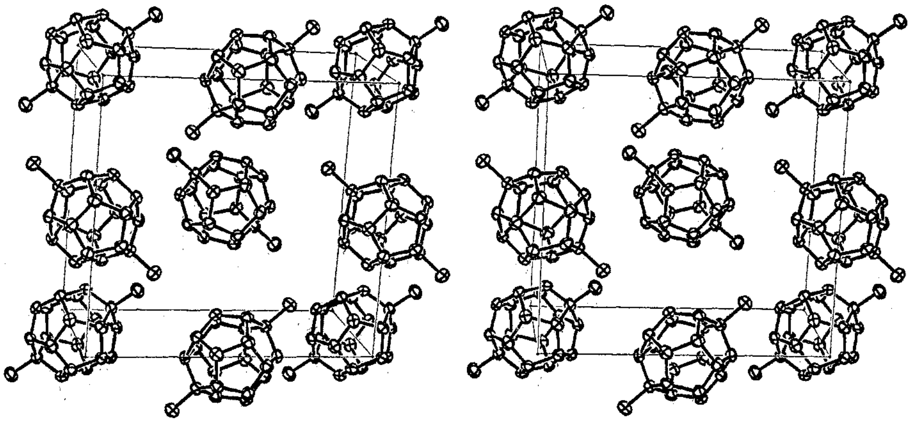

Fig. 2. Stereopair drawing of the crystal packing of **2**, viewed down the x axis.

squares and Fourier techniques (*12*). Atomic coordinates for all carbon and hydrogen atoms, anisotropic thermal parameters for the carbon atoms, isotropic temperature factors for the hydrogen atoms, a scale factor, and a secondary extinction parameter (*13*) were all refined in the last least-squares cycles. The current reliability index R for all 1918 reflections used in the refinement is 11.4 percent, while that for the observed data (> 3 standard deviations above background) is 5.6 percent, consistent with the large proportion of weak intensities. A difference Fourier synthesis shows no peaks greater than 0.2 $e^-/Å^3$, and the most significant of these are localized in the bonding regions between carbon atoms.

The structure of the molecule is illustrated in the ORTEP diagram on the cover and the molecular packing arrangement is shown in Fig. 2. The carbon-carbon and carbon-hydrogen bond distances of the dodecahedral cage that are related by the noncrystallographic $\bar{3}$ symmetry axis average to 1.546(2) (*14*) and 0.98(1) Å, respectively. The molecule possesses essentially perfect D_{3d} symmetry, although of the point symmetry operations, only a center of inversion is enforced by the crystal symmetry. Either because of induced rehybridization of C-1 and C-16 by the methyl substituents or because of steric crowding between the methyl and neighboring hydrogen atoms, there is a slight elongation of the molecule in the direction of the $\bar{3}$ axis. Although not particularly evident in the bond distances, this distortion from pure dodecahedral symmetry is apparent in the < 108.0° bond angles surrounding the methyl-substituted carbon and by the slight nonplanarity of the flanking five-membered rings. The elongation is most clearly evident in the transcavity distance between symmetry-related pairs of atoms: 4.389(4) Å for C-1 to C-16, but 4.327(1) Å for the remaining nine pairs of dodecahedral carbons. Taking account of the van der Waals radius of carbon (*15*), the transcavity diameter is only 0.9 Å, too small for encapsulation of any but the smallest ions.

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24 December 1980

Petroleum Drilling and Production in the United States: Yield per Effort and Net Energy Analysis

Abstract. *For the past three decades the quantity of petroleum (both oil and oil plus gas) found per foot of drilling effort in the United States for any given year can be expressed as a secular decrease of about 2 percent per year combined with an inverse function of drilling effort for that year. Extrapolation of energy costs and gains from petroleum drilling and extraction indicates that drilling for domestic petroleum could cease to be a net source of energy by about 2004 at low drilling rates and by 2000 or sooner at high drilling rates, and that the net yield will be less at higher drilling rates.*

Production and reserves of U.S. liquid and gaseous petroleum peaked in the early 1970's and generally have declined since then despite considerable increases in drilling effort. Continued increases in effort are likely in the near future because imports carry a heavy economic and political price and because recent increases in oil prices have given petroleum corporations considerable quantities of new working capital. But the Carter Administration and Congress have imposed a large "windfall profits tax" on petroleum corporations, which will decrease the capital available for additional exploratory effort. On the other hand, oil industry advertisements and some politicians have promised large new exploratory efforts and oil supplies if government decreases regulation and

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taxation of the industry. Finally, some geologists have been telling us for years that not very much new oil will be found no matter who does or does not regulate what. Clearly, an important question for this nation is to what degree we should increase drilling effort and to what degree such an increase would achieve the goal of finding additional new oil.

Fortunately, the statistical behavior of certain aspects of the industry as a whole has shown several regularities that make it possible to analyze past trends and, for the courageous, to make predictions. The principal proponent and practitioner of statistical approaches to analyzing the production history of the industry has been Hubbert (*1*), who has documented the very large decline in the rate at which new oil was discovered per foot of exploratory drilling as exploratory effort was expended over time. He found that in the early 1930's some 250 barrels of oil were found per foot of exploratory drilling as compared to about 40 barrels per foot in the 1950's. Hubbert extrapolated these observations to predict that discovery rates would continue to decline, and that the ultimate yield of petroleum from the lower 48 states of the United States would be from 150 to 200 × 10^9 barrels. He refined his analysis in successive publications, but all his later estimates have agreed reasonably well with his initial estimates made in 1956 and with the historical behavior of the petroleum industry. During the 1960's, however, there was a stabilization and even an increase in the rate at which petroleum was found per foot of exploratory well drilled, so that Hubbert's analysis appeared to some to be no longer applicable (*2*). This stabilization gave encouragement to those who thought that large new quantities of conventional petroleum would be found in the continental United States, since the increase in drilling effectiveness could be attributed to the many improvements in geophysical theory and technology that had occurred in the petroleum industry. During the 1970's, however, the ratio of petroleum found per unit of drilling effort fell to levels at and below those of the 1950's.

Our analysis is a revision and extension of the classic Hubbert analysis, based on the returns of petroleum per total drilling effort as a function of both time and drilling effort at any point in time. The inclusion of the effort component (that is, the number of feet drilled in any 1 year) is important because, as developed below, the variable success rate of drilling for any given year can be expressed simply as Hubbert's secular downward trend (as the resource is depleted over time as a function of cumulative effort) coupled with an inverse linear relation to drilling effort. Such a relation between yield and effort has been observed for copper (*3*) and for fish (*4*), and it is similar to the familiar economic concept of diminishing returns.

Our analysis, straightforward in principle, is constrained by the nature of the available data base, which was developed for purposes not closely related to the present analysis. It is possible to modify the data base slightly so that our requirements are met. Estimates of drilling effort, subdivided according to exploratory footage and development footage, are given yearly since 1925 (*5, 6*) (Fig. 1a). "Additions to proved reserves" also are available for each year, subdivided according to "new field" (NF), "new pools in old fields" (NPOF), "revisions" (REV), and "extensions" (EX). Our analysis is complicated by the fact that about 80 percent of the oil added to reserves comes from REV and EX rather than from NF and NPOF. Most REV and EX are confirmed through development drilling (D_d) rather than exploratory drilling (D_e), since D_d adds to the information base on a known field and adjacent regions in years subsequent to an initial discovery and gives concrete measurements of actual reserves. Because we are interested in total gains (additions to reserves) related to total drilling effort, we use the ratio

$$\mathrm{YPE} = \frac{\mathrm{NF + NPOF + REV + EX}}{D_d + D_e}$$

where YPE is yield per effort in barrels per foot (*7*). In a sense the use of this ratio overestimates the effort used to find petroleum since some of that effort was solely for production, but it does give a running average of the total effort used to bring new petroleum to society, and this relation is appropriate for both our later yield versus effort and our cost versus yield analysis (*8, 9*).

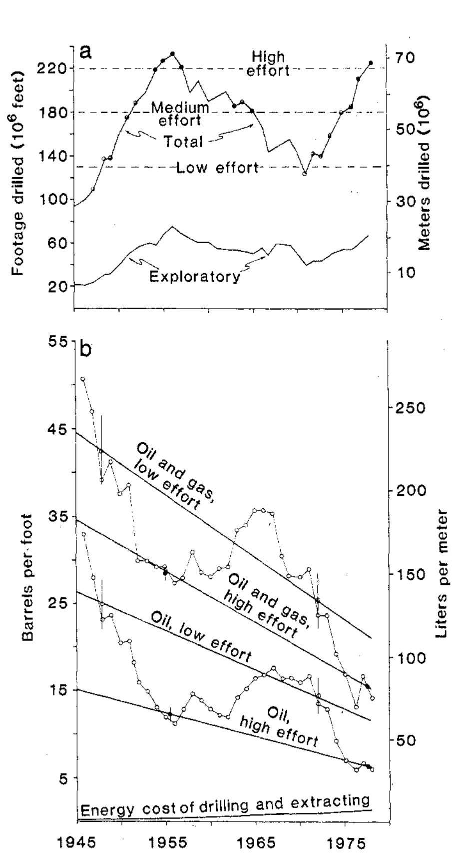

Fig. 1. (a) Rates of drilling for the U.S. domestic petroleum industry. Open circles represent years of low effort, half-filled circles years of medium effort, and filled circles years of high effort. (b) Gains and costs of petroleum exploration and development for the United States, 1946 through 1978. The energy content of gas used and found was converted to barrels of oil equivalents (5680 cubic feet of gas = 1 barrel of petroleum). The topmost irregular line is annual yield per effort for oil plus gas, the middle irregular line is annual yield per effort data for oil alone, and the bottom line is the mean energy cost of exploration and development per foot drilled that year. Vertical bars and associated points are the variance (where possible) and mean of years of low and high effort as per (a). The four straight sloping lines are the least-squares fits of all low-effort and all high-effort data to a linear regression (*11*).

Figure 1b shows the relation of YPE for oil, and oil plus gas, for the years 1946 through 1978. For both oil and oil plus gas, periods such as the late 1960's, when the finding rates were high relative to the general secular trend, were characterized by relatively low drilling effort. Conversely, periods such as the mid-1950's and late 1970's were characterized by high effort and low yield as compared to the secular trend. One can see the relation of yield and drilling effort more clearly if the points in Fig. 1a are connected for all years with high effort (about 220 × 10^6 feet per year), all years with medium effort (about 180 × 10^6 feet per year, not plotted for clarity), and all years with low effort (about 130 × 10^6 feet per year) as they have occurred at various times since 1946 (*10*) (Fig. 1b). The results of these analyses indicate that there has been an approximately parallel decline in finding rates per effort for high, medium, and low rates of effort, and that the actual yield per effort for any year is an inverse function of both the year (and hence the depletion of reserves left to be found) and the drilling effort for that year. In other words, the important trends of the year-to-year yield per effort for both oil and oil plus gas can be expressed as a secular decrease of about 2 percent per year in the rate of petroleum added to reserves per foot of drilling effort and an increase or decrease of about 5 percent for each million feet of lesser or greater effort. This conclusion is further supported by a multiple regression analysis of data points for both all oil and all oil plus gas (1946 through 1978), which confirmed ($P < .01$) that YPE is both decreasing with time and, at all times, is a decreasing function of effort (*11*). In this regression model the secular trend explained about 52 percent of the variation among all oil data points, the effort component explained another 40 percent, and only about 8 percent of the total variation was unexplained by either time or effort (*11*). For oil plus gas the corresponding percentages are 63, 82, and 18 percent, respectively, although a squared term for effort improves the fit, indicating the importance of effort. The only significant deviation between the linear model and the data occurs for the late 1960's, a time of relatively low effort: about 20 percent more gas was found than predicted.

There are two ways in which our analysis fails. First, when we include the previously excluded Prudhoe Bay find (the largest field ever found in the United States and a very atypical find), the YPE for oil and oil plus gas jumps to, respectively, 80 and 120 barrels per foot for 1968, and the associated R^2 values, as defined in (*11*), drop to about .05 (no effort) and .22 (with effort), respectively. Although the last 200 wells drilled in Alaska have been essentially dry holes (*12*), Alaska as a whole still has a YPE since 1965 of some 1580 barrels of oil per foot.

The second way in which our analysis fails is that our estimates of YPE for 1979, based on the data for 1946 through 1978, and the linear time and effort components used for our initial analysis, were low, predicting only 16 percent of the additions to oil reserves reported and 64 percent of the oil plus gas found in this high-effort year. There are three possible reasons beyond a statistical quirk. First, we may be, in fact, becoming more clever at finding oil. Second, we may have explored more new petroleum provinces in 1979 than in the past. Third, because of the increased value of oil relative to the cost of finding it, there were economic incentives for upgrading previously known, but previously uneconomic, low-quality fields to the status of reserves. This upgrading process took place in 1979 with a portion of the Kern River field (discovered in 1899), whose "revision" in 1979 was a large contributor to the additions to reserves reported in 1979.

The principal reason for the secular decline in petroleum finding rates appears to be that we are no longer locating many of the relatively rare large petroleum fields that historically have been the largest additions to reserves. Since there are about 2.5×10^6 petroleum wells in the United States, there is not much room left between boreholes in sedimentary rock for many of the very large fields that take up many tens to hundreds of square kilometers (*9*).

Why should YPE be related to effort? This makes sense for fish, as the fish can recover through reproduction and growth when not fished. Petroleum, obviously, cannot recover, at least on time scales of interest to our species. One possible explanation is that, when drilling rates are low, the petroleum industry drills at locations where present information suggests that success is most likely. During years of high drilling effort, additional drilling is done at other, less likely locations. Presumably relatively inexpensive petroleum-finding theory development, seismic charting, and interpretation occur at a more constant rate than drilling effort, so that when drilling effort (that is, economic incentive) is low, it is concentrated in areas where success appears most likely. When drilling effort (and economic incentive) is high, much of that effort is directed at additional targets less likely to produce a large find. In a sense it is promising but untested geologic information that is depleted as wells are drilled and that accumulates in the absence of drilling. The decrease in drilling rates after 1956 is associated with the inauguration of government taxation policy that decreased the profitability of finding oil. Had that not occurred, our present finding rates probably would be considerably lower than they are now. Other possible explanations are that since 1974 much of the increased effort has been concentrated in mature, well-known fields where chances of some success are great but the chances of large new discoveries (and hence large additions to proved reserves) are very low, or that less efficient drilling companies contribute a higher percentage of all drilling when economic incentives are high.

The principal use of petroleum is as fuel, and the oil exploration-extraction and refining industry (taken together) is the second most energy-intensive industry in the United States. The time at which domestic petroleum will no longer, on the average, be a net fuel for the nation is not when all the wells run dry but rather at some point before that time when the energy cost of obtaining a barrel of oil is the same as the energy in that barrel. The cost is, at a minimum, a running average of the energy cost of drilling a foot of petroleum well and delivering the petroleum found by that drilling to society. Comprehensive statistics on the economic activity and the energy use of the petroleum exploration and development industry are available (*13*), from which we were able to calculate the energy cost of drilling and extraction. A quantity of energy equivalent to about 1½ barrels of petroleum was used per foot of drilling by the petroleum exploration and development industry in 1977, slightly more than half directly as fuel and the rest as fuel to produce the equipment and services used. This energy use has been increasing in recent years (see Fig. 1b) as the petroleum industry has drilled increasingly to greater depths, at offshore locations, and in hostile environments such as Alaska, and as a larger percentage of petroleum is produced as a result of energy-intensive secondary and tertiary recovery. An additional 0.4 bar-

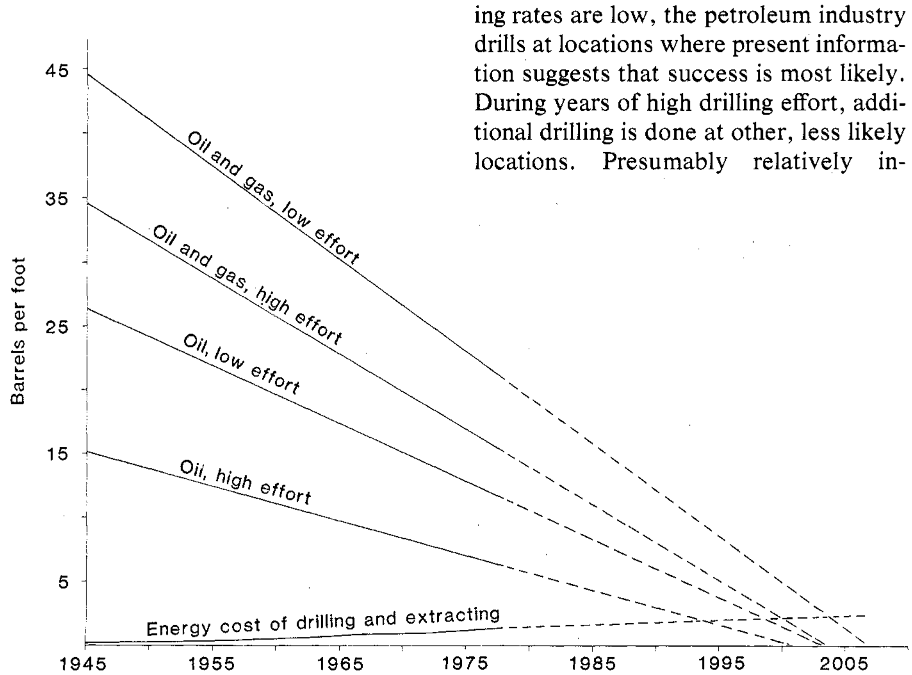

Fig. 2. Linear extrapolations (dashed lines) of energy gains and energy costs of Fig. 1 for high and low drilling intensity. Solid lines are from Fig. 1b. The inclusion of Prudhoe Bay finds into this extrapolation would extend the time of intersection by about 6 years.

rel equivalent per mean foot was used in 1977 for refining petroleum but was not included in Fig. 1b.

We have extrapolated linearly the trends in energy cost and energy gained as a function of drilling intensity (Fig. 2). If we were to decrease drilling rates to a low level of 130×10^6 feet per year, the lines would intersect in 2004. Were we to continue to drill at the 1978 levels of about 200×10^6 feet per year, the linear extrapolations would intersect in 2000. For oil alone, we could reach the break-even point within about a decade. An extrapolation of the rate of increase in the drilling rate that occurred from 1971 to 1978 indicates that the break-even point for oil could occur in the mid-1980's.

One might question our linear extrapolation, for certainly other finding rates may characterize the future. The assumption of linearity is most strongly supported by the remarkably parallel least-squares fit of all four lines in Fig. 1b and by the very high correlation coefficients associated with the analysis. It is, of course, possible that generic changes in the oil industry would make some other line (such as an asymptotic decline) a better fit 30 years from now, but that possibility cannot be supported now on the basis of existing data.

In our analysis we assume that the first derivative of changes in the petroleum industry's exploratory and development methods remains constant. There could be significant deviations from the projections of Fig. 2, if, for example, new provinces (such as the Bering or Chukchi Sea, very deep sediments, or overthrust belts) were explored differently from past years. Most remaining new petroleum provinces will be very energy-intensive to exploit, and so intensive new province drilling could work to either increase or decrease the time until the intersection of the energy costs and gains. But it is only from such unexplored areas that we reasonably can expect to find the very large oil fields that are necessary if a change in the sharply downward trend of the YPE in Fig. 1b is to occur. One possible conclusion from our analysis is that it might be advisable to do most exploration only in new provinces. A somewhat similar conclusion was reached by Menard and Sharman (*9*).

Most domestic oil (and presumably gas) that is now produced comes from reserves discovered before 1940 (*14*). We see little hope for changing this picture very much through increased conventional drilling effort, and in fact such effort could decrease the total energy delivered to society by the petroleum industry by lowering the efficiency of that energy-intensive industry. Integrating the extrapolated regions of Fig. 2 for the period from 1980 to the intersection of the energy cost and gain lines gives a projected ultimate additional net yield of 29×10^9 barrels equivalent for a low drilling effort and 27×10^9 barrels equivalent for a high drilling rate. Thus, developing our remaining reserves slowly could increase somewhat our projected ultimate net yield. On the other hand, after the energy gain decreases below the energy cost, petroleum could still be pumped at a monetary profit for feedstocks or, by using alternative fuels (such as coal), for an energy source in oil fields.

The results of our analysis indicate that the current trend of increasing conventional exploration effort by the oil industry may not be in the best interest of the nation as a whole because of the lower efficiency with which the industry delivers petroleum to society at higher rates of drilling, and also because such efforts appear to offer a "solution" to the decline in domestic conventional production. In fact, it appears that no genuine long-term solution exists unless there is a dramatic change in the way that we go about finding petroleum.

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7. Since the date at which a given oil or gas find is confirmed and added to official reserves estimates is often later than the year of actual discovery (and hence the year in which the effort was expended), it is necessary to back-correct (slip) the additions-to-reserves data. The lag is approximately 2 to 3 years for NF and NPOF and 1 to 2 years for REV and EX (E. Murphy and D. Moorehouse, personal communication). We have incorporated these corrections by determining 3-year running averages (and 3- and 5-year running averages for NF and NPOF) of yield with (i) 1- to 3-year slippage (1 year for final analysis) for REV and EX, and (ii) a 2- to 5-year slippage (2 years for final analysis) for NF and NPOF discoveries. The different slippages and averaging assumptions used had little effect on our results (R^2 varied by only .02 for oil and .19 for oil plus gas over the whole range of slippage tested). Our analysis also was insensitive to whether we used time or cumulative effort (as did Hubbert) for the abscissa. Regressing YPE versus time alone decreased the r^2 to about .51 for oil and about .62 for oil plus gas compared to a regression versus time and effort, and left a residual that was an almost perfect mirror image of effort.
8. Our method also avoids the problem of estimating Hubbert's α factor (the ratio of ultimate estimate of reserves in a field compared to initial estimates), an important consideration since the α factor has changed irregularly and sometimes rapidly since Hubbert's original use of the term. E. L. Dillon and L. H. van Dyke, *Bull. Am. Assoc. Pet. Geol.* **42**, 2549 (1958); C. F. Iglehart, *ibid.* **56**, 1145 (1972).
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10. The YPE for data before 1946 was in general higher and often much higher than for data after 1946 but showed large and irregular fluctuations associated with the depression and World War II. These fluctuations made the backward extension of our analysis less productive. The general trends, however, held at the .05 level when regression analyses were carried out for our full data set back to 1925.
11. For 1946 through 1978, level of effort is uncorrelated with time with respect to predicting YPE ($P \geq .05$). The simplest models that best describe variability in YPE from 1946 through 1978 are
$$\text{YPE (oil)} = 821 - 0.401\,(t) - 0.107\,(E),\quad R^2 = .92$$
$$\text{YPE (oil + gas)} = 1346 - 0.661\,(t) - 0.106\,(E),\quad R^2 = .82$$
where t is the year (1946, 1947, and so forth) and E is effort in millions of feet drilled per year. Standard deviations of model coefficients are 61.5, 0.0314, and 0.00869 for oil, and 133, 0.0677, and 0.0187 for oil plus gas. There can be a problem with the above equations because the same term appears on both sides of the regression model [D. Roff and D. Fairbairn, *Can. J. Fish. Aquat. Sci.* **37**, 1229 (1980)]. The equations can be rearranged to avoid this problem without changing our conclusions by making yield (Y) the dependent variable, or by using a polynomial model:
$$Y = a(E) + b(tE) + c(E^2)$$
$$Y = a + b(t) + c(E) + b(E^2)$$
Analyses of these regressions for both oil and oil plus gas show that t alone is the most powerful predictor of total yield, that E predicts little additional variation in total Y, that E had a weak positive, but diminishing with time, effect on Y in the past, and that any oil production gained through increased effort will decrease as total E becomes greater. In other words, total Y during this three-decade period was dominated by the 2 percent per year secular trend. Increasing drilling effort had little or no effect on that trend but did decrease considerably the YPE.
12. *Wall Street Journal* (26 November 1979), p. 1.
13. U.S. Bureau of Census, Census of Mineral Industries and Annual Survey of Manufacturers (various years). In 1977, it cost about $48 per foot for the average of all petroleum well-drilling in the United States when exploration and development wells, and extraction costs, are included. The costs can be subdivided further. In 1977 it took the following resources per mean foot of drilling in the industry: 1.5 m^3 of natural gas, 0.21 barrel of liquid petroleum, $8 of steel forms and pipes, and $11 of other equipment. The capital and operating equipment can be converted easily to energy equivalents with the use of straightforward national statistics [C. A. S. Hall, M. Lavine, J. Sloane, *Environ. Manage.* **3**, 505 (1980); R. A. Herendeen and C. W. Bullard, *Energy Costs of Goods and Services*, 1963 and 1967; Document 140 (Center for Advanced Computation, University of Illinois at Urbana-Champaign, 1974)]. Additional energy is required to refine, transport, distribute, and convert petroleum and to build and run the corporate buildings in Houston and New York, but we have excluded all of these indirect costs although they would substantially hasten the intersection of costs and benefits. An increasing proportion of exploratory effort is in nondrilling activities that use energy, such as sonar exploration and airplane mapping. An analysis of petroleum returns per constant dollar of exploratory-recovery effort presumably would show an even larger decline than those of Fig. 1b.
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15. We thank B. MacWilliams for assistance in locating data; J. Baker, C. McVoy, J. Downey, Dr. D. Robson, and Dr. M. Wilson for statistical assistance; and P. Bogdonoff, Drs. D. Chapman, E. Cook, J. Day, R. Herendeen, S. Kaufmann, D. Moorehouse, T. Mount, E. Murphy, C. Norman, and D. Pimentel for critical comments. This work was financed by funds from the New York College of Agriculture and Life Sciences.
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