Resources and Man

A STUDY AND RECOMMENDATIONS

by the Committee on Resources and Man

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NATIONAL ACADEMY OF SCIENCES—
NATIONAL RESEARCH COUNCIL

with the cooperation
of the Division of Biology and Agriculture

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8/Energy Resources

M. King Hubbert

"The optimist proclaims that we live in the best of all possible worlds; and the pessimist fears this is true."
—James Branch Cabell, 1926, p. 129

Into and out of the earth's surface environment there occurs a continuous flux of energy, in consequence of which the material constituents of the earth's surface undergo continuous or intermittent circulation. By far the largest source of this energy flux is solar radiation, a small fraction of which is captured by the leaves of plants and stored as chemical energy. This chemically stored solar energy becomes the essential biological energy source for the entire animal kingdom. In particular, it supplies the energy required as food for the human population at an average rate of about 2,000 kilocalories per capita per day, or at a per-capita consumption rate of about 100 thermal watts.

During geologic history, a minute fraction of the organic matter of former plants and animals became buried in sedimentary sands, muds, and limes, under conditions of incomplete oxidation. This has become the source of our present supply of fossil fuels—coal, petroleum, and natural gas.

During the last hundred thousand years or so, the human species has slowly learned to manipulate the energy supply of its biologic and inorganic environment in such a manner as to produce a continuous increase in its total energy supply, and a resulting increase in its population. However,

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until recent centuries the increase in the rate of total energy consumption was very much less than the increase in the rate of population growth. Consequently, the population has tended to remain in balance with the increase in energy supply, while the biologic and inorganic energy consumed per capita remained at a low, nearly constant level—only slightly more than that of the food supply.

Release from this constraint was not possible until an energy supply capable of exploitation faster than the human population could grow should become available. Such an energy supply is that represented by the fossil fuels. Continuous mining of coal began about eight centuries ago and production of petroleum just over one century ago. From small beginnings, the use of energy from these sources has grown until, during most of the last century, world consumption of energy from the fossil fuels has increased at about 4 percent per year. The world's human population has also responded to this stimulus and is now growing at a rate of just under 2 percent per year. Hence, at present, the world's average nonnutrient energy consumption per capita is increasing at about 2 percent per year.

Since the earth's deposits of fossil fuels are finite in amount and nonrenewable during time periods of less than millions of years, it follows that energy from this source can be obtained for only a limited period of time. In the present study, it is estimated that the earth's coal supplies are sufficient to serve as a major source of industrial energy for two or three centuries. The corresponding period for petroleum, both because of its smaller initial supply and because of its more rapid rate of consumption, is only about 70–80 years.

In particular, it is estimated that the United States (exclusive of Alaska) will reach its culmination in crude-oil production near the end of the 1960-decade and its culmination in the production of natural gas about a decade later. The date at which world production of petroleum will reach its maximum is estimated to be about the year 2000, or about 30 years hence.

In view of the fact that 60 percent of the world's present production of energy for industrial purposes, and 67 percent of the United States', is obtained from petroleum and natural gas, the imminent culmination and decline in the annual supplies of these fuels poses problems of immediate concern. In the United States, in particular, there is a need for immediate formulation of policies concerned with making up the deficit in the supply of liquid and gaseous fuels soon to result from the decline in the production rate of oil and natural gas.

Looking farther into the future, the energy needs of the United States and the world could be met for another century or two by coal alone. After that, dependence upon other sources of energy would become unavoidable. Of these, large-scale power production directly from solar energy appears technologically unpromising. The world's potential supply of water power is comparable in magnitude to the present rate of energy consumption from the fossil fuels. However, most of this occurs in the industrially undeveloped areas of Africa, South America, and southeast Asia, and could only be utilized by a parallel industrialization of these areas. In addition, although water power is capable of continuing for periods of geologic time, a practical limit in the case of large dams and reservoirs is set by the period of a few centuries required for the reservoirs to fill with sediments.

Geothermal and tidal energy is now being exploited in a few suitable sites around the world, but the ultimate amount of power from these sources does not promise to be larger than a small fraction of the world's present power requirements.

This leaves us with nuclear energy as the only remaining energy source of sufficient magnitude and practicability of exploitation to meet the world's future energy needs at either present or increased rates of consumption. Of the possible sources of nuclear energy, that from fusion has not yet been achieved and may never be. Power from the fission of uranium-235 is an accomplished fact, and reactors in the 500 to 1,000 megawatt-capacity range, fueled principally by this isotope, are rapidly being constructed. However, the supply of uranium-235 is such that serious shortages in the United States are already anticipated within the next two decades.

In the light of present technology, we are left then with the development of full-breeding nuclear reactors capable of consuming all of natural uranium or of thorium as our only adequate source of long-range industrial power. In view of the impending shortage of uranium-235, which is essential as an initial fuel for breeder reactors, it is urgent that the present generation of light-water reactors using uranium-235 be replaced by full breeders at as early a date as possible. Once this has been done, power production from low-concentration deposits of uranium and thorium becomes economically practicable. The amount of energy represented by these sources is many times larger than that of the fossil fuels.

With the nation's and the world's principal industrial energy requirements supplied by nuclear energy, it would be desirable to conserve the remaining fossil-fuel resources for chemical purposes. More important, with an adequate energy supply, and with a stabilization of the world's human population at some near optimum magnitude, it should be possible to extend the high energy-per-capita standard of living now characteristic of its more industralized areas to all of the world's peoples.

ENERGY IN HUMAN AFFAIRS

When *Homo sapiens* evolved from his immediate hominid ancestors a hundred thousand years or so ago, he existed in some sort of ecological adjustment with the rest of the ecological complex, and competed with other members of that complex for a share of the contemporary flux of solar energy essential for his existence. At its earliest stage, the sole capacity of the human species for the utilization of energy must have been limited to the food which it ate—then, as now, about 2,000 kilocalories, or 8 million thermal joules, per capita per day.

Between this earliest stage and the dawn of recorded history, this species distinguished itself from all others in its inventiveness of means for the conquest of a larger and larger fraction of the available energy. The invention of clothing, the use of weapons, the control of fire, the domestication of animals and plants, all had this in common: each increased the fraction of solar energy available for use by the human species, thereby upsetting the ecologic balance in favor of an increased population of the human species, forcing adjustments of all other populations of the complex of which the human species was a member.

From that early beginning until the present this progression has continued at an accelerating rate. It has involved the employment of beasts of burden, the smelting of metals, using first wood and later coal as fuel, and the development of power from water and wind. However, throughout this period until within the last few centuries the rate at which these changes were accomplished was slow enough that the growth of population was more than able to keep pace. The rate of consumption of energy per capita, therefore, increased but slightly.

Emancipation from this dependence on contemporary solar energy was not possible until some other and hitherto unknown source of energy should become available. This had its beginning about the twelfth or thirteenth century when the inhabitants of the northeast coast of England discovered that certain black rocks found along the shore, and thereafter known as "sea coales," would burn. From this discovery, there followed in almost inevitable succession, the mining of coal and its use for domestic heating and for the smelting of metals, the development of the steam engine, the locomotive, steamships, and steam-electric power.

This progression was further augmented when, a little more than a century ago, a second large source of fossil energy from petroleum and natural gas was tapped, leading to the internal combustion engine, the automobile, the aeroplane, and diesel-electric power.

A third source of energy, that from the atomic nucleus, was first brought under control as recently as 1942, but already it is rapidly becoming the world's largest source of power.

INDUSTRIAL ENERGY

Our principal concern in the present chapter is with the large quantities of energy required for industrial purposes, as contrasted with biological requirements. This had its principal development as the result of the exploitation of the fossil fuels. Although this began some eight centuries ago, the magnitudes reached before the nineteenth century were almost negligible compared with those reached subsequently. Our present analysis, accordingly, need not extend earlier than about the year 1800. Furthermore, earlier than 1860, statistical data become increasingly unreliable and difficult to assemble.

Since 1800, the principal sources of the world's industrial energy have been the fossil fuels and water power. The rise in the world's annual production of coal and lignite since 1860 is shown graphically in Figure 8.1, that of the world's crude-oil production since 1880 in Figure 8.2, and the annual production of energy from coal and crude oil in Figure 8.3. From Figure 8.3, it is seen that the energy from oil, as compared with that from coal, was almost negligible until after 1900. Since then, the contribution of oil to the total energy supply has steadily increased until now it is approximately equal to that of coal, and increasing more rapidly. Not included in Figure 8.3 is the energy from natural gas and natural-gas liquids. Were this added to that of crude oil, the energy represented by the petroleum group of fuels would by now (1968) be about 60 percent of the total from coal, petroleum, and water power. Water power alone contributes only about 2 percent.

The corresponding growth in the rates of production of coal, of crude oil,

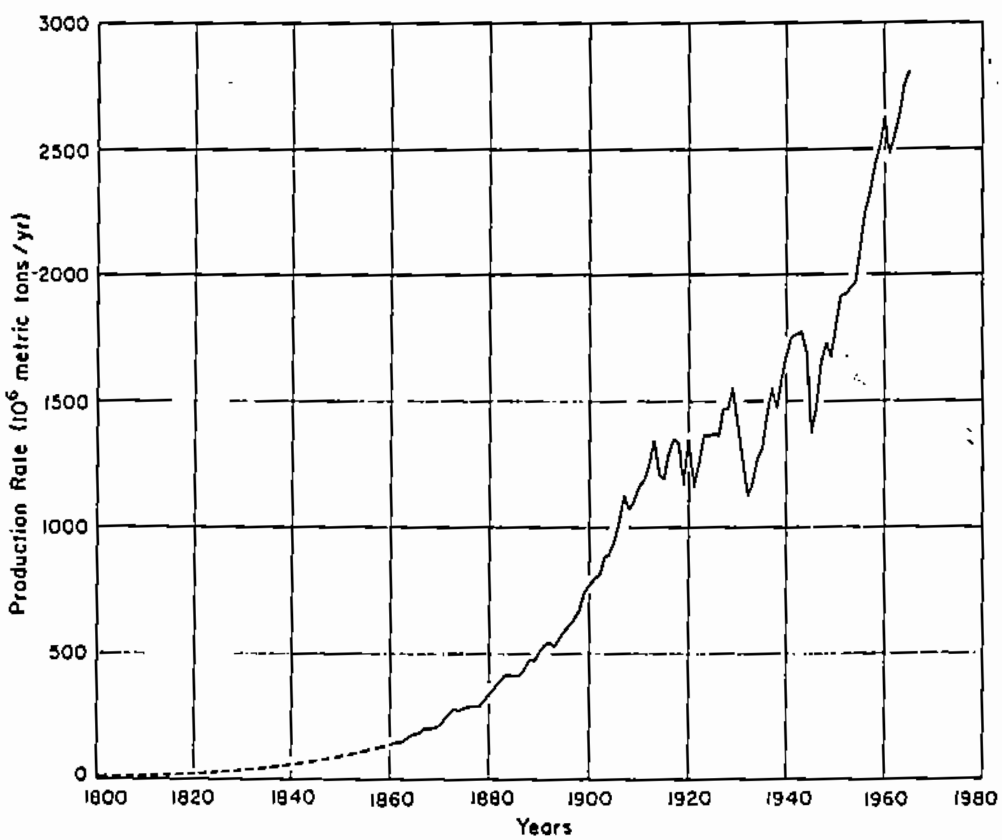

FIGURE 8.1
World production of coal and lignite.

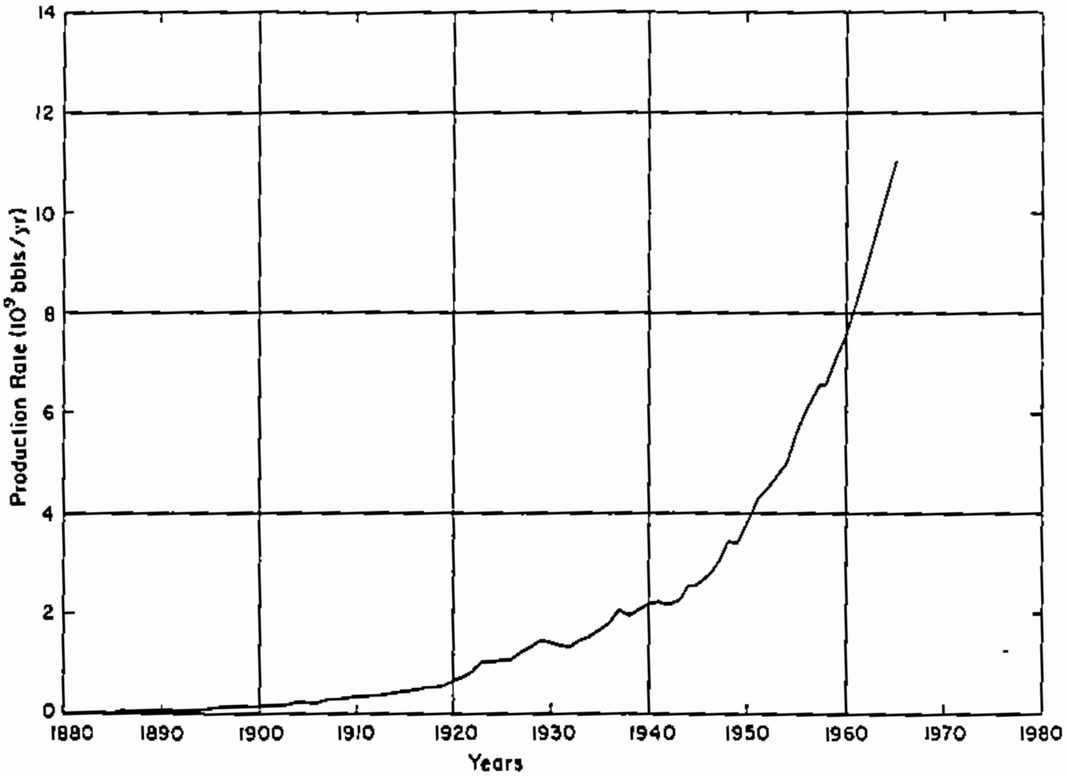

FIGURE 8.2
World production of crude oil.

and of natural gas in the United States are shown in Figures 8.4, 8.5, and 8.6, respectively. The growth in annual production of energy in the United States from coal, oil, natural gas, and water and nuclear power is shown in Figure 8.7. In the United States, as in the case of the world, since 1900 there has been a progressive increase in the fraction of the total industrial energy contributed by oil and natural gas. This fraction increased from 7.9 percent in 1900 to 67.9 percent by 1965. The contribution of coal, during the same period, decreased from 89.0 percent to 27.9. Water power, although continually increasing in magnitude, maintained a nearly constant percentage of the total energy produced. It increased only from 3.2 percent in 1900 to 4.1 percent in 1965. Nuclear power, by 1965, represented only 0.1 percent of the total.

These several growth curves have many properties in common. When replotted on semilogarithmic paper, each plots as a straight line for a period of a half-century or longer, indicating a constant exponential rate of growth. Following this period of constant growth rate, the rate of production falls steadily below its initial linear projection.

In the case of world coal production shown in Figure 8.1, the production rate falls into three distinct phases. During the first, extending from before 1860 to 1913 (the beginning of World War I), the production rate increased exponentially at an average rate of 4.4 percent per year, with the annual production doubling every 16 years. During the second period, including the two world wars and the intervening depression, the growth rate slowed to 0.75 percent per year with a doubling period of 93 years. Finally, during the third period from World War II to the present, a growth rate of 3.6 percent with a doubling period of 20 years has been resumed.

The world production of crude oil, except for a slight retardation during the depression of the 1930's and during World War II, has increased from 1890 to the present at a nearly constant exponential rate of 6.9 percent per year with a doubling period of 10 years. The second phase of retarded growth rate has not yet been reached.

From 1850 to 1907, the curve of the U.S. production of coal and lignite followed a constant exponential growth rate of 6.6 percent per year with a doubling period of 10.5 years. Before 1850, the growth rate was somewhat higher, but the production rate was so small that this period is not significant. From about 1910 to the present, production has oscillated about an average rate of about 550 million short tons per year.

U.S. crude-oil production, from 1875 to 1929, increased at a rate of 8.3

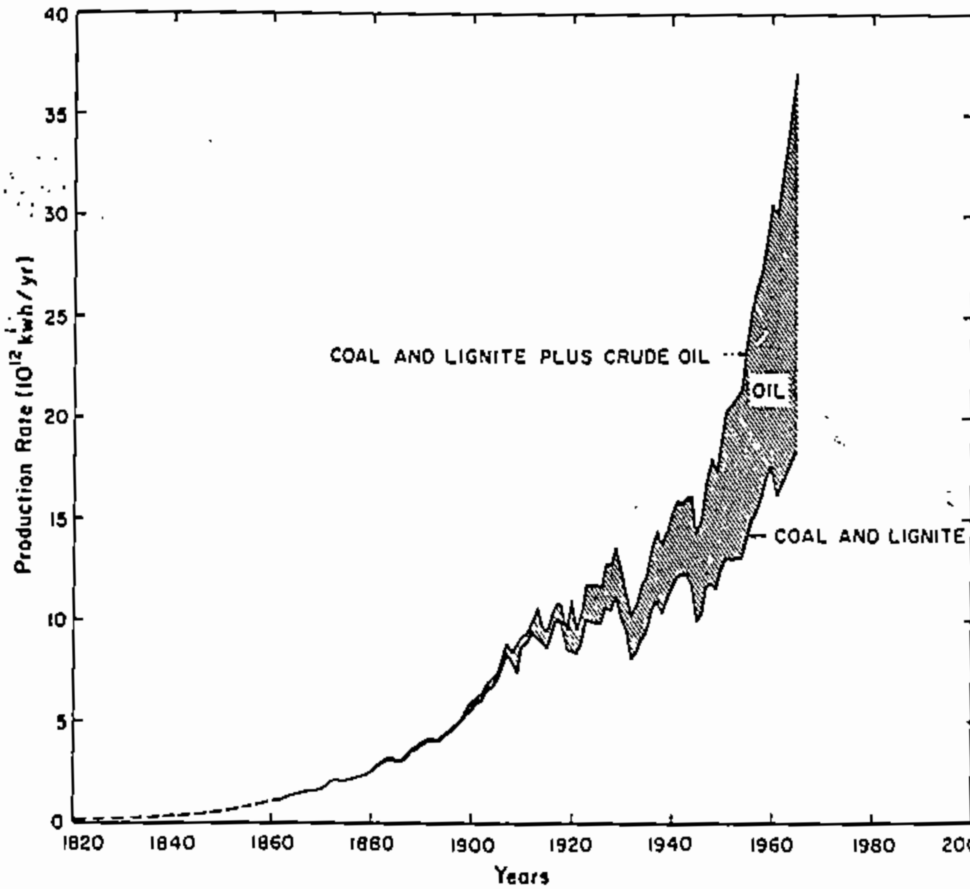

FIGURE 8.3
World production of thermal energy from coal and lignite plus crude oil.

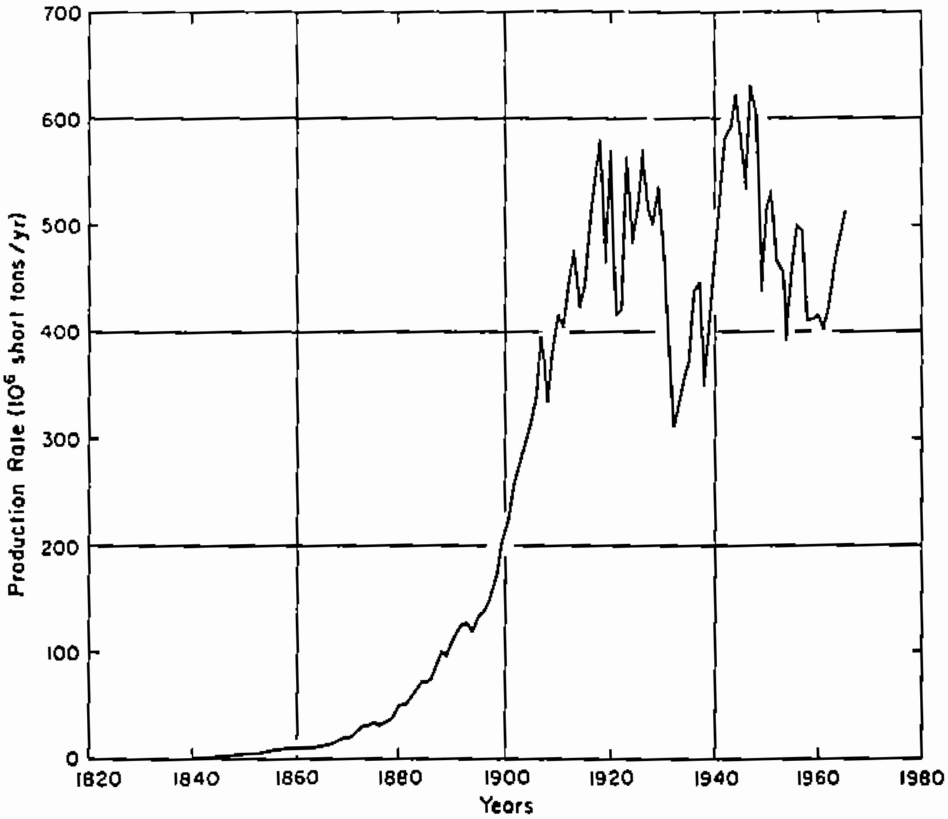

FIGURE 8.4
United States production of coal and lignite.

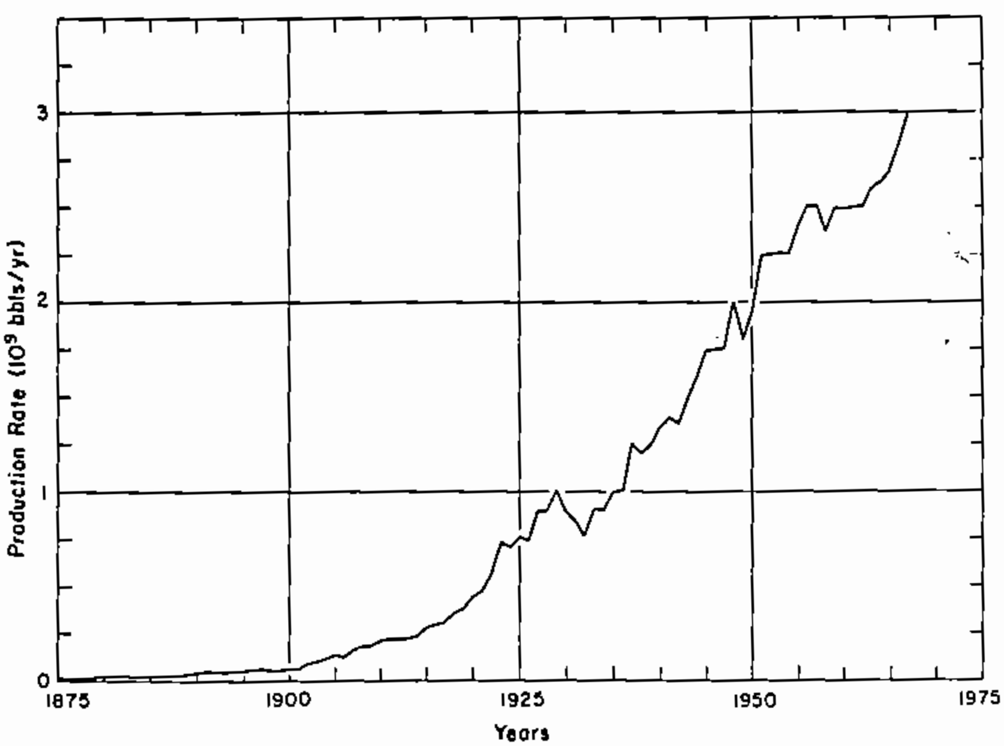

FIGURE 8.5
Production of crude oil in the United States, exclusive of Alaska.

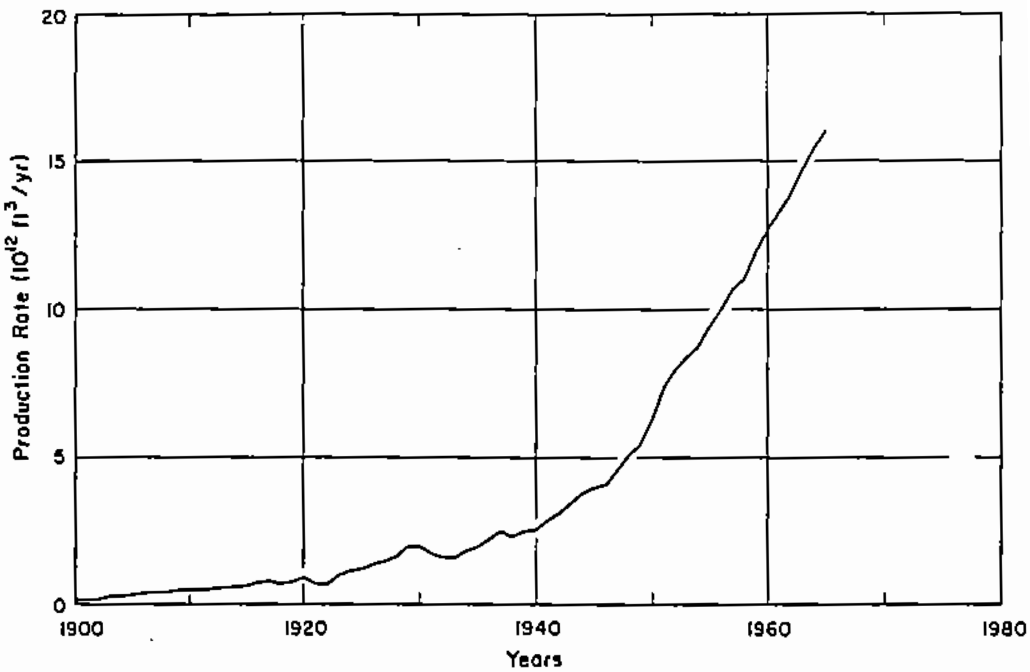

FIGURE 8.6
Production of marketed natural gas in the United States, exclusive of Alaska.

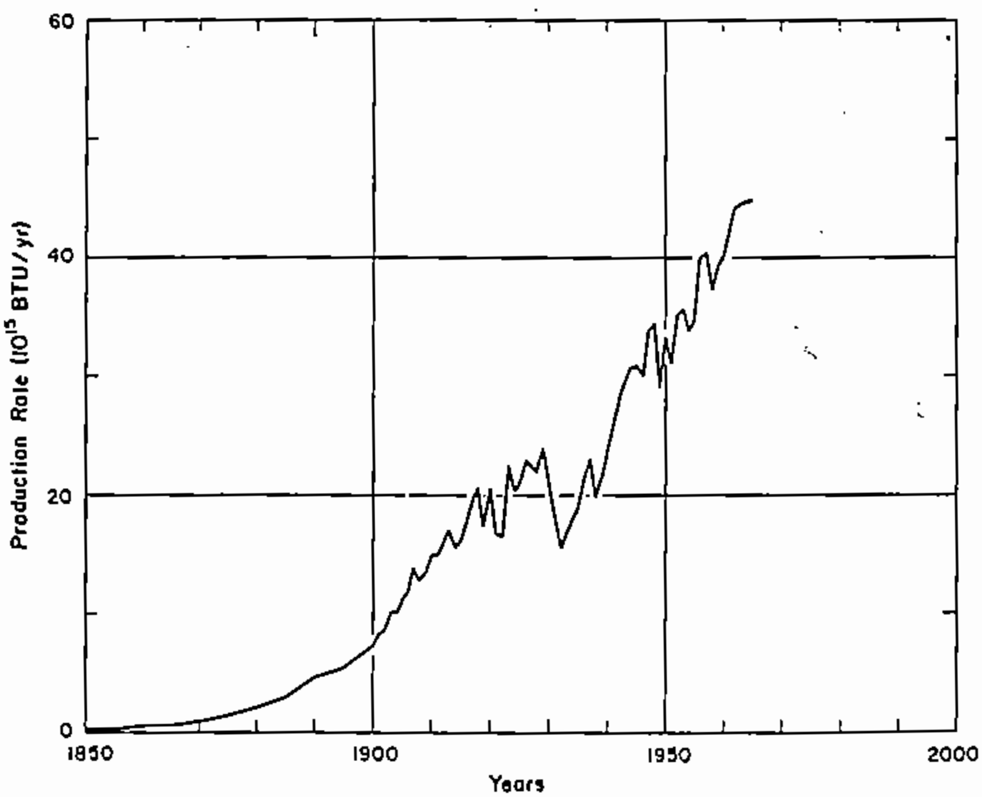

FIGURE 8.7
Production of thermal energy from coal, oil, gas, and water power in the United States, exclusive of Alaska.

percent per year with a doubling period of 8.4 years. Since 1929, the curve has gradually leveled off as the rate of production approaches its maximum. In parallel with crude oil, the U.S. production of marketed natural gas, from 1905 to the present, has increased at an almost constant exponential rate of 6.6 percent per year with a doubling period of 10.5 years.

Finally, U.S. production of total energy from coal, oil, natural gas, and water power, divides into two distinct growth periods. From before 1850 to 1907, energy was produced at a growth rate of 6.9 percent per year with a doubling period of 10.0 years. Then, from 1907 to the present, the growth rate dropped to 1.77 percent per year with a doubling period of 39 years.

Future Outlook for the Production of the Fossil Fuels

When consideration is given to the factual data pertaining to both the world and the U.S. rates of production of coal and oil, as shown in the preceding figures, two results of outstanding significance become obvious. The first of these is the extreme brevity of the time during which most of these developments have occurred. For example, although coal has been mined for about 800 years, one-half of the coal produced during that period has been mined during the last 31 years. Half of the world's cumulative production of petroleum has occurred during the 12-year period since 1956. Similarly, for the United States, half of the cumulative coal production has occurred during the 38-year period since 1930, and half of the oil production during the 16-year period since 1952. In brief, most of the world's consumption of energy from the fossil fuels during its entire history has occurred during the last 25 years.

The second obvious conclusion from these data is that the steady rates of growth sustained during a period of several decades in each instance cannot be maintained for much longer periods of time. The reason for this is that a steady exponential rate of growth implies a doubling of the production rate at equal intervals of time. This also involves the doubling of the cumulative production during the same time interval. Take, for example, the production of crude oil in the United States prior to 1930. During this period, the cumulative production was doubling every 8.4 years, and by 1930 it had reached 12.3 billion barrels. Were this rate of growth to be maintained for another century, about 12 more doublings would occur and the cumulative production would reach 48,000 billion barrels, which is about 74 times the highest estimates on record of the possible amount of oil that may ever be produced in the United States. Similar results are obtained for each of the other fuels shown in the preceding figures.

From such considerations we are led to the conclusion that the time span for the exhaustion of the bulk of the various fossil fuels, under modern industrial rates of consumption, is measurable in centuries, whereas the time required for the formation of these fuels by geological processes was about 600 million years. Hence, the rates of formation of these deposits are negligible as compared with their rates of consumption. Consequently, during the period of human exploitation, the resources of the fossil fuels may be considered to consist of fixed initial supplies which are continually diminished by human consumption. The quantity remaining in the ground at any given time must be equal to the difference between this initial supply and the cumulative production up to that time. Therefore, the complete history of the production of any fossil fuel must display the following characteristics. The curve of the rate of production, plotted against time on an arithmetic scale, must begin at zero, rise until it passes over one or more maxima, and finally decline gradually to zero.

If Q be a quantity of a given fuel, and t the time, then

$$P = dQ/dt \tag{1}$$

will be the production rate, where d signifies the amount of change. Then, if the production rate P be plotted on an arithmetic scale as a function of time, as we have done in Figures 8.1 to 8.6, the element of area under the curve with a base of dt and an altitude P, will be

$$dA = Pdt = (dQ/dt)\, dt = dQ. \tag{2}$$

Hence, on such a graph, the cumulative production Q up to any given time t will be proportional to the area between the curve of production rate and the time-axis from the beginning of production until the time t.

For the entire cycle of production, where the production rate begins at zero, and eventually returns to zero, the total area under the curve is a measure of the ultimate amount, Q_∞, of the given fuel produced during the cycle, as is illustrated in Figure 8.8. This fact provides a powerful means of keeping within reasonable limits in our estimations of the future course of the production of a given fuel. If an estimate can be made from geological data of the amount Q_i of the given resource which was initially present in the geographical area considered, then any extrapolation of the production curve for that area must be such that the ultimate area under the curve satisfies the condition

$$Q_\infty \eqless Q_i. \tag{3}$$

Mathematically, such a curve may assume an indefinite number of shapes, but the technology of production essentially requires that the early phase be one of a positive exponential rate of increase, and the declining phase an exponential rate of decrease, so between these two requirements, and that of

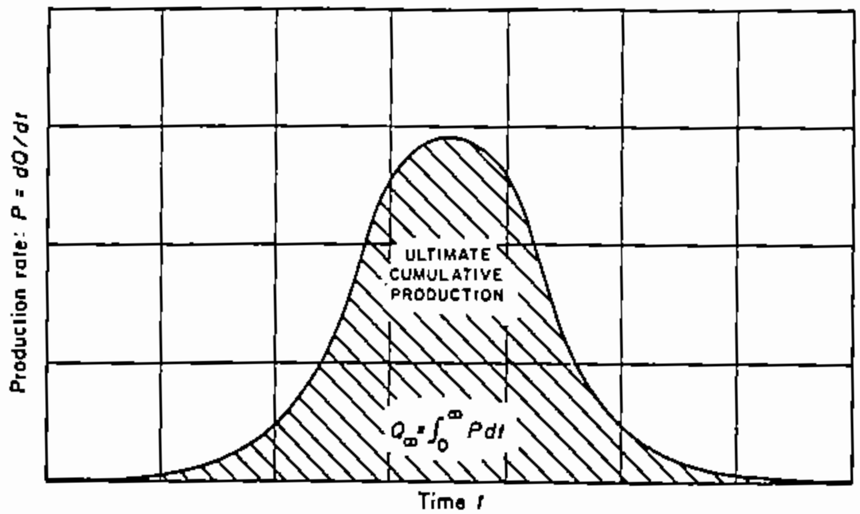

FIGURE 8.8
Full cycle of production of an exhaustible resource. (By permission of the American Petroleum Institute, from *Drilling and Production Practice,* 1956, Figure 11, p. 12.)

the limitation of the area circumscribed, the amount of latitude in such a curve is greatly reduced.

THE PETROLEUM GROUP OF FOSSIL FUELS

Let us first consider the petroleum group of fossil fuels. We have already seen that in just over a century this group of fuels has risen to dominance as the nation's and the world's leading source of industrial energy. Because of this fact, major policy questions resulting from scarcity of resources are likely to arise sooner for petroleum than for coal.

For statistical purposes, the petroleum group of fossil fuels is divided into gaseous, liquid, and solid components. The principal gaseous component is methane of chemical composition CH_4, which is the natural gas of commerce. The principal liquid component is crude oil, which is the stock-tank oil obtained by flow from the underground reservoir rocks by means of oil wells. It ranges all of the way from natural gasolines to very heavy and viscous oils which flow only with difficulty. The principal solid or pseudo-solid components are tars, found in tar sands, and the solid hydrocarbon, kerogen, found in oil shales. Actually, so-called tars are not solids, but viscous liquids whose principal distinction from crude oil is that they cannot be extracted from the ground by means of wells. Kerogen, on the other hand, is a true solid.

A product intermediate between natural gas and crude oil is natural-gas liquid (NGL). Natural-gas liquids, originally known collectively as "casing-head gasoline," constitute a family of hydrocarbons extracted as liquids during the production of natural gas. In addition to its principal component methane, natural gas also frequently contains diminishing fractions of heavier hydrocarbons of the series of compositions C_nH_{2n+2}, the first five members of which are methane, ethane, propane, butane, and pentane, for which *n* has the values 1 to 5, respectively. Natural-gas liquids consist of mixtures of propane and heavier components. A subclass of natural-gas liquids is liquified petroleum gases (LPG), consisting principally of mixtures of propane and butane, which are gaseous at atmospheric pressure but liquid at slightly higher pressures. These are familiar as "bottled gas" used for cooking and heating.

Until recent decades, only small amounts of natural-gas liquids were produced in the United States, and prior to 1945 the statistics of this production were lumped with those for crude oil. Since 1945, the annual production of natural-gas liquids and of crude oil have been reported separately. In the meantime, the production rate of natural-gas liquids has increased progressively until by the end of 1967 it amounted to 17.5 percent of the United States production of total liquid hydrocarbons.

As yet, only minor production of solid hydrocarbons has been achieved. Experimental work on the oil shales of Colorado has been under way for about two decades, but large-scale production has not yet begun. The mining of veins of the solid hydrocarbon, gilsonite, in the Uinta Basin of Utah has been in operation for more than a decade, but the reserves are not large. However, successful large-scale exploitation of the large Athabasca tar sands of northeastern Alberta, Canada, was begun in late 1967 by Great Canadian Oil Sands Limited, with a plant having a design capacity of 45,000 barrels of oil per day; other companies are only awaiting approval by the Canadian government to install additional productive capacity.

The production history of crude oil for the world has already been given in Figure 8.2, and of crude oil and natural gas for the United States in Figures 8.5 and 8.6. Were it possible to make reasonably accurate estimates from geological data of the amounts of oil and gas initially present underground, then, by use of the technique described heretofore and illustrated in Figure 8.8, reasonably good approximations of the future of the respective production curves could be made.

Unfortunately, because of the erratic manner in which accumulations of oil and gas occur underground, the problem of estimating the quantities of these fluids still undiscovered by drilling in any given region is difficult. For a preliminary appraisal of the petroleum-producing potentialities of a given region, the only available procedure is geological. Most of the geologists in the world are engaged in exploration for petroleum; and the knowledge of the geology of petroleum, and of the sedimentary basins of the world, that has been accumulated during the last half century is extensive.

In essence, the geological procedure is the following. It is generally agreed that petroleum is derived from plant and animal debris that was buried in sediments under conditions of incomplete decay during the geologic past. Consequently petroleum is now found only in or immediately adjacent to basins filled with sedimentary rocks. The geographical location and extent of the sedimentary basins in the land areas of the world are now reasonably well known. Sedimentary rocks are porous with an average porosity (ratio of pore volume to total volume) of about 15 to 20 percent. The pores are normally filled with water except where the water has been displaced by oil or gas. Oil and gas, being fluids, are driven by physical forces in this underground rock-water environment into limited regions of space where they are in stable equilibrium. These equilibrium positions are to some degree determinable by detailed studies of the subsurface structure of the rocks, and the associated state of rest or of motion of the water, by geological and geophysical procedures. Oil or gas wells are then drilled in what appears to be the most favorable locations for oil or gas entrapment.

Unfortunately, there is nothing in this procedure that permits better than a crude estimate of the quantity of oil or gas that a given basin may produce. The geological appraisal of the petroleum-producing potentialities of a new territory is carried out largely by analogy with known territories. For example, the geology of the coastal region of Nigeria was found to be similar to that of the coastal region of Texas and Louisiana. By analogy, it was assumed that the Nigerian sediments would probably contain a quantity of oil per unit of volume comparable to that which had already been discovered in the Texas-Louisiana gulf coastal region. Subsequent drilling in Nigeria has confirmed this assumption.

U.S. Crude-Oil Resources

Since the petroleum industry in the United States is the most advanced of that of any major region in the world, the United States experience is commonly used as one of the principal yardsticks in appraisals of the petroleum-producing potentialities of the rest of the world. The difficulty in this procedure, however, lies in the question of how good is the yardstick? How accurately are the undiscovered resources of oil and gas in the United States known? In this regard, it may be mentioned that estimates published within the last 12 years of the ultimate production of crude oil in the United States, exclusive of Alaska, have a fourfold range from about 145 to 590 billion barrels. Corresponding estimates for natural gas have a threefold range from 850 to 2,650 trillion cubic feet.

Estimates of the ultimate amount of crude oil which the world will produce have tended to be roughly proportional to the estimates made by the same authors for the United States.

In view of these circumstances, it is clear that the problem of estimating petroleum resources of the world is closely linked with the primary problem of estimating those of the United States. For the latter, geological analogy is no longer appropriate. We are left with the problem of a direct estimation, and this can only be based on the cumulative experience which is condensed into the statistics of exploration, drilling, discovery, and production of the petroleum industry in the United States. A problem of comparable or even greater importance is that of estimating the degree of advancement that the U.S. petroleum industry has reached in its evolutionary cycle. For these purposes two procedures have been evolved which yield reasonably unambiguous results (Hubbert, 1962, p. 50–65; 1967).

The first of these concerns the relationship between cumulative production, Q_p, cumulative proved discoveries, Q_d, and proved reserves, Q_r. Statistics on annual production of crude oil in the United States are available since 1860, and, from these, cumulative production up to any given year can be computed. Estimates of proved reserves of crude oil at the end of each year have been made annually by the reserves committee of the American Petroleum Institute (API) since 1937, and the series of proved reserves, based on older estimates, has been extended by the API statistical staff back to 1900. Cumulative proved discoveries up to any given time may be defined to be the sum of all of the oil produced up to that time plus the proved reserves. Hence, if we know the cumulative production and the proved reserves for any given time, the cumulative discoveries may be given by the equation

$$Q_d = Q_p + Q_r. \tag{4}$$

The corresponding rates of discovery are given by

$$dQ_d/dt = dQ_p/dt + dQ_r/dt, \tag{5}$$

in which the three terms represent the rates of discovery, of production, and of the increase of proved reserves, respectively.

From the principles previously set forth, we already know the general properties of each of the quantities in equations (4) and (5), when plotted graphically as a function of time. The production rate dQ_p/dt must begin at zero, increase to one or more maxima, and ultimately return to zero. The integral of this curve, the cumulative production Q_p, must begin at zero and then increase at an exponential rate as long as the production rate so increases. Then, when the production rate reaches its maximum value, the curve of Q_p will have its maximum slope. Finally, as the production rate declines, the Q_p-curve will gradually approach an ultimate quantity Q_∞, which represents the ultimate amount of oil produced during the entire cycle. The cumulative curve will accordingly exhibit the familiar S-shape common to growth phenomena. It can only increase with time, and it is asymptotic to zero at the beginning and to Q_∞ at the end.

The curve of proved reserves plotted against time has a different shape. At the beginning of production proved reserves are zero, and again at the end. The proved-reserves curve over the entire cycle must accordingly begin at zero, increase to a maximum, and then decline to zero.

From equation (4) it follows that the cumulative-discovery curve must resemble that for cumulative production except that discoveries must precede production by some time interval, Δt. At the end of the cycle, when $Q_r = 0$, the value of Q_d must be the same as Q_p. Hence both the Q_d- and the Q_p-curves must approach the same ultimate value Q_∞.

Strictly, the foregoing relations apply for a single-cycle growth curve. For oil production in a small area—the State of Illinois for example—there may be multiple cycles of production. For the whole United States, small local variations superpose and cancel one another out. Accordingly, all present evidence indicates that in this case we are dealing with but a single major cycle of discovery and production.

The general forms of the three curves of Q_d, Q_p, and Q_r, for a single growth cycle, are those shown in Figure 8.9. Corresponding curves of the rate of discovery, of production, and of increase of proved reserves, are shown in Figure 8.10. On these curves, one point is worthy of note. When the proved-reserves curve in Figure 8.9 reaches its maximum value, its slope, dQ_r/dt, which is the rate of increase of proved reserves, becomes zero. Then at this time equation (5) becomes

$$dQ_d/dt = dQ_p/dt. \tag{6}$$

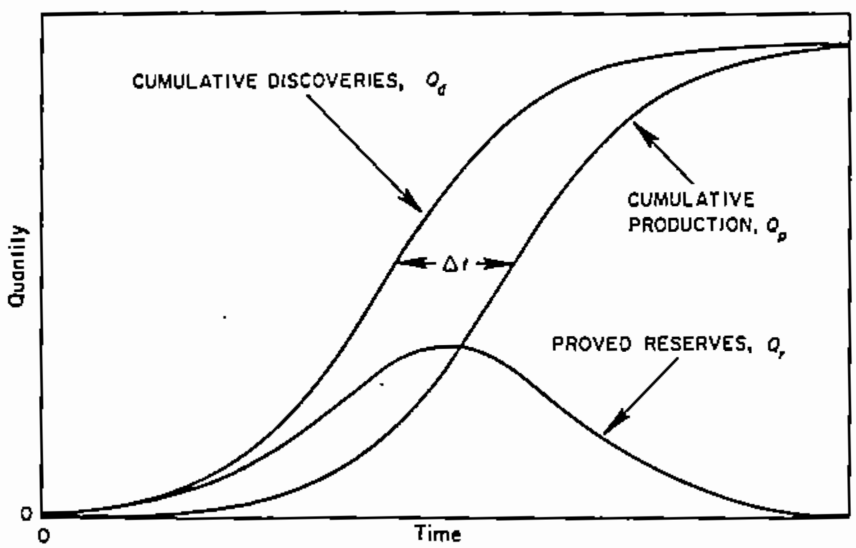

FIGURE 8.9
Generalized form of curves of cumulative discoveries, cumulative production, and proved reserves for a petroleum component during a full cycle of production. Δt indicates the time lapse between discovery and production. (From Hubbert, 1962, Figure 22, p. 55.)

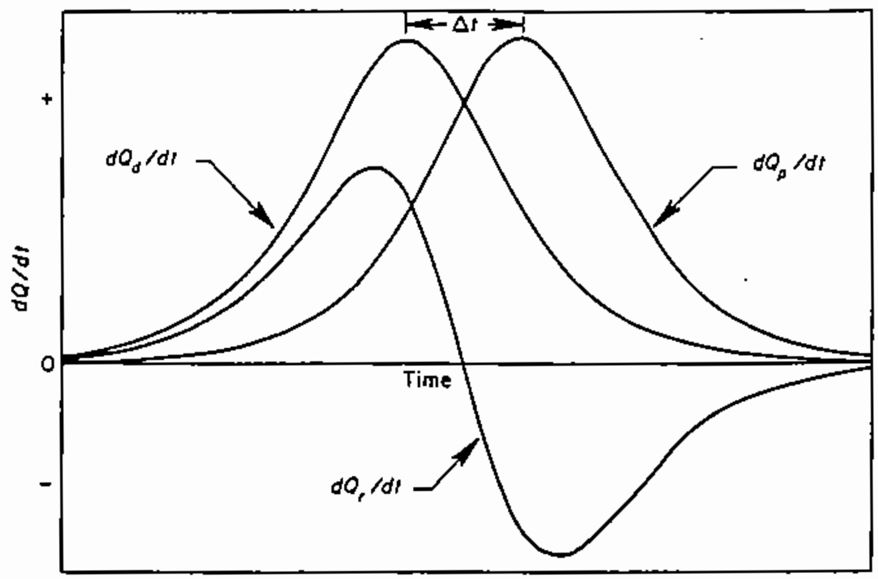

FIGURE 8.10
Relations between rate of production (dQ_p/dt), rate of proved discovery (dQ_d/dt) and rate of increase of proved reserves (dQ_r/dt) during a full cycle of petroleum production (From Hubbert, 1962, Figure 24, p. 56.)

This indicates that at the peak of proved reserves the curves of the *rate* of production and the *rate* of discovery cross one another, with the production rate still rising but the discovery rate already on its decline. The time at which this occurs is roughly halfway between the peaks in the discovery rate and the production rate. The study of the actual data of the U.S. petroleum industry in the light of these relationships can be very informative.

The data of U.S. cumulative discoveries, cumulative production, and proved reserves of crude oil, exclusive of Alaska, are shown graphically in Figure 8.11. The discontinuity at 1945 is caused by the separation, starting at that time, of natural-gas liquids data from crude oil data. The time delay, Δt, between cumulative discovery and cumulative production is shown in Figure 8.12. This is obtained by tracing the Q_d-curve and sliding it parallel to the time axis until it most nearly matches the Q_p-curve. For the last decade, as seen in the figure, this time-delay, Δt, has been about 12 years. Earlier, it would have been somewhat less, about 10–11 years. What is most significant is that for the last 40 years the curve of cumulative production has faithfully followed that of cumulative discoveries with a time delay rarely outside the range of 10–12 years. In consequence of this relationship, the Q_d-curve acts as about a 12-year preview of the behavior of the Q_p-curve In other words, the state of crude-oil production 12 years from now will probably not differ greatly from the state of discovery at present.

The proved-reserves curve in Figure 8.11 is plotted on too small a scale to show all of its significant detail. It is accordingly replotted on a magnified scale in Figure 8.13. From this it may be seen that a smooth curve

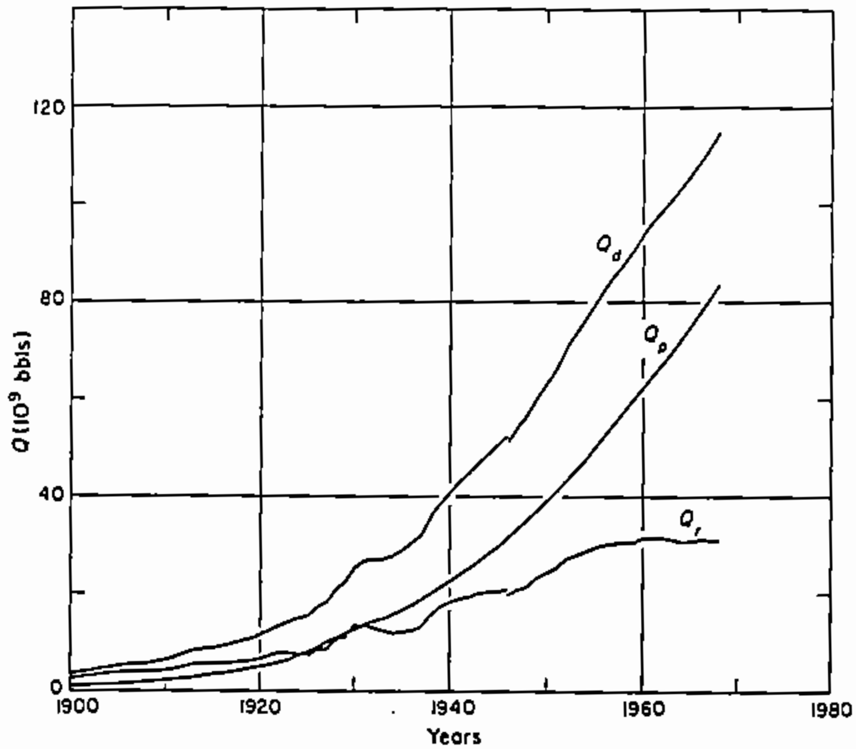

FIGURE 8.11
Data for the United States, exclusive of Alaska, on cumulative production (Q_p), cumulative proved discoveries (Q_d), and proved reserves (Q_r) of crude oil.

approximating the actual curve would have its maximum value at about 1961. This becomes even more clear in Figure 8.14, representing the rate of increase of proved reserves. The dashed-line curve represents the computed value of dQ_r/dt from an analytical curve approximating the actual proved-resources curve. The solid-line zig-zag curve represents the actual year-to-year data of increase of proved reserves. From the general form of the proved-resources curve, its slope, or rate of increase, must have a positive loop while reserves are increasing, and a negative loop while decreasing, and the curve must cross the zero line from the positive to the negative loop at the time when reserves reach their maximum value. From Figure 8.14 it can be seen that this cross-over also occurred about 1961. As evidence that this is not merely a temporary aberration, it may be noted that the rate-of-increase curve reached the maximum of its positive loop about 1942 and the actual year-to-year data, with only minor oscillations, have declined steadily since 1951.

Data on the rates of discovery and of production of crude oil in the United States are shown in Figure 8.15. As in the case of Figure 8.14, the dashed-line curves are analytical derivatives of smooth curves fitting the cumulative discovery and cumulative production curves of Figure 8.11. The solid line zig-zag curves are the actual yearly data. The maximum rate of discovery, according to the analytical curve, would have been about 1957. In the figure, a time-delay, Δt, of 10.5 years is shown between discovery and production. However, during the last decade the delay averaged about 12 years. Accordingly, the peak in the rate of production, which should lag behind that of discovery by about the same time interval, should be expected to occur about 1969 plus or minus a year or two.

Strictly speaking, this peak in the rate of production refers to the smooth analytical curve rather than to that of the actual year-to-year production oscillations. Since the actual production rate is somewhat less than the productive capacity of the country, it is possible that an all-time peak in the oil produced during a single year might occur during any given year within a time interval of five years or more. The data of Figures 8.11 to 8.15 are consistent in indicating that the U.S. petroleum industry, exclusive of Alaska, is now (1969) in the region of its all-time maximum rate of production, but it will probably not be possible to assign an accurate date to this event until about five years after it has happened.

Another result obtainable from the data in Figures 8.11 to 8.15 is an estimate of the magnitude of Q_∞, the ultimate amount of oil to be produced.

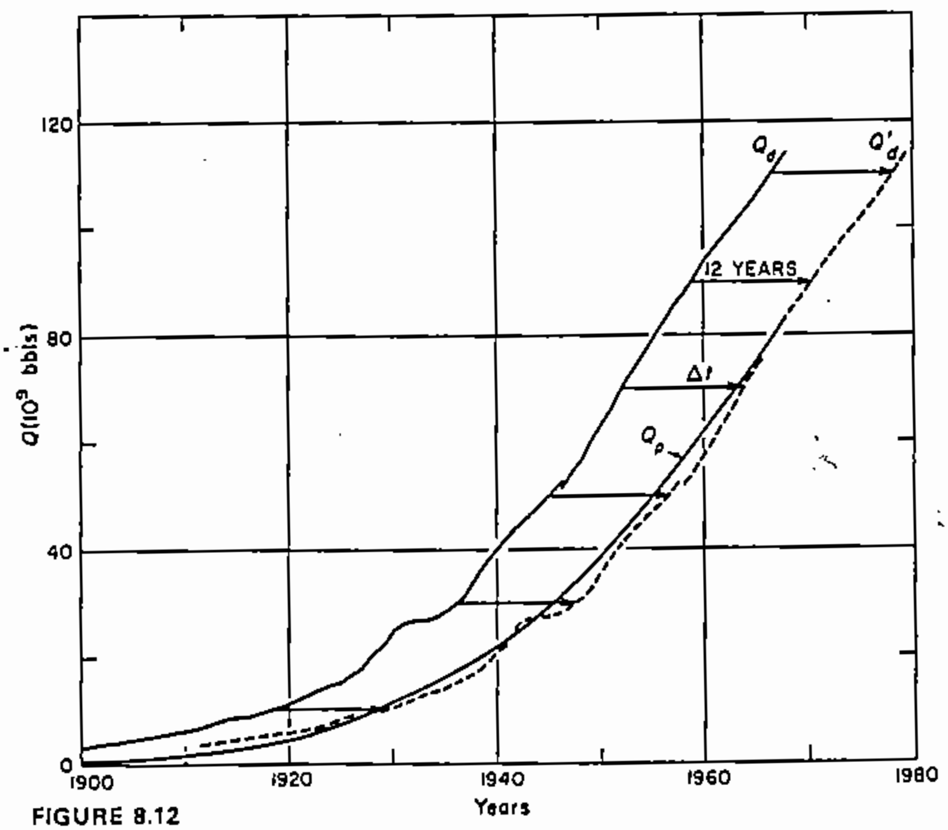

FIGURE 8.12
Time delay, Δt, between United States cumulative proved discoveries (Q_d) and cumulative production (Q_p) of crude oil. The dashed line Q'_d reflects the form of the curve Q_d when it is slid to the right, parallel to the time axis, until it most nearly matches the curve Q_p.

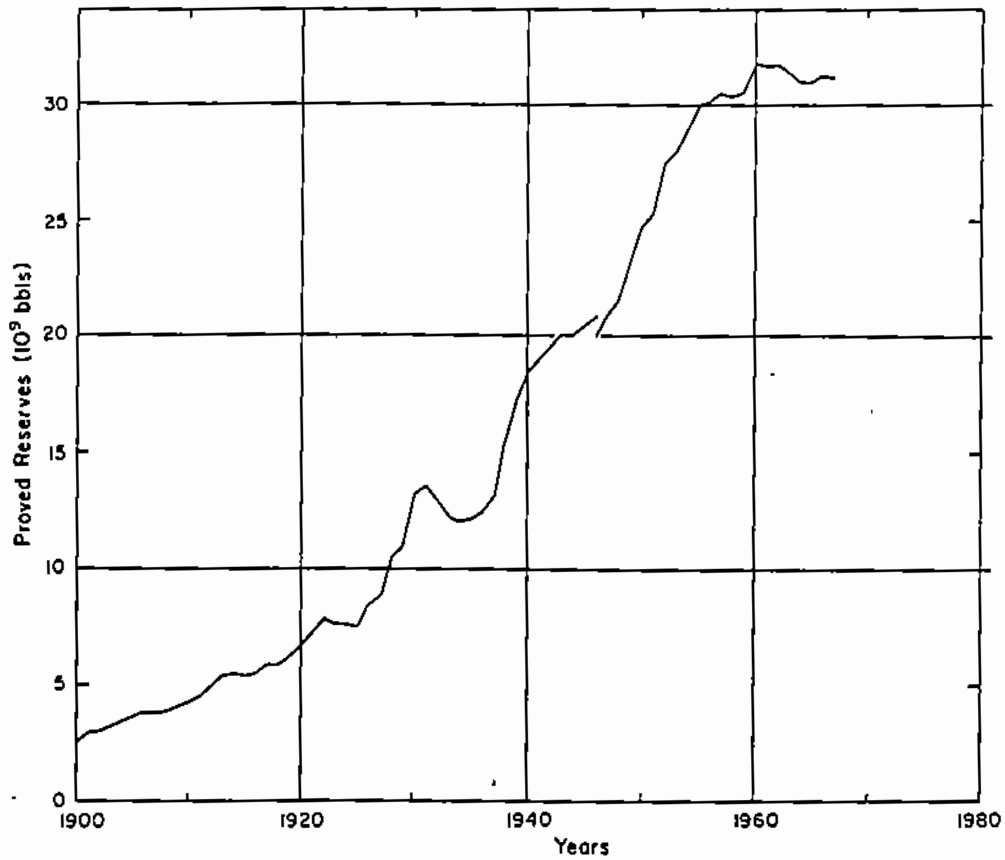

FIGURE 8.13
Proved reserves of crude oil in the United States, exclusive of Alaska

If we assume that peak rates in discovery and in production occur at about the halfway points of cumulative discoveries and production, then each of these curves will give an estimate for the value of Q_∞. At the beginning of 1957, the approximate date of the peak in the proved-discovery rate, cumulative discoveries amounted to 85.3 billion barrels. Twice this would give a figure of 170.6 billion barrels as an estimate for Q_∞. During the last decade, the time delay Δt of production with respect to discovery has averaged about 12 years. If we take the beginning of 1969 (12 years after the peak in the discovery rate) as the approximate date of the peak in the production rate, the cumulative production will be about 86.5 billion barrels. Twice this amount would give a value of 173.0 billion barrels for Q_∞.

It is to be emphasized that these figures are only approximate, since in either case it is possible that the peak rates of discovery or of production could occur somewhat earlier or somewhat later than the halfway points.

While the foregoing procedures are especially well suited for the determination of such critical dates as the peaks in the rates of discovery and production, and of that of proved reserves, they are somewhat less reliable as a means of estimating the ultimate amount of oil Q_∞ that will be produced.

For the latter purpose, a much better procedure has been developed; it was suggested by the studies of A. D. Zapp (now deceased) of the United States Geological Survey (Zapp, 1962, pp. H-22–H-33). The procedure is to express the rate of discovery in terms of barrels of oil discovered per foot of exploratory drilling, and then determine how this rate varies as a function of the cumulative footage of exploratory drilling. In this system of coordinates, if Q is the quantity of oil discovered, and h the cumulative footage drilled, then the rate of discovery dQ/dh would be plotted as the vertical coordinate in bbls/ft against cumulative footage, h, as the horizontal coordinate.

This system is mathematically analogous to that which we have used heretofore where the time-discovery rate dQ/dt has been plotted against cumulative time t. In both systems of coordinates, the area under the curve represents cumulative discoveries up to the cumulative depth h, or the cumulative time t, respectively. The former has several advantages over the latter, however. In the first place, the rate of discovery per foot depends principally on technological factors and is relatively insensitive to economic

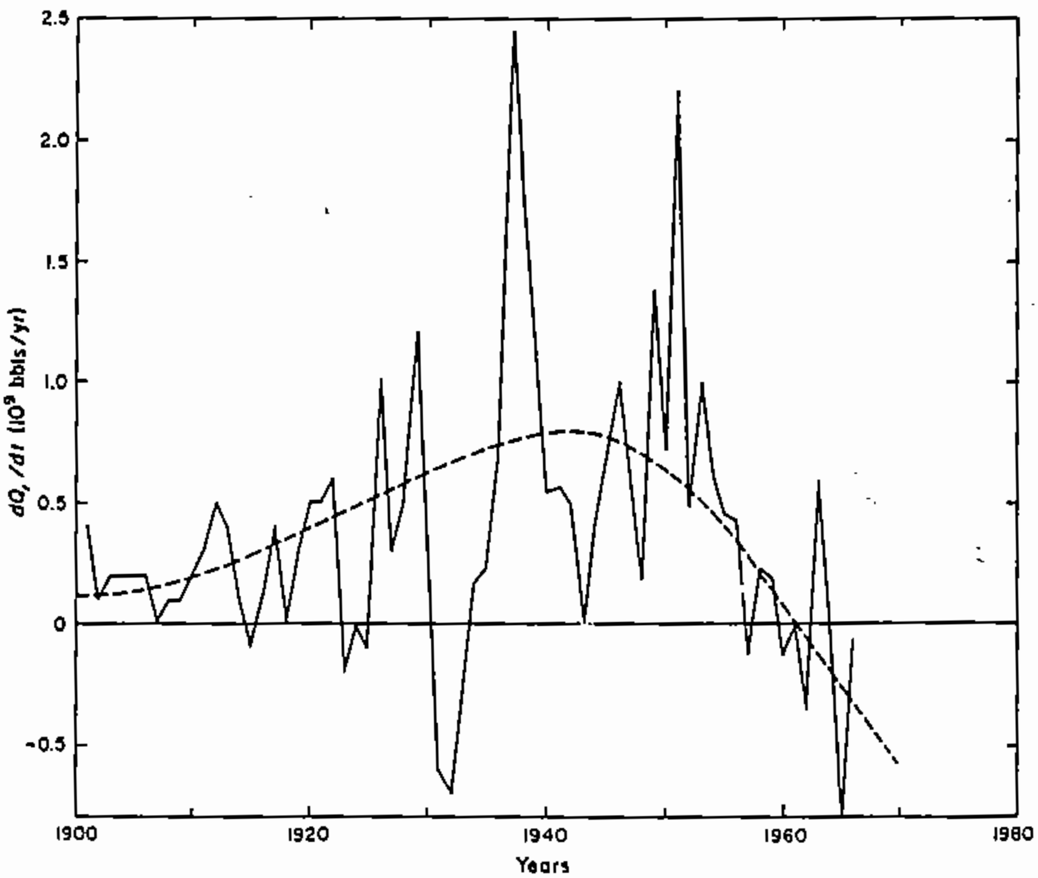

FIGURE 8.14
Rate of increase of proved reserves of crude oil in the United States, exclusive of Alaska. Solid line shows actual year-to-year increase in proved reserves, dashed line the computed rate of increase dQ_r/dt.

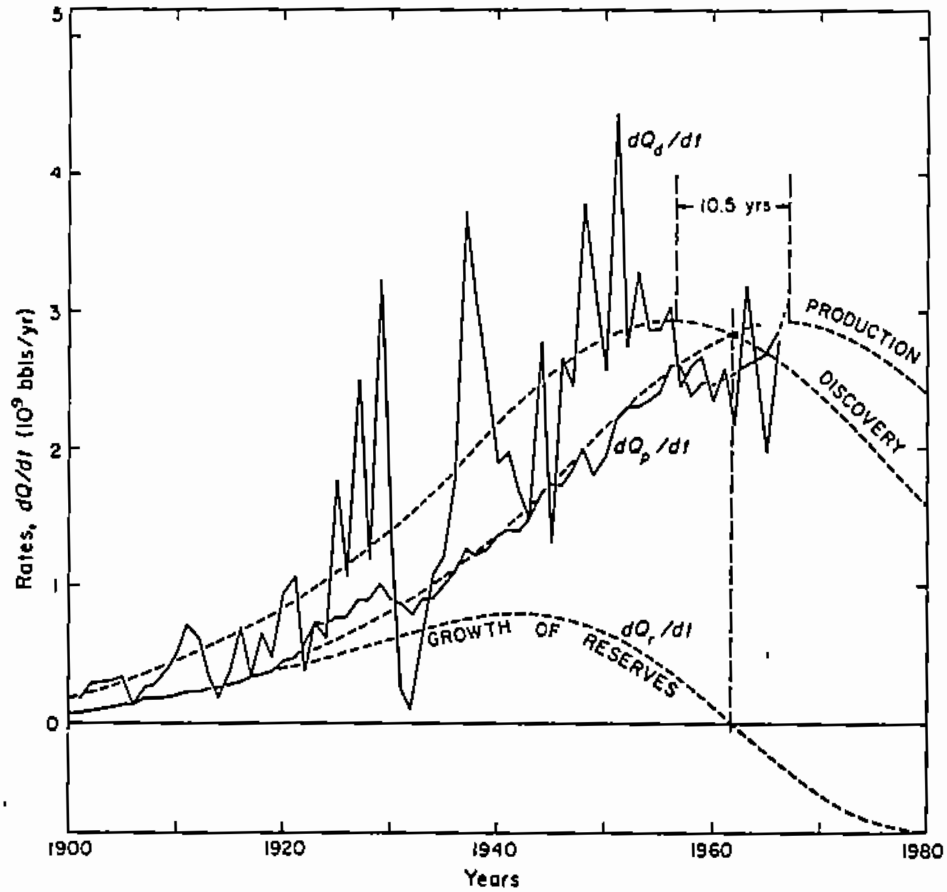

FIGURE 8.15
Rates of proved discovery (dQ_d/dt), production (dQ_p/dt), and increase (dQ_r/dt) of reserves of crude oil in the United States, exclusive of Alaska. Dashed line curves are analytical derivatives, solid lines are actual yearly data.

conditions. The rate of discovery per year, on the contrary, can swing widely from one year to the next in response to economic and political conditions. In the second place, a practical limit can be set to the ultimate amount of cumulative exploratory drilling in a given area, whereas no such limit can be assigned to cumulative time.

Although Zapp did not develop this method, its main features were implied in his important paper, "Future Petroleum Producing Capacity of the United States" (Zapp, 1962), whose principal results can only be presented graphically in this system of coordinates. This method thus permits not only a graphical presentation of the Zapp estimates, and of others based on the same premises, but it also permits an easy verification of those premises by means of petroleum-industry statistical data. And, more important, it permits a direct evaluation of the discovery history of the U.S. petroleum industry up to the present, and a more reliable appraisal of its future than has been obtainable previously.

Therefore, instead of reviewing initially the estimates of the ultimate amounts of crude oil which the United States may produce (estimates that have been made by Zapp and others) and the premises on which they have been based, it will be more economical for us to proceed directly with our own analysis of the data. What we seek is the curve of oil discovered per foot of exploratory drilling as a function of cumulative footage from the beginning of the industry to the present. Then, on the basis of this information—whether the curve is still rising, remaining stationary, or declining—we can make some prognostications on ultimate crude-oil production. This study has in fact already been made and published (Hubbert, 1967) and only its principal results will be summarized here.

To obtain the desired result, we must first work with the statistical data published by years. We thus require estimates of the oil discovered each year and of the footage of exploratory drilling each year. The ratio of these quantities then gives the oil discovered per foot *as a function of time*. By adding cumulatively the drilling footage, as a function of time, we are then able to determine the quantity of oil, ΔQ, discovered for each successive equal increment, Δh, of cumulative footage, and this ratio, $\Delta Q/\Delta h$, versus h will be a finite approximation to the desired curve.

For discoveries assignable to a given year, we require a different definition of discoveries from that of *proved discoveries* used heretofore. For this purpose, we adopt a procedure initiated by the Petroleum Administration for War (PAW) (Frey and Ide, 1946) in a study as of 1945, and continued in successive similar studies by the National Petroleum Council (NPC, 1961, 1965) and, finally, jointly by the American Gas Association (AGA), American Petroleum Institute (API), and Canadian Petroleum Association (CPA) (AGA, API, and CPA, 1967), in which all of the oil contained in any given field is credited to the year of discovery of the field. Studies have been made on this basis and estimates published as of January 1 for the years 1945, 1960, 1964, and 1967.

In these studies, the oil credited to a given year, as of a later date, consists of the sum of the cumulative production up to the date of the study plus the estimated proved reserves, of all of the fields discovered in the given year. However, by the rules of the API reserves committee, proved reserves at any given time are not intended to represent all of the oil that will eventually be produced by the fields already discovered at that time. Rather, they represent a working inventory of oil that is present and producible by wells and equipment already in operation. Additional reserves are added as the fields are developed.

For this reason, the oil discoveries ascribed to any given year, based in part on the API reserves estimates, gradually increase with time. This effect was studied (Hubbert, 1967), and on the basis of the successive published estimates, the *ultimate* amount of oil that the fields discovered each year since 1860 would produce was estimated. This involved negligible additions over the recent NPC estimates for fields discovered more than 50 years ago, but required progressively larger additions (up to 5.8-fold) as the year of discovery approached the present.

In this manner, the cumulative proved discoveries, computed on the basis of the NPC studies and brought up to 1 January 1967, amounted to 111.7×10^9 bbls for the United States exclusive of Alaska. The estimated ultimate production of the fields already discovered amounted to 136.2×10^9 bbls, an increase of 24.5×10^9 bbls.

For the feet of exploratory drilling per year, and cumulative exploratory footage, drilling statistics are available intermittently from 1927 to 1944 and annually since 1945. For the earlier periods, statistics exist on the total number of wells drilled per year, classified as oil wells, gas wells, and dry holes. During the period since exploratory well statistics have become available, the number of exploratory wells drilled has averaged about 0.67 of the total number of dry holes. Assuming that about the same ratio prevailed during earlier drilling, the approximate number of exploratory wells could be estimated from the dry-hole data. Then, to obtain the footage per year, the number of exploratory wells was multiplied by the estimated average depth. The latter is known approximately from the known depths of the fields discovered at successive times.

The net result of this study was that by 1 January 1967, the estimated cumulative footage of exploratory drilling amounted to 15.2×10^8 feet. This divides conveniently into 15 units of 10^8 feet for each of which the oil discovered, ΔQ, can be evaluated from previous discovery data, and the average discoveries per foot, $\Delta Q/\Delta h$, determined.

The results are shown in Figure 8.16. During the first 10^8-ft interval of drilling, which extended from 1859 to 1920, the average oil discovery rate was 194 bbls/ft. During the second interval, from 1920 to 1928, the rate dropped to 167 bbls/ft. Then, during the third interval, extending from 1928 to 1937 and including the discovery of the East Texas oil field, the discovery rate reached an all-time peak of 276 bbls/ft. Following this, the rate has fallen precipitately to a present level of about 35 bbls/ft.

This decline during the 30-year period since 1937 is particularly significant in view of the fact that the oil credited with having been discovered during this period represents the cumulative results of all of the advances in the techniques of exploration and production of the petroleum industry during its entire history up to 1967. This also was the period of the most intensive research and development in exploratory and production techniques in the history of the industry. The observed decline in the rate of discovery during this period is, accordingly, difficult to account for on any other basis than that undiscovered oil is becoming scarce.

The tops of the columns in Figure 8.16 represent approximately the curve of dQ/dh versus h, and the area under this curve represents cumulative

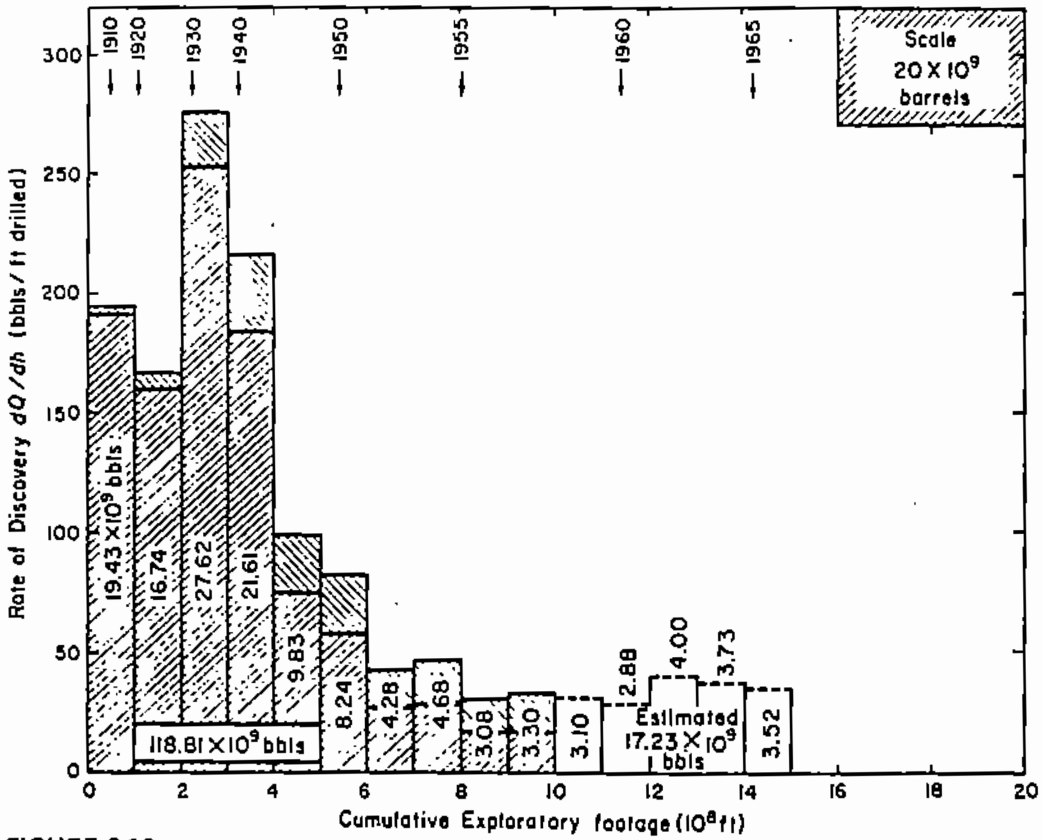

FIGURE 8.16
Crude-oil discoveries per foot of exploratory drilling versus cumulative exploratory footage in the United States, exclusive of Alaska, 1860–1967. (By permission from *Bulletin of American Association of Petroleum Geologists*, 1967, vol. 51, Figure 15, p. 2223.)

discoveries. Future discoveries can accordingly be estimated by extrapolating the decline curve of Figure 8.16, and computing the additional oil corresponding to the added area. In the study cited (Hubbert, 1967), this was done using two different negative-exponential rates of decline, the first an approximate average for the whole period, and a second slower rate from 194 bbls/ft for the first column to 35 bbls/ft for the last. The faster rate of decline gave 153×10^9 bbls as an estimate of Q_∞, and the slower rate, 164×10^9 bbls.

It will be noted, however, that during the last seven 10^8-ft units of drilling, the discoveries per foot have remained nearly constant. The reason for this is twofold. The time required for these last seven units of drilling was only the 12-year period from 1955 to 1967. This was the period during which the rate of exploratory drilling decreased sharply from an all-time peak of 16,207 wells in 1956 to 10,275 (excluding Alaska) in 1966. Since the highest-grade prospects are customarily drilled in preference to those of lower grade, a reduction in the number of wells drilled in a given year tends to increase the average grade of the prospects drilled, and hence to improve the rate of discovery per foot. The second, and principal reason for the slowdown in the decline of the discovery rate per foot, however, is that this was also the period during which most of the large discoveries were made, with a minimum of exploratory drilling, in offshore Louisiana.

Because these two effects are both intrinsically temporary, the slowdown in the decline rate of discoveries per foot during the last 12 years must be regarded as only a temporary episode in a long-term trend of decline. However, even in the improbable event that the discovery rate could be held constant at the present rate of 35 bbls/ft and the drilling rate also maintained at the 1967 level of 49×10^6 ft/yr, until the year 2000, the new oil discoveries would amount to but 57 billion barrels. When this is added to the 136 billion barrels already discovered by the beginning of 1967, the total by the year 2000 would still amount only to 193 billion barrels.

Independent confirmation of this long-term decline in the rate of discovery with cumulative drilling is afforded by the statistics published annually by the Committee on Statistics of Drilling of the American Association of Petroleum Geologists. Each year this committee reports on the number of new-field wildcat wells that were required 6 years previously to make one profitable discovery of either oil or gas. A profitable discovery is defined as 1 million barrels of oil or an equivalent amount of oil plus gas. In 1945, the first year of the series, 26 new-field wildcat wells were required per profitable discovery; by 1961, the last year of the series, this number had increased to 70 wells per discovery. (Dillon and Van Dyke, 1967, p. 994, Fig. 9; Van Dyke, 1968, p. 918, Fig. 9).

Hence, on the basis of the results shown in Figure 8.16, the highest figure that at present can be justified for Q_∞, the ultimate amount of oil to be produced by the conterminous part of the United States and its adjacent continental-shelf areas, is about 165×10^9 bbls. Of this, the amount of 136 $\times 19^9$ bbls, or 83 percent, is accounted for by fields already discovered, leaving but 17 percent for fields still to be discovered.

The absolute value of Q_∞, for these same fields, could be increased above the figure of 165×10^9 bbls, should a drastic improvement in the efficiency of recovery from the oil in place be effected. Even in this case, however, the improvement would involve the fields already discovered to the same degree as those still to be discovered so that the ratio of oil already discovered to that still to be discovered would remain essentially unchanged.

Offsetting any expectancy of a drastic improvement of the present recovery efficiency of somewhere near 40 percent are the following facts: (1) Every technique of improved recovery efficiency so far devised by petroleum-industry research is already in operation to about its economic limit. (2) More expensive procedures could be justified only by a corresponding increase in the price of oil. The latter, however, is precluded by the fact that should domestically-produced oil become more expensive, the public has access to alternate sources of less expensive liquid fuels, obtainable both from imports and from oil shales and coal.

The figure of 165×10^9 bbls is accordingly the best present estimate of the value of Q_∞ for the conterminous United States, although it is admitted that a somewhat higher figure resulting from further improvement in recovery efficiency is a physical possibility.

Having obtained the estimate of $Q_\infty = 165 \times 10^9$ barrels for the crude-oil production in the conterminous United States, we are now in a position to plot the complete cycle of production, utilizing the principle illustrated in Figure 8.8. This is shown in Figure 8.17 of which one grid square has the dimensions

$$10^9 \text{ bbls/yr} \times 20 \text{ yrs} = 20 \times 10^9 \text{ bbls.}$$

Hence, if the figure of 165×10^9 barrels is approximately correct as a value for Q_∞, the total area under the curve can contain only $8\frac{1}{4}$ of the grid squares of the figure. The area to the left of the vertical line at the year 1934 represents a cumulative production of 16.5×10^9 barrels, or the first 10 percent of Q_∞; the area to the right of the vertical curve at the year 1999 represents the last 10 percent. The area under the curve between these two dates represents the middle 80 percent of Q_∞. Hence, the time that will be required to produce and consume the middle 80 percent of the ultimate amount of crude oil to be produced in the conterminous United States is only about 65 years, or less than a single lifetime.

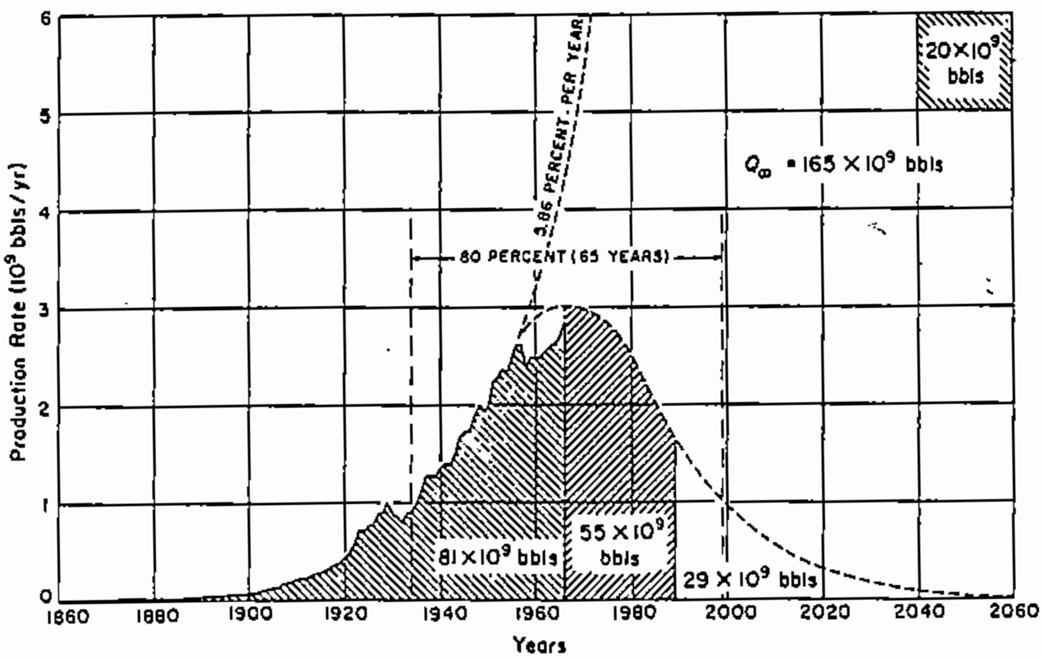

FIGURE 8.17
Complete cycle of crude-oil production in the United States and adjacent continental shelves, exclusive of Alaska.

The dashed-line curve in Figure 8.17 shows what the production rate would have been after 1955 had the rate of growth that prevailed from 1935 to 1955 continued.

In this estimate, Alaska has been excluded because it represents a large, almost virgin territory which has not yet developed far enough to contribute to the statistics on which the foregoing analysis has been based. Significant Alaskan oil production was begun in the Kenai-Cook Inlet area only as recently as 1958, with cumulative proved discoveries by 1 January 1968, amounting to 0.474 billion barrels, with an estimate of about 1 billion barrels of ultimate production.

Also, a very large oil discovery has been announced (*Oil and Gas Journal*, 22 July 1968, p. 34–35), near Prudhoe Bay on the Alaskan North Slope, which, according to a report by the consulting firm of DeGolyer and McNaughton, promises to be in the 5 to 10 billion-barrel class. This would make it equal to or larger than the East Texas field—the largest in the United States thus far—and comparable to the world's largest fields in the Middle East.

Aside from these developments, the Alaskan potentialities for petroleum production can at present be based only on comparisons by means of geological analogy. According to Hendricks (1965, p. 7) the total potential oil-producing area of the United States, including Alaska, and adjacent continental-shelf areas, is just over 2 million square miles; and for the United States minus Alaska, 1.86 million square miles. This would give for Alaska a potentially productive area of about 0.14 million square miles, or an area equal to 7.5 percent of that of the rest of the United States. If we use the crudest type of comparison (which could easily be wrong by a factor of 2 or more), we may assume that Alaska will produce as much oil per square mile of potentially productive area as the rest of the United States. This would give for Alaska a potential production of about 12 billion barrels.

As a consequence of the new Prudhoe Bay discovery, this figure appears to be too low. Even so, a provisional allowance of 25 billion barrels for the ultimate crude-oil production of Alaska is about as large a figure as can be justified from present evidence. This figure, when added to the 165 billion barrels for the remainder of the United States, gives 190 billion barrels as our present estimate of the approximate amount of crude oil ultimately to be produced by the whole United States and its adjacent continental shelf areas.

Estimates by Others

As we have remarked earlier, estimates published within the last 12 years of the ultimate amount of crude oil to be produced within the United States and its adjacent continental shelves, exclusive of Alaska, have had a fourfold range from 145 to 590 billion barrels. Estimates in the higher range fall into two principal groups: (1) estimates based on the Zapp hypothesis, or its modification, and (2) estimates based on geological analogy.

Production estimates based on the Zapp hypothesis (p. 177), or its modification, include: 590 billion barrels of crude oil for the United States, exclusive of Alaska (Zapp, 1961); 650 billion barrels, presumably including Alaska (McKelvey and Duncan, 1965); and 400 billion barrels, including Alaska (Hendricks, 1965). Since these have already been analyzed in detail in a recent paper (Hubbert, 1967), only brief comment regarding them will be made here.

The Zapp hypothesis, in the form that produced the above estimates, is based on the assumption that the oil to be discovered per foot of exploratory drilling in any given petroliferous region will remain essentially constant until an areal density of about one exploratory well per two square miles has been achieved. The nature of this hypothesis, as formulated by Zapp (1962, pp. H-22–H-23) for the conterminous United States as of the year 1959, is shown graphically in Figure 8.18.

In this, only percentages of ultimate exploration were given, Later (after the foregoing report was written, but before its publication), Zapp (1961) estimated that by 1961, about 130 billion barrels of crude oil had already been discovered in the United States by about 1.1 billion feet of exploratory drilling. This would have been at a rate of 118 bbls/ft. He also estimated that the cumulative footage required by a density of one well per two square miles, drilled either to the basement or to 20,000 feet, in the United States would amount to 5 billion feet, and that by such drilling 590 billion barrels of producible crude oil would be discovered. This corresponds to the maintenance of an average discovery rate of 118 bbls/ft for the entire 5 billion feet of drilling.

A simple test of the validity of this hypothesis can be made by determining whether or not the discoveries per foot made by past exploratory drilling have remained approximately constant. This we have done, and the results, which are given in Figure 8.16, show unequivocally that the Zapp hypothesis

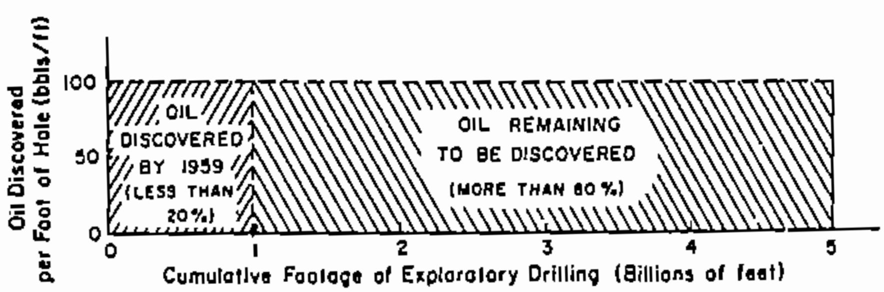

FIGURE 8.18
The Zapp hypothesis of the rate of oil discoveries per foot of exploratory drilling versus cumulative footage.

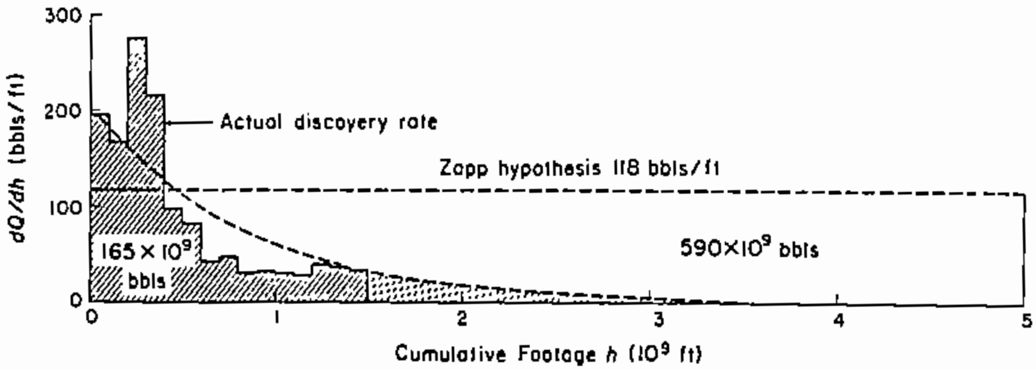

FIGURE 8.19
Comparison of Zapp hypothesis with actual United States discovery data from Figure 8.16.

in this simple form is untenable. Instead of remaining constant, discoveries per foot have fallen drastically during the last 35 years from a maximum value of 276 bbs/ft during the period 1928–1937 to a present figure of about 35 bbls/ft. In Figure 8.19 the data of Figure 8.16 are shown superposed on the rectangle generated by the Zapp hypothesis of a constant discovery rate of 118 bbls/ft. From this, it is evident why the estimate derived deductively from the Zapp hypothesis is about 3.5 times the highest figure of about 165 billion barrels that can be justified by the discovery data—an overestimate of about 425 billion barrels.

Consequently, since the Zapp hypothesis is not compatible with petroleum-industry data and leads consistently to figures that are much too high, estimates obtained by the use of that hypothesis in the form applied must be discounted.

Of the higher range of estimates based on geological premises and analogy, among the most notable are those by L. G. Weeks (1948; 1950; 1958; 1959), formerly a geologist of Standard Oil Company of New Jersey, and now a consultant. In 1948, Weeks gave a summary estimate, based on the technology and economics of that date, of 110 billion barrels as the ultimate amount of crude oil to be produced on the land areas of the United States. In 1958, he increased this to 240 billion barrels of "liquid petroleum" for both the land area and the adjacent continental shelves. When corrected for natural-gas liquids, this would reduce to about 200 billion barrels of crude oil. Then, in the following year (1959), he increased this estimate to 460 billion barrels of liquid petroleum, which would correspond to about 380 billion barrels of crude oil.

As to how these estimates were made, Weeks has remained consistently unclear. The figures apparently are to be accepted on the authority of the author's extensive knowledge of petroleum geology. Moreover, for the 11-year period from 1948 to 1959, for which Weeks more than tripled his estimate, there was no commensurate increase in the knowledge of the petroleum geology of the United States. It is, therefore, not possible to appraise the reliability of Weeks' estimates in terms of the methods used; they can only be checked against other sources of information. By this criterion, it appears that Weeks' earlier estimate of 110 billion barrels for the land area is more reliable than his later estimates. For, if to the figure of 110 billion barrels for the land area, we add a liberal additional 20–30 billion barrels for the adjacent continental shelves and another 25 billion barrels for improvements in exploratory and production techniques, we obtain an estimate in the range of 155 to 175 billion barrels, which is consistent with other present information. No justification, geological or otherwise, has yet been found for Weeks' more recent, much higher estimates.

Natural-Gas Resources of the United States

The rate of production of natural gas in the United States has been shown in Figure 8.6. As in the case of crude oil, we require an estimate of the ultimate quantity, Q_∞, of natural gas that the United States and adjacent continental shelf areas, exclusive of Alaska, may be expected to produce before we can construct a curve of the complete cycle of production.

The problem of estimating Q_∞ for natural gas is essentially the same as that for crude oil. However, because of the close genetic relationship between natural gas and crude oil, a good approximation of Q_∞ for gas can be obtained from the results of the analysis for crude oil which has already been given. We have seen that by 1 January 1967, the ultimate amount of crude oil that the fields already discovered in the conterminous United States are estimated to produce is taken to be 136 billion barrels, leaving 29 billion barrels for future crude-oil discoveries.

During the last 20 years, the ratio of natural-gas discoveries in the United States to those of crude oil have averaged about 6,000 ft^3/bbl.

Making a liberal assumption of 7,500 ft^3/bbl for the gas-oil ratio of future gas discoveries, we would then obtain an estimate of 218 trillion cubic feet for the gas to be discovered while the 29 billion barrels of future crude-oil discoveries are being made.

By 1 January 1967, the cumulative proved discoveries (cumulative production plus proved reserves) of natural gas in the conterminous United States amounted to 604 trillion cubic feet and the proved reserves alone to 286 (AGA, API, and CPA, 1967). In our previous study of crude oil, we found an estimated 24.1 billion barrels of producible crude oil in fields already discovered in excess of the 31.1 billion barrels of proved reserves. Assuming that about the same ratio prevails for natural gas, we obtain a figure of 222 trillion cubic feet for the fields already discovered beyond the 286 trillion cubic feet of proved reserves.

Then, adding these three figures, we obtain a rough estimate for the ultimate amount of gas Q_∞:

	$(10^{12} ft^3)$
Proved discoveries, as of 1-1-67	604
Additional gas in already discovered fields	222
Future discoveries	218
Total Q_∞	1,044

This figure is in close agreement with the estimate of 1,000 trillion cubic feet obtained from different data in the National Academy of Sciences report on *Energy Resources* (Hubbert, 1962, pp. 75–80) of 1962. It is much less than the Zapp (1961) estimate of 2,650 trillion cubic feet, and the Hendricks (1965) estimate of about 2,000 trillion cubic feet, including Alaska, or about 1,800 trillion cubic feet, excluding Alaska.

An estimate of a totally different character has recently become available as the result of the work of an industry committee, the Potential Gas Committee, under the chairmanship of B. Warren Beebe. At its meeting in Vancouver on 15–17 September 1967, the Committee on Resources and Man received from Beebe a confidential preview of a forthcoming report of the Potential Gas Committee.

This committee is made up of about 200 members from the oil and gas industry. It consists of a central committee, and 15 separate regional committees whose members are chosen on the basis of their extensive knowledge of the region concerned. The committee is a continuing committee and plans to revise its estimates at two-year intervals. Beginning at the local level, and using confidential information from the petroleum-industry files, local estimates are made, which are then assembled into regional estimates and these, finally, into an estimate for the whole conterminous United States.

The report of the Potential Gas Committee, released in October 1967, presents the following estimate of the natural-gas situation of the United States, exclusive of Alaska and Hawaii, as of 31 December 1966:

	$(10^{12} ft^3)$
Cumulative past production	314
Proved reserves	286
Total proved discoveries	600
Potential supply	690
Ultimate supply	1,290

The total potential supply of 690 trillion cubic feet is the sum of the following amounts of gas classified according to decreasing probability of discovery:

	$(6^{12} ft^3)$
Probable	300
Possible	210
Speculative	180
Total Potential Supply	690

A minor discrepancy exists between the Potential Gas Committee's figure of 600 trillion cubic feet for cumulative proved discoveries up to the beginning of 1967, and the figure of 604 trillion cubic feet used herein. The latter agrees with that given in the AGA, API, and CPA report of 1967 (p. 161). However, the principal difference lies in the amounts of gas estimated to be obtained from new fields still to be discovered, over and above the 825 trillion cubic feet estimated to be ultimately producible from fields already discovered. In the Potential Gas Committee's estimate, this would amount to 465 trillion cubic feet, which is just over twice the amount of our estimate of 218 trillion cubic feet, based on future oil discoveries.

At a gas-oil ratio of 7,500 ft^3/bbl, the new discoveries of crude oil that would have to accompany the future discovery of 465 trillion cubic feet of gas would amount to 62 billion barrels. The data in Figure 8.16 definitely do not support any such quantity but, rather, a figure of about half that amount.

Hence, although the estimate of the Potential Gas Committee of 1290 trillion cubic feet and that of 1044 trillion cubic feet based on a crude-oil analysis in conjunction with the gas-oil ratio are in substantial agreement, there still exists an excess of about 250 trillion cubic feet in the Potential Gas Committee's report which is difficult to reconcile with any likely amount of crude oil still to be discovered. If the 180 trillion cubic feet of gas classed as "speculative" by the Potential Gas Committee should be withdrawn, then a satisfactory agreement would be obtained.

Using the Potential Gas Committee's figure, Q_∞ = 1290 trillion cubic feet, the complete cycle of U.S. gas production is shown in Figure 8.20. According to this, a peak production rate of about 25 trillion cubic feet per year will occur about the year 1980. The time required to produce the middle 80 percent of the ultimate cumulative production will be the approximately 65-year period from about the years 1950 to 2015. Also shown is a curve of what the production would be until about 1985 if it were to continue the growth rate of 6.34 percent per year which has prevailed during recent decades.

A curve analogous to that in Figure 8.20 has also been computed for

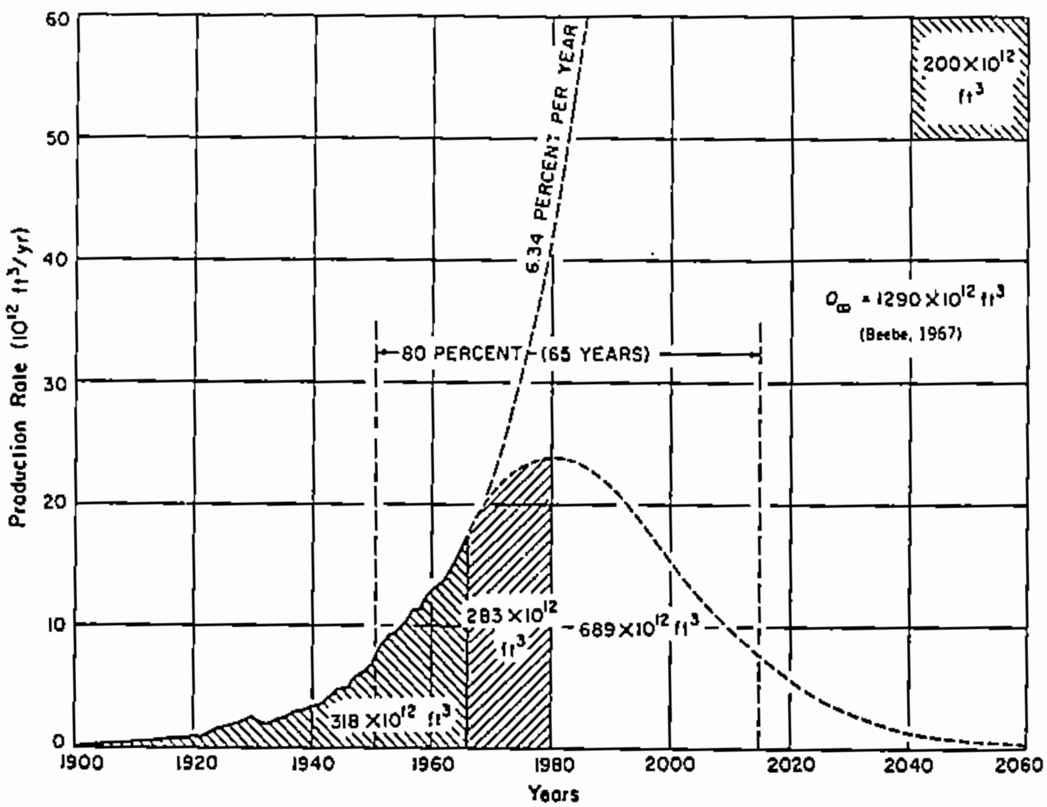

FIGURE 8.20
Complete cycle of natural-gas production in the United States and adjacent continental shelves, exclusive of Alaska.

Q_∞ = 1040 trillion cubic feet; it closely resembles the curve in Figure 8.20 except that the peak production rate is reduced to about 21 trillion cubic feet per year, and occurs at about the year 1978.

Estimates of Natural-Gas Liquids

The foregoing discrepancy in the estimates of future discoveries of natural gas carries over into estimates of natural-gas liquids. By 31 December 1966, the cumulative discoveries and proved reserves of natural-gas liquids for the conterminous United States were the following (API, AGA, and CPA, 1967, p. 116, 118, 207):

Cumulative production	9.86×10^9 bbls
Proved reserves	8.33×10^9 bbls
Cumulative discoveries	18.19×10^9 bbls

Since natural-gas liquids are produced along with natural gas, the significant ratio for these two fluids is that of gas/NGL. If we take the cumulative discoveries of these two fluids from 1860 to 1967, this ratio is

$$\text{gas/NGL} = \frac{604 \times 10^{12}\ \text{ft}^3}{18.2 \times 10^9\ \text{bbls}}$$

$$= 33{,}200\ \text{ft}^3/\text{bbl}.$$

If, on the other hand, we take the corresponding ratio for the decades 1947 to 1957 and 1957 to 1967, we obtain:

For 1947-1957,

$$\text{gas/NGL} = 27{,}000\ \text{ft}^3/\text{bbl};$$

For 1957-1967,

$$\text{gas/NGL} = 26{,}000\ \text{ft}^3/\text{bbl}.$$

From these figures, it appears that the gas-NGL ratio is progressively decreasing with cumulative gas production. In view of this progressive decline in the gas-NGL ratio, it is difficult to justify a figure larger than 25,000 ft^3/bbl for future U.S. discoveries. Using this figure, in conjunction with cumulative proved discoveries of 604 trillion cubic feet by the beginning of 1967, and the two estimates of Q_∞ for natural gas, of 1044 trillion and 1290 trillion cubic feet, we obtain for the estimates of future discoveries of natural-gas liquids:

For $Q_\infty = 1044 \times 10^{12}\ \text{ft}^3$,

$$\text{NGL} = \frac{(1044 - 604) \times 10^{12}\ \text{ft}^3}{2.5 \times 10^4\ \text{ft}^3/\text{bbls}} = 17.6 \times 10^9\ \text{bbls};$$

For $Q_\infty = 1290 \times 10^{12}\ \text{ft}^3$,

$$\text{NGL} = \frac{(1290 - 604) \times 10^{12}\ \text{ft}^3}{2.5 \times 10^4\ \text{ft}^3/\text{bbl}} = 27.4 \times 10^9\ \text{bbls}.$$

When these figures are added to the 18.2×10^9 bbls of cumulative proved discoveries, we obtain 35.8 billion and 45.6 billion barrels for the estimated ultimate quantity of natural-gas liquids to be produced in the conterminous United States. On the basis of our previous comments concerning the natural-gas estimates, only the lesser of these two figures is compatible with our earlier analysis of crude oil, and is accordingly favored here. Using the smaller figure, rounded off to 36 billion barrels, the full cycle of U.S. production of natural-gas liquids is shown in Figure 8.21. According to the calculations on which this figure is based, a peak production

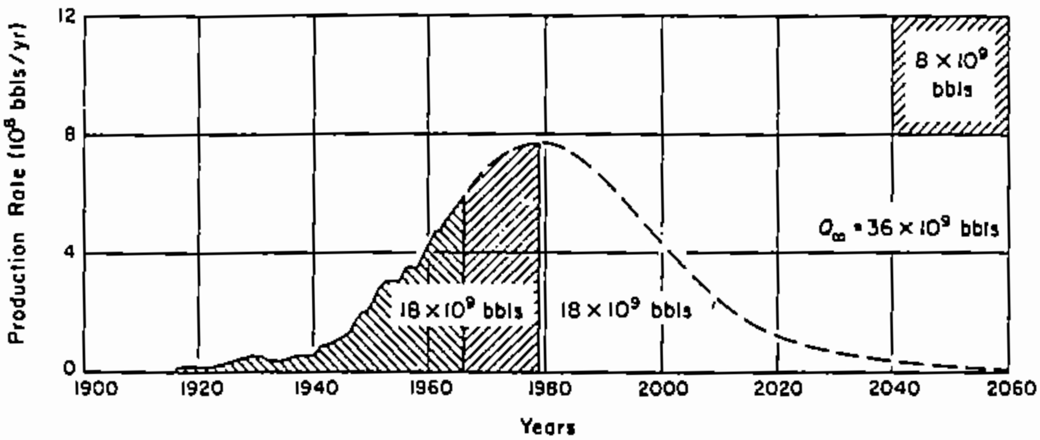

FIGURE 8.21
Complete cycle of production of natural-gas liquids in the United States and adjacent continental shelves, exclusive of Alaska.

rate of about 775 million barrels of natural-gas liquids per year will be reached at about 1980.

Total Petroleum Liquids

The sum of the production rate of crude oil and that of natural-gas liquids gives the production rate for petroleum liquids. Likewise, the sum of the ultimate amount of crude oil and of natural-gas liquids gives the ultimate amount of petroleum liquids to be produced. For the United States, exclusive of Alaska, this amounts to 165 billion barrels of crude oil plus 36 billion barrels for natural-gas liquids, or to 201 billion, rounded to 200 billion, barrels as the estimated magnitude of Q_∞ for petroleum liquids.

Using this value for Q_∞, the complete cycle of production of petroleum liquids is shown in Figure 8.22. A peak rate of production of about 3.5 billion barrels per year is estimated to occur during the first half of the 1970-decade, and production of the middle 80 percent of Q_∞ is expected to occur during the 64-year period from about the year 1937 to 2001. Also shown in Figure 8.22 is the course that the annual production would follow were it to continue at the constant rate of growth of 5.13 percent per year which prevailed from 1934 to 1952.

Estimates for Alaska. As stated above, the exploration for petroleum in Alaska is just in its beginning stages, and significant production of crude oil began only in 1958. Consequently, about the only guide for estimates at present is geological analogy coupled with the exploratory successes achieved thus far. On this basis a tentative allowance has already been made for an ultimate production of 25 billion barrels of crude oil. If we assume an average gas-oil ratio of 6,000 ft^3/bbl, which is about that for the rest of the

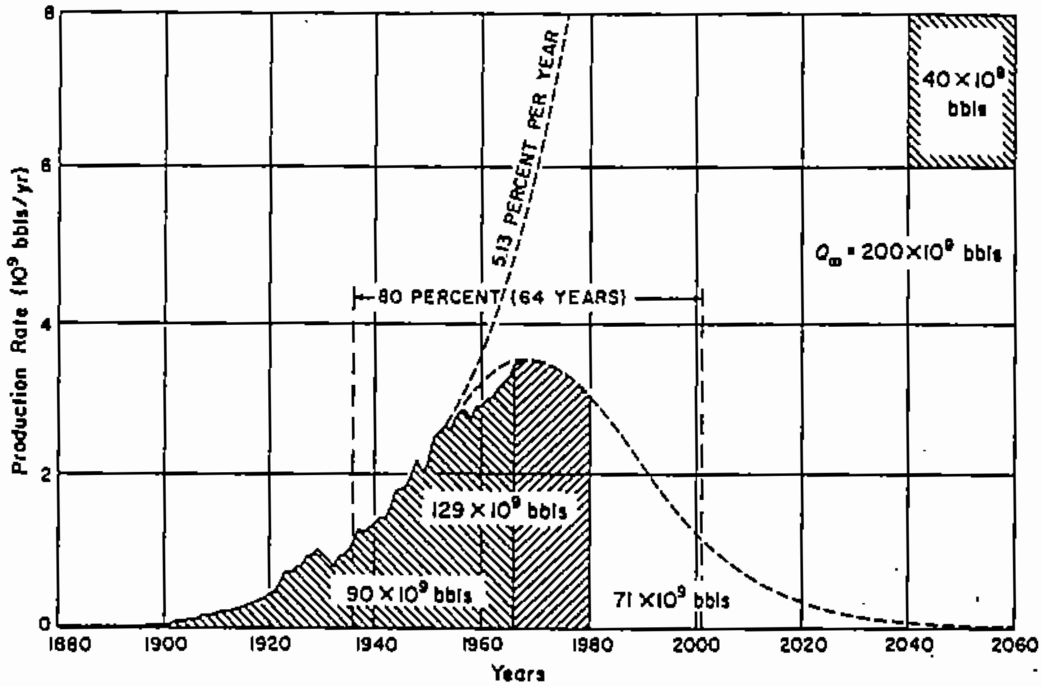

FIGURE 8.22
Complete cycle of production of petroleum liquids in the United States and adjacent continental shelves, exclusive of Alaska.

United States, this would give about 150 trillion cubic feet for the ultimate production of natural gas. And, at an average rate of 30,000 ft^3/bbl for the natural-gas—natural-gas liquids ratio, the estimated ultimate amount of natural-gas liquids would be about 5 billion barrels.

Total Petroleum for the Whole United States. These figures added to those already obtained for the rest of the United States give our present estimates for the ultimate amounts of petroleum fluids that the whole United States and its adjacent continental-shelf areas may reasonably be expected to produce. These estimates are given in Table 8.1.

TABLE 8.1
Estimated ultimate amounts of petroleum fluids to be produced by the United States (including contiguous continental shelves).

Region	Crude Oil (10^9 bbls)	Natural-gas Liquids (10^9 bbls)	Petroleum Liquids (10^9 bbls)	Natural Gas (10^{12} ft^3)
Conterminous United States	165	36	201	1,050
Alaska	25	5	30	150
Total	190	41	231	1,200

WORLD RESOURCES OF PETROLEUM

The Committee on Resources and Man is indebted to W. P. Ryman, Deputy Exploration Manager of Standard Oil Company of New Jersey, for several different world estimates of ultimate crude oil recovery, by major geographical areas (Table 8.2). Column one of Table 8.2 contains estimates made in January 1967 by *World Oil* of "proved" ultimately recoverable crude oil. Column two presents estimates of December 1966 made by *World Petroleum* of "proved and probable" ultimately recoverable crude oil. Finally, column three presents a 1962 estimate of L. G. Weeks, and column four a tentative estimate as of 1967 by W. P. Ryman of ultimately recoverable crude oil under normal expected recovery practices. The estimates of the last two columns each represent the sum of cumulative production plus proved reserves plus probable reserves plus future discoveries.

Our concern here is only with the estimates of Weeks and Ryman given in columns three and four, for these are the only ones that include future discoveries.

TABLE 8.2
Estimated ultimate recovery (EUR) of world crude oil, by geographical area (in billions of U.S. barrels).

	World Oil, Jan. 1967 Proved Reserves	*World Petr.,* Dec. 1966 Proved & Probable Reserves	L. G. Weeks, 1962 EUR[a]	W. P. Ryman, 1967 EUR[a]
Free World outside United States				
Europe	3.6	4.0	19	20
Africa	31.9	49.0	100	250
Middle East	273.7	304.1	780	600
Far East	15.1	17.1	85	200[b]
Latin America	56.9	64.4	221	225[b]
Canada	10.9	11.4	85	95
Total	392.1	450.0	1,290	1,390
United States	113.4	128.6	270	200
Total Free World	505.5	578.6	1,560	1,590
U.S.S.R., China, and satellites	65.5	86.7	440	500
Total World	571.0	665.3	2,000	2,090

Source: W. P. Ryman, Deputy Exploration Manager, Standard Oil Company of New Jersey.
[a]Based on normal expected recovery. Estimate includes: Produced + Proved + Probable + Future Discoveries.
[b]Includes offshore areas.

The Ryman estimates follow closely the earlier estimates of Weeks, but with some minor adjustments of the Weeks estimates for separate areas. With the exception of three cases, these adjustments to the Weeks estimates have been less than 11 percent. In the three exceptional cases, the Weeks estimate for Africa was increased from 100 billion to 250 billion barrels, that for the Far East from 85 billion to 200 billion barrels, and that for the United States was *decreased* from 270 billion to 200 billion barrels. For the world total, the Weeks estimate of 2,000 billion barrels was increased to 2,090 billion.

It is here considered that the Ryman estimates given in column four of Table 8.2 are about as accurate *relative* estimates of crude-oil resources of the various major regions of the world as can be made at the present time. The word "relative" is stressed, because the Ryman estimates follow closely those of Weeks. However, the Weeks estimates include a figure of 270 billion barrels for the United States, which is about 50 percent more than the highest figure that can be justified by the petroleum-industry data reviewed herein. Hence, if the Weeks method gives for the United States—the most completely explored region in the world (and its standard yardstick)—an estimate that is about 50 percent too large, it is a fair presumption that the same may be true of his estimate for the rest of the world also. In view of this possibility, two separate figures are here taken as the value of Q_∞ for the ultimate world production of crude oil: Ryman's estimate rounded off to 2,100 billion barrels, and a smaller figure of 1,350 billion barrels, which is about two-thirds of the Weeks estimate. It appears that the uncertainty of the world estimates at present is roughly within these limits.

The estimated full cycles of world crude-oil production, based on the two values, $Q_\infty = 2{,}100$ and $Q_\infty = 1{,}350$ billion barrels, are shown in Figure 8.23. For the smaller figure, a peak production rate of about 25 billion barrels per year is estimated to occur at about the year 1990, with the middle 80 percent of the cumulative production requiring only the 58-year period from 1961 to 2019. For the higher figure, the peak of the production rate of about 37 billion barrels per year would be delayed by only 10 years to about the year 2000. In this case, the time required to produce the middle 80 percent of the ultimate cumulative production would be increased to the 64-year period from about 1968 to 2032.

Mention should also be made of the recent world crude-oil estimates by Hendricks (1965). In these estimates, Hendricks used the same modification of the Zapp hypothesis that he used to obtain his estimate for the United States. Hendricks' estimate for the world crude oil eventually to be discovered is 6,200 billion barrels. This includes his estimate of 1,000 billion barrels for the United States. With an assumed 40-percent recovery factor, these two figures reduce to 2,480 billion and 400 billion barrels of recoverable crude oil for the world and the United States, respectively. Since his figure

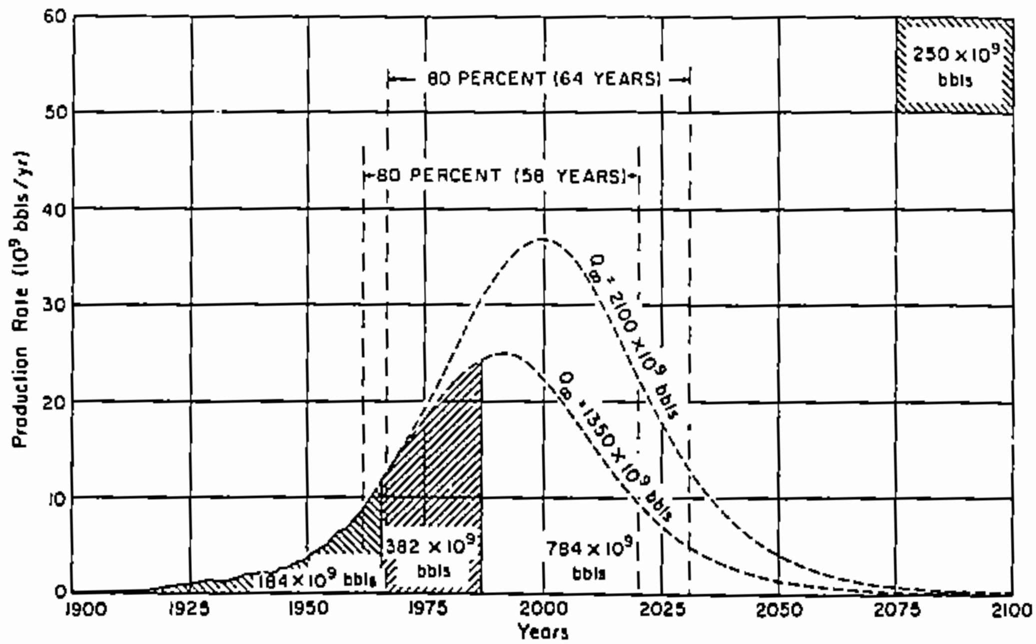

FIGURE 8.23
Complete cycles of world crude-oil production for two values of Q_∞.

of 400 billion barrels for the United States includes Alaska, it is to be compared with our present estimate of 190 billion barrels for the whole United States. Then, if a proportionate reduction is applied to the Hendricks world estimate, his figure of 2,480 billion barrels is reduced to 1,180, which is of the approximate magnitude of our lower figure of 1,350 billion barrels.

Another recent review of world petroleum resources was that given by D. C. Ion (1967) before the Seventh World Petroleum Congress in Mexico City, April 1967. This, however, was based so heavily upon the Hendricks estimate of 1965 that it can hardly be regarded as an independent estimate.

WORLD RESOURCES OF NATURAL GAS AND NATURAL-GAS LIQUIDS

As was true for U.S. production of natural gas during the earlier phases of the petroleum industry in the United States, the world production of natural gas has been handicapped in many areas by the absence of an accessible market. Consequently, much of the gas produced has been flared and wasted. However, recent advances in technology are eliminating much of this waste, so that eventually it is probable that most of the natural gas and natural-gas liquids produced will be conserved for industrial uses. Three main factors make this possible. One is an increase in gas-consuming industries, such as power production and the manufacture of Portland cement near centers of gas production. The second is the building of large-diameter pipelines for the transmission of gas from remote production areas to main industrial centers of consumption. The third is the development of cryogenic tankers for transoceanic transportation of natural gas in a liquefied form.

To make a rough estimate of the world resources of natural gas and natural-gas liquids, about the best that can be done at present is to assume that the ratios of natural gas and of natural-gas liquids to crude oil for the whole world will be about the same as those for the United States, and that shortly most of these fluids will be utilized rather than wasted.

For the United States, the ratio of the estimated ultimate amount of natural gas to be produced to that of crude oil is about 6,400 ft^3/bbl; the corresponding ratio of natural-gas liquids to crude oil is about 0.22 bbls/bbl. For a rough estimate, these figures may be rounded off to 6,000 ft^3/bbl for the natural gas—crude-oil ratio and to 0.2 bbls/bbl for the natural-gas liquids—crude-oil ratio. Applying these ratios to our two previous estimates for the ultimate world crude-oil production gives corresponding estimates for the ultimate world production of natural gas and natural-gas liquids. These are given in Table 8.3. The estimates given by W. P. Ryman at the Vancouver conference for the ultimate world production of natural-gas liquids and natural gas were 375×10^9 bbls and $12{,}000 \times 10^{12}$ ft^3, respectively. Both of these figures are within the ranges indicated in Table 8.3.

TAR OR HEAVY-OIL SANDS

So-called tar, or heavy oil sands are impregnated with what is essentially a heavy crude oil that is too viscous to permit recovery by natural flowage into wells. Since such sands are as yet almost unexploited, no convenient world inventory of their occurrence is available. However, the best known of such deposits, and possibly the world's largest, are in the Province of Alberta, Canada. Pow, Fairbanks, and Zamora (1963) report on the large Athabasca deposit near Fort McMurray in northeastern Alberta and two

TABLE 8.3

Estimates of ultimate world production of natural-gas liquids, total petroleum liquids, and natural gas, based on two estimates of the ultimate production of crude oil.

Ultimate world crude-oil production (10^9 bbls)	Ultimate natural-gas liquids production (10^9 bbls)	Ultimate total petroleum liquids production (10^9 bbls)	Ultimate natural-gas production (10^{12} ft^3)
1,350	250	1,620	8,000
2,100	420	2,520	12,000

TABLE 8.4
Tar-sand deposits of Alberta, Canada.

Area	Evaluated Reserves (10^9 bbls)
Athabasca	266.9
Bluesky-Gething	20.6
Grand Rapids	13.3
Total	300.8

Source: Pow, Fairbanks, and Zamora (1963).

smaller groups: the Bluesky-Gething deposits in northwestern Alberta, and the Grand Rapids deposits in north-central Alberta.

Of these, the Athabasca deposit has an area of about 9,000 square miles and contains about 88 percent of the total evaluated tar-sand reserves of the Province. The Bluesky-Gething deposits have an area of about 1,800 square miles and contain about 7 percent of the evaluated reserves. The remaining deposits have an aggregate area of about 1,600 square miles and contain about 5 percent of the evaluated reserves. The thickness of overburden in the various deposits ranges from 0 at surface outcrops to about 2,000 feet.

The evaluated reserves of recoverable upgraded synthetic crude oil from the three groups of deposits are given in Table 8.4.

During the last half century, small-scale efforts to exploit these sands have repeatedly failed. Since 1966, however, the first large-scale mining and extraction plant, developed by a combination of major oil companies, has gone into successful operation. Development work has also been under way since 1958 by a number of other oil companies, who only await the approval of the provincial government to begin further exploitation.

If we compare the magnitude of the reserves of these deposits with that of the crude-oil resources of the United States, their potential importance in the comparatively near future, when domestic crude-oil production begins its decline, is immediately apparent. The oil from these sands has the additional advantage that, being in the same chemical family as crude oil, it can be processed by existing oil refineries without major modifications.

OIL SHALES

As remarked previously, oil shales differ from tar or heavy-oil sands in that their hydrocarbon contents are in a solid rather than a viscous-liquid form. Also shale oil differs considerably from crude oil in chemical content; it includes objectionable nitrogen and other impurities. Consequently, the oils from oil shales pose special problems in refining.

In the United States, the principal and best known oil-shale deposits are those of the Green River Formation in the Piceance Basin of northwestern Colorado, the Uinta Basin of eastern Utah, and the Green River Basin of southwestern Wyoming. Because the oil contents of these shales range from about 65 U.S. gallons per ton (1.5 barrels/ton) for the richest shales to near zero, some confusion exists in where to place the cutoff limit of oil content in estimating the magnitude of the resources. According to a study by Duncan and Swanson (1965, p. 13):

> Known oil-shale deposits that yield 10-25 gallons of oil per ton contain about 800 billion barrels oil equivalent in the Piceance Basin, Colo.; about 230 billion barrels in the Uinta Basin, Utah; and about 400 billion barrels in the combined Green River Basin and Washakie Basin, Wyoming.

These figures tend to be misleading unless tempered with the same authors' discussion elsewhere of "recoverable resources." These are said to be (ibid., p. 6):

> . . . (1) deposits yielding 25-100 gallons of oil per ton, in beds a few feet thick or more, extending to depths of 1,000 feet below surface and (2) some lower grade deposits yielding 10-25 gallons of oil per ton, in units 25 feet thick or more, which are minable by open-pit methods. About 50 percent of the oil shale in place is assumed to be minable under present conditions, although larger percentages could be recovered from parts of deposits minable by open-pit methods.

In view of these restrictions, the same authors list (their Table 2, p. 9) only 80 billion barrels as being "recoverable under present conditions" from the Green River Formation in Colorado, Utah, and Wyoming. Duncan and Swanson also list the carbonaceous Devonian and Mississippian shales of east-central United States, and other shale deposits, whose aggregate chemical energy contents are enormous, but the oil-equivalent content per ton is so small that they are classed as "marginal and submarginal."

The same authors have compiled a comprehensive summary of the known major deposits of carbonaceous shales throughout the world, and have given estimates of their oil contents in their Table 3 on page 18 (our Table 8.5). Again, it is significant that although the table gives a figure of about 2×10^{15} barrels as the order of magnitude of the total oil-equivalent content of these shales, only 190×10^{9}, or 190 billion barrels (including 80 billion for the U.S. Green River Shale), is listed as recoverable under present conditions.

Hence, the organic contents of the carbonaceous shales appear to be more promising as a resource of raw materials for the chemical industry than as a major source of industrial energy.

TABLE 8.5
Estimates of shale oil resources of world land areas (in billions of barrels).

	Known Resources				Possible Extensions of Known Resources			Undiscovered and Unappraised Resources			Order of Magnitude of Total Resources[b]		
	Recoverable under Present Conditions	Marginal and Submarginal (oil equivalent in deposits)									Oil Equivalent in Deposits		
	Range in grade (oil yield, in gallons per ton of shale)												
Continents	10–100	25–100	10–25	5–10	25–100	10–25	5–10	25–100	10–25	5–10	25–100	10–25	5–10
Africa	10	90	Small	Small	ne[a]	ne	ne	4,000	80,000	450,000	4,000	80,000	450,000
Asia	20	70	14	ne	2	3,700	ne	5,400	106,000	586,000	5,500	110,000	590,000
Australia and New Zealand	Small	Small	1	ne	ne	ne	ne	1,000	20,000	100,000	1,000	20,000	100,000
Europe	30	40	6	ne	100	200	ne	1,200	26,000	150,000	1,400	26,000	140,000
North America	80	520	1,600	2,200	900	2,500	4,000	1,500	45,000	254,000	3,000	50,000	260,000
South America	50	Small	750	ne	ne	3,200	4,000	2,000	36,000	206,000	2,000	40,000	210,000
Total	190	720	2,400	2,200	1,000	9,600	8,000	15,000	313,000	1,740,000	17,000	325,000	1,750,000

Source: Duncan and Swanson, 1965, Table 3, p. 18.
[a]ne = no estimate.
[b]Of the approximately 2×10^{15} bbls here indicated, 190×10^{9} were considered recoverable under 1965 conditions.

RESOURCES OF COAL

World production of coal from 1860 to 1965 has already been shown in Figure 8.1, and that for the United States in Figure 8.4.

Unlike petroleum, coal occurs as stratified deposits in sedimentary basins. These commonly are continuous over wide areas and also frequently crop out at the surface of the ground. Consequently, by means of surface geological mapping, and a few widely spaced drill holes, it is possible to make reasonably accurate estimates of the coal resources of a given sedimentary basin in advance of mining, and to estimate the coal resources of the various sedimentary basins of the world. Then, with this knowledge, by means of the technique illustrated in Figure 8.8, it is possible to anticipate the period of time during which coal may be depended upon to supply a major part of the world's requirements for industrial energy.

The first world-wide inventory of coal, based on such considerations, was that reported to the Twelfth International Geological Congress at Toronto in the year 1913. Although many of the estimates at that time were very provisional, the estimate of minable coal resources for the entire world amounted to about 8×10^{12} metric tons. Since that time, geological mapping has been extended to all the land areas of the world. The result has been that large coal deposits in Siberia and China, which were little known in 1913, have been added to the estimates of that time, and estimates for other areas have been adjusted upward or downward as geological knowledge has increased.

During the last two decades, the U.S. Geological Survey has been engaged in a detailed study of the country's coal resources, and in connection with this study Paul Averitt has also made a succession of estimates of the coal resources of the world, using published national estimates of various countries, interpreted in conjunction with accruing geological information. In a report submitted to the Natural Resources Subcommittee of the Federal Council of Science and Technology, Averitt (1961) gave a table (Hubbert, 1962, p. 37) of the estimated remaining producible coal reserves of the world by principal regions and countries. Minable coal was taken to be 50 percent of the coal in the ground in seams 14 inches (0.36 meters) or more thick and less than 3,000 feet (900 meters) deep. Averitt's figure for the world was 2.3×10^{12} metric tons.

The foregoing figures pertain to coal deposits whose extent and magnitude are fairly accurately known from geological mapping and other data. Subsequently, Averitt has extended his studies to include not only the coal resources determined by mapping but also additional coal resources which, from geological information on the various coal-bearing areas, may

TABLE 8.6
Estimates of total original coal resources of the world by continents[a] (in billions of short tons).

Continent	Resources determined by mapping and exploration	Probable additional resources in unmapped and unexplored areas	Estimated total resources
Asia and European U.S.S.R.	7,000[b]	4,000	11,000[c]
North America	1,720	2,880	4,600
Europe	620	210	830
Africa	80	160	240
Oceania	60	70	130
South and Central Americas	20	10	30
Total	9,500[b]	7,330	16,830[c]

Source: Paul Averitt, 1969, Table 8, p. 82.
[a] Original resources in the ground in beds 12 inches thick or more and generally less than 4,000 feet below the surface, but includes small amounts between 4,000 and 6,000 feet.
[b] Includes about 6,500 billion short tons in the U.S.S.R.
[c] Includes about 9,500 billion short tons in the U.S.S.R. (Hodgkins, 1961, p. 6).

reasonably be inferred to exist. The results of these studies were presented to the Committee on Resources and Man during its meeting in Vancouver, 15–17 September 1967, and have since been published (Averitt, 1969) by the U.S. Geological Survey.

Averitt's current estimates, by continents, of the original coal in place are given in Table 8.6. In this case, the depth has been extended to 4,000 feet (1,200 meters), and in some cases to 6,000 feet (1,800 meters). Also the minimum thickness of seams considered has been reduced to 12 inches (0.3 meters). He pointed out, however, that the amount of coal added for the additional depth of 4,000–6,000 feet is small compared with that between 0 and 4,000 feet. In the United States, the coal in the 4,000–6,000-foot interval amounts only to about 10 percent of the total.

The data in Table 8.6 are expressed in short tons, and no breakdown by countries is given. However, in the footnote the Soviet Union is credited with $9{,}500 \times 10^9$ short tons, or $8{,}600 \times 10^9$ metric tons. In a separate detailed table, the original coal resources of the United States were given as $3{,}275 \times 10^9$ short tons, or $2{,}971 \times 10^9$ metric tons. From these data, the initial quantities of minable coal, taken as 50 percent of the coal present, have been computed by continents, and expressed in metric units, with separate estimates for the United States and the Soviet Union included. The results are shown graphically in Figure 8.24.

According to these estimates, about 65 percent of the world's initial coal resources were in Asia (including the European part of the Soviet

Union), about 27 percent in North America, less than 5 percent in Western Europe, and less than 3 percent in Africa, South and Central Americas, and Oceania (which includes Australia) combined. From these data, it is evident that the world's coal resources are not uniformly distributed.

World and United States production of coal and lignite have already been shown (Figures 8.1 and 8.4). Now, using Averitt's estimates of the ultimate amounts of minable coal for both the world and the United States, in conjunction with the principle that the area under the curves must not exceed those corresponding to the amounts of coal initially present, we can gain a reasonably reliable impression of the future possibilities in coal production. For world production, this is shown in Figure 8.25, using for the ultimate cumulative production Q_∞, Averitt's estimate of 7.6×10^{12} metric tons, and also a smaller figure of 4.3×10^{12}, which is approximately the amount of coal established by mapping.

For the larger value for Q_∞ of 7.6×10^{12} metric tons, should the annual production rate double only three more times to a maximum rate of eight times that of the present, the date of this peak rate would occur about 170 to 200 years hence. Should the maximum rate be higher than this, the peak date would occur sooner; should it be lower, later. For the smaller value for Q_∞ of 4.3×10^{12} metric tons, the curve is drawn for a sixfold increase in the production rate over that of the present. In this case, the peak rate would occur somewhat earlier, or about 140 years hence.

Corresponding graphs of future coal production in the United States are shown in Figure 8.26 for two values of Q_∞. The larger figure of $1{,}486 \times 10^9$

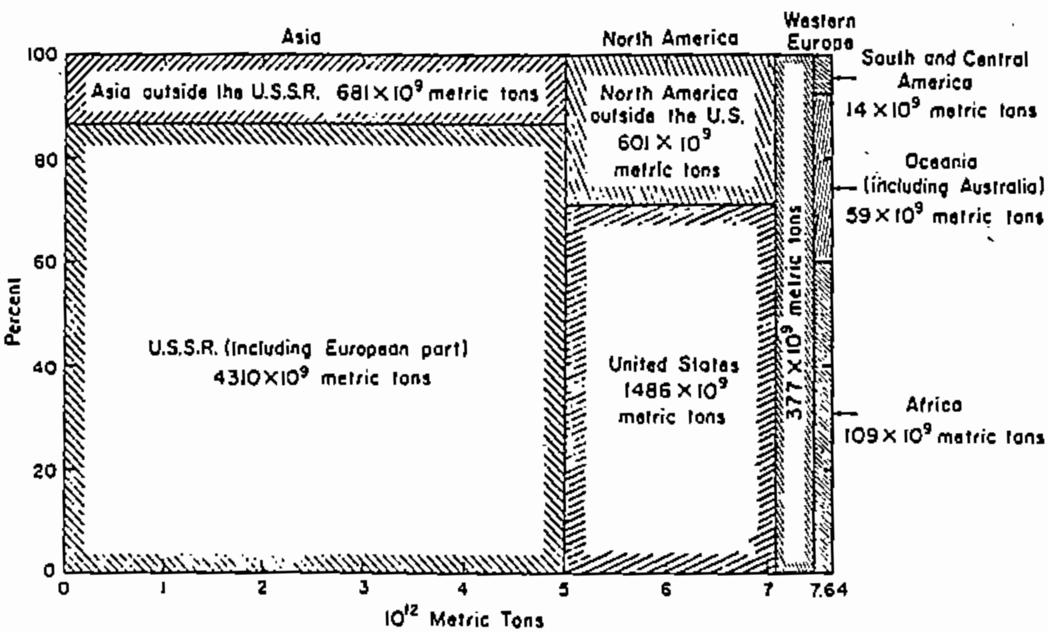

FIGURE 8.24
Estimates of world resources of minable coal and lignite. (Data from Averitt, 1969.)

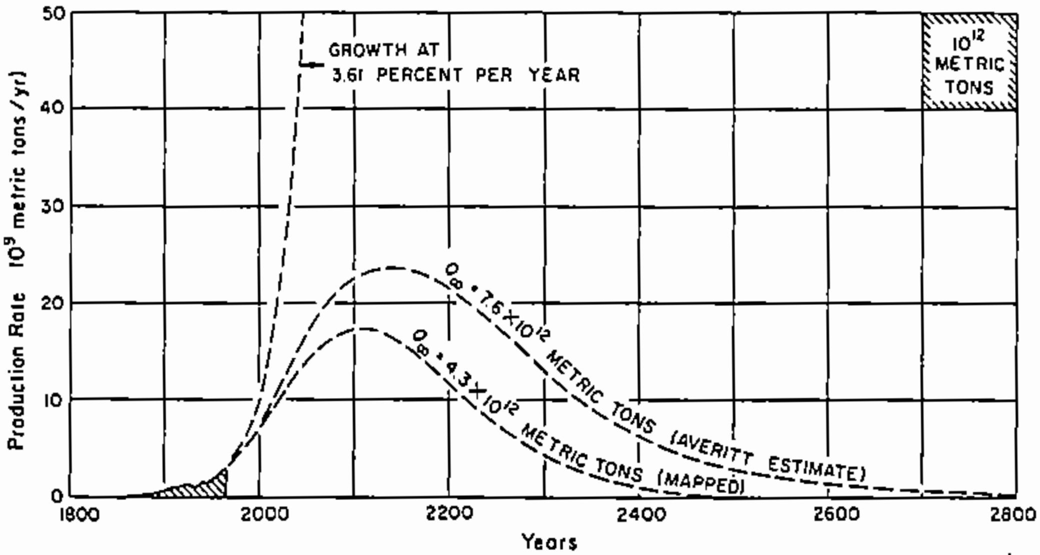

FIGURE 8.25
Complete cycles of world coal production for two values of Q_∞.

metric tons represents minable coal based on Averitt's recent estimate of the initial U.S. coal resources. The smaller figure of 740×10^9 metric tons is approximately the amount of coal determined by mapping. For the higher-rate curve, the assumed maximum production rate represents an eightfold increase over the present rate, or three future doublings. The smaller-rate curve assumes a fivefold increase in the rate of production. The peak production rates for these two curves would occur at about the years 2220 and 2170, respectively.

As was true for petroleum, the significant question about coal is not how

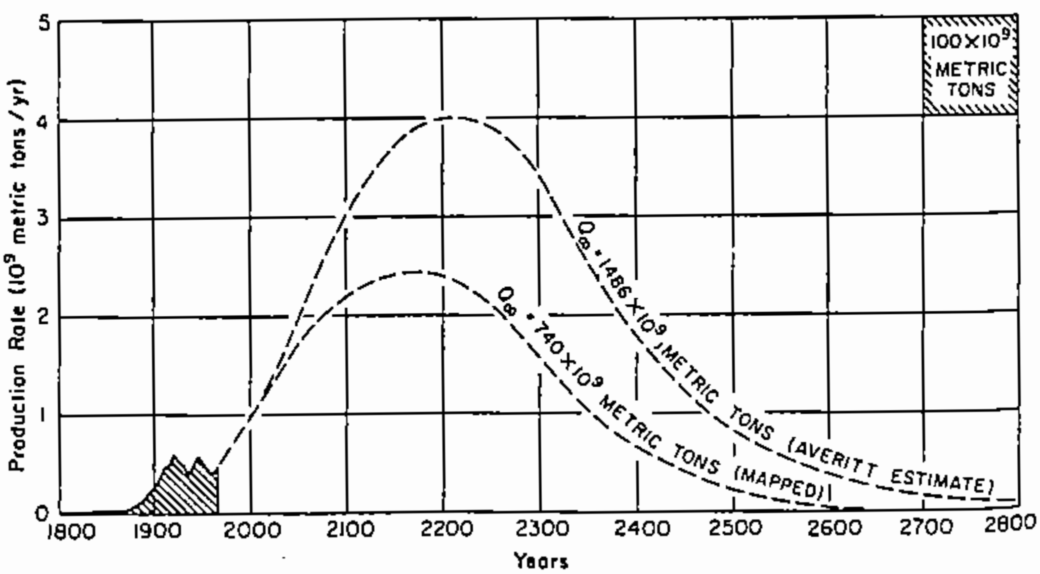

FIGURE 8.26
Complete cycles of United States coal production for two values of Q_∞.

long it will last, but rather, over what period of time can it serve as a major source of industrial energy? In answer to this, we may eliminate the long periods of time at relatively low rates of production required to produce the first and last 10-percentiles of the ultimate cumulative production Q_∞, and consider only the time span required to consume the middle 80 percent. For the world, using the higher value for Q_∞ of 7.6×10^{12} metric tons, the time required for the middle 80 percent, as determined from Figure 8.25, would be approximately the 340-year period from the year 2040 to 2380. For the United States, using the larger figure for Q_∞ of about 1.49×10^{12} metric tons, the time required to consume the middle 80 percent, as determined from Figure 8.26, would be approximately the 400-year period from about the year 2040 to 2440.

These figures, of course, are only approximate, but they do indicate the expectable order of magnitude of the length of time during which coal could serve as a major source of energy for the nation and the world. In both cases, should the smaller values of Q_∞ shown by the lower curves in Figures 8.25 and 8.26 be used, or should the peak rates of production be higher than those shown, the time would be correspondingly shortened.

CONCLUSIONS CONCERNING THE FOSSIL FUELS

For the purpose of the present study, the principal result of the foregoing estimates of the approximate magnitudes of both the United States' and the world's supply of the fossil fuels are the following:

If these substances continue to be used principally for their energy contents, and if they continue to supply the bulk of the world's energy requirements, the time required to exhaust the middle 80 percent of the ultimate resources of the members of the petroleum family—crude oil, natural gas, and natural-gas liquids, tar-sand oil, and shale oil—will probably be only about a century.

Under similar conditions, the time required to exhaust the middle 80 percent of the world's coal resources would be about 300 to 400 years (but only 100 to 200 years if coal is used as the main energy source).

To appreciate the bearing of these conclusions on the long-range outlook for human institutions, the historical epoch of the exploitation of the world's supply of fossil fuels is shown graphically in Figure 8.27, where the rate of production of the fossil fuels as a function of time is plotted on a time scale extending from 5,000 years ago to 5,000 years in the future—a period well within the prospective span of human history. On such a time scale, it is seen that the epoch of the fossil fuels can only be a transitory and ephemeral event—an event, nonetheless, which has exercised the most drastic influence experienced by the human species during its entire biological history.

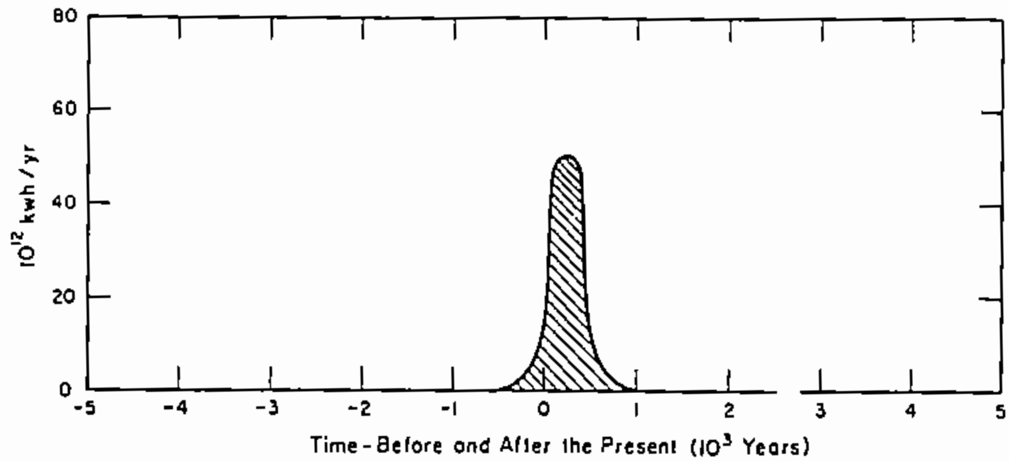

FIGURE 8.27
Epoch of exploitation of fossil fuels in historical perspective from minus to plus 5,000 years from present. (From Hubbert, 1962, Figure 54, p. 91.)

OTHER SOURCES OF ENERGY

In view of the exhaustibility and comparatively short time span for the duration of the fossil fuels, if the world's state of industrialization is to survive the decline of fossil fuels, other sources of energy and power of comparable magnitude must be found. Possible sources will now be reviewed with this requirement in mind.

Solar Energy

The first and most obvious of possible large energy sources is solar radiation, which is extensively discussed by Farrington Daniels (1964) in his excellent book, *Direct Use of the Sun's Energy*. In magnitude, the thermal solar power per square centimeter at the mean distance of the earth from the sun amounts, outside the earth's atmosphere, to 0.139 watts/cm^2, and the thermal power intercepted by the earth's diametral plane is 17.7×10^{16} watts, which is about a hundred-thousand times larger than the world's present installed electric-power capacity. Hence, solar power is of adequate magnitude. It also has the virtue of remaining nearly constant over time periods of millions of years—much longer than the probable duration of the human species. Solar radiation is also the energy source, through the mechanism of photosynthesis, for the entire biological system.

As Daniels discusses in detail, many practical nonbiological uses can be made of solar energy on a small scale. These include such uses as water and house heating, air conditioning, distillation, solar furnaces, solar cookery, and numerous thermoelectric, photoelectric, and other means of electrical conversion or storage of solar energy. However, our principal concern at present is with the question of whether it is likely that our requirements for large-scale electrical power, now supplied by the fossil fuels and water power, could be met by means of solar power. In particular, since modern power stations fall largely in the range of 100 to 1,000 megawatts each, what is the likelihood of building solar power plants of such magnitudes?

Consider, in particular, a solar-electric power plant of 1,000 electric megawatts capacity. With a conversion factor from solar power to electrical power of 10 percent, such a plant would require a solar power input of 10,000 megawatts, or 10^{10} thermal watts. According to Daniels (1964, Table 1, p. 22), the average solar power at the earth's surface amounts to about 500 cal/cm^2/day. This, when averaged over a full day, gives an average solar power input of about 2.4×10^{-2} watts/cm^2. Then, the area of the earth's surface required to collect 10^{10} watts of solar power would be

$$10^{10} \text{ watts}/(2.4 \times 10^{-2} \text{ watts/cm}^2) = 42 \times 10^{10} \text{ cm}^2,$$

which would be 42 km^2, or a square area of 6.5 km per side.

There is no question that it is physically possible to cover such an area with energy-collecting devices, and to transmit, store, and ultimately transform the energy so collected into conventional electric power. However, the complexity of such a process, and its cost in terms of the metals and physical, chemical, and electrical equipment required, in comparison with the requirements for present thermoelectric or hydroelectric equipment of the same capacity, renders such an undertaking to be of questionable practicability.

At present, therefore, the principal uses of solar energy, in addition to the natural processes of photosynthesis and the maintenance of the atmospheric, hydrologic, and oceanic circulations, appear to be small-scale, special-purpose uses.

Water Power

Water power represents the largest concentration of solar power that is produced by any natural process, and five hydroelectric plants already exist in the United States with power capacities exceeding 1,000 megawatts each. The history of the use of water power dates from Roman times, and, in the United States, water power has been extensively employed for the driving of grist mills, saw mills, textile mills, and other manufacturing establishments during the eighteenth and nineteenth centuries. However, because of the difficulties inherent in power transmission by mechanical devices, such plants rarely exceeded a few hundred kilowatts in power capacity.

It was not until the development of electrical-power transmission at about the beginning of the present century that large-scale generation and trans-

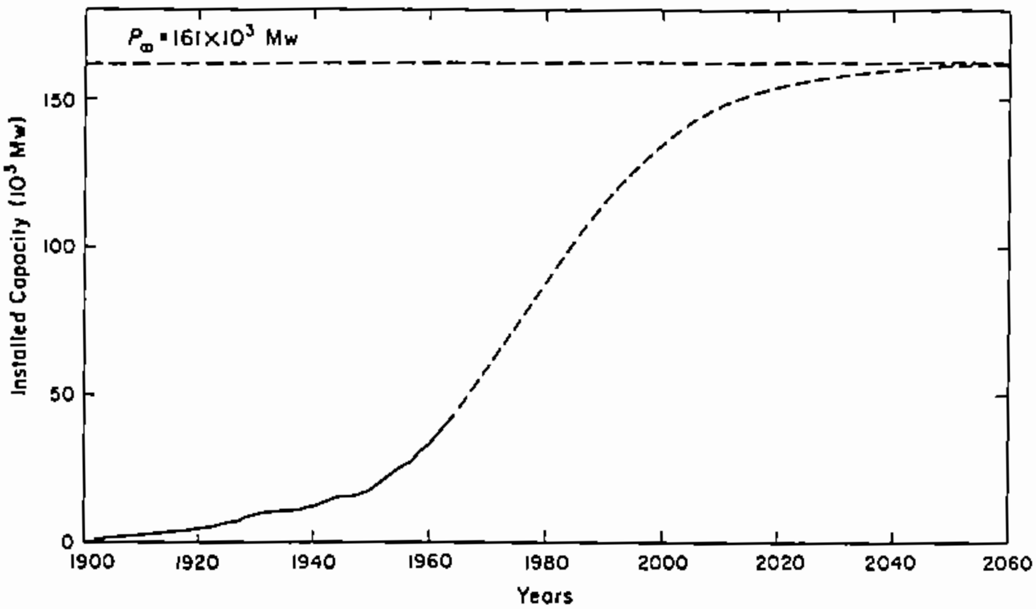

FIGURE 8.28
United States installed and potential water-power capacity.

mission of water power became possible. Since that time, the installation of hydroelectric power capacity in the United States has followed the customary growth curve shown in Figure 8.28. Installed capacity at present amounts to about 45,000 megawatts. As to the future, there is a fairly definitely determined ultimate maximum power capacity, P_∞, which for the United States is given by the Federal Power Commission to be about 161,000 megawatts. This is determined from the stream-flow records for the whole country which have been recorded for many years by the U.S. Geological Survey.

The Geological Survey has also made estimates from time to time of the potential water-power capacities of the various continents for the world as a whole.

Table 8.7, prepared from a summary by Francis L. Adams (Hubbert, 1962, p. 99), of the Federal Power Commission, utilizing basic U.S. Geological Survey data, gives the potential water-power capacities of the world by principal regions. The total world capacity is given as 2,857,000 megawatts. Of this, it is significant that the continents of Africa and South America, both of which are deficient in coal, have the highest potential water-power capacities of all the continents—780,000 megawatts for Africa and 577,000 for South America.

By 1964, the installed water-power capacity of the world amounted to 210,000 megawatts (U.S. Federal Power Commission, 1966, Table 5, p. 7), which is only about 7.5 percent of its potential capacity. The total installed electrical-power capacity of the world amounted at the same time to 734,000 megawatts. Hence, the total potential water-power capacity of the world is still about four times as large as total installed electric-power capacity.

It thus appears that if the world's potential conventional water-power capacity were fully developed it would be of a magnitude comparable to the world's total present rate of energy consumption. From this, it might be inferred that without the present supply of fossil fuels, the world could continue at an industrial level comparable to that of the present on water-power alone. Offsetting such an expectation are two contrary considerations. The first is the aesthetic one of whether the people of the world wish to sacrifice some of their most beautiful natural scenery in order to develop fully the associated water power. The second concerns the fact that in all reservoirs formed by dammed streams, the streams are continuously depositing their loads of sediments, so that in periods of a century or two most man-made reservoirs are due to become completely filled by such sediments. This problem has not been satisfactorily solved, and may never be. Hence, although the stream rates of discharge may remain relatively stable for millenia, most water-power sites may have periods of maximum usefulness measured by a century or two. It is accordingly questionable to what extent the world may be able to depend upon water power as a substitute for the depleted fossil fuels.

Tidal Power

Another source of power having a longevity measurable in geologic time is tidal power. Tidal power is similar in all essential respects to hydroelectric power except that, whereas hydroelectric power is obtained from the energy of unidirectional streamflow, tidal-electric power is obtained from

TABLE 8.7
World water-power capacity.

Region	Potential (10^3 Mw)	Percent of total	Development (10^3 Mw)	Percent developed
North America	313	11	59	19
South America	577	20	5	
Western Europe	158	6	47	30
Africa	780	27	2	
Middle East	21	1	—	
Southeast Asia	455	16	2	
Far East	42	1	19	
Australasia	45	2	2	
U.S.S.R., China and satellites	466	16	16	3
Total	2,857	100	152	

Source: M. King Hubbert, 1962, Table 8, p. 99, computed from data summarized by Francis L. Adams, 1961.

the oscillatory flow of water in the filling and emptying of partially enclosed coastal basins during the semi-diurnal rise and fall of the oceanic tides. This energy may be partially converted into tidal-electric power by enclosing such basins with dams to create a difference in water level between the ocean and the basin, and then using the waterflow while the basin is filling or emptying to drive hydraulic turbines propelling electric generators.

In order to obtain a quantitative evaluation of the amount of tidal energy potentially obtainable from a given basin, it is useful to determine the maximum amount of energy that can be dissipated into heat during one complete tidal cycle. This is the amount of energy that would be dissipated if the dam gates were closed at low tide when the water in the basin is at its lowest level, and then opened wide allowing the basin to fill at the crest of the tide; and, in a similar manner, by closing the gates when the basin is filled at high tide, and then allowing the basin to empty at low tide.

This maximum possible amount of energy dissipated during one tidal cycle is given by

$$E_{max} = \rho g R^2 S, \tag{7}$$

where ρ is the density of sea water, g the acceleration of gravity, R the tidal range, and S the surface area of the basin. When all of the quantities to the right in equation (7) are in meter-kilogram-second units, the energy will be in joules.

The maximum possible average power obtainable from such a basin would be obtained if all of the energy E_{max} in equation (7) were converted into electrical energy. This maximum average power would then be given by

$$\bar{P} = \frac{E_{max}}{T} = \frac{\rho g R^2 S}{T}, \tag{8}$$

where T is the half period of the synodical lunar day. This is 12 hours and 24.4 minutes, or 4.46×10^4 seconds. When T is in seconds, $\bar{P}$ will be expressed in joules/second, or watts.

The actual energy and power obtainable by means of turbines and electrical generators from such a basin can be only a fraction of the quantities given in equations (7) and (8). In engineering design computations for various tidal-power projects, the amounts of energy and power producible are commonly within the range of 8–20 percent of these maximum amounts, although in one instance, that of la Rance in France, the realizable power approaches 25 percent.

The source of tidal energy is the combined kinetic and potential energy of the earth-moon-sun system. Hence, as this energy is dissipated on the earth, equivalent changes must occur in the rotational energy of the earth, and in the orbital motions of the moon about the earth and of the earth about the sun. These motional changes, which have been observed astronomically over a period of about three centuries, indicate that the day is lengthening by about 0.001 second per century with a corresponding decrease in the earth's rotational velocity. From such astronomical data, Munk and MacDonald (1960, p. 219) have recently estimated that the rate of tidal dissipation of energy on the earth is about 3×10^{12} watts.

A considerable fraction of this dissipation occurs in the oceans, especially in the shallow seas, bays, and estuaries, where the tidal ranges and tidal currents, because of inertial effects, become much greater than those in the open oceans. The oceanic tides, as measured on islands in the open oceans, have ranges commonly of less than a meter, whereas those in bays and estuaries have ranges, as shown in Table 8.8, from 1 to more than 10 meters.

A method of estimating the amount of energy dissipated by tides in shallow seas was developed in 1919 by G. I. Taylor and applied to the Irish Sea. The following year, this method was extended by Harold Jeffreys (1920; 1959, p. 241–245) to most of the shallow seas of the earth for which he estimated a rate of energy dissipation at spring tides of about 22×10^{11} watts, of which 15×10^{11} watts, or two-thirds of the total was accounted for by the Bering Sea alone.

Recently, using oceanographic data subsequently acquired, Munk and MacDonald (1960, p. 209–221) have re-estimated the energy dissipation in shallow seas. They obtained an average rate of, at most, 10^{12} watts, which is slightly less than the 1.1×10^{12} watts obtained when Jeffrey's rate for spring tides is reduced by a factor of 0.5 to give an average rate. Munk and MacDonald obtained a drastic reduction of Jeffrey's estimate for the Bering Sea from 75×10^{10} ($\frac{1}{2}$ of 15×10^{11}) to only 2.4×10^{10} watts.

The significance of these estimates is that they establish a limit to the maximum amount of power that could possibly be developed from tidal sources. In Table 8.8, which is based on data compiled by Trenholm (1961) and by Bernshtein (1965), a summary is given of the average tidal ranges and basin areas for most of the more promising tidal-energy localities of the world. In addition, the average potential power, and maximum energy dissipation per year, as computed from equations (7) and (8), are given for each locality. The total maximum rate of energy dissipation for these localities amounts to 6.4×10^{10} watts, or 64,000 megawatts. This is about 6 percent of the Munk and MacDonald estimate of a dissipation rate of 10^{12} watts for all of the shallow seas. If we make a liberal allowance of 20 percent for the actual average power recoverable at each of these sites, we obtain a result of about 13×10^{9} watts, or 13,000 megawatts as the approximate magnitude of the average value of the world's potential tidal-electric power. Comparing this with the estimate of the world's potential water power of about 2,900,000 megawatts given in Table 8.7, it will be seen that the world's potential tidal power amounts to less than 1 percent of its potential water power.

TABLE 8.8
Tidal power sites and maximum potential power.

Location	Average range R (meters)	R^2 (m^2)	Basin area S (km^2)	R^2S (m^2)(km^2)	Average potential power P (10^3 kw)	Potential annual energy E (10^6 kwh)
North America						
Bay of Fundy						
Passamaquoddy	5.52	30.5	262	7,990	1,800	15,800
Cobscook	5.5	30.3	106	3,210	722	6,330
Annapolis	6.4	41.0	83	3,440	765	6,710
Minas-Cobequid	10.7	114	777	88,600	19,900	175,000
Amherst Point	10.7	114	10	1,140	256	2,250
Shepody	9.8	96	117	11,200	2,520	22,100
Cumberland	10.1	102	73	7,450	1,680	14,700
Petitcodiac	10.7	114	31	3,530	794	6,960
Memramcook	10.7	114	23	2,620	590	5,170
Subtotal					29,027	255,020
South America						
Argentina						
San José	5.9	34.8	750	26,100	5,870	51,500
Europe						
England						
Severn	9.8	96.0	70	7,460	1,680	14,700
France						
Aber-Benoit	5.2	27.0	2.9	78	18	158
Aber-Wrac'h	5.0	25.0	1.1	28	6	53
Arguenon & Lancieux	8.4	70.6	28.0	1,980		
Frênaye	7.4	[illegible]				
La Rance	[illegible]					

San José	5.9	34.8	750	26,100	5,870	51,500
Europe						
England						
Severn	9.8	96.0	70	7,460	1,680	14,700
France						
Aber-Benoît	5.2	27.0	2.9	78	18	158
Aber-Wrac'h	5.0	25.0	1.1	28	6	53
Arguenon & Lancieux	8.4	70.6	28.0	1,980	446	3,910
Frênaye	7.4	54.8	12.0	658	148	1,300
La Rance	8.4	70.6	22.0	1,550	349	3,060
Rothéneuf	8.0	64.0	1.1	70	16	140
Mont Saint-Michel	8.4	70.6	610	43,100	9,700	85,100
Somme	6.5	42.3	49	2,070	466	4,090
Subtotal					11,149	97,811
U.S.S.R.						
Kislaya Inlet	2.37	5.62	2.0	11	2	22
Lumbovskii Bay	4.20	17.6	70	1,230	277	2,430
White Sea	5.65	31.9	2,000	63,800	14,400	126,000
Mezen Estuary	6.60	43.6	140	6,100	1,370	12,000
Subtotal					16,049	140,452
Grand Total					63,775	559,483

Sources: N. W. Trenholm, 1961; L. B. Bernshtein, 1965 (1961), Table 5-5, p. 173.

Although small tidal mills for the grinding of grain and similar purposes have been used since about the twelfth century, it is only within recent decades that tidal-electric installations have been given serious engineering consideration, and only within the last three years actually brought into operation.

One of the best known of such projects has been that of Passamaquoddy Bay on the United States-Canadian boundary off the Bay of Fundy. This bay has an area of 262 km^2 and an average tidal range of 5.52 meters, with a maximum potential average power (Table 8.8) of 1,800 megawatts. Plans were drafted for such a project during the early 1930's and construction was actually started before the project was finally killed by lack of Congressional appropriation. In 1948, interest in a Passamaquoddy Tidal Power Project was revived and a new engineering study was authorized by the United States and Canadian governments. This involved the establishment of an International Joint Commission and The International Passamaquoddy Engineering Board to study and draw engineering plans for such a project.

The Engineering Board, in its report of 1959, recommended a two-pool project involving both Passamaquoddy and Cobscook Bays, but with the power obtained solely from Passamaquoddy Bay during its emptying phase. This would have a power plant consisting of 30 unidirectional turbogenerator units of 10,000 kw capacity each, or a total installed capacity of 300,000 kw, with an annual energy production of $1{,}843 \times 10^6$ kwh. Comparing the latter figure with that of $15{,}800 \times 10^6$ kwh given in Table 8.8 as the maximum energy obtainable annually indicates that the proposed system would utilize but 11.8 percent of the energy potentially available.

After studying this report, the International Joint Commission concluded that the project would be economically infeasible. In response, President John F. Kennedy, by letter of 20 May, 1961, requested the Department of the Interior to restudy the project and propose modifications. This resulted in a recommendation (Udall, 1963) that the power capacity be increased from 300,000 to 1 million kw in order to deliver most of the power during the brief period of peak demand. It also involved a slight reduction from $1{,}843 \times 10^6$ to $1{,}318 \times 10^6$ kwh in the annual energy production.

This was recommended to the President for authorization, but as yet no authorization has been obtained.

For the installation of the world's first major tidal-electric plant, that of la Rance estuary which began operation in 1966 (*Engineering*, July 1966, pp. 17–24), honor is due to France. Here, the average tidal range is 8.4 meters, and the power plant is in a dam enclosing an area of 22 km^2. The power plant comprises 24 units of 10,000 kw capacity each, and the annual production of energy was estimated to be 544×10^6 kwh, which amounts to about 18 percent of the total energy available (Table 8.8). If the capacity is increased, as planned, to 320,000 kw, this would increase the power utilization to about 24 percent of that potentially obtainable. This high figure has been made possible by the use of turbines of an advanced design. These are horizontal, axial-flow turbines with adjustable blades permitting operation during both the filling and the emptying of the basin, and also their use as pumps.

The most recent tidal-electric project to go into operation, as reported by *The New York Times* on 30 December 1968, is a small Russian experimental station in the Kislaya Inlet on the Coast of the Barents Sea, 80 kilometers northwest of Murmansk. This consists of a single unit driven by a 400-kilowatt turbine of French manufacture. A second unit is to be installed later, bringing the total power capacity to 800 kw.

According to the same article, a much larger 320,000-kilowatt plant is planned for the Lombovska River (Lumbovskii Bay, Table 8.8) on the northeast coast of the Kola Peninsula, and a 14-million-kilowatt plant for the Mezen Bay on the east side of the mouth of the White Sea. Since the stated capacities of these two plants are both larger than the maximum potential average power obtained from the Bernshtein data in Table 8.8, either the figures are exaggerated, or else it is now planned to enclose larger basins than those given by Bernshtein (1965, Table 5-5, p. 173).

In summary, it may be said that although the world's potential tidal power, if fully developed, would amount only to the order of 1 percent of its potential water power, and to an even smaller fraction of the world's power needs, it nevertheless is capable in favorable localities of being developed in very large units. It has the additional advantage of producing no noxious wastes, of consuming no exhaustible energy resources, and of producing a minimum disturbance to the ecologic and scenic environment. There are accordingly many social advantages and few disadvantages to the utilization of tidal power wherever tidal and topographical factors combine to make this practicable.

Geothermal Energy

One of the energy inputs into the earth's surface environment consists of the heat conducted from the earth's interior as a result of the increasing temperature with depth; another consists of the heat convected to the surface by volcanoes and hot springs. In special geological situations in volcanic areas, underground water is trapped in porous or fractured rocks and becomes superheated from volcanic heat. Wells drilled into such reservoirs of superheated water or steam permit the steam to be conducted to the surface where it can be used as an energy source for a conventional steam-electric power plant.

It is only within recent decades that large geothermal-electric power plants have been built (Table 8.9). The earliest utilization of geothermal

TABLE 8.9
Developed and planned geothermal-electric power installations.

Country and locality	Installed capacity 1969 (megawatts)	Planned additional capacity (megawatts)	Total capacity by early 1970's (megawatts)	Date of earliest installation
Italy[a]				
Larderello	370		370	1904
Monte Amiata	19		19	ca 1962
Total	389		389	
United States[b]				
The Geysers, California	82	100	182	1960
New Zealand[b]				
Wairakei	290		290	Nov. 1958
Mexico[b]				
Pathé	3.5		3.5	ca 1958
Cerro Prieto (Mexicali)		75	75	ca 1971
Total	3.5	75	78.5	
Japan[b,c]				
Matsukawa	20	40	60	Oct. 1966
Otake	13	47	60	Aug. 1967
Goshogate		10	10	
Total	33	97	130	
Iceland[d]				
Hveragerdi	(Geothermal energy for house and greenhouse heating)	17	17	1960
U.S.S.R.[e]				
Kamchatka				
Pauzhetsk	5	7.5	12.5	1966
Paratunka	0.75		0.75	1968
Bolshiye Bannyye	25		25	1968
Total	30.75	7.5	38.25	
Grand Total	828.25	296.5	1,124.75	

Sources: [a]Facca and Ten Dam, 1964. [b]Donald E. White, U.S. Geological Survey, June 1969, personal communication. [c]Julian W. Feiss, 1968, personal communication. [d]Icelandic Embassy, Washington, D.C., July 1969. [e]Donald C. Alverson, Foreign Geology Branch, U.S. Geological Survey, July 1969, personal communication.

energy for power was at Larderello, in the Tuscany province of Italy, in 1904. The capacity of power plants in this locality has been increased to about 370 megawatts as of 1969. Recently two new thermal fields in the Monte Amiata region about 70 kilometers southeast of Larderello have been discovered, and smaller power plants installed. The Bagnore field has two generators of 7 Mw each, and the Piancastagnaio field, one station of 5 Mw. This gives a total geothermal power capacity for Italy of just under 400 Mw.

After Italy, the largest development of geothermal power is at Wairakei, New Zealand. There, drilling for steam was begun about 1950 and the first power plant began operation in November 1958. The plant has been expanded to a capacity of 290 Mw in 1969.

The third largest project is in the United States at The Geysers in northern California. Here, power production began in 1960 with a 12.5 Mw unit. The plant capacity has been expanded to 82 Mw and an additional capacity of 100 Mw is planned for the near future.

In Japan, geothermal-power production was begun at Matsukawa in 1966 and at Otake in 1967. The total 1969 capacity of these two plants is 20 Mw and 13 Mw, respectively, with planned increases to 60 Mw each. These, plus a planned 10 Mw plant at Goshogate, will give Japan a total capacity of 130 Mw by the early 1970's.

Mexico now operates a small pilot plant of 3.5 Mw capacity at Pathé, about 200 kilometers north of Mexico City. A much larger thermal field has been drilled at Cerro Prieto, in Baja California, about 25 kilometers southeast of Mexicali on an extension of the San Andreas fault system. Two of the wells in this field are said to have the largest steam production of any in the world. Two power units of 37.5 Mw each are due to begin operation in 1970 or 1971.

Iceland has large geothermal fields. The steam from one of these is used for space heating of almost the entire town of Hveragerdi, and for large greenhouses nearby. No geothermal-electric power is yet produced (1 July 1969), but a plant of 17 Mw capacity at Hveragerdi is expected to begin operation before the end of 1969.

In the Soviet Union, the only geothermal power produced is at three small plants in Kamchatka (Pauzhetsk, Paratunka, and Bolshiye Bannyye) with a total present capacity of 30.75 Mw and a planned increase to 38.25 Mw.

The relevant data are summarized in Table 8.9, according to which the present installed geothermal-electric power capacity of the world amounts to 828 Mw with planned increases to 1,125 Mw by 1971–72. With regard to the ultimate world capacity of geothermal power, only an order-of-magnitude figure can be given. Basic information on geothermal installations and estimated potential power capacities of various countries is summarized by Baldwin and McNair (1967). By far the most comprehensive compilation on thermal springs, however, is that by Waring, Blankenship, and Bentall (1965), who give basic geologic data on flow rates and temperatures but do not interpret the data in terms of potential geothermal power.

A better appraisal of the quality of energy involved is given by Donald E. White (1965). For most of the better-known geothermal areas of the world, White has estimated the rate at which heat is discharged to the surface of the earth, and has also estimated the amount of stored heat above surface temperatures to depths of 3 kilometers and 10 kilometers. From the areas studied, he estimates that the world's total natural heat flow from all hydrothermal areas is of the order of 3×10^{10} cal/sec, or about 1.3×10^{11} thermal watts. He also estimates that the total stored heat of all hydrothermal systems to a depth of 3 kilometers amounts to 2×10^{21} cal (8×10^{21} thermal joules), while to a depth of 10 kilometers it amounts to 1×10^{22} cal (4×10^{22} thermal joules). Of the world's hydrothermal energy, White estimates that about 5–10 percent occurs in the United States, mainly in the western states.

To obtain an order of magnitude for geothermal power, White assumes that about 1 percent of the hydrothermal energy can be converted into electrical energy. For the depth of 10 kilometers, 1 percent of the estimated thermal energy would be 1×10^{20} cal, or 4×10^{20} thermal joules. For a 0.25 conversion factor, this would represent 1×10^{20} joules of electrical energy, or about 3×10^{6} Mw-yrs. Then, if this amount of energy were to be withdrawn during a period of 50 years, the average annual geothermal-electric power would be

$$\frac{3 \times 10^{6}\ \text{Mw-yrs}}{50\ \text{years}} = 60{,}000\ \text{Mw},$$

or about 60 times the present installed capacity. This agrees with White's conclusion that the world's geothermal energy resources could sustain a rate of withdrawal of 10–100 times that of the present for at least the next 50 years.

It thus appears that the ultimate magnitude of geothermal power production will probably be in the tens of thousands of megawatts. While this is a significant amount of power, a better idea of just how significant can be obtained by comparison with other sources of power. A figure of 60,000 Mw for geothermal power is about the same as that of 64,000 Mw given in Table 8.8 for the world's potential tidal power, but only 2 percent of the 2.8×10^{6} Mw given in Table 8.8 for the world's potential water power from conventional sources. It is only about a third larger than the present hydroelectric power capacity, or only about 20 percent of the present total installed electric power capacity of the United States. Hence, while geothermal energy is capable of sustaining a large number of small power plants in a limited number of localities, it still represents only a small fraction of the world's total energy requirements, and this for only a limited period of time.

NUCLEAR ENERGY

For a final source of energy appropriate for large-scale generation of power, we now direct our attention to nuclear energy. For this purpose, our present concern will be limited to the controlled release of energy from two contrasting nuclear processes, *fission* and *fusion*.

Energy from Atomic Fission

In its initial stages, the fission reaction is dependent solely upon the isotope uranium-235. Uranium, as it occurs naturally, consists of three isotopes, uranium-234, uranium-235, and uranium-238, with abundances of 0.006, 0.711, and 99.283 percent, respectively. Of these, uranium-234 may be regarded as negligible. Natural uranium would then consist of uranium-235 and uranium-238, with the former constituting only one part in 141 of the whole.

The significance of uranium-235 lies in the fact that of the several hundred naturally occurring atomic isotopes, it is the only one that is spontaneously fissionable by the capture of slow or thermal neutrons. This isotope is accordingly, of necessity, the initial fuel for all subsequent power development based on the fission reaction. The average amount of energy released by uranium-235 per fission-event is approximately 200 million electron-volts (Mev), or 3.20×10^{-11} joules. One gram of uranium-235 contains 2.56×10^{21} atoms. Hence, the energy released by the fissioning of 1 gram of uranium-235 is 8.19×10^{10} joules. This is equivalent to the heat of combustion of 2.7 metric tons of coal, or of 13.7 barrels of crude oil. It also is approximately equal to 1 thermal megawatt-day. Accordingly, a nuclear power plant with a capacity of 1,000 electrical megawatts, and a thermal efficiency of 0.33, would consume uranium-235 at a rate of about 3 kilograms per day.

Burner, Converter, and Breeder Reactors. A physical assembly in which a controlled chain reaction occurs is known as a nuclear reactor. For fission reactions, these reactors are divided into three principal types, *burners*, *converters*, and *breeders*.

A burner reactor is one that consumes the naturally occurring fissile isotope, uranium-235, in the manner indicated in Figure 8.29. However, despite the enormous amount of thermal energy per gram released by the fissioning of uranium-235, a severe limitation is imposed upon the amount of energy obtainable from this source by the facts that uranium is a comparatively rare chemical element, and that uranium-235 represents only 1/141 of natural uranium. A way out of this difficulty, however, is afforded by the fact that is it possible to convert both nonfissionable uranium-238, comprising 99.28 percent of natural uranium, and thorium-232, comprising essentially the whole of natural thorium, into isotopes which are fissionable.

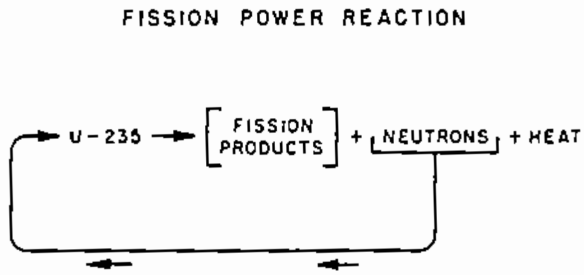

FIGURE 8.29
Schematic representation of nuclear-power-reaction from the fissioning of Uranium-235. (From Hubbert, 1962, Figure 56, p. 109.)

In each case, this is accomplished by exposing uranium-238, or thorium-232, to neutron bombardment, producing the following respective reactions:

$$ {}^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu}, $$

$$ {}^{232}_{90}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} \rightarrow {}^{233}_{91}\mathrm{Pa} \rightarrow {}^{233}_{92}\mathrm{U}. $$

In this notation, the superscript denotes the total number of protons plus neutrons in the atomic nucleus, which also is approximately equal to the atomic mass; the subscript, which also is the atomic number and determines the chemical element, denotes the number of protons.

Thus, uranium-238 absorbs a neutron and is converted to uranium-239. The latter, by two short-lived radioactive transformations changes spontaneously to neptunium-239 and thence to plutonium-239. Similarly, thorium-232 absorbs a neutron and is transformed into thorium-233. This, in turn, changes radioactively into protoactinium-233 and thence into uranium-233. A flow diagram for the breeding reaction is shown in Figure 8.30.

Both plutonium-239 and uranium-233 are fissionable in a manner similar to uranium-235. The isotopes uranium-233, uranium-235, and plutonium-239, are accordingly known as fissile isotopes. Uranium-238 and thorium-232, on the other hand, which are not themselves fissionable, but are capable of being converted into previously nonexistent isotopes which are fissionable, are known as *fertile* materials. The process of converting fertile into fissile materials is known as *conversion*, or, in special cases, as *breeding*.

The thermal energy produced per fission by either plutonium-239 or uranium-233 is approximately the same as that produced by uranium-235, about 200 Mev. Since the atomic masses of uranium-238 and thorium-232 are very close to that of uranium-235, the numbers of atoms per gram are also very nearly the same. Hence, the thermal energy per gram obtainable from natural uranium or thorium by means of conversion or breeding is approximately the same as from the initial fissile material, uranium-235, namely about 8.2×10^{10} joules per gram.

The neutrons required for conversion or breeding are those produced in a reactor whose initial supply of fuel is uranium-235. If uranium-238, or thorium-232, is placed in such a reactor, some of its atoms will absorb neutrons and become converted into its respective fissle isotope. The basic difference between conversion and breeding, is that by means of a conversion reactor, only a fraction of the fertile material can be converted into fissile material before the supply of the latter is completely exhausted. Whereas, for the breeder reactor, more fissile material is produced than is consumed, and it is possible, in principal, to utilize the entire supply of fertile material. provided that sufficient uranium-235 is available to start the process initially.

For the discussion of conversion or breeding, a significant quantity is that known as the *conversion ratio.* If Q_o be the initial amount of fissile material in the fuel inventory of a reactor, including its auxiliary fuel-processing equipment, and if Q be the amount of fissile material remaining after one cycle during which an amount of fuel Q_o has been consumed, the conversion (or breeding) ratio is defined by

$$K = Q/Q_o. \tag{9}$$

If $K = 0$, the reactor is a pure burner; if K is greater than 0, but less than 1, the reactor is a converter; and finally, if K is greater than 1, the reactor is a breeder.

Development of Nuclear Power. The foregoing principles are essential for an appraisal of the present status and future prospects of nuclear-power development based on atomic-fission reactors.

Historically, the technological evolution from the first experimental

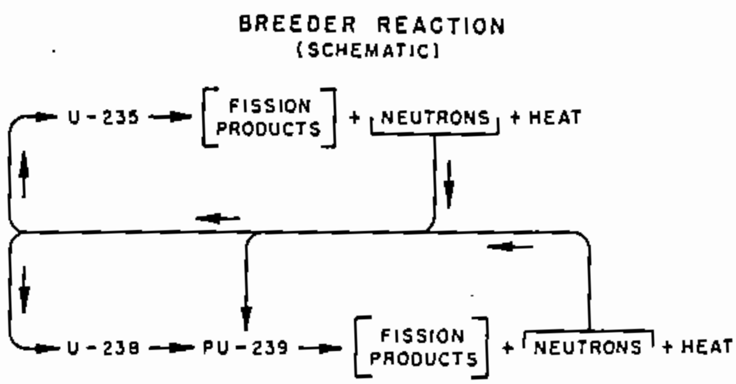

FIGURE 8.30
Schematic representation of breeder reaction for Uranium-238.
(From Hubbert, 1962, Figure 57, p. 109.)

achievement of atomic fission to the present design and construction of nuclear power plants of 1,000 electrical-megawatt capacities occurred in an incredibly short time. Fission was first achieved experimentally in 1938, and the first controlled chain reaction on 2 December 1945. The first electric power was produced in 1951, and the first large-size nuclear-electric power plant—that at Shippingport, Pennsylvania, with an initial capacity of 60 electrical megawatts—went into operation in 1957.

However, in the United States, until about 1963, the development program was largely experimental, with emphasis on alternative designs and cost reduction, in an effort to make nuclear power economically competitive with that from fuels and water power. The latter achievement was reached in 1963 when a contract was let to the General Electric Company for the Oyster Creek plant of the Jersey Central Power Company. This was to have a capacity of 515 electrical megawatts and a guaranteed cost of power production below that of a comparable fuel-powered plant.

Following this, further contracts for additional plants in the 500 to 1,000 electrical megawatt range have followed in such profusion that they can best be considered statistically rather than individually.

As a consequence of this acceleration, the U.S. Atomic Energy Commission (AEC) has recently been obliged to increase significantly its earlier forecasts of the growth of nuclear power. According to this latest estimate (U.S. AEC, 1967b, Table 5, p. 8), the median forecast for the nuclear-power capacity of the United States was for an increase from 1,800 electrical megawatts at the end of 1966 to 145,000 electrical megawatts by the end of 1980. This represents a mean exponential growth rate of 31 percent per year, with a doubling period of only 2.4 years. The corresponding forecast (ibid., Table 1, p. 3) for total U.S. electrical-power capacity for the same period was for an increase from 233,000 electrical megawatts at the end of 1966 to 579,000 by the end of 1980—a mean growth rate of 6.5 percent per year, with a doubling period of 10.6 years.

However, according to the AEC Annual Report for 1967 (U.S. AEC, 1968, p. 93, with the exception of two gas-cooled reactors, all of the central-station nuclear power plants ordered by utilities since 1958 are light-water reactors (as contrasted with heavy water). For present purposes, the distinctive characteristic of these reactors is that they consume uranium-235 as fuel, having such low conversion ratios that they are essentially burners. In the foregoing report (ibid., p. 86) it is stated that such reactors are capable of consuming only 1 to 2 percent of natural uranium or thorium. According to Milton Shaw (1968, Fig. 4), Director of the Division of Reactor Development and Technology, the cumulative production of plutonium by the light-water reactors up to any time between 1968 and 1980 will be approximately one-third of cumulative consumption of uranium-235 to that date. This corresponds to a total consumption of only 1 percent of natural uranium.

The significance of this is that these light-water reactors will effect a heavy drain on the lower-cost resources of uranium-235 if not soon supplanted by high-ratio converter or breeder reactors. As stated by Milton Shaw (ibid., p. 1), ". . . the phenomenal number of orders for nuclear power plants over the last three years . . . emphasizes the increasing importance of the timely introduction of breeder reactors into the utility environment. . . . It becomes more evident each day how dependent we are going to become on the successful introduction of breeders in order to be assured of practically limitless economic electric power and process heat."

The reason for this concern is clear when the magnitude of uranium resources is measured against the requirements between now and 1980. This situation has been succinctly reviewed by Rafford L. Faulkner, Director, Division of Raw Materials, U.S. Atomic Energy Commission, in his opening remarks before the Conference on Nuclear Fuel—Exploration to Power Reactors, Oklahoma City, Oklahoma, on 23 May, 1968. Using the AEC's most recent forecast of nuclear-power capacity to the end of 1980, Faulkner points out that, in addition to year-by-year current requirements, it will be necessary to maintain an 8-year forward reserve of uranium supply; that is, the total requirement to the end of 1980 must comprise not only the amount actually consumed to the end of 1980, but also the additional amount to be consumed during the next 8 years. This total figure he estimates to be about 650,000 tons of uranium oxide, U_3O_8.

To be compared with this requirement figure, Faulkner gives reserve estimates of uranium in three price ranges: (1) less than \$10/lb of U_3O_8, (2) \$10–15/lb, and (3) \$15–30/lb. For each price range, two categories of reserves are given: those that are reasonably assured, and estimated additional reserves. A composite of the price estimates of both producers and buyers of uranium is \$7.10/lb of U_3O_8 by 1970, and increasing to \$7.80 by 1973. The reserves of less than \$10/lb are accordingly the ones of principal interest at present. For this category, Faulkner gives for the United States:

Reasonably assured reserves	310,000 tons U_3O_8
Estimated additional	350,000
Total	660,000 tons U_3O_8

In the same category, the figures for the noncommunist countries of the world (including the United States) are:

Reasonably assured reserves	835,000 tons U_3O_8
Estimated additional	740,000
Total	1,575,000 tons U_3O_8

Against this world figure, however, allowance must be made for the fact that the growth of nuclear power outside the United States will probably be at a comparable rate to that in the United States.

From these figures, it is apparent that a very tight situation in uranium supply at anywhere near current prices is likely to develop within the next two decades. This surmise is confirmed by the U.S. Atomic Energy Commission in its report on civilian nuclear power (1967a), wherein, on page 14, the statement is made:

> With reactors of current technology, the known and estimated domestic resources of uranium at prices less than $10 per pound of uranium oxide (U_3O_8) are adequate to meet the requirements of the projected growth of nuclear electric plant capacity in the U.S. for about the next 25 years.

However, since that report was issued the estimate of nuclear power-plant capacity for 1980 has been increased from 95,000 to 145,000 electrical megawatts without a corresponding increase in the estimates of uranium reserves.

An even further restriction arises from the rate at which these reserves can be mined and processed. According to Faulkner, of the reasonably assured reserves of 310,000 tons of U_3O_8 in the United States, only about 210,000 tons can be produced by 1980. His corresponding estimate for cumulative world production is about 500,000 tons. This alone could force the low-priced reserves into a higher-price category in case, as appears likely, it should be necessary to double the rate of production.

Breeder-Reactor Program. This situation has forced the breeder-reactor program out of a state of lethargy into something more nearly resembling a crash program. A recent account of the program has been given by Milton Shaw, Director, Division of Reactor Development and Technology, U.S. Atomic Energy Commission, in his paper on "The U.S. Fast Breeder Reactor Program" given before the American Power Conference, Chicago, Illinois, on 23 April 1968.

According to Shaw, experimental work was begun by the U.S. Government as early as the late 1940's on the possibility of utilizing the almost limitless energy tied up in uranium-238 and thorium-232. This led to the experimental breeder-reactor program and to the construction and operation of several experimental breeder reactors of different designs, culminating in 1955 in the construction of the Enrico Fermi Atomic Power Plant in Michigan, the first large sodium-cooled fast breeder.

Nevertheless, on the whole, the program was diffuse and characterized by an atmosphere of complacency. The growth rate of nuclear power was seriously underestimated, and no scarcity of uranium resources was forseen.

During the 20-year period from 1948 through 1967, the budget for the entire AEC breeder program amounted to but $12,000,000 per year. "There was much less substance than image" according to Shaw, "in the industrial breeder program for there appeared to be ample time."

With the belated realization of the possibility of a crisis in the fuel supply, the breeder-reactor program is now being pushed with great vigor. A series of technical reviews concerning the status of the advanced breeder program was begun in 1965. About the same time, the unprecedented series of orders by the utilities for light-water reactors emphasized the need for a change of approach to the whole breeder-development program. Consequently, the development and introduction into utility usage of safe, reliable, and economic breeder-reactor power plants became the highest priority in the AEC's reactor-development program. In this program, the highest priority was given to the development of a liquid-metal cooled, fast-breeder reactor (LMFBR) utilizing the uranium-238–plutonium-239 cycle.

Accordingly, in 1966, the LMFBR Program Office (staffed currently with about 50 professional scientists and engineers) was established at the Argonne National Laboratory near Chicago to assist with the detailed planning and technical evaluation of various aspects of the LMFBR program. The time schedule on this program involves getting an initial power plant into operation by the early 1980's, and large commercial plants into operation between 1985 and 1990.

The program of breeder-reactor development is also reviewed in the 1967 annual report of the AEC (U.S. AEC, 1968, pp. 77–86), in which it is confirmed that the highest priority has been given to the development of the liquid-metal cooled, fast-breeder reactor, with the goal of achieving a safe, reliable, and economic 1,000 Mwe LMFBR plant in the 1980's.

In parallel with this, but of secondary priority, studies are being initiated on other types of breeders. The principal of these is the molten-salt breeder reactor (MSBR). This would be based on the thorium-232–uranium-233 cycle, and hence, as a user of thorium as a raw material, would be a highly desirable complement to the LMFBR using uranium-238.

The projected doubling times—the time required for the doubling of the initial fuel inventory—which it is hoped to achieve by these two types are about 10 years for the LMFBR, using the uranium-238–plutonium-239 cycle, and between 10 and 20 years for the MSBR, using the thorium-232–uranium-233 cycle. A doubling period of 10 years, assuming no uses of fissile material for nonbreeding purposes, would permit a maximum rate of growth of breeder-power production of about 7 percent per year; a doubling period of 20 years would allow a maximum growth rate of about 3.5 percent per year.

Another breeder, or possibly converter, program involves the modification of the present type of light-water reactors by means of adding blankets of fertile materials to increase the conversion ratio. In this manner, it is hoped to increase the energy obtainable from natural uranium or thorium from the present approximately 1 percent to possibly as high as 50 percent. For natural uranium, 50 percent burnup would correspond to a conversion ratio of about 0.98.

Long-Term View of Nuclear-Fission Energy. Taking a view of not less than a century, were electrical power to continue to be produced solely by the present type of light-water reactors, the entire episode of nuclear energy would probably be short-lived. With the growth rates now being experienced, the inexpensive sources of uranium would probably be exhausted within a fraction of a century, and the contained uranium-235 irretrievably lost. With the use of more costly uranium, the cost of power would increase until nuclear power would no longer be economically competitive with that from fuels and water.

This unhappy conclusion cannot be evaded by improvements of conversion ratios by any amount short of breeding, because for any conversion ratio less than 1, the initial supply of uranium-235 as well as all new fissile material generated by conversion will eventually be consumed completely, leaving only the inert fertile materials. Hence, the only long-time benefit from conversion is to multiply by some finite amount the initial quantity of fissile material, and to increase somewhat the length of time for the exhaustion of the initial supply. If such a consequence is to be avoided, it can only be done by the supplanting, at the earliest date possible, of all power reactors having conversion factors less than unity by true breeder reactors.

Since this is technologically possible, as well as necessary, we shall now assume that the present episode of burner and converter reactors is but a temporary developmental phase, and that probably before the end of the present century they will be almost entirely superseded by breeder reactors. When this occurs, as Alvin Weinberg has pointed out repeatedly (e.g., 1959, 1960), the problem of raw materials for energy will be drastically modified. For under these circumstances, it will become possible and practicable to utilize truly low-grade ores of uranium and thorium which cannot at present be given consideration.

A couple of examples will suffice to illustrate this point. For a low-grade source of uranium, we may consider the Chattanooga Shale of Devonian age which crops out along the western Appalachians in eastern Tennessee and neighboring states, and underlies at minable depths a sizable fraction of the total areas of the states of Tennessee, Kentucky, Ohio, Indiana, and Illinois. According to Vernon E. Swanson (1960, p. 4) of the United States Geological Survey, the Gassaway Member of this shale is about 15 feet thick, extends over an area of hundreds of square miles, and contains about

0.0060 percent by weight of uranium. Let us consider the amount of energy which this represents, assuming the use of breeder reactors operating on the uranium-238–plutonium-239 cycle.

Here we deal with a layer of rock 5 meters thick having a density of 2.5 grams/cm^3, or 2.5 metric tons per cubic meter, and a uranium content of 60 grams per metric ton, or 150 grams per cubic meter. Hence, for each square meter of surface area there are 5 cubic meters of rock containing 750 grams of uranium. As we have seen heretofore, the energy released by the fissioning of 1 gram of uranium is equivalent to that of the combustion of 2.7 metric tons of coal or of 13.7 barrels of crude oil. Therefore, the fuel equivalent of the uranium in 1 square meter of surface area would be 2,000 metric tons of coal or 10,000 barrels of crude oil. Per square kilometer, this would represent 2 billion metric tons of coal or 10 billion barrels of oil.

Rounding our previous estimates to 1,500 billion metric tons as the ultimate U.S. resources of producible coal, and about 200 billion barrels for producible crude oil, the areas for equivalent amounts of uranium are found to be 750 square kilometers for coal, and 20 square kilometers for oil. The area of 750 square kilometers for coal is about 300 square miles, or an area roughly 17 miles square. The 20-square kilometer area equivalent to the ultimate crude-oil resources would be only about 8 square miles, of an area somewhat less than 3 miles square.

For a similar calculation with regard to the energy obtainable from low-grade thorium deposits, using breeder reactors, we may consider the Conway Granite in New Hampshire. This is a granite which crops out over an area of about 300 square miles, or 750 square kilometers, and extends probably to some kilometers in depth. According to studies by John A. S. Adams and associates (Adams, Kline, Richardson, and Rogers, 1962), this granite has a remarkably uniform thorium content, averaging 56 grams per metric ton. In this case, 1 cubic meter of rock has a mass of 2.7 metric tons and contains 150 grams of thorium. Since the energy released by fissioning of 1 gram of thorium is substantially the same as for uranium, the fuel equivalent of the thorium contained in a cubic meter of rock is equivalent to about 400 metric tons of coal, or 2,000 barrels of crude oil.

Should the whole area be quarried to a depth of only 100 meters (330 feet) and the thorium used in breeder reactors, the fuel equivalent of the energy produced would be 30×10^{12} metric tons of coal, or 150×10^{12} barrels of crude oil. This would be 20 times the coal resources of the United States, or 750 times the resources of crude oil.

These are only illustrative examples. The energy potentially obtainable by breeder reactors from rocks occurring at minable depths in the United States and containing 50 grams or more of uranium and thorium combined per metric ton is hundreds or thousands of times larger than that of all of the fossil fuels combined. It is clear, therefore, that by the transition to a complete breeder-reactor program before the initial supply of uranium-235 is exhausted, very much larger supplies of energy can be made available than now exist. Failure to make this transition would constitute one of the major disasters in human history.

Energy from Fusion

In 1939, H. A. Bethe (1939a; 1939b) published the results of theoretical studies of the preceding year in which he derived from primary data the sequence of nuclear reactions whereby the enormous amounts of energy radiated from the sun and the stars are produced by the fusion of hydrogen of atomic-mass 1 into helium of atomic-mass 4[1]. Since that time, the question of whether controlled fusion may also be achieved in the laboratory has been a continuing challenge.

The chemical element hydrogen has three isotopes of mass numbers 1, 2, and 3, which have now come to be known by the separate names of *hydrogen* with the chemical symbol H, *deuterium* with the symbol D, and *tritium* with the symbol T, respectively. The problem of achieving controlled fusion reduces to that of fusing two or more of these isotopes of hydrogen into helium, the next higher element in the atomic scale. Helium also has two isotopes of present interest, helium-3 and helium-4.

The fusion of deuterium and tritium into helium in an uncontrolled explosive manner has already been achieved and is the basis for the so-called hydrogen, or thermonuclear bomb. Research in an effort to achieve a controlled fusion reaction has been under way in several laboratories in the United States during the last two decades, and comparable work is being conducted in several other countries. However, the British government has recently announced its intention of discontinuing the fusion work being conducted there. Although progress toward the achievement of controlled fusion is gradually being made, it still is not possible to estimate when, or even whether, the development of power from the fusion reaction may ever be accomplished. However, since the possible fusion reactions and their associated energy releases are known, it is possible to estimate the amounts of energy potentially obtainable from these reactions in terms of the earth's resources of the primary isotopes involved.

According to Samuel Glasstone (1964) of the U.S. Atomic Energy Commission, the most hopeful approaches to the achievement of controlled fusion are those that involve the fusion of two deuterium atoms, or of one deuterium and one tritium atom. Of these two, the latter appears to be the one more likely to be successful, at least initially.

[1] For this work Bethe was awarded a Nobel Prize in 1968.

The reactions of interest, and their associated energy releases, are the following:

$$^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He + n + 3.2 \text{ Mev},$$

$$^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + H + 4.0 \text{ Mev}.$$

Here, in addition to the chemical symbols already defined, n is a neutron and Mev signifies a million-electron volts, which is equal to 1.60×10^{-6} ergs or to 1.60×10^{-13} joules.

These two reactions are about equally probable. In the first, a stable product is produced, but in the second, the tritium atom reacts with another deuterium in the following manner:

$$^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + n + 17.6 \text{ Mev}.$$

Therefore, the net result of these three reactions can be written in the form

$$5\,^{2}_{1}D \rightarrow {}^{4}_{2}He + {}^{3}_{2}He + H + 2n + 24.8 \text{ Mev}.$$

Hence, the energy released per deuterium atom in these fusion reactions would be 4.96 Mev.

Further interest attaches to the deuterium-tritium reaction in view of the fact that another way exists for producing tritium atoms. When lithium-6 is bombarded with neutrons the following reaction occurs:

$$^{6}_{3}Li + n \rightarrow {}^{4}_{2}He + {}^{3}_{1}T + 4.8 \text{ Mev}.$$

When this is combined with the tritium-deuterium reaction,

$$^{3}_{1}T + {}^{2}_{1}D \rightarrow {}^{4}_{2}He + n + 17.6 \text{ Mev},$$

the net result is equivalent to the reaction

$$^{6}_{3}Li + {}^{2}_{1}D + n \quad 2\,^{4}_{2}He + n + 22.4 \text{ Mev}.$$

In this reaction, the limiting condition depends on the relative abundance of lithium and deuterium. The magnitude of total energy potentially obtainable will be limited by whichever isotope is the more scarce.

Let us now consider the amounts of energy that would be made potentially available in each case should the deuterium-deuterium, or the lithium-deuterium fusion reaction be achieved.

Energy from D-D Fusion. In the case of deuterium fusion, we have already seen that the release of energy per deuterium atom would amount to 4.96 Mev which is equivalent to 7.94×10^{-13} joules. The relative abundance of deuterium in water (including sea water) is 1 deuterium atom for each 6,500 hydrogen atoms. From these data, together with the respective atomic weights and Avogadro's number, it may be determined that 1 cubic meter of water contains about 1.028×10^{25} atoms of deuterium having a mass of 34.4 grams, and a potential fusion energy of 8.16×10^{12} joules. This is equivalent to the heat of combustion of 269 metric tons of coal, or of 1,360 barrels of crude oil.

Since a cubic kilometer contains 10^9 cubic meters, if follows that the fuel equivalents of 1 cubic kilometer of sea water are 269 billion tons of coal, or 1,360 billion barrels of crude oil. The latter figure is approximately equal to the lower of the two estimates of ultimate world resources of crude oil. Since the ultimate world coal resources as estimated by Averitt are about $7{,}600 \times 10^9$ metric tons, the volume of sea water required to be equivalent to this would be about 28 cubic kilometers. The total volume of the oceans is about 1.5×10^9 cubic kilometers. Should enough deuterium be withdrawn to reduce the initial concentration by 1 percent, the energy released by fusion would amount to about 500,000 times that of the world's initial supply of fossil fuels.

Energy from Lithium-Deuterium Reaction. Consider now the energy potential obtainable from the lithium-deuterium reaction. The amount of this energy will be limited by whichever of the two isotopes is in shortest supply. From our previous calculation, we found that there are about 10^{25} atoms of deuterium per cubic meter of sea water. This would be 10^{34} deuterium atoms per cubic kilometer, or a total of about 1.5×10^{43} atoms in total volume of the oceans. And a large fraction of this could readily be extracted at low cost by methods now in use.

Lithium, on the other hand, is found in readily extractible concentrations only in restricted localities on land. The geochemical abundance of lithium in sea water is only about 1 part in 10 million, and recent estimates (Parker, 1967, Table 20) for the average abundance of lithium in the crustal rocks of the earth all fall within the range of 20–32 parts per million. However, the isotope, lithium-6, required for fusion constitutes only 7.42 percent of natural lithium. Hence, lithium-6 is present in a concentration of but 7 parts per billion in sea water, and about 2 parts per million in the crustal rocks of the earth.

Minable deposits of lithium occur principally in the mineral spodumene in igneous pegmatites, and in concentrations of natural brines. As recently as 1965, the sum of the measured, indicated, and inferred reserves of Li_2O in the United States, Canada, and Africa, were estimated by James J. Norton of the U.S. Geological Survey, (unpublished) to be about 1.6 million metric tons. Comparable estimates have been published by Thomas L. Kesler, Chief Geologist of the Foote Mineral Company, the largest lithium producer in the United States (Kesler, 1960; 1961). These estimates include about 2 million metric tons for the United States, 390,000 for Canada, and 180,000 for Africa.

The Foote Mineral Company has begun exploitation of a brine deposit near Silver Peak, Nevada, which is reported (Foote Mineral Co., 1967) to contain reserves of 2.5 to 5 million short tons of lithium. This deposit alone would correspond to about 5 to 10 million metric tons of Li_2O. In addition, the brine of Great Salt Lake, Utah, with a lithium content of 0.006 percent, is beginning to be processed for this element by the Lithium Corporation of America.

In view of the large but only roughly known magnitudes of the lithium reserves in the Silver Peak and Great Salt Lake brines, Norton considers 10 million short tons of elemental lithium to be a good order-of-magnitude estimate of the presently known resources of lithium in the United States, Canada, and Africa. Using this figure and the previous estimates for Canada and Africa, revised lithium reserves of these three areas are shown in Table 8.10. Also, in each instance, the amount of the isotope lithium-6 is given in metric tons. From the latter figures, the number of lithium-6 atoms can be obtained from the relationship,

$$\frac{\text{Avogadro's number}}{\text{Atomic weight, } ^6\text{Li}} = \frac{6.0225 \times 10^{23}}{6.015 \text{ grams}}$$

$$= 1.0 \times 10^{23} \text{ atoms per gram.}$$

Then, since 1 metric ton = 10^6 grams, there are 1.00×10^{29} lithium-6 atoms per metric ton.

From the fourth column of Table 8.10, it is seen that the number of atoms of lithium-6 in the known lithium reserves of North America and Africa is about 7×10^{34}. Since this number is of the order of a hundred-millionth of the 1.5×10^{43} deuterium atoms in the oceans, it follows that the amount of energy potentially obtainable from the lithium-deuterium fusion reaction will be limited by the scarcity of lithium-6 rather than of deuterium. Accordingly, we may ascribe the total energy of 22.4 Mev, or 3.58×10^{-12} joules, obtainable from each atom of lithium-6 consumed, to the lithium-6 alone. On this basis, the energy potentially obtainable by the consumption of the amounts of lithium-6 shown in column 4 is given in column 5 of Table 8.10. This amounts to a total of about 2.4×10^{23} joules,

TABLE 8.10
Estimated lithium reserves of the United States, Canada, and Africa.

Location	Li_2O Measured, indicated, and inferred* (10^6 metric tons)	Lithium metal (10^6 metric tons)	Lithium-6 (10^4 metric tons)	Number of lithium-6 atoms (10^{33} atoms)	Equivalent fusion energy (10^{21} joules)
United States	19.0	8.8	65.4	65.4	234
Canada	0.4	0.2	1.4	1.4	5
Africa	0.2	0.1	0.7	0.7	2.5
Total	19.6	9.1	67.5	67.5	241.5

*Figures based on data from James J. Norton, U.S. Geol. Survey, Thomas L. Kesler (1961), and Foote Mineral Co., (1967).

which is approximately equal to the figure of 2.6×10^{23} joules for the energy obtainable from the combustion of the world's initial supply of fossil fuels.

Hence, unless much larger quantities of lithium of a lower grade than those now mined should be exploited, the scarcity of lithium renders the lithium-deuterium fusion reaction a much less promising ultimate source of energy than the deuterium-deuterium reaction. However, should the controlled lithium-deuterium reaction be the first to be achieved, it is technologically probable that achievement of the deuterium-deuterium reaction would follow.

DISPOSAL OF RADIOACTIVE WASTES[2]

An essential requirement for a nuclear-power industry based on the fission reaction[3] is a system for the safe management and disposal of radioactive wastes.

All common matter on earth is radioactive in some degree. Organisms on the earth are subjected continuously to a low level of damaging radiation from the radioactivity inside their tissues, from that of their immediately surrounding environment, and from cosmic rays. Men and other animals have evolved physiological systems able to repair tissue damage from "background" radiation at about the same rate the damage occurs. However, if the radiation rate is significantly increased, such repair is no longer possible, and permanent injury results. Depending on the nature of the exposure, radiation injuries take many forms, ranging from small and long-delayed effects to short-term lethal effects; a subtle and serious consequence of some radiation injuries is genetic transmission of physiological defects.

Radioactive wastes are distinguished from all other kinds of noxious wastes of chemical origin by the fact that there is no method of treating them to counteract their innate biological harmfulness. Radioactivity, a nuclear phenomenon, cannot be changed by any process less drastic than that which occurs inside nuclear reactors. Each radioactive isotope decays at a fixed negative-exponential rate peculiar to itself.

Health physicists and others have determined standards for the maximum concentration of radioactivity from different radioactive materials that is considered safe for human or other biological exposure. These maximum safe concentrations are different for different isotopes, but as a practical generalization the Health Physics Division of the Atomic Energy Commission

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[2] Prepared by Earl Cook, Texas A&M University, from notes provided by M. King Hubbert.

[3] In the alternative fusion reaction the end product is mainly nonradioactive helium.

has used 20 half-lives[4] as the minimum period a given type of high-level radioactive waste should be permitted to decay before being considered safe for biological exposure. This rule would require that wastes containing the long-lived isotopes strontium-90 and cesium-137, which have half-lives of 28 and 30 years, be isolated at least 600, and possibly as long as 1,000 years, to render them biologically harmless.

Radioactive wastes are produced mainly by the "burning" of the fissile fuel, and to a much lesser extent by neutron bombardment of otherwise neutral materials within the reactor, including reactor metals, coolant fluids, and air or other gases. *The mass of radioactive fission products produced in a reactor is very nearly equal to the mass of fuel consumed.*

Inside a reactor, the fuel elements are encased in metal containers which retain the fission products produced. After a certain percentage of "burnup" of the initial fuel, the fuel elements are removed from the reactors and taken to fuel-processing plants where the fission products are separated chemically from the unspent fuel, which is then refabricated into new fuel elements. As they come from the reactor the fission products represent a wide scatter of isotopes, the composite of which is highly radioactive.

Most radioactive waste is generated in the fuel-processing plants and is in liquid or slurry form; it is stored in tanks of steel, or of steel and concrete, for a preliminary period of "cooling" before disposition as waste. The principal solid wastes are radioactive trash (contaminated boxes, rags, and laboratory apparatus) and reactor and machinery parts that have acquired an induced radioactivity from neutron bombardment. Radioactive liquids or slurries are classified as high-level when their radioactivity is greater than 1 curie[5] per gallon, intermediate-level for radioactivities between 1 microcurie (10^{-6} curies) and 1 curie per gallon, and low-level for less than 1 microcurie per gallon.

In 1955, at the request of the Atomic Energy Commission, an advisory Committee on the Geologic Aspects of Radioactive Waste Disposal was established by the Division of Earth Sciences of the National Academy of Sciences—National Research Council. This committee, which included geologists, ground-water hydrologists, and mining and petroleum engineers, served until 1967, and made a succession of study visits to most of the AEC establishments concerned with management and disposal of radioactive wastes. The committee formulated three general principles on which any long-term program of disposal of radioactive wastes should be based. These principles may be paraphrased as follows:

1. All radioactive materials are biologically injurious. Therefore, all

[4] A half-life is the time required for any given species of radioactive material to disintegrate or decay to one-half its original mass.

[5] A curie is a measure of the rate of radioactive disintegration; it equals a rate of 3.7×10^{10} disintegrations per second, about the disintegration rate of 1 gram of natural radium.

radioactive wastes should be isolated from the biological environment during their periods of harmfulness, which for the long-lived isotopes exceeds 600 years.

2. The rate of generation of radioactive wastes is roughly proportional to the rate of power production from nuclear-fission reactors. In the period of its work, the committee regarded the rate of nuclear power and related radioactive-waste production as being on the very low portion of a steep exponential-growth curve. The committee therefore reasoned that no waste-disposal practice, even if regarded as safe at an initially low level of waste production, should be initiated unless it would still be safe when the rate of waste production becomes orders of magnitude larger.

3. No compromise of safety in the interest of economy of waste disposal should be tolerated.

These principles are still valid.

Present practices which satisfy these principles best are those pertaining to the high-level wastes that emerge from the chemical processing of spent reactor fuel elements. These extremely radioactive aqueous-solid slurries generate heat at rates as high as 200 watts per gallon (Zeitlin and Ullmann, 1955), and it is necessary to store them a year or more to dissipate thermal energy before attempting more permanent storage or disposal.[6]

For permanent storage, the AEC has a number of possible procedures under research and development at present (U.S. AEC, 1968; Fox, 1967).

One possibility is to retain the self-desiccated slurries permanently in the original storage tanks. More promising procedures involve reduction of the wastes to solids in the form of glass or ceramic slugs, or calcined granules. These solids can then be buried in natural salt beds or stored in concrete-and-metal bins on or near the earth's surface. In either case, the high-level radioactivity of the solids will be isolated from circulating ground water and from the biological environment. Of the two alternatives, underground storage in salt, which is highly impervious to ground-water flow, appears preferable.

Present practices with regard to intermediate- and low-level aqueous wastes, of gaseous wastes, and of radioactive trash, are less satisfactory. The large amounts of water involved in low-level aqueous wastes make the problem of concentrating the radioactive isotopes difficult. Oak Ridge National Laboratory puts intermediate-level wastes into slurry form and injects the slurry into hydraulically induced fractures at a depth of about 700–1,000 feet in shale, where the slurry "sets" as a solid. In the Oak Ridge locality these fractures appear to be principally horizontal, or parallel to the bedding planes of the shales, and there seems *little* chance that radioactivity will escape upward. In most areas, however, oil-industry experience shows hydraulically induced fractures to be vertical and therefore unfavorable to

[6] Storage implies that the material is retrievable; disposal, that it is not.

safe disposal by injection. In consequence, it is questionable whether the Oak Ridge practice can be extended to other areas without going to much greater depths in the interest of safety. In any area, the wastes should be placed below the level of circulating potable ground water.

At the Hanford Works in Washington and at the National Reactor Test Station in Idaho, intermediate-level wastes are either stored in earth ponds or discharged underground through special cribs. At both localities, low-level wastes are discharged through wells into the subsurface body of circulating ground water. In Great Britain and possibly elsewhere, low-level wastes are being discharged directly into the sea.

At most of the AEC localities, and at several sites recently authorized for operation by private industry, solid wastes are buried in trenches 10–15 feet deep and covered with soil. Although these trenches are above the groundwater table, they are within the domain of circulating soil moisture, some of which returns to the surface by evaporation and plant transpiration, and some of which descends to the water table.

Radioactive gases, after removal of most of the longer-lived isotopes and a period of storage of the rest, are discharged through tall dispersion stacks into the atmosphere.

From this brief outline, it can be seen that most present practices in the disposal of radioactive wastes *other than high-level liquid* violate the first of the three principles stated above, and probably the second also. These wastes are not being isolated from the biological environment at present, and it is questionable to what extent the same practices can be continued when the rate of waste production becomes 10 or 100 times larger than it is at present without causing serious hazard.

With regard to the third principle, which deals with the possible compromise of safety by economy, it should be pointed out that management costs for high-level wastes in the United States at present (Fox, 1967, p. 15) is less than 1 percent of the total cost of nuclear-power production. The cost of the entire waste-management program probably does not exceed 2 percent. In other words, the cost problem is not formidable. Nor is the physical problem intractible, for the rate of production of radioactive isotopes in the United States at present (1968) is only a metric ton or two per year.

It is more than penny-wise and pound-foolish to skimp on budgets for radioactive waste-disposal programs and to adopt *expedient* practices for economic reasons; it is hazardous to the health and genetic security of the nation.

A new monitoring system for radioactive-waste disposal practices is needed. This system must be independent of the agencies and organizations that produce such wastes, and would be somewhat analogous to the system of financial auditing which has been found both essential and effective in monetary affairs. Furthermore, reports generated by the group or body charged with operation of this monitoring system should be public, for every citizen is a shareholder in the common good.

HUMAN AFFAIRS IN TIME PERSPECTIVE

From the foregoing review, it is evident that the fortunes of the world's human population, for better or for worse, are inextricably interrelated with the use that is made of energy resources. Although the human species has always used energy to meet its minimum biological requirements, it is only within recent centuries, with the advent of energy from the fossil fuels and from wind and water power, that mankind has been able to increase its energy utilization per capita significantly above this minimum level. Despite the fact that the exploitation of these sources of energy has had a history extending over a period of several centuries, most of the developments during this entire period have occurred since 1900.

A much better perspective of the state of human affairs, and of the prospects for the future, can be obtained if the events in which we are concerned are regarded on a time scale of some tens of thousands of years. On such a scale, the quantities whose growth with respect to time we have been considering—the world's human population, the consumption of energy per capita, the development of water power, and the exploitation of the energy from fossil fuels—would all plot as curves with such uniform similarities as to be almost indistinguishable from one another. The curve of human population, for example, would plot as a nearly horizontal line just above zero for the entire period of human history until the last thousand years or so. Then a barely perceptible rise would begin and, as the present is approached, the curve would turn abruptly upward and rise nearly vertically to the 1969 world-population figure of about 3.5 billions.

The curve of the rate of energy consumption per capita would behave in a similar manner. Beginning with the biological minimum of about 100 thermal watts per capita represented by food, this curve would rise very slowly as other sources of energy—particularly that of firewood—are added, until it stabilized at about 500 thermal watts per capita. Then, a few centuries before the present when the exploitation of the energy from coal and of the power from water and wind was begun, this curve too would begin a slow and barely perceptible rise until, as the present is approached, it also would turn nearly vertically upward to a height of about 10,000 thermal watts per capita, which is the present average for the United States.

The curves of energy production from the fossil fuels would behave in a similar manner except that in the very recent past these would begin at zero.

Looking into the future on the same time scale, and assuming that a catastrophic event such as the near annihilation of the industrialized world by thermonuclear warfare can somehow be avoided, the physical realities discussed in this book dictate that the curve of human population must follow one of three possible courses: (1) It could continue to rise for a brief period and then gradually level off to some stable magnitude capable of being sustained by the world's energy and material resources for a long period of time; (2) it could overshoot any possible stable level and then drop back and eventually stabilize at some level compatible with the world's resources; or (3), finally, as a result of resource exhaustion and a general cultural decline, the curve could be forced back to a population corresponding to the lowest energy-consumption level of a primitive existence.

The one type of behavior for this curve that is not possible is that of continued and unlimited growth. To see that limits do exist, one need only consider that if the present world population were to be doubled but 15 more times, there would be one man for each square meter on all of the land areas of the earth, including Antarctica, Greenland, and the Sahara Desert. And at the present rate of growth, this would require but 525 more years.

Considering the other curves discussed previously, that of the production of the fossil fuels would continue upward for a brief period, and would then decline about as abruptly as it arose.

To sustain a high-energy-dependent world culture for a period much longer than a few centuries requires, therefore, a reliable source of energy of appropriate magnitude. The largest and most obvious of such sources is solar radiation, the continuance of which at close to present rates may be relied upon for millions of years into the future. The energy from solar radiation, with the exception of that fraction manifested as water power, does not offer much promise as a means of large-scale power production, although future technology may circumvent this difficulty. This leaves us with nuclear energy as our only remaining energy source of requisite magnitude. Although the earth's resources of uranium and thorium, and of deuterium, are finite and therefore exhaustible, the magnitudes of these resources in terms of their potential energy contents are so large that with breeder and fusion reactors they should be able to supply the power requirements of an industrialized world society for some millenia. In this case, the limits to the growth of industrial activity would not be imposed by a scarcity of energy resources, but by the limitations of area and of the other natural resources of a finite earth.

It now appears that the period of rapid population and industrial growth that has prevailed during the last few centuries, instead of being the normal order of things and capable of continuance into the indefinite future, is actually one of the most abnormal phases of human history. It represents only a brief transitional episode between two very much longer periods, each characterized by rates of change so slow as to be regarded essentially as a period of nongrowth. It is paradoxical that although the forthcoming period of nongrowth poses no insuperable physical or biological problems, it will entail a fundamental revision of those aspects of our current economic and social thinking which stem from the assumption that the growth rates which have characterized this temporary period can be permanent.

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