PREPRINT - SUBJECT TO REVISION

TECHNIQUES OF PREDICTION WITH APPLICATION TO THE PETROLEUM INDUSTRY

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HOUSTON, TEXAS
MARCH 1959

FOR PRESENTATION AT THE 44TH ANNUAL MEETING
OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
DALLAS, TEXAS
TUESDAY, MARCH 17, 1959

PUBLICATION 204
SHELL DEVELOPMENT COMPANY
EXPLORATION AND PRODUCTION RESEARCH DIVISION
HOUSTON, TEXAS

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Publication 204

ABSTRACT

The art of soothsaying, although probably not the world's oldest profession, can certainly offer strong claims for being its second oldest. Nonscientific soothsaying is based largely upon astute guesswork and ambiguous statement, whereas scientific soothsaying, or prediction, consists in trying to foretell as accurately as possible the future evolution of a material system in terms of a knowledge of its mechanism, its past history, and of the physical data upon which its evolution depends.

According to the second law of thermodynamics, the evolution of any material system, when viewed in its entirety, must be unidirectional and irreversible, and hence incapable of repetition. However, the evolution of some systems can be resolved into cyclical and noncyclical components--the swinging pendulum versus the falling weight of a clock, for example. If the mechanism is understood, the prediction of a cyclical phenomenon for limited periods of time can often be made with great precision.

The production of oil and gas, although slightly affected by a minor superposed seasonal cycle, is predominantly an example of a noncyclical phenomenon. The number of oil or gas pools still to be discovered continuously diminishes; the mean depth and cost of wells continuously increase; and the production of power from uranium (and probably later from deuterium also) is well advanced on its inexorable ascendancy.

From this point of view, a study has been made of the discovery and production history of the United States in order to estimate about how far the industry has progressed from its beginning to the ultimate exhaustion of its petroleum reserves. It has been found that since about 1925, discovery has preceded production by the nearly constant interval of 10 - 11 years. The peak in the rate of discovery occurred about 1952 or 1953, and the peak in the rate of production is expected to occur about 11 years later, or about 1964. The peak of proved reserves, which should occur between these two dates, appears to be about 1957 or 1958.

Assuming that the curve of cumulative discovery will be that of a simple logistic curve, then the peak of the rate of discovery should occur when the cumulative discoveries are about halfway to their ultimate asymptote (at constant efficiency of recovery). The cumulative discoveries by the end

of 1952 were about 73.3-billion barrels of crude oil, which suggests that the ultimate amount will be twice as great, or about 147-billion barrels.

Up to the end of 1958, there had been discovered approximately 21,000 oil fields of all sizes, of which 207 had ultimate reserves of over 100-million barrels. Yet these 207 fields accounted for about 54.4-billion barrels, or about 60 percent, of the total of 90-billion barrels discovered up until that date, leaving only 35.6-billion barrels for the remaining approximately 21,000 fields.

The logistic curve for these large fields is approaching an asymptote of about 220 fields, with an ultimate reserve of about 56-billion barrels. The discovery rate of the small fields is still increasing and an ultimate asymptote of about 50,000 fields is estimated. The average size of these fields is about 1.63-million barrels. Fifty thousand such fields would represent ultimate reserves of about 81.5-billion barrels. When this is combined with the 56-billion barrels for the large fields, we obtain an estimated ultimate reserve of 137.5-billion barrels.

Comparable data for natural gas suggest that the peak of production should not be reached before 1970, or shortly thereafter.

It is physically possible that these figures, which may be rounded off to 150-billion barrels, may represent only a temporary setback due to limitations of our exploratory techniques and philosophy. Of these, the one having the largest room for improvement appears to be petroleum geology itself.

THE ART OF SOOTHSAYING

The art of soothsaying, although probably not the world's oldest profession, can certainly offer strong claims for being its second oldest. The techniques of soothsaying may be divided roughly into those which have some rational basis, and those which do not have; and the results of soothsaying, namely, the prediction of some event, may be expressed in language whose meaning may fall anywhere within the range from the completely definite to the completely indefinite.

The nonrational techniques of prediction are well exemplified by the activities of many of the priestcrafts of the ancient world -- notably those of the famous oracle at Delphi in Greece -- and by the fortunetellers of today. These have commonly been characterized by a combination of astute guesswork and ambiguous statement, carried out usually behind a facade of mystical rites.

Prediction by ambiguous statement. - From examples of the soothsayer's art which have been handed down from antiquity, it appears to have been learned at a very early age that the soothsayer's expectancy of life could be considerably enhanced if his professional opinions, while appearing to convey useful information, were actually couched in language of such ambiguity as to cover all likely contingencies. For example, when King Croesus of Lydia, in the sixth century B. C., was desirous of conducting a military campaign against his neighboring states, but was doubtful as to the outcome, he consulted the Delphian oracle. The advice he received was: "If you embark upon this campaign a great empire will be destroyed."

He did embark upon the campaign, and a great empire was destroyed: his own.

The technique of prediction by ambiguous statement is not unknown to the petroleum industry.

RATIONAL TECHNIQUES OF PREDICTION

Let us now consider the techniques of prediction which have a rational basis, and will yield results which may be stated as definitely as the intrinsic uncertainty will allow. These again fall into two major classes, (1) the empirical extrapolation of the past performance of a system into the future, and (2) a much more comprehensive technique whereby the future evolution of a material system is deduced from a knowledge of its mechanism, its past history or present condition, and of the physical data upon which its evolution depends.

<u>Prediction by empirical extrapolation</u>. - Of these two methods of prediction, the first, although the one most commonly employed, is also much the more primitive and unreliable of the two. In practice, this has been reduced to two more or less standardized procedures. If the past history of some variable whose future it is desired to predict can be reduced, when plotted against time, to some kind of a linear graph, then the variable is said to be following a "trend", and the prediction consists simply in projecting this straight line, or "trend", into the future.

If, on the contrary, the past history of the variable can be shown to be cyclical in character, that is, if when plotted against time it exhibits either a simple or a compound sinusoidal variation, then the prediction of the future behavior of the system consists simply in assuming that the same cyclical variation will continue into the future.

The technique of prediction by means of linear trends is so ubiquitous in economic forecasting that innumerable examples occurring in everyday literature are available. But, merely to illustrate the use of the technique, there has here been reproduced as Figure 1 a chart showing "Past growth trends for petroleum demand with projections to 1965" from a recent paper by Pogue and Hill (1956) of the Petroleum Department of the Chase Manhattan Bank.

It is true that the variations of many physical phenomena can be plotted in such a manner as to follow a straight-line graph as a function of time, and when the phenomena themselves are understood, it may be found that extrapolations, either forward or backward, will reproduce the evolution of the system with great faithfulness. An outstanding example of this type of behavior is the decay curve of a radioactive isotope, where the number of atoms versus time plots as a declining straight line on semilogarithmic paper. The fact that such curves can be extended backward for billions of years in the case of some isotopes, is the basis for radioactive dating of geological events.

The danger inherent in the empirical extrapolation of linear trends of phenomena for which the mechanism either is not known or is ignored is illustrated by Figures 2 and 3. In Figure 2 there has been plotted on semilogarithmic paper the production of pig iron in the United States from 1850 to 1914, a period of 64 years. It will be observed that this curve, with only minor departures, faithfully follows a linear trend whose projection into the future allows of little ambiguity. I have been told by C. K. Leith, who was one of the best informed men in the country on the overall economics of the iron and steel industry, that during this time, and for the next ten years, all of the industry's plans were based upon the premise that the production of pig iron would continue along this trend for the "foreseeable future".

Figure 3 shows what actually happened.

Prediction by means of cycles. - The dangers inherent in the empirical prediction by means of trends are equally present when the prediction is by means of cycles. Many physical systems do indeed behave in a cyclical manner, and, as in the case of linear phenomena, if the mechanism is understood, the prediction of future events may, in many cases, be made with both precision and reliability. The most familiar of all cyclical phenomena are, of course, those resulting from the rotations and revolutions of the various members of the solar system. In this case the rates of change of the periods are so slow, and the possibility of interference by external astronomical bodies is so remote in time that the prediction of the future positions of the members of the solar system, and of the times and places of such events as eclipses of the sun and the moon, can be made with confidence for thousands of years in the future.

On the other hand, the prediction of a cyclical phenomenon for which the mechanism is not known or is ignored is hazardous indeed. For example, if the consumption of natural gas in Dallas were plotted against time, this curve would be found to have a well-defined annual cycle, which in this case is known to be determined by the variation of gas consumption for heating caused by the annual sinusoidal variation of the temperature due to the earth's revolution about the sun. While we can predict with some confidence that the mean monthly temperature in Dallas one hundred years hence will continue to be cyclical, we can make no such prediction about the consumption of natural gas, for the simple reason that there may not be any!

PREDICTIONS BASED UPON KNOWLEDGE OF THE PROPERTIES OF THE SYSTEM

It follows, therefore, that if predictions concerning the future evolution of any material system are to be made that are much better than guesswork, or at least than the blind extrapolation into the future of the system's past behavior, it can only be as the result of as complete an understanding as possible of the system's properties and mechanism. In this regard, it is known from the second law of thermodynamics that the evolution of any material system, when viewed in its entirety, must be unidirectional and irreversible, and hence incapable of repetition. However, as we have noted already, the evolution of some systems can be resolved into cyclical and noncyclical components -- the swinging pendulum of a clock, for example, versus the falling of its weight. Hence, in the long-term evaluation of a system, such cyclical components are essentially uninformative; or as has been better stated by Alfred J. Lotka (1925, p. 21 - 22):

> "The popular and also the scientific conception of evolution contains as an essential feature the element of progress, of development. We would not ordinarily class as evolution the history of such a system as a swinging pendulum, or a celestial body circuiting in its orbit, *in so far as these motions are purely periodic or cyclic.* In the history of such systems the element of progression in time, of development, is lacking. They repeat in endless succession the same series of events. The hand of

the clock, like a symbol of perpetual youth, goes through its daily double cycle, making no distinction between yesterday, today and tomorrow. It is the calendar that reminds us we grow older year by year, the calendar that turns a new and different leaf each day."

APPLICATION TO THE PETROLEUM INDUSTRY

The production of oil and gas, notwithstanding the fact that there is a minor annual variation in the rate of consumption of these fuels, is pre-eminently an irreversible phenomenon. In this case, the mechanism of the system with which we deal is simple and well understood. The plants on the earth derive their energy from sunshine and by combining the inorganic elements carbon, hydrogen and oxygen into complex organic molecules. This energy is stored in the form of chemical potential energy. During geologic time, at least as far back as the Cambrian, a small fraction of the plants and animals which have lived upon the earth have become buried in the accumulated sediments under such conditions that their complex organic molecules have not been entirely destroyed and so a fraction of this energy has been preserved. These buried organisms have in turn been the source of our present supply of fossil fuels: coal, petroleum and natural gas, and oil shales.

The period of time during which these deposits have accumulated has been roughly 500-million years and, although the same processes are occurring today, the rate of production of new fossil fuels is probably not greatly different now from what it has been during the geologic past. Hence, if our present initial reserves of fossil fuels have required 500-million years of geologic time for their accumulation, the amount of new reserves that may be expected to accrue during the next 1000 years would be a negligible fraction of the reserves which existed when the present period of exploitation began. Therefore, in the consumption of the fossil fuels, we are simply drawing upon a fixed supply of which the amount remaining at any given time must be the difference between the amount initially present and that which has been consumed already. The amount initially present was a finite magnitude, and the ultimate cumulative production may approach, but can never exceed, that initial quantity. Thus, if we plot a curve of cumulative production for any given area, this curve will start from zero with a very low slope, because of the slow rate of initial production, and will then rise more or less exponentially before finally leveling off asymptotically to some ultimate quantity, Q_{ult}.

A variation of this type of growth-curve of cumulative production would be one that first levels off to a temporary asymptote, due to some retarding influence, and then experiences one or more periods of rejuvenation before finally leveling off to its ultimate asymptote. These two types of growth behavior are illustrated in Figure 4 in which the cumulative production Q in Figure 4a is the familiar logistic curve for a single cycle of growth. Figure 4b represents a logistic curve for multiple growth cycles. In each case the derivative of the cumulative production curve with respect to time is

$$dQ/dt = P,$$

where P is the rate of production.

Since oil and gas are not continuously distributed like beds of coal, but occur as discrete aggregations in pools and fields, then instead of plotting a curve of cumulative production, we could equally well plot a curve of the cumulative number of fields discovered as a function of time. In this case also, if the initial number of fields is the finite number N_o, and if N is the number discovered up to any given time, then the number of fields remaining to be discovered is $(N_o - N)$. Here too the number N must ultimately approach an asymptote which is either equal to or less than N_o.

Integral technique of prediction. - The foregoing circumstances serve to define the question in whose answer we are currently interested: How far along has the petroleum industry in the United States progressed toward this ultimate asymptote?

One powerful technique by which an approximate answer to this question can be obtained is the integral technique first introduced by me in 1949. (See also 1950 and 1956.) This depends upon the mathematical principle that if y is a univalued function of x, and a graph of y versus x is constructed, then the

$$\int_{x_1}^{x_2} y\,dx = A \tag{1}$$

where A is the area between the y-curve and the x-axis. Now suppose the curve we are concerned with is that of the rate of production as shown in Figures 4a and 4b. In this case

$$\int_0^t P\,dt = \int_0^t (dQ/dt)\,dt = Q, \tag{2}$$

where Q is the cumulative production up to the time t, and from what has just been stated, the magnitude of Q is indicated graphically by the area between the P-curve and small t-axis (Fig. 5).

We also know, for reasons stated above, that during the entire life history of the petroleum exploitation in any given area, the rate-of-production curve must begin at zero, then rise and pass through one or more maxima, and finally decline ultimately to zero again. When this happens, the total area under the curve will be

$$\int_0^\infty P\,dt = Q_{ult} \tag{3}$$

where

$$Q_{ult} \leq Q_o.$$

Thus, if we have any independent method of determining *apriori* the magnitude of $\underline{Q_o}$, all possible production curves must satisfy the condition that the area under the curve cannot exceed $\underline{Q_o}$.

Application of integral technique to production of crude oil and natural gas in the United States. - In 1956, I employed this technique in an effort to get an approximate answer to the question of present interest. In that case rough estimates were made of the probable order of magnitudes of the ultimate reserves for crude oil in the United States, and for natural gas, based on the assumption of the *efficiency of recovery* being maintained constant at its present value. Starting with the estimate of L. G. Weeks (1948), that the ultimate reserves for the land area of the United States was about 110-billion barrels, I then made an estimate of the possible offshore reserves, and obtained a figure of 17-billion barrels, which was rounded off to 20-billion. Then, on the basis of development which had occurred since the Weeks estimate, it appeared that his figure for the land areas might be as much as 30-billion barrels too low. Adding these three figures, I obtained 150-billion barrels as a rough estimate for $\underline{Q_o}$, the amount of the ultimate reserves of crude oil in the United States producible by present methods.

A similar examination of the gas reserves, based on an ultimate gas/oil ratio of approximately 7500 ft^3 per barrel, led to a figure of about 840-trillion ft^3 which was rounded off to 850-trillion ft^3 to agree with the concurrent estimate of Wallace Pratt (1956, p. 94).

With these two values for oil and gas, respectively, the approximate future production curves for these two fuels were then shown to be those which are here reproduced as Figures 6 and 7. For the case of crude oil, although my own preferred figure was 150-billion barrels; two curves were drawn, one for 150-billion barrels and the second for the more optimistic figure of 200-billion barrels.

The significant results of these two sets of curves were the following:

a. If the ultimate amount of crude oil in the United States producible by present methods is 150-billion barrels, and if we continue to produce with the present efficiency of recovery, the peak of crude oil production in the United States should occur at about 1965.

b. For the same conditions, if the ultimate production were 200-billion barrels, the peak of production would be retarded by only about five years.

c. If the ultimate reserves of natural gas were 850-trillion ft^3, then the peak of production of natural gas should occur at about 1970.

The figures of 150-billion barrels for the ultimate reserves of crude oil, and 850-trillion ft^3 for natural gas, were in substantial agreement with informed industry opinion at that time. Concurrently with my own estimate, Wallace Pratt was engaged in the study of "The Impact of Peaceful Uses of Atomic Energy on the Petroleum Industry", which was published in January, 1956, as a part of the "Background Material for the Report of the Panel on the Impact of Peaceful Uses of Atomic Energy" (v. 2, p. 89 - 105). Pratt's figure for the ultimate reserves of total liquid hydrocarbons (based on a questionnaire sent to twenty-five leaders in the petroleum industry from whom twenty-three replies were received) was 170-billion barrels of liquid hydrocarbons. As a high or optimistic figure, he cited the estimate of 200-billion barrels of crude oil, submitted by DeGolyer and McNaughton. When Pratt's figure of 170-billion barrels of total liquid hydrocarbons is corrected for its content of natural-gas liquids, using the ratio 30/35 of the API estimates of crude-oil to liquid-hydrocarbon reserves, we obtain a figure of 144-billion barrels of crude oil, which is in substantial agreement with my own figure of 150-billion barrels.

Also concurrently with these two estimates, Pogue and Hill (1956) of the Chase Manhattan Bank of New York, were preparing a paper on the "Future Growth and Financial Requirements of the World Petroleum Industry" for presentation on February 21, 1956, before the American Institute of Mining, Metallurgical, and Petroleum Engineers. The Pogue and Hill figure for ultimate reserves of crude oil (p. 24) was 165-billion barrels, and that for natural gas was 750-trillion ft^3.

However, in parallel with Pratt's study of oil and gas reserves, the Department of Interior in a paper on "Impact of the Peaceful Uses of Atomic Energy on the Coal, Oil, and Natural Gas Industries" (Department of Interior, 1956), gives an estimate (p. 83) of 300-billion barrels as the ultimate reserve of oil (whether crude oil or total liquid hydrocarbons not stated) and 1000-trillion ft^3 for natural gas.

My figures of 150-billion barrels of crude oil and 850-trillion ft^3 for natural gas, while lower than the Department of Interior estimates, were in very good agreement with average industry opinion in 1956. However, it was apparently not generally realized in the industry what the implication of reserves of these magnitudes was with respect to future petroleum and natural-gas production. In fact, there appears to have been a complacency which was based on reasoning not greatly different from the following:

The oil industry in the United States has been a thriving industry for almost a century and during that time, only a little more than 50-billion barrels of oil have been consumed, therefore, if we have reserves of 100-billion barrels, this obviously will satisfy all of the nation's needs for the "foreseeable future" and our grandchildren can worry about reserves after that.

The conclusions that follow from the application of the integral technique to these reserve figures appear, therefore, to have been rather disturbing in some quarters of the petroleum industry. The only way, however, in which the conclusion of an early peak in crude oil production can be voided is by making a rather large increase in the estimates of ultimate reserves; and this, in fact, is what has been taking place during the last three years. On April 25, 1957, Hill, Hammar, and Winger, of the Chase Manhattan Bank, presented a new study on "Future Growth of the World Petroleum Industry" before an American Petroleum Institute meeting in Casper, Wyoming, in which the Pogue and Hill estimate of ultimate reserves of crude oil, presented only fourteen months previously, was raised from 165-billion to 250-billion barrels. In 1958, L. G. Weeks, whose original estimate of 110-billion barrels for the ultimate crude oil reserves for the land areas in the United States was increased to 240-billion barrels of liquid hydrocarbons for both the land and offshore areas. When this is corrected for its content of natural-gas liquids, it reduces to approximately 200-billion barrels of crude oil. Also during 1958, Bruce C. Netschert in a study of "The Future Supply of Oil and Gas" arrived at a figure of 500-billion barrels as the future producible reserves of crude oil in the United States, which would correspond to an *ultimate* reserve of about 560-billion barrels. His corresponding figure for the future reserves of natural gas appears to be a little less definite but is in the approximate magnitude of 1200-trillion ft^3, which would correspond to an ultimate production of about 1400-trillion ft^3. Recently, in an article in *World Oil*, Ralph L. Miller (1958) of the United States Geological Survey has estimated that the ultimate reserves of natural gas will probably be between 1150- and 1700-trillion ft^3, of which the upper figure was regarded as being the more probable of the two.

From these examples, it is clear that the estimation of the ultimate oil and gas reserves of the United States has frequently been revised upward with no well-defined limits; nor is it easy to refute any particular figure cited within a range of comparatively wide latitute. In particular, if someone tells me that he does not like my original estimate of 150-billion barrels of crude oil but prefers a figure twice or three times as great, it is no easy matter to show that he is wrong. Consequently, in conducting the present study, I have attempted to re-examine my premises for obtaining the desired information, including the possibility that this earlier figure might indeed be too low. Earlier I had assumed that the methods which had been used by

L. G. Weeks for getting an order-of-magnitude estimate of the ultimate reserves from a combination of geologic considerations, and the petroleum-development history in a given area, was perhaps the best procedure. In fact, this still seems to be the best for setting upper bounds to what may be expected in areas which have had as yet only minor development. However, the fact that Weeks' figure for the United States for 1958, when allowance is made for the offshore reserves, is the order of twice that of his figure for 1948, with both estimates having been made after the industry had reached an advanced state of development, convinces me that the intrinsic reliability of this method is considerably less than I had earlier assumed. If we discount this method, what we have left to examine are the statistical data from the industry itself. It is proposed, therefore, to examine a few of these data without any *apriori* assumptions regarding the magnitude of the ultimate reserves in order to see if we can arrive at some estimate of this quantity from the data themselves.

PREDICTIONS FROM STATISTICAL DATA

Relation between cumulative discoveries, cumulative production and proved reserves. - One such method involves the relationship which exists between cumulative discoveries, cumulative production and proved reserves. If we let Q_D be the cumulative discoveries up to any given time t, Q_P the cumulative production, and Q_R the proved reserves, then, since all the oil that we can claim to have been discovered up to any given time is a sum of the oil that has already been produced plus the oil which has been discovered but not yet produced, it follows then that

$$Q_D = Q_P + Q_R. \qquad (4)$$

The approximate relation between these quantities for a single cycle of growth is shown in Figure 8. Here it will be noted that the curve of cumulative production is similar to that of cumulative discoveries, and has the same asymptote, but has a time lag $\Delta\underline{t}$.

If we take the time derivative of equation (4), we obtain

$$\frac{dQ_D}{dt} = \frac{dQ_P}{dt} + \frac{dQ_R}{dt}, \qquad (5)$$

the separate terms of which represent, respectively, the rate of discovery, the rate of production, and the rate of increase of proved reserves. Then, when proved reserves reach their maximum,

$$\frac{dQ_R}{dt} = 0, \qquad (6)$$

and equation (5) becomes

$$\frac{dQ_D}{dt} = \frac{dQ_P}{dt} \qquad (7)$$

This indicates that at the time when reserves reach their peak, the curve of the rate of production, still on its ascendency, must cross that of discovery which has already begun its decline.

The rates of discovery, production, and of increase of proved reserves for the growth curves of Figure 8 are shown in Figure 9. It will be noted that the peak of discovery precedes that of production by the time interval $\Delta\underline{t}$, and that the reserves reach their peak about halfway between.

Therefore, if we have data on cumulative production and on proved reserves as a function of time, then equation (4) will permit us to compute a curve of cumulative discoveries for the same period. For the petroleum industry in the United States, the American Petroleum Institute, through its Committee on Reserves, has been issuing annually since 1937 an estimate of the U. S. proved reserves. In addition, the statistical staff of the API (API *Petroleum Facts and Figures*, 1950, 1956) have computed estimates of proved reserves from older data as far back as 1900. In addition, statistical data exist on the annual production of petroleum since the beginning of the industry. Therefore, with this information, we can plot curves of Q_P and Q_R since 1900, and by means of equation (4) we can combine these data and obtain the curve of cumulative discoveries, Q_D. These three curves are shown graphically in Figure 10.

In order to determine from these data the magnitude of Δt, we simply lay a piece of tracing paper over this figure and trace Q_D. The paper is then skidded to the right, parallel to the time axis, until the Q_D-curve most nearly coincides with that of Q_P. The results of this operation are shown in Figure 11. It will be noted that since 1920, Δt has had a nearly constant value of 10 - 11 years. With this figure in mind, a study of the cumulative discovery curve and its derivative may then be regarded as constituting an approximate 10 - 11 year preview of the growth of the cumulative-production curve.

The time derivatives of the Q_D- and the Q_P-curves for the crude-oil production in the United States are shown graphically in Figure 12. For the rate of production, dQ_P/dt, the actual year-by-year annual production has been plotted. The same has been done for the rate-of-discovery curve, dQ_D/dt, but this shows, as is to be expected, extremely wide oscillations. In order to avoid these, and to obtain an approximate mean curve of the rate of discovery, the Q_D-curve of Figure 10 has been smoothed with a French curve and then differentiated graphically. The result of this operation is shown by the smoothed

(dQ_D/dt)-curve of Figure 12. From this it will be observed that the rate of discovery of crude oil in the United States passed its peak at about 1952 or 1953, and that the curve showing the rate of discovery, and that showing the rate of production, crossed each other about 1957 or 1958. This also coincides with a peak in the curve of cumulative reserves.

In Figure 13 is shown the corresponding rate of increase of proved reserves of crude oil in the United States. The very jagged curve represents the actual year-by-year increase in the estimated total reserves. The smooth curve, as in the case of the preceding figure, is the graphically computed slope of the reserve curve of Figure 10 after smoothing with a French curve. This figure indicates that the mean rate of increase of proved reserves reached a maximum value of about 0.9-billion barrels per year at about 1946, and that the mean value of the rate of increase of proved reserves has been consistently declining since that date. From the data of preceding years, this curve should cross t-axis at about 1957 or 1958, and, in fact, it is interesting to note that for the first time since 1944 -- a war-time year -- the estimate of proved reserves for the year ending December 31, 1957, was indeed less than that for the preceding year. In view of the wide year-to-year oscillations of the reserve increments, this one point by itself is not significant, but the fact that it is also consistent with the decline of the smoothed mean curve indicates that this negative value is not just a wild point on the curve and that, in fact, the peak in proved reserves should have occurred at about this time.

The peak in the rate of discovery, as shown in Figure 12, and the date of the peak of proved reserves from Figure 13, together, may be used to obtain an estimate of the approximate date at which the peak of production is likely to occur. If we take 1953 for the date of the peak of discovery and add a time lag of eleven years to this, we obtain the date of 1964 for the approximate date of the peak of production. Again, if reserves reached their peak near the end of 1957, and if this peak should occur about halfway between the dates of the peaks of discovery and of production, the peak of production again should occur at about 1963 or 1964. The composite relation of these three curves up to the end of the year 1957 is shown in Figure 14.

Another significant deduction can be drawn from the date of the peak of the rate of discovery as shown in Figures 12 and 14. If we assume that the ultimate growth of both cumulative discoveries and cumulative production in the United States can be represented by a single-cycle logistic curve, then the rate of discovery should be a maximum when cumulative discoveries have reached approximately the halfway point to the final asymptote of the growth curve. Therefore, the total oil discovered in the United States up to the end of 1952 should represent approximately half of the oil ultimately to be discovered. By the end of 1952, the United States' cumulative production of crude oil was 45.3-billion barrels and the API estimate of proved reserves was 28.0, giving for the cumulative discoveries up to that time, 73.3-billion barrels. Then, if we multiply this figure by 2, we obtain 146.6-billion barrels as an estimate of the ultimate amount of crude oil to be found in the United States which is recoverable by current production practices.

We shall have occasion to refer to this figure subsequently.

DATA OF COMMITTEE ON STATISTICS OF EXPLORATORY DRILLING OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

Still another line of evidence concerning the state of evolution of the petroleum industry in the United States is to be obtained from the annual reviews which have been made since 1938 by the Committee on Statistics of Explorator

Drilling of the American Association of Petroleum Geologists on the results of exploratory drilling. In the Committee reports, the fields are grouped into the following classifications according to size:

A. Fields with estimated ultimate reserves greater than 50-million barrels.

B. Fields with reserves from 25- to 50-million barrels.

C. Fields with estimated reserves from 10- to 25-million barrels.

D. Fields from 1- to 10-million barrels.

E. Fields with reserves less than 1-million barrels.

F. Abandonments.

In the more recent reports of the Committee, the estimates of earlier years have been revised on the basis of subsequent development following the initial discovery. In Figure 15 the results of these Committee reports for the years 1938 to 1957 (except for the year 1955 on which no report has yet been issued) are shown graphically. Here fields in categories E and F have been lumped together and the groups in categories A and B have been too small to show graphically. Nevertheless, in this graph it will be observed that, with the exception of the last two years for which enough time has not yet elapsed to provide the desired revision, the discovery of fields less than 1-million barrels (plus abandonments) has been steadily increasing; the fields in the 1- to 10-million-barrel category have been slightly increasing; the discovery rate of fields in the 10- to 25-million-barrel category has remained roughly constant; and the discovery rate of fields over 25-million barrels has been steadily decreasing. This contrast is brought out more clearly in Figure 16 in which separate graphs have been drawn for all fields having less than 25-million barrels of reserves each, and for fields whose initial reserves were greater than 25-million barrels. From this it will be seen that the discovery rate of fields less than 25-million barrels has risen from 200 per year in 1938, to about 750 per year by 1957. At the same time, the fields having intial reserves greater than 25-million barrels have declined from 25 per year in 1938 to zero by 1957. In this curve, as may have been expected, there was a war-time minimum extending from 1939 to 1948, with two lucky post-war years in 1949 and 1950 when the discoveries averaged about 15 per year. Following this the curve dropped sharply to zero. The data of these two curves appear clearly to indicate that the industry has not yet reached its peak in the discovery of fields with reserves less than 25-million barrels each, but that the peak of discovery for fields with reserves greater than 25-million barrels each must have occurred some time before 1938. Regrettably, it is not possible at present to determine the amount of crude-oil reserves which is represented by each of these AAPG categories.

EVIDENCE FROM FIELDS WITH INITIAL RESERVES IN EXCESS OF 100-MILLION BARRELS

Since 1946, the Oil and Gas Journal in its Review-Forecast number has been making an annual statistical summary of the ultimate reserves, cumulative production, and annual production of the fields in the United States whose ultimate reserves are in excess of 100-million barrels. The significance of these fields as a gauge of the progress of the entire industry was pointed out by Kenneth C. Heald in 1950 in an article on "Major Oilfields in the United States and Canada". He showed that the number of these "giant fields" represented only 3 percent of the total of all fields and yet they accounted for 59 percent of the cumulative production. He also plotted a curve of the number of such fields that were discovered during successive five-year periods from 1871 - 1875 to 1941 - 1945, which showed that the peak of such discoveries occurred, with a total number of 28, during the five-year period 1926 - 1930. The graph indicated that the rate of discoveries rose smoothly to this peak and then rather sharply declined.

In view of the outstanding significance of these large fields, the statistics of those occurring in the United States have been examined in somewhat more detail. In Figure 17 there is a graphical plotting of the cumulative discoveries of these large fields from 1870 until the present time. It is seen by inspection that this curve approximates the mathematical logistic curve for a single cycle of growth with remarkable fidelity. The equation of the logistic curve which most nearly fits the actual curve is the following:

$$N = \frac{220}{1 + 28.5e^{-0.109(t-1900)}} \qquad (8)$$

Where N is the number of such fields discovered up to the time t, and e equals 2.718 is the base of natural logarithms, and $(t - 1900)$ is the time in years referred to 1900 as an origin of time. It will be seen from the equation; that as, $(t - 1900)$ becomes very large, the total number of fields discovered, according to this curve, will approach the asymptotic limit of 220. The fields already discovered through 1958, according to the *Oil and Gas Journal* tabulation (January 26, 1959, p. 140), have already reached 210 (which have here been reduced to 207 by combining the Panhandle field of Texas), which indicates that at least for this cycle of discovery we have only about 10 or 15 more such discoveries to expect. It is instructive to observe that the discoveries indicated by this curve represent all of the fields of this class which have been found in the United States from 1859 to date by every method of discovery known, from rank wildcatting to the most precise of modern exploratory methods. It is also interesting that this curve represents the cumulative discoveries in a progressively expanding area of exploration embracing initially the Appalachian region and ultimately the whole land area of the United States as well as the Continental Shelf. Yet, despite these variations in the methods of petroleum exploration and in the progressive extension of the area explored, the curve represents but a single logistic cycle.

The rate of discovery of these large fields is shown in Figure 18 which has been computed by means of a five-year running average. That is to say, each point on the curve represents the average number of discoveries per year during the five-year period of which that date is the midpoint. Superimposed upon the actual discovery rates is the smooth discovery rate computed from the logistic curve in Figure 17. It will be seen that the peak in the rate of discovery occurred at about 1930 or 1931, in agreement with Heald's earlier analysis, and that by now the rate of discovery of these fields has declined almost to zero.

In Figure 19, there is plotted a logistic curve of the estimated ultimate reserves of these fields, referred in each instance to the date of discovery of the field. This curve is also a single-cycle logistic curve in an advanced state of development whose fit to the corresponding mathematical curve is only slightly inferior to that of the cumulative number of such fields shown in Figure 17. In this case, the equation of the logistic curve which most nearly agrees with the actual cumulative discoveries is

$$Q = \frac{56 \times 10^9 \text{ bbls}}{1 + 19.8e^{-0.106(t-1900)}}, \qquad (9)$$

which indicates that at infinite time the ultimate reserves represented by these fields will approach the asymptote of about 56-billion barrels.

In the Oil and Gas Journal tabulation there have been some inconsistencies in the data whereby in some instances the ultimate reserves have been said to represent total liquid hydrocarbons, while, in other instances they have referred explicitly to crude oil. Hence, if the asymptote of 56-billion barrels of ultimate reserves represents liquid hydrocarbons, then the ultimate reserves of crude oil would be slightly less than this amount. Figure 20 shows the rate of discovery and rate of production of the fields greater than 100-million barrels. The time lag here shown is 24 years which is approximately twice that of the total number of fields discovered in the United States.

By the end of 1957, the total United States discoveries of crude oil, as determined by the sum of cumulative production and the API estimate of proved reserves, amounted to 87.8-billion barrels. For the same year, the Oil and Gas Journal figure for the ultimate production of these large fields was 53.6-billion barrels, which leaves only 34.2-billion barrels as representing the ultimate reserves for all of the fields smaller than 100-billion barrels each which had been discovered in the United States up until that date. Thus, the reserves of these 207 large fields represented about 61 percent of all of the oil discovered. The average reserves per field was 259-million barrels.

Total number of fields. - An estimate of the total number of fields that had been discovered up to 1957 can be obtained from the tabulation of producing oil fields in the United States in the volume on "Statistics of Oil and Gas Development and Production" of the American Institute of Mining, Metallurgical and Petroleum Engineers for the year 1956. In this volume, there are listed a total of 20,389 producing oil fields in the various states excluding Pennsylvania, West Virginia, and Ohio. If we consider that Indiana had

239 fields and Illinois 1568, then it is conservative to estimate that Pennsylvania, Ohio and West Virginia together must account for at least 600 fields. Adding these to the figure obtained already gives approximately 21,000 producing oil fields in the United States with a much smaller, but unknown number, of exhausted fields. Then, if these 21,000 fields have an estimated ultimate production of 34.2-billion barrels, this would then give for all less-than-100-billion barrel fields an average size of 1.63 million barrels.

Since the discovery rate of these small fields is still increasing, we evidently have not yet reached the midpoint of their logistic growth curve. If we assume that this midpoint will be within the next few years, then the ultimate asymptote should be of the order of 50,000 fields. The total ultimate reserves for the United States at the present recovery efficiency would then be:

220 large fields	56-billion barrels
50,000 small fields at 1.63×10^6 bbls each	81.5
Total	137.5-billion barrels.

Thus by two independent methods: that of considering the logistic curve of total cumulative discoveries, and that of considering the fields greater than and less than 100-million barrels separately, we are led to substantially the same results. The first method gave a figure of 146.6-billion barrels of crude oil, and the second the figure of 137.5. In the light of this evidence, there appears to be no factual basis upon which an increase in my 1956 estimate of 150-billion barrels, at present efficiency of recovery, can be justified.

Reserves added by improvement of recovery efficiency. - On the other hand, there is no question that the recovery efficiency of oil production can be increased. Techniques of secondary recovery, such as water drive and gas drive, have already been in operation in some areas for more than twenty years, and the same techniques are also widely employed for primary production in many of the fields more recently discovered. The primary production of the East Texas field, for example, is in response to a water drive, and the efficiency of recovery is estimated to be about 80 percent.

What I mainly wish to emphasize is that improved recovery efficiency is not a process that will sharply differentiate the production practices of the future from those of the past. Improved recovery practices are in operation now, although further improvements will certainly be made in the future. Hence, the amount of additional oil that may be expected from fields which would yield 150-billion barrels at present recovery efficiency is necessarily speculative. Nevertheless, a one-third improvement over present practices appears to be a reasonable possibility; and this would yield an additional 50-billion barrels of oil from the same fields. Combining these separate figures, we then obtain as an estimate ultimate crude-oil production of the United States:

Cumulative production to end of 1958	60×10^9 barrels
Proved Reserves	30×10^9 barrels
Future Discoveries	60×10^9 barrels
Oil Added by Improved Recovery Efficiency	50×10^9 barrels
Total	200×10^9 barrels.

These quantities are shown graphically in Figure 21 wherein it still appears that the peak of production will occur somewhere near 1965, but that the rate of decline will be retarded, due to the oil added by improved recovery efficiency, with respect to what it would be were no improvement to occur.

APPRAISAL OF PRESENT OUTLOOK

Having reached the foregoing conclusions, let us now consider the possibility that they may be wrong. In our examination of the data available, the most diagnostic evidence in support of the foregoing conclusions is that afforded by the discovery history of the large fields. By the end of 1958, the number of such fields was 207. Yet these 207 fields have ultimate reserves of 54.4-billion barrels which is 60 percent of the cumulative discoveries of 90-billion barrels for all the fields in the United States. The average size of these fields is 262-million barrels, which is 160 times the average size of the fields smaller than 100-million barrels.

The plot of the number N of these large fields discovered as a function of time, as shown in Figure 17, is accordingly the distilled essence of the history of the exploration for petroleum in the United States during the last 100 years. It was remarked earlier that the number N_0 of the fields of any category is finite, and that after N fields have been discovered, the number remaining to be found is $(N_0 - N)$. In the case of the large fields, the number N_0 is necessarily small. In Figure 17 the plot of N versus time shows that the increase of N with time is in very close agreement with the standard mathematical, single-cycle, logistic growth curve. It shows further than N has already approached its asymptote so closely that the latter may be taken to be 220 fields, with an uncertainty of not more than ± 5 fields. The number of fields remaining to be discovered in this cycle is, therefore, only about 13 ± 5 fields.

The only remaining question is whether the 220-field asymptote represents the total number N_0 of such fields in existence, or whether it is possible that this may represent a temporary asymptote, N_0'. If the first of these two possibilities is the case, then it is apparent we have but 10 - 15 more large fields to discover, after which we are through. If the second possibility is the true situation, and the actual number of large fields is, say, 25 - 50 more than the 220 indicated, then this would imply that there exists a remaining group of large fields which either are not detectible by present exploratory techniques short of drilling, or else occur in positions where drilling would not be recommended in accordance with our present philosophy of where oil ought to occur.

Assuming that a group of such fields does still exist, then the question may be asked: What types of improvement in our exploratory procedures is most likely to lead to their discovery? In answer to this, I think that we can rule out any radical improvement in geophysical techniques -- particularly the seismograph. Our seismographs are already so good that we are finding an ever-increasing number of smaller and smaller fields at greater and greater depths. However, we should not forget that wells are drilled on seismically made maps on the basis of *geological* premises.

It appears, therefore, that of all of our exploratory techniques, the one most in need of improvement, and the one for which the latitude for possible improvement is the greatest, is petroleum geology itself. In making this statement I am reminded of an observation which I made some years ago that may help to convey what I have in mind. At that time, for my own information, I reviewed the history of the development of geological thinking with respect to the occurrence of oil and gas, from the time of the Drake well to the date of the study. As I read the early literature, I was impressed by the lucid thinking and writing of a number of the early pioneers of petroleum geology: H. D. Rogers, T. Sterry Hunt, E. B. Andrews, E. W. Evans, and Alexander Winchell, who together, during the first decade following the Drake well in 1859, formulated the anticlinal theory roughly as we know it now. Then there was the work of I. C. White, and especially the lucid writings of Edward Orton during the consolidation period of the 1880's; and finally, what I am inclined to regard as the golden age of petroleum geology -- the period from about 1910 to 1925, which was illuminated by the provocative inquiries of Chester W. Washburne, Frederick G. Clapp, Alexander McCoy, E. W. Shaw, Van A. Mills and John L. Rich, who were asking the persistent questions: How and where does oil originate? How does it migrate? And, finally, what determines a trap? And then, as I read further, I gained the distinct impression that oil geology, as a field of active scientific inquiry, at least in the United States, died about 1930.

Should we not, therefore, return to those fundamental questions: Where does oil come from? How does it migrate? And what determines its positions of entrapment? However, let our reconsideration of these questions be from the point of view that oil geology pertains to oil, rocks, and water. Should this be done, along with continued attention to structural and stratigraphic traps, there could occur a renaissance in our ability to find oil that would be most heartening to experience.

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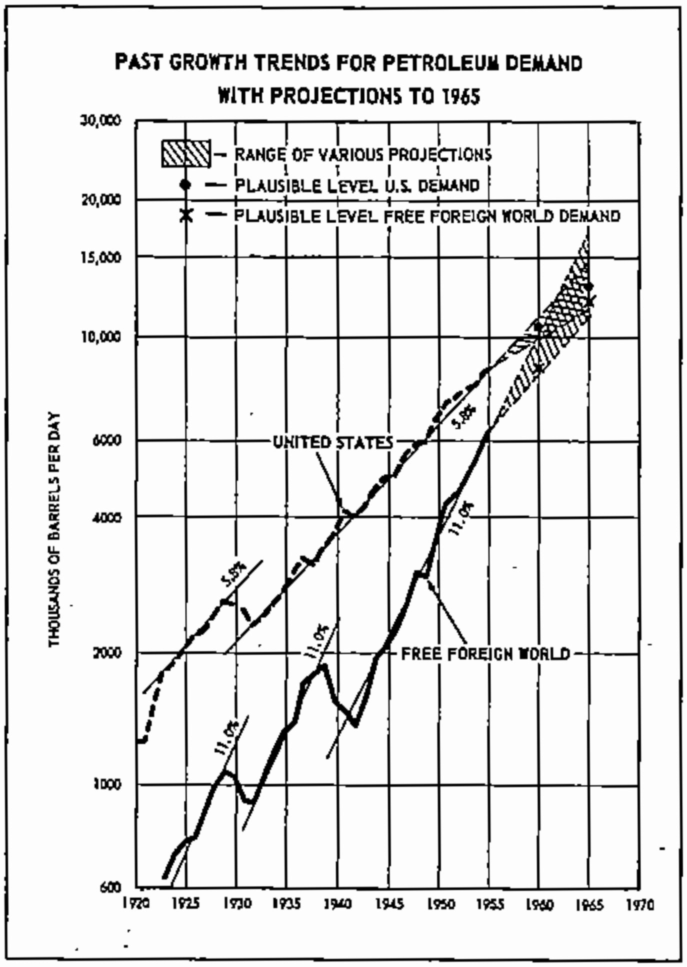

Fig. 1.-An example of prediction by means of trends.
(Pogue and Hill, 1956, Figure 1)

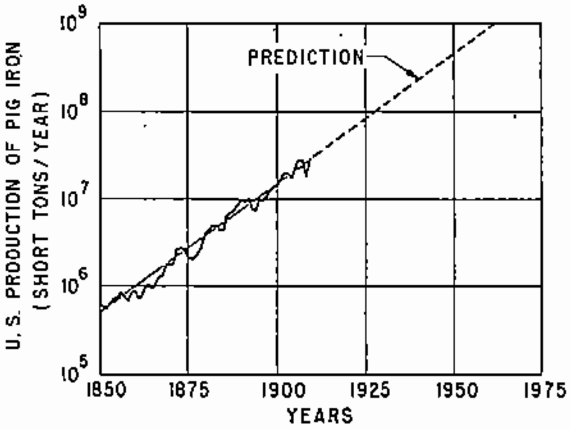

Fig. 2.-The trend of pig iron production in the United States from 1850-1914 and its use for predicting future production.

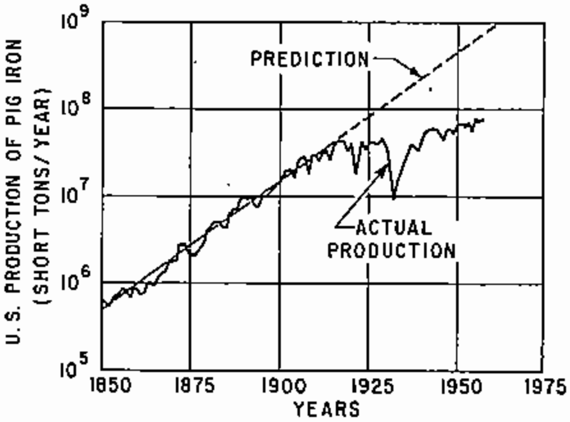

Fig. 3.-What actually occurred in pig iron production.

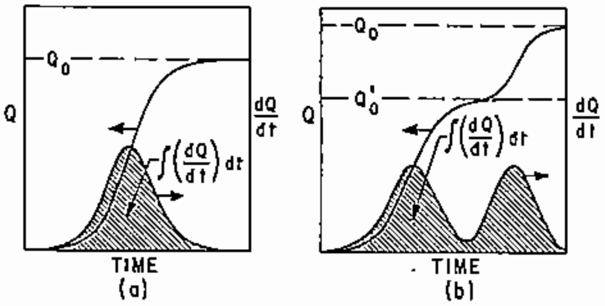

Fig. 4.-Logistic growth curves of cumulative production and their derivitives which give the rates of production.

(a) single-cycle curve
(b) multiple-cycle curve

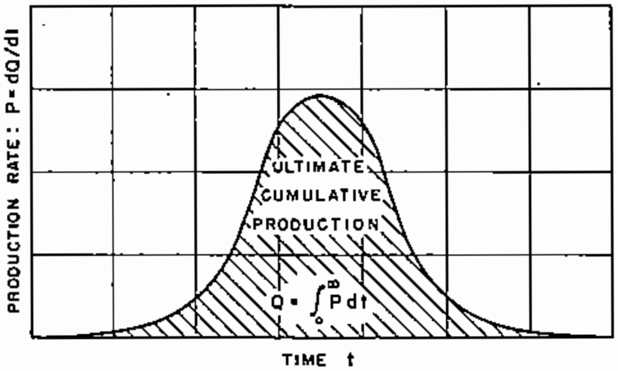

Fig. 5.-Illustration of the integral technique of prediction.

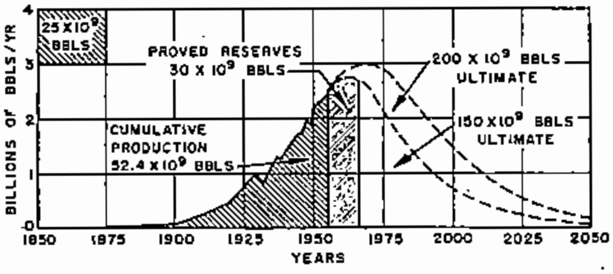

Fig. 6.-Application of integral technique to prediction of crude-oil production in the United States. (Hubbert, 1956, Fig. 21)

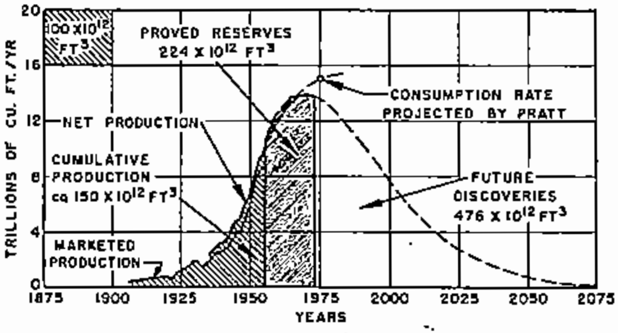

Fig. 7.-Application of integral technique to prediction of natural-gas production in the United States. (Hubbert, 1956, Fig. 22)

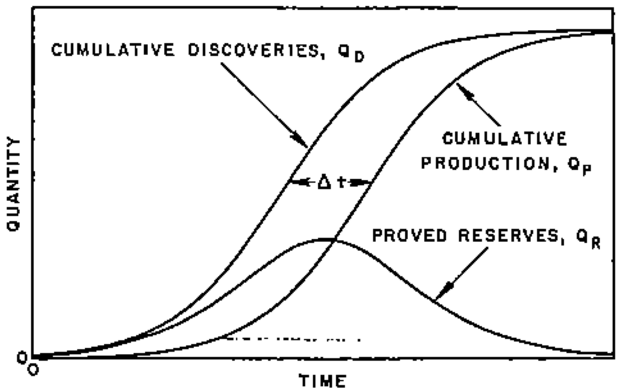

Fig. 8.-Single-cycle growth curves for cumulative discoveries, cumulative production, and proved reserves.

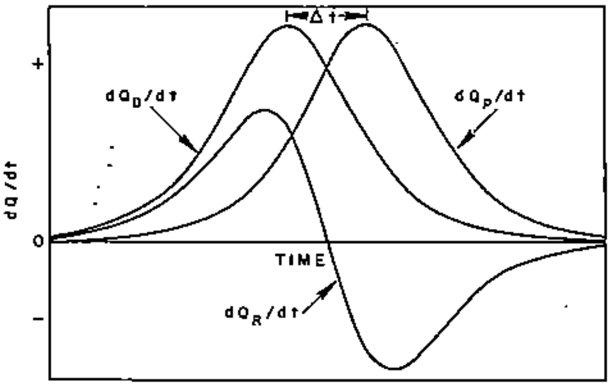

Fig. 9.-Rates of discovery and production and rate of increase of proved reserves for growth curves shown in Fig. 8.

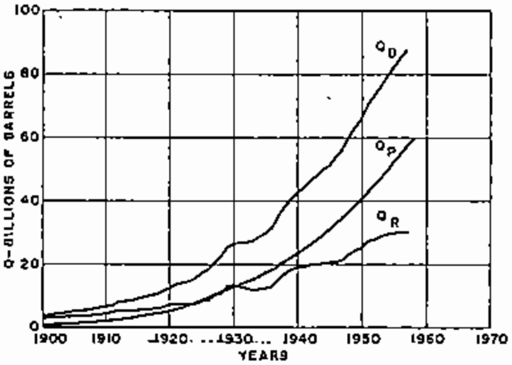

Fig. 10.-Growth of cumulative discoveries, cumulative production, and proved reserves in the United States. (API Petroleum Facts and Figures)

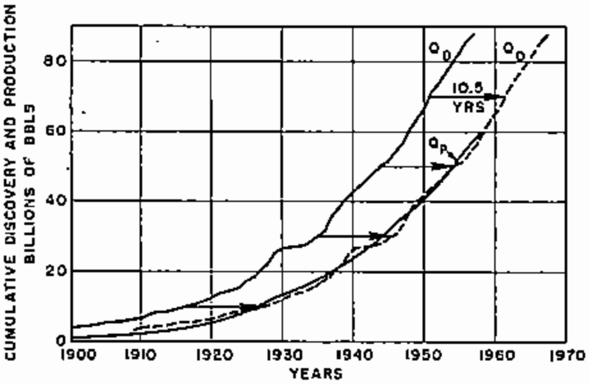

Fig. 11.-Determination of time lag, Δt, of production with respect to discovery of U. S. crude oil.

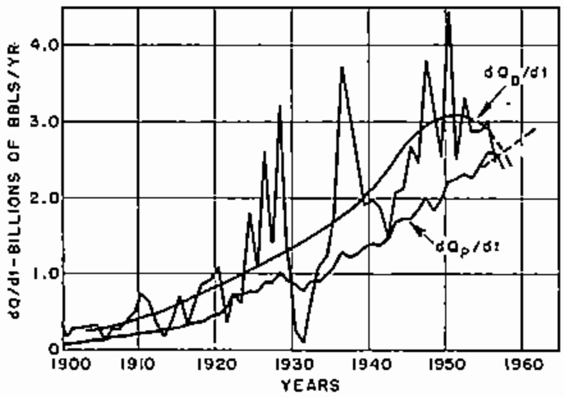

Fig. 12.-Rates of crude-oil discovery and production in the United States.

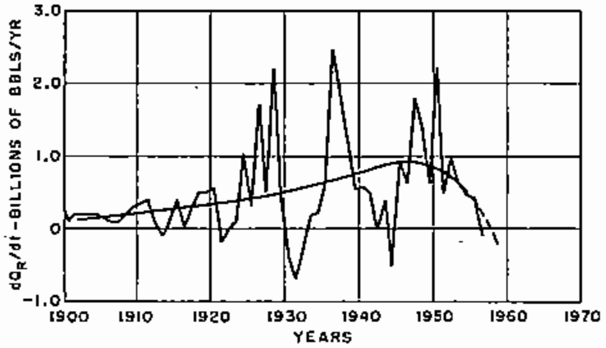

Fig. 13.-Rate of increase of API estimates of crude-oil proved reserves in the United States.

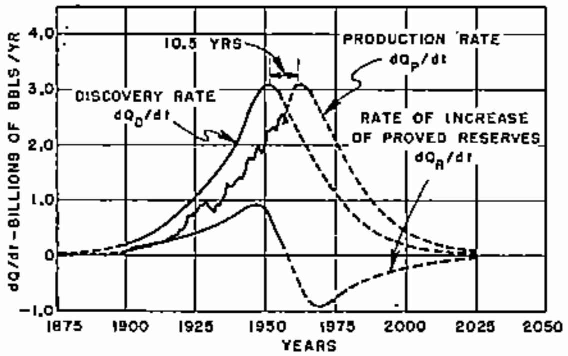

Fig. 14.-Present state of evolution of U. S. petroleum industry as shown by combined graphs of rate of discovery, rate of production, and rate of increase of proved reserves of crude oil.

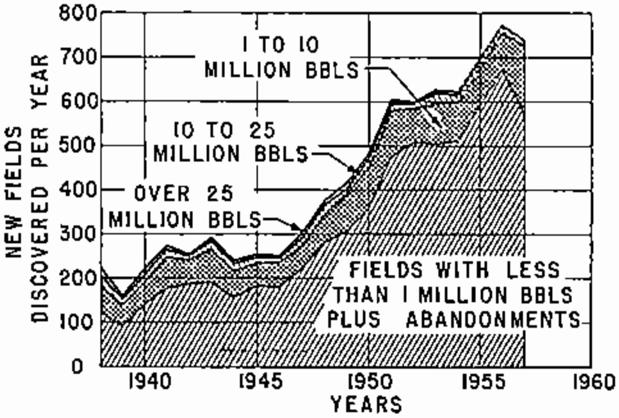

Fig. 15.-Oil field discoveries, 1938-1957.
(AAPG Committee on Statistics of Exploratory Drilling)

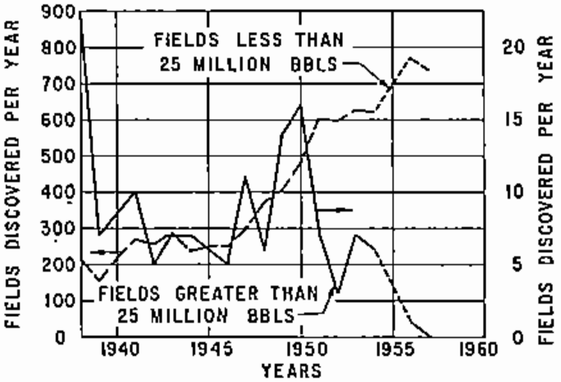

Fig. 16.-Rates of discovery in the United States of fields smaller than and greater than 25-million barrels.
(AAPG Committee on Statistics of Exploratory Drilling)

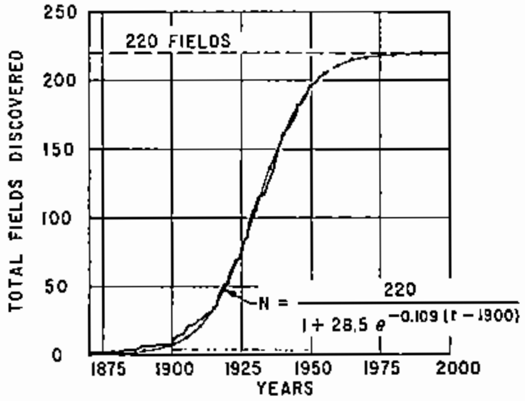

Fig. 17.-Cumulative discoveries of U. S. fields greater than 100-million barrels.

(Review-Forecast issues of
Oil and Gas Journal)

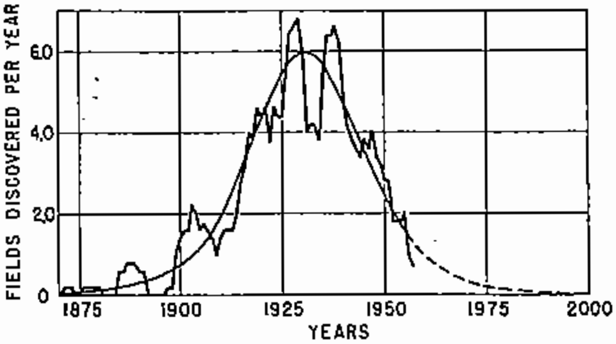

Fig. 18.-Rate of discovery of U. S. fields greater than 100-million barrels.

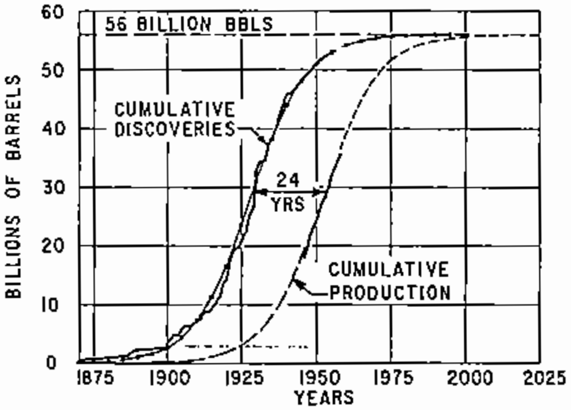

Fig. 19.-Cumulative discoveries and cumulative production of ultimate reserves of liquid hydrocarbons of U. S. fields greater than 100-million barrels.

(Review-Forecast issues of <u>Oil and Gas Journal</u>)

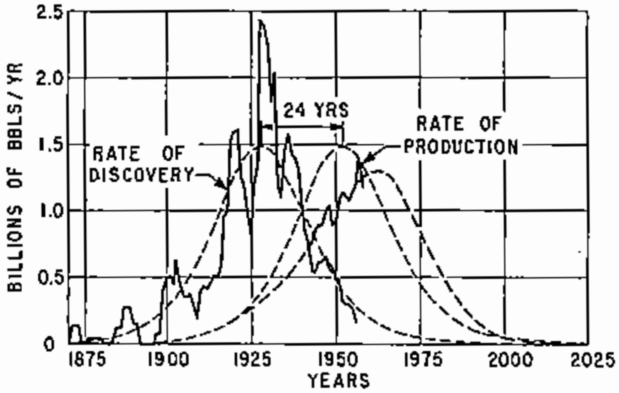

Fig. 20.-Rates of discovery and production of liquid hydrocarbons for U. S. fields greater than 100-million barrels.

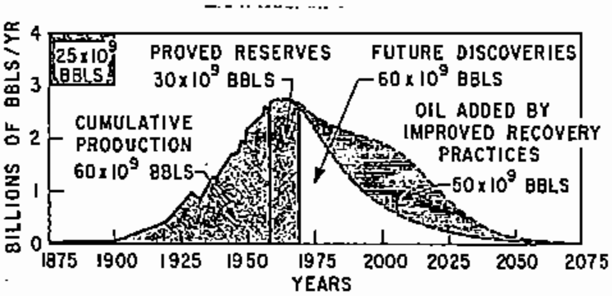

Fig. 21.-Estimate of future U. S. production of crude oil with an allowance for oil added by improved recovery practices.