A far greater amount of work is required preparatory to making the curves, such as collecting the full and varied information needed to construct them properly. It may be necessary to visit the field; discuss general conditions with superintendents, drillers, and other field men; obtain access to the production records of neighboring tracts; and to study underground conditions by the use of well logs, cross sections, and maps.

FACTORS TO BE CONSIDERED.

As the recovery of oil from a tract is influenced by conditions both in the tract itself and throughout the pool, a knowledge of the facts concerning the tract is not enough in itself for forming a reliable estimate of the ultimate production of the tract. There should be available segregated records of production from each sand and, for tracts still being drilled, either the individual well records or tract records giving the initial production of each well. The policy of future development and method of operation should be considered and the calculations influenced accordingly. The time of drilling greatly affects the ultimate recovery.

TIME OF DRILLING.[38]

The following comparison of the ultimate recovery per acre has been computed from production figures for adjoining and intervening tracts when all conditions were apparently similar except time of drilling. This indicates what have been the losses in recovery in several typical fields through delayed drilling.

TABLE 23.—*Data showing the effect of time of drilling on ultimate recovery.*

ADAIR POOL, NOWATA COUNTY, OKLA.

Location of tracts.	Number of tracts.	Combined area of tracts, acres.	Year drilling began.	Ultimate production, barrels per acre.	Loss per acre, per cent.
Within 480 acres	2	160	1909	930	
	2	160	1912	678	27 in 3 years.
In two adjoining tracts	1	60	1906	3,240	
	1	40	1907	2,946	9 in 1 year.

BARTLESVILLE-DEWEY DISTRICT, OKLA.

Location of tracts.	Number of tracts.	Combined area of tracts, acres.	Year drilling began.	Ultimate production, barrels per acre.	Loss per acre, per cent.
In four adjoining sections	1	40	1905	5,785	
	4	190	1906	2,700	53 in 1 year.
	5	200	1907	1,926	29 in 1 year.
	1	80	1908	1,435	25 in 1 year.
	1	30	1910	1,152	20 in 2 years.
In four adjoining sections	1	40	1907	3,521	
	4	170	1909	2,560	27 in 2 years.
In four adjoining sections	4	340	1906	3,050	
	6	235	1907	2,880	5 in 2 years.
	1	50	1910	2,520	12 in 3 years.

NOWATA DISTRICT, ROGERS AND NOWATA COUNTIES, OKLA.

Location of tracts.	Number of tracts.	Combined area of tracts, acres.	Year drilling began.	Ultimate production, barrels per acre.	Loss per acre, per cent.
In two adjoining sections	3	90	1910	4,291	
	2	100	1911	2,189	49 in 1 year.

Another example that may be cited is a tract in the Buena Vista Hills, Midway field, California. Here the ultimate recovery for a certain drilled-up tract which is at least as favorably situated (as shown by a comparison of initial productions the same year) as an adjoining drilled-up tract, is estimated to be 24 per cent less per acre, apparently due to a delay of two years in drilling.

In the Hewitt field, Carter County, Okla, " four wells on 10 acres all came in for more than 500 barrels per day initial production, one and one-half months later a neighbor's offset came in for 220 barrels the first 24 hours, while four months later an offset only made 120 barrels the first 24 hours." [39] The estimated loss in ultimate production per well through delay in drilling was probably great but can

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[38] Cutler, W. W., jr., and Clute, Walker S., Relation of drilling campaign to income from oil properties: Reports of Investigations, Serial 2270, Bureau of Mines, August, 1921.

[39] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil field, Okla. Cooperative bulletin of the Bureau of Mines and the Ardmore, Okla., Chamber of Commerce, January, 1921, p. 33.

not be estimated, as the wells with a small initial production (due to decreased gas pressure) may have declined slower than the wells with high initial production and high gas pressure.

The percentage loss in ultimate production that an operator will sustain through delay in drilling will vary with the amount and location of other drilling in the same pool, the size of the pool, the size of the undrilled tract, the amount of delay in drilling, and the amount of protection which the operator has obtained by offset wells.

SPACING OF WELLS.

It has been noted [40] that the production of widely spaced wells is more sustained than of wells spaced closely.

A study of the past performance of wells in fields throughout the United States was undertaken to ascertain the relative gain in production of widely spaced as compared with closely spaced wells. Of the fields examined, the Speechley pool, Butler County, Pa.; the pools in Nowata and Rogers Counties, Okla.; the Bartlesville-Dewey district, Okla.; the Hewitt field, Carter County, Okla.; and the Buena Vista Hills area, Calif., furnish typical examples of the difference in production that may be expected from wide and from close spacing. Average production-decline curves drawn for the widely spaced and the closely spaced wells indicated a decided increase of production per well in favor of the wide spacing. This increase of production per well is, however, accompanied by a lessened recovery per acre.

The following tables, which show for several pools the difference in ultimate production per well, and in ultimate production per acre, due to differences in the spacing of wells, were formed from the average production-decline curves of all available records of wells and tracts in these pools. Each group represents wells producing from approximately the same average thickness of the same sands, and with all other conditions similar except spacing. The fourth column of the tables shows the relative ultimate production per well for wells of the same size but with different spacings, this relation being expressed as a percentage; the fifth column shows the percentage ratio of the square roots of the number of acres drained by each well.

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[40] Beal, Carl H., White, Norval, and others, Manual for the Oil and Gas Industry, published by the Treasury Department, 1919. Discussion of Buena Vista Hills area, Midway field, Calif., p. 115. Beal, Carl H., and Lewis, J. O., Some principles governing the production of oil wells. Bull. 194, Bureau of Mines, 1919, pp. 25–27.

NOWATA DISTRICT, ROGERS AND NOWATA COUNTIES, OKLA.

Table 24 includes 23 tracts containing 134 wells in the same pool producing from the Bartlesville sand, which has an average thickness of 28 feet in this area.

TABLE 24.—*Effect of spacing on ultimate production in the Nowata district, Oklahoma.*

Spacing, acres per well.	Initial year's production, barrels.	Ultimate production per well barrels.	Ratio of ultimate production per well, per cent.	Ratio of $\sqrt{\text{areas}}$ drained, per cent.	Ultimate production per acre, barrels.
10	6,000	16,900	100	100	1,690
8	6,000	15,200	90	89.5	1,900
6.3	6,000	14,300	84.5	79.5	2,386
10	4,000	12,200	100	100	1,220
8	4,000	10,900	89	89.5	1,366
6.3	4,000	10,300	84.5	79.5	1,717
10	2,000	6,900	100	100	690
8	2,000	6,100	88.5	89.5	766
6.3	2,000	5,700	82.5	79.5	950

BARTLESVILLE-DEWEY DISTRICT, WASHINGTON COUNTY, OKLA.

Table 25 covers 80 tracts (337 wells) in one pool producing from the Bartlesville sand, which in that area has an average thickness of 25 feet.

TABLE 25.—*Effect of spacing on ultimate production in the Bartlesville-Dewey district, Oklahoma.*

Spacing, acres per well.	Initial year's production, barrels.	Ultimate production per well, barrels.	Ratio of ultimate production per well, per cent	Ratio of $\sqrt{\text{areas}}$ drained, per cent	Ultimate production per acre, barrels.
15	4,000	14,800			987
10	4,000	14,200			1,420
7	4,000	14,000	100	100	2,000
5	4,000	11,300	81	84	2,260
3	4,000	9,750	70	65	3,250
15	2,000	7,770			513
10	2,000	7,770			770
7	2,000	7,770	100	100	1,100
5	2,000	6,100	78.5	84	1,220
3	2,000	5,180	67	65	1,727
15	1,000	3,850			257
10	1,000	3,850			385
7	1,000	3,850	100	100	550
5	1,000	3,160	82	84	632
3	1,000	2,630	68	65	876

Table 25 shows that in the Bartlesville-Dewey district the interference of wells as shown by production decline is not noticeable when the spacing is greater than 7 acres per well. Therefore, in order to properly drain the tracts in this field, the ultimate spacing per well should not be greater than 7 acres.

HEWITT DISTRICT, CARTER COUNTY, OKLA.[41]

TABLE 26.—*Effect of spacing on ultimate production in the Hewitt district, Oklahoma.*

Spacing, acres per well.	Ratio of ultimate production per well, per cent.	Ratio $\sqrt{\text{areas}}$ drained per cent.	Ratio of ultimate production per acre, per cent.
10	100	100	50
2.5	50	50	100

In the Hewitt district, Carter County, Okla., the recovery per well will be almost twice as great with one well to 10 acres as with four well to 10 acres. However, the total recovery from 10 acres is almost twice as much with four wells as with one well.

SPEECHLY POOL, BUTLER COUNTY, PA.

Table 27 includes 10 tracts with 114 wells, all in the same pool.

TABLE 27.—*Effect of spacing on ultimate production in the Speechly pool, Pennsylvania.*

Spacing, acres per well.	Initial year's production, barrels.	Ultimate production per well, barrels.	Ratio of production per well, per cent.	Ratio $\sqrt{\text{areas}}$ drained, per cent.	Ultimate production per acre, barrels.
10	1,600	9,300	100	100	930
6	1,600	7,850	83	78	1,308
10	1,000	6,500	100	100	650
6	1,000	5,600	86	78	933
10	800	5,400	100	100	540
6	800	4,800	89	78	800

BUENA VISTA HILLS, KERN COUNTY, CALIF.

Table 28 includes all the wells drilled in Buena Vista Hills field, California, between 1913 and 1917.

TABLE 28.—*Effect of spacing on ultimate production in Buena Vista Hills, Calif.*

Spacing, acres per well.	Initial year's production, barrels.	Ultimate production per well, barrels.	Ultimate production per acre, barrels.
Isolated[a]	260,000	1,030,000	25,750
10	260,000	600,000	60,000
Isolated[a]	172,000	742,000	18,550
10	172,000	413,000	41,300

[a] Estimated drainage, 40 acres to the well.

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[41] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil fields, Oklahoma: Cooperative bulletin of the Bureau of Mines and the Ardmore, Okla., Chamber of Commerce, January, 1921, p. 33.

BARTLESVILLE FIELD AND GLENN POOL, OKLAHOMA.

An example of the variation in production per acre with different spacing of wells in two Oklahoma oil fields is furnished by Beal and Lewis.[42] Their results have been tabulated as follows:

TABLE 29.—*Effect of spacing on ultimate production in the Bartlesville field, Oklahoma.*

Spacing, acres per well.	Average daily production per well first year, barrels.	Average total production of oil per acre, barrels.	Total production per well, barrels.	Ratio of total production per well, per cent.	Ratio $\sqrt{\text{areas}}$ drained, per cent.
6–8	15	2,090	14,630	100	100
5	14	2,550	12,750	87	84.5
2–4	14	2,930	8,790	60	65.5
6–8	25	3,000	[a] 21,000		
5	26	5,650	28,250	100	100
3–4	24	6,500	22,750	80.5	83.5

[a] Evidently influenced by factors other than spacing, as the total production per well for 7-acre spacing is less than that of 3½-acre spacing.

Table 29 covers 74 properties producing from the same sand, which has a thickness of from 26 to 30 feet.

Table 30 includes 20 properties producing from the same sand, which has a thickness of from 28 to 46 feet.

TABLE 30.—*Effect of spacing on ultimate production in the Glenn Pool, Oklahoma.*

Spacing, acres per well.	Average daily production per well first year, barrel.	Average total production of oil per acre, barrels.	Total production per well, barrels.	Ratio of total production per well, per cent.	Ratio $\sqrt{\text{areas}}$ drained, per cent.
6–10	7	880	7,040	100	100
5	6	1,000	5,000	71	79
8–10	23	2,070	18,630	100	100
6–7	24	2,320	15,080	81	85

RULE FOR DETERMINING EFFECT OF SPACING.

Examination of the preceding tables shows that in the same pool, approximately the same ratio exists between the ultimate productions of the wells with different spacings, regardless of the initial year's productions. For example, in Table 24, for the Nowata district, Oklahoma, wells with an initial production of 6,000 barrels show with closer spacing a decrease in the ratio of ultimate production per well as follows: 100, 90, 84.5; while wells with an initial production of 4,000 barrels with the same spacings have a

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[42] Beal, Carl, and Lewis, J. O., Some principles governing the production of oil wells: Bull. 194, Bureau of Mines, 1919, p. 30.

decrease of 100, 89, 84.5, which is almost the same. A corresponding similarity (although an increase and not a decrease) is noted in the column of ultimate production per acre. For all sizes of wells this likeness was so marked in these several pools that the conclusion is that both the percentage of loss per well and also the percentage gain per acre due to closer spacing is almost the same regardless of the size of the wells. The following tentative rule is deducted from the above examples: *The ultimate productions for wells of equal size in the same pool, where there is interference (shown by a difference in the production decline curves for different spacing), seem approximately to vary directly as the square roots of the areas* drained by the wells. This rule may be also stated thus: The recovery from wells of equal size producing under similar conditions in the same pool is proportional to the average distance that the oil moves to get to the well. As no production records were available for very closely spaced wells (1 or 1½ acres per well), it can not be stated whether this relation is applicable to such wells. From this rule it follows that where interference exists betwen wells, doubling the distance between wells doubles the ultimate production per well and halves the ultimate recovery per acre. By employing this relationship, production-decline curves for wells of different spacing in the same sands may be derived from a given production-decline curve for wells of a known spacing.

This (tentative) rule seems to rest on the fundamental mechanical law that the energy required to move a fluid (either liquid or gas) through a pipe, or analogous conductor, is proportional to the distance. Thus to force water twice as far through a pipe line requires twice the force. According to this theory doubling the spacing means doubling the distance the oil must be forced to the well, and inasmuch as the proportion of gas energy to oil is not increased, it would naturally be expected that the energy would be effective to only half the degree and hence result in only half the recovery, which accords with the facts. Though other theoretical and practical considerations enter into the problem, which probably will prevent this rule holding exactly true for very close or very wide spacings or for every specific instance, nevertheless it is evident that recovery will be approximately proportional to spacing whenever the primary expulsive force is gas and the reservoir rock is continuous throughout the area under consideration. Thus the facts so far adduced clearly prove that exact adherence to this general rule can not be expected. however, for an oil sand is not uniform in texture and is not always continuous. But the rule is a good working rule and enables the operator to judge what he is doing far more intelligently than heretofore.

The spacing to be employed and the time of drilling wells in undrilled acreage have a most important bearing on the amount of oil that will be recovered, and therefore must be considered in an estimate of the recoverable underground reserves of oil.

METHODS OF OPERATION.

The production of an oil well depends on its method of operation, and therefore in any estimate of future output the method in use at the time, and also the probable method to be employed in the future, must be considered. The projection of the production-decline curve, as constructed from the past records, may be used as the base line for measuring the effect of changes of operation on yield in order to ascertain the probable gain or loss to the ultimate production of a property.

Figure 23 illustrates the use of production-decline curves to determine the average effect of vacuum on the production of oil in the Glenn pool, Oklahoma. The average production-decline curve before vacuum was used is shown as a full line, its extension as a broken line. This extension indicates what the average well would have produced had no vacuum been installed. The full line beginning at the point marked " vacum installed " shows the average production per well from the time of using vacuum. The hatched area represents the gain in production of the average well in Glenn pool, Oklahoma, due to the installation of vacuum.

Table 31 shows the effect of vacuum on production for the average well in the pool.

TABLE 31.—*Average effect of vacuum on the production of oil in 368 wells in the Glenn pool, Oklahoma.*

Effect of vacuum.	Number of tracts.	Acreage.	Number of wells.	Last yearly production before vacuum installed, barrels.	Estimated average future production per well as of no vacuum at time of installation, barrels.	Estimated average future production per well with vacuum at time of installation, barrels.	Effect of vacuum on future production gain, per cent.	Ultimate production per acre, no vacuum, barrels.	Ultimate production per acre, with vacuum, barrels.	Effect of vacuum on ultimate production, gain, per cent.
Increased production.....	26	2,316	368	1,850	4,200	11,360	171	5,460	6,600	21

This same method of procedure may be used for determining the effect of any change in operation on the production of a tract, either by using the production records of the tract itself or, if the records of production since the change in method of operation are insufficient, by analogy with other similar tracts.

Such factors as the encroachment of edge water, flooding, collapse of the casing, and caving of the sands should be considered in determining the probable life of the wells. Calculations also must take into account reserves in proved lower sands, the factors of spacing, thickness of sand, and the effect on the tract in question of installation of stimulative methods by neighbors. Only by utilizing all available information concerning these various factors can a reliable estimation be found.

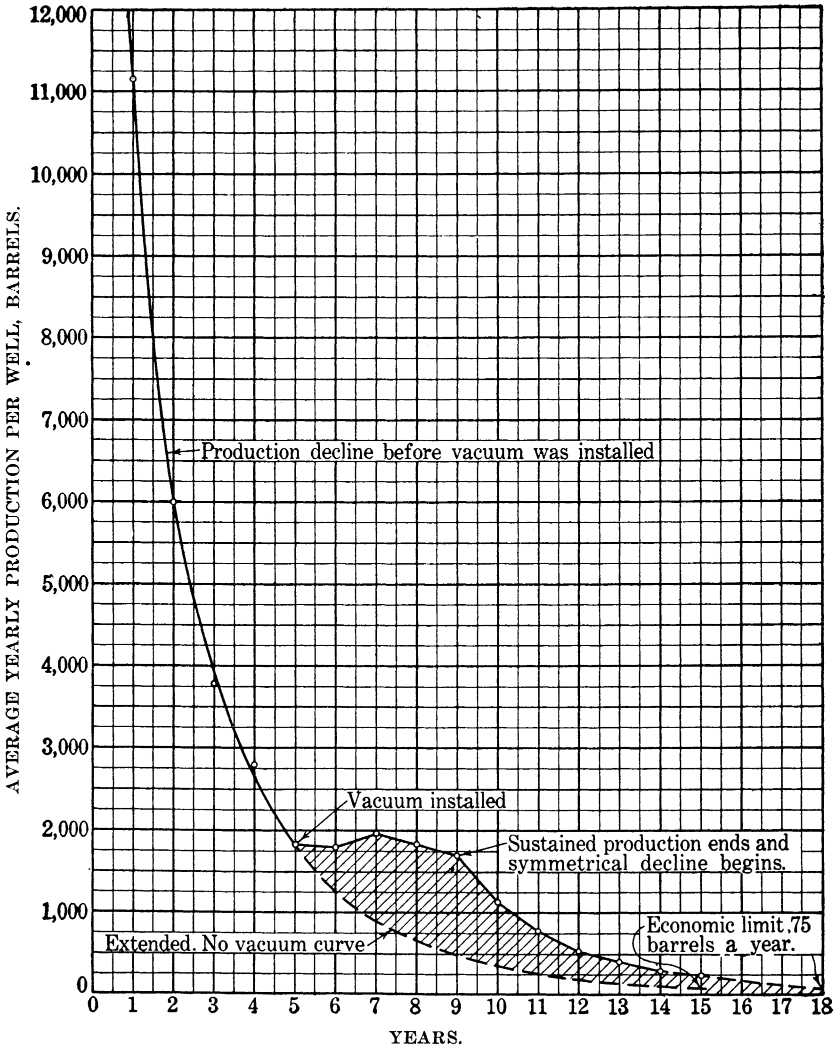

FIG. 23.—Method of determining the effect on the production of oil of introducing a change in the method of operations.

DRILLED ACREAGE.

GENERAL METHODS.

The production-decline curve is sufficient in itself for making estimates of future production for drilled acreage, inasmuch as there is no need to estimate the initial productions of wells to be drilled. There are three general types of this curve which may be used in estimating the future production of completely drilled tracts. These are well curves, tract curves, and average curves.

APPLICATION OF INDIVIDUAL-WELL RECORDS.

Where individual well records are available over a long enough period the future production of each well may be estimated from its own production-decline curve. This procedure, used to determine the total recoverable oil in a tract, is only practical where the number of wells is small, and is only necessary where there is a marked difference in the decline of each well.

Individual well records are usually used to construct an average curve of all of the wells in the tract and this curve then employed in the estimation of future production for the tract. If the rates of production of the various wells vary considerably the future production of each well or groups of wells of approximately equal rates of production should be estimated separately.

APPLICATION OF TRACT RECORDS.

The average production-decline curve of a tract may be used to estimate the future output of that tract if most of the wells are producing at approximately the same rate. Curves formed from tract records that include wells of greatly varying production, whether initial or settled, should be used with caution. Such a curve may not be symmetrical, and its extension would be unreliable.

APPLICATION OF AVERAGE CURVES.

Estimations of underground recoverable reserves of oil should be based upon the records of the wells or tracts under consideration. If such production records are not available or the tract curve can not be used an average production-decline curve of neighboring wells or of the pool or even the district may be used. For a discussion of the use of average curves, see page 38.

UNDRILLED ACREAGE.

LIMITATIONS.

The estimation of recoverable oil from undrilled acreage should be confined to proved oil land. The definition of proved oil land usually accepted is as follows: " Proved oil[44] land is that which has been shown by finished wells, supplemented by geologic data, to be such that other wells drilled thereon are practically certain to be commercial producers."

In order to estimate the probable ultimate production of an undrilled area it is necessary first to determine if it lies within the confines of a proved pool, and if so, its relative productivity to other areas already producing.

To determine the probable area of a pool an underground contour map of the producing horizon should be made from the logs of all wells which have penetrated it. This map may be supplemented by a surface structural contour map.

Plate II[45] shows an underground-contour map of the Hewitt field, Oklahoma, with the productive area marked on it. At the time the map was made the west border of the pool followed irregularly the 1,400-foot contour.

An underground-structure map with the location of producing wells plotted on it usually helps to determine whether the undrilled area in question lies within the proved area.

There are two general methods of estimating the recoverable oil from undrilled proved oil land: the barrel-per-acre method and the production-decline curve method.

BARRELS-PER-ACRE METHOD.

The ultimate production per acre of an undrilled area may be estimated by a comparison with the reasonably assured ultimate production per acre of a completely drilled similar area. See page 8 for description of method.

A map, such as shown in Plate II, on which areas are defined according to the initial production of early wells, will serve as a basis for establishing the original relative values of different areas.

As already stated, the barrels-per-area method is good only for approximate estimates, as the rate of drilling and spacing greatly affect the ultimate recovery and the method considers neither of these factors. The method may be used where the production-decline curve method is not applicable; that is, for tracts in proved but undeveloped pools or in areas distant from producing wells in the same pool.

PRODUCTION-DECLINE CURVE METHOD.

The estimation of future output of oil from an undrilled but proved area may be made by first determining the location and ex-

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[44] Manual for the Oil and Gas Industry. Treasury Department, first ed., 1919, p. 74.

[45] Swigart, T. E., and Schwarzenbek, F. X., Petroleum engineering in the Hewitt oil field, Oklahoma: Cooperative bulletin of the Bureau of Mines and the Ardmore Chamber of Commerce, January, 1921, Fig. 25, opposite p. 118.

pected time of bringing in each well, then estimating the initial production of each well, and, finally, estimating the ultimate production of these wells. This may be done by using the production-decline curve for near-by wells or tracts after it has been modified to meet the specific conditions of the area to be drilled.

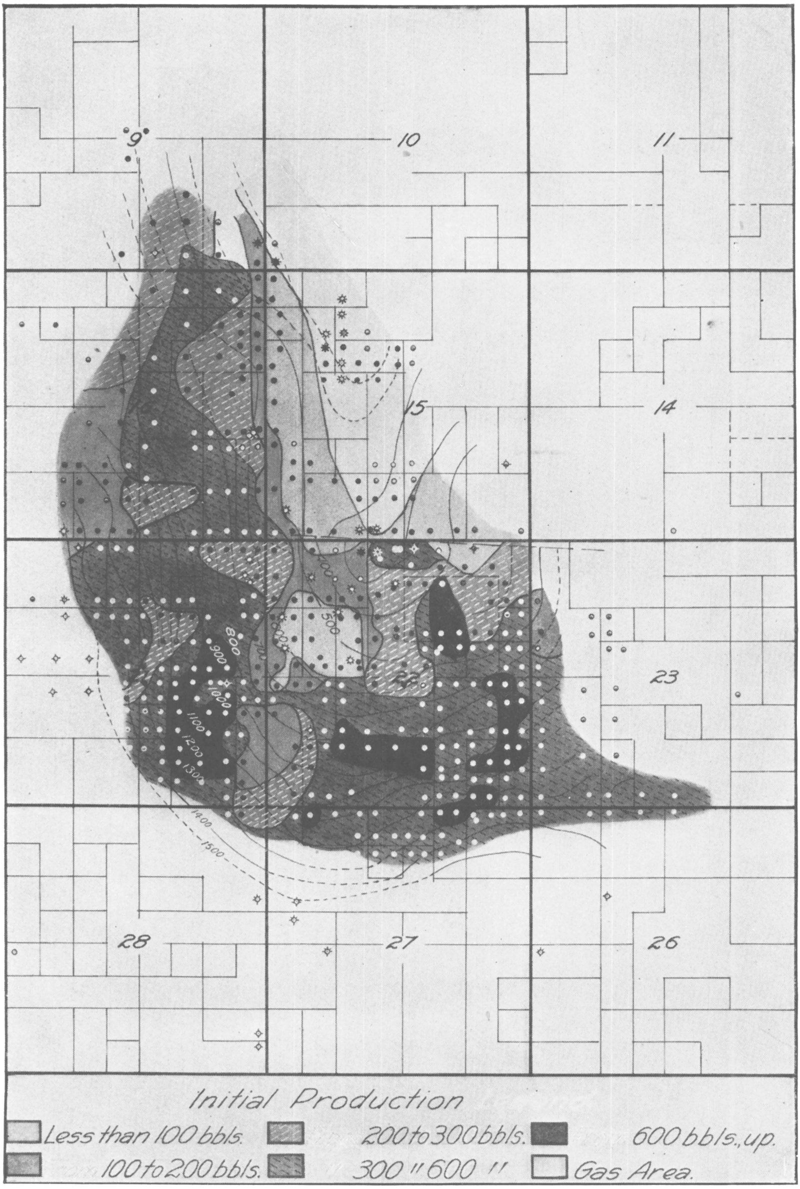
This method takes into consideration the drilling campaign for the undrilled acreage and utilizes the knowledge of both natural and artificial conditions in the field, and the production records or average production-decline curve of wells already producing and therefore is desirable where it can be employed. Too much refinement in the estimations of reserves in undrilled areas is not warranted because too many unknown factors enter into the problem. Estimates are at the mercy of the vagaries of the company's policies. The drilling program, the effectiveness of the production department, development on near-by areas, and the exact underground conditions are unknown until a property is developed. The reasonableness of the estimates should be checked by the ultimate recovery-per-acre method. Estimating the initial productions of undrilled wells is an important but difficult problem. Such estimates should not be attempted for wells in undeveloped pools or in areas distant from producing wells in the same pool.

OLD METHODS OF ESTIMATING INITIAL PRODUCTION.

Several methods have been used by various engineers for determining the initial production of wells and at present no method is generally accepted as giving reliable results. A description of the methods used by many engineers follows. The author attempted to obtain production records with which to illustrate these methods, but was unable in a search among many thousands of records to discover any that would apply.

INITIAL PRODUCTION-DECLINE CURVE.

An initial production-decline curve (see Fig. 24) is constructed by plotting the initial monthly or initial yearly production of each well in the tract or pool according to the time when the well began producing. For some tracts an extension of this curve will furnish an estimation of the initial productions of wells to be drilled. The initial production period used should be long enough to indicate the ultimate production of the wells. In pools where the initial or flush production of the wells is erratic the initial production period should be longer than in pools where the production of the wells at once shows a symmetrical decline.



UNDERGROUND CONTOUR MAP OF HEWITT FIELD, OKLAHOMA, SHOWING IRREGULARITY IN PRODUCTIVITY. LOOSE INTERPRETATION OF PRODUCTION. RELATIVE DATES OF COMPLETION AND OTHER CONTRIBUTING FACTORS ARE CONSIDERED.

SUSTAINED PRODUCTION-DECLINE CURVE

The sustained production-decline curve of a tract shows the production of its average well during the development period. Such a curve is formed from the record of the average well production of the tract, and necessarily includes the initial productions of new wells. If the average initial production of new wells exceeds the output of the average old well at the time the new wells come in, the production-decline curve of the average well of the tract will be sustained, and will not decline as rapidly as if no new wells had been drilled. Conversely, if the average initial productions of the new wells are less than the average productions of the old wells during the same period, the decline of the average well of the tract will be accelerated. (Graph C, Fig. 24.)

If the sustained production-decline curve of a tract is symmetrical for a reasonable length of time it may be extended to estimate the production of the average well during the period new wells are being brought in without estimating the initial productions of the new wells. When drilling is completed the sustained production-decline curve should not be used, but future productions should be estimated from the average production-decline curve constructed from the production records of the individual wells of the tract.

CRITICISM OF INITIAL PRODUCTION AND SUSTAINED PRODUCTION-DECLINE CURVES.

Among the factors that influence the initial production of a well are the location, time of drilling, distance from a producing well, and number of producing wells in the pool. An initial production-decline curve or a sustained production-decline curve for a tract may be expected to retain its symmetry throughout the development period only if the same number of producing wells are to be drilled each year and if also the average of the wells drilled each year will be in equally favorable locations. Such a drilling program is seldom followed, and therefore the initial-production-decline curve and the sustained-production-decline curve of most tracts are unreliable and should be used with caution. Graphs B and C of Figure 24 illustrate the error that may be introduced by the use of either the initial-production curve or the sustained-production curve. At the end of 1917 either curve if extended would have given much higher estimations of future production than was proved by later drilling.

RELATION OF INITIAL PRODUCTIONS TO THE PRODUCTIONS OF OLD WELLS.

Another method of estimating initial productions has been to attempt to establish a relation between the average initial yearly production of the wells drilled each year and the average yearly production of the old wells during the same calendar year. To establish such a relation complete individual well records must be avail-

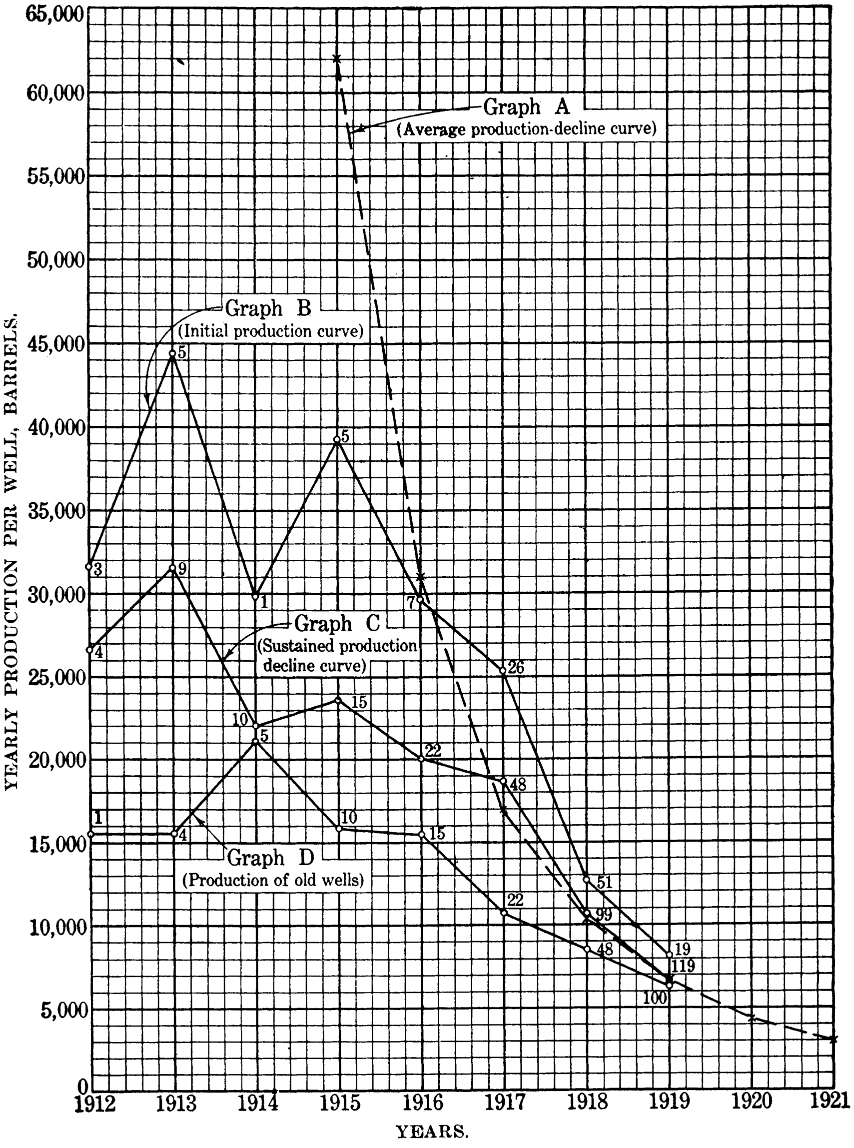


FIG. 24.—Production graphs for area in the Mooringsport pool, Caddo Parish, La.

able. Graph B, Figure 24, shows the average initial production of the wells drilled each year, and Graph D shows the average yearly production of all wells over a year old for an area in the Mooringsport pool, Caddo field, La.

Table 32 gives this information in tabulated form and shows the difficulty of establishing any relation between the production of the old and of the new wells.

TABLE 32.—*Relation between the production of old and new wells the same calendar year in a tract in the Mooringsport pool, Caddo Parish, La.*

1	2	3	4	5
Calendar year.	Average initial production of new wells drilled between July 1 of one year and July 1 of the following year, barrels.	Average yearly production of old wells during calendar year, barrels.	Percentage of initial production of new wells to yearly production of old wells. $\frac{\text{Column 2}}{\text{Column 3}}\times 100$	Time during which an average well declines from the initial yearly production of new wells to the same year's production of the old wells, years.
1912	31,600	15,600	202	1.2
1913	44,400	15,600	285	1.61
1914	29,900	21,100	142	.61
1915	39,300	15,800	248	1.43
1916	29,700	15,500	256	1.09
1917	25,400	10,700	237	1.53
1918	12,700	8,600	148	.84
1919	8,200	6,200	132	.61

Column 4 shows the relation between the average initial yearly production of the new wells and the average yearly production of the old wells during the same calendar year, expressed in terms of percentage. The relation is so erratic that it can not be used to estimate what the percentage would be in future years.

Column 5 shows this relationship expressed as time during which an average well declines from the average initial yearly production of new wells to the average production of the old wells each year; in other words, it shows the time interval on the average production-decline curve (Graph A, Fig. 24) between new and old wells during the same calendar year. The relationship for the different years is so variable that it can not be used for estimating future initial production.

It is often assumed that new wells will have an initial production equal to the average production of the old wells at that time. Such an assumption can only furnish approximate estimations, as no consideration is paid to the location of the wells and their distance from old producing wells.

INITIAL PRODUCTIONS AND SUGGESTED METHOD OF DETERMINATION.

In lieu of any reliable method of estimating initial productions the author gives a few observed facts bearing on initial productions and also suggests a method of attacking the problem.

The porosity, texture, oil content, thickness, and bedding of the producing oil zone and the pressure existing therein at the time of drilling determine the initial production of a well which is properly brought in. All of these conditions except pressure and oil content are inherent to the location of a well and are little affected by the drilling of other wells. A producing well gradually reduces the pressure existing in the surrounding areas and to a less extent the oil content of sands in adjoining locations. An estimation of the initial production of a well yet to be drilled must consider its location with respect to (1) structure and (2) wells already producing.

LOCATION WITH RESPECT TO STRUCTURE.

In some districts the initial productions have a definite relation to the geological structure. In many pools of the same district the greatest initial productions may be obtained near the crest of the structure; in other districts the area of greatest production may lie on one flank of the structure, often on that flank which conforms in dip with the general dip of the district. A relationship thus established in a district greatly aids in the determination of the initial productions.

Figure 25 shows the relation in a large tract in the Mooringsport pool, Caddo Parish, La., between the underground contours of the producing sand and the initial productions of the early wells. The initial productions were greatest about one-fourth to one-half miles north of the crest of the structure and lessened toward the edges of the pool. On the east side the productive area extends to a lower contour than on the west. The regional dip in this district is southeast.

Plate II (p. 93) gives the relation between the initial productions of the early wells and the underground geological structure in the Hewitt field, Oklahoma[46] and illustrates approximately the effect of location on initial productions in that field. The general relation of the outline of the pool to the structural contours may be seen in the western border of the pool when the productive area is approximately bounded by the 1,400-foot contour. However, in such a pool it would be impossible to predict even approximately the initial productions of wells a half mile from producing locations and to the south and east the edgewater contour departs greatly from the 1,400-foot contour.

In some fields the sands are irregular. Dry holes are found inside of proved areas and good wells in what was expected to be a poor area. In such fields initial production can not be estimated.

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[46] Swigart, T. E., and Schwarzenbek, F. X., Petroleum Engineering in the Hewitt oil field, Oklahoma. Cooperative bulletin of the Bureau of Mines, the State of Oklahoma, and the Ardmore Chamber of Commerce, January, 1921. Fig. 25, opposite p. 118.

LOCATION WITH RESPECT TO WELLS ALREADY PRODUCING.

As a pool becomes older and more wells are drilled the initial production of the new wells decreases, especially that of wells drilled near old producing wells.

The effect of distance from producing wells on initial production is important. Isolated wells will have greater initial productions than wells drilled close to producing wells if sand conditions are at all similar. In the Buena Vista Hills area, Kern County, Calif., the average yearly initial production of 24 isolated wells during the 5-year period, 1913–1917, was 260,000 barrels, whereas during the same period that of 104 wells drilled within one location of producing wells was 172,000 barrels. The initial yearly productions of isolated wells exceeded those of closely spaced wells by 50 per cent.

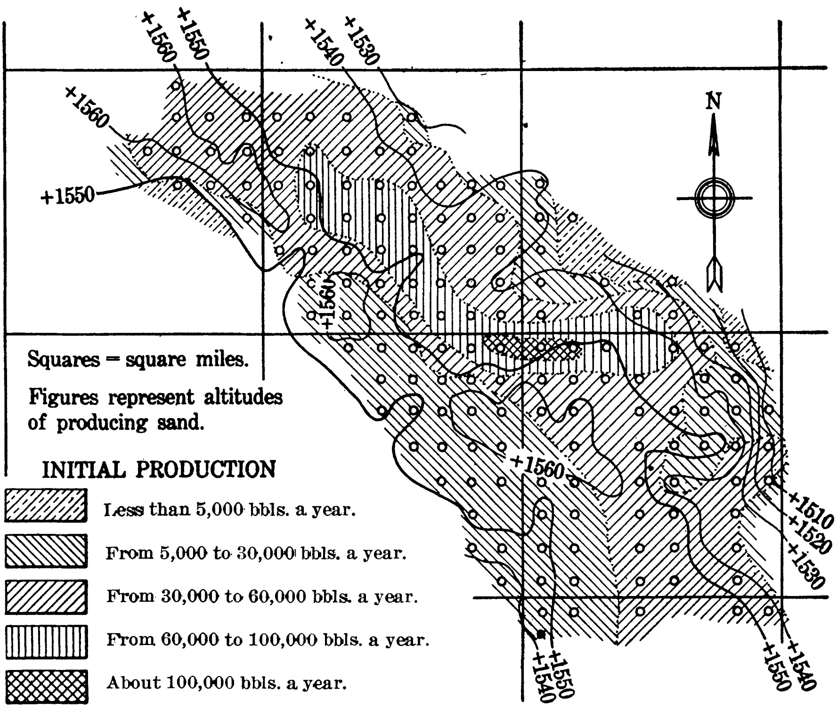

FIG. 25.—Production map of a large tract in the Mooringsport pool, Caddo Parish, La., showing relation between the areas of high initial production and the contours of the producing sand.

In Osage County, Okla., the effect of distance from already producing wells on the initial productions of new wells was noticeable on a large tract investigated, as is shown by Table 33.

TABLE 33.—*Effect on initial production of distance from already producing wells in Osage County, Okla.*

Year.	Spacing, feet.	Number of wells.	Average initial daily production, barrels.
1917	1,000-2,000	18	328
1917	660	14	246

In 1917 those wells that were drilled several locations from producing wells had an initial daily production 33⅓ per cent larger than that of wells drilled only one location from producing wells.

An area in the Mooringsport pool, Caddo Parish, Louisiana, was examined. All of the wells in the table were scattered throughout one producing area.

TABLE 34.—*Effect on initial production of distance from already producing wells in the Mooringsport pool, Caddo Parish, Louisiana.*

Year.	Distance from producing wells, feet.	Number of wells.	Average initial yearly production per well, barrels.
1917	660	21	18,200
1917	1,320	6	30,500
1918	660	21	15,000
1918	1,320	8	18,500

The average well drilled 1,320 feet from the producing wells was apparently no more favorably situated as regards sand and other conditions for large production than the average of the wells drilled 660 feet from producing wells, but in 1917 the initial yearly production of the wells 1,320 feet distant was to that of wells 660 feet distant as 10 is to 6; in 1918 it was as 10 is to 8. The smaller initial productions near old producing wells may be attributed to the lessened gas pressure, the drainage of oil from the sands, and the establishment of definite drainage channels to the wells already producing. When a well is drilled into a sand the equilibrium of the pressure in the sand is disturbed. The rush of oil, gas, or water into the hole causes a local reduction in pressure; more oil, gas, or water rushes from the surrounding sand to equalize the pressure. Thus the lowering of pressure and the drainage of oil spreads from the well. The only important drainage of oil, however, seems to be limited to the contiguous area, the greatest drainage occurring near the well and usually decreasing with distance in all directions from the well. This distance varies according to the conditions of the sand in the pool and may be determined by comparing the production-decline curves of groups of wells of various spacing. (See p. 85.) In some of the pools considered, single wells practically drain oil from 5 to 10 acres only; in other pools they drain comparatively large areas, 20 to 40 acres. In some pools with more open sands, single wells drain oil from much larger areas. This is evident, as single isolated wells in these parts ultimately produce more oil than the total oil produced from several wells in more closely spaced areas.

LOSS OF PRESSURE THROUGH PRODUCING WELLS.

Although the drainage of oil by an oil well is practically limited to the contiguous area, nevertheless the gas drawn from the pool by an oil well results in a lessened pressure, which, in a uniform sand, will eventually lessen pressures throughout the whole pool, and thereby decrease the oil recoverable by natural methods from any location in the pool.

It is difficult to obtain records that show the loss in pressure caused by producing wells because few companies record the pressure of producing oil wells. E. G. Gaylord, geologist for the Pacific Oil Co., kindly furnished monthly pressure records, for periods of 1 to 36 months, from 22 oil wells in the Midway Sunset district, California. These records showed great differences in the pressure of wells in the same tract during the development period. New wells had initial pressures greater than the pressures in near-by older wells at the time the new wells were brought in. Table 35 shows how producing wells affected the pressure in undrilled locations.

TABLE 35.—*Effect of producing wells on pressures in undrilled locations in Buena Vista Hills, California.*[a]

[Well locations, 660 feet apart.]

Number of old producing wells.	Distance measured in well locations, from undrilled locations.	Years producing to affect pressure appreciably.
1	1	2
	2	3
	3	......
2	1	1
	2	2
	3	3
3 or more.	1	1
	2	1
	3	2
	4	5

[a] Not enough data were available to make a table showing the quantitative loss in pressures.

Large initial production was accompanied by high pressure and usually, but not always, high pressure gave large initial production. Small production with high pressure evidently indicates unfavorable natural conditions. It is evident from these records that the production of oil from these wells is directly dependent on the pressure of the gas included in and associated with the oil. The loss of initial production of wells through delay in drilling is due to a loss in pressure and varies with the number and proximity of the producing wells in the same pool, the size of the pool, and the length of the delay in drilling.

However, a study of initial productions alone is not enough to determine the probable initial production of new wells, as producing wells affect greatly the pressures in both the drilled and undrilled areas, and hence affect the relation between the rates of production of producing wells and the initial productions of new wells.

SUGGESTED METHOD OF ESTIMATING INITIAL PRODUCTIONS.

The author believes that a consideration of the structural location, the wells already producing, and their pressure records would serve as a basis for reliable estimates of initial production for wells in many pools.

A map, such as Figure 25, giving the outline of areas of similar initial productions in the early life of pools or fields, shows what the initial production of the wells would have been had they been drilled when the pool was first discovered. A study of pressure records from producing wells in the same pool would show the decline in pressure in undrilled areas due to producing wells.

RELATION OF PRESSURE TO PRODUCTION.

Pressure records available from the Buena Vista Hills district, California, indicate that in areas where original conditions were equally favorable the existing pressures determine the rate of oil production of the various wells, regardless of the ages of the wells. At present not enough pressure records are available to substantiate this hypothesis, but the following example, taken from Buena Vista Hills, is in accordance with the hypothesis:

Figure 26 shows the production decline of a well with the pressures indicated while the well was flowing through a seven-eighths inch aperture at different periods. The well was drilled in 1914. In February, 1922, an offset well was drilled one location distant. The initial pressure of the offset well was 270 pounds per square inch while flowing through a seven-eighths inch aperture, and its production during the first 30 days was 28,440 barrels. This flow was approximately the same as the monthly production of the first well in February, 1919, when its pressure was about 270 pounds per square inch while it was flowing through a seven-eighths inch aperture. In other words, irrespective of the ages of the wells or the calendar years, these two wells produced at the same rate when their pressures were the same.

From this example it would seem that if the initial pressure in the well to be drilled can be estimated, its initial production may be assumed to be equivalent to the average production of near-by wells at the time their pressures were equal to the estimated initial pressure of the well to be drilled. Only near-by wells that lie in the same area of similar original conditions should be considered.

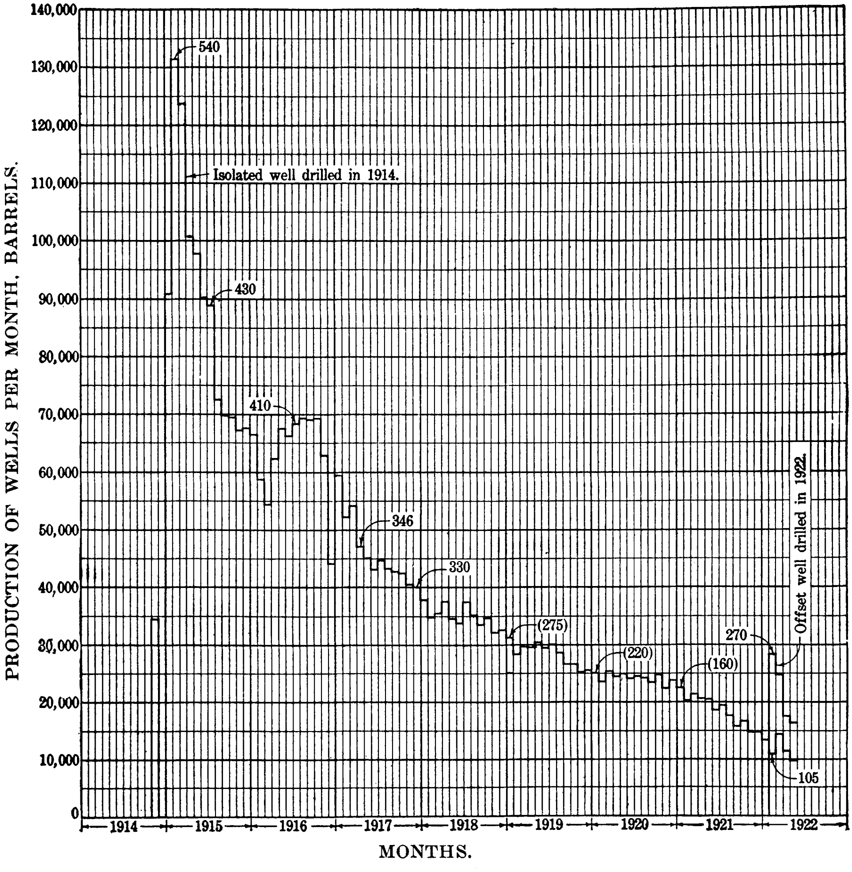

FIG. 26.—Relation between the productions and pressures of two wells in the Buena Vista Hills, Kern County, Calif. (Pressure figures in parenthesis were estimated.)

The author advances these suggestions, after a consideration of all the facts he could obtain bearing on initial productions, in the hope that they may lead to the collecting of pressure records by various operators, a study of these records by engineers, with a resulting advance in the methods of estimating initial productions.

TRACTS WITH MORE THAN ONE PRODUCING SAND.

In many fields oil is obtained from two or more horizons. For tracts in which each well is producing from only one horizon the production from each horizon should be recorded separately and an average production-decline curve should be constructed for it. The future production of each horizon should be estimated separately from the average production-decline curve for that horizon.

If several producing horizons are drained by one well the percentage of the oil contributed by each at any given time to the total production may differ greatly. Moreover, the percentage of the whole production that each horizon contributes may vary greatly at different periods through differences in the initial pressures of the several sands. For these reasons an extension of the average production-decline curve of a tract with several sands usually will not represent the future production of the average well.

Tract-production records may include the production of wells that have been deepened to lower sands, and the average production per well of the tract would be unduly sustained if an increased production was obtained from the lower sands.

However, estimates of future production for tracts in which there are wells that produce from two or more sands are from necessity based on combined sand productions. If possible, a careful segregation of the individual well records should be made. An average curve may then be made for combined sands and others for each separate sand and these curves used for groups of wells according to the sand or sands from which they produce. If individual well records are not available a general average curve which may apply to any well, irrespective of its source of production, will have to be used. Such curves can furnish only approximate estimations.

ESTIMATION OF THE RECOVERABLE UNDERGROUND RESERVES OF OIL IN A FIELD.

If there is more than one producing horizon, an estimate of the future production of each horizon should be made. The person making the estimate should remember that the productive area of the several sands may differ greatly.

For new fields or for fields with large undrilled areas in developed pools the barrels-per-acre method may be used if the rate of recovery is not desired.

For fields which are fairly developed average production-decline curves should be constructed by the family curve or other methods already described (pp. 41 to 60). Unless information is available to the contrary it may be assumed that new wells will have initial productions equal to the average of the old wells at the time.

An estimate of the future output of a developed field may be obtained by estimating the future production of the individual tracts or areas in the field by the production-decline curve method and adding these estimated future productions together to obtain the total. This method is the most exact that can be employed but involves more work than is usually warranted for the accuracy desired.

For developed fields with one sand in which the number of new wells drilled during the preceding four or five years is negligible an average curve of the field for that period may be constructed by dividing the total yearly productions of the field by the number of wells producing each year. The future production of the producing wells may then be estimated by the use of this average curve.

USE OF CURVES IN PROBLEMS OF OPERATION.

INTRODUCTION.

The preceding chapters have discussed the formation and uses of curves for estimating the future output of oil. This section deals briefly with the use of curves as an aid in determining policies regarding methods of operation. The effect of various spacings of wells and of different operating methods on the recovery of oil may be estimated by the use of curves.

SPACING.

As already shown on page 89, the spacing employed affects materially the ultimate production per well and also per acre. The production-decline curve may be used to determine what spacing will provide the greatest return on the investment. The cost of drilling, the cost of producing oil, the amount of royalty, and the price of oil must be considered in determining the spacing.

Large production per acre, shallow wells with attendant low cost of drilling, and a high price of oil permit closer spacing than do small production per acre, deep wells, and a low price of oil. It is a significant fact that operators, though they usually determine the spacing by experience, often space their wells most economically; but there are striking exceptions. In Burkburnett (Northwest Extension and Townsite pools), in Santa Fe Springs and Signal Hill, Calif., close spacing resulted in financial loss to many operators. In the past too close spacing has usually been the result of competition between owners of small tracts.

The future price of oil is an uncertainty, but it must be estimated in order to determine the correct spacing. The only tangible factors in determining future price are the present price and the present situation as to production, consumption, and stocks of oil on hand.

In ordinary times the price of oil in the near future may be expected to remain close to the existing price. In times of financial depression or inflation the price may be expected to fluctuate. If the price of oil for a long period for the particular field in question be plotted, a line showing the general trend of price may be drawn. If the present price is above the general trend it may be expected to drop; if below the general trend it may be expected to rise. The trend of general market conditions also affects the price of oil, and should be considered. Predictions of this kind are almost impossible and it is not surprising how many prophets in the past have been wary in their predictions of the price of oil.

The following example illustrates a method of determining the spacing that may be expected to furnish the greatest return on the investment. Assume the tract under consideration was leased for one-eighth royalty and a bonus of $500 per acre. Surrounding wells indicate the initial production of wells to be drilled on this tract will be about 50 barrels per well a day. The cost of drilling and equipping a well will be about $10,000. The cost of producing oil per barrel, including overhead, pumping, tanks, and other charges has been found to be about $0.35 a barrel in that locality.

The average production-decline curve of wells in the pool with an average spacing of 7 acres shows that wells with an initial daily production of 50 barrels a day may be expected to produce during their entire life 20,000 barrels with a life of about 12 years. Discounted at 10 per cent the average barrel of production throughout the life of a well has a present value of 65 per cent of the value of the oil at the time it is received. This value is determined by discounting the value of each year's estimated production of an average well of the pool (50 barrels a day initial production) at 10 per cent to the present time, noting what percentage the present discounted value of the total oil bears to the value of the total oil at the estimated time of production. The average production-decline curve of the pool is used for this calculation, and the slight error due to the difference in life of wells of different spacing is ignored. It is assumed that the selling price of oil during the life of the tract will be the same as the present price, namely, $2 per barrel.

DETERMINATION OF THE TOTAL NET PROFIT PER ACRE TO LESSEE WITH WELLS SPACED 6 ACRES TO THE WELL.

Receipts from one well in this pool may be estimated in the manner shown below.

The wells of 7-acre spacing have an average ultimate production of 20,000 barrels. On page 89 the relation between ultimate production and spacing is given as follows: The ultimate production for wells of equal size in the same pool where there is interference (shown by a difference in the production-decline curves for different spacing) seem approximately to vary as the square roots of the areas drained by the wells. Therefore the ultimate production of a well with 6-acre spacing may be expected to be $\frac{20,000}{\sqrt{7}}=\frac{x}{\sqrt{6}}$ or $x=18,500$ barrels, the ultimate production of a well with 6-acre spacing. Then 18,500 barrels at $2×65 per cent (discounted)=$24,050, the present value of oil to be received from 1 well with 6-acre spacing.

Cost of operating may be figured as follows:

Drilling and equipping well	$10,000
Lifting oil, 18,500 barrels, at $0.35×65 per cent (discounted)	4,208
Present value of money spent in receiving ultimate production	14,208

As a royalty of one-eighth is to be charged against this oil, the value of the oil to the lessee will be $24,050×0.875=$21,043.

The present value of the profit from this well to the lessee will be $21,043−$14,208=$6,835.

This represents the present value of the profit the lessee may expect to derive from the average well which drains 6 acres: $6,835÷6=$1,139, his profit per acre.

As the lessee paid a bonus of $500 per acre for his lease the total present value of an acre to him will be $1,139−$500=$639, if wells are spaced 6 acres to the well.

In like manner the profit that the operator may derive from various spacings may be computed and tabulated as in Table 36.

TABLE 36.—*Method of determining most economical spacing of wells.*

1	2	3	4	5		6
Spacing, acres per well.	Ultimate production per well, barrels.	Present value of oil per well to lessor (column 2 ×$1.1375).[a]	Present value of cost per well (column 2× $0.2275+ $10,000).[b]	Present value of profit.		Total net profit per acre to lessee (profit per acre—$500.)
				Per well (column 3—column 4).	Per acre (profit per wells divided by acres to well).	
5	16,900	$19,200	$13,840	$5,360	$1,072	$572
6	18,500	21,043	14,208	6,835	1,139	639
7	20,000	22,750	14,550	8,200	1,171	671
8	21,400	24,350	14,870	9,480	1,196	696
9	22,650	25,750	15,160	10,590	1,176	676
10	23,900	27,150	15,450	11,700	1,170	670
11	25,100	28,550	15,700	12,850	1,167	667

[a] $1.1375=discounted value of price of oil×⅞ (interest in lease)=65 per cent×$2×$0.875.
[b] $0.2275=discounted value of lifting cost=$0.35×65 per cent.

For this tract the maximum profit per acre to the lessee would be obtained from a spacing of 8 acres to the well. If early development of the tract showed a change in any of the factors entering into the calculations the remaining acreage could be spaced accordingly.

OPERATING METHODS.

The production-decline curve is the best method as yet developed for determining how production is affected by changes of operation. Any change of operation will cause a deviation in the production-decline curve and the effect on production can therefore be determined by referring to the extension of the production-decline curve as constructed from previous records which is thereby used as a base line for measuring the efficiency of the new method. See Figure 23 and accompanying discussion, p. 90.

The advisability of introducing a new method of operation, such as the use of compressed air (Smith-Dunn process), water drive, or the installation of vacuum is a matter of dollars and cents. If the financial gain through increased production (both oil and gas considered) is greater than the additional cost involved the change is warranted. The effect of the proposed method on the production of similar properties in the same field can be used as a criterion of its probable effect on production in the tract being considered.

The effect of minor changes in operation, such as cleaning, shooting, use of back pressure on the wells, the position of the working barrel, change of management, and so on, may be determined by using the projection of the production-decline curve. If the gain, as shown by the production-decline curve, from shooting and cleaning of wells is greater than the cost involved, the operator is justified in shooting and cleaning certain other wells.

In this way, the production-decline curve can be used to increase efficiency in the operation of oil properties.

SUMMARY.

NEED FOR FURTHER INVESTIGATION.

This bulletin discusses the production-decline curve method as developed at the present time for estimating recoverable underground reserves of oil and also its use for solving operating problems. Perfection of this method or the development of better methods may be accomplished through a further study of the fundamental principles governing oil production and the application of the knowledge derived thereby. For such a study laboratory experiments, field observations, and the collection of more data on production are necessary. Many enlightening facts concerning production could be determined from production records if data on the pressure and the volume of gas accompanying the oil were available. Plate I, *B* (p. 40), shows how a pressure gage can be attached to a flowing well to determine the pressure. These data with an analysis of the gas[47] accompanying the oil at different periods in the life of the wells might form the basis for a better method of estimating oil reserves.

It is hoped, as the value of oil-well production curves becomes more generally recognized, that operators will cooperate by assembling and distributing additional data, even at some expenditure of time and money. By so doing they will contribute to technical knowledge and will unquestionably benefit the oil industry by helping to increase efficiency in operation.

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[47] Suggested by J. O. Lewis, formerly chief petroleum technologist, Bureau of Mines.

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