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Scientific Uses of Random Drilling Models

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Success in petroleum exploration is chancy. In 1973 the chance of discovering an oil or gas field by drilling a wildcat hole in the United States was 1/7 and the chance of finding a million-barrel field or its gas equivalent was 1/54 (*1*). The relative importance of the factors that influence the chance of success has been difficult to evaluate, although it is known that success varies with the system of exploration, meaning the combination of theory and technology, that is used. In this article we develop a simple model of random exploration and apply Monte Carlo methods to generate possible histories of exploration for oil within the land area of the contiguous United States. The actual historical record of exploration is then shown to correspond in general form for long periods to a random search using a system of exploration with relatively constant effectiveness. The correspondence between the model and history suggests that the powerful tools of probability theory can be useful in analyses of future success in exploration, volume of petroleum reserves, and other matters of deep national concern. The beginnings of a probabilistic analysis of some aspects of petroleum exploration are presented here.

Model of Exploration

The model is based on the following assumptions: in a region of area S there is a fixed total amount of oil in undiscovered fields; the fields have a total horizontal cross-sectional area F and are located within the region by fixed, although not necessarily known, size and spatial distributions. One means of locating the oil is conducting a purely random search of the region. This method, after infinite effort, certainly locates the oil present and can be used as a standard for exploration success at intermediate times.

The probability P of discovering oil in a single unit of random search effort, a single drill hole, is

$$P = F/S$$

where F is the area of potential success (undiscovered oil) and S is the area of possible search. Measured in area per search effort, the rate at which F decreases is the same as the rate at which oil is discovered. The rate of discovery is, in turn, directly proportional to the probability of discovery. In mathematical terms, this leads to the differential equation

$$\frac{dF}{dE} = -k_1\frac{F}{S}$$

where E is search effort. Approximating S as constant, the equation has a solution of the form

$$F = Ae^{\frac{-k_1}{S}E}$$

an exponential relationship having a number of powerful and convenient properties. A similar result can be derived for an explicit class of equal-sized oil fields. Let N be the number of undiscovered fields, all of equal area f, distributed as in the previous case over the area S. The probability of discovery is

$$P = \frac{Nf}{S}$$

the rate of discovery, in terms of number of oil fields, is

$$\frac{dN}{dE} = -k_2\frac{f}{S}N$$

and the solution is

$$N = N_0e^{-k_2\frac{f}{S}E}$$

The exponential relationship has several mathematical implications. First, all derivatives and integrals are also exponential, differing only by a constant factor; rates and totals can be calculated. The rate of discovery is then

$$\frac{dN}{dE} = -N_0k_2\frac{f}{S}e^{-k_2\frac{f}{S}E}$$

and N_0k_2f/S is the initial rate at the time of N_0 undiscovered fields. Second, the exponential implies that with equal effort a constant fraction of the remaining undiscovered fields will be found. Third, exponential data, when plotted on a semilogarithmic graph, will fall on a straight line, the slope of which is proportional to the exponent factor. Fourth, that exponent factor consists of two parts. The first, k_2, is the number of trials in a unit of effort, equal to unity if the unit effort is the single drill hole. The second part is the probability of finding a specific single oil field, f/S. This is the relative target cross section, or R, the relative size of a single target compared with the entire search area. Finally, N_0, the initial number of undiscovered oil fields, is a fixed constant. In terms of the rate of discovery, the integral of that rate over effort must be the same constant. In graphical terms, the area beneath the curve for rate plotted against effort is that constant.

There are two broad directions in which the mathematical model may be applied. One is to the direct problem of assigning values to the variables and calculating a result for comparison or prediction in the real world. This entails selecting values of numbers and sizes of oil fields and the area being searched for the prediction of discovery rates. The other is the inverse problem, using the historic trends of discovery and exploration to assign values to the parameters. In particular, the value of R, combined with a discovery rate, can be used to estimate total undiscovered oil.

Two units of exploration effort are used in the ensuing discussion, the Hubbert unit (HU), 10^8 feet of exploratory drilling (*2*), or our own measure, 10^7 feet of new field wildcat drilling for oil (1 foot ≈ 0.3 m). Rate of discovery refers to the number of fields or area or volume of oil discovered per unit of exploration effort. Slope refers

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to the change in rate of discovery per unit of exploration effort. Specifically, on a semilogarithmic graph, this slope is directly proportional to R. Clearly, this is also a measure of the fraction of remaining oil fields discovered with each additional effort.

By comparing the R of a specific technology with that predicted for a random search, success of the technology can be numerically evaluated. Effective technology will be more successful than random search in locating undiscovered oil and will thus have a larger $R = f/S$. This can be interpreted as reducing the area of search or as enlarging the targets. In either case, the relative target cross section is increased. A numerical comparison of two technologies can be made by dividing the R's of the technologies by the R's of the equivalent random searches.

The effect of a hypothesis or technology reducing the search area includes the possibility of excluding oil along with search area. Such a situation will be called a partially exclusionary hypothesis, such as searching only the white squares of a chessboard when, in fact, some fraction of the targets lies on the black.

Economics dictates the lower thresholds of field size and discovery rate—that is, when a field is too small or too hard to find to be economically productive. This article does not deal with economic fluctuations, but the model allows for calculating the difference in total recovery by varying technologies.

With a history of changing technologies, there are a number of possible configurations of slope and rate as well as transitions from one to another. Since the slope is related to f/S, one would expect different slopes for different size classes, the smaller classes having the lesser slopes. Likewise, a change from a less effective to a more effective technology should cause an increase in both rate and slope. There are possible configurations which conflict with the simple model and would point to such things as a partially exclusionary hypothesis. One such configuration would be a transition to steeper slope, indicating an increase in relative target cross section (effectiveness) without a corresponding increase in rate.

The effect of combined technologies, two different systems operating in the same region but analyzed in terms of the individual systems, would be additive and would produce inconsistent rates and slopes. In this case the individual rates would reflect the relative effectiveness of the particular technologies, while the slope would reflect the decline in undiscovered fields due to the discoveries of both methods. The region, considered as a whole with both technologies acting as one, would conform to the model. If, however, one of the competing technologies is operating under a partially exclusionary hypothesis, an abnormally low rate would be expected, since only a fraction of the total population is being targeted. Another effect would be to improve the effectiveness of a competing random search by eliminating some of the search area, thus improving the relative target cross section. The net effect would be transition from steep slope to that of random drilling as the more effective technology operating under an exclusionary hypothesis completes its search and thus depletes the undiscovered fields available to it.

In the following sections the history of oil exploration in the United States is examined toward two ends, testing the model and analyzing history in terms of the model. Since historic records have been conveniently broken down into size classes, the analysis is by class and in terms of the specific model dealing with numbers and rates.

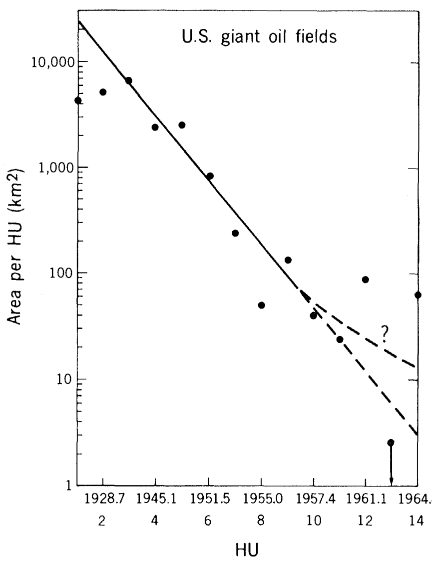

Fig. 1. Area of all giant oil fields discovered per Hubbert unit in the land area of the 48 contiguous United States. The trend is uncertain where lines are dashed. The upper dashed line is more consistent with data from other sources (*5*).

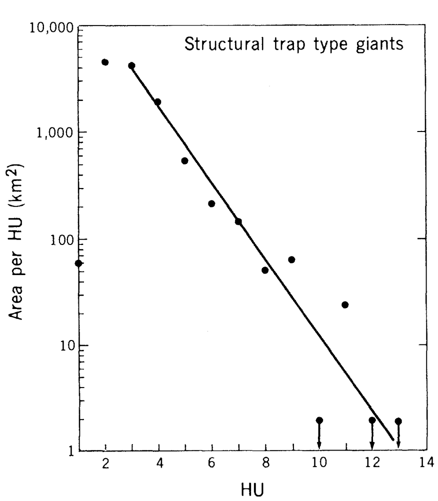

Fig. 2. Area of the structural trap type of giant oil fields discovered per Hubbert unit in the land area of the 48 contiguous United States.

Tests of the Model

Hubbert (*2*) states that the number of barrels of oil discovered per 10^8 feet of exploratory drilling has declined approximately exponentially. This conclusion is confirmed by analysis of the history of exploration for different sizes and types of oil fields by different methods. The American Association of Petroleum Geologists (AAPG) classifies oil fields by size in millions of barrels as follows: A, greater than 50; B, 25 to 50; C, 10 to 25; D, 1 to 10; E, less than 1; and F, wells originally completed as new productive fields but abandoned within the year. In addition, fields larger than 10^8 barrels are commonly called giants. The area, volume, and date and mode of discovery of giant oil and gas fields in the United States have been compiled by Halbouty (*3, 4*). Our initial analysis is restricted to giant oil fields within the land area of the 48 contiguous states in order to have a coherent population and constant area. During the period of the first three Hubbert units the system of exploration changed rapidly and the rate of discovery increased (Fig. 1). However, from 1937.4 to 1956, the rate declined exponentially from 6800 km^2/HU to an average of about 100 km^2/HU. Evidently during this period the major factors that influenced the success rate were those included in the probability model. This relationship is even clearer if the population is limited to giant structural traps, which have a smaller range of sizes than the quite different stratigraphic traps (Fig. 2).

The probability model also predicts both the decline of success in finding smaller oil fields during the period from 1945 to 1966 (*1*) (Fig. 3) and the fact that the rate of decline (slope) tends to diminish with field size.

Some of the factors that influence the chance of success in drilling can be isolated by consideration of the discoveries per unit effort of different modes of discovery. With regard to giant oil fields, discovery by surface seeps was most successful in the first Hubbert unit and declined exponentially to near zero four units later (Fig. 4). Surface geology had a peak of success during the second Hubbert unit and approached zero five units later. The success of subsurface geology and geophysics peaked in the third Hubbert unit and declined exponentially to near zero four and five units later, respectively. The slopes of the curves are essentially the same for all methods but the maximum rate of success was achieved by surface geology—the first application of science to exploration. Thus, each method of discovery was equally successful in sampling a dwindling population of giant oil fields. Each method quickly found the fields that it was capable of finding. Each group of fields successively approached exhaustion until about 1950, when none of the methods of exploration had any more cream to skim. At that time an inflection in the discovery rate curve occurred, and since then it has declined very slowly because giant discoveries are few.

The rate-of-discovery curves for smaller oil fields also tend to be inflected in the 1950's, although the amount of the inflection decreases for smaller field sizes (Fig. 3). For classes C and D it appears that the transition is gradual, which can be interpreted according to the probability model as indicating that two systems of exploration—for example, random and scientific—were operating simultaneously. Indeed, the inflections in these curves give strong evidence that in the 1950's the system of exploration for oil in the land area of the 48 contiguous states decreased markedly in average effectiveness.

In this analysis we have lumped all industry together for lack of appropriate data to make a separation. However, there are striking differences in the operations,

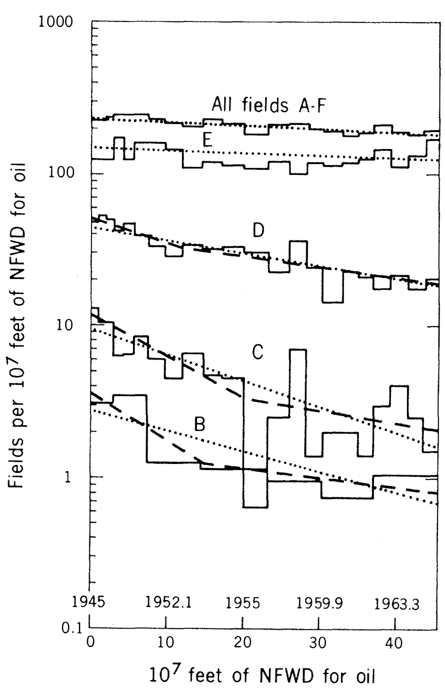

Fig. 3. (Solid lines) Number of fields of different sizes discovered per 10^7 feet of new field wildcat drilling (NFWD) for oil in the land area of the 48 contiguous United States. (Dashed and dotted lines) Interpretations of trends.

success, and possibly even goals of exploration systems in use by major and independent oil companies and investment funds (*5*). This can be seen in the fact that from 1969 to 1973 the independents drilled 22,792 new field wildcats and the majors drilled only 2,770 (*1*). A significant difference is also shown by the discovery rate, in that the independents required 46.6 wells to find one new field while the majors needed only 19.4 wells. The contrast is even more striking when the size of the fields is considered, because the independents found most of the little fields and the majors found most of the big ones. Thus, although the majors drilled only roughly 10 percent of the wells, they found roughly 60 percent of the oil. It is possible that part of the change in the rate of discovery in the 1950's reflects an increase in the proportion of drilling by independents, as the majors were beginning to obtain cheap foreign oil in increasing volume.

Success of Exploration

It is possible to calculate the probability of the actual history of oil exploration and compare it with other possible histories. Thus, a technique exists for determining the success of exploration systems, comparing them with purely random drilling.

In order to make a comparison it is necessary to know the discovery history of a class of oil fields, the total area being explored, and the total area of the fields. The last of these is the most difficult to assess with reasonable accuracy. Two pertinent bodies of information are available. The area of giant oil fields is given by Halbouty (*3*) and the trivial rate of discovery at present indicates that this closely approximates the total area. For smaller fields, the discovery rate can be extrapolated to infinite effort to give the total number, which can be converted empirically to area or volume.

We begin with the discovery of giant fields (Figs. 1 and 2). Halbouty's data were reorganized to give the history of discovery per Hubbert unit by area (and volume). Thus it was established, for example, that the 3947th through 4048th square kilometers of giant fields discovered were in the Midway-Sunset field in California. A computer was programmed to simulate random search in a total area of 4,700,000 km^2 (*6*) for a total area of giant oil fields of 23,455 km^2. Numbers were selected between 0 and 4,700,000 according to a random number generator. If one was selected between 0 and 23,456, it was printed in the output. A Hubbert unit was taken to be 20,000 tries, equivalent to 20,000 wildcat holes 5,000 feet deep. The printout identified a particular square kilometer of oil field discovered by a random hole, and this could be related to a particular oil field of known area and volume by comparison with the reorganized historical data.

The historical record is that the first Hubbert unit discovered 4.6×10^9 barrels of oil with an area of 4,100 km^2. The average of ten computer runs equivalent to the first Hubbert unit was 22.7×10^9 barrels and 13,780 km^2, with a range between 17.5×10^9 and 26.0×10^9 barrels and 12,600 and 14,600 km^2. The random search was four to five times more successful than the early gropings of the oil industry. The only substantial error in the calculation lies in the simplifying assumption that each well was 5,000 feet deep and thus that a Hubbert unit included only 20,000 wells. This is a fair approximation for the more recent Hubbert units after the fourth, but the average depth of the first unit may have been only 500 feet (*2*). If so, the first Hubbert unit included 200,000 exploratory wells; the computer program would have discovered much more oil with the additional tries. There is a compensating fact in that, historically, some fields were discovered by holes deeper than average, perhaps even deeper than 5,000 feet. However, the larger fields were discovered by the computer repeatedly on each run. Many would have been found by reducing the number of holes and varying the depth randomly within a desired range. With these uncertainties, the program was left unchanged, although it appears to be biased in favor of history.

The reason that random drilling is relatively successful is that the probability of finding giant fields is quite high because many have a large area. For example, historically the largest field by far, East

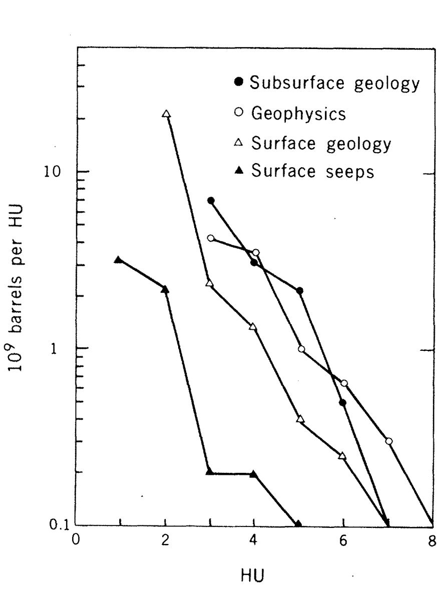

Fig. 4. Rate of discovery of giant oil fields per Hubbert unit by mode of discovery.

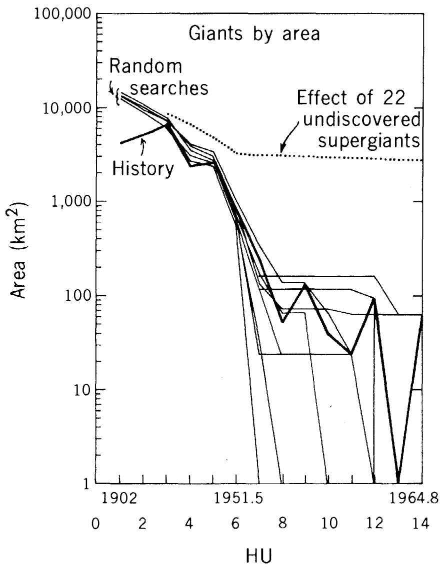

Fig. 5. Historical rate of discovery of giant oil fields, by area, compared with ten random searches for the fields historically remaining at the end of each Hubbert unit. If 22 extra supergiant fields exist, the probable average discovery rate of random searches would exceed the historical record 50-fold.

Texas, was not discovered until 1930, in the third Hubbert unit. On nine of ten runs the computer program found the 5.1×10^9 barrels of East Texas by 1902, in the first Hubbert unit, because the area of 567 km^2 is so large. Indeed the probability is

$$1 - (1 - \frac{f}{A})^n = 0.91$$

where f is the area of the field (5.67×10^2 km^2), A the area of U.S. sedimentary basins (4.7×10^6 km^2), and n the number of holes per Hubbert unit (2×10^4)—or just nine to one in favor of finding in a single Hubbert unit.

The historical procedures of the American oil industry clearly were not favorable to the discovery of large oil fields, although that might be thought of as the objective. Perhaps it was not entirely chance that even in the historical record the East Texas field was discovered by random drilling. Very roughly 300,000 exploratory holes had already been drilled in the sedimentary basins of the United States. The probability of not finding this field with that many random tries is 2×10^{-16}. There are many possible explanations for this bad luck. The important point here is that exploration systems are not uniformly successful in achieving different objectives. What may be reasonable and traditional for some times and objectives may be quite irrational for others.

The random searches of a computer in successive Hubbert units may be compared with history in two useful ways. One procedure is to determine what a random search finds in the first Hubbert unit and reset the program to search for what remains in each successive unit. In some ways a more interesting approach is to reset the computer program after each Hubbert unit by subtracting the area discovered historically during that unit. This approach makes it possible to see how closely the discovery of giant fields corresponds to a random search for the targets that were still undiscovered at a given time. Ten computer runs have been compared with history (Fig. 5). All were far more successful than history in the first and second Hubbert units. By the third unit, ending in 1937.4, the historical rate of discovery was just what would have been achieved by a typical random search. From then on history did not differ significantly in its rate of discovery from a random search. Sometimes, as from 1937.4 to 1945.1, it was in the lower range of discovery rates and at other times, such as the early 1950's, it was on the high side, but it was always within the range of the computer runs.

This whole history can be viewed in terms of the mode of discovery. In the earlier years, when the mode was principally by random drilling, seeps, and surface geology, the rate of success did not match the computer. The introduction of subsurface geology and geophysics as the dominant modes of discovery managed to bring the success rate up to what would have been achieved by random sampling.

In terms of oil volume rather than oil area, historical discoveries compare more favorably with chance targeting (Fig. 6). During the period from the first to the fifth Hubbert unit, 1902 to 1948.9, the historical discovery rate was greater than that of any of the ten random searches and as much as twice their average. Before and after that period, however, the historical successes were within the range of the random searches.

In historical perspective, the American oil industry has had mixed success in finding giant oil fields. With regard to finding the less prolific giant fields with large areas, it has never been as successful as an average random search. With regard to the more prolific giant fields with small areas, its actual targets, it was more successful than any of ten random searches during the period when geology and then geophysics was used to find a still abundant population. Since then it has been only slightly more successful than the average random search. The high point of the search for giant fields was in the fourth Hubbert unit, when the volume of oil discovered was more than twice the average volume found in ten random searches, even though the area found was less than average. That was a period when a profusion of 100- to 200-

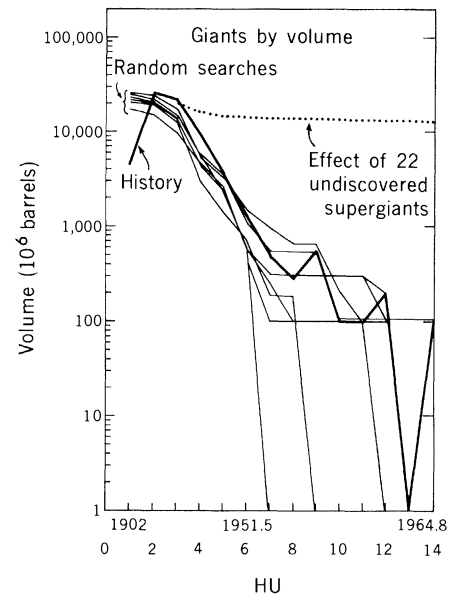

Fig. 6. Historical rate of discovery of giant oil fields, by volume, compared with ten random searches for the fields historically remaining at the end of each Hubbert unit. If 22 extra supergiant fields exist, the probable average discovery rate of random searches would exceed the historical record 50- to 100-fold.

million-barrel fields were found over salt domes in Louisiana, which were precisely and easily located by geophysics. In such circumstances the industry did far better than average random drilling. Otherwise it did not.

The effectiveness of exploration systems in finding nongiant fields can be assessed provided the total number and average size of fields in each class and the area of search are known. Consistent data on historical discoveries of all sizes of fields are available from 1945 to 1966 (Fig. 3). The population as yet undiscovered in 1966 can be determined by extrapolating the discovery rates to infinity. The remaining unknowns are the number and size distribution of fields discovered before 1945, which can be estimated, perhaps only crudely, from analysis of other rate curves. The curve for "wildcat producers" (*1, 7*) is roughly parallel to that for giant fields during the critical interval from 1945 to 1955. The rate of discovery per Hubbert unit for the total and for each class of field can be adjusted to the total number of fields discovered before 1945 and an approximation of the giant field and wildcat producer data. Combining all the estimates from time zero to infinity gives a population of 243 giants (approximates class A); 449 class B; 998 class C; 4,700 class D; and 42,100 class E (Table 1). The larger the fields the earlier the median field was discovered.

The relationship of volume to area of oil fields in the Denver-Julesburg Basin, Colorado, is known (*8*), and a similar relationship can be constructed for the dead or moribund oil fields of California from the data of the California Division of Oil and Gas (*9*). The average for the two regions reasonably approximates the expected relationship that area varies as the volume (V) to the 2/3 power. However, the range of sizes in each class is very large (Table 1).

The area of all nongiant fields in the contiguous United States can be estimated by subtracting the area of giant oil and gas fields from the total area of all sizes. When the remainder is compared with the size-frequency distribution for nongiant fields, it appears that the class sizes of the Denver-Julesburg Basin are a reasonable approximation of those in the whole United States.

The remaining uncertainty is the area being searched, and in 1945 and later this is taken to be 2,600,000 km², the most explored and most productive area of sedimentary basins (*10*).

A computer program incorporating the data on number, target size, and area of search was used to make the same random searches as for giant fields. Numerous combinations of number and target size were investigated and printed out in terms of number of discoveries per search unit. Some of the results appear as averages in Fig. 7, which compares some of these computer searches with history.

For class B fields, the average slope of the historical success curve is steeper than that for any of the computer searches. This indicates that industry has been more successful than random search in finding this class of field. However, there appears to be an inflection in the curve, and the slope after about 1950 is within the values for random searches for fields the size of the California or Denver-Julesburg ones. The slope corresponds to a random search for fields with an area of 11.7 km². Industry has already found most class B fields (Table 1).

The discovery of class C fields bears about the same relationship to a random search as that of class B fields. The average slope indicates far greater effectiveness than random drilling, the population has been depleted, and the inflected slope indicates effectiveness only slightly greater than that of a random search since 1955. The class D and class E fields are not so depleted. For class D, the inflected slope is hardly steeper than that for a random search, and yet the discovery rate is at least twice that of the most successful type of random search. Perhaps the inflection is not real and the slope remains constant. If so, the population will be depleted relatively rapidly.

The record for class E fields is that the

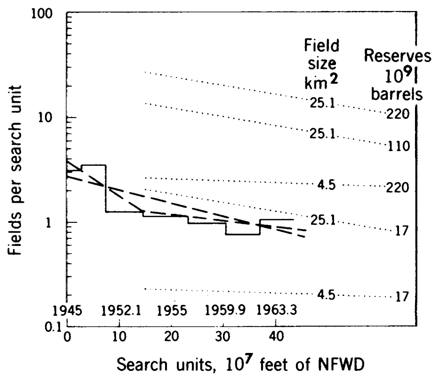

Fig. 7. Historical discovery rate of class B oil fields compared with random searching for different total populations (reserves) and field areas. (Solid line) Historical discovery rate. (Dashed lines) Two interpretations of the historical trend. (Dotted lines) Average discovery rates for random computer searches.

slope of the discovery rate curve is constant and steeper than for a random search. The remaining population is a large fraction of the original one, and therefore the effective industry is about 70 times as successful as ineffective random searches.

In sum, for oil fields of classes B to E, actual oil exploration has been more effective than a random search. Its successes have effectively depleted not only giant fields but also class B and C fields. Smaller fields are not so depleted, and they are located by industry far more successfully than by a random search.

Undiscovered Oil Fields and Reserves

There are at least five different methods of estimating the volume of undiscovered hydrocarbon resources (*11*). One of the methods was pioneered by Hubbert (*2*). Extrapolating the historical data on the rate of discoveries per exploration unit according to the equation of change in the rate, he determined that in 1966 the undiscovered recoverable oil in the United States, including the continental shelf but exclusive of Alaska, was 71×10^9 barrels. Essentially the same method is used here, but with the refinement that the distribution of oil field sizes is also determined.

Although the giants are mainly gone and the intermediate fields are following, a very large number of small fields remain undiscovered. However, infinity is a long time to explore for oil, and it may be worthwhile to examine the more modest discoveries predicted for drilling 140 more units of 10^7 feet of new field wildcat holes. At present rates that would be the year 2020 and, by exponential extrapolation of the uninflected rate of discovery curves, 14,300 fields will have been discovered. Very few class A or giant fields will be discovered; in the other classes the numbers discovered will be: B, 21; C, 41; D, 890; and E, 13,400. The numbers are not too different for the inflected curves in this brief interval.

Converting the area or number of fields to volume of recoverable oil involves considerable uncertainty. For the older discoveries Hubbert (*2*) calculates a multiplier of 5.8 to the estimates of new discoveries at the end of the first year to obtain the ultimate amount recovered including secondary recovery and field extensions. For 1959, however, the increase after 6 years was only 20 percent, and a reevaluation of all AAPG data since 1943 indicates that after 9 years the original estimates were good within +60 percent and -30 percent (*12*). In recent years the original estimates have tended to be high (*13*), which further complicates the problem. These inconsistencies are the result of some combination of actual increases of oil discovered and differences in methods of estimating volumes. The analyses of the data used here in predicting the number of undiscovered fields indicate that the average of the volumes as originally estimated is essentially correct, particularly for the smaller fields, which will predominate in the future.

The accepted average size in the year of discovery for various classes of fields is expressed in millions of barrels as follows: B, 37; C, 17; D, 3; and E, 0.13. Accordingly, the undiscovered reserve of oil in new fields in the land area of the contiguous United States lies between 14×10^9 barrels, indicated by the constant decline curves, and

Table 1. Size-frequency distribution of oil fields discovered in 1945 to 1966 and estimated equivalent distributions from the beginning to the end of exploration.

Class	Number of fields				Area (km²)		
	Before 1945	1945–1966	1967– ∞	Total	Denver-Julesburg	California	$V^{2/3}$
A (giants)	211	32	Few	243+			
B	328	64	57	449	25.1	4.5	10.5
C	690	196	112	998	13.4	2.8	6.2
D	2,240	1,324	1,140	4,700	3.6	1.0	1.9
E	5,150	5,828	31,100	42,100	0.6	0.2	0.4

17×10^9 barrels, indicated by the inflected curves. About two-thirds of the oil is in class E fields, which are not considered economically significant.

It is difficult to obtain estimates of undiscovered reserves which are completely comparable to those given here because offshore and Alaskan areas are usually added to the past and future discoveries in the United States, and oil and gas equivalents are not separated. However, there are two recent estimates of the amount of oil and natural gas liquids still undiscovered in the land area of the contiguous states. One, by Mobil Oil Co., is 13×10^9 barrels and the other, by the U.S. Geological Survey (USGS), is 110×10^9 to 220×10^9 barrels (*11, 14*).

If the overall prospect for domestic oil discoveries appears bleak, the economic prospect is far bleaker. This is because two-thirds of the oil is in class E fields. Moreover, not all the oil can be found in less than infinite time, and eventually it will become uneconomic to preserve the exploration systems just when they need to be expanded to continue successful searching. Consider no farther ahead than the 1980's. Probable discoveries in that decade are 10 class B, 21 class C, 210 class D, and 2200 class E fields. The probable annual rate of discovery is about 2×10^8 barrels, which is equal to only a few weeks of consumption even at present rates. This small quantity will be concentrated in minor fields that are relatively difficult to find and expensive to develop. Accelerated drilling could bring a surge of successes at any time compared to these estimates, but it would only hasten the end.

Trade-off Between Exploration Success and Quantity of Undiscovered Reserves

The probability theory of oil exploration provides a trade-off between the discovery rate of an exploration system and the quantity of undiscovered oil. This makes it possible to determine the implications of seemingly unrelated estimates about resources.

Consider, for example, the specific hypothesis of Moody *et al.* (*15*) that in 1968 25 to 28 supergiants of 5×10^8 barrels or more remained undiscovered in North America. The undiscovered fields are assumed to have sizes that are spread throughout the range of known ones larger than 5×10^8 barrels and to be evenly distributed within the regions where the known ones have been found. Accordingly, there were 22 undiscovered supergiants with an average area of 168 km^2 in the land area of the contiguous United States. If so, the computer program should be adjusted to add 3700 km^2 of oil fields to the total remaining after each Hubbert unit. At first this makes little difference, but as the undiscovered fields of the historical record decrease, the hypothesized addition looms ever larger. By the end of the fourth Hubbert unit the average random search would be about three times as successful as history (Figs. 5 and 6). After the eighth unit in about 1955, a random search would be roughly 50 times more successful than the oil industry.

The implications can also be determined by calculation. The probability of discovering one of these giant fields by random drilling is 3,700 km^2 divided by 2,600,000 km^2, where the denominator is the area of the more promising and better explored sedimentary basins. Thus the chance of discovering one field with a single random hole is about 1/700. In order to obtain a fifty-fifty chance of finding some field it is necessary to drill only 488 holes. A total of 57,200 holes would give a fifty-fifty chance of finding all of them. In terms of a Hubbert unit drilled not just to 5,000 feet but to 10,000 feet per hole, the chances are about a million to one in favor of finding at least one field. These calculations lead to two plausible conclusions that are compatible with the fact that new giant oil fields have not been discovered since 1968 at the indicated rates: either the hypothetical oil fields do not exist, or the system of exploration is drilling in the wrong places. This second possibility has been seriously advanced by several eminent experts on petroleum exploration. Hubbert (*16*) refers to a decline in the ability to find oil fields as "in part the result of our inflexibility with regard to our geological ideas concerning where oil *ought* to be found. In fact, it is entirely possible, physically, that a large class of undiscovered fields may exist which, on the basis of present geological premises, would be discovered only by accident or not at all." Halbouty (*3*, p. 1150) proposes that many stratigraphic traps can be found "but only if geologists direct these methods and their thinking *toward* them, not around them. Only by looking *purposely* for such traps will giant fields continue to be found."

Another example of a trade-off is based on the USGS estimates of undiscovered oil reserves. The volume of oil in undiscovered fields of classes B to E as of 1945 has been calculated. To this is added the excess of the USGS estimates over the present estimates of reserves in 1974. Volume is directly convertible to area, and the new area is distributed in some way among the classes. Consider classes B and C after a division of the additional oil in proportion to future discoveries per class (Table 1). The average area of the undiscovered fields is taken to be equivalent to that of the same class in the Denver-Julesburg Basin. If the reserve remaining in 1974 was 220×10^9 barrels, a random search beginning in 1945 would have found about 20 times more class B fields than were found. Even with the minimum estimate of 110×10^9 barrels, a random search would have discovered oil at ten times the historical rate. If the undiscovered fields in each area are the same size as the discovered ones, or even as small as those in California, the estimates of the USGS require that the oil industry since 1945 has been much less successful in finding class B fields than a random search. The same conclusion follows from analysis of class C fields.

Perhaps the extra oil is not proportionally distributed among the classes but is instead concentrated in smaller fields which industry is less apt to seek. Assume that the excess is divided equally between classes D and E. If so, a random search beginning in 1945 would still have been more successful than the historical record. Perhaps all the oil is in class E fields. Once again, history fails to match a random search.

According to the probability model of exploration, an exploration system can be less successful than chance only if it contains some flaw that causes it to deliberately search in the wrong places. The trade-off is that either the USGS estimates are unrealistically large or the oil industry has gone astray for the last quarter of a century.

Conclusions

Successful oil finding is influenced by chance as well as social, economic, scientific, and technological factors (*17*). The history of success in petroleum exploration in the United States indicates that for long periods most of the factors have tended to balance each other and statistical fluctuation and progressive depletion of a finite resource have been the dominant variables.

An industrial exploration system is aimed at targets which could also be hit without aiming. Thus, the success of the system is determined not by its discoveries but by how much it exceeds what might have been achieved by random drilling. Judged by the historical record, industry has been successful in finding small targets but less so in finding large ones. The most plausible explanation of this is that industry has selectively, if inadvertently, aimed at the small targets. This, in turn, reflects in some way the factors that influence the exploration system.

The goals of the exploration system are

also complexly determined; certainly they have never been limited to just finding oil. At the minimum the target had to be conceived as a commercial quantity of oil, under a property controlled by the producer, and recoverable at a rate that gave an appropriate return on capital. With those goals it might be entirely reasonable for an exploration system to aim at small targets. However, quite different goals now exist in the world. The governments of many large countries are not concerned about the location of an oil field because they control all the mineral rights anywhere in the country or in some region such as the continental shelf. Likewise a quick return on capital may not be as important as an inventory of energy resources to serve as a guide for national policy. With these changing goals in mind, it may be appropriate to reconsider the relevance of the exploration systems which have brought the discoveries of the past. An apparently venturesome fractional investment in a search for subtle giant stratigraphic traps (*3*) or hydrodynamic ones (*16*) may actually be a prudent course for many large countries. The mean random search of the sedimentary basins of the United States would have discovered more than 227 barrels of oil per foot of exploratory drilling for the first 10^8 feet. Venturesome scientific targeting, such as drilling on a grid, might be comparably successful in a relatively undrilled large country or region.

The future for oil exploration in the land area of the contiguous states appears relatively bleak. With existing exploration systems, a search effort will discover less and less. A significantly improved technology, if one can be devised, will meet with increased success briefly but will only hasten the exhaustion of domestic reserves. Moreover, about two-thirds of the oil undiscovered by existing exploration systems is probably in small traps which are difficult to target. In the United States, therefore, there will be a growing need for ever more detailed and exhaustive searches. Presumably there will also be need for more and more earth scientists until the expanding exploration becomes economically or energetically profitless.

The methods we have used in this study predict that the undiscovered reserves of oil in new fields in the land area of the contiguous states are only 14×10^9 to 17×10^9 barrels, about the same as the Mobil Oil Co. estimate. Moreover, at present rates of drilling the discovery rate in the 1980's will average only 2×10^8 barrels per year. This is equal to a mere few weeks of consumption even at present rates. The methods permit an evaluation of the probability of much larger reserves as predicted by the USGS. If the large reserves exist, the petroleum industry is far less successful than it would be if it just drilled holes at random. This is only possible if the exploration system has inadvertently been designed to search in what are now the wrong places. A similar analysis of a hypothesis that many giant fields remain undiscovered leads to the same conclusion. With regard to national energy policy, most of the undiscovered oil of the future probably can be expected only from Alaska, the continental shelf, or imports.

There is one possible basis for optimism, namely the hypothesis advanced by some geologists that the oil industry is no longer searching in the right places. If the decline curves merely apply to an exclusionary hypothesis, they give little information about the reserves in the area being excluded. With the data available to us we are unable to test this idea by separating the decline curves for random and aimed targeting but we believe that it may be possible to do so.

References and Notes

1. F. J. Wagner and C. F. Iglehart, *Am. Assoc. Pet. Geol. Bull.* **58**, 1475 (1974).
2. M. K. Hubbert, *ibid.* **51**, 2207 (1967).
3. M. T. Halbouty, *ibid.* **52**, 1115 (1968).
4. ———, in *Geology of Giant Petroleum Fields*, M. T. Halbouty, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1970), p. 1.
5. We are indebted to D. A. White for documenting these differences.
6. The area is that of outcrops of sedimentary rocks in the 48 contiguous United States according to I. H. Cram [in *Future Petroleum Provinces of the United States—Their Geology and Potential*, I. H. Cram, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1971), vol. 1, p. 1]. The computer knows just enough geology to avoid drilling outcrops of igneous or metamorphic rocks.
7. F. H. Lahee, *Am. Assoc. Pet. Geol. Bull.* **29**, 620 (1945); W. E. Pratt, *ibid.* **21**, 697 (1937).
8. J. J. Arps and T. G. Roberts, *ibid.* **42**, 2549 (1958).
9. *Calif. Div. Oil Gas 58th Annu. Rep.* (1972), p. 61.
10. T. A. Hendricks, *U.S. Geol. Surv. Circ. 522* (1965).
11. W. F. Lovejoy and P. T. Homan, *Methods of Estimating Reserves of Crude Oil, Natural Gas, and Natural Gas Liquids* (Resources for the Future, Washington, D.C., 1965); Committee on Mineral Resources and the Environment, *Mineral Resources and the Environment* (National Academy of Sciences, Washington, D.C., 1975).
12. E. L. Dillon and L. H. van Dyke, *Am. Assoc. Pet. Geol. Bull.* **42**, 2549 (1958).
13. C. F. Iglehart, *ibid.* **56**, 1145 (1972).
14. In a press release of 7 May 1975 the USGS reduced its estimates of the undiscovered, recoverable oil by about two-thirds and applied probability limits to the significance of the estimates.
15. J. D. Moody, J. W. Mooney, J. Spivak, in *Geology of Giant Petroleum Fields*, M. T. Halbouty, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1970), p. 8.
16. M. K. Hubbert, *Am. Assoc. Pet. Geol. Bull.* **50**, 2517 (1966).
17. For a probabilistic analysis of the factors that have influenced exploration in the Powder River Basin of Wyoming, see L. J. Drew, *U.S. Geol. Surv. Bull. 1328* (1974), p. 1; *U.S. Geol. Surv. J. Res.* **3**, 169 (1975).

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