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THE WORLD'S EVOLVING ENERGY SYSTEM

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Because of their dimensional differences, quantities of power and energy cannot be compared directly with one another. Such a comparison can be made, however, if we note that the energy represented by power is given by

$$\text{Energy} = \text{Power} \times \text{Time.}$$

By this relationship, the thermal energy represented by the influx of solar radiation at a rate of 174×10^{15} joules per second would be sufficient to bring the oceans from freezing to boiling temperatures in 100 years. At this rate of influx, the solar energy is equivalent to the initial energy of the recoverable fossil fuels every 15 days. Hence, when it is considered that solar radiation at about the present rate has been continuous for some billions of years in the past and will probably continue for a comparable time in the future, it becomes evident that cumulative solar energy is by many orders of magnitude the largest quantity of energy available to the earth past, present, or future.

As is shown in Figure 1, about 30 percent of incident solar radiation, the earth's albedo, is reflected and scattered into outer space as visible short-wavelength radiation and is ineffective in terrestrial processes. The remaining 70 percent is captured and is responsible for terrestrial processes before becoming degraded to heat at the lowest ambient temperature and then being radiated into outer space as spent, long-wavelength thermal radiation. About half the total solar influx is converted directly into heat, warming the atmosphere, the oceans, and the ground, and maintaining the earth's warm climate. About a quarter drives the winds, the ocean currents, and the evaporation, convection, and precipitation of water in the hydrologic cycle. Finally, a very small fraction, about 0.02 percent, is captured by the green leaves of plants and drives the process of photosynthesis,

THE WORLD'S EVOLVING ENERGY SYSTEM

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Introduction

To appreciate the significance of energy in the processes occurring on the earth's surface, about as general a view as we can take is to consider that all terrestrial events are events of matter and energy. With regard to matter, the earth is essentially a closed system. It is true that a few meteorites are being captured by the earth, and a few gases are escaping from the upper atmosphere, but with these minor exceptions the earth is a closed material system composed of the 92 naturally occurring chemical elements. Of these, all but a minute fraction are nonradioactive and obey the rules of indestructibility and conservability of classical chemistry.

With regard to energy, the earth is an open system. Within minable or drillable depths the earth contains certain large stores of energy, the chemical energy of the fossil fuels, geothermal energy, and the nuclear energy of the fissile or fusible chemical isotopes. In addition, into and out of the earth's surface environment there occurs a continuous influx, degradation, and efflux of energy. As a consequence, the mobile materials of the earth's surface are kept in a state of continuous or intermittent circulation. This combination of energy flux and degradation and material circulation comprises the totality of events on the earth's surface. We ourselves are a part of that matter-energy system.

This is also an evolving system. Much of the evolution - the accumulation of the fossil fuels, for example - occurs very slowly with a geologic time scale of hundreds of millions of years. Other aspects, such as the application of the fossil fuels, evolve very much more rapidly with a time scale of centuries or decades and it is the latter with which we are most intimately concerned at present. In fact, the rise to dominance of the human species during the last 2 or 3 million years has been as a direct consequence of the inventiveness of this species in learning to convert an ever-larger fraction of the ambient energy supply to human uses.

During the last several decades, the present author has been engaged in a continuing study of this evolving system, with particular regard to its implications in the evolution of human society and the outlook for the future. From time to time, in response to requests from various organizations, papers amounting to progress reports on this study have been prepared giving an account of the energy outlook as it appeared from information currently available. Among such successive papers have been the following: Hubbert, 1950; 1956; 1962; 1967; 1969; 1974a; 1974b; 1978b; 1979.

Although the general outline of this evolution has been reasonably clear for several decades, interpretations have evolved as the picture has unfolded and as better and more complete information has become available. There is an unavoidable overlap in these successive reviews, and the present one differs in only minor details from others written during the last two years. In particular, since there has been little change in the total picture during the last few months, the present review differs insignificantly from that written during the present year and published in the Transactions of the American Society of Mechanical Engineers, whose priority is hereby acknowledged.

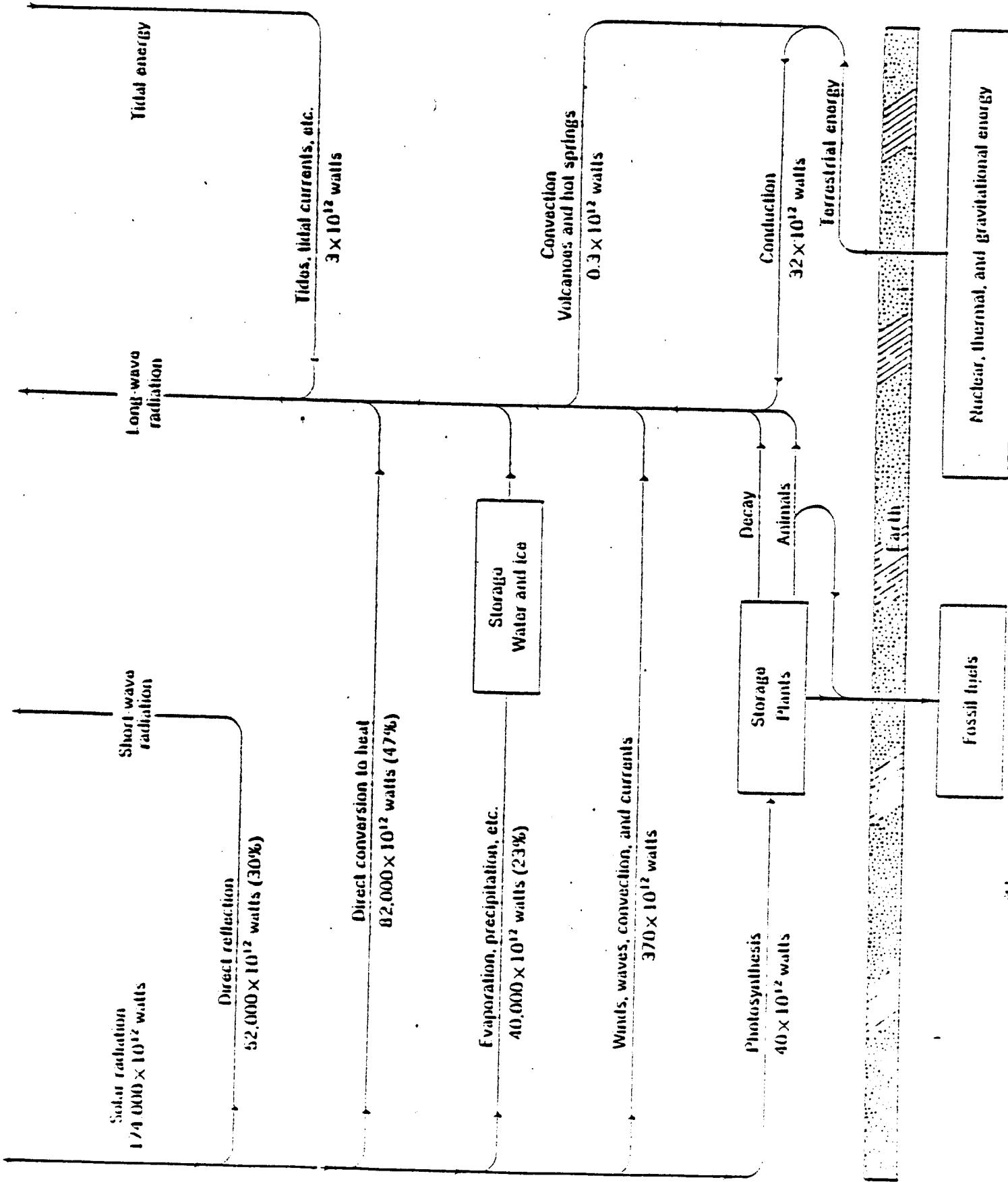
Energy System of the Earth's Surface

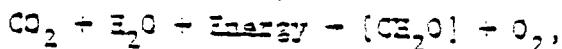
The earth's energy system is depicted graphically in Figure 1. The bar near the bottom of the chart represents the earth's surface below which occur the stores of energy of the fossil fuels, of thermal energy, and of nuclear energy. These stores are measurable in energy units, and for an order of magnitude, the energy stored in the initial recoverable supply of fossil fuels may be taken to be about 2×10^{23} joules.

The upper part of the diagram is an energy flow sheet representing the flux of energy in the earth's surface environment. These energy fluxes have the dimensions of energy/time, or power, and hence are measurable in power units, or watts. In the diagram the unit used is 10^{12} watts, or the terawatt. In terms of this unit the energy influxes from the only three significant sources are:

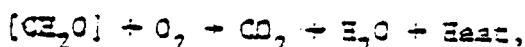
Solar	174,000
Geochemical	32
Tidal	3

It is evident, therefore, that the influx from solar radiation is approximately 5,000 times the sum of the influxes from the other two sources combined.





where $[\text{CH}_2\text{O}]$ is the building block of a series of carbohydrates of increasing complexity in which radiant energy is stored chemically. This is the sole source of physiological energy for the earth's biological system. Plants capture and store solar energy. Plants also die and decay, and by the reverse oxidation reaction,



the materials revert to their initial state and the stored energy is released as heat. Through the food chain,



the plants also supply the energy required by the animal kingdom, which is also dissipated eventually to heat.

This is a near steady state when averaged over a few years, as is evident when it is considered that liquid oceans have existed for longer than 3 billion years, which indicates that the earth's mean temperature must have been thermostated within a temperature range of 0 to 100 degrees Celsius for that period of time.

A very small but important exception results from the fact that a minute fraction of the organic material becomes deposited in peat bogs and other oxygen-deficient environments where the oxidation reaction cannot occur, nor can the energy be released when such materials become buried beneath accumulating sedimentary sands and muds. They are preserved and eventually transformed into the fossil fuels, coal, petroleum, and natural gas.

Industrial-sized oil and gas fields are found in rocks of all geological ages, from Late Precambrian, over 600 million years ago, to the last million years in the Mississippi and Niger River deltas. The oldest significant coal deposits

are the great coal fields of what was formerly known as the Carboniferous Period, 300 to 350 million years of age, in Western Europe, the British Isles, the eastern half of the United States, and elsewhere. Younger subbituminous coals were accumulated during the Mesozoic Era (65 to 200 million years ago). Lignite and brown coals are still younger, and peat, the first stage in coal taking, is accumulating at present.

This time scale is significant in that it shows that some 600 million years were required for natural processes to accumulate the world's supply of fossil fuels. The same processes of accumulation are active at present, but at a rate so slow that no significant additions to the world's supply could occur during the few centuries required to deplete the initial supply. In effect, therefore, we are mining a stockpile to which no new additions will occur during the period of exploitation.

Man's Conquest of Energy

In Figure 1 the human species operates in the energy channel of the animal kingdom. Man, being an omnivore, draws his physiological energy supply from both vegetable and animal sources. However, about 2 to 3 million years ago, our ancestors distinguished themselves from other animals in terms of inventiveness of means of capturing and controlling an ever-larger fraction of the ambient energy supply. At first this was accomplished largely by manipulation of the biological system and of the environment. This included the use of tools and weapons and the development of clothing and housing. About a million years ago a tremendous advance was made when it was learned how to make and control fire. This added a nonfood energy source, namely wood, and approximately doubled the energy use per capita. Then, about 8,000 to 10,000 years ago the domestication

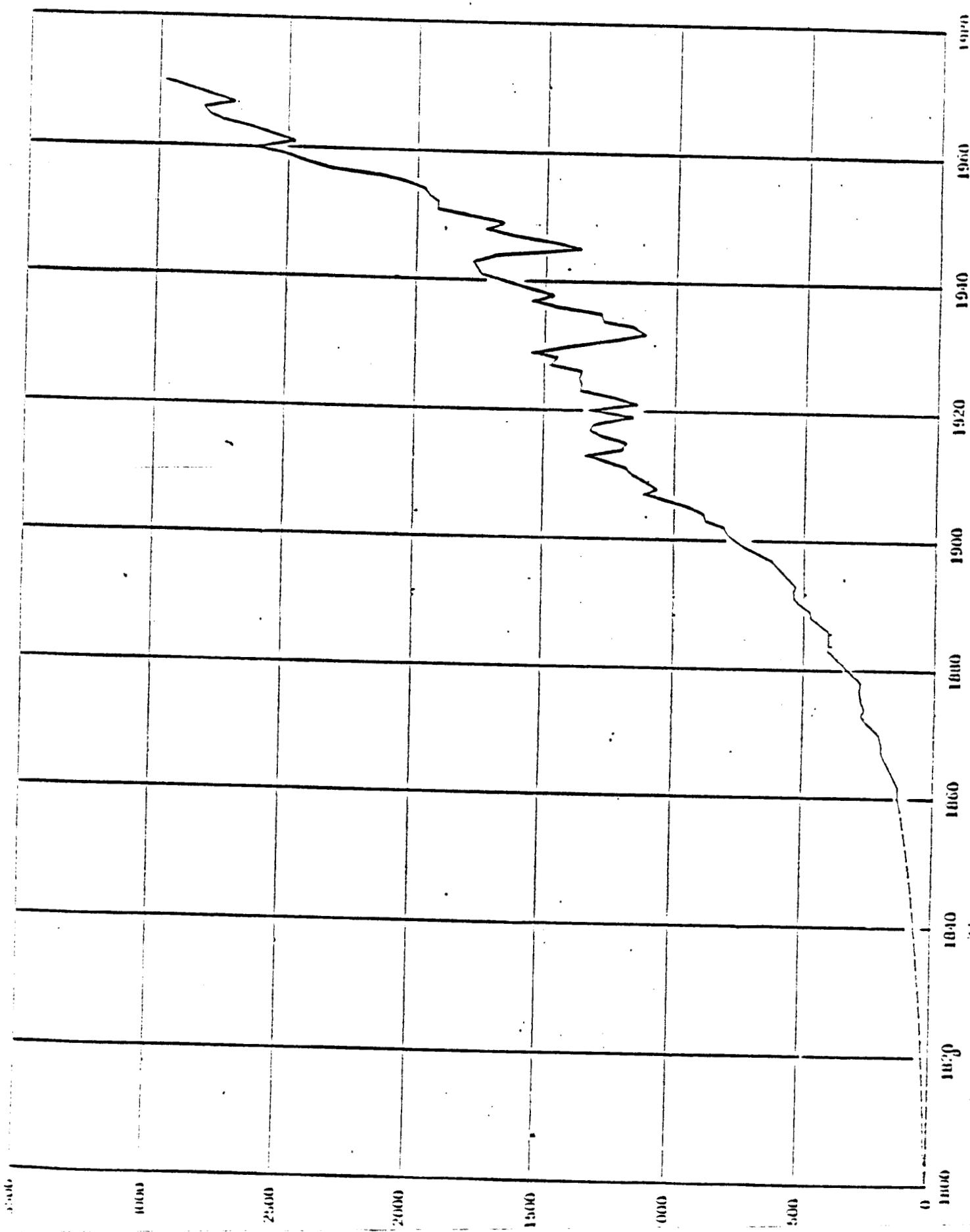
of animals and plants made it possible to channel still larger amounts of local energy into human uses and led to the beginning of the ancient city-states and the early civilizations of the Nile, the Indus, and the Tigris and Euphrates valleys. About 5,000 years ago the smelting of nonferrous metals, using wood as an energy source, was begun in Anatolia. This was followed 1,500 years later by the smelting of iron. The first major utilization of a nonbiological energy channel was made by the Egyptians about 3,500 years ago when they learned to drive their boats on the Nile by wind power. The second nonbiological channel, water power, was tapped in a small way by the Romans about 2,000 years ago when they developed small water-powered mills for grinding grain.

However, during all this time, most of the world's work was done by human and animal labor, and the per capita utilization of energy was limited to about twice that of the food consumed, or to a rate of about 16-20 million joules per capita per day, or roughly 200 thermal watts per capita. Release from this constraint was not possible until the large concentrated supplies of the fossil fuels were discovered and the essential technology for their utilization developed.

Energy from Fossil Fuels

Coal mining as a continuous enterprise began near Newcastle-upon-Tyne in northeast England about the middle of the eleventh century A.D. The production of petroleum on an industrial scale came much later, beginning in Romania in 1857, and two years later in the United States in 1859.

Annual world coal production since 1860, and the approximate rates back to 1800, is shown graphically in Figure 2. Although annual production statistics are difficult to assemble earlier than 1860, from the known history of coal mining and from scattered earlier production statistics, it can be shown that



coal production grew during the preceding 800 years at an average rate of about 2 percent per year, with an average doubling period of about 35 years. At this rate, cumulative production by 1860 would have amounted to about 7 billion metric tons, and cumulative production to the end of 1976 to 158 billion metric tons.

What Figure 2 shows most emphatically is the contrast between the magnitude of coal-mining operations during the period since the year 1860 and that during the preceding 8 centuries. Twenty-two times as much coal has been mined since 1860 as in all preceding history. Of the 158 billion metric tons of coal mined during the last 9 centuries, 79 billion tons, or one-half, have been mined since 1943. It is also seen from Figure 2 that three different periods of growth in the rate of coal mining have occurred since 1860. From 1860 to World War I, annual production increased at a uniform exponential rate of 4.2 percent per year with a doubling period of 16.5 years. From World War I to the end of World War II the growth rate slowed down to an average of 0.79 percent per year with a doubling period of 88 years. Then, following World War II, the rate increased to 3.0 percent per year, with a doubling period of 23 years.

Annual world production of crude oil from 1885 to the end of 1977 is shown in Figure 3. This shows a smooth exponential growth until the disturbance of the Arab embargo of 1974-1975 at an average rate of 7.04 percent per year, with a doubling period of 9.8 years. At a uniform exponential growth rate, the cumulative production also doubles during the same time period as annual production. Hence the amount of oil produced during the decade 1960-1970 was equal to all of the oil produced prior to 1960. By the end of 1978 cumulative world production of crude oil amounted to 382 billion barrels. Of that, slightly more than one-half was produced since the end of 1967.

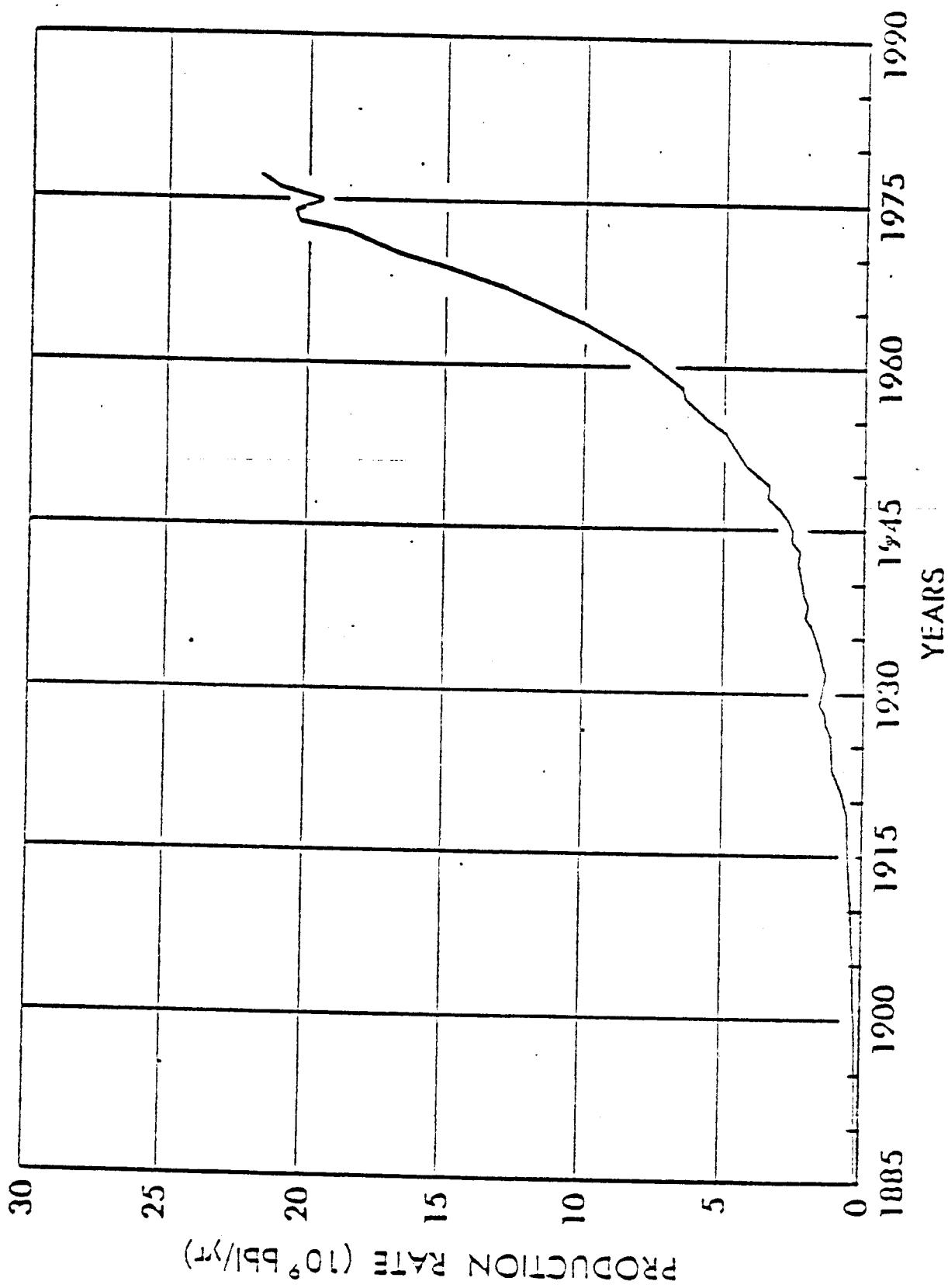


Fig. 3 - World crude-oil production.

A direct comparison cannot be made between crude oil measured by volume in U.S. 42-gallon barrels, and coal measured by mass in metric tons. However, a common denominator exists in terms of the respective heats of combustion, and the rates of heat production are expressible in thermal watts. The average heat of combustion of the world's combined-production of coal and lignite is about 2.47×10^{10} joules per metric ton. Then, burning coal at a rate of 1 metric ton per year would generate heat at a rate of 783 joules per second, or 783 thermal watts. Similarly, the average heat of combustion of 1 barrel of crude oil is approximately 6.10×10^9 joules. Hence, at a consumption rate of 1 barrel of crude oil per year, the thermal rate would be 193 joules per second, or 193 thermal watts.

Using these conversion factors gives the rate of energy production, expressed in units of thermal power from the world production of coal and lignite, and from crude oil, shown in Figure 4. From this, it is seen that the energy contribution from crude oil was barely significant compared with that of coal until 1900. Subsequently the crude-oil fraction steadily increased until by 1970 it was slightly larger than that of coal. Were the energy from natural gas and natural-gas liquids to be added to that of crude oil, the total energy contribution from petroleum fluids would amount to about two-thirds and coal only about one-third of the energy consumption from the fossil fuels at present. For comparison, about 75 percent of the industrial energy used in the United States is obtained from oil and natural gas, about 16 percent from coal, and the remaining 6 percent from hydro- and nuclear power. Hence the world and the United States are both dependent heavily upon petroleum as their principal source of industrial energy.

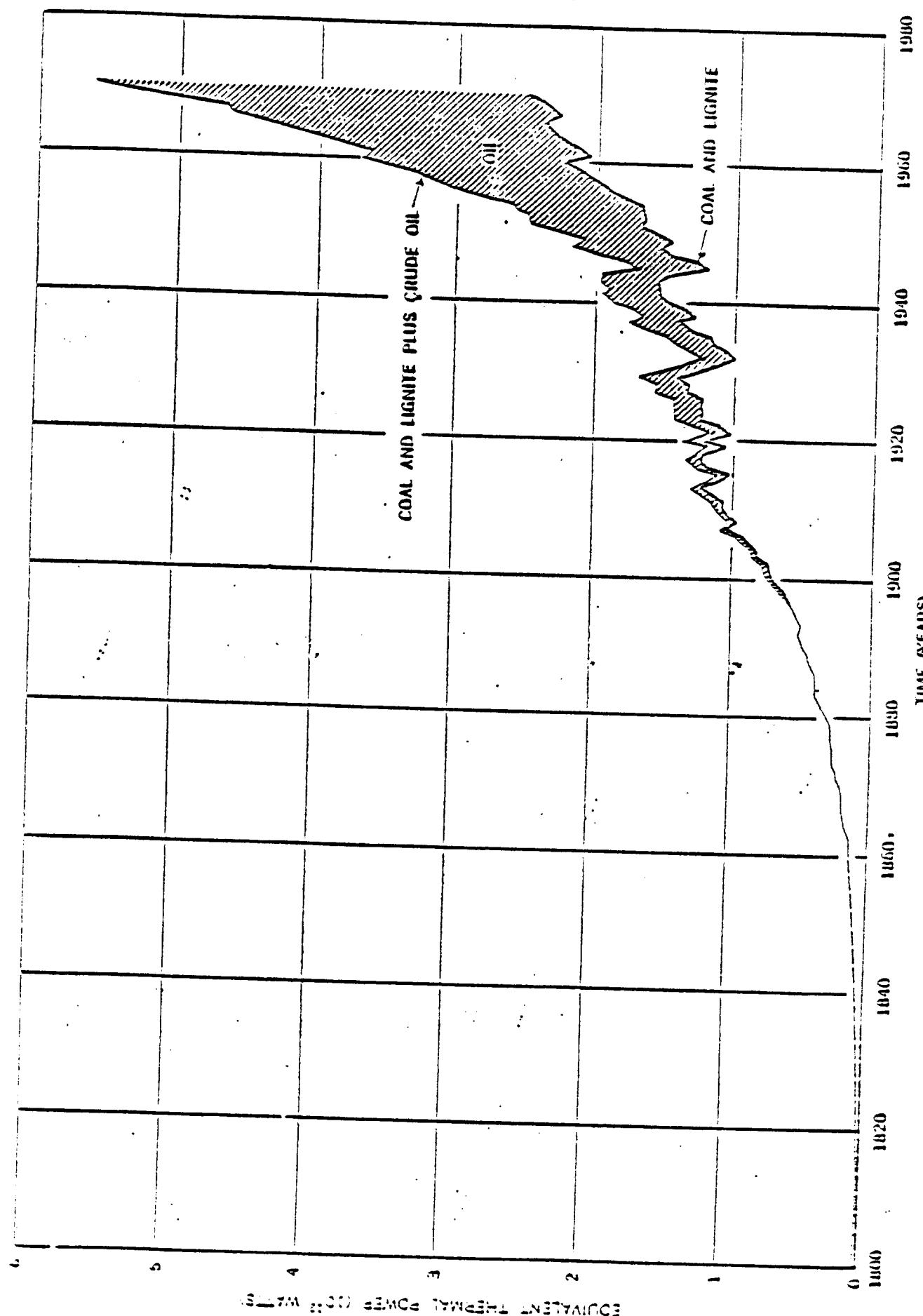
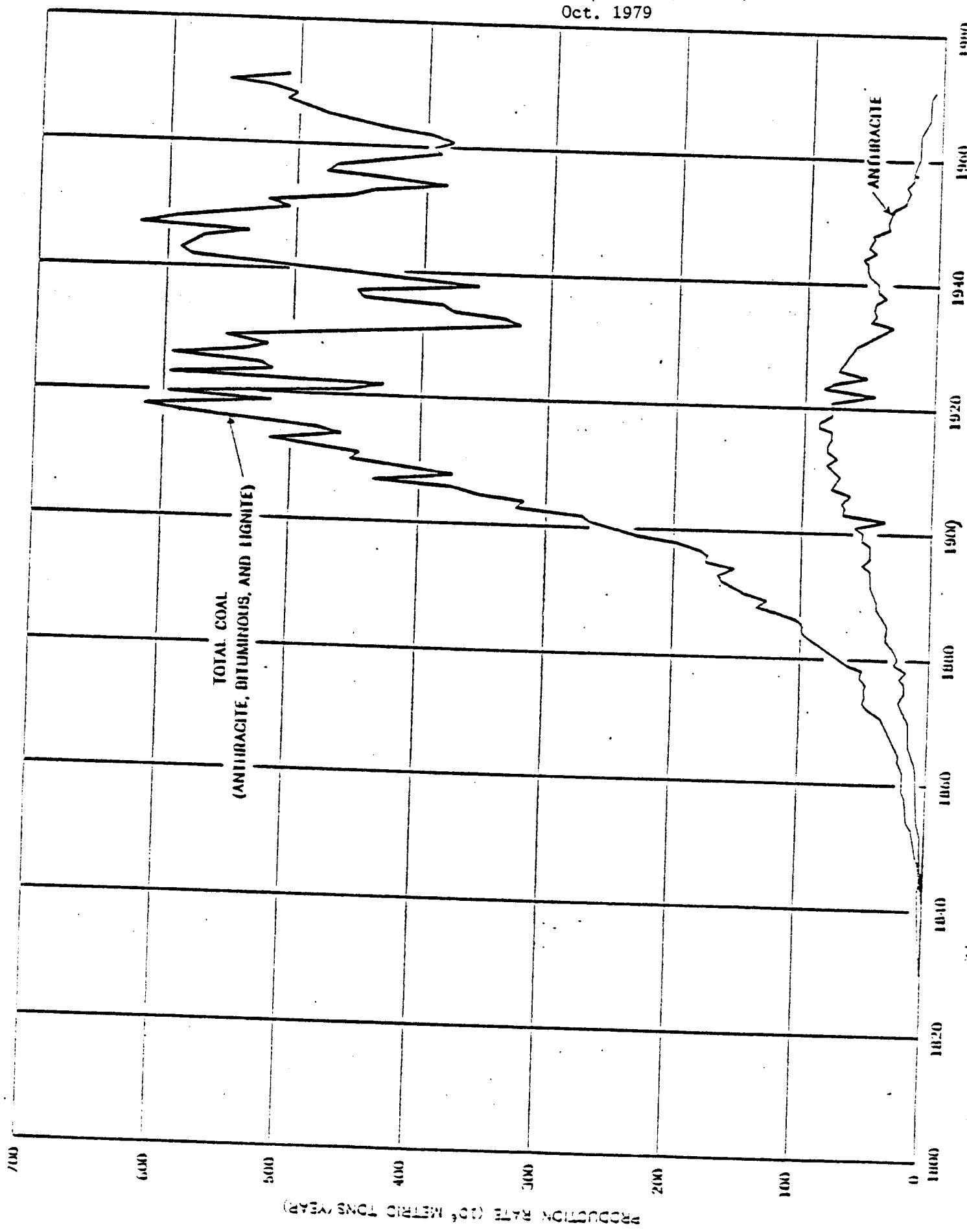


FIG. 4 - World energy production from coal and lignite plus crude oil (thousand barrels per day)

Annual coal production in the United States from 1830 to 1971 is shown in Figure 5. The upper curve is the sum of anthracite, bituminous coal, and lignite. The lower curve is Pennsylvania anthracite alone. From year zero in 1830, U.S. annual coal production increased exponentially until 1907 at an average annual growth rate of 6.69 percent, with a doubling period of 10.4 years. Then since 1920 it has fluctuated about a mean rate of 500 million metric tons per year. This slowdown in the growth rate after 1920 was due largely to the replacement of coal by oil and gas. Since 1970 there has been a gradual increase in coal production in response to increasing shortages of oil and gas.

The production of Pennsylvania anthracite, shown separately in the lower curve of Figure 5, represents an almost ideal example of the complete cycle of exploitation of an exhaustible and nonrenewable resource. Anthracite is very hard coal, composed of almost pure carbon, that occurs in a small region of the folded Appalachian mountains of eastern Pennsylvania. Its combustion is almost smokeless, and for that reason it was the principal fuel used by New York and other cities of the eastern seaboard during the last century and the first quarter of the present century. The production rate increased exponentially from 1830 to about 1900. It then slowed down, reached a maximum in 1917, and thereafter, with minor oscillations, declined negative-exponentially until it is now almost back to zero.

The annual production of crude oil from the Lower-48 states from 1830 to 1971 is shown in Figure 6. For purposes of analysis, the oil and gas production from the Lower-48 states, and from Alaska, need to be examined separately. Alaska is a large, newly developing region in which significant oil production did not begin until 1968. Accordingly, it does not yet have sufficient statistical data



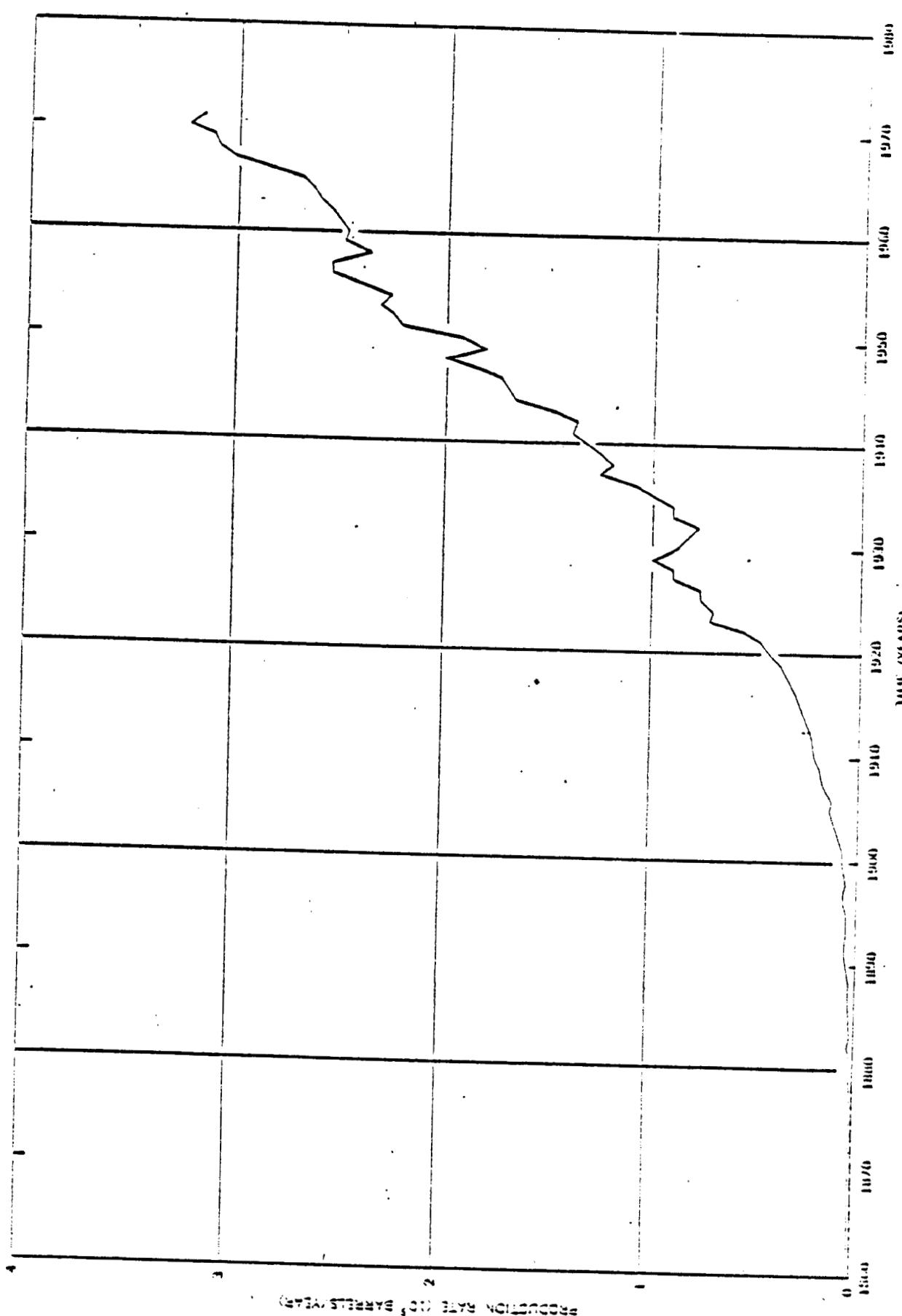


Fig. 6 - Oil production rate projection to the end of 1971 through 1990.

to permit the same kind of analysis that can be used for the Lower-48 states.

Crude-oil production in the United States began in 1859 when oil was first discovered at Titusville, Pennsylvania. From 1875 to 1929 the annual production increased exponentially at a mean growth rate of 3.3 percent per year and a doubling period of 8.4 years. By 1929 the production rate reached 1.007 billion barrels per year. Then, during the Depression, it dropped to a ~~minimum~~ rate of 0.735 billion barrels per year in 1932. From 1932 to 1970, as is seen in Figure 6, the annual production increased approximately linearly, reaching 3.494 billion barrels in 1970.

Besides crude oil, other petroleum raw materials are natural gas and natural-gas liquids. The latter are low-density hydrocarbons, essentially gasoline, produced as a by-product of natural gas.

Complete Cycle of Fossil-Fuel Production

In reviewing the growth in the rate of exploitation of the fossil fuels as shown in Figures 2 to 6, one can hardly refrain from wondering about the future. How long can such growth rates continue? How much longer can the fossil fuels continue to provide the bulk of the world's industrial energy requirements?

The method that has been most widely used in the past to estimate the future of such curves is that of empirical extrapolation. If a near-linear trend can be observed during the recent past, extrapolation of this trend is said to be a "projection" of the trend and is used to estimate the future. While such a procedure has a limited usefulness, it is also hazardous when applied to the production of an exhaustible resource, for it fails utterly to take into account the fact that a future point on each production curve is known already, namely, zero. As was illustrated by the anchracite curve in Figure 5, the rate-of-production

curve for any exhaustible resource, after having reached one or more principal maxima, must eventually decline in a negative-exponential manner back to zero. This fact provides a simple but powerful means of analysis.

Let

$$P = dQ/dt$$

(1)

be the production rate, where dQ is the quantity produced in time dt . Then the cumulative production to any given time t_1 is given by

$$Q(t_1) = \int_0^{t_1} P dt = \int_0^{t_1} dQ,$$

(2)

and for unlimited time,

$$Q_\infty = \int_0^\infty P dt$$

(3)

where Q_∞ is the ultimate magnitude of cumulative production in a given region. During this complete cycle, the curve of production rate P , plotted graphically as a function of t , must begin initially at zero, increase exponentially for a period, slow down, pass one or more maxima, and finally decline negative-exponentially back to zero as the initial recoverable resource approaches depletion. An idealization of such a curve is shown in Figure 7. We have also the further constraint that

$$Q_\infty < Q_i$$

(4)

where Q_i is the quantity of the resource initially present.

By the first principle of the integral calculus the area beneath the curve of P versus t to any given time is a graphical measure of the cumulative production to that time, and for the complete cycle the ultimate area beneath the curve, as t increases without limit, will be fixed by the magnitude of Q_∞ . If, therefore, from geological or other means, the magnitude of the

quantity of the recoverable resource initially present in a given area can be estimated, this estimate sets a rigid bound to the area that can be subtended by the complete-cycle curve of production.

This is the inverse of the conventional problem of the integral calculus. There, one is usually given the function $y = f(z)$, and the area A beneath the curve from $z = 0$ to $z = z_1$ is uniquely determined by

$$A = \int_0^{z_1} y dz. \quad (5)$$

The present problem is: Given $A(z)$, find the curve $y = f(z)$. Or, in terms of a resource production, given the ultimate quantity to be recovered in a given region, find the production rate as a function of time.

This inverse problem obviously has no unique solution; in fact, for the complete cycle there is an infinity of different curves which subtend the same area. However, when the first part of the curve has already been developed, and the technological constraints are added that the curve, after passing one or more maxima must return to zero by a roughly negative-exponential decline, the range of possible shapes for the complete-cycle curve is severely restricted.

In any graphical plot of such a curve, the graphical interval for ΔP as the ordinate, and for Δt as the abscissa, must be chosen arbitrarily. On such a coordinate system, the area of one $\Delta P \Delta t$ -grid rectangle is a graphical measure of the cumulative production ΔQ at a rate ΔP for the time Δt , since

$$\Delta P = \Delta Q / \Delta t,$$

or

$$\Delta Q = \Delta P \Delta t. \quad (6)$$

Then, if for a given region an estimate for ϵ_s can be made,

$$\epsilon_s / \Delta Q = n \quad (7)$$

will be the number of grid squares that can be subtended by the compleat-cycle curve.

Application to Coal. - Let us apply this to coal. Because coal is a solid which occurs in stratified seams that are often continuous for tens of kilometers and frequently crop out on the surface of the ground, the quantity of coal in a given region can be determined by geological mapping and a limited amount of drilling. Such studies by the U.S. Geological Survey have been under way in the United States for the last 80 or 90 years and the coal-bearing basins are shown in Figure 8. Other countries have made similar studies of their coal resources, and from such published data Averitt (1969) of the USGS has compiled the estimates shown in Figure 9 of the coal recoverable by mining that was initially present in the various major geographical regions of the world, assuming that 50 percent of the coal can be recovered.

Two quantities in Figure 9 are of principal present interest, that of 7.6×10^{12} metric tons for the world, and of 1.49×10^{12} metric tons for the United States. These two figures represent the limiting values of q_0 for coal production for the world and the United States respectively. However, in terms of actual coal mining, these quantities may be unrealistically high because they include coal in seams as thin as 0.3 meters, and occurring to depths of 1,200 meters. Subsequently Averitt was asked to estimate the recoverable coal resources of the United States in more practical mining terms. What was the initial quantity of recoverable coal in the United States occurring at depths less than 300 meters and in beds of not less than 0.7 meters thick for bituminous coal and anthracite, and 1.5 meters for subbituminous coal and lignite? With these constraints, the estimate of initial recoverable coal for the United States was reduced from 1.49 to 0.39 trillion metric tons, a reduction of 74 percent. Assuming that a similar reduction would occur were the same kind

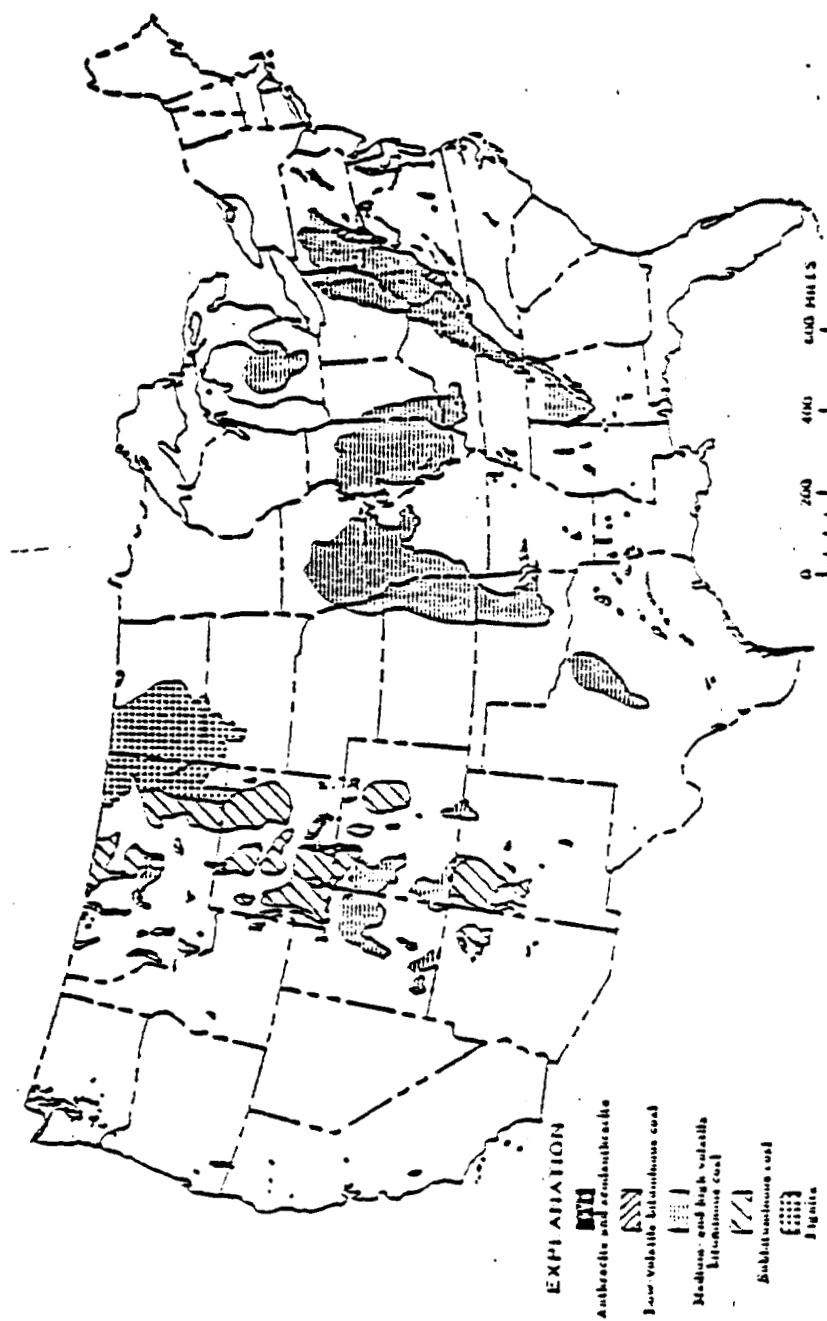


FIG. 8 - Coal fields of the conterminous United States (Averitt, 1969, FIG. 1).

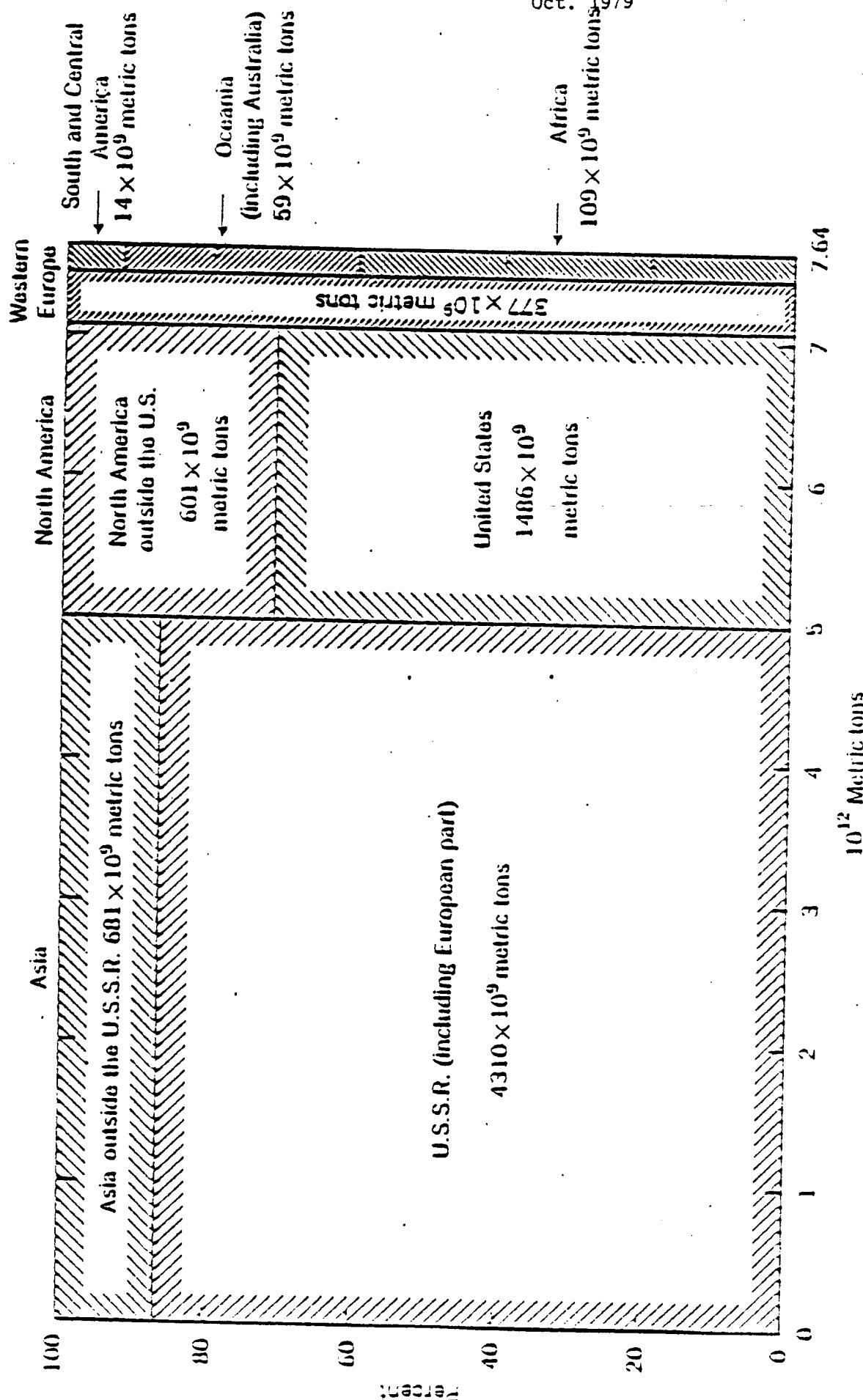


FIG. 9 - Averitt (1969) estimates of initial world recoverable coal (Hubbert, 1974a, Fig. 19).

of analysis made for the world, the world initially recoverable coal would be reduced to about 2×10^{12} metric tons. These two pairs of figures may be taken as high and low estimates of Q_s for the world and for the United States respectively.

Two complete cycles of world coal production, based upon the high figure of 7.6 and the low of 2 trillion metric tons, are shown in Figure 10. In this figure, one API-6 grid rectangle has the dimensions

$$\Delta Q = 10^{10} \text{ metric tons} \times 10^2 \text{ yr} \\ = 10^{12} \text{ metric tons.}$$

Therefore, using the higher figure of 7.6 trillion metric tons for Q_s , the complete-cycle curve can subtend but 7.6 grid squares; for the lower figure of 2 trillion tons only 2 squares.

The shapes of the two curves are not fixed by the value of Q_s , but, as drawn, the higher curve is based upon a technologically reasonable assumption of three more doublings, or an 8-fold increase in the present rate of production. The lower curve assumes 2 more doublings. Should the ~~maximum~~ production rate be higher than that assumed, the time span would be shortened. If lower, the time span would be lengthened.

What emerges from such a plotting is a sense of the approximate length of time during which coal can serve as a major source of industrial energy. For the upper curve the ~~maximum~~ production rate would occur about the year 2200; for the lower curve, about a century earlier. Another time parameter of interest is the period required to produce the middle-80 percent of Q_s . Disregarding the 1,000 years required to produce the first 10 percent, and possibly another 1,000 years for the last 10 percent, how long a period would be required to produce the quantity between 10 and 90 percentiles of Q_s ? According to the

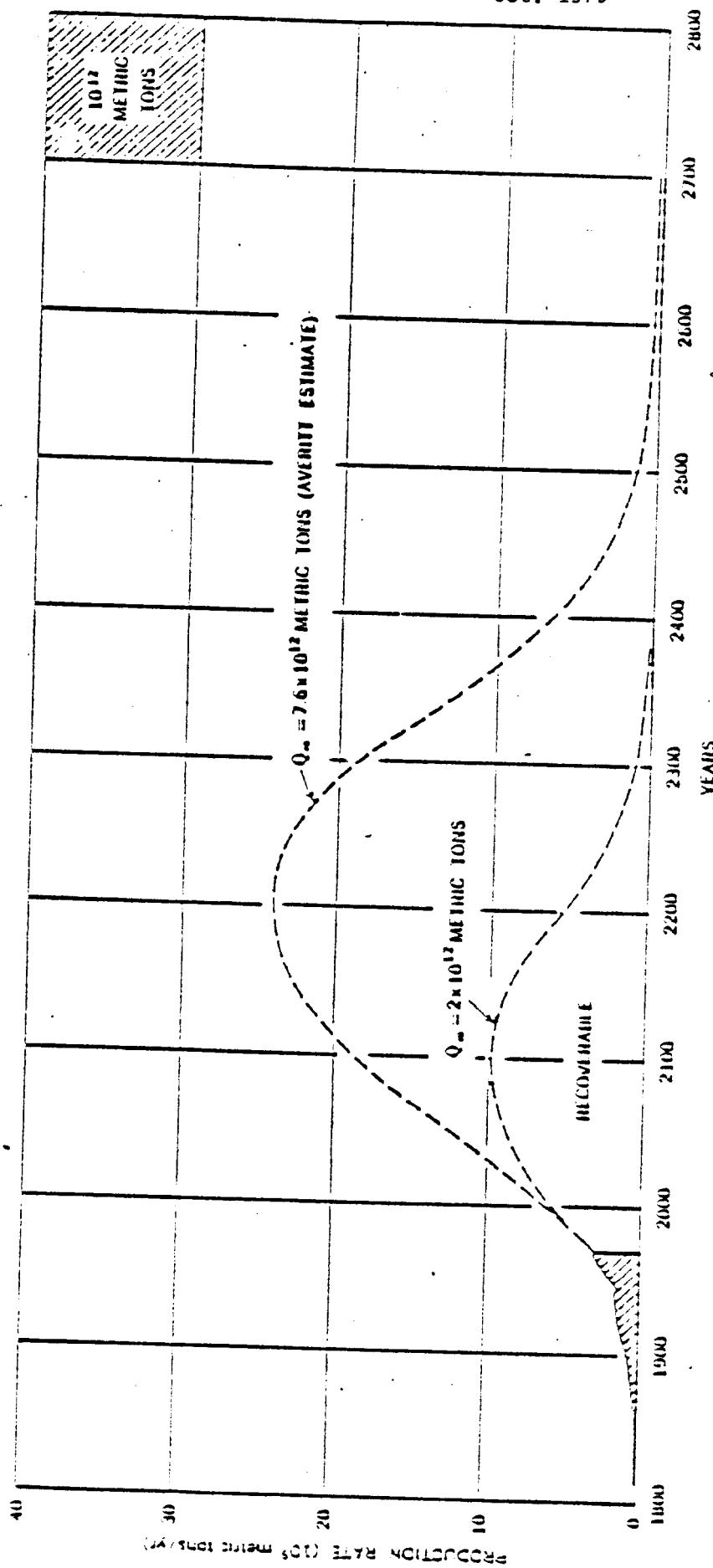


FIG. 10 - Complete production cycles for high and low estimates of world recoverable coal (Hubbert, 1974a, Fig. 21).

upper curve, this would be about 4 centuries, from the year 2000 to 2400; for the lower curve, about 2 centuries. For a single approximate figure, it appears that the middle 30 percent of the world's initial coal supply will probably be exhausted within about 300 years, and that the ~~maximum~~ production rate will be reached within the next 150 years or less.

Two corresponding complete cycles for U.S. coal production are shown in Figure 11, based upon high and low estimates of 1.49 and 0.39 trillion metric tons, respectively, for Q_0 . The assumptions are the same as those for the world analysis, and the time spans are about the same.

Application to Petroleum. - Petroleum is much more difficult to estimate than coal. Oil and gas are fluids that become concentrated in certain volumes of underground sandstones or other porous sedimentary rocks, which are otherwise filled with water. Oil and gas accumulations commonly occur in such rocks when an upper impermeable surface is downwardly concave. In such a space gas, oil, and water commonly are found in a stratified arrangement with the less dense fluid overlying the more dense.

Oil and gas fields range in areal extent from city-block size to hundreds of kilometers in linear dimensions, and in depth from a few tens of meters to as much as 6 kilometers for oil and 3 kilometers for natural gas. For fields that have already been discovered and developed, reasonably good estimates can be made of the amount of oil or gas that can ultimately be recovered, but how can the amount of oil or gas that has not yet been discovered by drilling be estimated?

Essentially two procedures are available. From geology, it is known that oil and gas are found only in basins of thick sedimentary rocks, and the locations of all such basins in the world are by now reasonably well known.

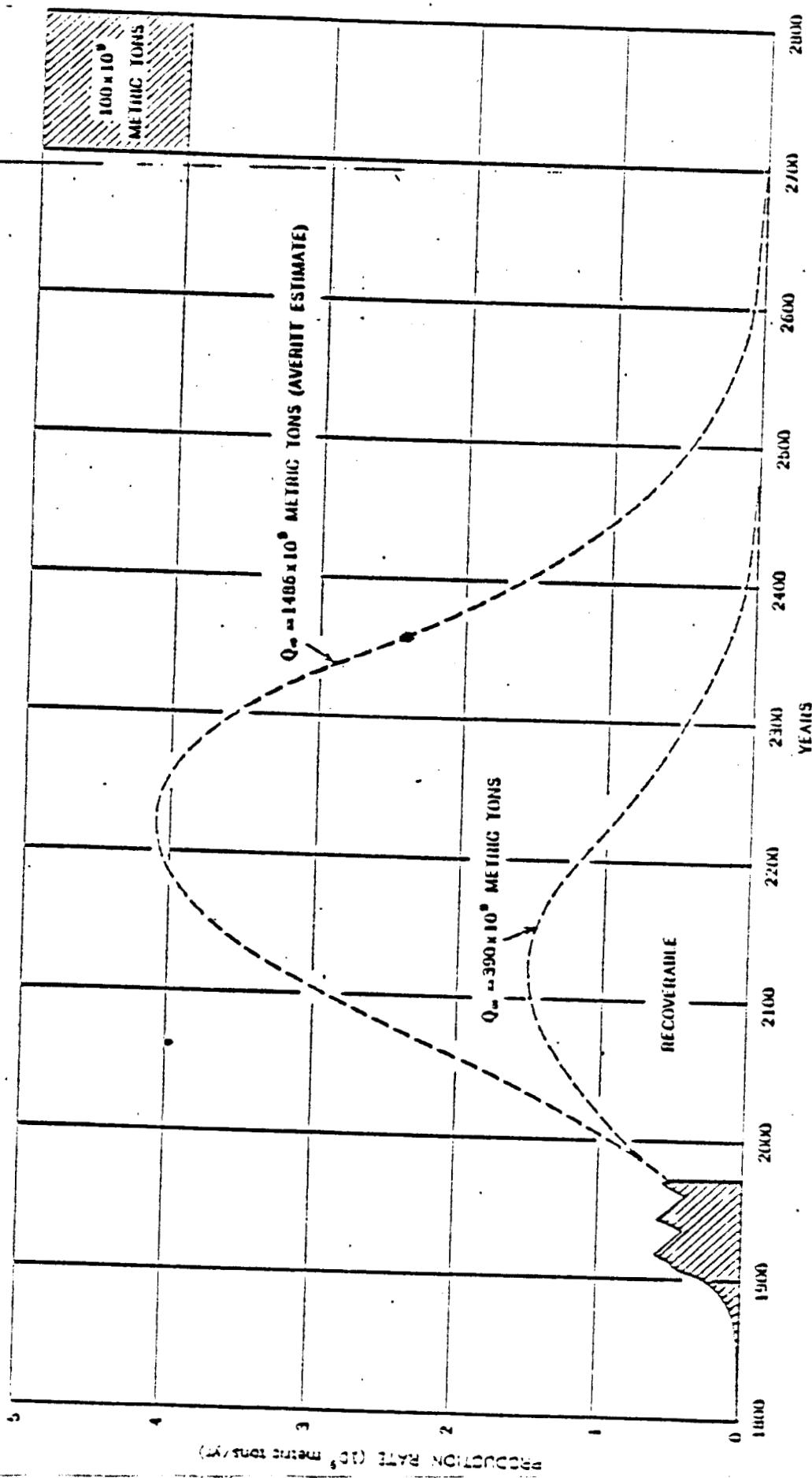


Fig. 11 - Complete production cycles for high and low estimates of U.S. recoverable coal (Hobbert, 1974a, Fig. 22).

In a petroleum-bearing region such as the United States, which is in a mature state of development, the cumulative experience in petroleum exploration and production, in conjunction with the known geology of petroleum-bearing basins, affords a basis for judgment concerning about how much more oil or gas remains to be discovered in the region.

For a new territory, however, that has not yet been drilled, the method of estimation must be based upon geological analogy with known areas. Suppose that by preliminary geological and geophysical mapping a new area C is found to be geologically similar to a known area A which is rich in petroleum accumulations. It is inferred that C will probably also have comparable amounts of oil per unit area, or unit volume, of sediments. On the other hand, if a new territory D is found to be similar to a known area B which is barren of petroleum, the petroleum prospects for D would not be considered very favorable. Petroleum estimates for the various areas of the world are derived by a combination of these two methods.

For a primary area in a mature stage of development, the United States is the best example. The United States historically has been the world leader in petroleum exploration and production technology. Also, during most of its history, the United States has been the leading oil-producing country in the world. In fact it remained so until as recently as 1974. At that time it was overtaken by production from the U.S.S.R.

In March 1956 I was invited to address a meeting of petroleum engineers of the American Petroleum Institute in San Antonio, Texas, giving a broad-brush picture of the world energy situation. At that time it had been 96 years since oil was first discovered in Pennsylvania, and during that period 32.4 billion barrels of oil had been produced in the conterminous United States. A review

of the published literature gave estimates by leaders of the petroleum industry of from about 150 to 200 billion barrels as the ultimate amount of crude oil likely to be produced in the United States. I was in research with Shell Oil and Shell Development Companies at the time, and my own independent information agreed that the ultimate amount of oil would probably fall between 150 and 200 billion barrels.

These were the figures generally accepted in the U.S. petroleum industry at that time, but the current interpretation of their significance for the future is of especial interest. Essentially the question asked was: If in just under a century we have produced just over 50 billion barrels of oil, and if 2 to 3 times this amount of oil remains to be produced in the future, how soon may an oil shortage in the United States be expected to occur? To this question the intuitive answer accepted by petroleum geologists, engineers, and oil-company officials alike was that such a shortage would not occur during our lifetime; during that of our grandchildren, possibly. A widely used public-relations dictum of the time stated: "The United States has all the oil it will need for the foreseeable future."

Using the two figures of 150 and 200 billion barrels for Q_u , the drawing reproduced here as Figure 12 was presented in that paper. On this drawing, one grid square represents 25 billion barrels. For the lower figure of 150 billion barrels for Q_u , the area beneath the complete-cycle curve would be but 6 squares, two of which represent cumulative production to 1956, leaving but 4 squares for the future. Allowing for the future negative-exponential decline, it became almost impossible to draw the curve in a significantly different manner from that shown in Figure 12. According to this, the peak in the rate of production would have to occur in about 10 years, or at about 1966. Assuming the higher

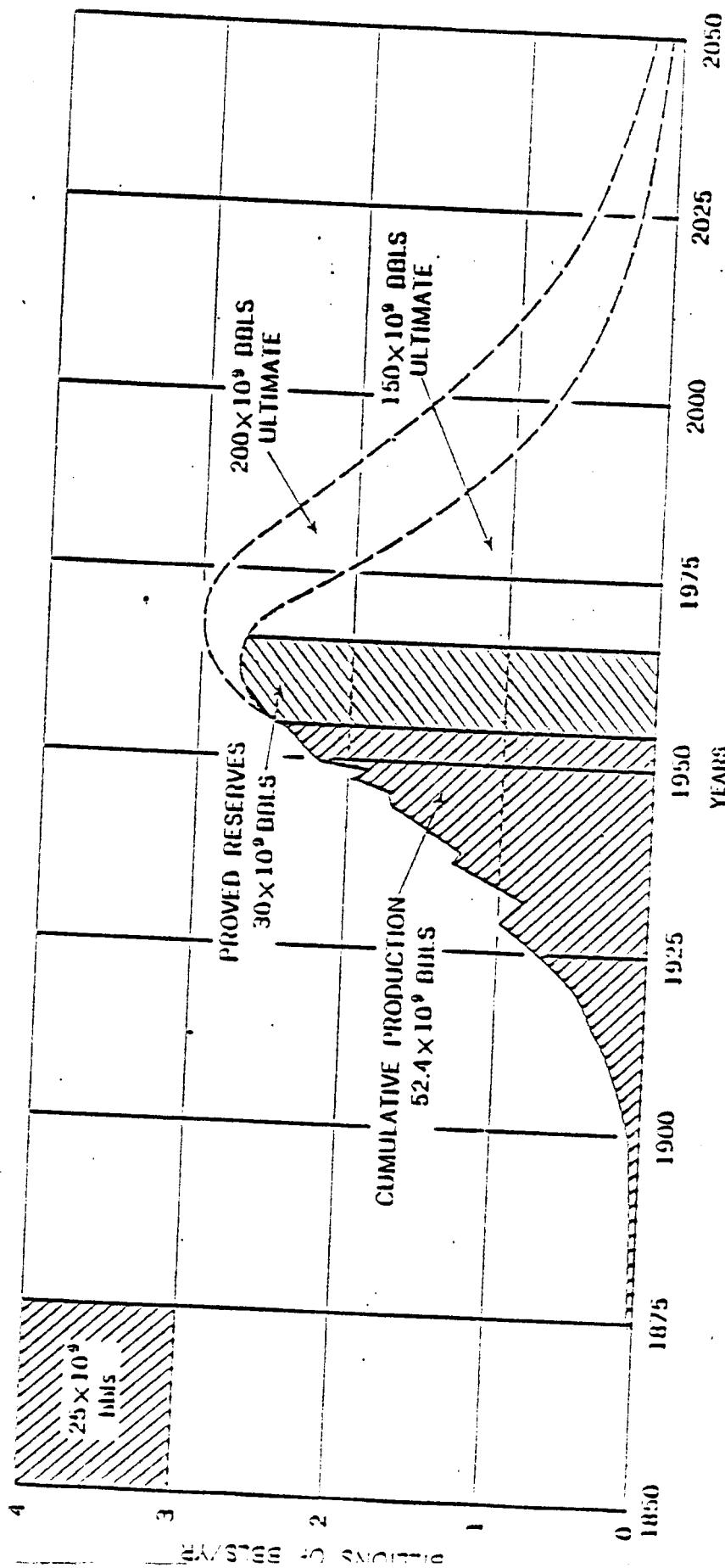


Fig. 12 - Hubbert predictions of 1956 of future rates of crude-oil production from Lower-48 states and continental shelves (Hubbert, 1956, Fig. 21; reproduced with permission of American Petroleum Institute).

figure of 200 billion barrels for Q_u gives the upper curve in Figure 12. For this, 2 more squares are added to the area, but these occur between the two curves principally during the decline. The date of peak production rate would be delayed by only about 5 years, or to about 1971. The inescapable conclusion was that if the ultimate amount of crude oil to be produced in the Lower-48 states and adjacent continental shelves should, as all available evidence indicated, fall within the range of 150-200 billion barrels, the production rate should reach a peak within the next 10-15 years, or between about 1966 and 1971.

The initial reaction to this conclusion was one of incredulity - the sun must be crazy! After the first shock subsided it was found that the validity of the analysis could not be challenged, so the only way the conclusion could be changed would be by increasing the magnitude of the estimate of Q_u . In order to delay the date of peak production to as late as the year 2000, Q_u would have to be increased to 600 billion barrels, a 4-fold increase over the lower figure of 150 billion barrels used in 1956, or a 3-fold increase over the higher figure. In other words, to delay appreciably the date of peak production would require increases in the estimate of Q_u , not by small percentages, but by multiples.

In response to this realization, the oil industry divided into two camps. One group found that their best estimate of the value of Q_u was in substantial agreement with the range of 150 to 200 billion barrels and could not be changed. The conclusion of an early date for peak production, unpleasant as this might be, could therefore not be avoided. The second group found this conclusion so abhorrent that they refused to accept it. For this group, the only alternative was to increase the estimates of the magnitude of Q_u . Consequently, with insignificant new information, published values of Q_u began to escalate. Beginning

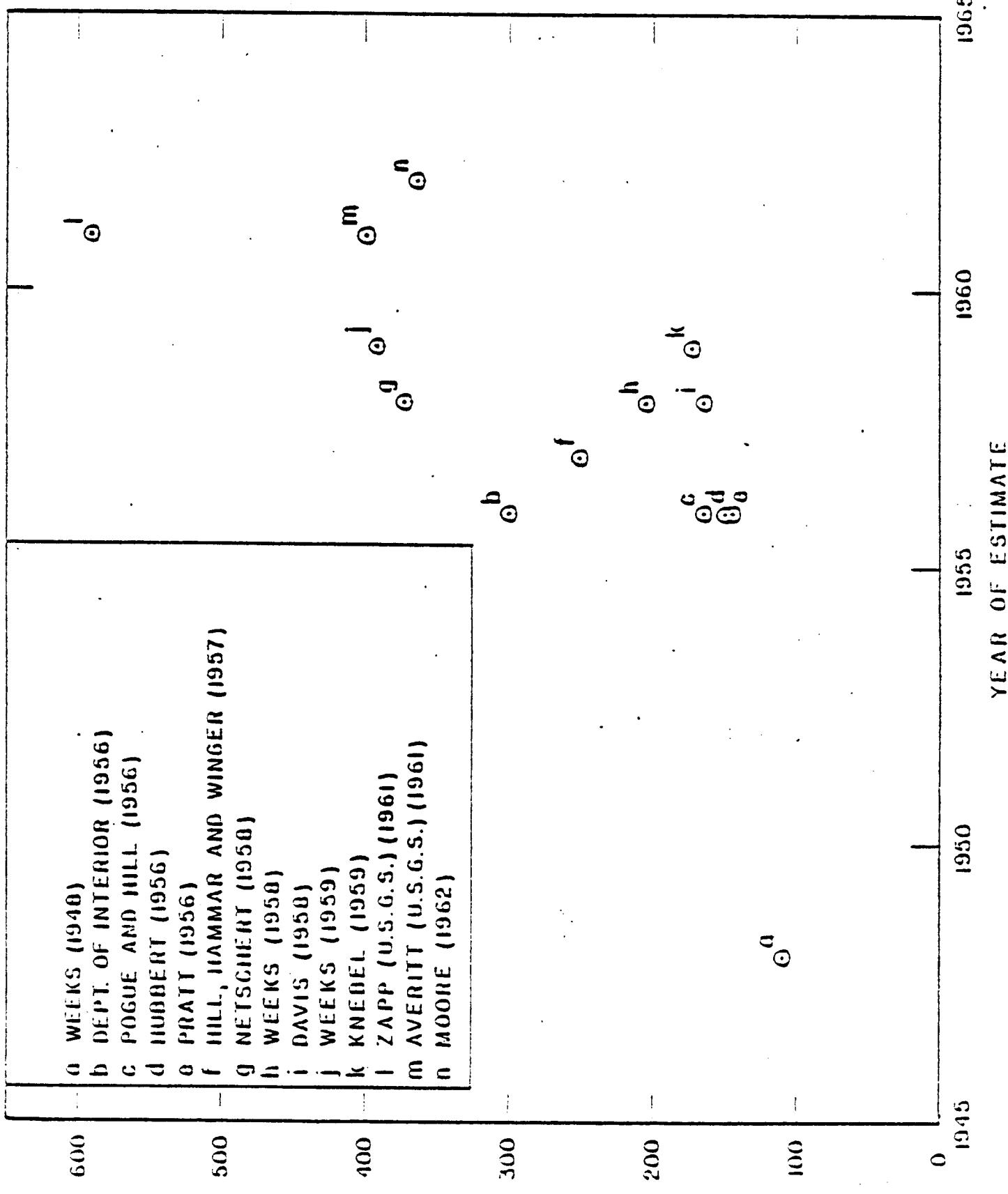
within a year (Figure 13), successive values of estimates for Q_a of 204, 250, 372, 400, and, after 5 years, 590 billion barrels were published. All of these estimates were from respectable sources, so if "authorities" were to be quoted, all of the above figures could be regarded as equally authoritative.

National Academy of Sciences Report of 1962

In 1961 President John F. Kennedy asked the National Academy of Sciences to establish a committee to advise him regarding natural resources. I was a member of that committee and chairman of its study and author of its report on Energy Resources (National Academy of Sciences, 1962). In view of this 4-fold range in recently published values of Q_a , it was evident that competent advice could not be given to the President based upon such a wide range of uncertainty of the basic data. Accordingly, a different method of analysis was required. Make no a priori assumptions regarding the magnitude of Q_a . Instead, let the cumulative petroleum-industry data of discovery and production as a function of time provide a means of estimating the date of the peak of production, and as a secondary objective, the approximate magnitude of Q_a .

Reliable petroleum-industry data exist on annual production since 1860. By summing these data we obtain cumulative production Q_p as a function of time. Another statistical quantity, with an accuracy of about 10 percent, is the industry annual estimate of proved reserves Q_r . Proved reserves is a conservative figure of the amount of oil in known fields, recoverable by present technology and equipment, that is almost certainly available. Reasonably good annual figures for proved reserves are available since 1900. Finally, there is a derived quantity, Q_d , which may be regarded as representing cumulative proved discoveries. This is defined by

$$Q_d = Q_p + Q_r. \quad (3)$$



(MILLIONS OF FIELDS)

THE NUMBER OF RECOVERABLE OIL FIELDS

In other words, the ~~minimum~~ amount of oil already discovered is the sum of the oil already produced plus the proved reserves.

For the complete cycle of production, the curve of cumulative production, Q_p , as a function of time will begin at zero, increase exponentially initially, then pass an inflection point and finally level off asymptotically as the limit Q_∞ is approached. The curve of proved reserves, Q_p , must begin at zero, reach a ~~maximum~~ in the midrange of the cycle, and then decline negatively exponentially back to zero. The curve of cumulative proved discoveries, Q_d , being the sum of Q_p and Q_r , will resemble that of cumulative production and will also approach the same limit, Q_∞ , except that in the midrange of the cycle it will precede the Q_p -curve by a time interval Δt .

Although the curves Q_p and Q_d can only increase monotonically with time, for small areas it is possible that they may have more than one inflection point. For a large area such as the whole United States these irregularities compensate one another and the composite curves tend to rise smoothly with only a single inflection point. Such a family of curves is illustrated in Figure 14.

The time derivatives of the Q_d -, Q_p -, and Q_r -curves are shown in Figure 15. The time derivative of equation (8) is

$$\frac{dQ_d}{dt} = \frac{dQ_p}{dt} + \frac{dQ_r}{dt}. \quad (9)$$

For the complete production cycle, the rate of proved discovery will begin at zero, rise to a ~~maximum~~, and decline to zero. The production-rate curve will be an approximate duplication of the discovery-rate curve displaced forward on the time axis by the amount Δt .

The curve of the rate of increase of proved reserves, dQ_r/dt , will begin at zero and go through a positive loop while reserves are increasing, cross the zero line when reserves are at their ~~maximum~~, and then follow a negative

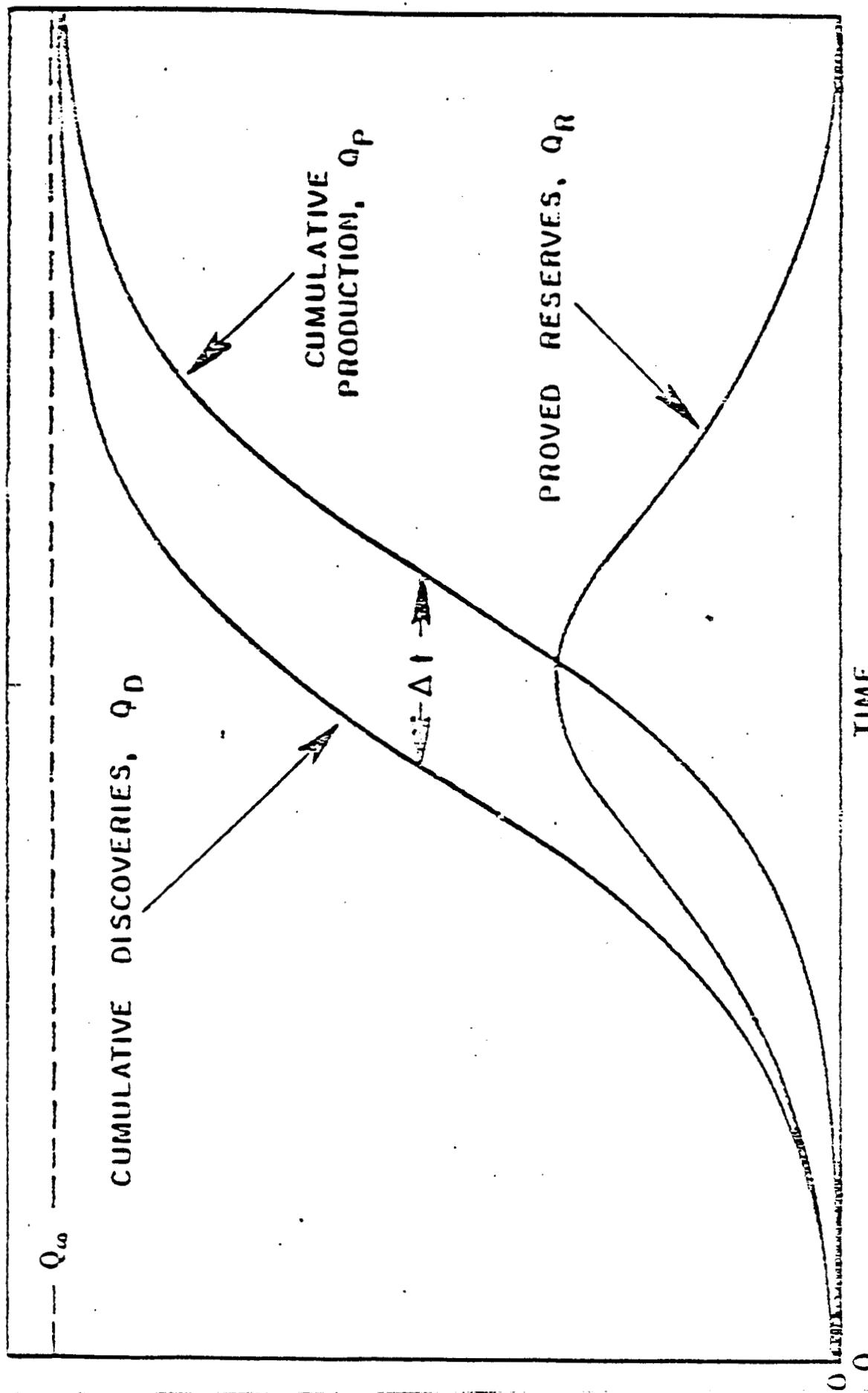


FIG. 14 - Variation with time of cumulative discoveries, proved reserves, and cumulative proved discoveries of oil during complete cycle of exploration and production (Hubbert's study, Fig. 1).

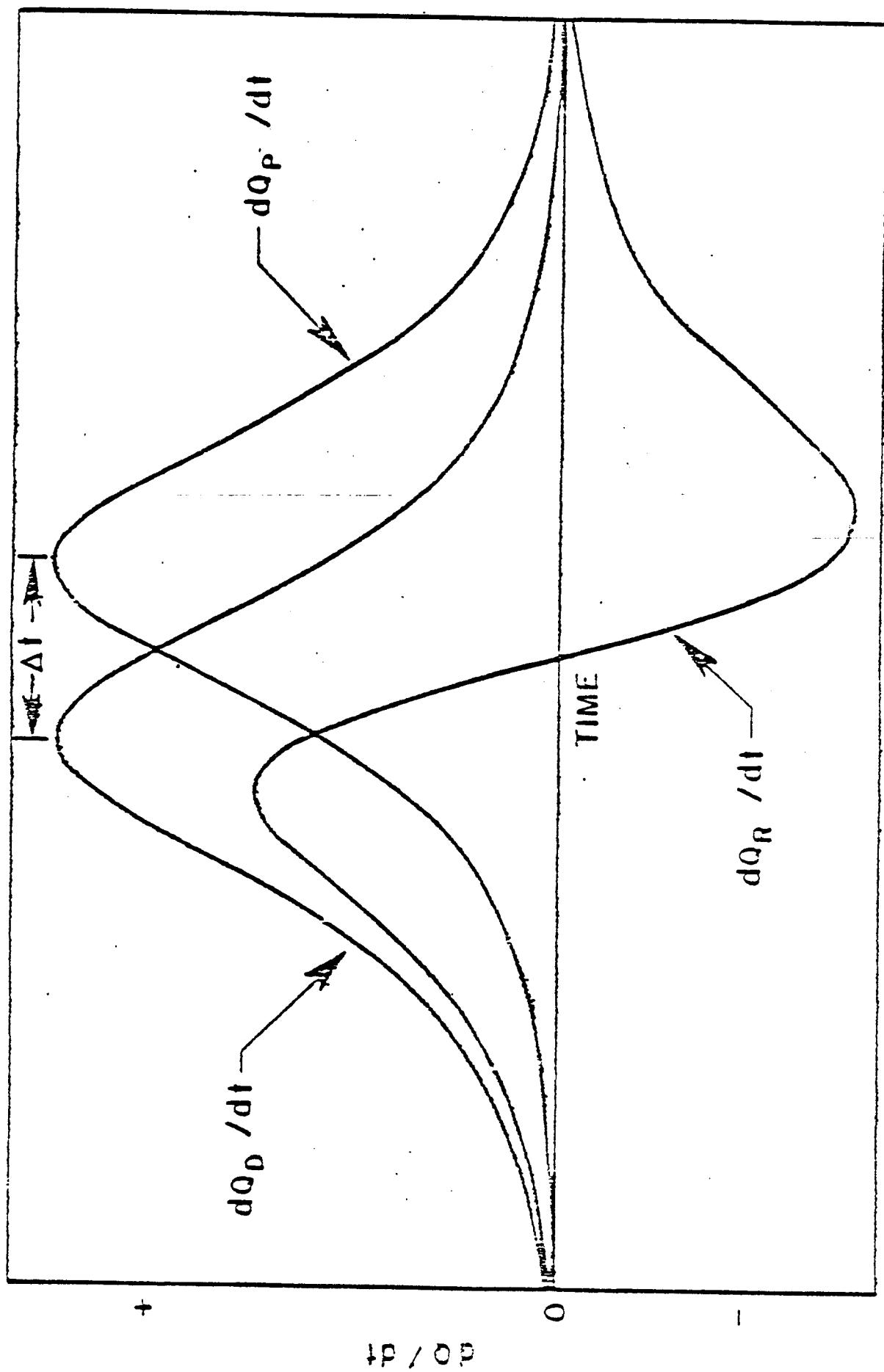


FIG. 15 - Time derivatives of curves in FIG. 14 (Hahlfert, 1962, FIG. 24).

loop before returning ultimately to zero. When reserves are at their maximum

$$\frac{dQ_p}{dt} = 0, \quad (1)$$

and equation (9) becomes

$$\frac{dQ_d}{dt} = \frac{dQ_p}{dt}. \quad (1)$$

At that time, the rate-of-discovery curve, already declining, is crossed by the still rising rate-of-production curve. Hence the dates of the peaks in the rate of discovery and of proved reserves are critical dates in the cycle. The discovery peak precedes the date of the proved-reserves peak by a time interval of approximately $\Delta t/2$, and the proved-reserves peak precedes that of the production rate by an interval of approximately $\Delta t/2$.

This was the method of analysis used in the Academy report of 1962. The raw data to the end of 1961 for Q_d , Q_p and Q_r are shown in Figure 16. By visual inspection, Δt is about 10-11 years, the inflection point on the Q_d -curve occurred at about 1957, and proved reserves appear to be approaching their maximum at about 1962. For purposes of taking analytical derivatives, it was found that a remarkably good fit for the Q_d -curve could be obtained by the logistic equation of the form

$$Q_d = Q_\infty / [1 + c \exp b(t - t_0)]. \quad (12)$$

Then,

$$Q_p = Q_\infty / [1 + c \exp b(t - (t_0 + \Delta t))], \quad (13)$$

and

$$Q_r = Q_d - Q_p,$$

where the values of the parameters were found to be,

$$Q_\infty = 170 \times 10^9 \text{ barrels}$$

$$c = 46.3$$

$$b = -0.0637 \text{ yr}^{-1}$$

$$t_0 = 1900 \text{ yr}$$

$$\Delta t = 10.5 \text{ yr}.$$

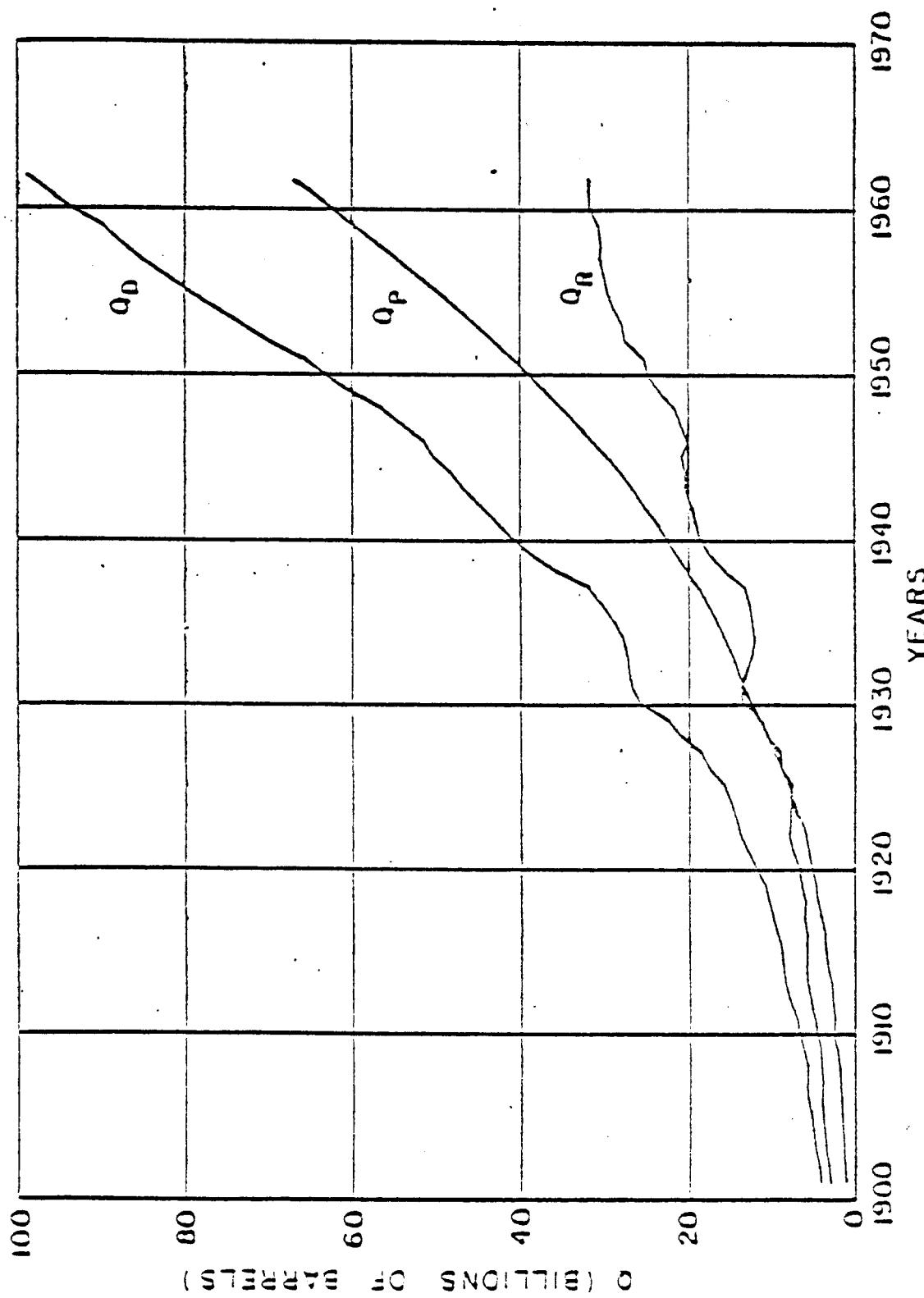


Fig. 16 - U.S. data on cumulative production, cumulative proved discoveries, and proved reserves of crude oil from 1900 to the end of 1961 (Hubbert, 1962, Fig. 25).

The data for Q_x , Q_y , and Q_z , superposed upon the analytical curves of the above equations, are shown graphically in Figure 17. The derivative curves, and the annual data for the rates of discovery and production are shown graphically in Figure 18, and those for the rate of increase of proved reserves in Figure 19.

What emerges from this analysis is that the peak in the rate of discovery occurred at about 1957, that of proved reserves was due to occur about 1962, and the peak in the rate of production at about 1968, with an uncertainty of not more than two or three years. An approximate, but less certain, value of 170 billion barrels emerged as an estimate of Q_x .

For natural gas in the same study it was found to be 16 years, and the date of the peak in the rate of gas discoveries about 1960. The date of the peak of proved reserves was estimated to be about 1969, and that of the rate of production, about 1976.

U.S. Geological Survey Estimate of 1961

In response to a directive from President Kennedy, the U.S. Geological Survey assigned its Assistant Chief Geologist, Vincent E. McKelvey, the duty of assembling the official Survey estimates on energy resources for submission to the Academy Committee. For the ultimate amounts of crude oil and natural gas to be produced in the Lower-48 states and adjacent continental shelves, the USGS figures for Q_x were 590 billion barrels for crude oil and 2,633 trillion cubic feet for natural gas. These figures were by a wide margin the highest estimates ever made until that time for the ultimate amounts of oil and gas to be produced in the Lower-48 states. They were 3.5 times higher for crude oil, and 1.5 times higher for natural gas than could be justified by petroleum-industry data.

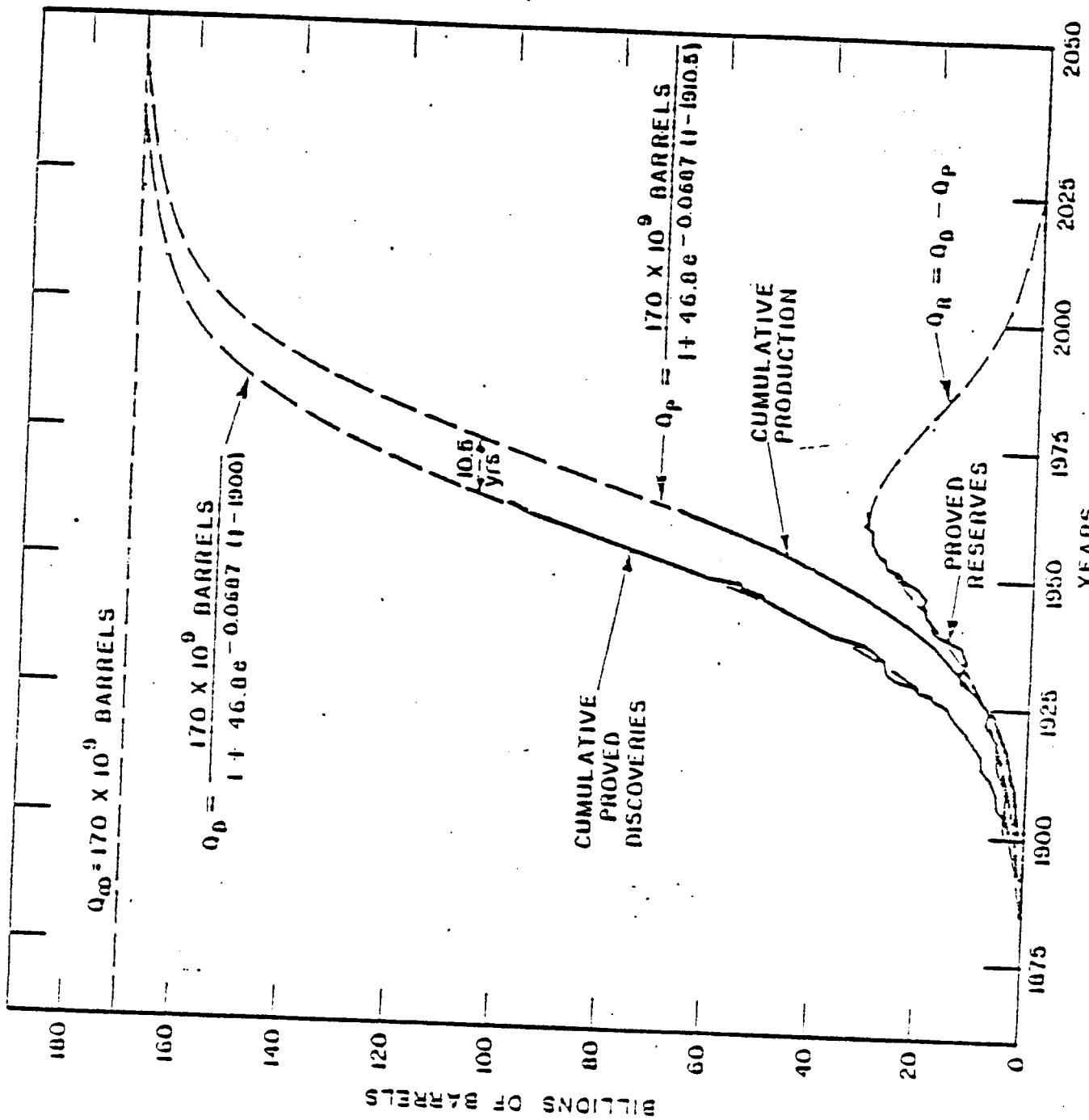


FIG. 17 - Mathematical fitting of curves of cumulative production, cumulative proved discoveries, and proved reserves.

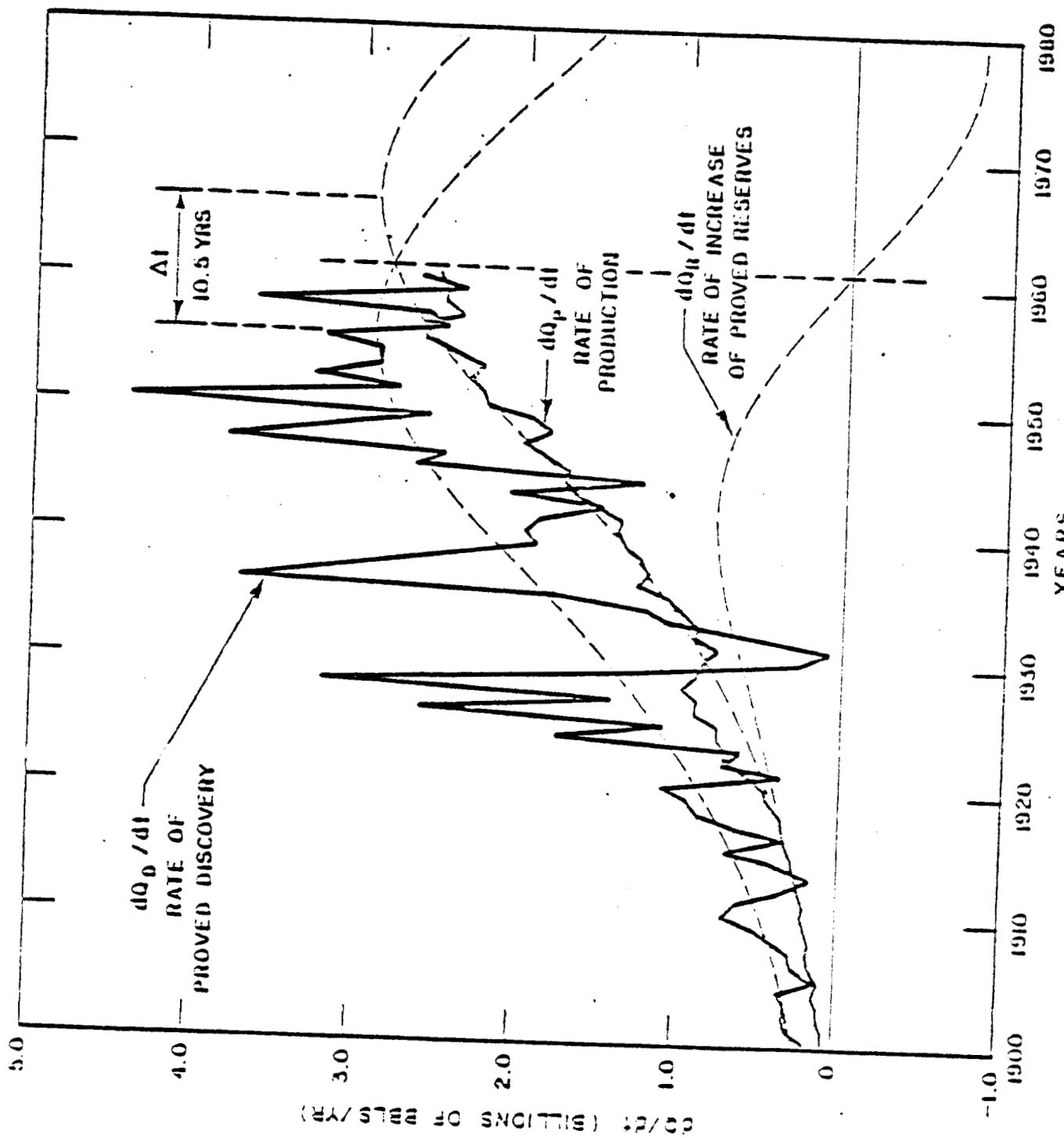


Fig. 18 -- Annual production and proved discoveries of U.S. crude oil summarized from *various sources*.

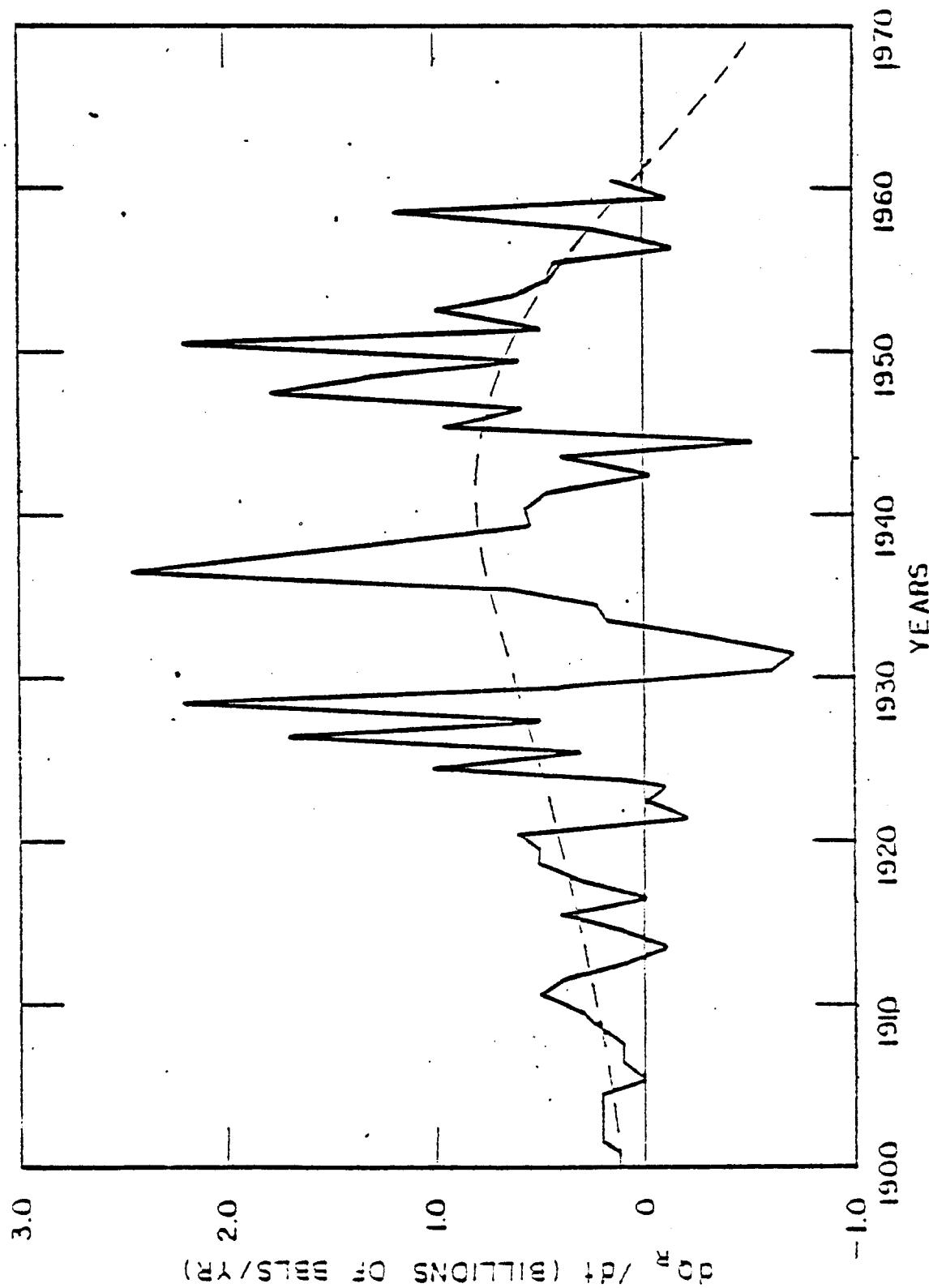


FIG. 19 - Annual Increase of proved reserves of U.S. crude oil superposed upon curve of mathematical derivative (Hubbert, 1962, FIG. 29),

The several Academy reports were sent to the President in November 1961, and released to the public by the President in January 1963. For the remainder of the 1960 decade, McKelvey, as the principal spokesman for the U.S. Geological Survey, continued to issue successive reports, without supporting evidence, with estimates of about 600 billion barrels for crude oil for the Lower-48 states. Also, during that period, as is seen in Figure 6, the rate of U.S. crude-oil production continued to rise. As a consequence, the influence of the Academy-report analysis was essentially zero. The problem was: When a rational analysis of data is ineffective, what else can one do? Since all such estimates are in effect predictions of future events, the final solution is obviously to wait and let the future make the decision. The Geological Survey figure of 600 billion barrels for q_0 was tantamount to a prediction that the peak in the rate of U.S. crude-oil production from the Lower-48 states would not occur until close to the year 2000.

Oil Discoveries as Function of Exploratory Drilling

In the meantime a different kind of analysis was devised. In the complete cycle of petroleum exploration in a given region there initially exist some fixed but unknown number of undiscovered fields. As exploration proceeds and successive fields are discovered, the number of remaining undiscovered fields continuously diminishes. Initially the probability that a given exploratory well will discover a field is near a maximum. But as the larger and shallower fields are discovered, the remaining fields become fewer and more difficult to find. Consequently the amount of exploratory effort per unit of oil discovery must be expected to increase continuously. Or, reciprocally, the amount of oil discovered per unit of exploratory effort must be expected to decline in roughly a negative-exponential manner as a function of cumulative exploratory activity.

A convenient measure of this is the oil discovered per unit depth of exploratory drilling dc/dh as a function of cumulative depth h of drilling. This would be a curve which, for the whole Lower-48 states, would be a statistical measure of the best that the petroleum industry has been able to do at any given stage of the cycle. Furthermore, it would be determined almost entirely by the technology of exploration and highly insensitive to economic influences such as price fluctuations or the financial climate.

In fact, the Geological Survey estimate of 590 billion barrels of 1961 was arrived at on the basis of unchecked assumptions regarding the form of this curve. It was estimated that by the end of 1961 130 billion barrels of oil had been found by 1.1 billion feet of exploratory drilling. This would have been at an average rate of discovery of 118 barrels per foot of drilling. It was further assumed that for near complete exploration an additional 3.9 billion feet, or a total of 5 billion feet of exploratory drilling, would be required, and that an additional 460 billion barrels of oil would be discovered by this amount of drilling. This also would be at a discovery rate of 118 barrels per foot. At this same rate, the oil discovered by the ultimate amount of drilling of 5 billion feet would be 590 billion barrels. Plotted as a curve of dc/dh versus h , this would be a horizontal line of 118 bbl/ft from $h = 0$ to $h = 5 \times 10^9$ ft.

The problem is: What would this curve have been if it were based upon actual petroleum-industry data rather than guesswork? Would it have been nearly constant in the past, or principally declining? What is required are the statistical data of exploratory drilling and the oil discoveries as a function of time since 1860. From this, the oil discoveries per foot versus cumulative depth of drilling can be determined. However, for this purpose a different measure of

oil discoveries from that used previously is required. To correlate with the drilling in any given year, all of the oil that the fields discovered in that year will ultimately produce must be credited to the drilling done in that year.

To answer these questions, I made such a study for the Lower-48 states, which was published in 1967 (Hubbert, 1967). The principal results are those shown in Figure 20. By 1966, cumulative exploratory drilling amounted to 1.5×10^9 feet. This divides conveniently into 15 units of 10^8 feet each. For each of these units the amount of oil discovered and the average discoveries per foot are shown. The first unit spanned the time period of 60 years from 1860 to 1920. This was a primitive period of exploratory technology, yet the average rate of discovery was high, 194 bbl/ft. A ~~maximum~~ rate of 276 bbl/ft was reached during the third interval extending from about 1927 to 1937. That followed a spectacular decline to 35 bbl/ft for the last interval from 1963-1966. The cumulative discoveries by this amount of drilling amounted to 136 billion barrels.

This is approximately an exponential decline curve. For this a conservative fit would be an exponential curve which has the same ordinate at $h = 15$ (10^8 ft), 3.63 (10^3 bbl/ 10^8 ft), as the last column in Figure 20, and whose integral from $h = 0$ to $h = 15$ is the same as the actual discoveries, 136×10^9 bbl. Such a curve is given by

$$\frac{dQ}{dh} = (dQ/dh)_0 \exp(-ch), \quad (14)$$

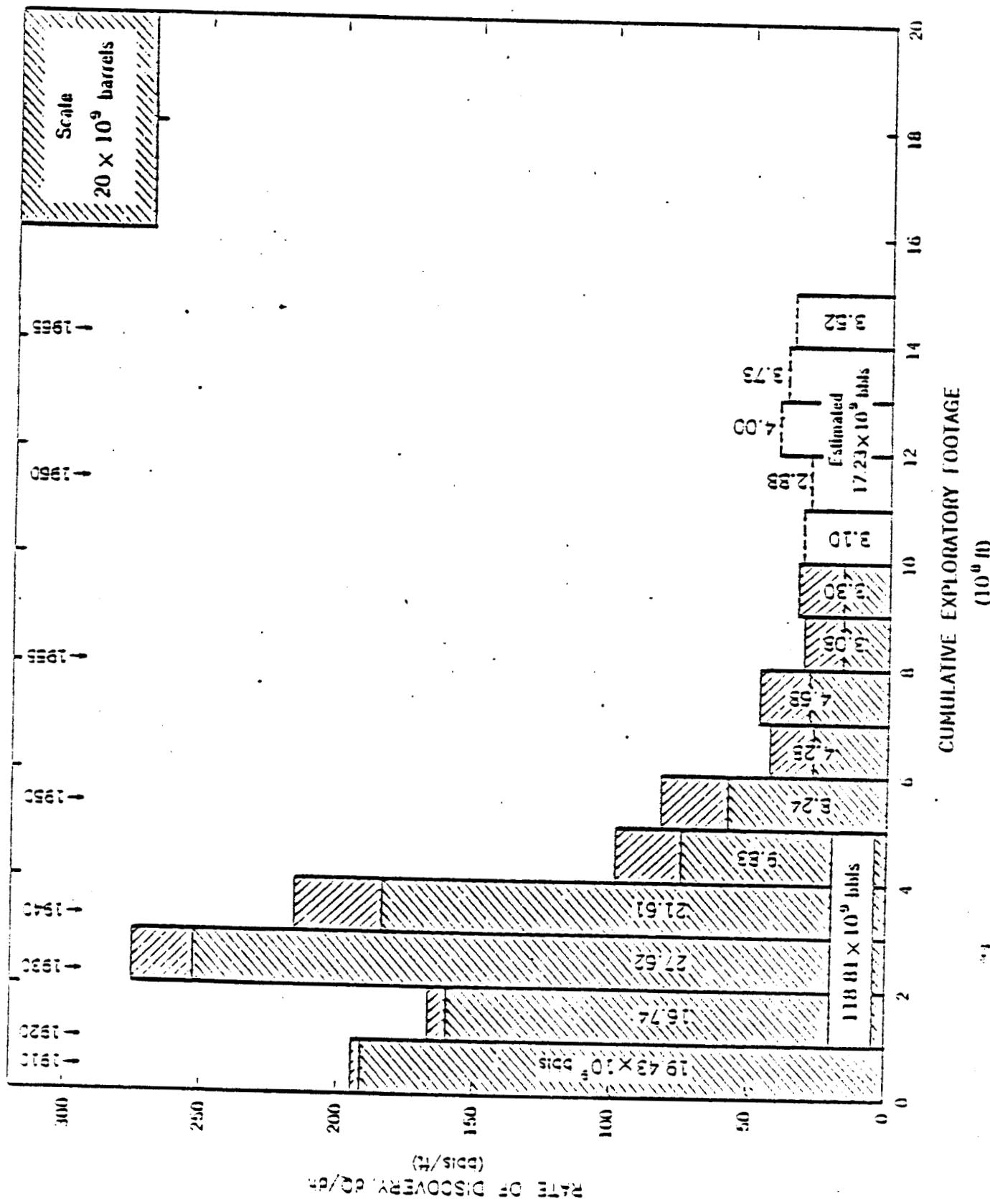
where

$$(dQ/dh)_0 = 13.63 (10^3 \text{ bbl}/10^8 \text{ ft}),$$

$$c = 0.1111 \text{ per } 10^8 \text{ ft.}$$

For unlimited drilling, the value of Q_0 , given by the integral of this equation, is

$$Q_0 = (dQ/dh)_0 / c = 163 \times 10^9 \text{ bbl.} \quad (15)$$



Of this, 136 billion barrels had already been discovered by the first 15 units of drilling, leaving 32 billion barrels still to be discovered.

Thus it is seen that when actual petroleum-industry data on discoveries and exploratory drilling are used, instead of guesswork, the value, 168 billion barrels, obtained for Q_0 , is in close agreement with that of 170 obtained previously using a different method of analysis and different data. In particular the data given in Figure 20 completely invalidated in 1967 the assumption on which the USGS estimate of 590 billion barrels had been based. Yet, with only minor modifications, the assumption upon which the estimate of 590 billion barrels was based continued to be the theoretical basis of USGS estimates until September 1974. At that time the Appraisals Group of the USGS Branch of Oil and Gas Resources, under the joint direction of two experienced oil geologists, Betsy M. Miller and Barry L. Thompson, was authorized to make an independent appraisal of the undiscovered oil and gas resources of the United States. In that study, which was published in June 1975 as U.S. Geological Survey Circular 725, drastically reduced estimates were obtained which were in substantial agreement with those given in my Academy report of 1962 and in my Senate report of 1974. This was confirmed by the then Director of the U.S. Geological Survey in a USGS News Release of June 20, 1975. In commenting on the Appraisal Group's report, which was then being released, he stated:

"The procedures used by the authors yield more conservative results than those made earlier, which were based mainly on the assumption that an equivalent volume of unexplored sediments would contain 50 to 100 percent as much petroleum as similar explored sediments."

Since the volume of sediments exploited is proportional to the cumulative depth of drilling, this statement is equivalent to the assumption that future discoveries per foot would be from 0.5 to 1.0 of the average of the past.

Report of 1974 for U.S. Senate Committee

By 1971 it was becoming evident that a serious shortage in U.S. domestic oil production was impending. At that time the U.S. Senate Committee on Interior and Insular Affairs began a new study of National Fuels Policy, and I was invited by its Chairman, Senator Harry M. Jackson, to bring my previous energy studies up to date for the Committee. In this study (Hubbert, 1974) the data were reviewed as of the end of 1971.

Figure 21 shows the three curves Q_d , Q_p , and Q_r with 10 more years of data since the Academy report of 1961. An entirely new computation was made for the best mathematical fitting with logistic equations, but the best value for Q_d was still 170 billion barrels. By 1972, it was clear that the peak in the curve of proved reserves did occur at about 1962, and reserves had been declining ever since. Figure 22 shows the derivative curve of proved reserves, dQ_p/dt . This crossed the zero line in 1962 from its positive loop and was rapidly descending on its negative loop.

Figure 23 shows the rate-of-discovery curve, dQ_d/dt , and Figure 24 that of the rate of production, dQ_p/dt , superposed upon their respective mathematical curves. The rate-of-discovery curve definitely passed its maximum at about 1957 and was well advanced in its decline. The actual data on the rate-of-production curve were more ambiguous. The annual production dropped sharply in 1957 at the time of the first Suez Crisis. It remained well below the mathematical curve until 1967 and then rose sharply to an eccentric peak of 3.43×10^9 bbl in 1970, followed by a small drop in 1971. Considering the annual production curve alone, there is no visual evidence that this curve by 1971 must have been approaching its maximum. However, the composite evidence of the relation between the three curves made the conclusion inescapable that the

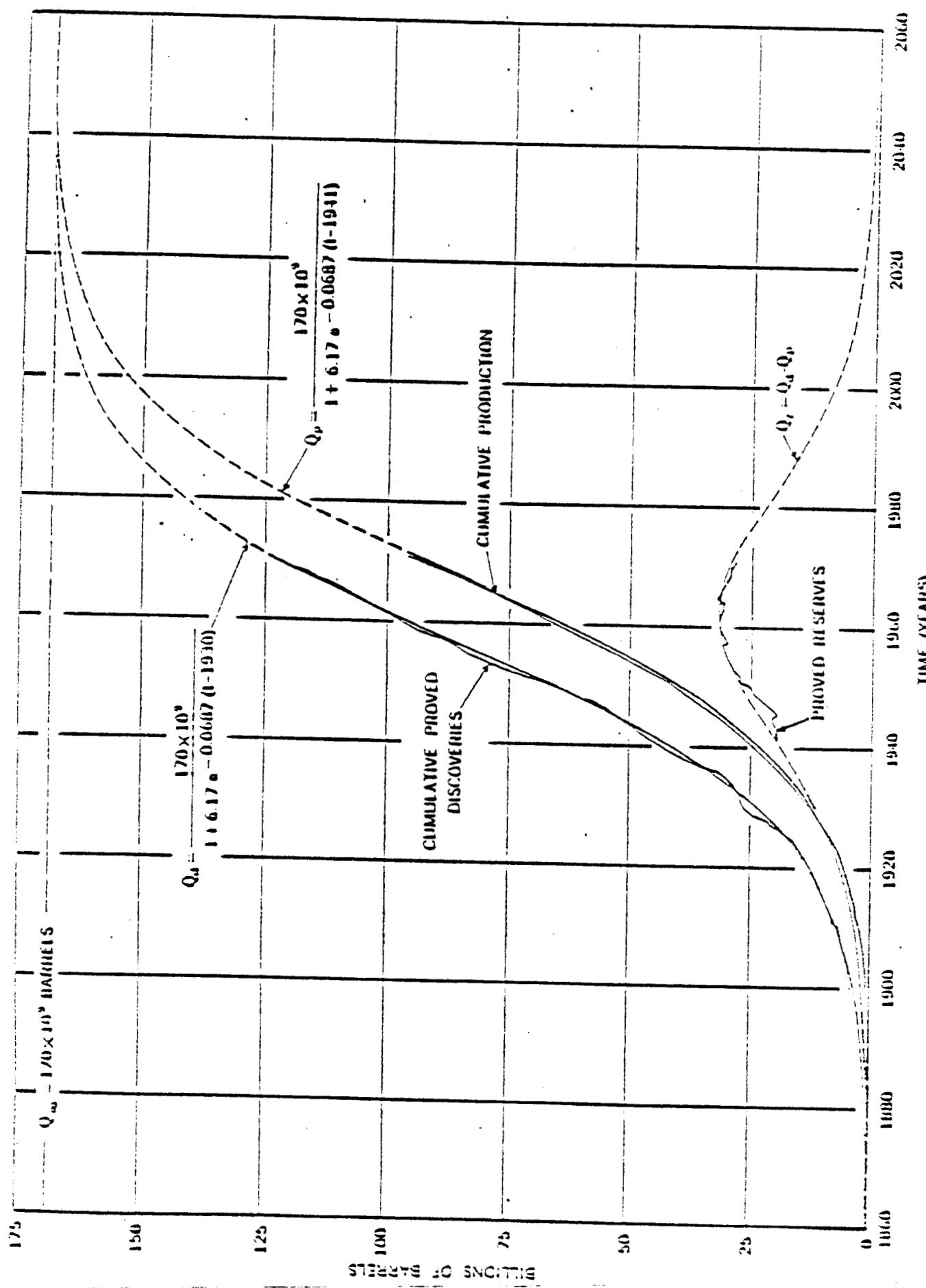


FIG. 21 - New mathematical fitting of data for cumulative proved discoveries, cumulative production, and proved reserves of U.S. crude oil from lower-48 states to the end of 1971 (Hubbert, 1974a, FIG. 16).

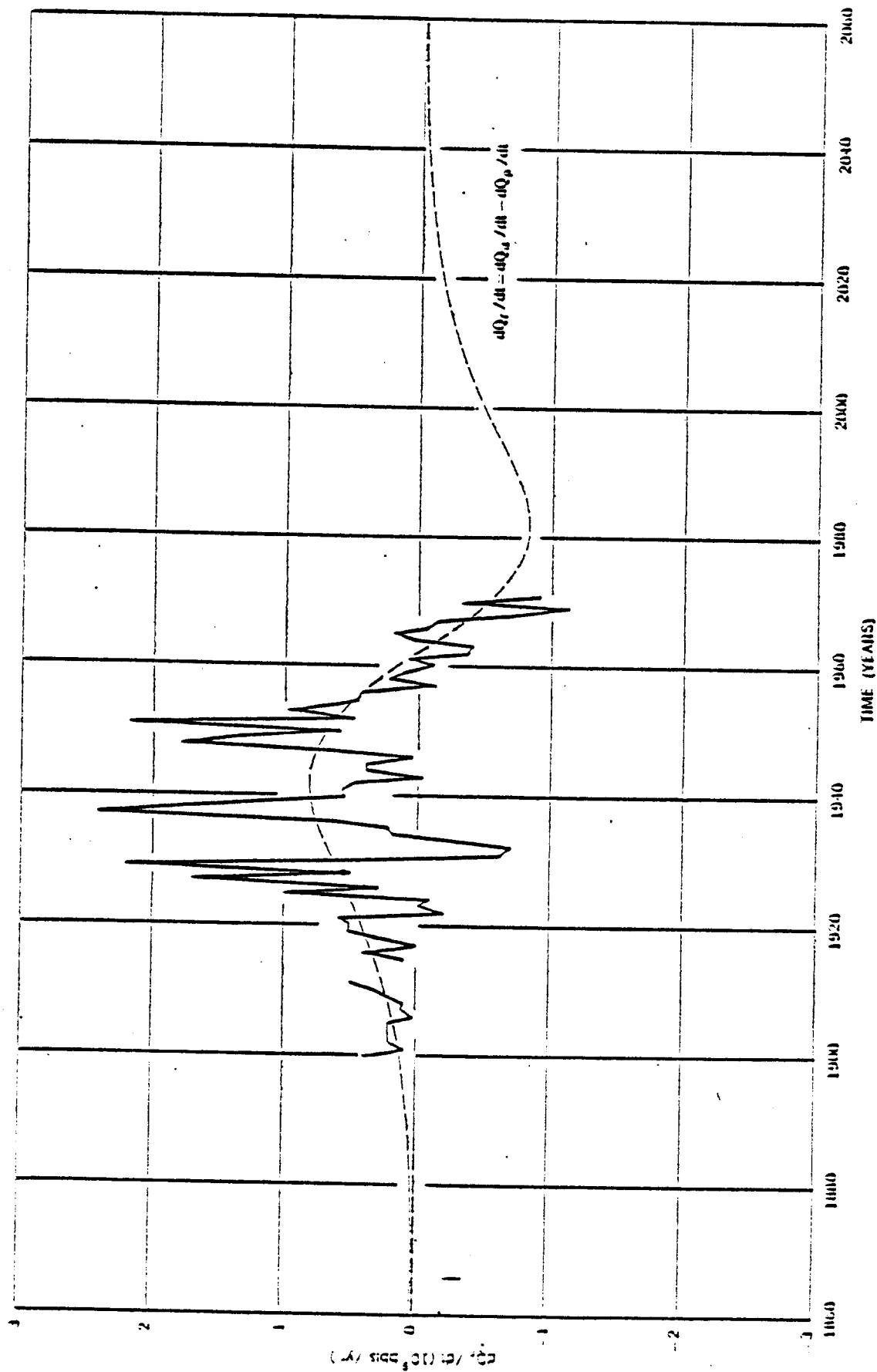


Fig. 22 - Annual increases in proved reserves of crude oil from Lower-40 states to the end of 1971, superposed upon curve of mathematical derivative (Hubbert, 1974a, Fig. 40).

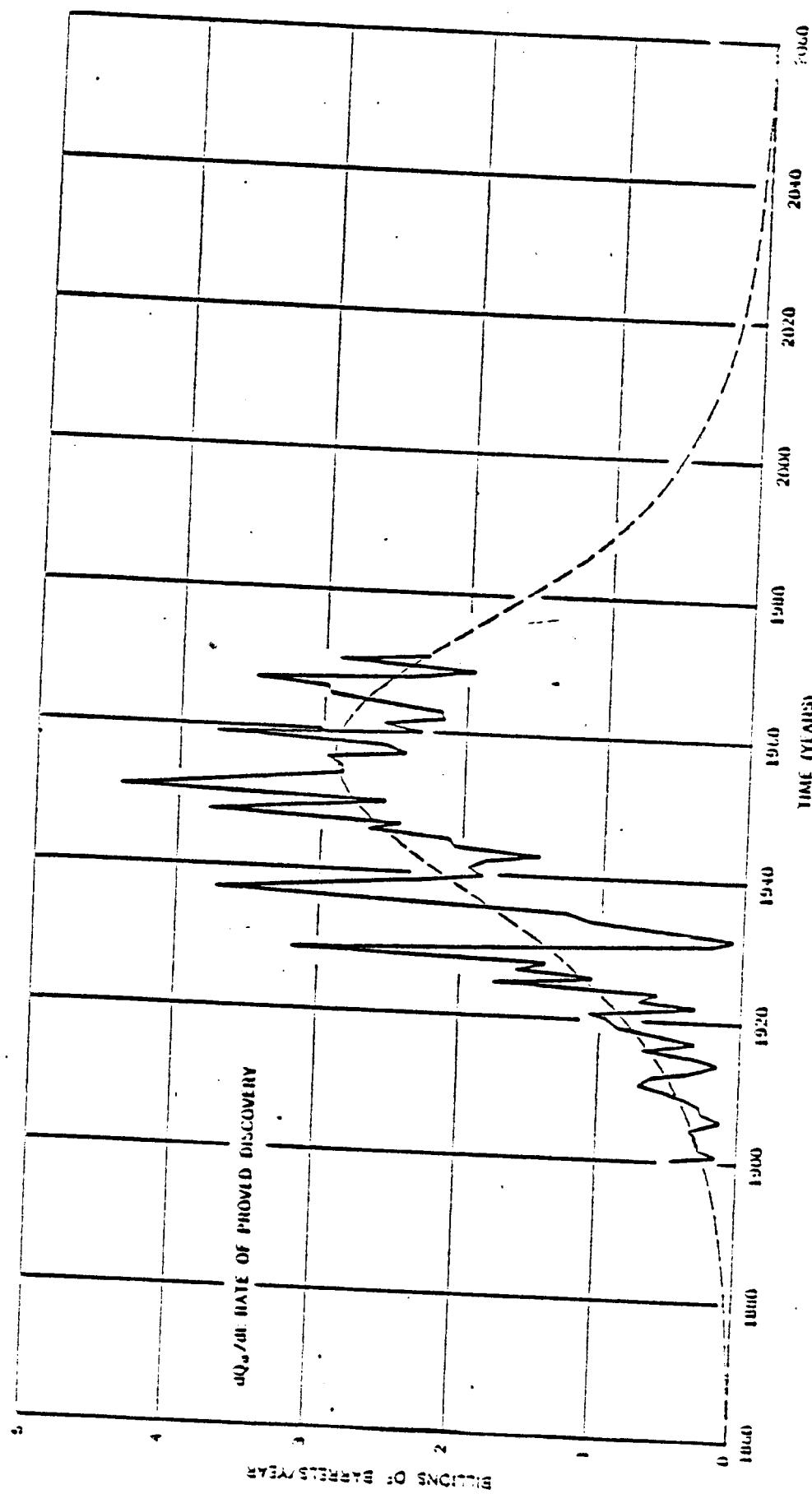


FIG. 21 - Annual proved discoveries of crude oil from Lower-40 states to the end of 1971, superposed upon curve of mathematical derivative (Hubbert, 1974a, Fig. 10).

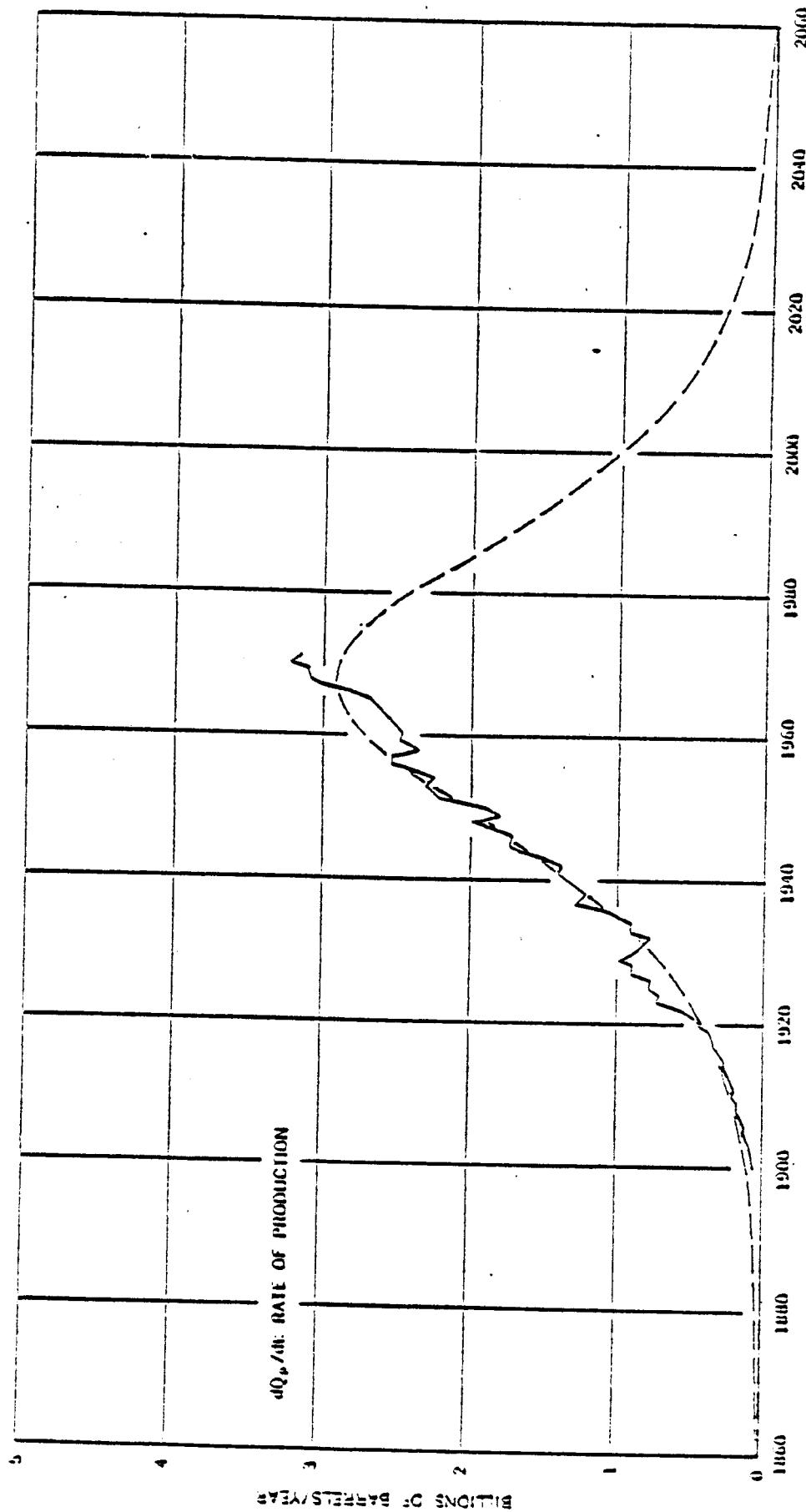


Fig. 24 - Annual production of crude oil from Lower-48 states to the end of 1971, superimposed upon a curve of initial derivative (Halibut, 1974, Fig. 39).

production rate must have been just on the brink of decline.

This was confirmed independently by a new study of the oil discoveries per foot shown in Figure 25. This closely resembles Figure 20 of 1967, except that more and better data were available. By 1972, 17 units of 10^3 -ft each had been drilled, and 143 billion barrels of crude oil had been discovered. This included cumulative production plus proved reserves, plus the estimated additional oil the known fields would produce in excess of the 1971 estimate of proved reserves. The discovery rate per unit of drilling had dropped 90 percent, from a maximum rate of 29.95 (10^3 bbl/ 10^3 ft), or 299.5 bbl/ft, for the third unit, to 3.02, or 30.2 bbl/ft, for the 17th unit. Extrapolation of the negative-exponential curve passing through the last point and having an integral of 143×10^9 bbl for the first 17 units gives 29×10^9 bbl for future discoveries, or a total of 172×10^9 bbl for Q_s .

The estimated complete-cycle curve for crude-oil production from the Lower-48 states as of 1972 is given in Figure 26, based upon a value of 170 billion barrels for Q_s . Of this, the time required to produce the first 10 percent, or 17 billion barrels, was from 1860 to 1932; that for the middle 30 percent would be the 67-year period from 1932 to 1999; and finally for the last 10 percent, from 1999 onward. It is impressive to note the brevity of the major period of oil exploitation. Children born in the middle 1930's will see the United States consume most of its oil during their lifetimes.

In 1972 the peak in the rate of natural-gas production had not yet occurred. The peak in natural-gas proved reserves had already occurred in 1967, two years earlier than had been predicted in 1962, and the production peak was imminent. It occurred, with a production of 22.6 trillion ft³, in 1973.

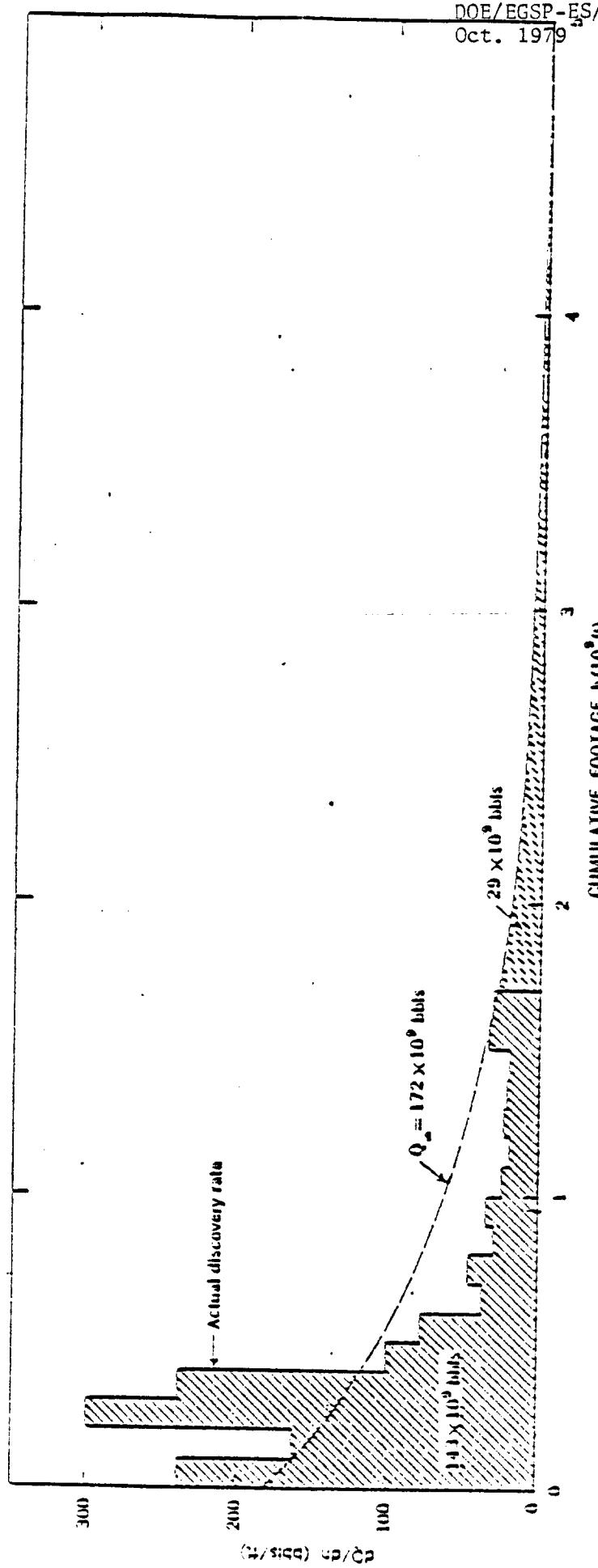
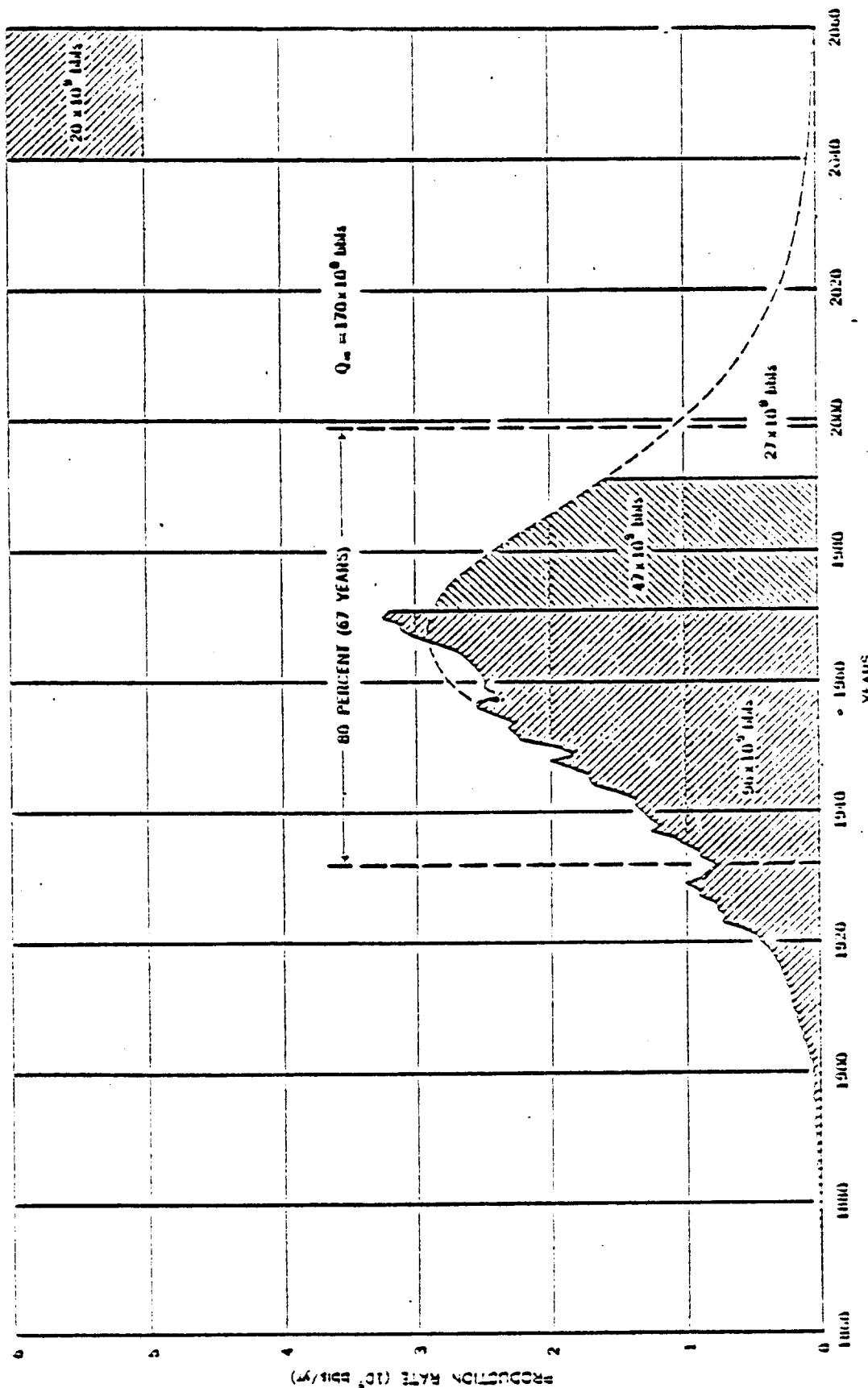


FIG. 25 - Crude-oil discoveries per foot for each 100-ft interval in the Lower-4B unit from 1960 to the end of 1971 (Hubbert, 1974n, Fig. 50).



U.S. Crude-Oil Developments, 1972 - 1977

Annual data for 6 more years, to the end of 1977, have become available since 1971. These are shown in Figures 27 to 30. Figure 27 brings the curves of cumulative discovery, proved reserves, and cumulative production to the end of 1977, superposed in each case upon the mathematical curves derived in 1972. Note that in each case the actual data have fallen short of the mathematical predictions of 1972.

Figure 28 shows the rate of increase of proved reserves. Since about 1970 proved reserves have been decreasing more rapidly than predicted by the mathematical derivative curve. For the years 1975, 1976, and 1977 proved reserves had an average annual decline of about 1.5 billion barrels per year, more than twice that shown by the mathematical curve. Similarly, Figure 29 shows that for the 5-year period, 1973 to 1977, even the high points in the rate-of-discovery all fall below the mathematical curve. Finally, Figure 30 shows unequivocally that the year 1970 was the date of the all-time peak in the rate of oil production in the Lower-48 states. After 1972 the annual production dropped more steeply than had been estimated by the mathematical curve. It could be that all of these accelerated declines during the 1970 decade represent only a temporary aberration. If not, it is doubtful whether the ultimate cumulative production will reach 170 billion barrels.

World Crude-Oil Resources

Space here does not permit a detailed discussion of world oil resources, there is agreement among international oil companies and petroleum geologists the value of ϕ_0 for cumulative world oil production is about 2,000 billion. Of this, approximately one-half has already been discovered and about

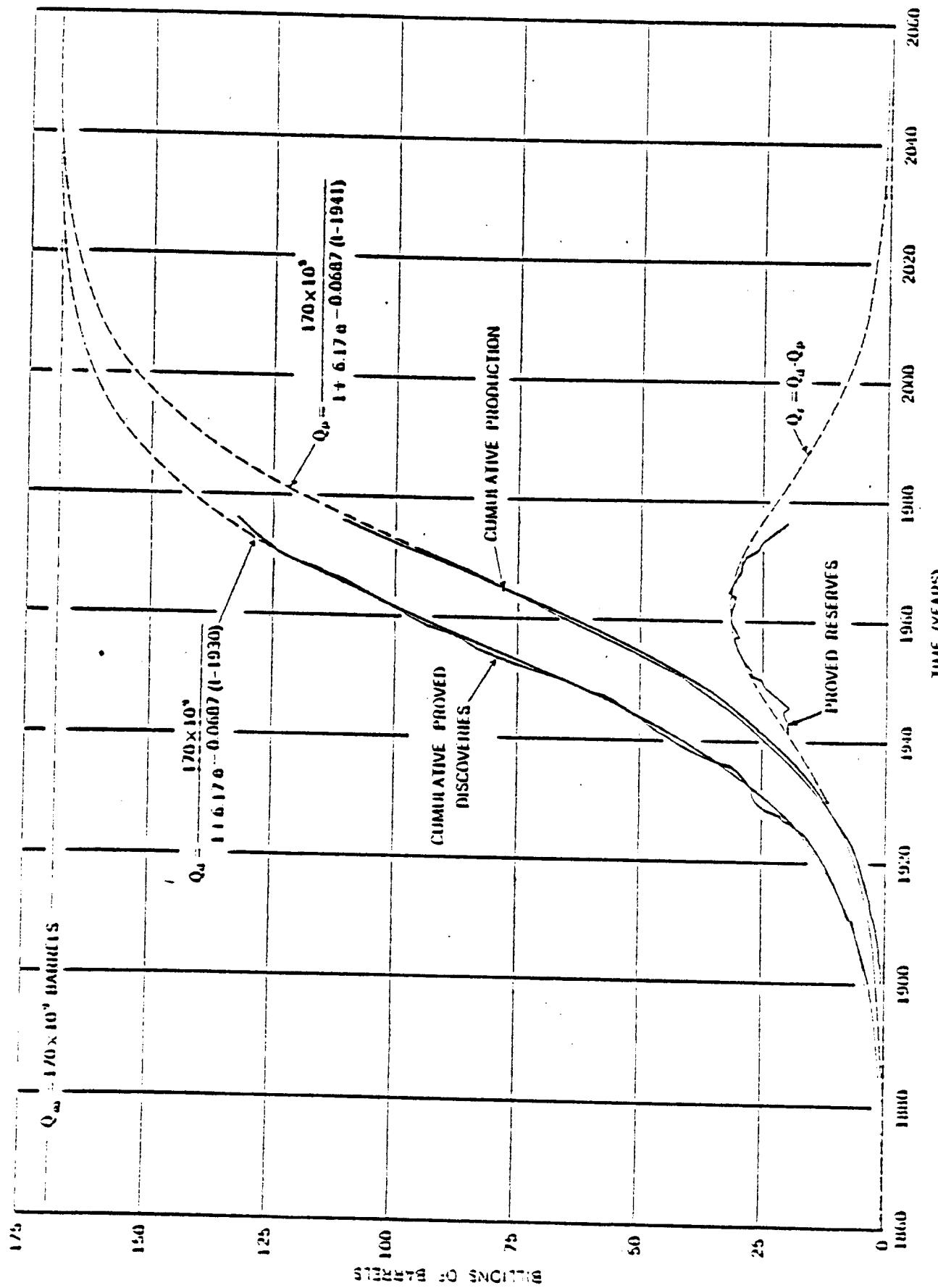


FIG. 27 - Cumulative proved discoveries, cumulative production, and proved reserves of crude oil from the Lower-48 states to the end of 1977; superposed upon mathematical curves based upon data to the end of 1971 (Lohrbert, 1978).

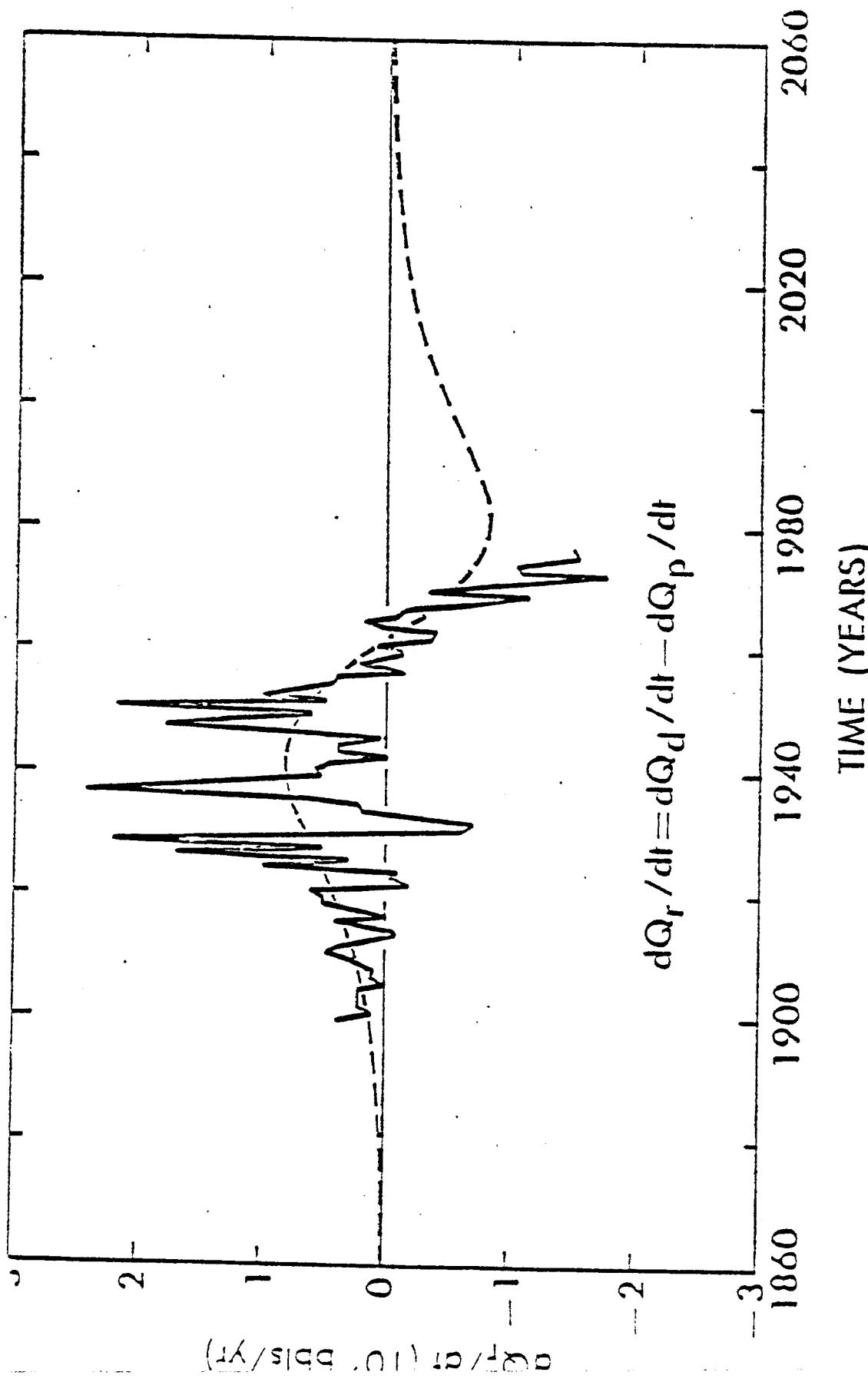


Fig. 2b - Rate of increase of proved reserves in Lower 48 states to the end of 1977, superposed upon curve of mathematical derivative based upon data to the end of 1971 (Ruthert, 1978, Fig. 12).

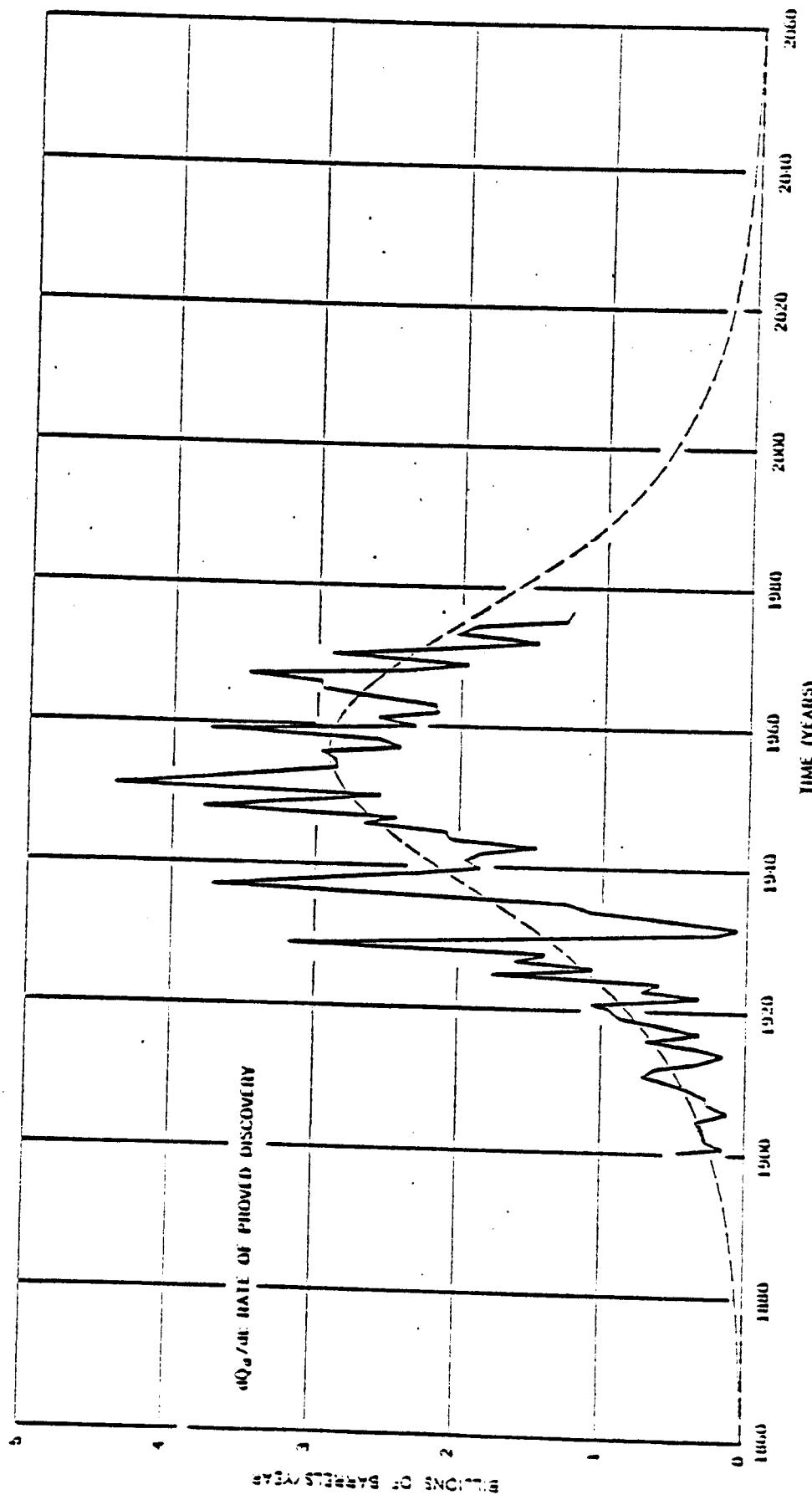


FIG. 29 - Annual rate of proved crude-oil discovered in Lower-48 states to the end of 1977, superposed upon curve of mathematical derivative based upon data to the end of 1971 (Holdbert, 1970, FIG. 13).

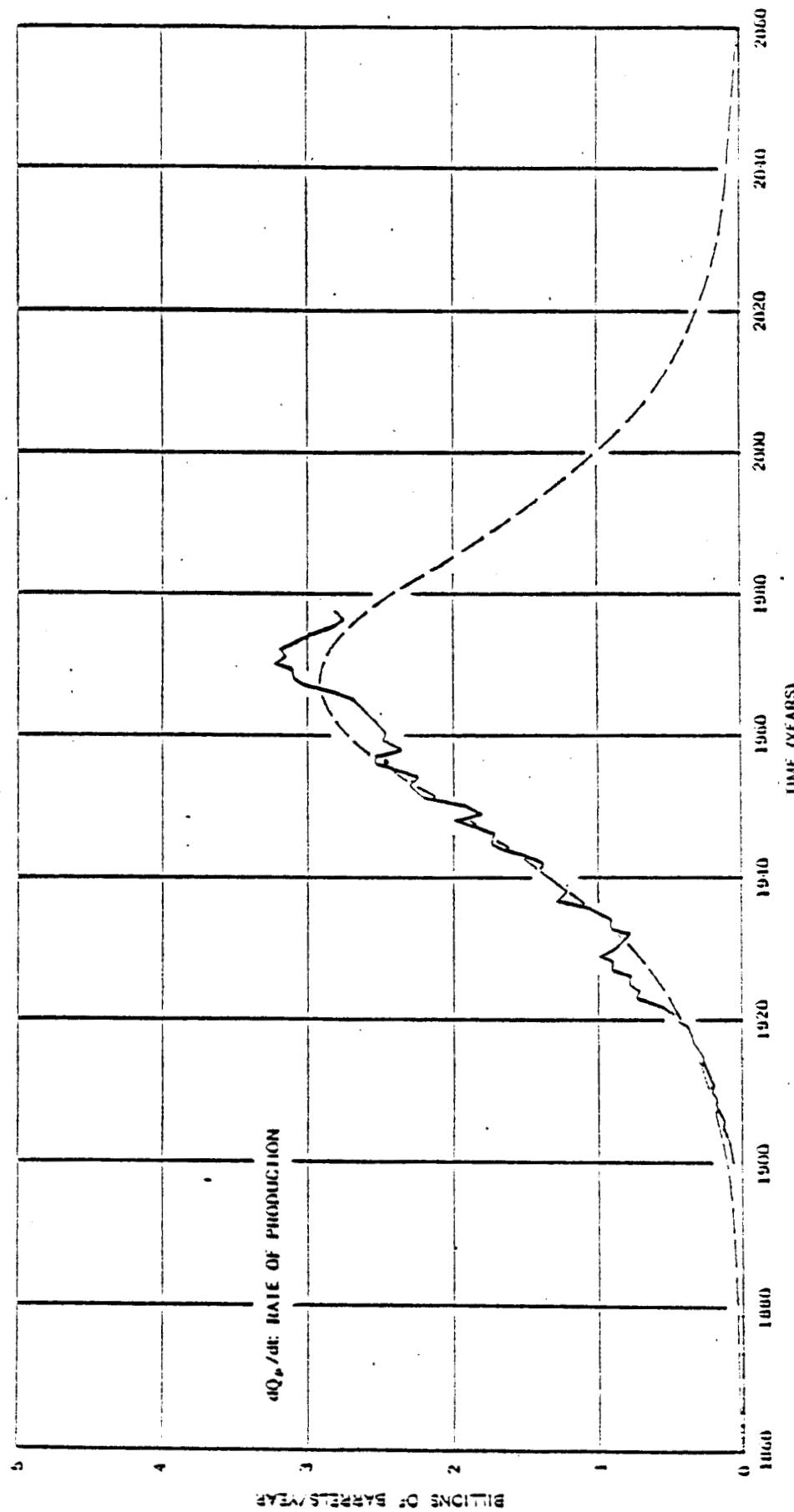


FIG. 10 - Annual crude-oil production in Lower-48 states, superposed upon curve of mathematical derivative based upon data to the end of 1971 (Hubbert, 1970, FIG. 14).

10 percent already consumed. The approximate geographical distribution of the world's initial recoverable crude-oil resources, and the quantities already produced are shown in Figure 31.

Attention is directed to the contrast between the 215 billion barrels initial supply of oil of the whole United States, half of which has already been consumed, and the estimated 1,000 billion barrels or more of the Middle East and Communist countries. When it is considered that the United States, with only about 11 percent of the world's initial oil supply, has been the world's leading oil-producing country, it becomes obvious why the United States should also lead the world in its oil depletion.

Figure 32 shows the rate of world crude-oil production to the end of 1977, and two possible complete-cycle curves, based upon a value of 2,000 billion barrels for G_0 . The first represents an orderly rise and decline, on the assumption of no major political or economic disturbances. This curve would reach its peak about the year 1995, and its middle-50-percent time span would be about 58 years from 1965 to 2023. The second curve assumes that, due to Middle East and other disturbances, the rate of production remains fixed at the present rate of about 20 billion barrels per year until depletion decline occurs. For this curve the middle-50-percent span would be extended to about 81 years, or from about 1965 to 2056. In either case, most of the world's oil will be consumed during the lifetimes of children born within the last decade.

Other Petroleum Resources

Other petroleum resources include natural gas and natural-gas liquids, heavy oils, and oil shales. The world geographical distribution of natural gas is similar to that of crude oil, and the time period of consumption is also about

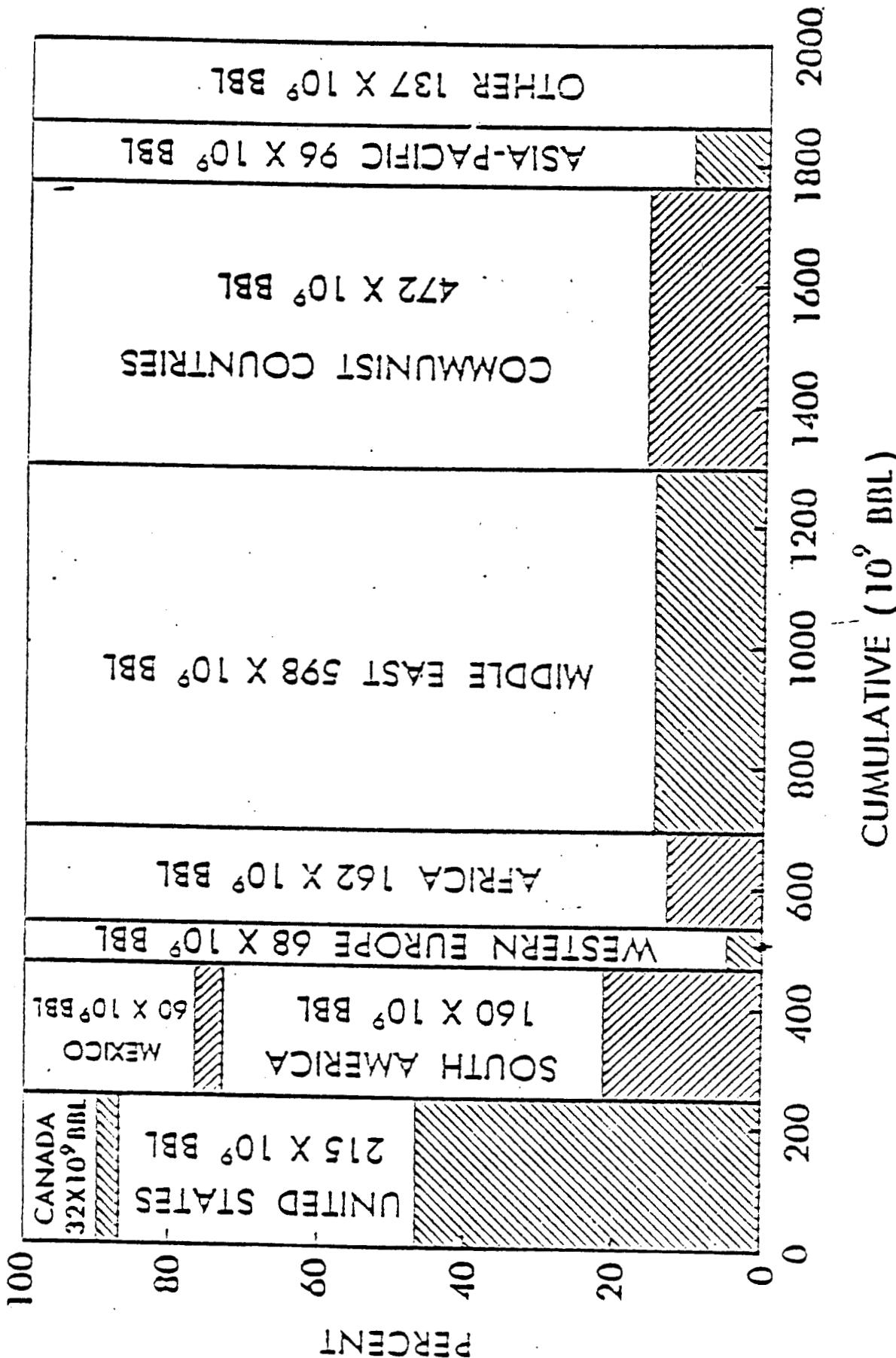


FIG. 31 - Cumulative crude-oil production (shaded areas), and estimated ultimate production for the world, by major geographical region.

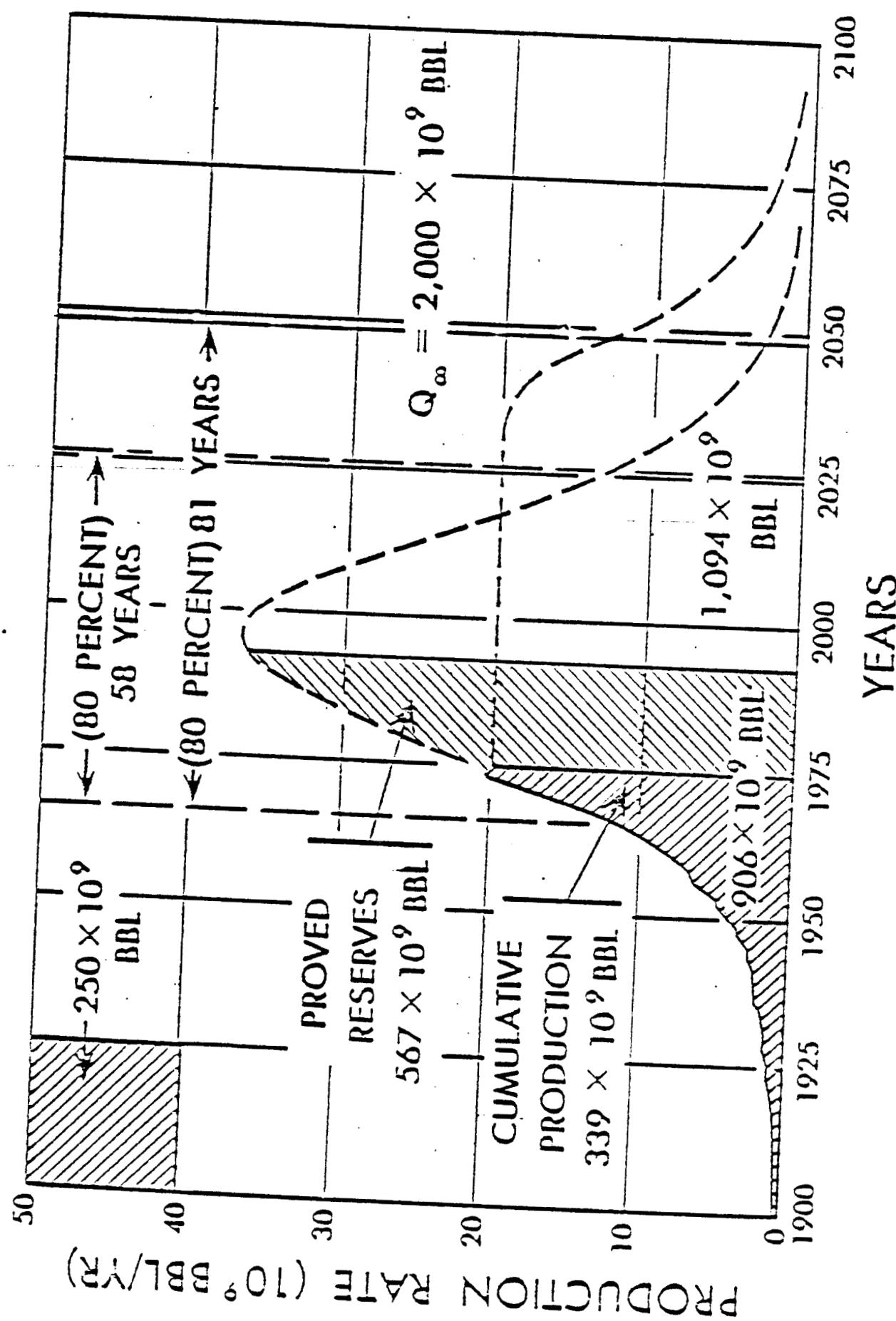


FIG. 32 - Alternative complete cycles of world crude-oil production starting 1970 etc., etc.

the same. The present estimate for the ultimate amount of natural gas to be produced in the United States, including Alaska and adjacent continental shelves, is about 1,250 trillion cubic feet; and for the world, about 10,000 trillion cubic feet.

Heavy oils are essentially crude oils of a density of approximately 1 kilogram per liter, and a high enough viscosity to preclude their being recovered by conventional oil wells. The best known of such deposits are those of the Athabasca heavy-oil sands of northern Alberta, occurring in several separate areas at depths from zero to 800 meters. The total quantity of oil-in-place is about 1,000 billion barrels, of which about 330 billion barrels is considered recoverable. Exploitation by surface mining began about 1968 and further development is under way.

The second major deposit occurs along the Orinoco valley in Venezuela. This is at a depth of 450 to 600 meters, and extends in an east-west belt 650 kilometers long and about 78 kilometers wide. The oil-in-place is estimated to be as much as 2,000 billion barrels, of which 10 percent may be recoverable.

The best known oil-shale deposits are those of the Green River shales of Eocene age in three separate deposits in southwestern Wyoming, western Colorado, and eastern Utah. Another major deposit occurs in the Iraty shale of Late Permian age in the Paraná basin of southern Brazil, Uruguay, and eastern Paraguay.

The oil content of the Green River shales ranges from 5 to 100 gallons per ton (20 to 420 liters/metric ton), and the aggregate amount is large, 1,500 barrels or so. This figure is deceptive, however, because only thick beds containing 30 gallons or more per ton (125 liters/metric ton) are considered favorable for extraction at present, and the oil obtainable from these reduces

to about 20 billion barrels. During the 1970 decade several leases of the richer oil shales have been granted to various combinations of oil and shale-oil companies for early exploitation, but most of these have tabled their operations because of mounting costs.

World Outlook for the Fossil Fuels

On the basis of the foregoing information, we can now see with reasonable clarity the nature of the fossil-fuel epoch in human history. The time to produce the first 10 percent of the fossil fuels is roughly the 1,000 years before the year 2000. The time required to consume the middle-30 percent will be approximately the three centuries from 2000 to 2300, and the last 10 percent may require another 1,000 years after 2200.

The brevity of this in human history can best be appreciated if we plot a graph of the complete cycle of exhaustion of the fossil fuels on a time axis extending from 5,000 years in the past to 5,000 years in the future, as is shown in Figure 33. In this figure the obelisk-like spike near the middle with a 300-year span for the middle-30 percent represents the epoch of the fossil fuels. Yet this is responsible for the development of our modern industrial civilization, and has also exerted the most drastic influence that has ever been experienced by the human species.

What of the Future?

The maintenance of a high-energy technological society in the future plainly requires that sources of energy capable of being used at a rate comparable to that of the fossil fuels - about 7×10^{12} watts at present - must be developed. The principal remaining sources to be considered are: (1) nuclear energy from the fissioning of the heavy elements, or fusion of isotopes of hydrogen; (2) geo-

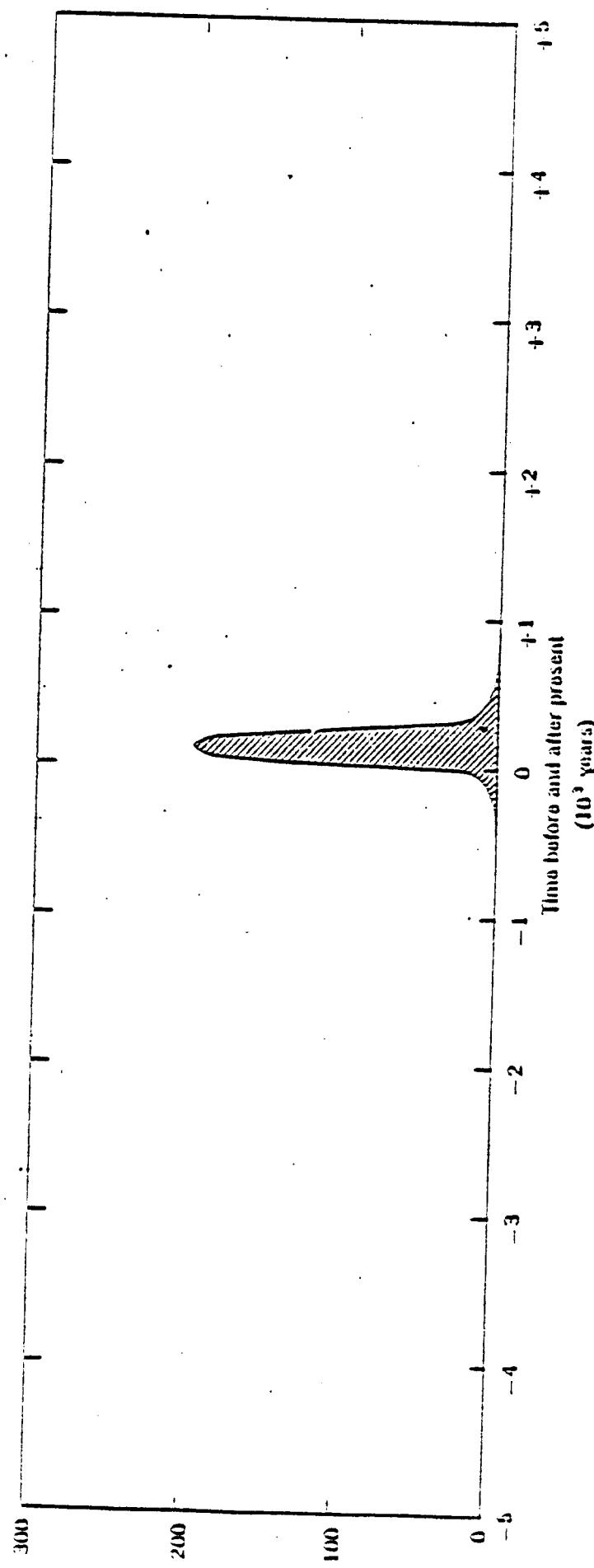


FIG. 31 - Epoch of fossil fuels in a longer span of human history (Hubbert, 1974a, FIG. 69).

thermal energy from inside the earth; (3) tidal energy from the earth-moon-sun system; or, finally, (4) the energy influx from solar radiation. Of these, nuclear and geothermal energy depend upon nonrenewable resources, whereas tidal and solar energy, while exhaustible on an astronomical time scale, are inexhaustible during any period of interest to the human species.

Fission Power. - Nuclear power from fission is already a fact accomplished and nuclear power plants in the 1,000 Mw range are rapidly proliferating around the world. However, at present these are largely based upon the consumption of the rare isotope of uranium, U-235, of which the world supply promises to become short within a few decades. Provided a transition can be made to breeder reactors capable of utilizing nearly all of uranium as well as thorium, then the potential energy supply from these sources becomes orders of magnitude larger than that from the fossil fuels.

Offsetting this are the hazards inherent in fission technology. These include the continuous generation of radioactive fission products which must be isolated from the biological environment in perpetuity, a problem which unfortunately has not yet been resolved. They also include the production of plutonium which is a convenient raw material for fission bombs, and the international arms race based upon nuclear explosives. In a world of social and political stability all of these problems might be technologically manageable in an acceptable manner, but in the present world of political and social instability the prospect of an eventual nuclear holocaust is becoming increasingly ominous.

Fusion Power. - If fusion were based upon the D-D fusion of deuterium from sea water, the supply of such deuterium is so large that it is unlikely that it could be appreciably reduced during any time of human interest, but we do not have D-D fusion. Deuterium-tritium fusion is the more likely achieve-

ment, but tritium does not occur naturally and must be produced from lithium, another scarce element. And even with this, there appears little likelihood that industrial power from D-T fusion is likely to be accomplished within the next quarter-century.

Geothermal Power. - Geothermal power from volcanic heat is being developed in favorable localities. The largest such installation, that of The Geysers in California, already amounts to more than 500 electrical megawatts, and may go to twice that capacity. The total geothermal installations around the world have an aggregate capacity of around 1,500 Mw, about one and a half times the capacity of a modern fuel- or nuclear-powered plant.

The heat sources for geothermal plants are not inexhaustible. In fact such plants are, in effect, simply taking a supply of volcanic heat near the earth's surface. Just how long the heat supply at The Geysers will last is not accurately known, but the decline is more likely within decades than centuries. While the total amount of heat at temperatures above that of the earth's surface that is accessible within drillable depths is very large, the problems of extracting this and converting it into electrical power or other surface uses are formidable. It appears at present that the world's development of geothermal power is likely to be principally dependant on very special geological conditions such as those at The Geysers, and, for an order of magnitude, the power from such sources appears likely to be small compared with water power.

Tidal Power. - Tidal power is appealing, and is capable of being developed in coastal regions having high tidal amplitudes with large embayments susceptible to being enclosed. An inventory of such sites around the world indicates that, if fully developed, the average power output would amount to about 7×10^{10} watts, which is only about 2 percent of the world's potential water power.

Solar Power. - This leaves us with solar power, obtained either indirectly from water power, wind power, ocean waves and currents, ocean thermal gradients, and biotransformation by photosynthesis, or by the direct conversion of solar radiation. Of these, water power is at present the principal component in industrial use of solar power. The potential water power of all of the world's streams amounts to about 3×10^{12} watts, of which only about 10 percent has been developed. The largest quantities of undeveloped water power are found in the relatively unindustrialized regions of Africa, South America, and south-east Asia. Yet, even if fully developed, water power would still provide only about half of the rate of the world's energy consumption at present.

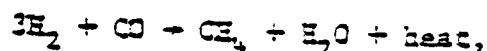
Wind power, wave and ocean-current power, and power from ocean thermal gradients are potentially large but how practical as sources of industrial energy remains to be determined. There are also biological wastes such as forest and agricultural by-products, and, above all, municipal wastes as potential sources of secondary solar energy. Heretofore the latter have been treated as useless and expensive nuisances to be disposed of in dumps and landfills. These are unsatisfactory expedients which lead only to increasing difficulties. The only proper solution of such problems is by a steady-state system whereby such products are regarded as continuous sources of materials and energy, and are processed at the same rates as they are generated, with the materials recycled into appropriate uses, and the energy converted to chemical, electrical, and thermal uses.

A promising new development in biochemical solar-energy conversion is being worked upon by Melvin Calvin, one of the world's leading researchers in photosynthesis, at the University of California, Berkeley. Calvin (1973) has called attention to the genus *Euphorbia* which synthesizes hydrocarbons instead of carbohydrates. According to Calvin, the species *Euphorbia heterophylla* may be

vehicle, obtained thermally or electrically from water. Upon combustion the reaction product would also be water. Another possibility would be a closed-loop pipeline, as in the proposed "Eva and Adam" reaction (Chemical and Engineering News, Aug. 14, 1978; Jan. 8, 1979), whereby as one end heat is added at high temperature to drive the endothermic reaction,



At the other extreme reverse exothermic reaction,



occurs and the reaction products are then recycled.

Industrial Metals

Although the industrial metals are outside the scope of the present paper, in view of the fact that modern industry is just as dependent upon metals as on energy, it would be misleading not to take at least a cursory glance at the metals outlook. Like energy from the fossil fuels, metals are obtained by mining. But, unlike energy, the metals, except in nuclear reactions, are not destroyed or transmuted from one chemical element to another. They remain on the earth but become dispersed. The customary cycle of production of a given metal consists in (1) the mining of an ore deposit in which the particular metal has been concentrated by geological processes, (2) extraction of the metal from its ore and fabrication into some form for industrial usage, and (3) withdrawal from use and dispersion as irretrievable waste, or reutilization and recycling into further industrial use. Hence, although the metallic elements remain upon the earth and are not destroyed, after dispersion they become as irretrievable as if they had been destroyed. Ore bodies, like oil fields, are finite in number and are just as depletable. A given ore deposit is only mined

expected to yield approximately 10 barrels of hydrocarbon material per acre (3.4 metric tons per hectare) in semi-arid land during a seven-month annual growing period. The potentialities of this in the semi-arid lands of south-western United States, now growing principally sage brush, are intriguing.

Finally, we consider the direct conversion of solar radiation into industrial power. From recent measurements made by the Desert Research Institute of Nevada, the solar power incident upon a horizontal surface at ground level in southern Nevada, averaged day and night, and summer and winter, amounts to 250 watts per square meter. Were 10 percent of this converted into electric power, this would yield 25 Mw per square kilometer of collection area. At this rate, a collection area of 40 square kilometers would supply a 1,000 Mw electrical power plant. When the extent of such areas of low cloudiness and high solar radiation around the world is considered, it becomes evident that only a minute fraction of such areas would need to be devoted to solar collectors to supply all the industrial-energy needs of the world.

The two major associated problems are the requirements for energy storage due to intermittency of sunshine, and for long-distance transmission to major centers of utilization. The optimum solution to both of these problems appears to be by following a chemical route, rather than by direct electrical power generation and long-distance transmission. By the chemical route, energy would be collected in arid regions and converted by either electrical or thermal means into a convenient chemical gaseous or liquid storage vehicle. Then, using the present petroleum-industry technology of pipelines and tankers, this could be transported to the consuming areas of the world in the same manner as oil and natural gas are delivered at present. Although many alternative possibilities no doubt exist, one of the simplest would be to use hydrogen as this energy

once. However, the fraction of a used metal that becomes irretrievable is amenable to being reduced much below most present levels.

Hence, regarding the ore accumulations of specific metals, one has to face the problem of about how extensive are these deposits, and approximately what is the time scale of their depletion? With regard to these questions, the world's known deposits of the ores of most industrial metals, exploitable by present technology, are sufficient to sustain present rates of production for decades, rather than for centuries. This question has recently been studied by W. von Engelhardt (1976) of the University of Tübingen, West Germany. He found that of the nine principal industrial metals, for only three, iron, manganese, and chromium, are a five-fold increase in the known world ore reserves sufficient to sustain present rates of production for more than 100 years. Von Engelhardt also pointed out that, while the quantities of metals at the low concentrations represented by their geochemical abundances are very much larger, these concentrations for most metals are several orders of magnitude below the cut-off level of exploitable ores.

Types of Growth

During the last two centuries, especially in the United States, one of the most ubiquitous characteristics of social and industrial activities has been that of sustained exponential growth. If one's view of history is limited to this brief period, the impression is gained that exponential growth is the normal order of things. In fact, one of our present major preoccupations is with the question of how such growth rates are to be sustained. But, if one takes a longer view of history, and also does a bit of arithmetic, it becomes evident that exponential growth of any biological population or industrial activity can

only be a transient phenomenon because a few tens of doublings of any such activity are all that the earth can sustain.

For example, the world's human population is now about 4.4 billion and the growth rate about 2 percent per year, with a doubling period of 35 years. Beginning with a biologically infinite population of 2, only 31 doublings are required to reach the world's present population. If we assume that the present rate of growth has always prevailed, then this initial pair, say Adam and Eve, must have lived only 31 doubling periods, or 1,085 years ago. If, on the other hand, we accept the geological and biological evidence that our ancestors were present a billion years ago, the maximum possible number of doublings that could have occurred during that time would still be only 31, but the minimum average period of doubling could not have been less than 32,000 years. By a similar analysis it must be concluded that the normal state of any biologic population must be, when averaged over a few years, a near steady state. A rapid increase or decline must be a transient ecological disturbance from one near-steady state to another.

Three types of growth are illustrated in Figure 34. Initially all three are assumed to increase at the same exponential rate. In the case of an activity based upon an exhaustible resource, such as the fossil fuels or ores or metals, the curve reaches a maximum and then declines back to zero. The second type represents the transient growth of an activity based upon a renewable or inexhaustible resource. Any biologic population, or the development of water power, would be such an example. This curve, after a few initial doublings slows down and stabilizes asymptotically to some finite magnitude. The third type of growth curve is that of a mathematical exponential increase. This curve has no finite limit, but increases indefinitely. The only phenomenon with which

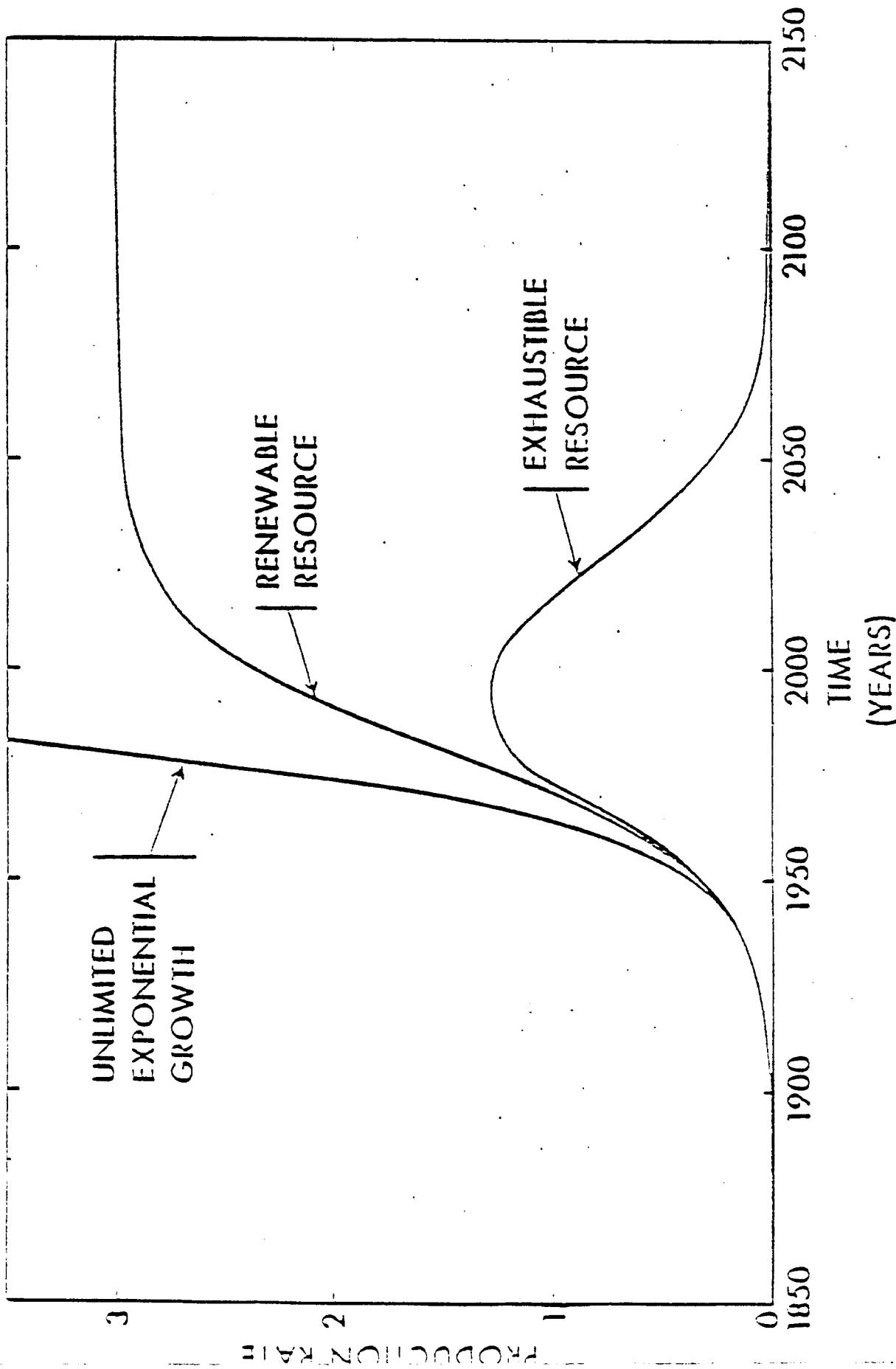


Fig. 34 - Three types of growth (Hubbert, 1974b, Fig. 1).

we deal that approximates this behavior is the growth of a sum of money at compound interest with a constant interest rate. This curve also has no assignable upper limit. Our present industrial society is now in the divergence region of these three curves.

Human Affairs in Time Perspective

In the light of the foregoing information, the situation in which mankind now finds itself, and its prospects for the future, can better be appreciated if we consider this against a background of the time span shown in Figure 35, extending from 5,000 years in the past to 5,000 years in the future. In this context, the events of the last two centuries, including exponential growth in industry and a nearly 6-fold increase in the human population, instead of being the normal order of things, actually represent the most abnormal events in human history. This epoch of exponential growth is but a transient period of about three centuries duration between two other much longer periods of history.

The first of these, comprising all history prior to about two centuries ago, was characterized by a small human population, simple handicraft technology, a low level of energy utilization, and very slow rates of change. The second, into which we are now in transition, extends from roughly a century hence into the indefinite future. This, however, at least initially, will have a large human population, a high technological level, a high rate of energy utilization, but again slow rates of change.

One of the foremost problems facing humanity today is how to make the cultural adjustments appropriate for a stable high-technology and high-energy, but essentially non-growing, society of the future. If we succeed, we could achieve

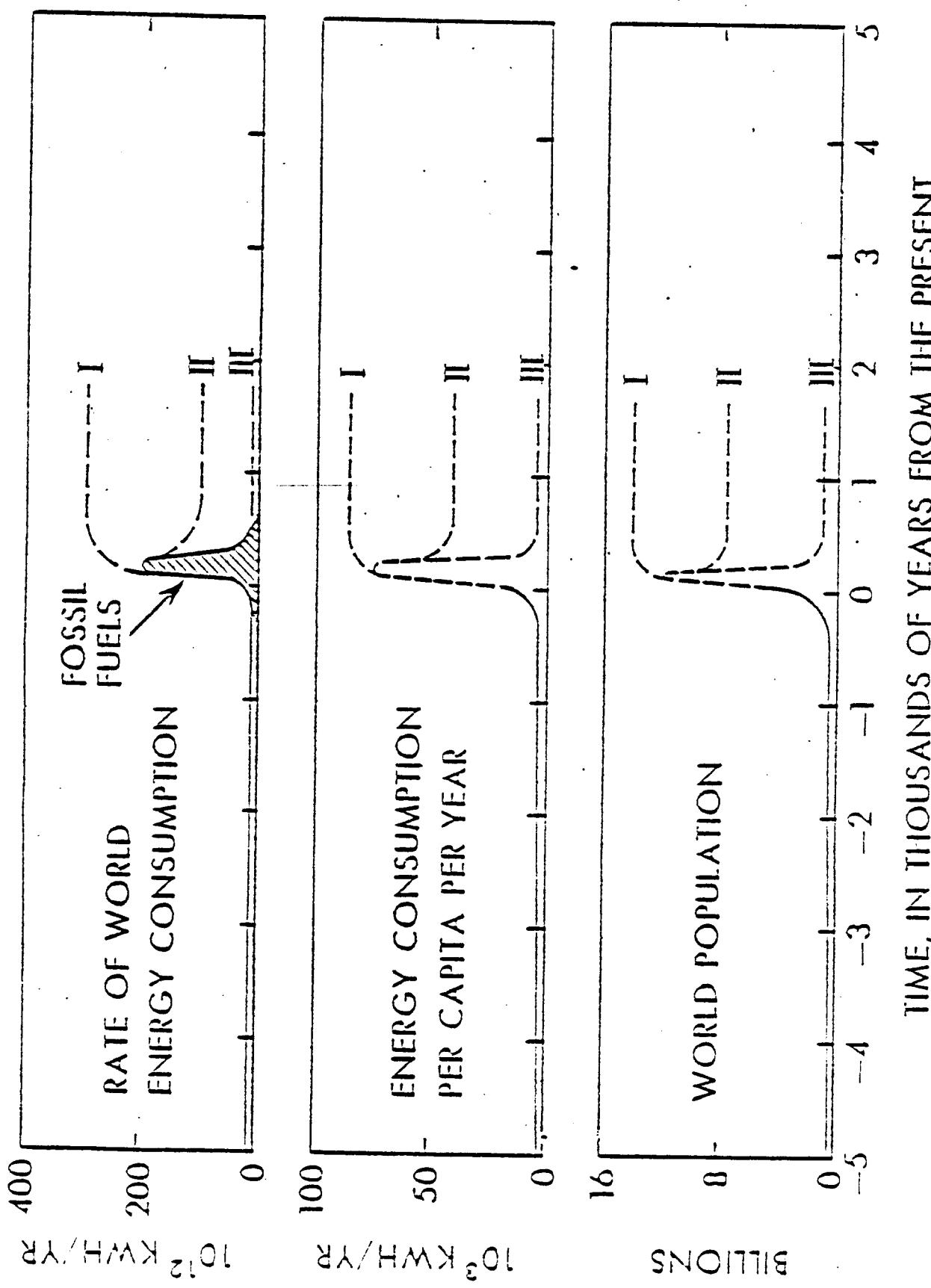


FIG. 3b - Hypothetical future in time perspective (Modified from Mabro et al., 1970)

a state of well-being which could provide an environment for the flowering of a great civilization. Should we fail, the consequences are not pleasant to contemplate.

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