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ENERGY RESOURCES

A Report to the Committee on Natural Resources

National Academy of Sciences

National Research Council

Publication 1000-D

This is one of seven special reports supporting a research study of natural resources conducted by the National Academy of Sciences—National Research Council at the request of the President of the United States. Each of these seven supporting documents was prepared under the supervision of a member of the Academy-Research Council Committee on Natural Resources, who called upon the expert advice of a number of consultants to assist in identifying the research needs and opportunities relating to the particula resource area or problem under consideration.

The seven reports of supporting studies are as follows:

A. Renewable Resources
B. Water Resources
C. Mineral Resources
D. Energy Resources
E. Marine Resources
F. Environmental Resources
G. Social and Economic Aspects of Natural Resources

The general conclusions and recommendations of the Committee a a whole are presented in a summary report which has been forwarded t President Kennedy, together with the supporting studies.

The grateful thanks of the Committee on Natural Resources and of th Federal Government, for which these special reports were prepared, are du those whose experience and ideas are reflected in this report.

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December, 1962

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Committee on Natural Resources
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National Academy of Sciences—National Research Council

by

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M. King Hubbert

Chairman of the Energy Resources Study

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Washington, D. C.
1962

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CHAPTER I

INTRODUCTION

If we are to appreciate the significance of energy resources in the evolution of our contemporary society it will be necessary not only for us to understand the principal physical aspects of the conversion of energy in the complex of activities transpiring on the earth, but also to view these activities in a somewhat longer historical perspective than is customary. For those of us who live in the more industrialized areas of the world—particularly in the United States—it is difficult to appreciate the unique character of the industrial and social evolution in which we are participating. During our own lifetimes, and during the immediately preceding period of history with which we are most familiar, the pattern of activity we have observed most consistently has been one of continuous change, usually continuous growth or increase. We have seen a population begun by a small number of European immigrants to North America expand within a few centuries to over 200 million, while still maintaining such a growth-rate, even now, as to double within the next 40 years. We have seen villages grow into large cities. We have seen primeval forests and prairies transformed into widespread agricultural developments. We have seen a transition from a handicraft and agrarian culture to one of complex industrialization. Within a few generations we have witnessed the transition from human and animal power to continent-wide electrical power supernetworks; from the horse and buggy to the airplane.

Out of this experience it is not surprising that we have come to regard continual growth and increase as being the normal order of things.

However, if we are to appraise more accurately what our present position is in our social and industrial evolution, and what limitations may be placed upon our future, it is necessary that we consider, not only for the present but in historical perspective, certain fundamental relationships which underlie all our activities. Of these the most general are the properties of matter and those of energy.

From such a viewpoint the earth may be regarded as a material system whose gain or loss of matter over the period of our interest is negligible. Into and out of this system, however, there occurs a continuous flux of energy in consequence of which the material constituents of the outer part of the earth undergo continuous or intermittent circulation. The material constituents of the earth comprise the familiar chemical elements. These, with the exception of a small number of radioactive elements, may be regarded as being nontransmutable and constant in amount in processes occurring naturally on the earth.

For the present discussion our attention will be directed primarily to the flux and degradation of a supply of energy, and secondarily to the corresponding circulation of the earth's material components.

Flux of Energy on the Earth

The overall flux of energy on the earth is shown qualitatively and diagrammatically in the flow-sheet of Figure 1.

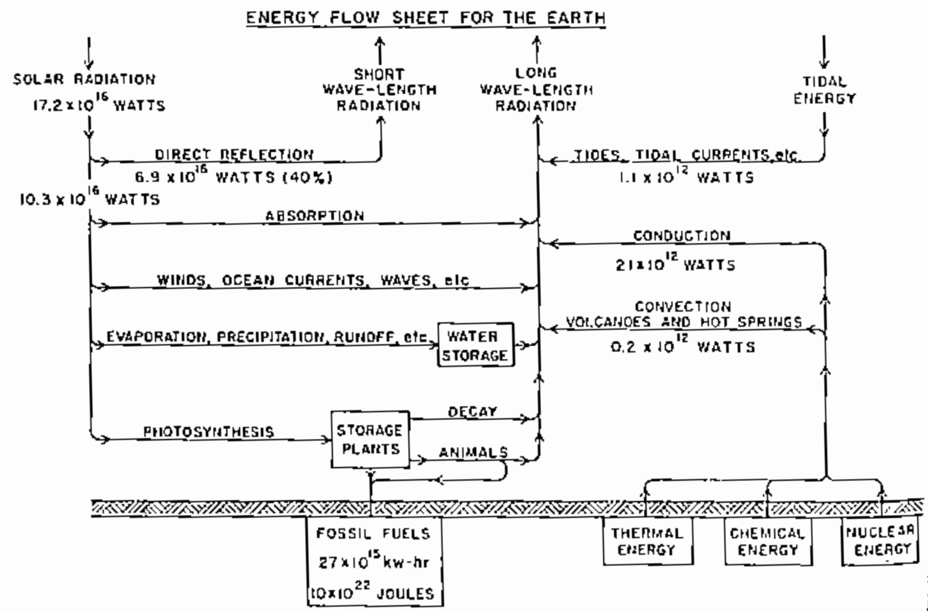

Figure 1. Energy Flow Sheet for the Earth

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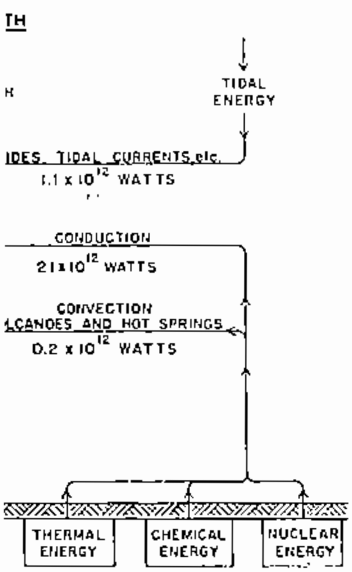

for the Earth

The energy inputs into the earth's surface environment are principally from three sources: (1) the energy derived from the sun by means of solar radiation, (2) the energy derived from the mechanical kinetic and potential energy of the earth-sun-moon system which is manifested principally in the oceanic tides and tidal currents, and (3) the energy derived from the interior of the earth itself in the form of outward heat conduction, and heat convected to the surface by volcanos and hot springs. Secondary sources of energy of much smaller magnitude than those cited are the energy received by radiation from the stars, the planets, and the moon, and the energy released from the interior of the earth in the process of erecting and eroding mountain ranges.

No definite quantity can be assigned to the energy from any of the foregoing sources because we are confronted not with a fixed quantity of energy but a continuous flux of energy from the various sources, at nearly constant rates. The rate of energy flux is measurable in terms of power, defined by

$$\text{power} = \frac{\text{energy}}{\text{time}},$$

and if the energy is measured in terms of the work unit, the joule, and the time in seconds, the power is then in joules per second, or watts.

Energy from Solar Radiation

The rate of energy flux from the sun, or the solar power, intercepted by the earth is readily obtainable from the solar constant, and the area of the earth's diametral plane. The solar constant is the quantity of energy which crosses unit area normal to the sun's rays in unit time in free space outside the earth's atmosphere, at a distance from the sun equal to the mean distance to the earth. It is, accordingly, the power transmitted by the sun's rays per unit cross-sectional area at the mean distance of the earth.

In heat units, the value of the solar constant, I, has been found to be 1.94 calories per minute per square centimeter (Landsberg, 1945, p. 929). This can be converted explicitly to power units by noting that 1 calorie of heat is equal to 4.19 joules of work, and 1 minute is 60 seconds. The solar constant in watts/cm^2 is, accordingly, given by

$$I = \frac{1.94 \times 4.19 \text{ joules/cm}^2}{60 \text{ seconds}}$$

$$= 0.135 \text{ watts/cm}^2.$$

The total solar power intercepted by the earth is then

$$P = IA = I\pi r^2,$$

where _A_ is the diametral area of the earth and _r_, equal to 6.37 x 10^8 cm, is the mean radius of the earth. Supplying the numerical values of _I_ and _r_, we then obtain for the total solar power incident upon the earth

$$P = 17.2 \times 10^{16} \text{ watts.}$$

For comparison, the installed generating capacity of all the electric utilities in the United States in 1959 amounted to 15.7 x 10^{10} watts (Dept. of Commerce, 1961, p. 525). Hence, the power of the solar radiation intercepted by the earth is about a million times the power capacity of all the electric utilities in the United States in 1959.

Energy From the Earth's Interior

The second largest input of energy into the earth's surface environment is that which escapes from the interior of the earth, which is estimated to be at a rate of about 21 x 10^{12} watts. Of this, about 99 per cent is by thermal conduction, and only about 1 per cent by convection in volcanos and hot springs.

Tidal Energy

The tidal energy is derived from the combined potential and kinetic energy of the earth-moon-sun system. The total rate of dissipation of this energy, as indicated by the rates of change of the earth's period of rotation and the moon's period of revolution, is estimated by Harold Jeffreys (1952, p. 227, 231) to be about 1.4 x 10^{19} ergs/sec, or 1.4 x 10^{12} watts. Of this, about 1.1 x 10^{12} watts, or about 80 per cent, is estimated to be accounted for by oceanic tidal friction in bays and estuaries around the world.

Thus, tidal power is about an order of magnitude smaller than that of the heat escaping from the earth's interior, and both together are less than one-thousandth of the power impinging upon the earth from solar radiation.

Energy Flow-Sheet

In view of its predominance, our principal concern is in tracing the flow of the 17.2×10^{16} watts of solar power that is being shed continuously on the earth. About 40 per cent of this, or 6.9×10^{16} watts (Landsberg, 1945, p. 933), known as the albedo, is directly reflected back into space. This leaves about 10.3×10^{16} watts which are effective in propelling the various material circulations occurring on the earth.

No further quantitative breakdown will be attempted. However, a part of the remaining solar power is absorbed directly by the atmosphere, the oceans, and the lithosphere, and is converted into heat. A large part of this heat is immediately reradiated back into space as long-wavelength thermal radiation. Another part, however, sets up differences of temperature in the atmosphere and the oceans, in such a manner that convective currents of both water and air are generated, producing the winds, ocean currents, and waves. The oceans and the atmosphere serve in this manner as the working fluids of a world-girdling heat engine whereby a fraction of the thermal energy from sunshine is converted into mechanical energy. The mechanical energy of the wind, waves, and currents is again dissipated by friction into heat at the lowest temperature of the surroundings.

Still another part of the solar energy follows the evaporation, precipitation, and surface run-off channel of the hydrologic cycle. Heat energy is absorbed during the evaporation of water, but it is again released when the water is precipitated. However, the water vapor, being a part of the atmosphere, is convected to high elevations by means of the convective energy already discussed; and, when precipitation occurs at these elevations, the water possesses potential energy, which again is dissipated back to low-temperature heat on the descent to sea level. It is this energy, however, that is responsible for all precipitation on the land, and for the potential and kinetic energy of surface lakes and streams.

A final fraction of incident solar radiation is that which is captured by the leaves of plants by the process of photosynthesis. Although enormously complex in detail, this is the driving mechanism for the synthesis of common inorganic chemicals, such as H_2O, and CO_2, into the chemical compounds of living plants. Schematically this process is represented by the reaction

$$\text{Energy} + CO_2 + H_2O \rightarrow \text{Carbohydrates} + O_2,$$

during which solar energy becomes captured and stored as chemical energy. By the reverse reaction, as in the burning of wood,

$$O_2 + \text{Carbohydrates} \rightarrow CO_2 + H_2O + \text{Heat},$$

and the stored energy is released as thermal energy.

The energy-flow channel whose first step is photosynthesis is that which sustains the entire complex of organisms on the earth. We have the familiar food chain:

$$\text{Plants} \rightarrow \text{Herbivores} \rightarrow \text{Carnivores} \rightarrow \text{Parasites} \rightarrow \ldots.$$

in which the energy of each link is a small fraction of that of the preceding, the remainder being dissipated by heat. The end-product of this chain is the complete degradation of the photosynthetic energy to heat at the ambient temperature, and the conversion of the material constituents back to their initial inorganic state.

The Fossil Fuels

If the energy stored in plants by photosynthesis could be systematically retained, as for example in the form of firewood, it is clear that the aggregate amount would increase without limit, and could, in a few decades or centuries, become very large indeed. Actually, in the natural state, the rate of decay of organic compounds and the release of their stored energy as low-temperature heat is very nearly equal to the contemporary rate of photosynthesis. However, in a few favored places such as swamps and peat bogs, vegetable material becomes submerged in a reducing environment so that the rate of decay is greatly retarded and a storage of a small fraction of the photosynthesized energy becomes possible.

This, in principle, is what has been happening during the last 500 million years of geologic history. During that time a minute fraction of the existing organisms have become buried in sedimentary muds under conditions preventing their complete decay. These accumulated organic remains comprise our present stores of the fossil fuels: coal, petroleum and natural gas, and related products, the energy content of these fuels being derived from the solar energy of this 500 million-year period which was stored chemically by contemporary photosynthesis.

Summary

The energy flow-diagram, which we have just reviewed, represents, in broad outline, all the major channels of energy flux into and out of the earth's surface environment. By the First Law of Thermodynamics, the quantity of energy in any particular channel, although repeatedly transformed in transit, remains constant in amount. It follows, therefore, that, with the exception of an insignificant amount of energy storage, the energy which leaves the earth by long-wavelength thermal radiation into space must be equal to the combined energy inputs from solar and stellar radiation, from tidal forces, and from the earth's interior.

By the Second Law of Thermodynamics, however, this flux of energy is unidirectional and irreversible. It arrives as short-wavelength electromagnetic radiation, corresponding to the temperature of the sun; or as mechanical energy of the tides; or as thermal energy from a temperature higher than that of the earth's surface environment. By a series of irreversible degradations it ultimately is reduced to thermal energy at the lowest temperature of its environment, after which it is radiated from the earth in the form of spent, long-wavelength, low-temperature radiation.

During this energy flux and degradation the material constituents of the earth's surface, while remaining essentially constant in amount, are circulated. The wind blows; oceanic currents, tides, and waves are formed; rain falls and rivers flow; volcanos erupt and geysers spew; and plants grow and animals eat, move about, procreate, and die.

But for this energy flux none of these things would or could happen and the matter of the earth's surface would be as dead or inactive as that of the moon.

Biologically, the human species is simply a member of the energy-consuming chain which begins with the energy capture and storage of plants by photosynthesis. Man is both an herbivore and a carnivore, and, as such, is merely another member of the biological complex, depending for his essential energy supply—his food—upon other members of the complex, and ultimately on the energy from the sun captured and stored in plants by photosynthesis.

In addition, however, man has been able to do what no other animal has ever achieved; he has learned to tap other channels of the energy flow-sheet, and he has managed to divert the energy flow from its customary path into other channels appropriate to his own uses.

An understanding of these processes is essential if we are to appreciate the significance of energy resources in determining what is possible and what is impossible in human affairs.

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CHAPTER II

EVOLUTION OF MAN'S ABILITY TO CONTROL ENERGY

Since energy is an essential ingredient in all terrestrial activity, organic and inorganic, it follows that the history of the evolution of human culture must also be a history of man's increasing ability to control and manipulate energy.

Consider the earliest stages of this evolution. From geological and archeological evidence, organic evolution had proceeded far enough that by about a million years ago one of the ape-like species had reached the stage where his few skeletal remains are now classed as those of early man. How many of this species there may have been at that time can only be conjectured, but from the scarcity of the remains it may be surmised that the numbers were not large—possibly comparable to those of gorillas or chimpanzees at the present time.

This species must have coexisted in some sort of ecological adjustment with the other members of the biologic complex of which it was a member, and upon which it depended for a share of the solar energy essential to its existence. At this hypothetical stage its sole capacity for the utilization of energy was limited to the food it was able to eat—the order of 2,000 kilocalories per capita per day.

Between that stage and the dawn of recorded history, this species distinguished itself from all others in its inventiveness of means for the capture of a larger and larger fraction of the available flux of energy. The invention of clothing, the use of tools and weapons, the control of fire, the domestication of animals and plants, and other similar developments all had this in common: Each increased the fraction of the contemporary flux of solar energy which was available for the use of the human species, and each upset the ecological balance in such a manner as to favor the increase in the human population, with corresponding adjustments in all other populations of the biologic complex.

Although little is known about the time when many of these developments first occurred, tool making and the use of fire date back at least as far as Peking man (estimated at about 500,000 years ago), but from the length of time involved the rate of change must have been extremely slow (Harrison, 1954). The pace quickened, however, at about 10,000 to 12,000 years ago when, with the domestication of animals and the cultivation of plants, man began to change from a food-gathering to a food-producing species (Childe, 1954).

After a few thousand years of cultural incubation, there followed almost simultaneously in each of three localities, the Tigris-Euphrates delta and the Indus and the Nile valleys, at about 3500 B. C., the rise of cities with populations estimated at 8,000-10,000 supported by an intensive agriculture.

At least as early as about 1900 B. C. the use of oxen for ploughing is depicted in paintings in Egyptian tombs (Harrison, 1954, Fig. 43). Similarly, pictures of sailing ships of advanced design occur in Egypt as early as 1500 B. C. (Childe, 1954, Fig. 32).

This quickening of pace continued for the next few thousand years, but the energy supply available was dominantly that which was tapped from the biological channel of solar energy. It permitted a very large increase in the population density in favorable agricultural areas, and a corresponding increase of the total human population as the new culture spread geographically, but throughout this period the energy available per capita was still not much more—possibly only two or three times greater—than that of the food consumed.

Energy from a nonbiological source was first obtained when the energy of the winds and the hydrologic cycle was tapped for human uses. This apparently occurred first with the use of sails for the propulsion of boats and ships. Then followed water mills and windmills.

According to Forbes (1956a), both the water mill and the windmill are thought to have originated in the Middle East, the water mill during the last century or so B. C., but the windmill not until about 900-1000 A. D. The first water mills were small affairs, with a horizontal wheel and vertical shaft requiring a continuous stream of water and capable of turning small family-size grain mills. This type of mill was improved by the Roman, Vitruvius, during the first century B. C. by making the wheel vertical and gearing the horizontal shaft to a vertical shaft turning the millstone.

However, water mills were not extensively used by the Romans before near the end of the Roman Empire. From this time forward, even during the Dark Ages, the use of the water mill spread throughout Western Europe, until by the sixteenth century it had been adapted to every kind of industrial use requiring stationary power. This use has continued subsequently in both Europe and North America.

However, it has only been since about the beginning of the twentieth century that advancing technology, particularly the transmission of power by electricity, has made it practical to build water mills larger than the tens-to-hundreds of kilowatts range of power capacity. This new technology made the small mills obsolete at the same time that it rendered practical the building of water-power plants in the hundreds-of-megawatts range.

Windmills appear to have been first developed in the Persian province of Seistan about the tenth century A. D. Windmills began to be built in the Low Countries and elsewhere in Western Europe about the thirteenth century, but whether as an independent invention, or introduced by the Muslims by way of Morocco and Spain, is uncertain. In any case, since the thirteenth century, windmills have been used in Western Europe and later in North America and the West Indies for such uses as grinding grain, pumping water, and operating mills for crushing sugar cane.

Escape from this dependence upon contemporary solar energy with its inherent limitations in the quantity utilizable per person was not possible until a new and hitherto unknown source of energy should become available. Such a source was represented by the fossil fuels. Although Marco Polo reported that the Chinese used "black rocks" for fuel (Nef, 1957), and recent studies indicate that the Chinese may have used coal in small amounts for two or three millenia previously, the use of coal as a major source of energy did not begin until about the twelfth century, when the inhabitants of the northeast coast of England discovered that certain black rocks found along the seashore, and thereafter known as "sea coles," would burn.

Since this initial discovery coal has been mined continuously, first in England and shortly thereafter in present Belgium, France and Western Germany, and finally in all coal-bearing areas of the world, in ever-increasing amounts. Then, about a century ago, first in Romania in 1857 and then in the United States in 1859, petroleum in commercial quantities began to be produced, thus tapping the second of the great stores of energy preserved in the fossil fuels. Other fossil fuels, large in amount, are the tar sands and the oil shales. Although oil has been obtained in limited quantities from oil shale for more than a century, the period of large-scale exploitation of the tar sands and the oil shales is still in the future.

Finally, only within the last two decades a way has been found to tap a still larger and more concentrated reservoir of potential energy, that of nuclear energy.

While the evolution of the means of controlling energy had been proceeding at a gradually accelerating rate for many millenia, it did not reach its crescendo stage until after the exploitation of the fossil fuels had begun. Once it was learned that "sea coles" would burn, it did not take long to discover that these loose chunks found along the shore had been derived from the outcropping strata in the sea cliffs above, which were gradually being undercut by the waves. The digging of these strata, first along the cliffs, and then by means of holes sunk to the beds from above, initiated the mining of coal in Western Europe.

So superior was this fuel to wood and peat that the digging proceeded apace. It is recorded that in 1234 King Henry III confirmed a privilege for the mining of coal granted to Newcastle-upon-Tyne by King John (Forbes, 1956b). At this time coal was already being transported by barge to London, where by 1273 the smoke from coal burning had become so obnoxious as to provoke complaints from the gentry. In addition to its use as a domestic fuel, coal was promptly adopted as a fuel for lime burning, and was used by blacksmiths and for other post-smelting metallurgical purposes, and for glass making.

Statistics of early production are few, but it is recorded that coal shipments from Newcastle-upon-Tyne in the year 1563-1564 amounted to 32,951 tons. By 1658-1659, nearly a century later, the yearly production had increased to 529,032 tons—more than 16-fold. Between 1580 and 1660 the imports of coal to London increased 20-25-fold. In the meantime, coal mining in Britain had become general in England, Scotland, and Wales, and the annual production for the whole country by 1660, or shortly thereafter, had reached about 2 million tons per year, which is estimated to have been five times as much as the production of the rest of the world (Nef, 1957, p. 77). By 1750 the annual production had reached 7 million tons (Ritson, 1958, p. 79).

This rapid increase in the mining of coal immediately created grave technological problems. The influx of water into the mines forced the development of continually larger and better pumps. First, water was removed by bailing, then by pumps powered by human labor, and finally by animal power, with pumps driven by as many as 100 horses on treadmills.

Ultimately, so desperate had this problem become that attention was directed to the powers of steam and the newly discovered properties of a vacuum (Dickinson, 1958). This led in 1698 to the development by Thomas Savery of the first successful water pump powered by steam. Water was lifted through a vertical pipe to fill the vacuum induced by the condensation of steam in an otherwise closed chamber. By the repetition of this cycle, with the opening and closing of appropriate valves, water could be pumped indefinitely.

This was followed shortly by the "atmospheric engine" of Thomas Newcomen in 1712, which was the first practical steam engine to be developed. This consisted of a walking beam, to one end of which was attached the plunger of a pump, and to the other the piston rod from a vertical steam cylinder. Steam at atmospheric pressure filled the cylinder during the nonworking stroke, and the work was done by atmospheric pressure on the piston when a vacuum was created in the cylinder by the injection of a jet of water.

The use of this engine for pumping water spread rapidly throughout Britain and also to the Continent. However, as it had no rotary motion it did not meet the needs of mills driven by water, except as a means for pumping water from the tailrace to the mill pond, permitting rotary power to be extracted by the water wheel.

Fundamental modification of the Newcomen engine did not occur until more than 50 years later when James Watt introduced a succession of radical improvements, including a separate condenser, a double-acting cylinder and piston, a governor, and, most important of all, a rotary shaft and fly wheel, making the engine suitable for the driving of all types of rotary machinery.

It was only after this, late in the eighteenth century, that the steam engine was able to compete with, and eventually to displace, water as a principal source of industrial power.

A second problem that was made critical by the mining of coal was the land transportation of heavily laden wagons of coal. While the principal transportation of coal was by water, that from the collieries to the docksides was by horse-drawn wagons. This led to the development of railroads with longitudinal wooden rails, but with the wagons drawn by horses. Finally, the idea of putting the steam engine on wheels and making it self-propelling was successfully accomplished by Richard Trevithick in 1802. Shortly thereafter, the use of the steam engine for the propulsion of boats was successfully accomplished by Robert Fulton and others.

Thus, by the second decade of the nineteenth century the steam engine had been adapted to supply all contemporary needs for mechanical power: the pumping of water, the driving of stationary industrial machinery, and transportation by water and land. However, the transmission of power was still limited to mechanical means, and hence to short distances.

The end of this era was foreshadowed when, in November 1831, Michael Faraday announced his epoch-making discovery of electromagnetic induction. Within a year Hippolyte Pixii publicly exhibited in Paris the first magnetoelectric machine, a hand-cranked magnetoelectric generator. After this, the further development of magnetoelectric generators and equipment proceeded in England, France, and Germany at a rapid rate. By 1857 a successful experiment of powering an arc light with a steam-driven generator of about 1-1/2 kilowatts capacity was demonstrated by Holmes in London. In 1858 illumination of a lighthouse in this manner was accomplished. By 1875 in France, and by 1878 in London, whole buildings were being illuminated (Jarvis, 1958). Finally, in 1881 the generation and public distribution of electric power by a central-power station was initiated when Thomas A. Edison installed the Pearl Street power station and its associated distribution network in New York. From that time forward, the steady advance of the technology of electrical-power generation, distribution, and utilization has advanced to the extent that it has rendered obsolete most other forms of stationary power.

Another major use of the energy from coal, of which scant mention has been made, has been in the smelting and processing of metals. The working of metals has been one of the major uses of coal since the beginning, but it was not until about the middle of the eighteenth century that coal supplanted charcoal for smelting. This was made possible only after it had been discovered how to rid coal of its injurious sulfur and gases by coking—a procedure quite analogous to the manufacture of charcoal from wood. Since the eighteenth century the metallurgical industries, principally iron and steel, have become almost solely dependent upon coal as a source of fuel, and thus among its largest consumers.

Oil and natural gas, as was mentioned earlier, came into commercial production during the last half of the nineteenth century, first for heat and light, and then as fuel for steam-power plants and to some extent in metallurgical industries. A dominant new use for petroleum was generated with the development in the 1880's of the high-speed, internal-combustion engine. This led immediately to the development of motorized vehicles for travel by land, water, and eventually by air. Gradually, oil and natural gas have succeeded in large measure in displacing coal as the traditional fuel for steamships, railroad locomotives, and even for central electric-power plants.

Finally, by 1962, progress is well underway in the controlled use of the last and largest known source of potential energy, the atomic nucleus. During the brief period since the attainment of the first controlled fission of uranium at Chicago on December 2, 1942, central power plants in the hundred-megawatt range have been built and are already in operation in the United States, Great Britain, and the U. S. S. R.; nuclear-propelled ships and submarines are also in operation.

Growth of Human Population

As was pointed out earlier, the human proclivity for capturing an ever larger fraction of the total flux of the energy on the earth, and eventually for tapping the large supplies of stored energy, has had the effect of continuously upsetting the ecological equilibrium in the direction of an increase in the human population. The magnitude of the upset and the rates at which it has occurred are best seen by plotting the estimates of the human population graphically as a function of time.

This has been done in Figure 2 for the period from 1000-2000 A.D., inclusive, using Putnam's (1953, Figs. 2-2, 2-9) graphs of

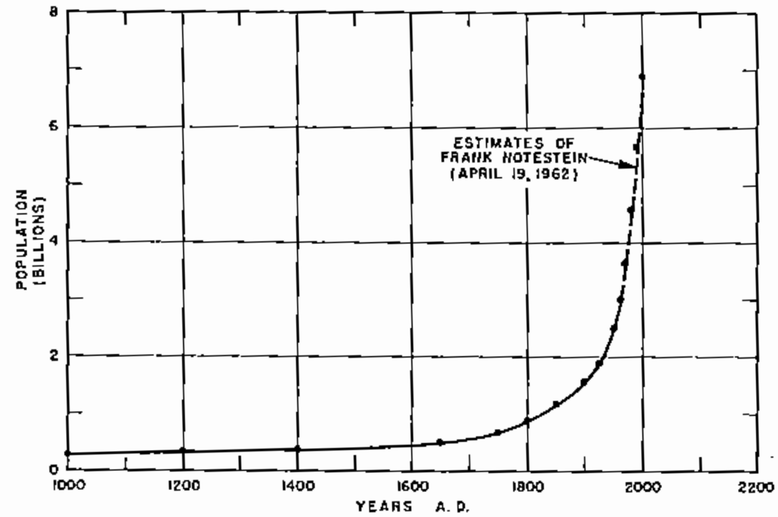

Figure 2. Growth of World Population

the means of various demographic estimates for the period 1000-1890, inclusive, United Nations (1958, p. 23) estimates for the period 1900-1950, inclusive, and estimates of Frank W. Notestein (1962) for the period from 1960 to 2000. These data are given numerically in Table 1.

For the period earlier than that shown in Figure 2, Putnam (1953, p. 7-11) estimates the world population for the year 10,000 B. C. to have been about 1 million and that at 1 A. D. at about 275 million, with a maximum of around 290 million about 225 A. D. and a minimum of 270 million at about 700 A. D.

For the period earlier than 10,000 B. C. about all we have to go on is the archeological evidence that the culture was Paleolithic and the subsistence was by hunting and food-gathering rather than food-producing, and the ecological evidence that the gradual evolution of Paleolithic culture should have been, on the whole, in the direction of a population increase with time.

We infer, therefore, that the human population at 1 million B. C. must have been less than that at 10,000 B. C., but equal to or greater than 2, the least number biologically possible. However, since this population did not arise by "creation," but by continuous evolution from its immediate forebears, and since for very small numbers of a population the chances of extinction are

TABLE 1

World Population Estimates

Year	Population (Millions)	Source
10,000 B.C.	1 ± x 10	Putnam
1 A.D.	275 ± 80	"
225	290 Max.	"
700	270 Min.	"
1000	295	"
1200	310	"
1400	350	"
1650	493	"
1750	694	"
1800	887	"
1850	1,170	Carr-Saunders
1890	1,500	Putnam
1900	1,550	U. N.
1925	1,907	"
1950	2,497	"
1960	2,996	Notestein
1965	3,297	"
1970	3,655	"
1975	4,080	"
1980	4,562	"
1985	5,096	"
1990	5,687	"
1995	6,278	"
2000	6,919	"

Putnam, Palmer Cosslett, 1953, Energy in the Future: New York, D. Van Nostrand Co., Inc., p. 16-17.

United Nations, 1958, The Future Growth of World Population: New York, Department of Economic and Social Affairs, p. 17.

Notestein, Frank W., 1962, letter to John S. Coleman dated April 19.

very high, it is doubtful that a population as small as two individuals ever existed. What the minimum number may have been is unknown, but it is improbable that it was ever as small as 1,000.

Assuming 1,000 as a minimum number at 1 million B. C., we have a basis for judgment concerning the rates of growth of the population during the principal divisions of subsequent history. An initial population of 1,000 would only have to be doubled 21.5 times to reach 3.0 billion, which is the estimate of the world population in 1960. Accepting Putnam's estimates of populations of 1 million at 10,000 B.C. and 275 million at 0 B.C., then the first 10 of these 21.5 doublings would have occurred by 10,000 B.C., and 18 by 0 B.C. The remaining 3.5 doublings have occurred between the beginning of the Christian Era and the present time.

Consider, however, the lengths of time required for the successive doublings. If only ten doublings occurred during the million years prior to 10,000 B.C., then the average length of time required for each must have been 100,000 years. A change in a population increasing at such a rate would probably not be detectable by two censuses taken a thousand years apart. We do not assume that the population during this period actually grew in this manner. It probably fluctuated up and down with famines, plagues, and climatic changes, but its average growth rate over the whole time must have been not very different from this.

For the period from 10,000 B.C. to 0 B.C. about 8 doublings occurred with an average length of time for each of 1,250 years. This plainly shows the quickening of the growth rate over that of the preceding period—an increase of about 8-fold.

Then, during the Christian Era, 3.5 more doublings have occurred with an average length of about 560 years. This, however, fails to tell the whole story, because the time for each successive doubling has been shorter than for the one before. Thus, the first doubling after 0 A.D. occurred at about 1690, the second at about 1845, and the third at about 1937. Thus, during the interval since 0 A.D. the first doubling required 1,690 years, the second 155, and the third only 92.

That this reduction of the doubling period, or increase in the rate of growth, is still continuing may be seen by the population increase for the decade 1950-1960. The United Nations (1958) estimate of the population in 1950 is 2.497 billion. By 1960 this had increased to an estimated 2.996, or roughly 3.0 billion. This corresponds to a rate of increase of 1.82 per cent per year, at which rate the population would double in only 38.2 years. The instantaneous rates of growth and the corresponding lengths of time which would be required for the population to double are plotted graphically in Figure 3 for the world population data as given in Table 2.

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What emerges from this examination is the very great contrast between the population growth during the last 1,000 years, particularly during the last few decades, and all preceding history. If we may define the term "normal" as describing a state of affairs

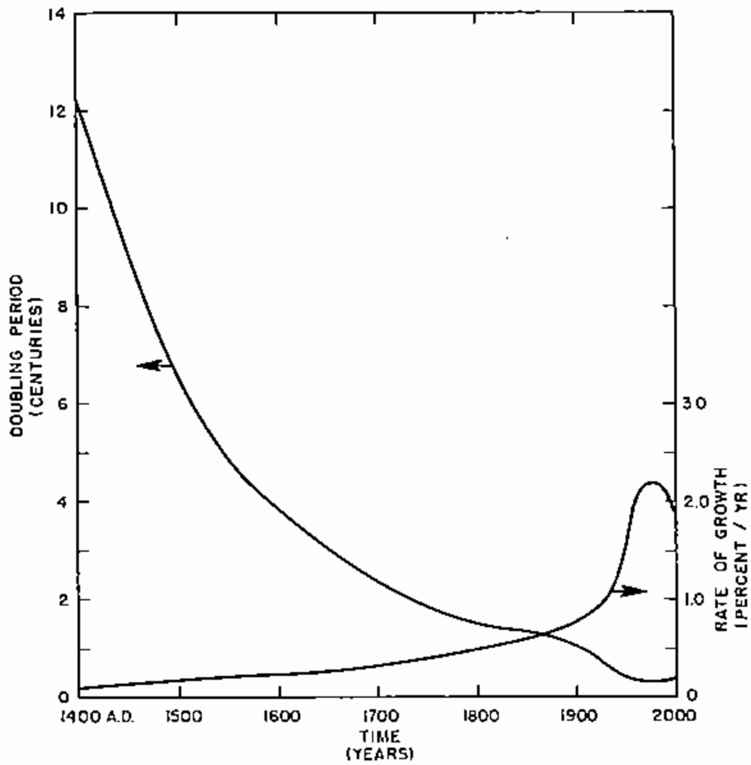

Figure 3. Decrease of Doubling Period and Rate of Increase of World Population

which subsists most of the time, then we must recognize that the normal state of the human population, and of biologic populations in general, is a state of extremely slow secular change. We must, accordingly, regard the rate of growth of the human population and the concurrent disturbances of all other biologic populations during the last few centuries as being extremely abnormal. It represents, in fact, one of the greatest biological upheavals known in geological as well as in human history.

TABLE 2

Rate of Population Growth

Time (Years)	Δt (Years)	Population (Billions) N	$\frac{N_t}{N_{t-\Delta t}}$	Exponential Constant a	Doubling Period (Years)
1000 A.D.		0.295			
1200		0.310			
1400		0.350*		0.000565*	1,225*
1500		0.382*		0.001064*	650*
1600		0.442*		0.00177*	390*
1700		0.570*		0.00263*	267*
1800		0.860*		0.00495*	140*
1900		1.550*		0.00618*	112*
	25		1.230	0.00829	83.6
1925		1.907			
	25		1.310	0.0108	64.1
1950		2.497			
	10		1.200	0.01824	38.2
1960		2.996			
	5		1.110	0.0209	33.1
1965		3.297			
	5		1.110	0.0209	33.1
1970		3.655			
	5		1.116	0.0220	31.4
1975		4.080			
	5		1.117	0.0221	31.2
1980		4.562			
	5		1.116	0.0220	31.4
1985		5.096			
	5		1.114	0.0216	32.0
1990		5.687			
	5		1.103	0.0196	35.3
1995		6.278			
	5		1.100	0.0190	36.4
2000		6.919			

*From graph of data in Table 1.

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CHAPTER III

ENERGY FROM FOSSIL FUELS

Production Data and Coal Reserves

The historical background in the use of energy from the fossil fuels has already been given in outline form in Chapter II. From here on it will be more informative if we consider the rates of growth of energy consumption from these sources, with the data presented in graphical form.

World Production of Coal and Crude Oil

Production of Coal

World production statistics before 1860 are not available, but, as we noted in Chapter II, the principal production during the first few centuries was in Britain, where the production began in the twelfth century and increased steadily over the next seven centuries. The British production rate reached 2 million tons per year by 1660 and 7 million by 1750, and world production reached 134 million metric tons by 1860.

Statistical data on annual production are available from 1860 to 1960, and the rate of production as a function of time is shown graphically in Figure 4 for that period. At a glance it will be seen that the growth in the rate of production during this period falls into three distinct phases: (1) a period of steady growth extending from 1860 until 1913, during which the production rate increased from 134×10^6 to $1,257 \times 10^6$ metric tons per year, (2) a period of unsettled growth and oscillation extending from 1913 to 1954, during which the production rate increased from $1,257 \times 10^6$ to $1,631 \times 10^6$ metric tons, and, finally, (3) a period from 1954 to 1960 when the production rate assumed a spurt of renewed growth from $1,631 \times 10^6$ to $2,414 \times 10^6$ metric tons per year.

The nature of this growth is brought out more clearly in Figure 5 where the same data are plotted logarithmically against time. Here the growth from 1860 to 1913 is seen to plot as an essentially straight line. This indicates that during that period

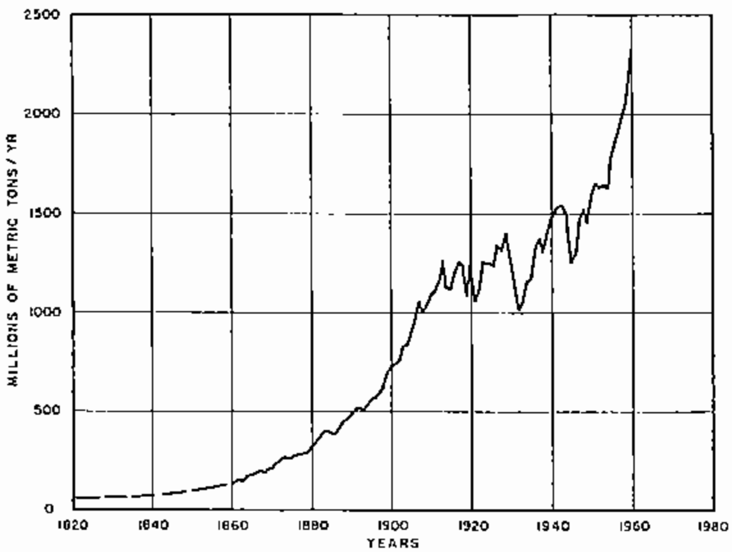

Figure 4. World Production of Coal

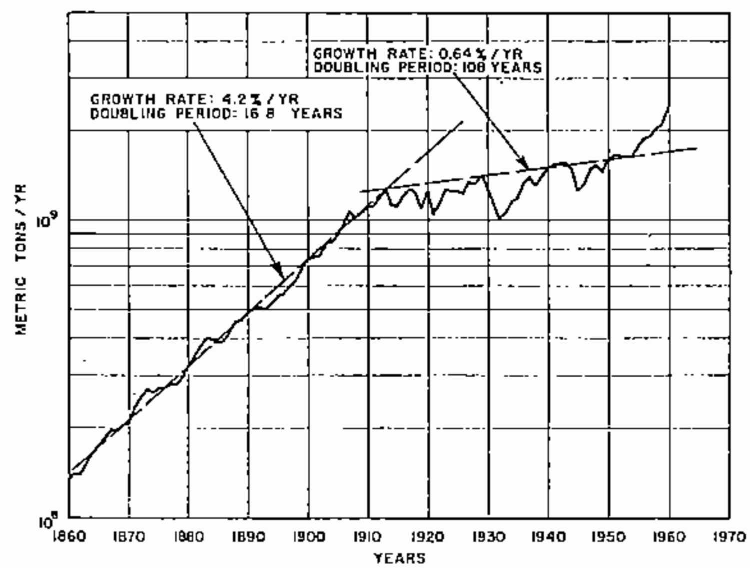

Figure 5. World Production of Coal (Logarithmic Scale)

the rate of coal production increased with time at an exponential, or compound-interest, rate of 4.2 per cent per year, or at such a rate of growth that the production rate doubled every 16.8 years.

During the intermediate period from 1913 to 1954 production increased much more slowly, averaging only about 0.64 per cent per year, while during the last period from 1954 to 1960 the rate of growth has been very nearly the same as for the earlier period—about 4.2 per cent per year.

Because Figures 4 and 5 present data for only the last century of the approximately 900 years during which coal has been mined, they do not properly convey an appreciation of the relative importance of coal mining during this period compared with that of earlier history. A better sense of this may be gained if we consider the cumulative production of coal during the total period. For the period prior to 1860, from the few production statistics and the knowledge that coal mining increased continually, it can be estimated that the total coal mined from the twelfth century until 1860 could only have been about 5.4 billion (5.4×10^9) metric tons. That mined during the 100 years from 1860 to 1960 amounted to 93.6×10^9 metric tons, giving a total of 99.0×10^9 metric tons for all coal mined from the beginning until 1960. However, the first half of this required the seven centuries up to 1927, whereas the second half required only the 33 years from 1927 to 1960. Only 20 per cent of the coal mined by 1960 was produced before 1900, and the remaining 80 per cent has been produced since that time.

Production of Crude Oil

Figures 6 and 7 show graphs of the world production of crude oil, in which the production rates are plotted arithmetically and logarithmically, respectively, against time. Production actually began in 1857, but the rates before 1885 were too small to plot on Figure 6. In this case, except for minor setbacks during the depression of the 1930's and during World War II, the production rate has been characterized by steady growth.

On the logarithmic scale of Figure 7 it will be seen that for the 50-year period from 1880 to 1930, the production rate increased linearly with time. Before 1880, although the production rate was very small, the rate of increase was even greater than that after 1880. Subsequent to 1880 the rate of increase has

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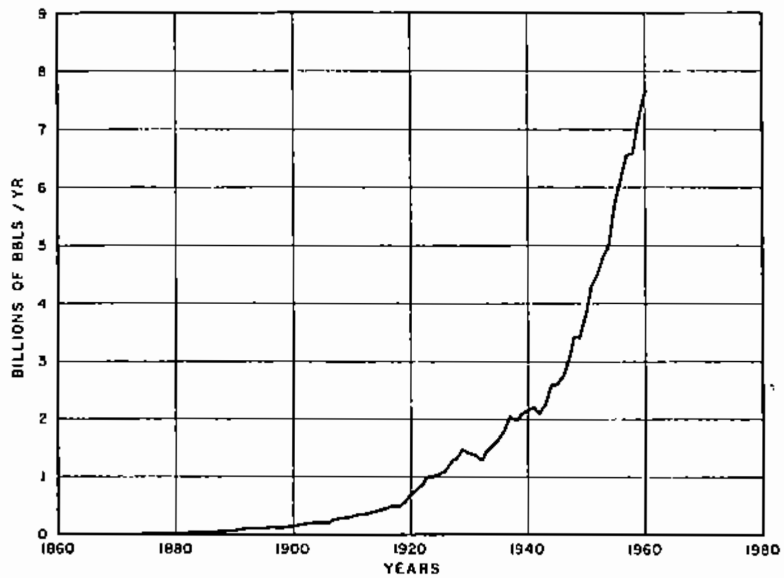

Figure 6. World Production of Crude Oil

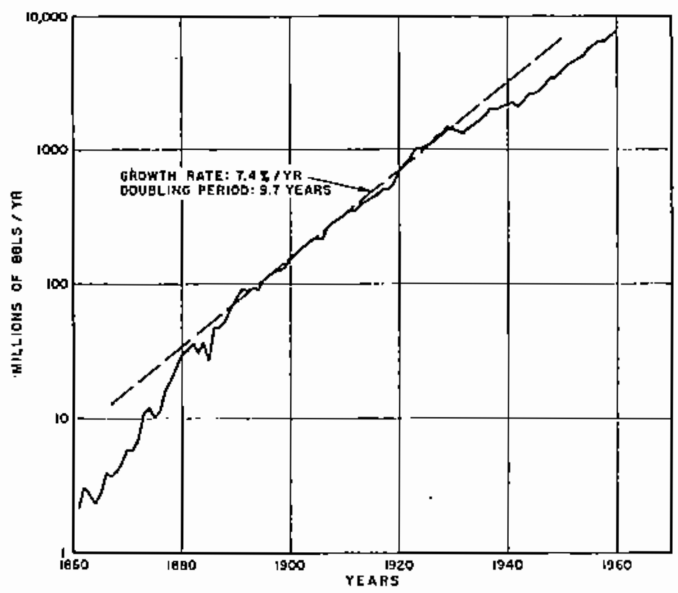

Figure 7. World Production of Crude Oil (Logarithmic Scale)

Energy from Coal and Crude Oil Combined

Finally, in Figure 8 there has been plotted on an arithmetic scale the production of energy from both coal and crude oil, in which the thermal energy of each fuel is expressed in the common unit, the kilowatt-hour of heat, obtained by combustion. Until

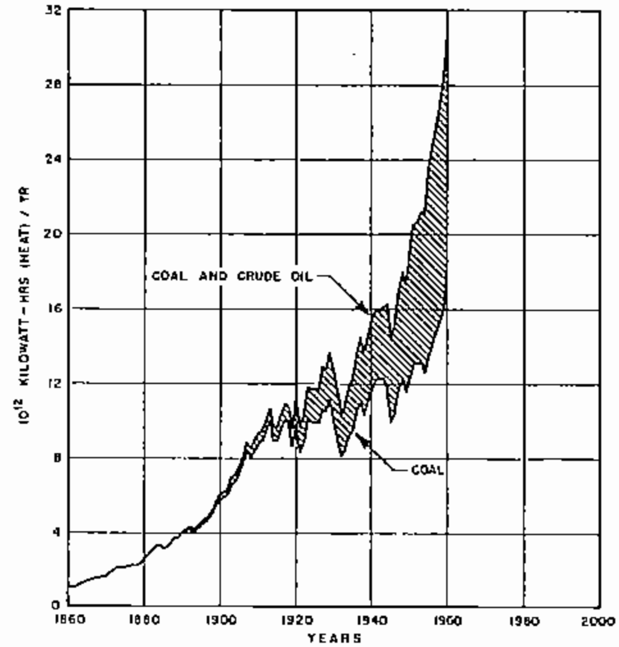

Figure 8. World Production of Energy from Coal and Crude Oil.

about 1900, it will be noted, crude oil contributed a negligible amount of the total energy. From that time on, the fraction contributed by crude oil has steadily increased until, by 1960, it amounted to almost one-half of the total.

United States Production of Energy from Coal, Oil and Natural Gas

Production of Coal

The production of coal in the United States started about 1820, when 14 tons are reported to have been mined. Since that time the production of coal increased steadily until about 1907, after which the rate has fluctuated between the extremes of about 400 and 700 million short tons per year, as shown in Figure 9.

In Figure 10 the same data are shown plotted on a logarithmic scale. Here again, after an initial more rapid rate, the

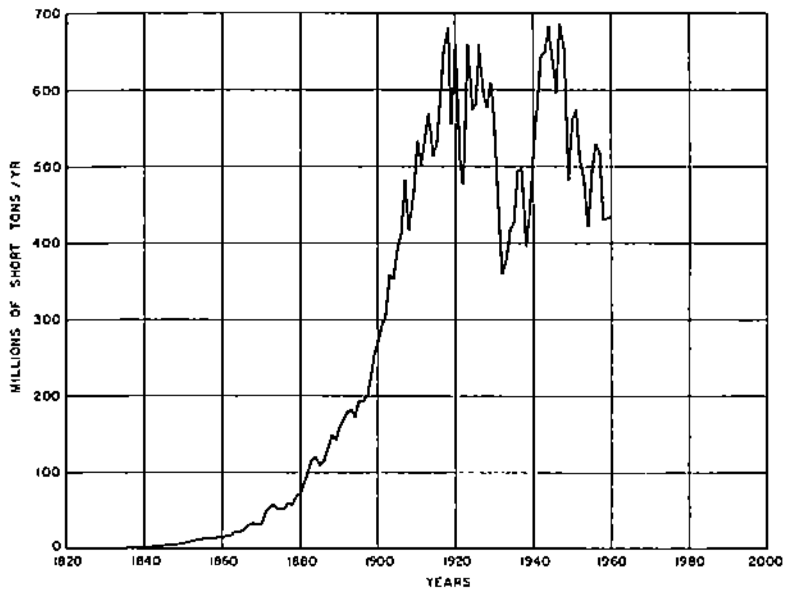

Figure 9. U.S. Production of Coal

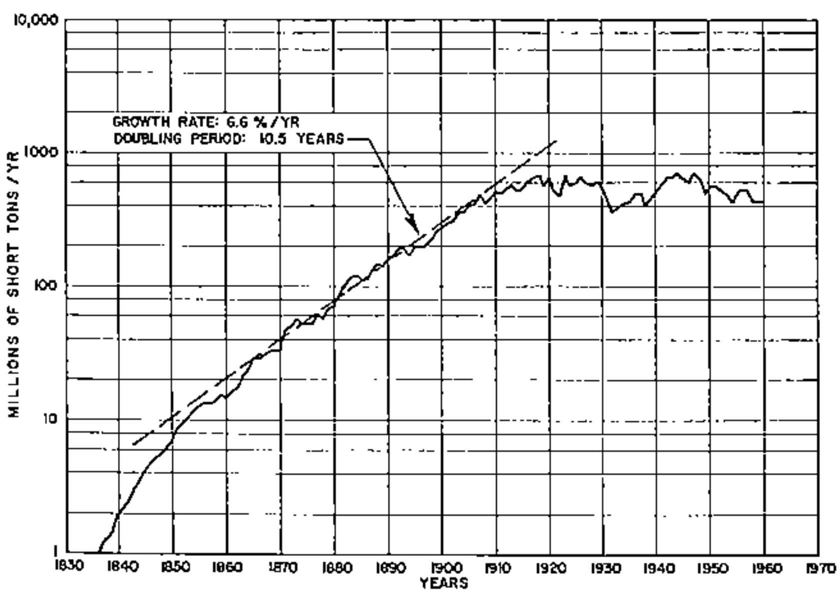

Figure 10. U.S. Production of Coal (Logarithmic Scale)

growth settled down to a linear plot on semilogarithmic paper indicating a steady exponential rate of increase. This persisted from about 1850 to 1907, during which period the production rate increased 6.6 per cent per year, with a doubling period of 10.5 years. After 1907 the growth practically ceased, due in large measure to the increasing displacement of coal by the complementary fuels, oil and gas.

Production of Crude Oil

The production of crude oil in the United States since 1860 is shown graphically on arithmetic and logarithmic scales, respectively, in Figures 11 and 12. Oil was first discovered in the United States by the Drake well drilled at Titusville, Pennsylvania, in 1859. Since that time, with only an occasional setback, the production rate has continually increased. On the semilogarithmic plotting of Figure 12, the production rate increased exponentially from about 1875 to 1929 at 7.9 per cent per year, doubling every 8.7 years. Since 1929 the growth has continued, but at a decreasing rate.

Production of Natural Gas

Figure 13 shows the U. S. production of marketed natural gas since about 1905. In the early days of the petroleum industry only a small amount of gas could be utilized, and the rest was

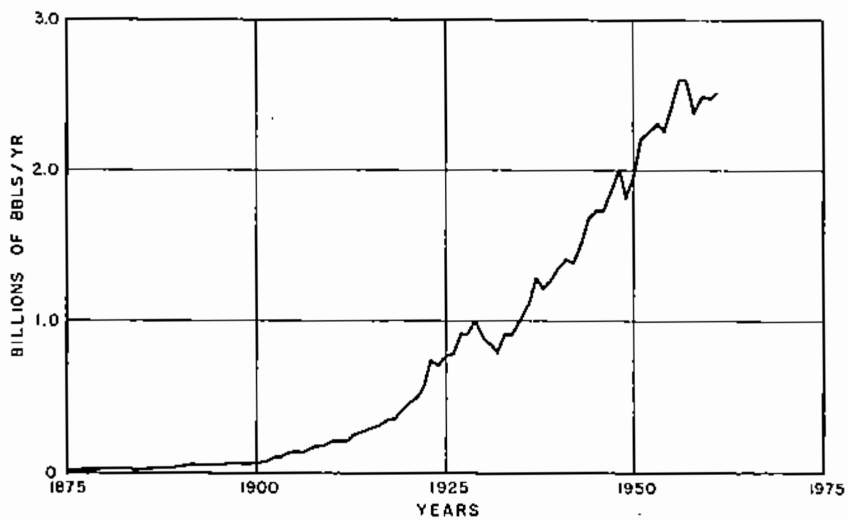

Figure 11. U.S. Production of Crude Oil

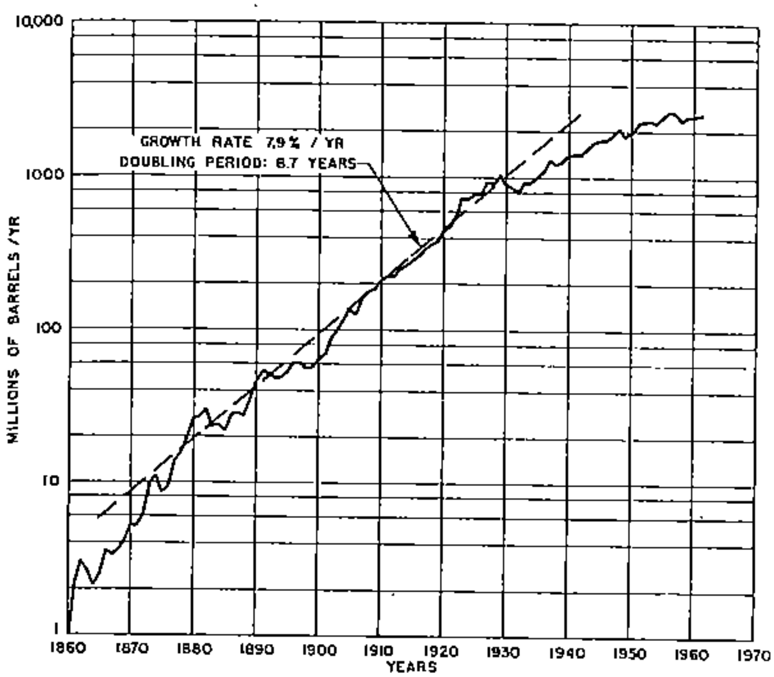

Figure 12. U. S. Production of Crude Oil (Logarithmic Scale)

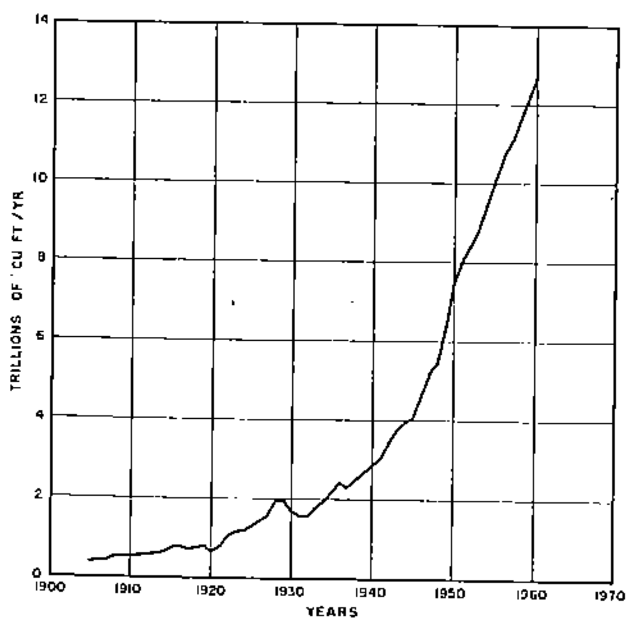

Figure 13. U. S. Marketed Production of Natural Gas

disposed of by flares. Gradually, however, gathering and distributing pipelines have been built, and facilities for using gas as fuel made available, so that very little gas is now wasted. As gas is genetically related to oil, the rate of growth of gas production and consumption is similar, except for a time delay, to that of oil.

Energy from Coal, Oil, Gas, and Water Power

Finally, the total energy produced in the United States from coal, oil, gas, and water power combined is shown in Figure 14 (Dept. of Commerce, 1949, p. 155; 1954, p. 22; 1961, p. 522) plotted on an arithmetic scale, and in Figure 15, plotted logarithmically. In the latter plot it will be seen that the straight-line section of the curve, or the period of exponential growth, persisted from 1845 until 1907, after which the growth rate abruptly dropped to a much smaller value. During the 60-year period of exponential growth the rate of increase was 7.4 per cent per year, with a doubling period of 9.7 years.

From 1907 to 1960 the consumption of energy from the fossil fuels and water power increased from 14.6×10^{15} B.t.u. per year to 44.9×10^{15}. The mean exponential rate of growth for the 53-year period dropped to only 2.04 per cent, and the mean doubling period increased to 34 years. The amounts of energy contributed from the separate sources for the period 1920-1960 are shown in Figure 16. During this period the percentage contribution by wate power increased only from 3.1 to 3.9 per cent. The dramatic transition, however, has been the displacement of coal by oil and gas. In 1920, 89 per cent of the energy consumed was supplied by coal and only 8 per cent by oil and gas; by 1960 the contributio of coal had dropped to only 23 per cent, while that by oil and has had increased to 73 per cent, or about three-quarters of the total.

The importance of the information on the U.S. consumption of energy from coal, oil, gas, and water power, with respect to the industrial rate of growth can hardly be overemphasized, since with the exception of energy derived from biologic sources, and a small amount of wind power, almost every wheel that turns, every industrial process that is in operation, and a predominant amount of space heating are made possible by the energy from these sources. Furthermore, it is this energy consumption which distinguishes the activities in the United States from those of othe major areas of the world whose energy supplies are limited principally to biological sources. Hence, the curve of the consumptio

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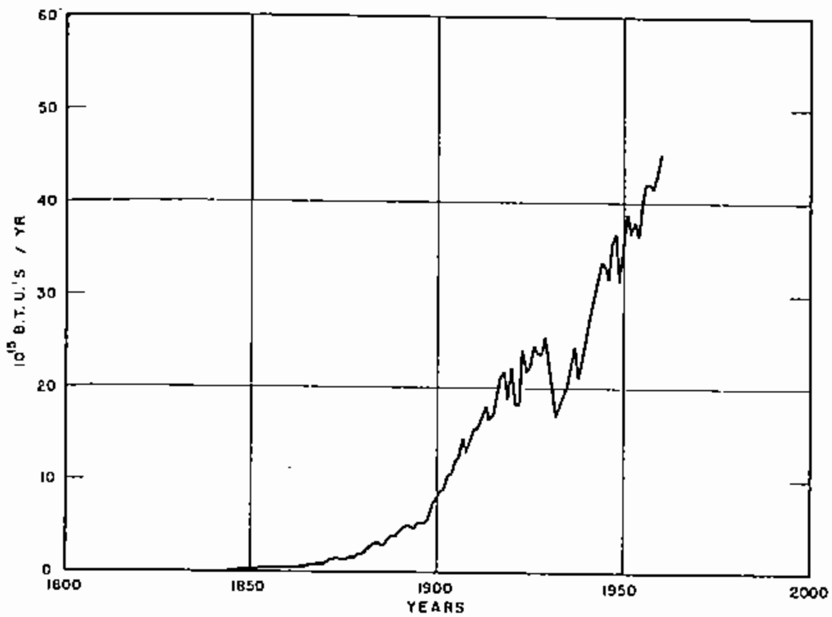


Figure 14. U.S. Consumption of Energy (Coal, Oil, Gas and Water Power)

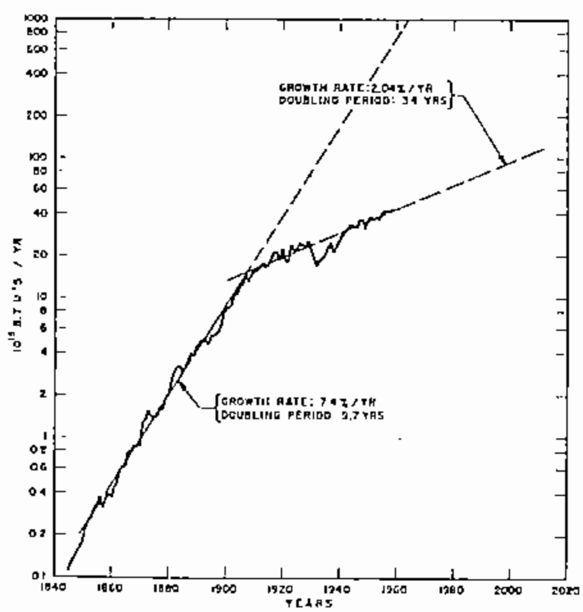


Figure 15. U.S. Consumption of Energy (Logarithmic Scale)

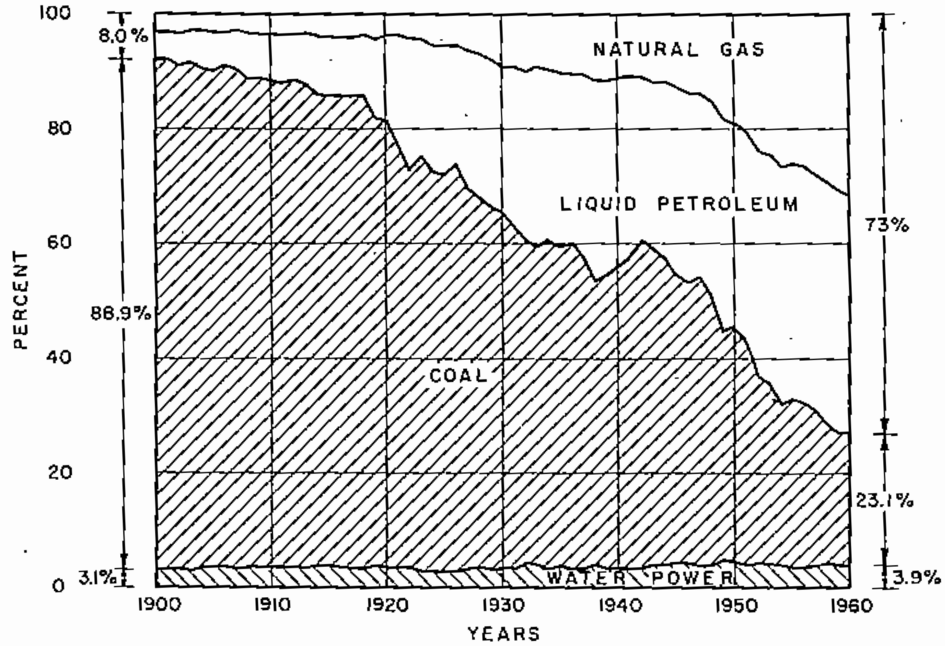


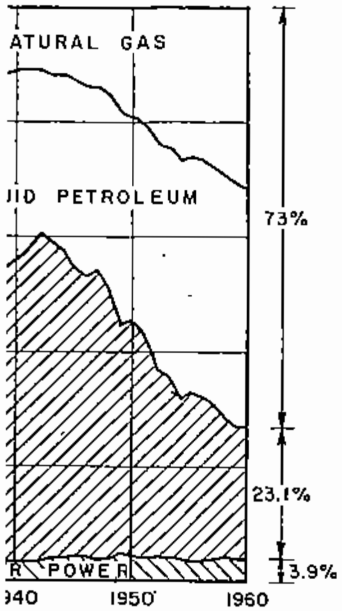
Figure 16. U.S. Consumption of Energy since 1900. Percentages Contributed by Coal, Oil, Gas and Water Power

of nonbiological energy in the United States is, in effect, a physical integration of all the industrial activity in the country.

While it is true that the industrial output per unit of energy consumed is also increasing with time, because of physical limitations this tends asymptotically to a maximum. Hence, if the total rate of energy consumption were to be maintained constant, the industrial output would continue to rise, but at a decreasing rate of growth, until it also leveled off to an essentially constant rate. The curves of Figures 14 and 15, therefore, may be considered to represent minimum rates of the industrial growth of the United States. During most of the nineteenth century the industrial rate of growth was somewhat greater than 7 per cent per year, and the rate of output doubled in somewhat less than 10 years. During most of the twentieth century there has been a drastic reduction in this rate of growth.

Future Production of Fossil Fuels

The history of the production and consumption of energy from the fossil fuels for both the world and the United States is



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graphically and accurately summarized in Figures 4 to 16. Beginning from zero, it is seen how the consumption of these fuels has gradually increased until during the last century the rates of consumption have reached magnitudes many times greater than the energy derived from all other sources in the industrialized areas of the world. Furthermore, as we have noted, most of this has occurred within the last 30 years.

It is difficult to contemplate these curves without wondering: How long can we keep this up?

That it cannot continue indefinitely can be seen very simply. The supply of fossil fuels initially in the ground before human exploitation began was some fixed finite amount. As was observed earlier, these fuels are the residues of organisms which became buried in the sedimentary muds and sands over a period of some 500 million years of geological history. Their energy content represents solar energy, stored by photosynthesis as chemical energy, from that same span of time. Geologically, this process is still continuing but probably at a rate not greatly different from that of the past. Hence, the new fossil fuels to be generated during the next million years will probably not differ greatly from 1/500th of that of the last 500 million years, and that for the next 1,000 years correspondingly less.

Hence, we may regard the initial supply of fossil fuels as constituting a nonrenewable resource which is exhaustible. When we burn oil or coal, as we observed, the energy content, after various degradations during use, degenerates to unusable heat at the lowest ambient temperature, and then leaves the earth as long-wavelength radiation. The material content is reduced to common inorganic chemicals such as H_2O and CO_2, and a residue of mineral ash.

This fact provides us with the most powerful means we have available for anticipating the future history of the consumption of these sources of energy. If we plot a curve of the production rate $\underline{P}$ against time $\underline{t}$ on arithmetic paper, as we have done in Figures 4, 6, 8, 9, 11, and 13, for any nonrenewable resource, this curve must have the following properties:

1. It must begin with $\underline{P} = 0$, and, after passing through one or more maxima, it must ultimately decline to zero. This last state would be due either to the exhaustion of the resource or to the abandonment of its production for other reasons.

2. The cumulative production $\underline{Q}$ up to any given time is given by the equation

$$Q = \int_0^t (dQ/dt)dt = \int_0^t P dt\,, \qquad (1)$$

and this, on the graphical plot, is proportional to the area $\underline{A}$ between the rate-of-production curve and the time axis. This principle is illustrated in Figure 17, where the ultimate cumulative production $\underline{Q_\infty}$ at very large time is proportional to the total area under the curve.

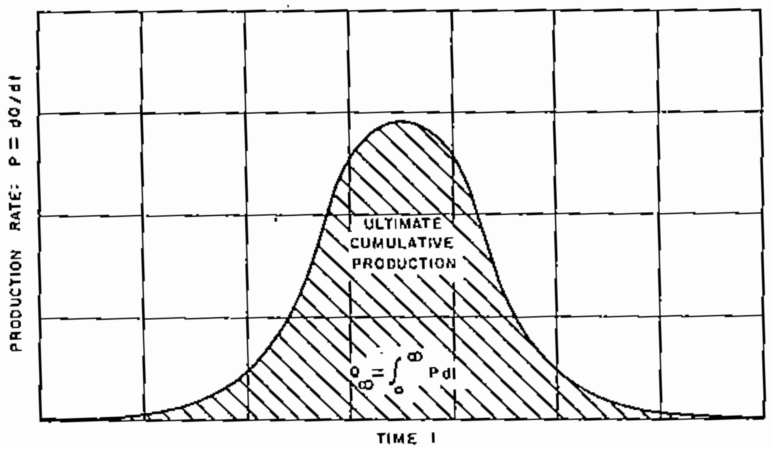

Figure 17. Production of an Exhaustible Resource

The fundamental fact with which we here must deal is this:

(Quantity ultimately produced) $\leqq$ (Quantity initially present),

or

$$Q_\infty \leqq Q_i. \qquad (2)$$

Hence, if we can estimate $\underline{Q_i}$, the amount of the quantity initially present, the curve of production rate $\underline{P}$ versus time $\underline{t}$ must begin at zero and end at zero, and it must not encompass an area greater than that corresponding to $\underline{Q_i}$.

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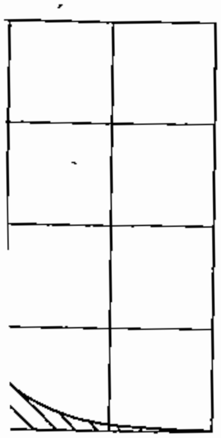

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Application to Coal

The production of coal lends itself readily to this type of treatment because coal occurs in stratified deposits which frequently extend over large areas, or whole sedimentary basins, and hence are amenable to comparatively accurate estimates of their amount. Coal beds frequently crop out on the surface of the ground, and in the subsurface they can be mapped by comparatively few widely spaced drill holes.

The first world inventory of coal resources was made during the Twelfth International Geological Congress at Toronto in the year 1913. Any estimates that could be made at that time were necessarily very provisional. Nevertheless, the estimate of minable coal resources for the whole world amounted to about 8×10^{12} metric tons, which is only about 50 per cent higher than the present estimates.

Since that time, extensive and intensive geological exploration has been extended to all parts of the world. Also during the last decade the Fuels Branch of the United States Geological Survey has been engaged in a detailed re-examination of the coal resources of the United States, and also has maintained currently the estimates being made of the coal resources of the rest of the world.

The latest such world summary is that prepared by Paul Averitt (1961a) from the preliminary reports of the Geological Survey for presentation to the Federal Council. These estimates are given in detail in Table 3 and are shown graphically in an abbreviated form in Figure 18.

It is to be emphasized that these are the remaining coal reserves, and to obtain the initial reserves we shall have to add the quantity already produced, which for the world was about 99×10^9 metric tons by the end of 1960. That for the United States amounted to 32.0×10^9 metric tons. Then, from the data in Table 3 and the above figures on cumulative production, the estimates of initial minable coal reserves of the world as of 1961 are $2,419 \times 10^9$ metric tons; the corresponding figure for the United States is 785×10^9 metric tons.

The figures in Table 3 are of recoverable reserves defined as ".... reserves in the ground, as of the date of the estimate, that past experience suggests can actually be produced in the future"

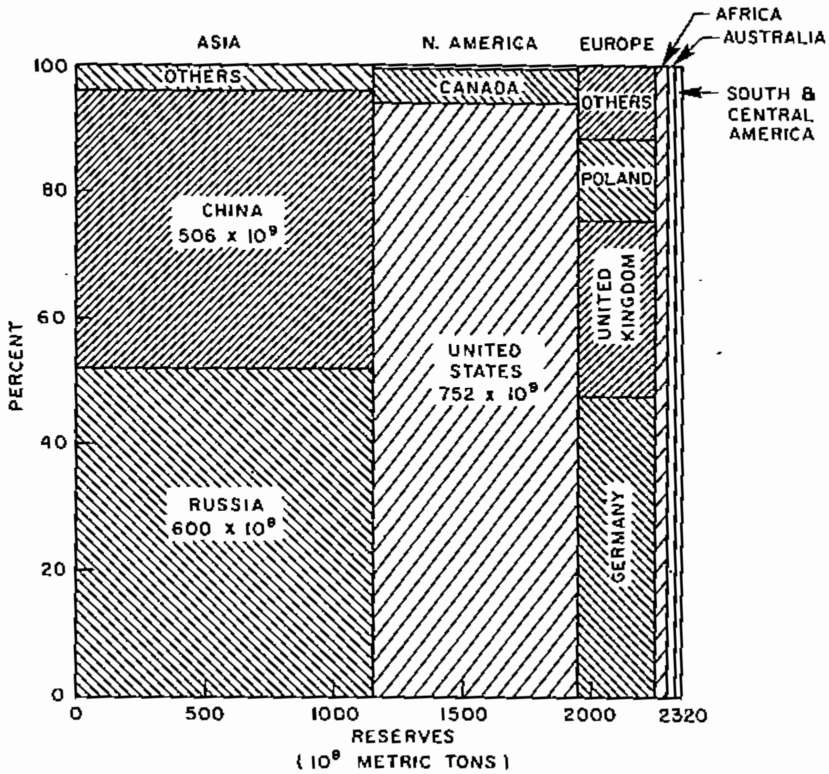

Figure 18. Recoverable World Coal Reserves

(Averitt, 1961b, p. 22). Elsewhere it is explained that these include all seams 14 inches or more thick, occurring at depths of 3,000 feet or less, with an allowance for nonrecovery of 50 per cent of the coal in place.

Before proceeding further it is worthy of note that the coal reserves of the world are far from equitably distributed among the world's people. The continent of Asia, for example, has 49.4 per cent, or almost exactly half, of the world's coal reserves, nearly all of which are in the U. S. S. R. and China. North America has 34.4 per cent, or about one-third; Europe has 13.0 per cent; and the remaining 3.2 per cent is divided between the three whole continents: Africa, South America, and Australia.

By countries, the United States has approximately one-third, Russia one-fourth, and China one-fifth of the world's coal

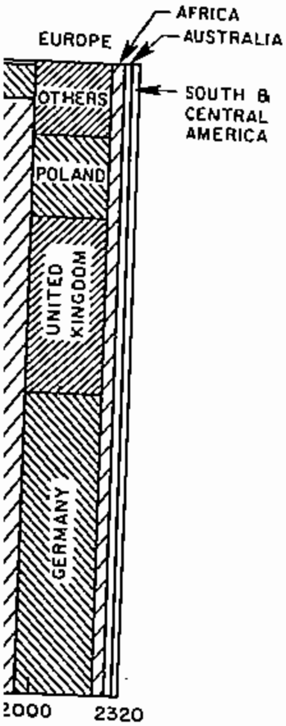

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TABLE 3

Estimated Remaining Coal Reserves of the World
by Region and Principal Coal-Producing Countries*

Region and Country	Producible Coal ($\times 10^9$ metric tons)	Percent of Regional Total	Percent of World Total
Asia:			
U.S.S.R.	600	52.3	25.8
China	506	44.1	21.8
India	32	2.8	1.4
Japan	5	0.4	0.2
Others	4	0.4	0.2
Total	1,147	100.0	49.4
North America:			
United States	753	94.4	32.5
Canada	43	5.4	1.8
Mexico	2	0.2	0.1
Total	798	100.0	34.4
Europe:			
Germany	143	47.5	6.2
United Kingdom	85	28.2	3.7
Poland	40	13.3	1.7
Czechoslovakia	10	3.3	0.4
France	6	2.0	0.3
Belgium	3	1.0	0.1
Netherlands	2	0.7	0.1
Others	12	4.0	0.5
Total	301	100.0	13.0
Africa:			
Union of South Africa	34	97.1	1.5
Others	1	2.9	–
Total	35	100.0	1.5
Australasia:			
Australia	29	99.0	1.3
Others	–	1.0	–
Total	29	100.0	1.3
South and Central America:			
Colombia	6	60.0	0.2
Venezuela	2	20.0	0.1
Others	2	20.0	0.1
Total	10	100.0	0.4
WORLD TOTAL	2,320	–	100.0

*From: Averitt, Paul, 1961, Coal Reserves of the United States and of the World, p. 5 in Domestic and World Resources of Fossil Fuels, Radioactive Minerals, and Geothermal Energy; Preliminary Reports Prepared by Members of the U. S. Geological Survey for the Natural Resources Subcommittee of the Federal Science Council.

reserves. Of the 13.0 per cent in Europe, Germany has about one-half, the United Kingdom one-fourth, and Poland one-eighth.

A fairly widespread delusion among the citizens of the United States is that this country owes its phenomenal industrial development, as contrasted with the lack of development of regions such as Africa, South and Central America, and India, to the superiority of American personal and institutional characteristics. It may be well to remind ourselves that, but for a fortuitous combination of a large fraction of the world's resources of coal and iron in the eastern United States, the growth of which we are justly proud could never have occurred.

Returning now to the problem of predicting the future of coal production, let us apply the technique illustrated in Figure 17. For the world the results are shown in Figure 19 and for the United States in Figure 20. In Figure 19 the world production of coal through 1960 is first plotted. From this point the graph must continue with time until it passes through one or more maxima, and then the production of coal must ultimately decline to zero. The area under the curve, however, must not exceed that corresponding to the estimated initial reserves, $2,400 \times 10^9$ metric tons.

A scale for the conversion of area to tons of coal is shown in the upper left-hand corner of the chart. Here one square in the coordinate grid is seen to have the dimensions

$$2 \times 10^9 \text{ metric tons/yr} \times 100 \text{ yrs},$$

and so represents 200×10^9 metric tons. Hence, the area under the production curve between the beginning of coal mining and its end cannot exceed 12 grid rectangles, representing $2,400 \times 10^9$ metric tons of coal.

The curve is drawn subject to these conditions. The shape of the curve, of course, is not known, but if the world should continue to be heavily dependent on coal, and if the peak of production should reach as much as 6×10^9 tons/yr--about three times the present production rate—this peak would occur about the year 2150, or 200 years hence. If the production rate went higher than this the peak would occur sooner; if less high the date of the peak would be postponed.

In Figure 20 the coal production of the United States is treated in a similar manner, except that the coal is measured in

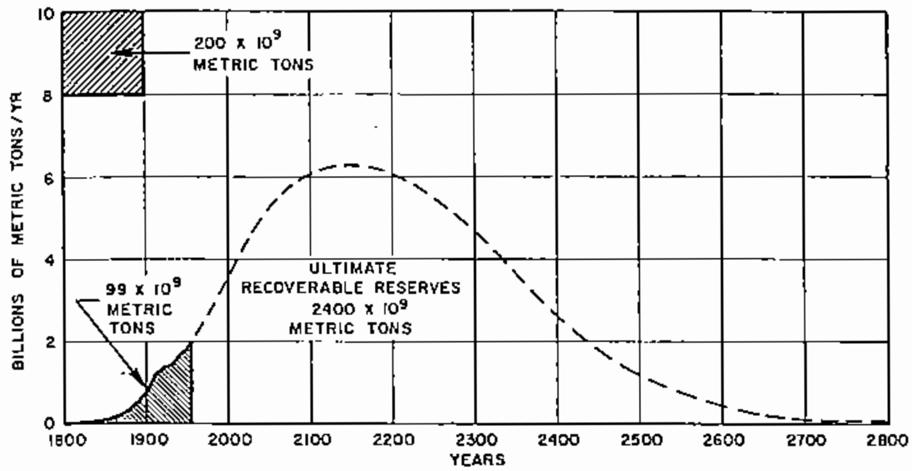

Figure 19. Ultimate World Coal Production

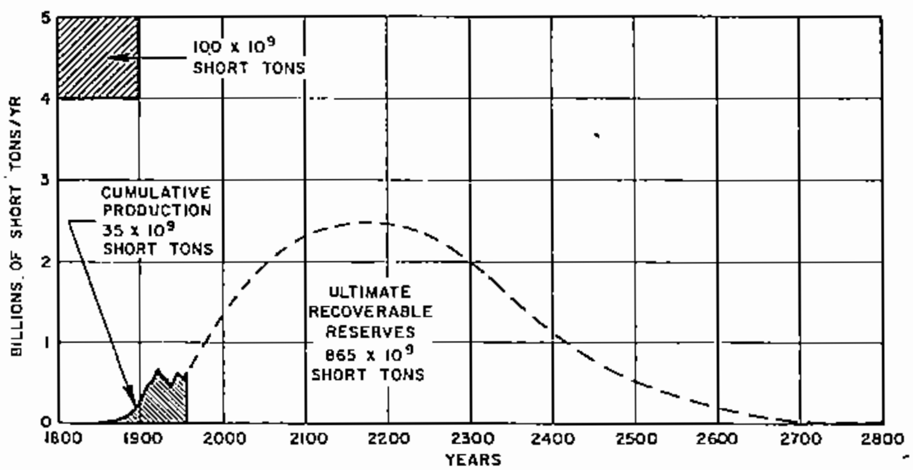

Figure 20. Ultimate U. S. Coal Production

short tons instead of metric tons. By January 1, 1961, the cumulative coal production of the United States amounted to 35.2×10^9 short tons. The remaining reserves by that date were 830×10^9 short tons. The initial reserves, which are the sum of these two figures, are thus 865×10^9 short tons.

The grid rectangle in Figure 20 represents 100×10^9 short tons, so the coal-production curve must be drawn in such a manner as to enclose 8.65 grid rectangles. Again, assuming that we continue to require coal, and assuming a production peak of 2.5×10^9

tons per year—two more doublings of the present rate—the peak again would occur about 200 years hence.

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CHAPTER IV

ENERGY FROM FOSSIL FUELS (continued)

Future Production of Petroleum and Natural Gas

Necessity for Extended Discussion

The technique described in Chapter III is also applicable to petroleum and natural gas, only in this case it is much more difficult to estimate the producible amounts of these fuels initially present. Because of this difficulty, as indicated by the wide disparity among recent estimates by different investigators, it will be necessary to consider petroleum and natural gas in much more detail than was the case for coal.

Such an extended examination not only is justified, but also is becoming increasingly urgent, in view of the fact that oil and gas are approaching equality with coal as a source of energy on a world scale, whereas, in the United States, the energy consumption from these fuels is already three times as large as that from coal. Yet, preliminary evidence indicates that the total energy reserves from oil and gas are much smaller than those from coal. Thus, because of the relative smallness of the reserves and their rapid rate of depletion, critical problems are due to arise with respect to supplies of oil and gas much sooner than with any other source of energy.

Petroleum Classification

Since a great deal of unnecessary confusion in discussing petroleum-reserve problems arises from the failure to distinguish between the different classes of petroleum fluids, let us first define what these classes are.

The first of these fluids is crude oil, which is the liquid petroleum obtainable from an oil reservoir after the gaseous constituents have been removed or have escaped. Next comes natural gas, consisting principally of methane (CH_4), the constituent of petroleum fluids which remains gaseous at standard conditions of temperature and pressure. Finally, there are the natural-gas liquids, which are the liquid constituents obtained from wells which otherwise produce natural gas.

The sum of the liquid phases, crude oil and natural-gas liquids, is frequently combined statistically and classed as petroleum liquids, or liquid hydrocarbons.

The extraction of natural-gas liquids became significant only after about 1920. Since that time its production rate has risen in the United States until by 1961 it represented about 15 per cent of the total production of liquid hydrocarbons. Thus, originally crude oil was the sole liquid hydrocarbon, but more recently natural-gas liquids have achieved a significant fraction of total production.

A great deal of confusion has been introduced into discussions of petroleum reserves by the failure to distinguish between crude oil and total petroleum liquids. In what follows this distinction will clearly be made. We shall first deal with crude oil, for which our data are the most complete, and then use the results obtained as a basis for estimating the reserves of natural gas and natural-gas liquids. Also, since the petroleum industry in the United States is more advanced in its evolution toward total depletion than that of any comparable area of the rest of the world, we shall use the data of the United States as a yardstick for estimating the reserves of other areas.

Estimation of the Crude Oil Reserves of the United States

Geological Background

Before proceeding with this problem in detail, let us first consider a few of the fundamental facts concerning the manner of occurrence of oil and gas underground. If a well is drilled deep enough at any place on the earth it will eventually encounter some form of dense, crystalline rock such as granite, or gneiss, or schist, of either igneous or metamorphic origin, whose grains are so tightly packed that the pore space is practically zero.

We shall refer to this system of crystalline rocks, which is continuous over the whole surface of the earth, as the basement or basement complex.

In many parts of the world, such as eastern Canada, Scandinavia, and a large part of Africa, the rocks of the basement complex occur at the surface of the ground. In other areas these rocks are covered with a veneer of unmetamorphosed rocks such as sandstones, shales, and limestones, which are sedimentary in origin. The thicknesses of these deposits of sedimentary rocks vary from zero to possibly 10 miles or more. The average thickness is probably not more than about a mile. The sediments having thicknesses of one to several miles occupy basin-like depressions in the upper surface of the basement complex.

These unmetamorphosed sediments comprise the habitat of the fossil fuels. They are the sands and muds in which the organic remains of the geologic past got buried and preserved. These rocks, or contiguous fractured basement rocks, are therefore the only rocks in which commercial quantities of fossil fuels have ever been found, or are ever expected to be found.

The unmetamorphosed sedimentary rocks are mostly porous, with the pore volume comprising about 20 per cent of the total volume. This pore space forms a three-dimensional interconnected network which normally is completely filled with water. Exceptionally, in very local regions of space whose horizontal dimensions may range from a few hundred feet to some tens of miles, oil and gas may have displaced the water in certain strata of the sedimentary deposit. These local concentrations of oil and gas in the sedimentary rocks are the sources of our commercial production of these fluids.

This knowledge provides us with a powerful geological basis against unbridled speculation as to the occurrence of oil and gas. The initial supply is finite; the rate of renewal is negligible; and the occurrences are limited to those areas of the earth where the basement rocks are covered by thick sedimentary deposits.

The geographical distribution of all of such basins on earth is reasonably well known. If we can estimate about how much oil and gas is contained per unit volume in the sediments in the better-known areas, such as the United States, then, by assuming comparable oil and gas contents in similar sedimentary basins in the rest of the world, an estimate in advance of extensive development can be made of the possible oil and gas that other areas may eventually produce.

This, in essence, is the geological basis for estimating the ultimate petroleum reserves. It is an essential method, but as we shall see, it has inherent limitations of accuracy. The sedimentary rocks of the United States and its continental shelves to a depth of two miles have a volume of about 3×10^6 cubic miles, or about 14×10^6 km^3. With an average porosity of 20 per cent the pore volume of these rocks would be about 2.8×10^6 km^3. Now suppose that these rocks contain 1,000 billion barrels of crude oil in commercially producible concentrations. The volume of this amount of oil would be 159 km^3, which would represent a fraction of 5.7×10^{-5} of the entire pore volume, or about 6 parts per 100,000.

There is no geological information in existence that will permit us to know whether this is a high figure or a low figure. We have no a priori way of knowing whether the average content of oil occurring in commercial quantities in sedimentary rocks should be a few parts in 100,000, or ten times or one-tenth this amount.

If the oil production of the United States is to be used as a primary standard for estimating the petroleum potentialities of the rest of the world, then the only possible way we have of determining how much oil the United States will produce is by pure empiricism, based on our actual experience in the exploration and production of petroleum. The United States experience can then be used to estimate what may be expected from other comparable regions.

Reserve Estimates

According to Wallace E. Pratt (1942, 1944, 1947), then Vice President for Exploration and Production of the Standard Oil Company of New Jersey, the world's largest oil company, one of the Jersey Standard Oil geologists, L. G. Weeks, had made an extensive world-wide study along the general lines sketched above. This report has never been published, but in 1948 Weeks (1948, p. 1094) published a summary of the results that had been obtained

This consisted of estimates of the ultimate potential reserves of various areas, defined as the total amount of crude oil that could reasonably be expected to be produced by productive methods, and under economic conditions, prevailing in 1947. These estimates are reproduced here as Table 4. For our purposes the two principal results were:

Land area of the United States (excluding Alaska)	110×10^9 barrels
Land areas of entire world	610×10^9 barrels

Two years later, during a discussion on petroleum reserves at the United Nations Scientific Conference on the Conservation and Utilization of Resources, held at Lake Success, New York, Weeks (1950, p. 107-110) amplified his earlier estimate by adding about 400×10^9 barrels for the continental-shelf areas of the world, and arrived at a round estimate of $1,000 \times 10^9$ barrels for the whole world. This was in criticism of an estimate of $1,500 \times 10^9$ barrels by A. I. Levorsen (1950, p. 94-99).

Weeks gave his own appraisal of the reliability of these figures in the following words (Weeks, 1950, p. 109):

> I look upon my estimates for the United States as reasonable at this time. Furthermore, I now know of no good reason for considering that the incidence of oil occurrence in the United States should be much, if any, above that of the average for the world. As previously stated, I feel that the actual measure of oil recoverable by conventional methods and under present economies is more likely to be 50 per cent larger than 10 per cent smaller than my estimate of same. However, again I must warn that these are not proved reserves. The actual figure of ultimate reserves may very easily vary from my figure by considerably more than the percentages I have just cited.

It should be emphasized that the foregoing estimates were for crude oil only.

In March 1956 Hubbert (1956) added 20 billion barrels to Weeks' estimate for the land area of the United States (excluding Alaska) and 20 billion barrels for the U. S. offshore areas, and arrived at a figure of 150×10^9 barrels for the ultimate potential reserves of crude oil in the United States, and $1,250 \times 10^9$ barrels

TABLE 4

(Weeks' Table II.) Production and Reserve Summary

Country or Region	Cumulative January 1, 1948		1947 Daily Average		Proved Reserves		Ultimate Potential Reserves		Percentage of Ultimate Produced
	Millions Bbls.	%	Barrels	%	Millions Bbls.	%	Millions Bbls.	%	
United States	35,080.7	64.1	5,082,000	61.5	21,488[1]	31.6	110,000	18.0	32
Balance N.America	2,435.7	4.4	175,000	2.1	1,200	1.7	40,000	6.6	6
Total N. America	37,516.4	68.5	5,257,700	63.6	22,688	33.3	150,000	24.6	25
Venezuela	4,046.6	7.4	1,190,800	14.4	9,650	14.2	80,000	13.1	7
Balance S. America	1,549.8	2.8	226,865	2.8					
Total S. America	5,596.4	10.2	1,417,665	17.2	9,650	14.2	80,000	13.1	7
Total W. Hemisphere	43,112.8	78.7	6,675,365	80.8	32,338	47.5	230,000	37.7	14.4
Europe, excl. Russia	1,655.0	3.0	129,410	1.6	650	1.0	13,000	2.1	12.7
Middle East, incl. Egypt	2,541.5	4.6	864,000	10.5	28,800	42.3	155,000	25.4	1.6
Balance Asia, excl. Russia	429.9	0.8	11,400	0.1	100	.15	24,000	4.0	1.8
Indonesia	1,241.8	2.3	56,000	0.7	1,100[2]	1.6	30,000	4.9	4
Africa, excl. Egypt	0.6	0.01	–	–	50	.07	8,000	1.3	.01
Total E. Hem. excl. Russia	5,868.8	10.7	1,060,810	12.9	30,700	45.1	230,000	37.7	2.5
Russia	5,783.9	10.6	525,000	6.4	5,000	7.4	150,000	24.6	3.8
Total E. Hemisphere	11,652.7	21.3	1,585,810	19.2	35,700	52.5	380,000	62.3	3
Total World	54,765.5	100.0	8,261,175	100.0	68,038	100.0	610,000	100.0	9
Total Foreign	19,684.8	35.9	3,179,175	38.5	46,550	68.4	500,000	82.0	4

[1] A.P.I. [2] *Oil and Gas Journal*.

Russia	5,783.9	10.6	525,000	6.4	5,000	7.4	150,000	24.6	3.8
Total E. Hemisphere	11,652.7	21.3	1,585,810	19.2	35,700	52.5	380,000	62.3	3
Total World	54,765.5	100.0	8,261,175	100.0	68,038	100.0	610,000	100.0	9
Total Foreign	19,684.8	35.9	3,179,175	38.5	46,550	68.4	500,000	82.0	4

[1] A.P.I.

[2] Oil and Gas Journal.

for the whole world. Almost simultaneously, Pratt (1956) published an estimate for the United States of 170 x 10^9 barrels of liquid hydrocarbons (which implies about 145 x 10^9 barrels of crude oil); and Pogue and Hill (1956) of the Chase Manhattan Bank published a figure of 165 x 10^9 barrels of crude oil for the ultimate potential reserves of the United States.

At the meeting of the American Association of Petroleum Geologists in Dallas in March 1959, G. Moses Knebel, Chief Geologist of the Standard Oil Company of New Jersey, stated that he and his staff had a few years previously made a comprehensive review of the oil potentialities of both North and South America, and that their estimates for the United States were in substantial agreement with the 150 billion-barrel figure of Hubbert, an estimate which was still regarded as valid. He later disclosed privately that their estimate for the United States was 203 billion barrels of liquid hydrocarbons. Of this, crude oil would comprise about 85 per cent, or about 173 billion barrels.

These figures are cited because they represent a very good cross-section of informed petroleum-industry opinion at that time. Pratt's estimate was based, in part, on twenty-two returns to a questionnaire he had sent to a selected group of well-informed people in the petroleum industry. The high figure in these returns was an estimate of 200 x 10^9 barrels of crude oil by the consulting firm DeGolyer and MacNaughton.

The only discordant figure of this series was an estimate of 300 billion barrels from an anonymous source in the Department of the Interior (1956).

Shortly after 1956, however, all consistency in the estimates of petroleum reserves vanished. Within a year after the Pogue and Hill estimate of 165 billion barrels, Hill, Hammar and Winger (1957), also of the Chase Manhattan Bank, raised the Pogue and Hill estimate to 250 billion barrels. In 1958, published estimates ranged from a low figure of 165 billion barrels by Davis (1958) of Gulf Oil Corporation to a high of about 372 billion barrels by Netschert (1958) of Resources for the Future.

In 1958 L. G. Weeks (p. 434) raised his earlier estimate of 110 billion barrels for the ultimate potential reserves of crude oil for the land area of the United States to 240 billion barrels of liquid petroleum for both the land and offshore areas. This quantity was said to represent ". . . . the ultimate potential liquid petroleum resources, recoverable by conventional primary methods in terms of current economics. . . ." Of this, about 85 per cent, or 204 billion barrels, would be represented by crude oil.

What Weeks meant by "conventional primary methods" is not entirely clear since his 240 billion-barrel figure was stated to include both cumulative production and proved reserves, each of which is a composite of oil already produced, or producible, by both primary and secondary methods. He did mention, however, that a means might ultimately be found to recover by secondary methods an additional quantity as large as the one cited. A year later (Weeks, 1959, p. A-27) this ambiguity was resolved. In a new estimate Weeks raised the figure of 240 billion barrels of liquid petroleum recoverable by conventional primary methods to 270 billion and then added 190 billion barrels producible by "secondary recovery," giving a total of 460 billion barrels. Again, about 85 per cent of this, or about 391 billion barrels, would be represented by crude oil.

This last estimate was still adhered to by Weeks as recently as May 1961 (Weeks, 1961, p. 144).

The 1958 and 1959 estimates of Weeks were used by Paul Averitt (1961, p. 99-100) of the United States Geological Survey as the basis for his figure of 470 billion barrels of liquid petroleum (or 400 billion barrels of crude oil) for the United States exclusive of Alaska. However, what appears to be the "official" estimate of the U. S. G. S. is that prepared by A. D. Zapp (1961, Table 1) for presentation by V. E. McKelvey to the Natural Resources Subcommittee of the Federal Science Council, November 28, 1961. Zapp's estimate of the ultimate U. S. resources of crude oil (including past production) was 590 billion barrels. Concerning this estimate, V. E. McKelvey (1961, p. 12), in the same report, remarked:

> Those who have studied Zapp's method are much impressed with it and we in the Geological Survey have much confidence in his estimates.

A published exposition of Zapp's method (Zapp, 1962) has subsequently appeared in the U. S. Geological Survey Bulletin 1142-H, entitled "Future Petroleum Producing Capacity of the United States." In this, no estimate is given explicitly of the ultimate amount of crude oil the United States may be expected to produce, but such an estimate is implied in two statements on page H-24:

1. But this much is certain: it cannot be safely assumed that even the 20-percent mark has been reached in exploration for petroleum in the United States, excluding Alaska and excluding rocks deeper than 20,000 feet.

2. With the crude yardstick of at least 100 billion barrels of oil found so far, and a rough appraisal of the extent of exploration so far, an objective estimate of the approximate minimum ultimate "reserves" appears to be in sight.

As an aside, petroleum-exploration people are intimately familiar with the initial 20 per cent of the petroleum exploration postulated by Zapp, but many are at a loss as to how to proceed with respect to his postulated remaining 80 per cent.

The most recent estimate available is that of C. L. Moore (1962) of the U. S. Department of the Interior, Office of Oil and Gas. From a study of petroleum-industry statistics, Moore (pp. 8, 18) has arrived at an estimate of 364 billion barrels for the ultimate U. S. recovery of crude oil.

These various estimates are shown graphically in Figure 21. To review the often lengthy arguments whereby they were derived

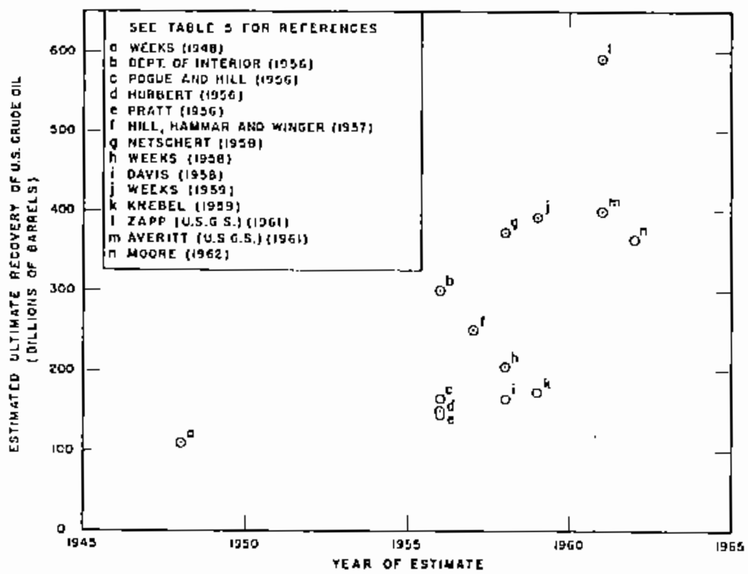

Figure 21. Estimates of Ultimate Recovery of Crude Oil

would be time-consuming and profitless, as the extent of their unreliability is attested by the range of disagreement exhibited among the estimates themselves. There exists some definite quantity of crude oil, Q_∞ (at the moment unknown) which will ultimately be produced in the United States. The estimates plotted in Figure 21 are each intended to represent this quantity. Suppose that the correct value happened to be 590 billion barrels, the highest figure cited. Then the lowest figure since 1955, 145 billion barrels, would be in error by 445 billion barrels; and the errors of the other estimates, except the correct one, would range between 190 and 445 billion barrels.

If the smallest figure happened to be the correct one, then all the others would be erroneously high, with the errors again ranging from 5 to 445 billion barrels.

If the correct figure happened to fall about mid-range, say at 370 billion barrels, then the errors on either side would range between zero and about 200 billion barrels.

It is thus demonstrable, without making any hypothesis whatever of what the true value of Q_∞ should be, that the preponderance of recent attempts to determine this quantity are grossly in error. This raises the question of whether the desired quantity is intrinsically indeterminate, except within these wide limits, or whether from data now available it should be possible to determine this quantity within a much narrower range of uncertainty. It is the thesis of the present report that such data do exist, and that from them a much more reliable estimate can be made.

New Method for Estimating the Ultimate Crude-Oil Production of the United States

Theory

The method we shall now employ makes explicit use only of two of the most reliable series of statistics of the petroleum industry: (1) the quantity of crude oil produced in the United States per year, for which data are available annually since 1860, and (2) the estimates of proved reserves of crude oil in the United States made annually since 1937 by the Committee on Petroleum Reserves of the American Petroleum Institute.

TABLE 5

Estimated Ultimate U. S. Crude-Oil Reserves

	Date	Author	Estimate (Barrels)
a	1948	Weeks	110×10^9
b	1956	Dept. of Interior	300×10^9
c	1956	Pogue and Hill	165×10^9
d	1956	Hubbert	150×10^9
e	1956	Pratt	145×10^9*
f	1957	Hill, Hammar and Winger	250×10^9
g	1958	Netschert	372×10^9*
h	1958	Weeks	204×10^9*
i	1958	Davis	165×10^9
j	1959	Weeks	391×10^9*
k	1959	Knebel	173×10^9*
l	1961	Zapp (U.S.G.S.)	590×10^9
m	1961	Averitt (U.S.G.S.)	400×10^9*
n	1962	Moore	364×10^9

*Calculated from author's estimate of total liquid hydrocarbons on the basis that crude oil equals 85% of liquid hydrocarbons.

a Weeks, L. G., 1948, Highlights on 1947 Developments in Foreign Petroleum Fields: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 1094.

b Interior, Dept. of, 1956, Impact of the Peaceful Uses of Atomic Energy on the Coal, Oil- and Natural-Gas Industries: Background Material for the Report of the Panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, v. 2, January, p. 82.

c Pogue, Joseph E., and Hill, Kenneth E., 1956, Future Growth and Financial Requirements of the World Petroleum Industry: New York, The Chase Manhattan Bank, Petroleum Dept., p. 24.

d Hubbert, M. King, 1956, Nuclear Energy and the Fossil Fuels: Drilling and Production Practice, Am. Petroleum Inst., p. 18.

e Pratt, Wallace E., 1956, The Impact of the Peaceful Uses of Atomic Energy on the Petroleum Industry: Background Material for the Report of the Panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, v. 2, January, p. 94.

f Hill, Kenneth E., Hammar, Harold D., and Winger, John G., 1957, Future Growth of the World Petroleum Industry: Paper for Presentation at the Spring Meeting of the API Division of Production, Rocky Mountain District, Casper, Wyoming, April 25 (preprint), p. 26.

g Netschert, Bruce C., 1958, The Future Supply of Oil and Gas: Baltimore, Resources for the Future, Inc., Johns Hopkins Press, p. 24, 55.

h Weeks, L. G., 1958, Fuel Reserves of the Future: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 434.

i Davis, Warren, 1958, A Study of the Future Productive Capacity and Probable Reserves of the U. S.: Oil and Gas Jour., v. 56, February 24, p. 114.

j Weeks, L. G., 1959, Where Will Energy Come from in 2059: The Petroleum Engineer, v. XXXI, August, Table 1, p. A-25.

k Knebel, G. Moses, 1959, personal communication.

l Zapp, A. D., 1961, World Petroleum Resources, Table 1 in Domestic and World Resources of Fossil Fuels, Radioactive Minerals, and Geothermal Energy: Preliminary Reports Prepared by Members of the U. S. Geological Survey for the Natural Resources Subcommittee of the Federal Science Council.

m Averitt, Paul, 1961, Coal Reserves of the United States—A Progress Report January 1, 1960: U. S. Geol. Survey Bull. 1136, p. 100.

n Moore, C. L., 1962, Method for Evaluating U. S. Crude Oil Resources and Projecting Domestic Crude Oil Availability: U.S. Dept. of Interior, Office of Oil and Gas, p. 8.

The data on the annual production of crude oil requires no comment. The meaning of the term "proved reserves," as defined by the Reserve Committee, however, needs to be clearly understood, because the Reserve Committee operates on the basis of this definition, and their reserve figures are not susceptible to any other interpretation. The following is a partial quotation from the definition of the term "proved reserves of crude oil" taken from the Report of Committee on Petroleum Reserves of the American Petroleum Institute of March 9, 1962, (p. 3):

> <u>Proved Reserves of Crude Oil—Definition</u>
>
> The reserves listed in this Report, as in all previous Annual Reports, refer solely to "proved" reserves. These are the volumes of crude oil which geological and engineering information indicate, beyond reasonable doubt, to be recoverable in the future from an oil reservoir under existing economic and operating conditions. They represent strictly technical judgments, and are not knowingly influenced by policies of conservatism or optimism. They are listed only by the definition of the term "proved." They do not include what are commonly referred to as "probable" or "possible" reserves.
>
> * * *
>
> Both drilled and undrilled acreage are considered in the estimates of the proved reserves. However, the undrilled proved reserves are limited to those drilling units immediately adjacent to the developed areas which are virtually certain of productive development, except where the geological information on the producing horizons insures continuity across the undrilled acreage.

The report adds that the estimates do not include oil that may become available by fluid injection or other methods from fields in which such operations have not yet been applied.

Each year's report presents data in each of the following classifications:

1. Estimate of proved reserves at the end of the preceding year.
2. Changes in proved reserves due to extensions and revisions during the subject year.

3. Proved reserves discovered in new fields and in new pools in old fields during the subject year.
4. Production during the subject year.
5. Proved reserves as of December 31 of the subject year. (Items 1 + 2 + 3 - 4)
6. Changes in reserves during the subject year. (Items 5 - 1)

Added reserves due to extensions and revisions (Item 2) each year are the order of 6 to 7 times the reserves due to new discoveries (Item 3).

The significance of the A. P. I. estimates of proved reserves can perhaps best be understood by considering a hypothetical field discovered in a given year. Suppose the field is destined, ultimately, to produce a total of 100 million barrels. Suppose that during the year of discovery only five wells were drilled. The proved reserve estimate would perhaps show:

Reserves added by extensions and revisions: None
Reserves due to new discovery: 150,000 barrels

For a number of years each successive year would then show sizeable reserve additions due to extensions and revisions, but none by new discoveries. Then, as the field approaches complete development, the changes due to extensions and revisions would diminish from one year to the next, ultimately to zero.

The sum of the reserves added, year by year, in this manner would ultimately equal the total amount of oil which the field will produce. This process mightcontinue, however, for thirty or forty years after the date of initial discovery. The reason is that, although the field may eventually produce 100 million barrels of oil, this amount of oil was not discovered at the date of discovery of the field; it was discovered only gradually as the field was developed.

The estimates of proved reserves for the whole United States have exactly the same significance. In fact, all the oil we can claim to have discovered in the United States up to the end of any given year is the total amount of oil already taken from the ground up to that date, the cumulative production, plus the proved reserves. We may call this quantity the "cumulative discoveries" up to that date; or, if one prefers, the "cumulative proved discoveries."

If we represent the cumulative production by the symbol Q_P, the cumulative proved discoveries by Q_D, and the proved reserves by Q_R, then for each year,

$$Q_D = Q_P + Q_R \tag{3}$$

The relation between rates of change of these quantities with time is obtained by taking the derivative with respect to time of equation (3), giving

$$\frac{dQ_D}{dt} = \frac{dQ_P}{dt} + \frac{dQ_R}{dt}, \tag{4}$$

in which dQ_D/dt is the rate of discovery, dQ_P/dt is the rate of production, and dQ_R/dt is the rate of increase of the proved reserves.

The manner in which the three quantities Q_D, Q_P, and Q_R must vary with time during the entire history of petroleum production from start to finish must be approximately as follows: The cumulative production Q_P, when plotted as a function of time, will increase slowly during the early stages of petroleum exploitation, increase more and more rapidly with time to about the halfway point, and then continue its ascent by rising more and more slowly, finally leveling off to the ultimate figure Q_∞ as production ceases.

The curve of proved reserves Q_R will start at zero, rise gradually until a maximum is reached at about the halfway point, and then gradually decline to zero.

As oil must be found before it can be produced, the curve of cumulative proved discoveries must closely resemble that of cumulative production, except that it must plot ahead of the production curve by some time interval Δt, which itself may vary during the cycle.

A plot of the family of the three curves Q_D, Q_P, and Q_R is shown in Figure 22 as they may be expected to appear in the case of cumulative production of crude oil in the United States. All present evidence indicates that the U. S. discovery and production is following a single growth cycle, rather than a multiple cycle like the State of Illinois which has two production peaks 30 years apart. One- and two-cycle growths are illustrated in Figure 23.

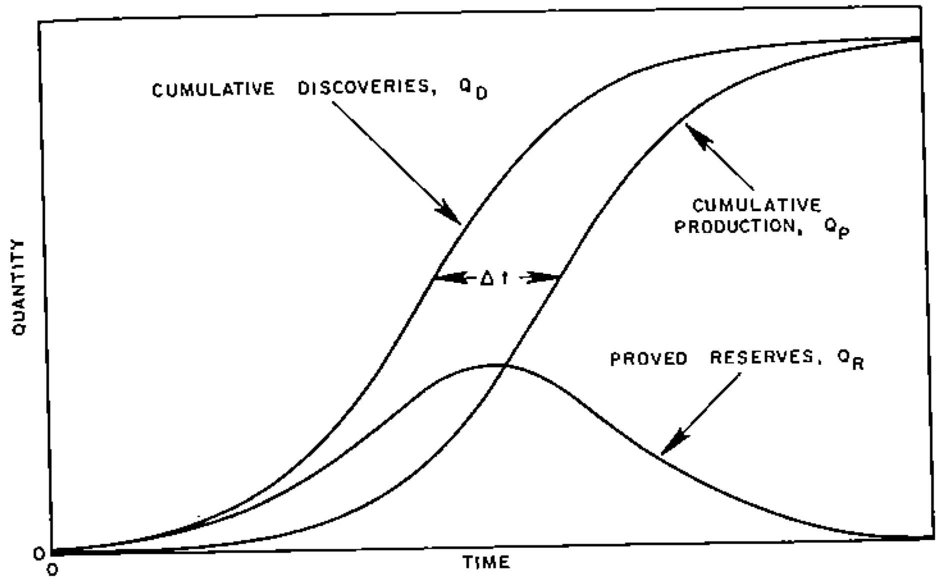

Figure 22. Cumulative Discoveries and Production and Proved Reserves

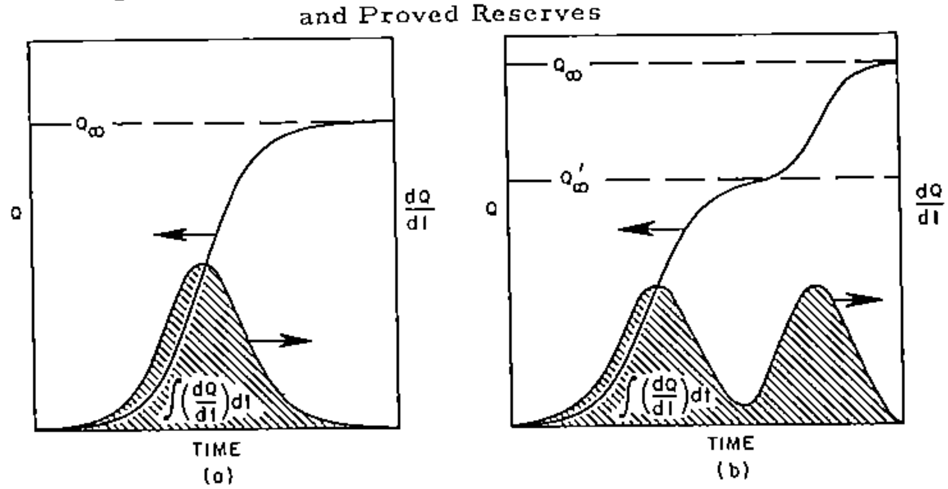

Figure 23. Growth Curves and Production Rates for Single- and Multiple-Cycle Developments

Because of the close similarity between the curve of cumulative proved discoveries and that of cumulative production, it follows that the study of the discovery curve must give one a preview of what production will do at a time of approximately Δt in the future.

Taking the time derivatives of the three curves shown in Figure 22 gives us the rate of discovery, rate of production, and rate of increase of proved reserves, which are plotted as a function of time in Figure 24. It will be noted that the rate of discovery will reach a peak at about mid-range and, thereafter, gradually

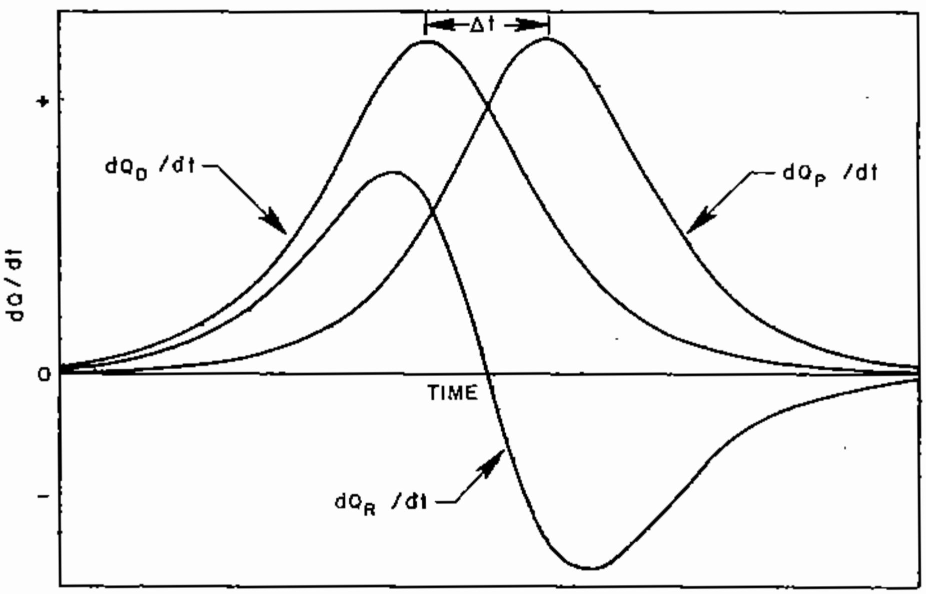

Figure 24. Rates of Discovery, Production and Change of Proved Reserves

decline to zero. The rate of production will reach a peak at a time about Δt after that of discovery, and the increase of proved reserves will change from positive to negative about halfway between the discovery and production peaks. The reserves themselves, Q_R, will reach a maximum at this same time.

The relations between the three curves at this mid-point can be seen by noting that when reserves reach their maximum value, their derivative

$$\frac{dQ_R}{dt} = 0 \qquad (5)$$

which, when inserted into equation (4), gives

$$\frac{dQ_D}{dt} = \frac{dQ_P}{dt}\,. \qquad (6)$$

This tells us that when reserves reach their maximum value the curves of discovery rate and production rate will cross, production going up and discovery going down. This is shown in Figure 24.

Observations

This is the theoretical framework in which we now propose to examine the crude-oil production data and proved-reserve data of the United States (excluding Alaska)*. Graphs of cumulative production Q_P, proved reserves Q_R, and cumulative proved discoveries Q_D for the United States are shown in Figure 25 (American Petroleum Institute, 1959, 1960, 1961, 1962). The curve for Q_D is the sum of the first two.

In order to obtain the approximate magnitude of Δt, we trace the Q_D curve on tracing paper and then translate it parallel to the time axis until the closest fit with Q_P is obtained. This is shown in Figure 26. Ten years is too small and 11 years is too large; the best fit is at about 10.5 years. Thus, since 1925 cumulative production in the United States has lagged discovery by the nearly constant interval of 10-11 years.

Growth phenomena such as those represented by the Q_D and Q_P curves, which start slowly, gradually accelerate, and finally level off to a maximum, are said to follow a logistic growth curve and are describable by an empirical equation of the form....

$$y = \frac{h}{1 + ae^{-bx}}, \qquad (7)$$

in which h, a, and b are parameters whose magnitudes are to be determined by the data, and e the base of natural logarithms. Adapting this equation to the data of Figure 25, we have for the curve of cumulative proved discoveries

$$Q_D = \frac{Q_\infty}{1 + ae^{-bt}} \qquad (8)$$

in which Q_∞ is the asymptotic value to which Q_D will tend as the time t becomes unlimitedly large.

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*In all subsequent discussions the petroleum data for the United States are to be understood to refer to the conterminous part of the United States, and to exclude Hawaii and Alaska, unless stated otherwise.

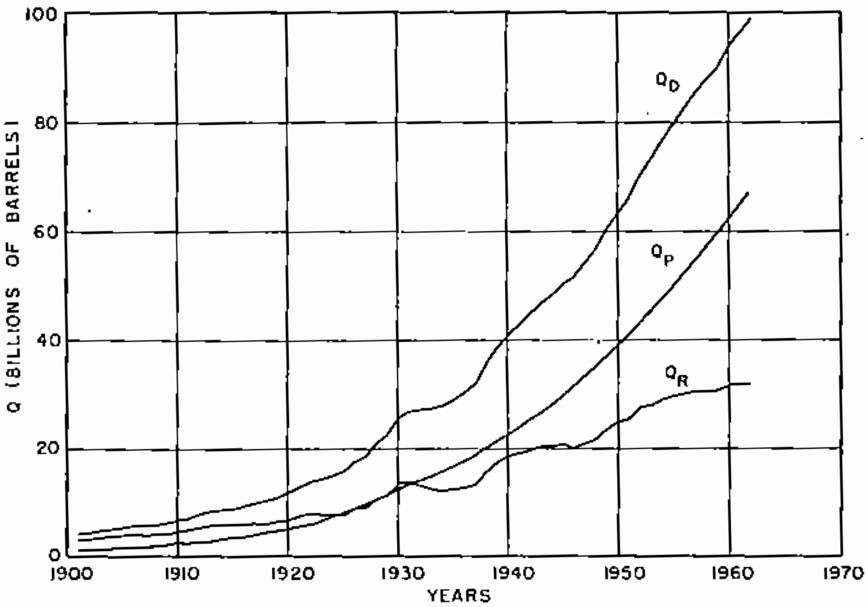

Figure 25. Cumulative Proved Discoveries and Production and Proved Reserves of U.S. Crude Oil

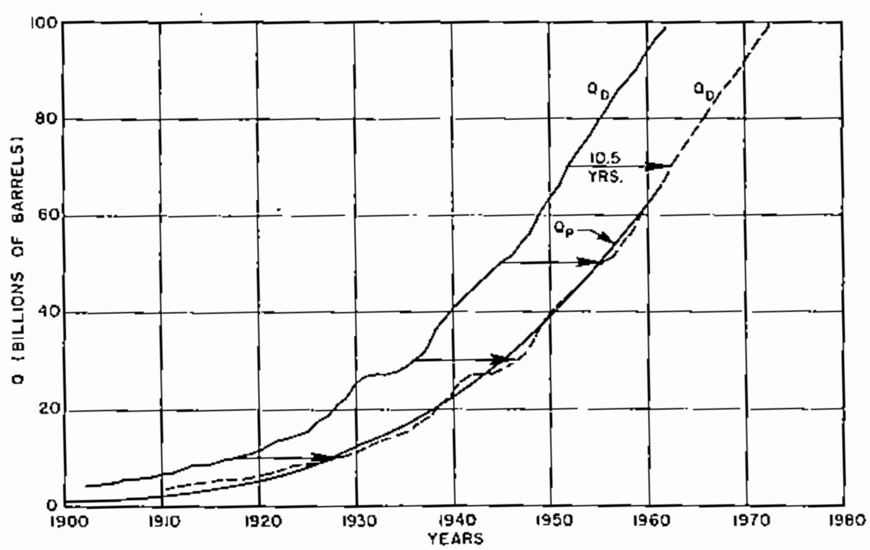

Figure 26. Time Lag Between Cumulative Proved Discoveries and Cumulative Production of U.S. Crude Oil

The best values of the parameters for the Q_D data can be determined by converting equation (8) to a linear form. By transposition

$$\frac{Q_\infty}{Q_D} - 1 = ae^{-bt}.$$

Then, by taking the logarithms of both sides, we obtain

$$\log [(Q_\infty/Q_D) - 1] = \log a - bt \log e, \qquad (9)$$

which is a linear equation between $\log [(Q_\infty/Q_D) - 1]$ and t.

The quantity $[Q_\infty/Q_D - 1]$ is then plotted as a function of time on semilogarithmic paper, using an assumed value of Q_∞. If the correct value is used for Q_∞, and if the data otherwise satisfy equation (8), the curve will be a straight line. By repeating this procedure, using several different values for Q_∞, it is possible to find the best value for this quantity. Then the other two parameters a and b can be obtained from the linear graph.

As determined in this manner, the increase of cumulative discoveries Q_D with time has been found to be approximated very closely by the equation

$$Q_D = \frac{170 \times 10^9 \text{ barrels}}{1 + 46.8\, e^{-0.0687\,(t - 1900)}}\,; \qquad (10)$$

and cumulative production Q_P by

$$Q_P = \frac{170 \times 10^9 \text{ barrels}}{1 + 46.8\, e^{-0.0687\,(t - 1910.5)}}\,. \qquad (11)$$

Analytically, the curve for Q_R is given by the difference between equations (10) and (11).

The results of these calculations and the closeness of the fit between the actual data for Q_D, Q_P and Q_R (shown in solid curves) and the computed curves (shown dashed) are presented graphically in Figure 27.

The discovery curve has plainly passed its inflection point at about 85 billion barrels, and this should be about the halfway point. This agrees with the asymptote of $Q_\infty = 170 \times 10^9$ barrels as given by the curves.

The significance of the cumulative production curve needs no particular discussion. It will simply level off to the maximum Q_∞ when production is finished. The discovery curve Q_D, however, merits further attention, because this curve is the embodiment of the results of all the improvements which have been made

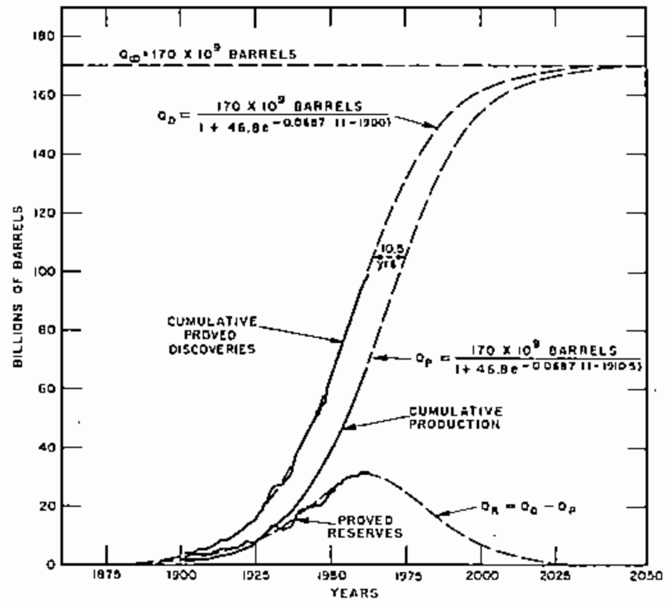

Figure 27. Cumulative Proved Discoveries and Production and Proved Reserves of U. S. Crude Oil

in discovery techniques, in drilling techniques, in recovery techniques, and all the oil added by geographical extensions within the United States and its offshore areas, since the beginning of the industry.

We thus do not have to worry about how much oil may be contained in known oil fields over and above the A. P. I. estimates of proved reserves, or how much improvement may be effected in the future in both exploration and productive techniques, for these will all be added in the future, as they have been in the past, by revisions and extensions in addition to new discoveries. And there is as yet no evidence of an impending departure in the future from the orderly progression which has characterized the evolution of the petroleum industry during the last hundred years.

In Figure 28 is shown the actual year-by-year plotting of the rates of discovery and of crude-oil production in the United States since 1900, on which have been superposed the analytically determined rates from equations (10) and (11). The rate of discovery, as is to be expected, oscillates rather widely from year to year, yet the data plainly indicate that the peak of the discovery rate occurred in the early or middle 1950's. The analytical-derivative

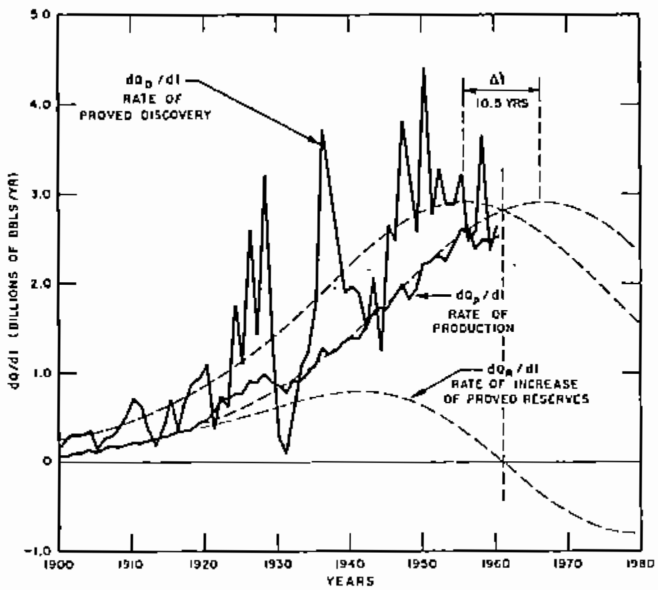

Figure 28. Rates of Discovery, Production and Increase of Proved Reserves of U. S. Crude Oil

curve places the date of this peak at 1956 and that for the production rate at about 1966-67. The analytical derivative of the curve of proved reserves crosses the zero point from increasing to decreasing reserves at about 1961-62, which should be the date of the peak of the proved reserves.

The rate of increase of proved reserves is shown in detail in Figure 29. Here, superposed on the actual data is the rate curve (shown dashed) as determined analytically. Here again, although the reserve additions oscillate widely from year to year, it will be seen that the analytical curve follows faithfully the trend of the actual data.

A composite view on a longer time scale of the rates of discovery and production and the increase of proved reserves is given

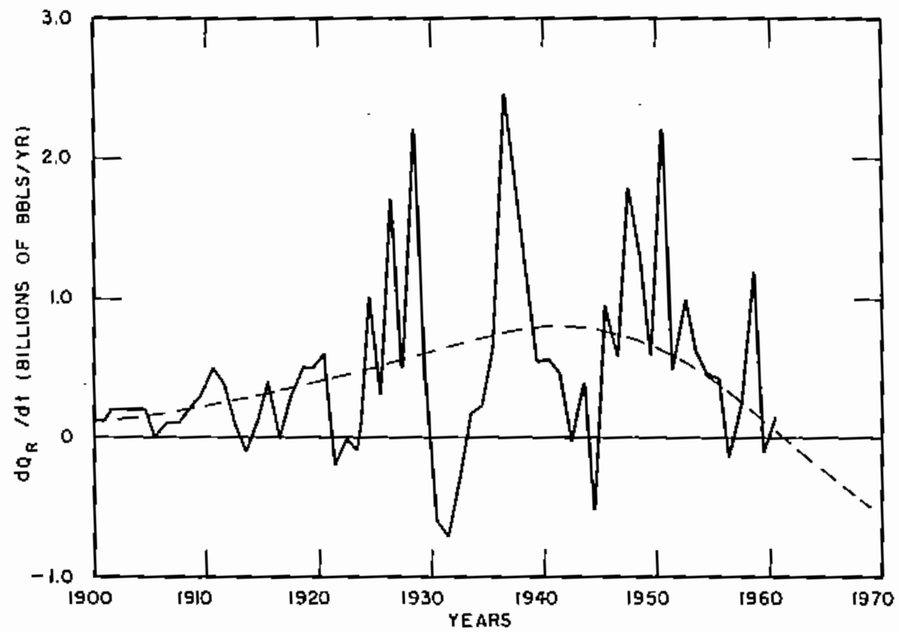

Figure 29. Rate of Increase of Proved Reserves of U.S. Crude Oil

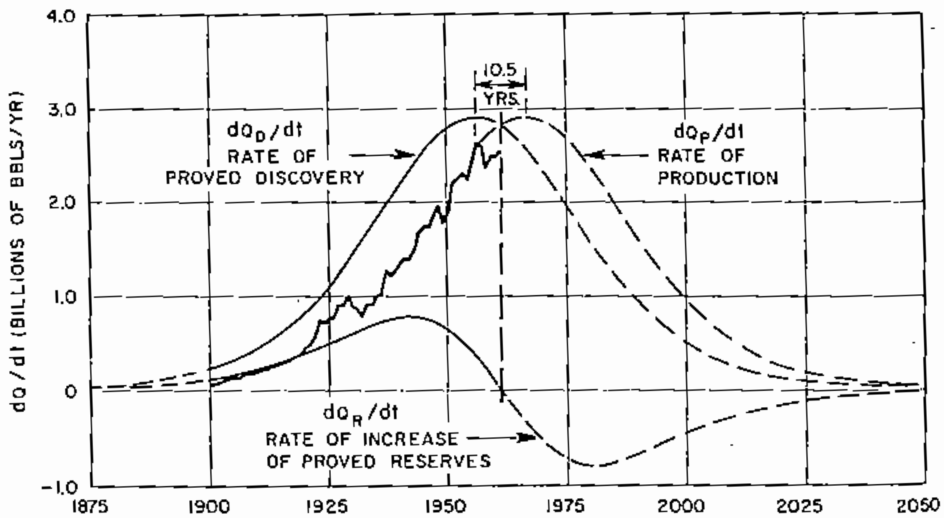

Figure 30. Rates of Discovery, Production and Increase of Proved Reserves of U.S. Crude Oil

in Figure 30. From the evolution which has occurred up to now it is difficult to escape the conclusion that the petroleum industry in the United States is somewhere near the halfway point in its exploration for and production of crude oil. By the end of 1961 the cumulative production of crude oil had reached 67.37 billion barrels, and proved reserves were estimated at 31.76 billion barrels, from which the cumulative proved discoveries amounted to 99.1 billion barrels.

However, the peak rate of discovery occurred about 6 to 7 years previously, at about 1956; proved reserves appear to be very nearly at their maximum in 1962; and the peak of production is expected to occur by about 1967 or earlier. Unless the evolution of the industry departs radically in the future from the orderly progression it has followed for the last hundred years, the most probable estimate that can now be derived from past experience for the ultimate cumulative production of crude oil is about 170 billion barrels.

With regard to the date of the peak of crude-oil production, mention should be made of a minor qualifying circumstance. Due in large measure to petroleum imports, which have been building up since World War II and now amount to approximately 20 per cent of domestic production, the present rate of production is somewhat less than full capacity. According to a recent report of the National Petroleum Council (1961, Table IV), the total crude-oil production capacity of the United States, excluding Elk Hills shut-in capacity, was 10.422 million barrels per day, or 3.8 billion barrels per year, in 1960. This figure for capacity assumes that all wells are operating at capacity, independently of whether pipelines and storage facilities could handle the production at this rate. Actual production for the year 1960 was 2.47 billion barrels.

This discrepancy between the actual rate of production and a hypothetical maximum productive capacity, therefore, allows some latitude in the exact year at which the peak of production could occur. Conceivably, if, for some reason comparable to the Suez Crisis, the production were to be at the maximum capacity for some given year, then in whatever year this may have occurred between 1962 and possibly 1975 the peak of production could occur. This possibility, however, is largely irrelevant with respect to the present analysis, in which only long-term secular changes, rather than the fluctuations which occur from year to year, are the subject of concern.

The real significance of the curtailment of U.S. production is that it conserves the domestic reserves of crude oil and thus tends to postpone the date of the production decline due to diminishing reserves of oil. Had there been no imports and had the domestic industry been operating at capacity ever since World War II, the oil that has been imported would have had to be replaced by oil from domestic reserves. This would have advanced the peak date of production with respect to that which is now anticipated.

Verification by Means of Data on Large and Small Fields

An independent check on whether Q_{∞}, the ultimate cumulative production of crude oil in the United States, is of the order of 170 billion barrels is afforded by a study of the large and small fields separately. Since 1943 the Oil and Gas Journal, in its Review-Forecast number which is issued annually about the last week in January, has been publishing statistics on the oil fields in the United States in which the large or so-called "giant" fields have been segregated for special attention. These are defined as those fields whose ultimate production is estimated to exceed 100 million barrels. All other fields are classed as small fields.

In the January 29, 1962 issue of this Journal, on page 135, the following data are given for all the oil fields in the United States:

Number of giant fields	240
Estimated ultimate production:	
All fields	103.26×10^9 barrels
Giant fields	59.22×10^9 barrels
Percent by giant fields	57.4

From this information, the average size of the large fields is found to be 0.247×10^9 barrels.

The number of small fields was not given, but a few years ago an independent estimate was made of the cumulative number of such fields which had been discovered by the end of 1957. This was about 12,000, and about 3,000 more have been discovered subsequently, giving a total by the end of 1961 of about 15,000

A table on the discovery rate of all fields up to 1959 is given by B. W. Blanpied (1959, p. 1130-1131). Of these, all but an insignificant fraction are small fields. These two results, the cumulative number of small fields discovered, and the number discovered per year, are shown graphically in Figure 31. The same data with longer time scale are shown in Figure 32. The peak in the discovery rate occurred in 1955, when the total number of smal' fields was 10,000. Assuming that this peak represents about the halfway point in small-field discovery, then the ultimate number of small fields is estimated to be about 20,000.

The ultimate liquid hydrocarbons credited by the *Oil and Gas Journal* to the then discovered small fields by the end of 1955 was 36.5 billion barrels (*Oil and Gas Journal*, January 30, 1956, p. 179), of which the crude-oil content would be about 85 per cent, or 31.0×10^9 billion barrels. Then assuming that this represents about half the ultimate for all the small fields we obtain an estimate of 62.0 billion barrels of crude oil as the ultimate production of all the small fields including those still to be discovered.

A corresponding ultimate figure for the large fields could be obtained if we could estimate how many big fields are likely ultimately to be discovered. This should be a particularly significant figure since, despite their small number, the large fields account for nearly 60 per cent of all the oil so far discovered in the United States. The ultimate number of large fields, $\underline{N}_\infty$, which can hardly be larger than a few hundred, is the quantity we now seek to determine.

The obvious way to do this is simply to enumerate the fields, giving them the serial numbers 1 to 240 in the order of their dates of discovery, and then plot the curve of the number $\underline{N}$ as a function of the dates of discovery, to see whether evidence of the approach to an ultimate number $\underline{N}_\infty$ can be detected. This has been done in Figure 33, and the curve for the fields listed in the January 1962 issue appears to be approaching an ultimate number of about 250.

That this is a false conclusion can be seen by the curve of analogous data as of December 31, 1951, also shown in Figure 33. This curve appears to have an asymptote, or limiting value, at a number of about 175 fields. Thus, it will be noted that these curves increase not only longitudinally as ordinary growth curves do, but they also skid sidewise.

While this may be unexpected, the reason for it is simple. For an ordinary growth curve, such as that of cumulative production, the data for each successive year are added to the curve

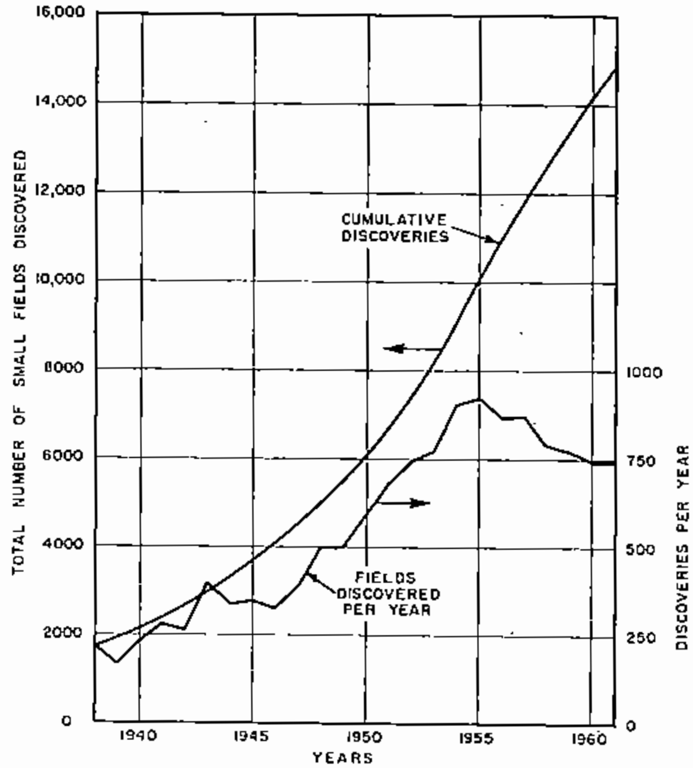

Figure 31. Cumulative Discoveries and Rate of Discovery of U. S. Small Fields, 1938-1961

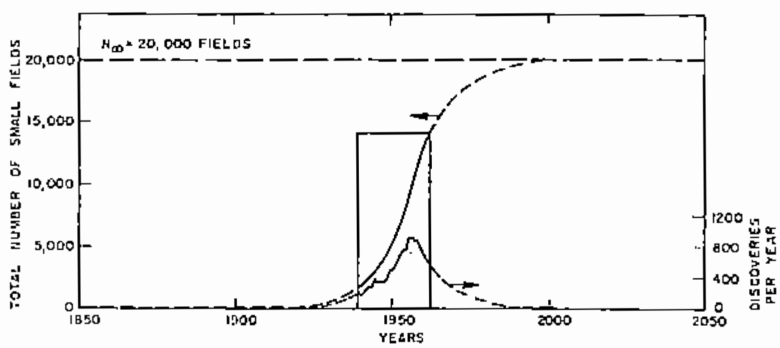

Figure 32. Long-Time Outlook for Discovery of Small Oil Fields in the U. S.

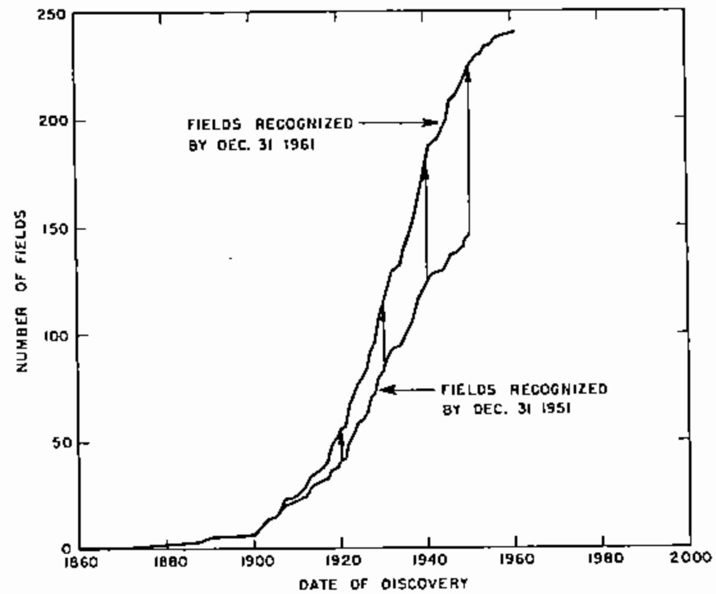

Figure 33. Large U.S. Oil Fields Recognized by December 31, 1951 and December 31, 1961

only at its extremity. For the large fields, however, each field has two separate dates, a date of discovery (when the field is classified as small) and a date of recognition as a large field. In other words every field which ultimately becomes a large field must go through an embryo, or incubation, stage as a small field before it ultimately hatches out as a large field. The first date is the date of discovery; the second is the date of recognition as a large field.

The fallacy involved in plotting the fields by dates of discovery lies in the fact that they cannot be plotted until after recognition, which may be years or decades after discovery. Thus, when a field discovered in 1945 is not recognized as a big field until 1961, then inserting it into the curve at 1945 displaces the whole curve up by 1 point from 1945 onward. The repetition of this process for each field added produces the behavior shown in Figure 33.

However, if the fields are plotted by dates of recognition only, as is shown in Figure 34, the curve behaves as any growth-curve should. The false asymptote is missing and the curve has the appearance of being about halfway to its true asymptote. The logistic equation for this curve is

$$\dot{N} = \frac{460 \text{ fields}}{1 + 110\, e^{-0.078\,(t - 1900)}} \, . \tag{12}$$

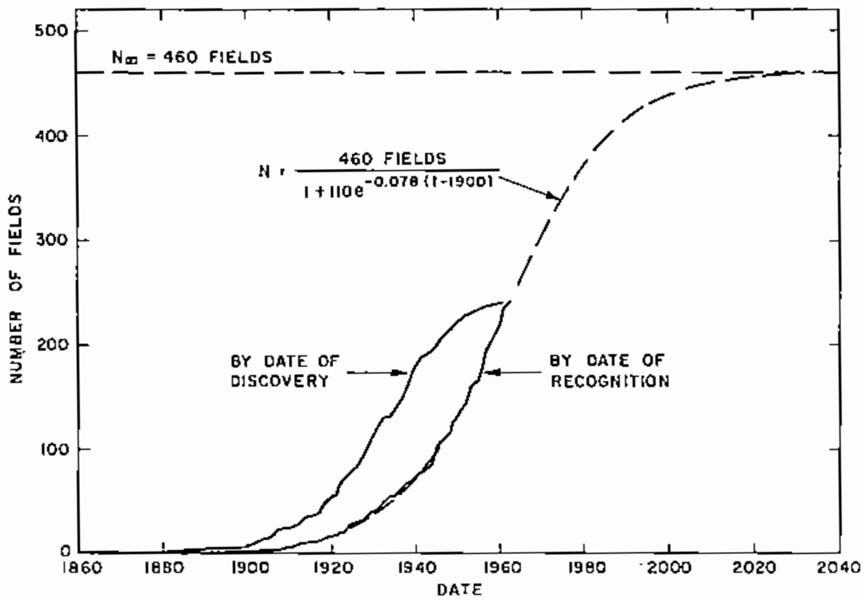

Figure 34. Large U. S. Oil Fields Plotted by Date of Discovery and by Date of Recognition

We may, accordingly, either limit our analysis to the curve of the number of large fields plotted by their dates of recognition, or we may attempt, in addition, to estimate the limiting position of the curve plotted by dates of discovery after all the large fields have been discovered and recognized.

This can be done approximately by investigating the statistical nature of the time delay, τ , defined as

$$\tau = t_r - t_d \tag{13}$$

where t_r is the time of recognition and t_d the time of discovery of a given large field. A curve of the number of fields plotted cumulatively against increase time-delay τ for a sample of 186 fields, excluding fields discovered after 1940, is shown in Figure 35. It is clearly seen that the cumulative number of fields as a function of τ is represented very closely by the equation

$$n = n_\infty (1 - e^{-0.046\,\tau}), \tag{14}$$

where $\underline{n}_\infty$ is the asymptotic number for the sample. Expressing the number of fields as a fraction of this asymptotic number we have

$$\frac{n}{n_\infty} = \frac{n}{206} = (1 - e^{-0.046\tau}), \qquad (15)$$

which is shown graphically in Figure 36. From this it will be seen that about half the large fields have time delays between discovery and recognition of more than 15 years.

The advantage of this time-delay curve is that it permits us to apply a correction to the number of fields discovered in any given year that have been recognized by some definite later date. For example, suppose that by December 1961 $\Delta \underline{N}$ fields discovered in 1946 have been recognized. As the time delay from 1946 to 1961 is 15 years, then according to Figure 36 only about half the fields discovered in 1946 should have been recognized by 1961. We therefore estimate that of all the large fields discovered in 1946 which will ultimately be recognized as large fields, only about half were recognized by 1961. We accordingly apply the correction

$$\Delta N' = 2\Delta N .$$

An analogous procedure is followed for each year prior to 1961 with τ equal successively to 1, 2, 3, ... $\underline{n}$ years. The $\Delta \underline{N}'$ are then integrated into a new curve which should represent, approximately, the cumulative number of large fields ultimately to be recognized, plotted by dates of discovery.

The results of such a computation applied to the data of December 31, 1961, are shown in Figure 37. The lower solid-line curve shows the fields already recognized by dates of discovery, and the upper solid-line curve shows the fields probably already discovered by the end of 1961 which will ultimately be recognized as large fields. The difference between the two curves represents the embryo large fields probably already discovered, but not yet recognized.

The logistic equation for the revised number of fields by dates of discovery shown in Figure 37 is

$$N = \frac{460 \text{ fields}}{1 + 5.0\, e^{-0.0856\,(t\,-\,1920)}} . \qquad (16)$$

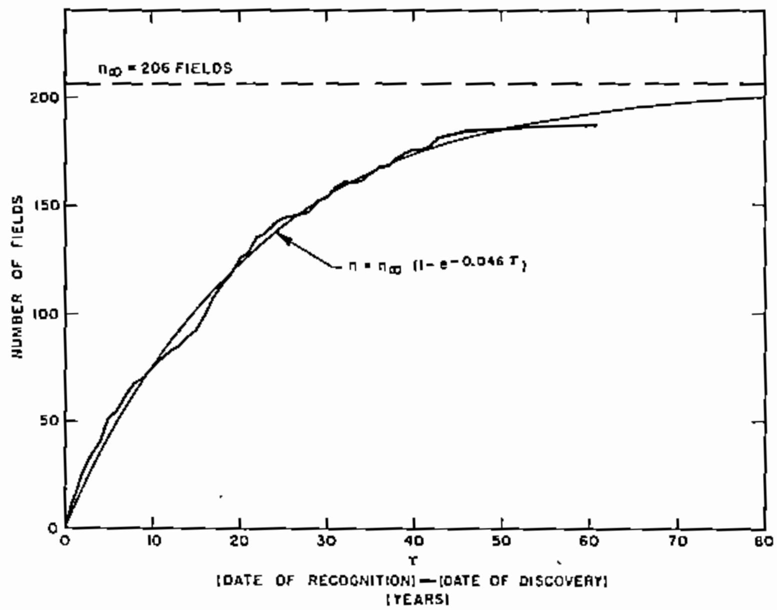

Figure 35. Time Lag Between Discovery and Recognition of U. S. Large Fields (Fields Discovered Since 1940 Excluded)

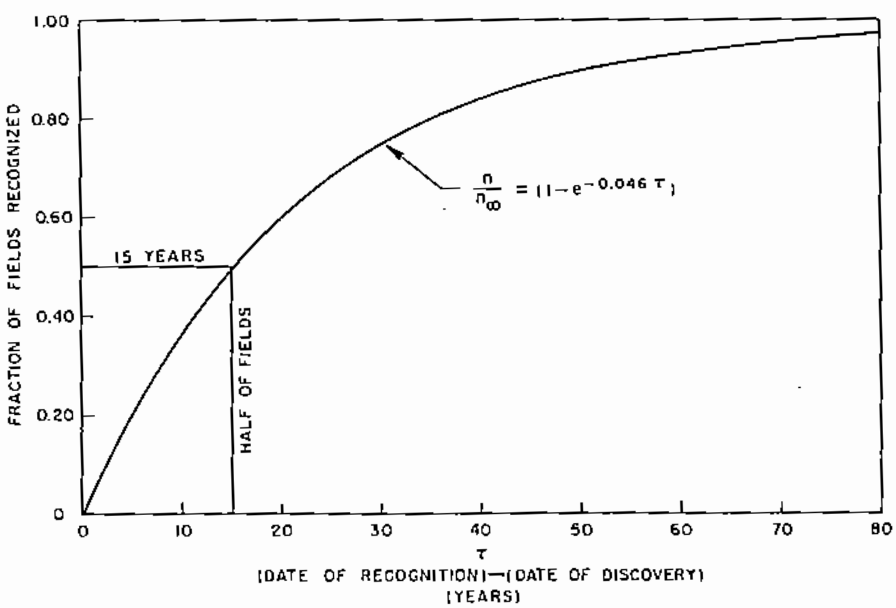

Figure 36. Fraction of U. S. Large Fields Recognized Within Time-Delay τ After Discovery

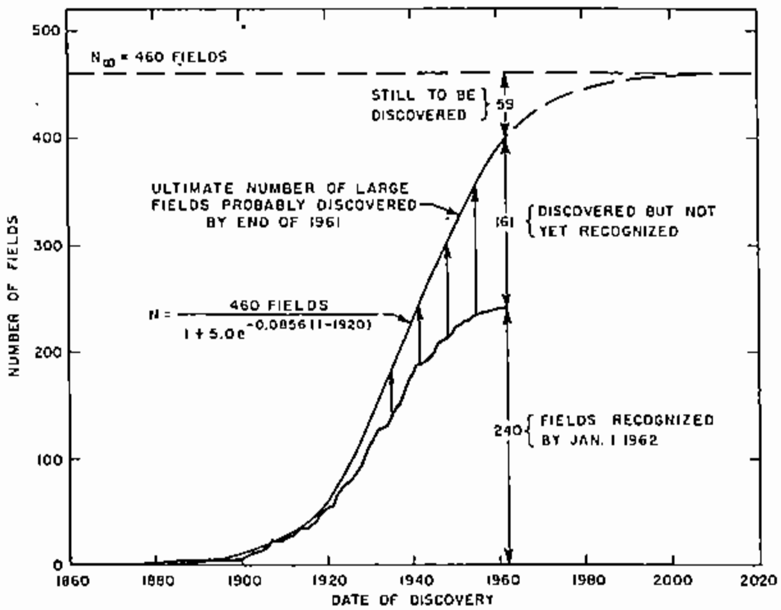

Figure 37. Cumulative Discoveries of Recognized and Probable U.S. Large Fields

It therefore appears from the data on both the number of large fields plotted by date of recognition, and the revised curve on the probable fields by date of discovery, that the ultimate number of large fields is about 460. Of these, as it will be seen from Figure 37, about 401 have probably already been discovered, leaving about 59 still to be discovered. Of the 401 fields already discovered 240 have already been recognized by the end of 1961, and about 161 are in the incubation stage as small fields which with further development will eventually become large fields.

Average Size of Large Fields

It has already been pointed out that according to the estimate of the Oil and Gas Journal the average size of the 240 large fields of December 31, 1961, is 0.247×10^9 barrels, or about one-quarter of a billion barrels.

Figure 38 shows the average size of successive groups of 25 large fields each in the order of discovery. This indicates that there is little ground to expect the average size of the large fields in the future to be very different from that of the past. Assuming,

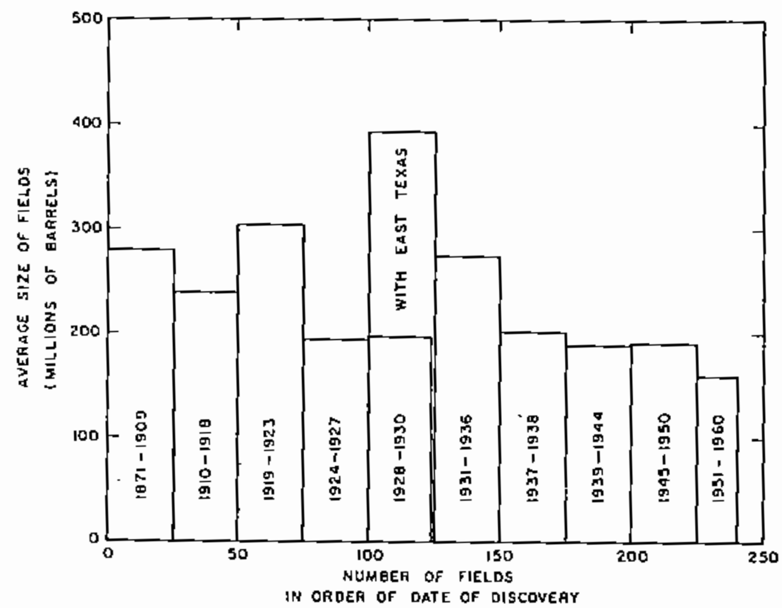

Figure 38. Average Size of Large Fields in the U. S. in Order of Dates of Discovery

then, a constant average size, the ultimate amount of crude oil expectable from 460 large fields should be about 113×10^9 barrels.

If we now add the 62×10^9 barrels for the small fields to the 113×10^9 barrels for the large fields, we obtain an estimate for the total ultimate production of crude oil in the United States of 175×10^9, or 175 billion, barrels.

The method of estimation based on the use of the Oil and Gas Journal data for the large and small fields is not considered to have as high a reliability as that using the growth curves. It is nevertheless considered to be valid as to order of magnitude, and to this extent it corroborates the estimate of 170 billion barrels obtained previously. As a contingency, however, we shall adapt the higher figure of 175 billion barrels as representing our present estimate of the ultimate potential reserve of crude oil in the United States. Of this, 67 billion barrels have already been produced, and 99 billion barrels (including that already produced) have already been discovered, leaving about 76 billion barrels still to be discovered.

If a contingency allowance were to be made of how much the actual figure of Q_∞ might exceed the present estimate of 175 billion barrels, a figure higher than an additional 50 billion would be hard to justify.

Should the future of 175 billion barrels be approximately correct, the future crude-oil production of the United States would have to follow a curve closely resembling that shown in Figure 39.

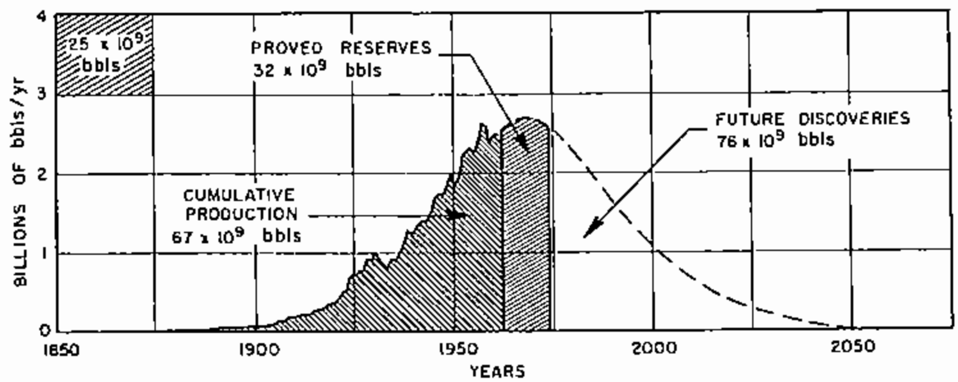

Figure 39. Estimate of Ultimate U. S. Production of Crude Oil

In this figure one grid rectangle represents 25 billion barrels of oil. The total area under the curve from start to finish could, therefore, comprise only 7 rectangles, and the culmination in the rate of production should occur in the late 1960's. If the figure of 225 billion barrels (including the 50 billion-barrel contingency allowance) should be more nearly correct, then the curve would encompass an area of 9 grid rectangles and the culmination would occur in the early 1970's.

Ultimate Potential Crude-Oil Reserves of the World

Using the United States estimate as a yardstick, we may now give an approximate estimate of the ultimate potential crude-oil reserves of the world. This is shown for the major geographical and political subdivisions of the world in Table 6. This is obtained by using Weeks' (1948) estimate as a base and then applying modifications which subsequent developments indicate to be necessary. The same data are shown graphically in Figure 40. The total world estimate comes to 1, 250 billion barrels, of which 850 is for land areas and 400 is allowed for the offshore areas.

Of particular interest is the preponderance of the reserves of the Middle East and North Africa (300 billion barrels) over

TABLE 6

Estimated Ultimate World Crude-Oil Production

Area	Ultimate Recovery ($\times 10^9$ bbls)	Percent of World Total
United States (including offshore)	175	14.0
Remainder of North America	45	3.6
South America	80	6.4
Europe (excluding U.S.S.R.)	13	1.1
U.S.S.R.	200	16.0
Middle East and North Africa	300	24.0
Indonesia	30	2.4
Australia	3	0.2
Remainder of Asia	24	1.9
Offshore areas (excluding U.S.)	380	30.4
World Total	1,250	100.0

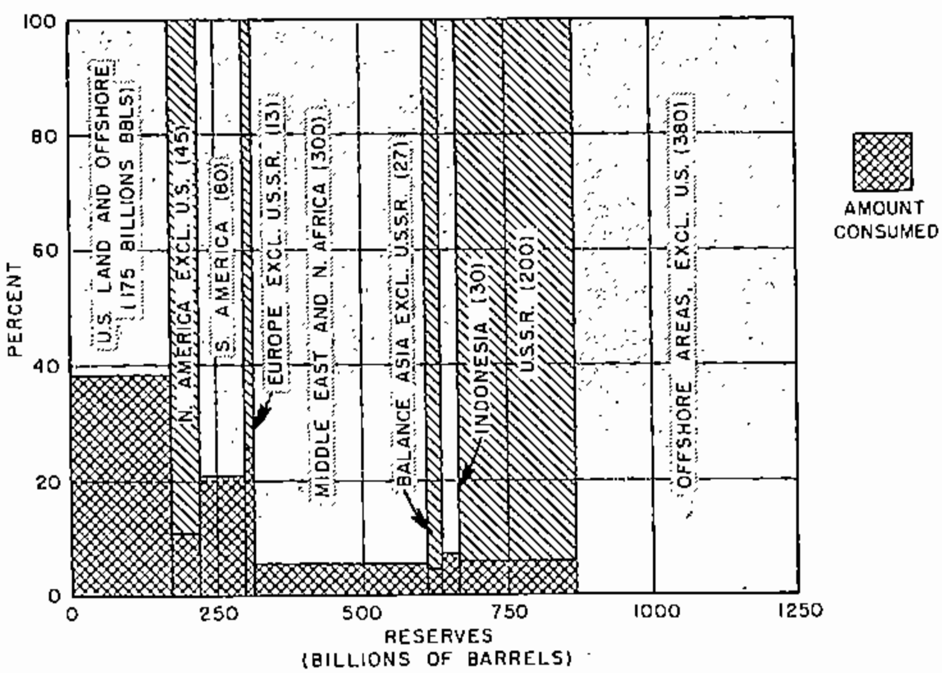

Figure 40. World Ultimate Potential Petroleum Reserves

those of any other geographical region of comparable area. Also, it is to be noted that because the United States was the world's largest producer of crude oil for nearly a century, it is also the farthest advanced toward ultimate depletion of any of the major oil-producing areas.

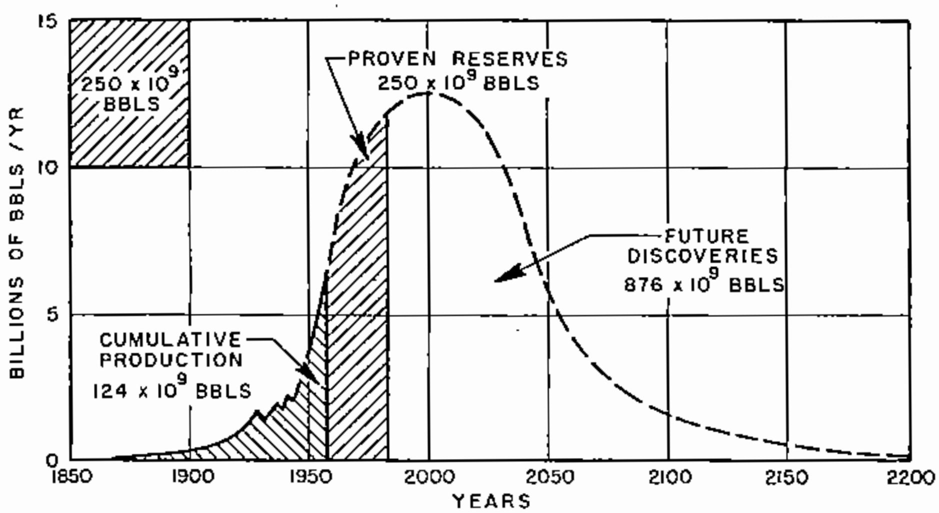

Figure 41. Ultimate World Production of Crude Oil

A curve of the ultimate world production is shown in Figure 41. Using 1,250 billion barrels as the ultimate potential reserve, and assuming a peak rate of production of 12.5 billion barrels per year—about twice the present production rate—the culmination of world production should occur about the year 2000 A.D.

United States Production and Ultimate Reserves of Natural Gas

The production rate of marketed natural gas in the United States has already been shown in Figure 13. Because pipelines for long-distance transmission of natural gas have only become available since World War II, the consumption of gas in the United States has reached a relatively less advanced state toward ultimate depletion than crude oil. It is, accordingly, not yet possible to estimate the ultimate asymptote of the curves of cumulative production and cumulative proved discoveries for natural gas, as was done for crude oil.

The next best procedure is to make use of the fact that natural gas and crude oil are genetically related, and then to base the estimate of the ultimate amount of natural gas on that of the ultimate amount of crude oil, using the observed ratio of gas to oil. It follows that the estimates of the ultimate potential reserves of gas obtained in this manner will vary, percentagewise, about as widely as the estimates of the reserves of crude oil. This is

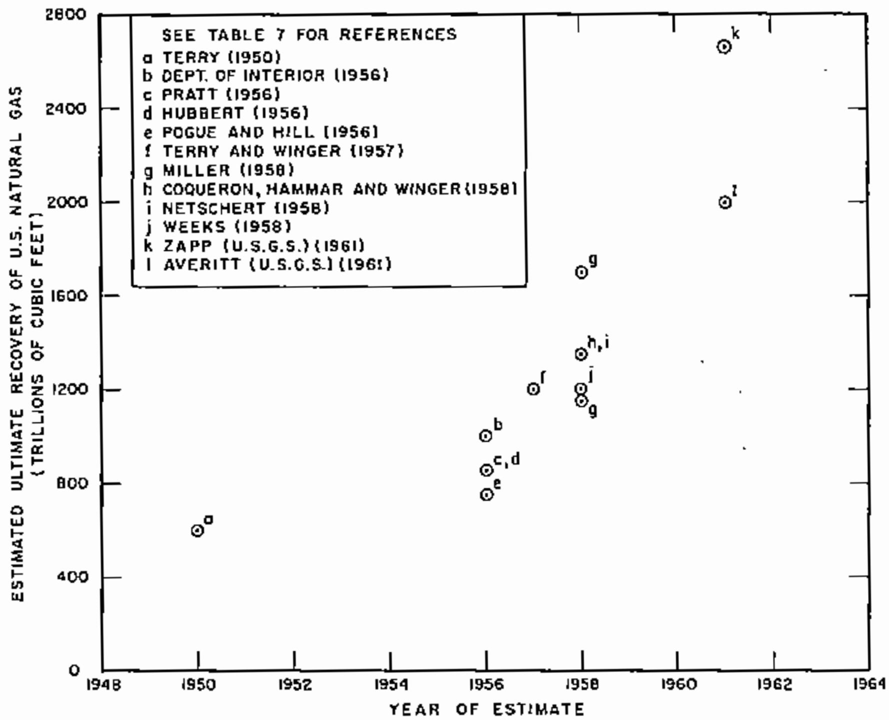

Figure 42. Estimates of Ultimate Recovery of U. S. Natural Gas

borne out by Figure 42 in which the principal published estimates since 1950 are presented. These estimates range from a low value of 600 trillion cubic feet by Terry (1950) to a high value of 2,650 trillion cubic feet by Zapp (1961) of the United States Geological Survey.

The remarks made earlier with regard to published estimates of the ultimate reserves of crude oil apply equally to those for natural gas. Regardless of what the correct value for the ultimate gas reserves may be, most of the published estimates are seriously erroneous.

TABLE 7

Estimated Ultimate U. S. Natural-Gas Reserves

	Date	Author	Estimate (Barrels)
a	1950	Terry	600×10^{12}
b	1956	Dept. of Interior	$1{,}000 \times 10^{12}$
c	1956	Pratt	850×10^{12}
d	1956	Hubbert	850×10^{12}
e	1956	Pogue and Hill	750×10^{12}
f	1957	Terry and Winger	$1{,}200 \times 10^{12}$
g	1958	Miller	$1{,}150 \times 10^{12}$ $-1{,}700 \times 10^{12}$
h	1958	Coqueron, Hammar and Winger	$1{,}350 \times 10^{12}$
i	1958	Netschert	$1{,}350 \times 10^{12}$
j	1958	Weeks	$1{,}200 \times 10^{12}$
k	1961	Zapp (U.S.G.S.)	$2{,}650 \times 10^{12}$
l	1961	Averitt (U.S.G.S.)	$2{,}004 \times 10^{12}$

a Terry, Lyon F., 1950, The Future Supply of Natural Gas Will Exceed 500 Trillion Cu. Ft.: Gas Age, October 26, p. 98.

b Interior, Dept. of, 1956, Impact of the Peaceful Uses of Atomic Energy on the Coal, Oil- and Natural-Gas Industries: Background Material for the Report of the Panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, v. 2, January, p. 83.

c Pratt, Wallace E., 1956, The Impact of the Peaceful Uses of Atomic Energy on the Petroleum Industry: Background Material for the Report of the Panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, v. 2, January, p. 94.

d Hubbert, M. King, 1956, Nuclear Energy and the Fossil Fuels: Drilling and Production Practice, Am. Petroleum Inst., p. 18.

e Pogue, Joseph E., and Hill, Kenneth E., 1956, Future Growth and Financial Requirements of the World Petroleum Industry: New York, The Chase Manhattan Bank, Petroleum Dept., p. 26.

f Terry, Lyon F., and Winger, John G., 1957, Sees 1,200 Trillion Cu. Ft. U. S. Recoverable Gas: Am. Gas Assoc. Monthly, July-August, p. 12.

g Miller, Ralph L., 1958, A New Look at Ultimate Natural Gas Reserves: World Oil, v. 147, October, p. 222.

h Coqueron, Frederick G., Hammar, Harold D., and Winger, John G., 1958, Future Growth of the World Petroleum Industry: New York, The Chase Manhattan Bank, Petroleum Dept., p. 34.

i Netschert, Bruce C., 1958, The Future Supply of Oil and Gas: Baltimore, Resources for the Future, Inc., Johns Hopkins Press, p. 93.

j Weeks, L. G., 1958, Fuel Reserves of the Future: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 436.

k Zapp, A. D., 1961, World Petroleum Resources, Table 1 in Domestic and World Resources of Fossil Fuels, Radioactive Minerals, and Geothermal Energy: Preliminary Reports Prepared by Members of the U. S. Geological Survey for the Natural Resources Subcommittee of the Federal Science Council.

l Averitt, Paul, 1961, Coal Reserves of the United States—A Progress Report January 1, 1960: U. S. Geol. Survey Bull. 1136, p. 101.

For our own estimate we shall take our figure of 175 billion barrels of crude oil as a base, and then apply the ratios of gas to oil obtained from petroleum-industry experience. One aspect of this experience is shown in Figure 43. Here a graph is shown of the ratio of cumulative proved discoveries of natural gas to the

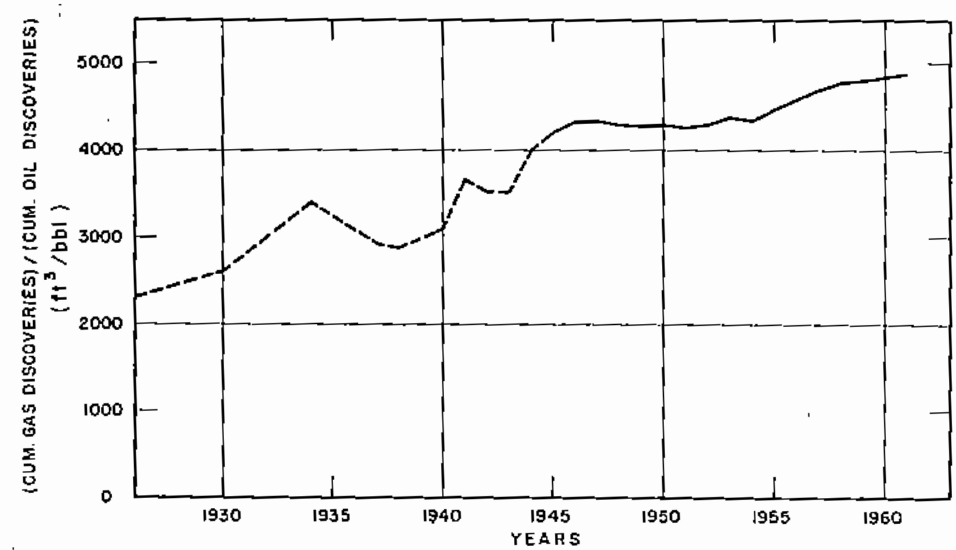

Figure 43. Gas-Oil Ratios for U. S. Based on Cumulative Discoveries of Oil and Gas

cumulative discoveries of crude oil in the United States for each year from 1925 to 1961. It will be seen that the gas-oil ratio gradually increased during this period from about 2,200 ft^3/bbl in 1925 to about 4,900 in 1961. Although this ratio is still increasing, it is probably too low, because of the large volumes of gas dissipated without any record during the history of the petroleum industry prior to World War II. A more reliable ratio should, therefore, be obtained from the gas and oil discovered during recent decades. In Figure 44 is shown a five-year running average of the ratio of the gas discovered per year to the oil discovered per year for each year from 1941 to 1961. The curve fluctuates between a low value of 4,000 ft^3/bbl and a high value of 10,000 ft^3/bbl, but without any pronounced secular trend. The average value for the 20-year period is 6,250 ft^3/bbl.

The figure of 6,250 ft^3/bbl represents the average gas-oil ratio for very large samples of gas and oil taken near the mid-range of the industry's history at a time when particular stress has been placed on exploration for gas. It does not appear likely, therefore, that this ratio will increase by a great deal in

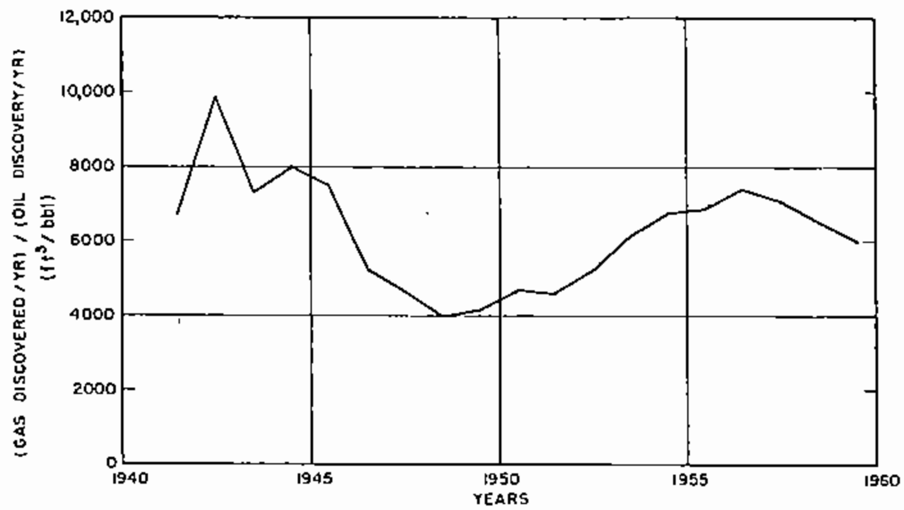

Figure 44. Gas-Oil Ratios for U.S. Based on Annual Discoveries (5-Year Running Average)

the future. However, as a contingency, let us assume that the ratio of gas to oil for future discoveries may be as high as 7,500 ft^3/bbl.

These two gas-oil ratios, a low of 6,250 ft^3/bbl and a high of 7,500 ft^3/bbl, will accordingly be used for a low and a high estimate of the ultimate reserves of natural gas in the United States.

Using these two ratios, and the estimate of the ultimate crude-oil production of 175×10^9 barrels, we obtain the corresponding estimates of the ultimate reserves of natural gas in the following manner:

Estimated ultimate production of crude oil	175.0×10^9 bbls
Cumulative discoveries of crude oil to 12-31-61	$- 99.1 \times 10^9$ bbls
Undiscovered reserves of crude oil, 12-31-61	75.9×10^9 bbls

Ultimate Reserves of Natural Gas

	Minimum Estimate	Maximum Estimate
Undiscovered crude oil	75.9×10^9 bbls	75.9×10^9 bbls
Gas-oil ratio	$\times$ 6,250 ft^3/bbl	$\times$ 7,500 ft^3/bbl
Undiscovered nat. gas	474×10^{12} ft^3	569×10^{12} ft^3
Cum. disc. nat. gas	$+ 484 \times 10^{12}$ ft^3	$+ 484 \times 10^{12}$ ft^3
Ultimate potential reserves nat. gas	958×10^{12} ft^3	$1,053 \times 10^{12}$ ft^3
Average	$\approx$ $1,000 \times 10^{12}$ ft^3	

We accordingly adapt the round figure of $1,000 \times 10^{12}$ ft^3, which is very nearly the arithmetical mean between our low and high estimates, as our present best estimate of the ultimate reserves of natural gas in the United States.

Using the asymptote of $1,000 \times 10^{12}$ ft^3 for the curves of cumulative proved discoveries and cumulative production of natural gas, we are then able to evaluate the logistic equations for these curves. The curve of cumulative production is obtained for the period from 1859 to 1917 from that of crude oil by assuming the production of 2,000 ft^3 of gas per barrel of oil. From 1917 to 1961 actual gas-production statistics are used (Dept. of Commerce, 1949, p. 146; 1954, p. 20; 1953-1961). Estimates of proved reserves of natural gas have been made annually by the Reserves Committee of the American Gas Association since 1945 (American Gas Association, 1945-1961). The addition of cumulative production and proved reserves from 1945 to 1961 then gives that portion of the curve of cumulative proved discoveries.

The logistic equations for cumulative discoveries and cumulative production, respectively, are then found to be

$$Q_D = \frac{1,000 \times 10^{12} \text{ ft}^3}{1 + 465 \, e^{-0.0793 (t - 1884)}} , \tag{17}$$

and

$$Q_P = \frac{1,000 \times 10^{12} \text{ ft}^3}{1 + 465 \, e^{-0.0793 (t - 1900)}} . \tag{18}$$

As heretofore, the equation for the proved reserves $\underline{Q_R}$ is the difference between those for $\underline{Q_D}$ and $\underline{Q_P}$.

This family of curves is shown in Figure 45. It will be noted that in this case the time lag Δt between the curve of cumulative discoveries and cumulative production is about 16 years as compared with the 10-11-year lag for crude oil. This is due principally to the fact that a large backlog of proved reserves of natural gas was being accumulated before the present large pipelines for gas distribution were put into operation.

The time derivatives of the family of curves in Figure 45 are shown in Figure 46. These represent, respectively, the rate

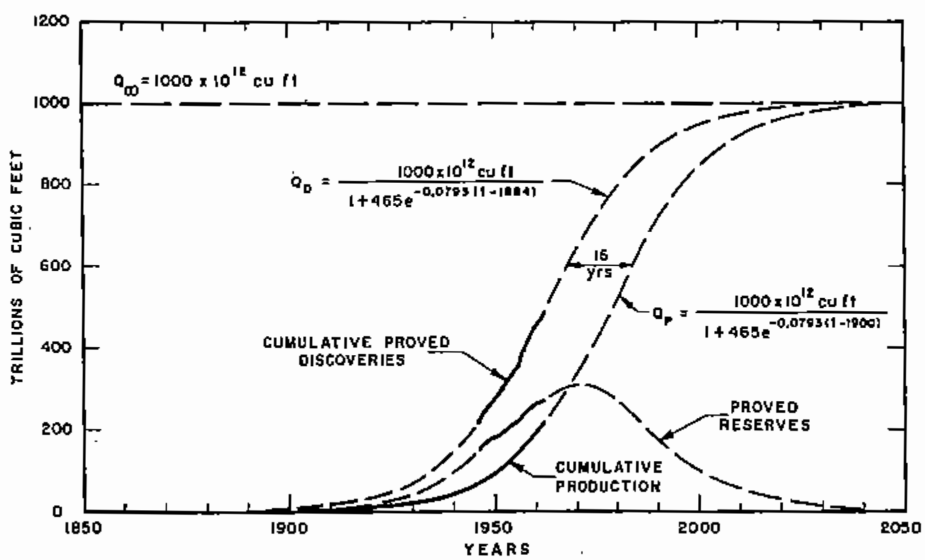

Figure 45. Cumulative Discovery and Production and Proved Reserves of U. S. Natural Gas

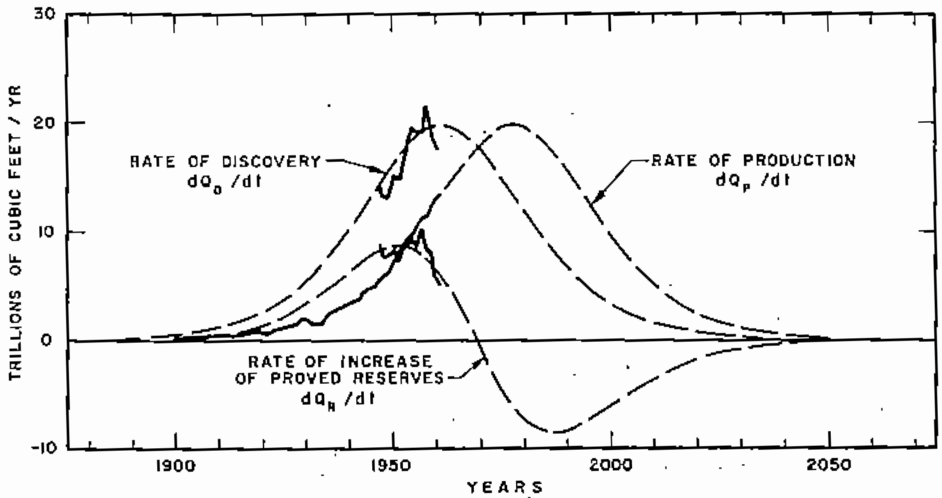

Figure 46. Rates of Discovery, Production and Increase of Proved Reserves of U. S. Natural Gas

of discovery, the rate of production, and the rate of increase of proved reserves. The date of the peak in the rate of discovery of natural gas should be about when the curve of cumulated proved discoveries reaches one-half the ultimate, $\underline{Q}_{\infty}$, or about 500 x x 10^{12} ft^3. To the end of 1961 cumulated proved discoveries amounted to 484 x 10^{12} ft^3, and the rate of discovery during recent years has been about 18 x 10^{12} ft^3/yr. Accordingly, the halfway point, or the inflection point of the curve, should be reached by about the end of 1962. This should also be about the date of the peak of natural-gas discoveries. The peak in production should occur about 16 years later, or about 1978, and the peak of proved reserves near the mid-point between these two dates, or about 1970.

Figure 47 shows the future production of natural gas as derived from the data of Figures 45 and 46, for both the low and the high estimates of ultimate reserves.

United States Production and Ultimate Reserves of Natural-Gas Liquids

The annual production of natural-gas liquids in the United States is shown graphically in Figure 48 (American Petroleum Institute, 1959, p. 80-81; American Gas Association, 1959-1962).

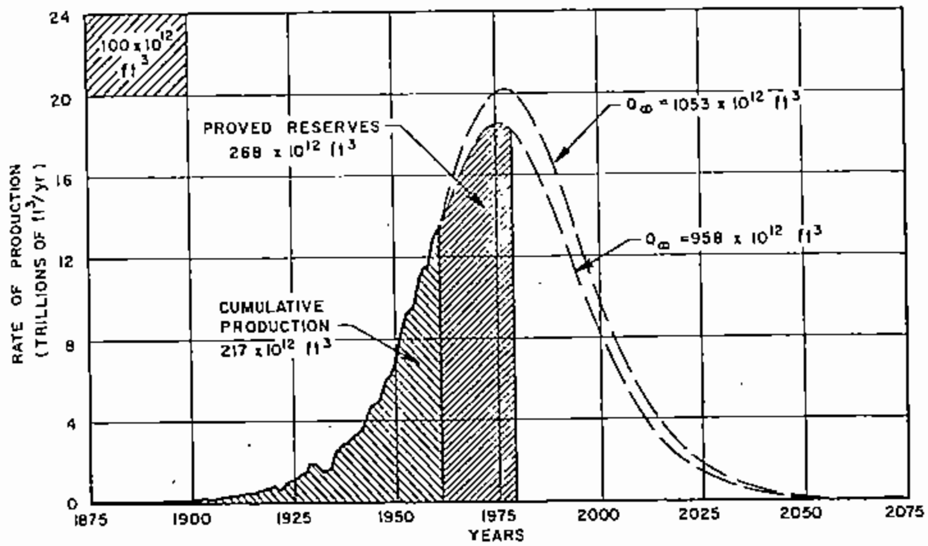

Figure 47. U. S. Production of Natural Gas for High and Low Estimates of Ultimate Reserves

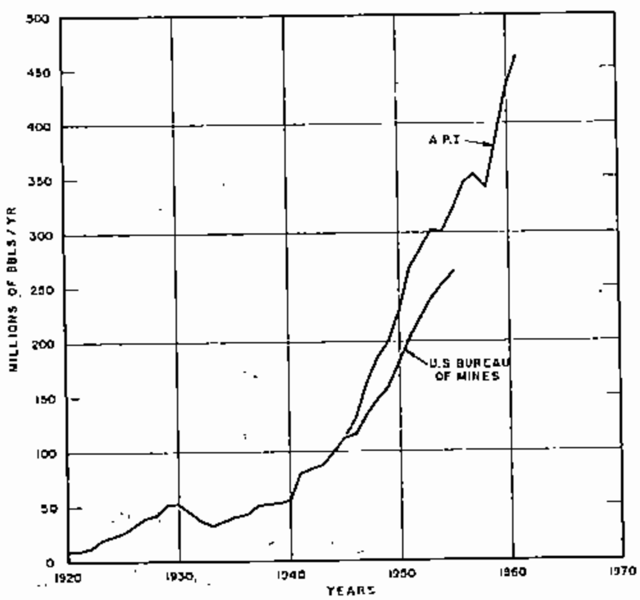

Figure 48. Rate of Production of U. S. Natural-Gas Liquids

Because natural-gas liquids are a by-product of the production of natural gas, an estimate of the ultimate potential reserves of natural-gas liquids may be made very simply from the estimate of the ultimate reserves of natural gas, and the ratio of natural gas to natural-gas liquids in past production experience.

From the statistics of the American Gas Association on production rates and proved reserves of both natural gas and natural-gas liquids (American Gas Association, 1948-1962), the cumulative proved discoveries of natural gas during the period 1947 to 1961, inclusive, increased by 250.2×10^{12} ft^3. During the same period the increase of the cumulative proved discoveries of natural-gas liquids increased by 8.45×10^9 bbls. The ratio of the gas to the natural-gas liquids discovered during this period amounts to 29.6×10^3 ft^3/bbl. If we assume that this ratio will remain approximately unchanged for the undiscovered gas reserves we can use it to estimate the undiscovered natural-gas liquids.

By December 31, 1961, the cumulative proved discoveries of natural gas amounted to 484×10^{12} ft^3. Subtracting this from the estimated ultimate natural-gas reserves of $1,000 \times 10^{12}$ ft^3 gives an estimate of 516×10^{12} ft^3 of natural gas still to be discovered. Then, by dividing the undiscovered gas by the ratio of gas to natural-gas liquids, we get

$$\frac{516 \times 10^{12} \text{ ft}^3}{29.6 \times 10^3 \text{ ft}^3/\text{bbl}} = 17.4 \times 10^9 \text{ bbls}$$

as the estimate of undiscovered natural-gas liquids. Adding to this the estimated cumulative discoveries of natural-gas liquids we obtain:

Cum. disc. nat.-gas liq. through 12-31-61	13.0×10^9 bbls
Nat.-gas liq. to be discovered as of 12-31-61	17.4×10^9 bbls
Est. ultimate potential res. nat.-gas liq.	30.4×10^9 bbls

as the estimated ultimate potential reserves of natural-gas liquids for the United States. Rounding this off to 30×10^9 bbls and adding it to the 175×10^9 bbls for crude oil, we then obtain 205×10^9 bbls as our present estimate of the ultimate potential reserves of liquid hydrocarbons of the United States.

The curves for cumulative proved discoveries, cumulative production, and proved reserves for natural-gas liquids are shown in Figure 49.

United States Production and Ultimate Reserves of Liquid Hydrocarbons

By combining the U. S. data for crude oil with those for natural-gas liquids, we obtain composite U. S. data for total liquid petroleum. These data for cumulative production, proved reserves, and cumulative proved discoveries are plotted graphically in Figure 50. The logistic curves for production and discovery, as obtained graphically from the data and independently of earlier

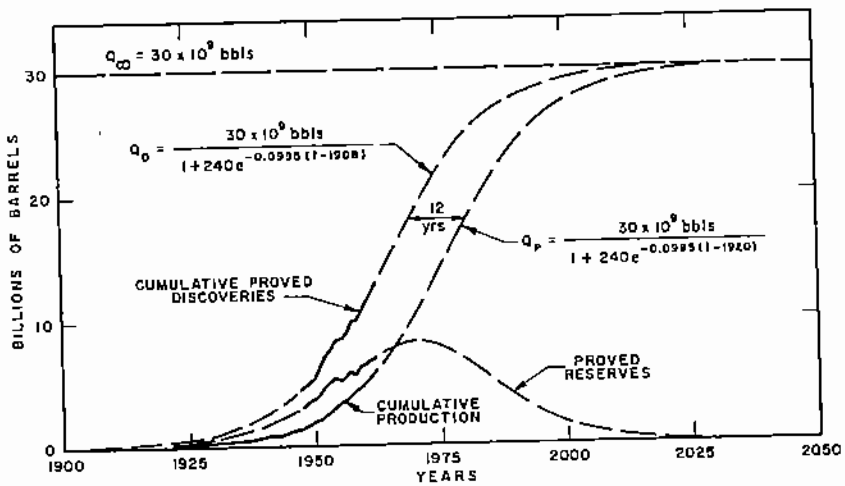

Figure 49. Cumulative Discoveries and Production and Proved Reserves of U. S. Natural-Gas Liquids

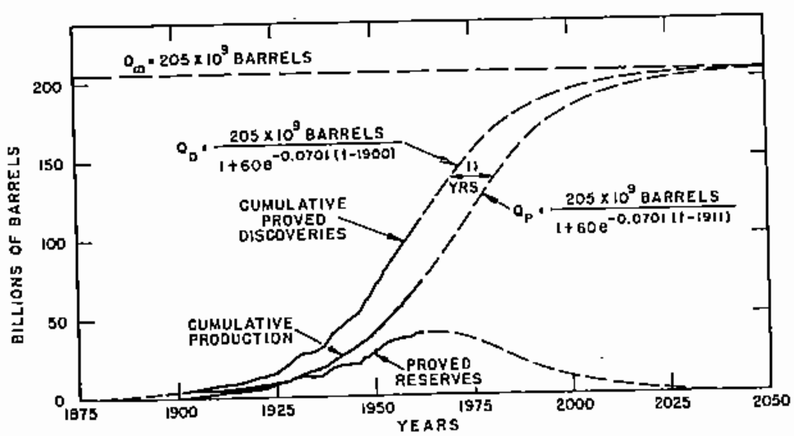

Figure 50. Cumulative Discovery and Production and Proved Reserves of U. S. Liquid Hydrocarbons

considerations, still give an asymptotic value of 205 billion barrels for Q_∞, the ultimate expectable cumulative production.

The time derivatives of the curves are shown in Figure 51.

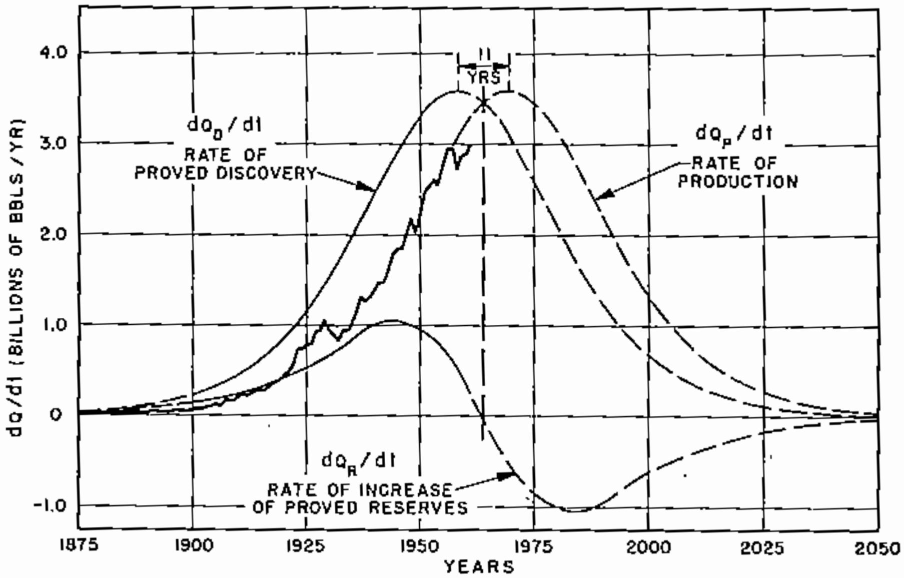

Figure 51. Rates of Proved Discovery, Production and Increase of Proved Reserves of U. S. Liquid Hydrocarbons

From the composite data on total petroleum liquids, the lead time, Δt, of discovery with respect to production is about 11 years. The peak discovery rate appears to have occurred about 1958; the peak of proved reserves is expected to occur at about 1964, and that of the rate of production at about 1969.

Ultimate World Reserves of Natural Gas and Natural-Gas Liquids

Although markets do not as yet exist for the natural gas and natural-gas liquids of the oil and gas fields in the parts of the world remote from centers of industrialization, there is promise that such markets soon will exist. Recent developments in the transportation of natural gas in a liquified form by means of insulated and refrigerated tankers make it possible to transport natural gas from any region of production to remote centers of consumption.

Although statistical data do not exist for natural gas and natural-gas liquids on a world scale, the approximate amounts potentially available can be estimated from the estimated reserves of crude oil and the amount of natural gas and natural-gas liquids produced per bbl of crude oil in the United States. For a world estimate we assume 6,000 ft^3 of natural gas per bbl of crude oil, and that natural-gas liquids and crude oil comprise, respectively, 15 and 85 per cent of the total liquid hydrocarbons. This gives 0.1765 of a bbl of natural-gas liquids per bbl of crude oil.

Then, on the basis of our estimate of $1,250 \times 10^9$ bbls of crude oil as the ultimate reserves of the world, the ultimate reserves of natural gas and of natural-gas liquids will be $7,500 \times$ $\times 10^{12}$ ft^3 and 220×10^9 bbls, respectively.

This would give a world estimate of $1,470 \times 10^9$, or roughly, $1,500 \times 10^9$ bbls for liquid hydrocarbons.

Oil Shales and Tar Sands

The world reserves of oil shales and tar sands are much less well known than those of the United States and Canada. The United States has the largest known reserve of oil shales in the world, and Canada the largest reserve of tar sands. The principal oil shale in the United States is the Green River shale in western Colorado, southwestern Wyoming, and eastern Utah. The tar sands of Canada occur in four known localities in Alberta, with reserves possibly as large as 600×10^9 bbls of crude-oil equivalent.

The reserves for the United States used here are those prepared by the United States Geological Survey and presented by V.E. McKelvey to the Natural Resources Subcommittee of the Federal Council, on November 28, 1961. According to this report, the estimates of the reserves of shale oil in the United States in the categories of <u>known</u>, <u>potential</u>, and <u>known marginal</u> reserves amount to 850×10^9 bbls. The reserves in the corresponding categories for oil in bituminous rocks, or tar sands, amount to only about 2.6×10^9 bbls.

The corresponding world figures in the same report are:

Shale oil	$1,297 \times 10^9$ bbls
Oil in bituminous rocks	$> 490 \times 10^9$ bbls

Potential marginal reserves in each of these categories could be much larger. The foregoing figures are those used here, although it is recognized that they are minimal figures.

Total Energy of the Fossil Fuels

Having reviewed the ultimate potential reserves of the various classes of the fossil fuels, we need now to compare them with respect to their total energy contents. For this purpose we adopt the heat of combustion expressed in the energy unit, the kilowatt-hour. A kilowatt-hour represents the work done at a rate of 10^3 joules/second during a time of 1 hour of 3,600 seconds. It, therefore, represents 3.60×10^6 joules. A kilowatt-hour of heat is the heat produced by a kilowatt-hour of work. For the world reserves of energy from the fossil fuels a convenient larger unit is 10^{15} kilowatt-hours.

Ultimate World Reserves

In Figure 52 are shown the present estimates of the ultimate reserves of energy for the different classes of fossil fuels, and the fraction of each which has been consumed already. The total ultimate energy for all the fossil fuels is approximately 27.4×10^{15} kilowatt-hours of heat. Of this 71.6 per cent is represented by coal, 17.3 per cent by petroleum and natural gas, and 11.1 per cent by tar sands and oil shale. The fraction consumed already is 4.1 per cent for coal, 10 per cent each for petroleum and natural gas, and zero for tar sands and oil shales.

United States Reserves

The corresponding data for the United States are given in Figure 53. The total ultimate reserves of energy from the fossil fuels in the United States is about 8.7×10^{15} kilowatt-hours, or about one-third of the world total. Of this, 78 per cent is represented by coal, 16 per cent by oil shale, and 3 per cent each by petroleum and natural gas. The amount consumed already is about 3 per cent for coal, 38 per cent for petroleum and 22 per cent for natural gas.

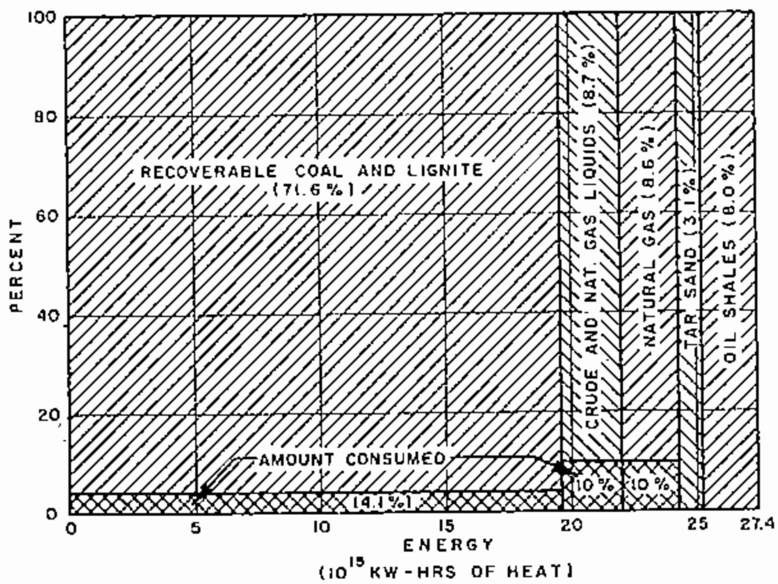

Figure 52. Total World Energy of Fossil Fuels

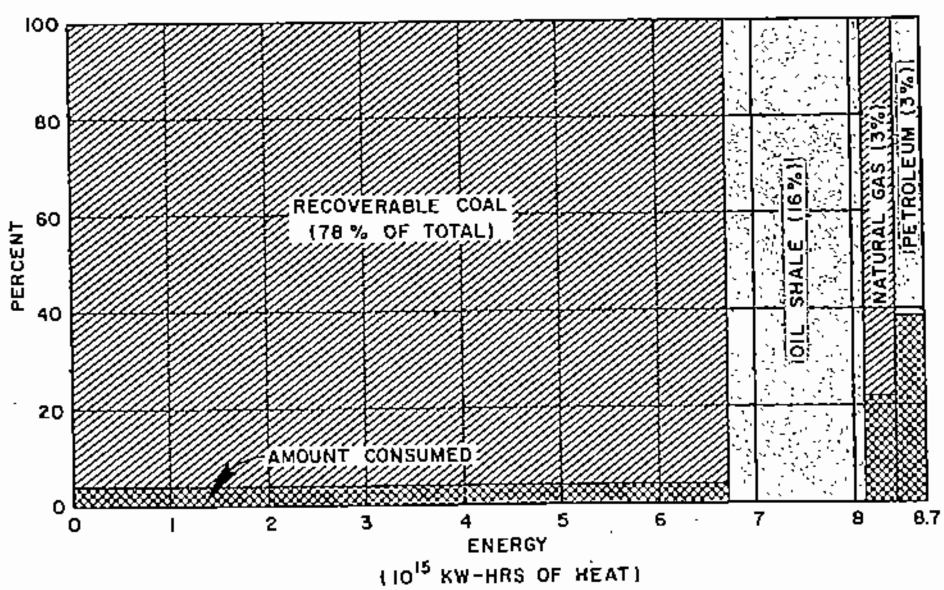

Figure 53. Total U. S. Energy of Fossil Fuels

Summary of Energy from the Fossil Fuels

To summarize the data that we have assembled on the energy supply from the fossil fuels, the world's total supply of energy from these sources, including that already consumed, amounts to about 27×10^{15} kilowatt-hours, of which about one-third occurs in the United States exclusive of Alaska. Of this energy supply, both for the world and for the United States, about three-quarters is represented by coal and one-quarter by petroleum, natural gas, oil shales, and tar sands.

The energy content of the fossil fuels consumed by the end of 1961 amounted to only about 4.7 per cent of the ultimate reserves for the world, and 5.0 per cent for the United States. However, the smallness of these figures tends to be deceptive and to lead to a false sense of security, because, as we have shown heretofore, with only a modest additional increase in the present rates of consumption, the peak in coal production for both the world and the United States will occur in about 200 years.

Since the reserves of petroleum and natural gas are much smaller than those of coal, and the ratio of their rates of consumption to their total reserves is much higher, it follows that these fuels will be much more short-lived than coal. In fact, the culmination in the world production of petroleum is expected to occur by about the end of the present century. In the United States the culmination in the production of crude oil is expected to occur before 1970, and that of natural gas before 1980.

This does not imply that the United States is soon to be destitute of liquid and gaseous fuels, because, as we have seen, there are still large reserves of oil shale and still larger reserves of coal from which such fuels can be produced, if necessary.

However, in keeping with the historical perspective with which we began this review, it is well to consider the exploitation of the fossil fuels in a span of history extending for some thousands of years before and after the present. On such a time scale the exploitation of the fossil fuels from the beginning to ultimate exhaustion, as is shown in Figure 54, will comprise but a brief episode.

The total length of time during which a fuel may be exploited to some trivial amount is not a significant figure; the significant time span is that during which the cumulative production increases

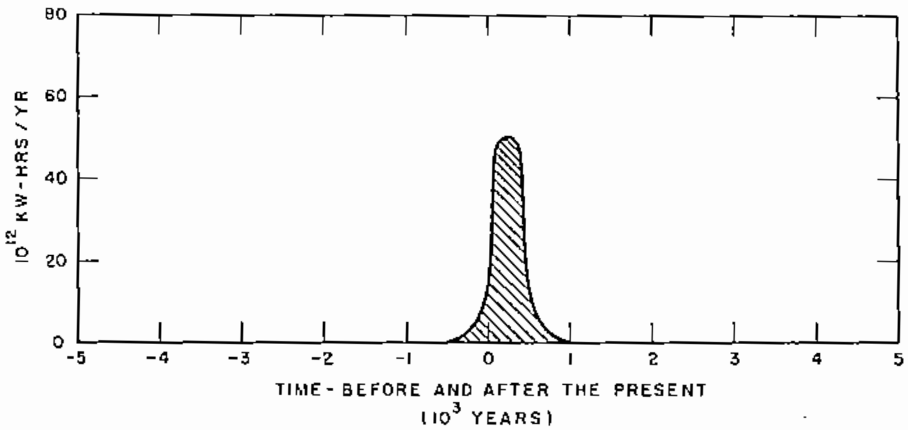

Figure 54. Total World Production of Fossil Fuels in Time Perspective

from, say, 10 per cent to 90 per cent of the ultimate reserves. For coal this figure promises to be only about 350 years. For the world's petroleum reserves, since only 10 per cent have been consumed up to now and the culmination is expected in about 40 years, it is estimated that an additional 40 per cent of the initial reserves will be produced between 1960 and the year 2000 and another 40 per cent between 2000 and 2040. Thus, about 80 per cent will be produced during the 80-year period between 1960 and 2040 A. D. The corresponding period during which 80 per cent of the petroleum and natural-gas reserves of the United States will be consumed will be somewhat shorter. The United States cumulative production of crude oil reached 17 x 10^9 bbls, or about 10 per cent, of the ultimate reserves by 1935. It is expected to reach 50 per cent by 1970 and 90 per cent by about 2005. The middle 80 per cent will accordingly be produced during the approximately 70-year period from 1935 to 2005. As compared with the production rate during this central period, that during the first and last 10 per cent of the ultimate reserves is relatively unimportant.

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CHAPTER V

CONTINUOUS SOURCES OF POWER

We now direct our attention to continuous sources of power, or sources which, if exhaustible, represent so great a reserve of energy that, for time periods of a few thousand years, they may be treated as if they were inexhaustible.

Solar Energy

The first of these is solar energy. As we have already pointed out in Chapter I, solar energy is intercepted by the earth at a mean rate of about 17.2 x 10^{16} watts, which is about a million times greater than the installed electrical-generating capacity of the United States in 1959.

At present only two channels of the flux of solar energy are available as large-scale sources of energy for human utilization. The first is the biological channel, beginning with photosynthesis; the second is the heat-engine channel, which produces the atmospheric and oceanic circulations and the hydrologic cycle, leading to wind power and water power.

Biologic Channel

At the Committee's conference on energy held in New York on July 19-20, 1961, the energy flux of the biologic channel was reviewed briefly by G. Evelyn Hutchinson of Yale University.

Professor Hutchinson pointed out that the rates of the photosynthetic process in terms of the fixation of carbon per year are presently estimated to be as follows:

	Grams/yr of fixed carbon
Forests	12×10^{15}
Agricultural lands	5.1×10^{15}
Grass lands	4.6×10^{15}
Total for land areas	21.7×10^{15}

The total amount of fixed carbon involved is about 1 to 3×10^{17} grams. The energetic efficiency of the process is only about 0.2 per cent.

Thus, while the biological efficiency in the capture of solar energy is low, the aggregate quantity is very large, the annual fixation of carbon on land by this process being about 7 times the fixed carbon in the fuels consumed per year.

The oceanic fixation of carbon per year is not accurately known, but could be as high as 35×10^{15} grams/year.

There is evidence that the greatly increasing use of the fossil fuels, whose material contents after combustion are principally H_2O and CO_2, is seriously contaminating the earth's atmosphere with CO_2. Analyses indicate that the CO_2 content of the atmosphere since 1900 has increased 10 per cent. Since CO_2 absorbs long-wavelength radiation, it is possible that this is already producing a secular climatic change in the direction of higher average temperatures. This could have profound effects both on the weather and on the ecological balances.

In view of the dangers of atmospheric contamination by both the waste gases of the fossil fuels and the radioactive contaminates from nuclear power plants, Professor Hutchinson urges serious consideration of the maximum utilization of solar energy.

Wind Power

The historical background on the development of power from both water and wind has been reviewed in Chapter II. Wind power is essentially limited to comparatively small units and is suitable for such special uses as pumping well water and charging batteries for local household electrical uses, but it does not offer much promise of competing with other prime movers in producing large-scale electric power. Even for the traditional uses such as the propulsion of sailing ships and the Dutch windmills for pumping water from the Dutch polders and for grinding grain, the use of power from the fossil fuels and water power has almost completely displaced wind power.

Water Power

The only channel of solar energy which lends itself to large-scale power production is water power, which is made possible only by the fact that natural streams are a means of concentrating very large amounts of power in small areas. Yet it was not possible to utilize power in such quantities at a single locality before the development of the means for generating power electrically and transmitting it over large areas for utilization. Thus, while water power is one of the oldest and most important sources of industrial power, individual water-power units rarely exceeded a few tens of kilowatts in size prior to the introduction of electrical generation and distribution. Now sites are being developed in which individual installations have power capacities measurable in hundreds of megawatts.

Unlike the fossil fuels, water power is a rate of production rather than a quantity of energy. The long-term history of the development of water power accordingly should be represented by a logistic type of growth. The installed capacity must start at a very low level, increase with time, at first slowly and then more rapidly, and finally level off to a maximum when all available water power is being utilized.

When all available power is thus being used, power can be generated at this maximum rate more or less indefinitely, provided the climate does not change significantly, and also provided that a steady-state method of desilting the reservoirs can be devised. At present rates of deposition of silt, most of the large reservoirs will require only the order of a few centuries to become filled with sediment. Unless this sediment eventually is removed from the reservoir at the same rate as it is added, the power capabilities of the reservoirs will be greatly diminished.

The significant quantities pertaining to water power in any given area are the maximum potential water power available and the amount of this that has been utilized up to any given time.

A summary of the developed and potential water power of the world has been compiled by Young (1955) of the United States Geological Survey. Using this as basic information, Francis L. Adams (1961) of the Federal Power Commission presented a comprehensive review of water power before the Committee's conference on energy in New York on July 19, 1961.

According to Adams the Federal Power Commission assumes a power capacity equal to 60 per cent of the U. S. Geological Survey's estimate of power at mean rate of flow at 100 per cent efficiency. Using this factor, Adams estimated the ultimate potential water-power capacity of the United States to be 148,000 megawatts, of which the amount already installed by the end of 1960 was 33,000 megawatts, or 23 per cent of the ultimate. A logistic curve of water-power development for the United States is shown in Figure 55.

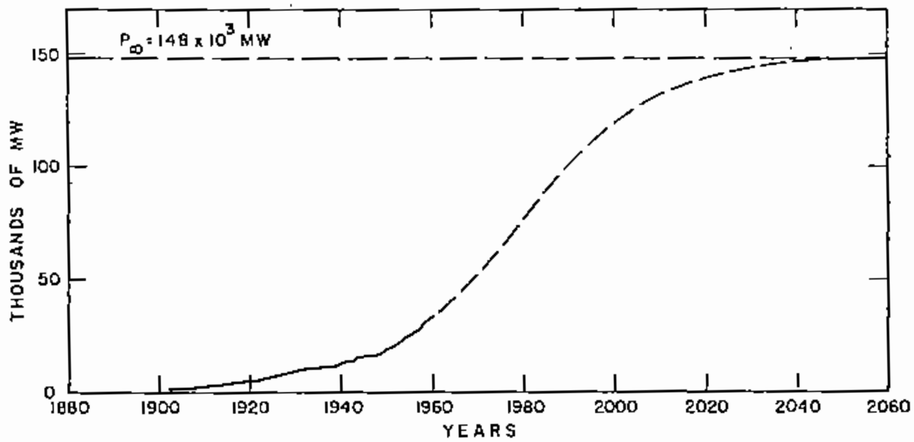

Figure 55. U. S. Installed and Ultimate Hydroelectric Power Capacity

Adams did not give data on the potential water power of the world in terms of megawatts of capacity, but rather in terms of the energy which could be produced per year expressed as kilowatt-hours per year. Using his ratio between installed power capacity and annual energy produced for the United States, it is possible to estimate the potential power capacity for the various areas of the world and the extent to which this has already been developed. The results of this calculation are shown in Table 8.

TABLE 8

World Water-Power Capacity

Region	Potential (10^3 Megawatts)	Per Cent of Total	Development (10^3 Megawatts)	Per Cent 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	

Computed from data given by Adams, Francis, L., 1961, Statement on Water Power: At Conference on Energy Resources, Committee on Natural Resources, National Academy of Sciences, Rockefeller Institute, New York, N. Y., July 19, Chart I.

It will be noted that, whereas the United States has an ultimate potential water-power capacity of 148×10^3 megawatts, of which 23 per cent is already developed, the world has a potential capacity of 2.86×10^6 megawatts, of which only 152×10^3 megawatts, or 5.3 per cent, has been developed.

Also, it is interesting to note that Africa, with a potential water-power capacity of 780,000 megawatts, has the largest water-power resources of any continent; and South America is second.

To obtain some idea of how large the potential water-power resources are in comparison with other energy sources, the total installed electricity-generating capacity in the United States in 1959 was 174,000 megawatts (Dept. of Commerce, 1961, p. 525) and the electrical energy produced was 795×10^9 kilowatt-hours, which, had it been generated by coal, would have required 1.53×10^9 short tons. The world in 1959 produced 2.096×10^{12} kilowatt-hours of electric power, which required an equivalent of 4.37×10^9 short tons of coal (Dept. of Commerce, 1961, p. 931).

If the water power of the world were fully developed, the electrical energy produced per year would be about 12.0 x 10^{12} kilowatt-hours (Adams, 1961), which would be about 6 times the electrical-power production of the world in 1959. The coal required to produce this amount of power would be about 25 x 10^9 short tons per year, or about 10 times the world's coal production in 1959.

Direct Conversion of Solar Energy

The fact that a large fraction of the total solar power occurs as direct solar radiation in desert and semidesert areas in tropical to middle latitudes makes an intriguing problem of somehow capturing this energy for human uses. At the Committee's conference on energy resources in New York on July 19-20, 1961, Farrington Daniels, Director of the Solar Radiation Laboratory of the University of Wisconsin, reviewed the work and prospects of the direct utilization of solar energy.

Later, an all-day conference on this same subject was held at the National Academy of Sciences in Washington on May 25, 1962. This meeting, under the chairmanship of Roger Revelle, was attended by representatives of the principal industrial corporations doing research in this field, as well as by Professor Farrington Daniels from the University of Wisconsin and Professor Eric A. Farber who is in charge of an extensive research program on solar-energy utilization at the University of Florida.

At these conferences attention has been devoted principally to small, specialized uses of solar energy such as cooking, water heating, heating and cooling of domestic residences, electrical generation for rural telephone circuits, and use for space craft.

The outstanding exception was an account given by Frank Edlin of the Du Pont Corporation, Wilmington, Delaware, of a pilot-plant experiment designed to produce electrical power on a much larger scale. In this experiment the energy-capturing device was a 5-layer transparent plastic cover over an artificial pond. It was expected that 45-50 per cent of the incident solar radiation would be captured, heating the pond to 200° F. This pond would serve both as a collector and a storer of energy, the storage capacity being large enough to operate a heat engine continuously without a serious drop in temperature. A steam engine would be driven on a Rankine Cycle with an efficiency of 12-14 per cent, operating between the high temperature of the pond and the low temperature of sea water. The expected overall efficiency was about 6 per cent.

The experiment was not a complete failure, but not up to expectations either. Only a 70° F. temperature increase was obtained; sunlight capture was only 17 per cent, which would give an efficiency of converting sunlight into work of only 2 per cent. Even under these conditions, however, it appeared that the production of electrical power at a cost of 6 cents per kilowatt-hour may be within range. A minimum size for the pond for a pilot plant would be about 5,000 ft^2. Experiments of this type were said to be very expensive.

This experiment is here singled out as being particularly significant because it tended to avoid the principal difficulty inherent in solar-energy collection. The radiation density of solar energy is small, so that collection must be accomplished over large areas if large amounts of power are to be developed. Most systems of collection are prohibitively expensive, so that, if extended over large areas, they would involve capital costs many times that for power generation from conventional sources.

An extension of the type of collection described by Mr. Edlin to really large areas might have possibilities, especially in areas deficient in power from other sources. Unless large-area, inexpensive collecting devices can be developed, the direct use of solar energy appears to be destined to be restricted to comparatively small special-purpose uses. These may still be widely developed, however, as in domestic water heating in Florida and Japan and refrigeration and residential heating and air conditioning.

Tidal Power

In Chapter I it was pointed out that the total tidal power dissipated by the earth is about 1.4×10^{12} watts, of which about 1.1×10^{12} watts is accounted for by tidal friction in bays and estuaries around the world. It is the latter fraction which is susceptible to capture and conversion to electric power by suitable water-power devices.

A summary of data pertaining to actual and potential tidal power sites was presented by Francis L. Adams (1961, Chart XII), given here as Table 9. These comprise nine Bay of Fundy sites in Maine, Nova Scotia and New Brunswick, and four additional sites in France, England, and Argentina.

TABLE 9

(Adams' Chart XII) Tidal Power Data for the Bay of Fundy and Other Potential Developments

Bay or Basin	Tidal Ranges—Feet Springs	Neaps	Mean H	Area Sq.Mi. A	Proposed Development Scheme	Installed 10^3kw	Annual 10^6kwh
Bay of Fundy Sites							
Passamaquoddy	27	12	18	101	2-Pool	—	—
Cobscook	27	12	18	41	1-PH	300	1,843
Annapolis	33	14	21	32	1-Pool	37	79
Minas-Cobequid	54	24	35	300	—	2,000	—
Amherst Point	54	24	35	4	2-Pool	39	275
Shepody	50	22	32	45	2-Pool	—	—
Cumberland	51	23	33	28	2-PH	450	2,140
Petitcodiac	54	24	35	12	2-Pool	—	—
Memramcook	54	24	35	9	1-PH	201	1,310
						3,027	5,647
Other Sites							
San Jose (Argentina)	27	15	19	300	—	1,050	4,500
Severn (England)	47	22	32	30	1-Pool	800	2,300
La Rance (France)	38	11	23	8	1-Pool	324	890
Mont St. Michel (France)	41	12	25	200	2-Pool	3,000	25,000
						5,174	32,690
Total						8,201	38,337

Adams, Francis, L., 1961, Statement on Water Power: At Conference on Energy Resources, Committee on Natural Resources, National Academy of Sciences, Rockefeller Institute, New York, N. Y., July 19, Chart XII.

The largest of the Bay of Fundy sites would have an installed power capacity of 2,000 megawatts, the Argentina site 1,050 megawatts, and the French site at Mont St. Michel 3,000 megawatts. The remaining sites range between 37 and 800 megawatts. The total potential capacity of the Bay of Fundy is 3,027 megawatts, with an estimated annual energy output of 5.6×10^9 kilowatt-hours. The total potential capacity of all the sites is 8,201 megawatts, with an estimated annual output of 38.3×10^9 kilowatt-hours.

A comparison of these figures with the energy production from water power in the United States can be made by noting that in 1959 the energy produced from water power was 172×10^9 kilowatt-hours (Adams, 1961, p. 3).

Geothermal Energy

As was pointed out in Chapter I, the temperature in the earth increases with depth, in consequence of which heat is conducted from the earth's interior to its surface. An additional amount of heat is convected to the earth's surface by the gases and lavas of volcanos, and by hot springs in regions which have been heated above normal by volcanic activity.

The mean rate of increase of temperature with depth in areas remote from volcanic disturbances is about 1° C. per 30 meters, or about 33° C. per kilometer of depth. Hence, within drillable depths of 5 to 8 kilometers, temperatures as high as 150° - 200° C. above surface temperatures may be expected.

Superficially, it would appear that with such temperatures at drillable depths, earth heat sufficient for significant power generation could be obtained anywhere. Actually this is not the case. Rocks are very poor conductors of heat; thus the heat that could be obtained in this manner is negligible. The only situations in which earth heat can be used on a large scale are those at which hot volcanic rocks are comparatively near the surface and either volcanic, or circulating, ground waters act as heat collectors from large volumes of rocks. Since these hot rocks are finite in quantity and have finite contents of heat, it follows that the amount of energy extractable from such a source must also be limited.

A review of the present developments in the production of power was given by Earl F. English (1959), Consulting Engineer and Vice President, Thermal Power Company. According to this review, major drilling operations which have resulted in usable quantities of steam for power production have been conducted in only three principal localities. These are: Lardarello in Italy, Wairakei and Kawerau in New Zealand, and The Geysers in Sonoma County, California.

Electric power has been produced at Lardarello for 40 years, and the capacity is now 400 megawatts. Wells are now being drilled in New Zealand, and a power plant is under construction and partly in operation. The steam capacity is estimated to be in excess of 400 megawatts.

The Geysers in California produce enough steam for 25 megawatts of electric power. Pacific Gas and Electric Company has built one plant with a capacity of 12.5 megawatts, and this capacity is soon to be doubled.

A more comprehensive approach to the power potentials of thermal areas is made by determining the total heat output from such areas. Data of this kind have recently been compiled by Donald E. White of the U. S. Geological Survey in two papers not yet formally published. According to White (1961a) the thermal outputs in ten localities in New Zealand range from a low value of 59 megawatts to a high value of 1,260 megawatts. In the four localities in the western United States the thermal outputs are the following:

Steamboat Springs, Nevada	27×10^6 watts
	4.3 YRS AT THIS RATE = (APPX) TO TOTAL KWH USED IN U.S. IN 1963
Yellowstone Park:	
Norris Basin	33×10^6 watts
Upper Basin	380×10^6 watts
Mammoth and Hot River	140×10^6 watts

White (1961b) also points out that at Steamboat Springs, Nevada, the quantity of excess heat stored in a volume of rock 5 square kilometers in area by 3 kilometers deep amounts to 1.6×10^{18} calories, which is equal to 1.9×10^{12} kilowatt-hours. This is equivalent to the heat of combustion of about 235 million tons of coal, and at the present rate of flow would require 7,000 years to dissipate.

Further information on the world distribution of potential power sites utilizing volcanic heat has just been received from the Italian volcanologists, Francesco Penta and Giorgio Bartolucci (1962). These authors, in a paper entitled "Sullo stato delle 'ricerche' e dell'utilizzazione industriale (termoelettrica) del vapore acqueo sotterraneo nei vari paesi del mondo" ["On the state of the 'researches' and the industrial (thermoelectric) utilization of the underground steam in the various countries of the world"]. As the title implies, this is a review of the known localities in the world. It is accompanied by a bibliography of 98 references to pertinent technical literature.

This review is in agreement with the data cited above on volcanic steam power developments in Italy, the United States, and New Zealand. Altogether about 46 separate localities are cited as having potentialities for power production of industrial magnitudes. From the data given, it would appear that a few thousand megawatts is the expectable order of magnitude for the world power capacity from geothermal sources.

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CHAPTER VI

NUCLEAR ENERGY

We come now to the most recent source of energy to become available for human use—the atomic nucleus. Nuclear energy results from each of two contrasting processes, the fissioning of a few of the isotopes of heavy elements in the atomic scale, producing lighter elements; and the fusing of light elements near the lower end of the scale of atomic numbers to produce heavier elements. In each instance the mass of the reaction products is slightly less than that of the reactants and the lost mass is converted into energy in accordance with the Einstein equation relating mass to energy,

$$E = \Delta mc^2, \tag{19}$$

where $\underline{E}$ is the energy released, $\Delta \underline{m}$ the reduction in mass, and $\underline{c}$ the velocity of light.

Since the velocity of light is 3.00×10^8 m/sec, then, if $\Delta \underline{m}$ is 1 gram,

$$E = 10^{-3}\ \text{kg} \times 9.00 \times 10^{16}\ \text{m}^2/\text{sec}^2$$

$$= 9.00 \times 10^{13}\ \text{joules}.$$

Energy from the Fissioning of Heavy Isotopes

The only isotope naturally capable of fissioning is uranium-235, which comprises 0.7 per cent of whole uranium. The remainder of natural uranium is the isotope U-238.

It was found by J. Chadwick in England in 1932 (Smyth, 1945, p. 9-10) that in certain nuclear experiments a strange particle having approximately the mass of the hydrogen atom, or the proton, but zero electric charge, was emitted. This was known later as the neutron. Further experiments during the 1930's showed that normally nonradioactive elements, when bombarded with neutrons, can be made artifically radioactive. Finally, in January 1939, O. Hahn and F. Strassmann in Germany (Smyth, 1945, p. 24) reported obtaining barium from the neutron bombardment of uranium. Since barium is an element remote from uranium in the atomic scale, it could not have been produced by any simple radioactive transformation. This led to the surmise that the barium plus a complementary atomic particle must have been produced by the fissioning of uranium. This surmise was verified within the next few weeks in several different laboratories in the United States.

Subsequent studies showed that the fissionable uranium isotope was the comparatively rare U-235, and that the products from numerous fissionings comprise a wide scatter of isotopes, many highly radioactive, in the mid-range of the table of atomic numbers. The energy released per fission was found to have an average value of 200 million electron volts, or 8.90×10^{-18} kilowatt-hours. From Avogadro's Number, there are

$$\frac{6.02 \times 10^{23}}{235} = 2.56 \times 10^{21}$$

U-235 atoms per gram. From this it follows that the energy released upon the fissioning of 1 gram of U-235 must be

$$\begin{aligned} 2.56 \times 10^{21} \times 8.90 \times 10^{-18} &= 2.28 \times 10^{4} \text{ kw-hr} \\ &= 8.21 \times 10^{10} \text{ joules.} \end{aligned}$$

This is equal approximately to the heat of combustion of 3 tons of coal or or 13 barrels of crude oil.

The reduction in mass of 1 gram of U-235 upon being fissioned is then obtained from the Einstein equation

$$\begin{aligned} \Delta m = \frac{E}{c^2} = \frac{8.21 \times 10^{10}}{9.00 \times 10^{16}} &= 0.913 \times 10^{-6} \text{ kg} \\ &= 0.913 \times 10^{-3} \text{ gm,} \end{aligned}$$

which is very nearly 1 part per 1,000. Hence, the fissioning of 1 gram of U-235 produces 0.999 grams of fission products and loses approximately 1 milligram of mass which is converted into 2.28 x 10^4 kilowatt-hours of heat.

In addition to radioactive isotopes, the fission products of U-235 also include neutrons. No sooner had the fissioning of uranium been demonstrated than intensive investigations were begun in the United States in an attempt to obtain a sustained fission chain reaction. This would be a reaction in which, if a single fissioning occurred from a stray neutron, then the neutrons produced would cause still other fissionings to occur and so be able to sustain the reaction.

Such a reaction was first achieved by E. Fermi and associates (Smyth, 1945, p. 98) in Chicago on December 2, 1942, using a "pile" with a graphite matrix in which lumps of common uranium or its oxide were placed in a three-dimensional lattice. When the pile had been built up with about 6 tons of uranium, it reached the critical stage and a sustained chain reaction was achieved.

At just beyond the critical level the reaction could be controlled by the insertion or removal of neutron-absorbing cadmium strips, making it possible to start, stop, increase, or retard the reaction at will.

The object of the wartime experiment was to produce nuclear bombs. Our present interest is limited to the fact that, by means of variations of the original Chicago experiment, it is possible to produce and control sustained fission reactions, and that the heat released can be used to operate conventional steam-power plants.

A schematic flow diagram of the fissioning of U-235 in a chain reaction is shown in Figure 56. The material products produced by the fissioning of a single atom are two other atoms plus neutrons, whose combined weights are a little less than that of the U-235 atom. The fission product of a large number of separate fissions comprises a scatter of atoms in the mid-range of the table of atomic numbers. Many of these fission products are extremely radioactive, some with half-lives of approximately 30 years.

The difficulty posed by the use of U-235 for power generation is its comparative scarcity. However, it has been found that the two much more abundant isotopes, U-238 and Th-232

FISSION POWER REACTION

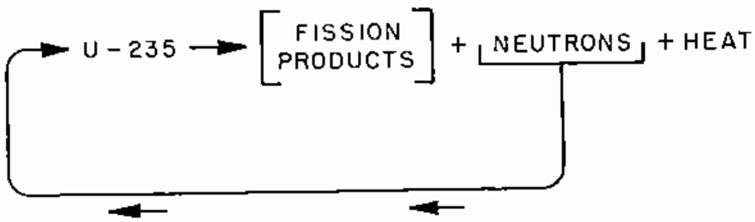

Figure 56. Schematic Representation of Nuclear-Power Reaction Involving the Fissioning of U-235

(which is essentially the whole of natural thorium), can be converted into fissionable isotopes by being placed in a nuclear pile powered initially by U-235. By this process, omitting intermediate details,

$$\text{U-238} \rightarrow \text{Pu-239},$$

and

$$\text{Th-232} \rightarrow \text{U-233};$$

and both plutonium-239 and uranium-233 are fissionable.

BREEDER REACTION
(SCHEMATIC)

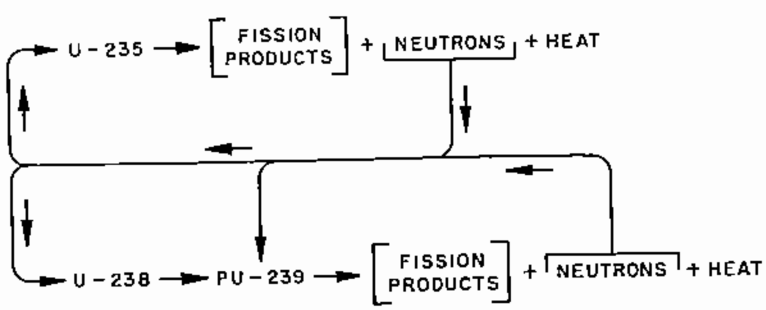

Figure 57. Schematic Representation of Breeder Reaction for U-238

The nonfissionable isotopes, U-238 and Th-232, from which the fissionable isotopes, Pu-239 and U-233, are made, are known as <u>fertile</u> materials. The process of converting fertile isotopes to fissile isotopes is known as <u>breeding</u>. The process of breeding is illustrated for U-235 and U-238 in Figure 57. The same diagram would apply were Th-232 and U-233 substituted for U-238 and Pu-239.

By the breeding process, in principle all of uranium and all of thorium are potentially usable as nuclear fuels, instead of only the much scarcer isotope U-235. Since U-238 is 140 times as abundant as U-235 and thorium is geochemically about 3 times as abundant as U-238, it is evident that the available fuel is increased by a factor of about 400 if breeder reactors are developed. This, however, according to Alvin M. Weinberg, Director of Oak Ridge National Laboratory, is only a minimum of the gain potentially obtainable. The development of complete or nearly complete breeding changes the cost of the operation in such a manner as to make it economical to utilize rocks with low uranium or thorium contents. The fuel added in this manner is millions of times greater than that available when only U-235 can be used. Hence the energy gain contingent upon the development of breeder reactors is a very large factor.

The development of large-scale power by means of the fissioning of uranium and thorium and their derived isotopes reduces to three fundamental problems:

1. the development of breeder reactors,

2. an adequate supply of uranium and thorium, and

3. proper disposal of the extremely dangerous fission products.

Breeder Reactors

An extensive experimental program for the development of breeder reactors is underway by the Atomic Energy Commission, but its details will not be reviewed at this time.

The Supply of Uranium and Thorium

Uranium and thorium are of widespread occurrence in the rocks of the earth's crust, but in very small amounts. The granites which are the principal parent rocks of the continents contain thorium and uranium in the approximate average amounts of 12 parts per million of thorium and 4 parts per million of uranium. Since the sediments are principally derived from granitic rocks, and since the ocean waters contain essentially no thorium, it is expectable that the ratio of thorium to uranium in sediments should also be about 3 to 1. So far, however, nothing like this amount of thorium has been found. Uranium in sediments is fairly widespread, so we are led to suspect that some large concentrations of thorium in sediments, as yet undiscovered, will eventually be found.

Figure 58 is a map of the United States showing the locations and amounts of the principal known uranium and thorium deposits of the United States. The figures shown are supplemented by the data of Tables 10 and 11 from McKelvey, Butler, Olson and Gottfried (1961) of the U. S. Geological Survey. In addition, the data on the Conway granite in New Hampshire is from a recent and as yet unpublished paper by Adams, Kline, Richardson and Rogers (1962).

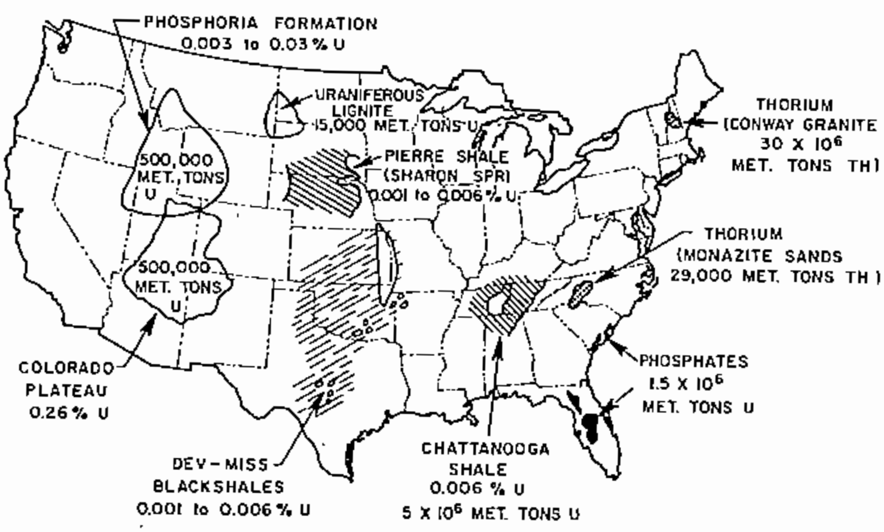

Figure 58. Major Uranium and Thorium Deposits in the U. S.

TABLE 10

Potential Uranium Reserves and Resources of the United States Comparable in Quality to Ore Mined from 1948 to 1960[1]

(Table 2 of McKelvey, Butler, Olson, and Gottfried)

Estimates of tonnage correspond to the sum of past production, known reserves, and undiscovered resources. Uranium content of ore in the districts listed averages 0.17 to 0.30 percent and costs $8 to $10 per pound to recover. All estimates and totals are rounded.

GENERAL AREA AND GEOLOGIC UNIT	Uranium[2] (metric tons)	
Colorado Plateau		
Triassic rocks	200,000 –	700,000
Morrison formation outside San Juan Basin	40,000 –	80,000
Morrison and Todilto formations, San Juan Basin, New Mexico	280,000 –	1,300,000
Subtotal, Colorado Plateau	500,000 –	2,000,000
Other western sandstone and lignite ores		
Eastern N. Mex., Western Okla., NW Texas, Permian and Triassic Rocks	18,000 –	30,000
Black Hills, S. Dak., and Wyo. — Inyan Kara Group	9,000 –	20,000
Wyoming and NW Colo. — Wasatch, Wind River, and Browns Park formation	80,000 –	200,000
Gulf Coast, Texas, mainly Jackson and Goliad formations	30,000 –	60,000
Lignite, N. and S. Dak.	15,000 –	30,000
Subtotal, areas outside Colo. Plateau	150,000 –	350,000
Other kinds of deposits and areas		
Tertiary clastic, mixed volcanic and sedimentary rocks, Western U. S.	8,000 –	20,000
Veins, Western U. S.	9,000 –	20,000
Appalachian Region, all types	1,500 –	15,000
Subtotal, all others	20,000 –	55,000
Total	700,000 –	2,300,000
Coal equivalent (metric tons)	2100×10^9	6900×10^9

[1] Indicated and inferred reserves of uranium in the United States are about 185,000 metric tons (R. D. Nininger, 1960, U.S.A.E.C. TID-8207).

[2] The minimum figure represents uranium in ore that is believed to occur in known geologic horizons, at depths comparable to deposits mined now, and in the vicinity of known districts. The maximum is based on projected occurrence of ore further from known districts, (generally also at depths greater than those in which uranium mining is being undertaken now) and makes moderate allowance for the existence of ore in horizons not now known to be mineralized. The minimum compares with an estimate of about 500,000 tons made for similar material by Nininger (idem). The deeper ores included in the maximum figures very likely would cost more than $8-10 per pound to recover.

McKelvey, V. E., Butler, A. P., Olson, J. C., and Gottfried, David, 1961, Uranium and Thorium Resources in the United States and World, Table 2 in Domestic and World Resources of Fossil Fuels, Radioactive Minerals, and Geothermal Energy: Preliminary Reports Prepared by Members of the U. S. Geological Survey for the Natural Resources Subcommittee of the Federal Science Council.

TABLE 11

Potential World Uranium Reserves and Resources Comparable in Quality to Those Mined from 1948 to 1960

(Table 3 of McKelvey, Butler, Olson, and Gottfried)

Area	Uranium[1] (metric tons)
United States	700,000 – 3,000,000
Canada	450,000 – 3,000,000
Europe and Asia	480,000 – 18,000,000
Africa	300,000 – 10,000,000
Latin America	2,000 – 8,000,000
Australia	8,000 – 3,000,000
Total	1,840,000 – 45,000,000
Coal equivalent (metric tons)	5×10^{12} – 1×10^{14}

[1]The minimum figure for the United States are those of A. P. Butler, 1961 (see table 2). Those for Canada, Africa, Latin America and Australia are the combined "reasonably assured reserves" and "Geologic estimates of possible future discoveries" of table 2 of R. D. Nininger, 1960, U. S. A. E. C. TID-8207. The minimum estimate for Europe and Asia includes about 110,000 tons estimated by Nininger as combined assured and possible for non-Communist Europe, and 370,000 tons estimated by the staff of the Joint Committee on Atomic Energy as the maximum resources of the U. S. S. R., European Satellites, and China (see Robert McKinney, 1960, Background material for the review of the international atomic policies and programs of the United States, 86th Congress, p. 1613-1618). All of the maximum estimates are based on the assumption that U. S. reserves are at least equal to the crustal abundance of uranium in percent (0.00026) time 10^{10}, and that reserves elsewhere are proportionate (see figure 1 and table 1).

McKelvey, V. E., Butler, A. P., Olson J. C., and Gottfried, David, 1961, Uranium and Thorium Resources in the United States and World, Table 3 in Domestic and World Resources of Fossil Fuels, Radioactive Minerals, and Geothermal Energy: Preliminary Reports Prepared by Members of the U. S. Geological Survey for the National Resources Subcommittee of the Federal Science Council.

The significant fact in these tables is that the United States is estimated to have potential reserves from 700,000 to 2,300,000 metric tons of uranium in ores of comparable quality to those mined during the period 1948 to 1960. These ores have uranium contents ranging from 0.17 to 0.30 per cent, or contents ranging from 1,700 to 3,000 grams per metric ton.

Data are not given on the reserves of much smaller concentrations in the range of 50 to 100 grams per ton, but the quantities in this range in various black shales and phosphate rocks are very much larger.

According to the paper by Adams and associates (1962), the Conway granite in New Hampshire has an average thorium content of about 56 grams per metric ton. This rock crops out over an area of 300 square miles and has a thorium content of about 3×10^6 metric tons per hundred feet of depth.

From these data it is evident that the amount of uranium and thorium in concentrations of 50 grams or more per metric ton of rock at minable depths in the United States must be of the order of tens if not hundreds of millions of metric tons.

The significance of this will be apparent when the energy content of these nuclear fuels is compared with that of the world reserves of the fossil fuels. Assuming complete breeding, 1 gram of uranium or thorium upon fissioning will release 2.28×10^4 kilowatt-hours of heat.

The ultimate energy reserve of all the fossil fuels is about 28×10^{15} kilowatt-hours. The amount of uranium or thorium required to produce this much heat would accordingly be

$$\begin{aligned} \text{Mass of U or Th} &= \frac{28 \times 10^{15}}{2.28 \times 10^4} \\ &= 12.3 \times 10^{11} \text{ grams} \\ &= 1.23 \times 10^6 \text{ metric tons.} \end{aligned}$$

Hence, the uranium and thorium reserves in the United States occurring in rocks having a content of 50 or more grams per metric ton must be of the order of hundreds to thousands of times greater than the world's initial supply of fossil fuels. Also, a rock having a uranium or thorium content of 50 grams per ton is energetically equivalent to about 150 tons of coal or 650 barrels of crude oil per ton of rock.

It is clear, therefore, that if breeding becomes the established practice, we shall have achieved almost unlimited supplies of energy from the fissionable and fertile isotopes of uranium and thorium.

Waste Disposal of Fission Products

The principal remaining problem is the development of means for economical and safe disposal of the fission products. Mention has already been made of the fact that when 1 gram of U-235 is fissioned 0.999 grams of fission products are formed, consisting of a wide spectrum of isotopes in the mid-range of the table of atomic weights. According to F. L. Culler, Jr. (1955), Director, Chemical Technology Division, Oak Ridge National Laboratory, the fission products produced by 1,000 grams of U-235 with 30 per cent burnup, consist, after 100 days of cooling, of 230.00 grams of inactive isotopes, 15.93 grams of short-lived radioactive isotopes, and 16.61 grams of long-lived radioactive isotopes. The short-lived isotopes comprise fifteen different species with half-life periods ranging from seconds to 290 days. The long-lived isotopes consist of four species of which the two longest and most dangerous are ceasium-137 and strontium-90 with half-lives of 33 and 25 years, respectively. These occur in amounts of 7.05 and 4.63 grams, respectively, and represent about two-thirds, by mass, of the long-lived isotopes.

All of these radioactive fission products are extremely dangerous until they have decayed to the very low levels of tolerance prescribed for biological safety. A rule of thumb that has been used as an order of magnitude among the members of the Atomic Energy Commission's health physics division is that none of these materials can be considered to be safe for biologic exposure until a period of at least 20 half-lives has elapsed. For the short-lived fission products, this would be a period of the order of 20 years; for the long-lived isotopes the corresponding period would be at least 660 years, and possibly even 1,000 years.

On February 28, 1955, at the request of the Atomic Energy Commission, an Advisory Committee on Waste Disposal of the Division of Earth Sciences was established by the National Academy of Sciences—National Research Council. After a number of conferences with A. E. C. personnel and visits to Oak Ridge National Laboratory, the Committee issued a report dated April, 1957, in which, on page 3, the following basic principle was stated:

> Unlike the disposal of any other type of waste, the hazard related to radioactive waste is so great that no element of doubt should be allowed to exist

regarding safety. Stringent rules must be set up and a system of inspection and monitoring instituted. Safe disposal means that the waste shall not come in contact with any living thing. Considering half-lives of the isotopes in waste this means for 600 years if Cs^{137}, and Sr^{90} are present or for about one-tenth as many years if these two isotopes are removed.

At one of the earlier conferences, held in Washington, D. C., on November 15, 1954, the views on radio-active waste disposal of the Atomic Energy Commission were presented by Arthur E. Gorman. He pointed out that from the point of view of the A. E. C. the problem of where and how to dispose of high-level wastes is quite serious. Yet, at that time all such wastes were being held in underground storage tanks (stainless steel)--a practice which could only be regarded as a temporary expedient, since the period of activity of the long-lived wastes is much longer than the potential life of the tanks. In effect, they were buying time until a satisfactory ultimate disposal method could be worked out (Gorman, 1955, p. 2-3).

After the preliminary conferences mentioned above, the Committee concluded that the rate of generation of radioactive wastes at present is very small as compared with magnitudes which will be produced when the generation of power by nuclear fission begins its eventual exponential rate of growth. However, policies and practices initiated now should be of such a nature as still to be valid when the rate of production of wastes should be many times larger than it is at present. The total quantity of wastes was found not to be large, since if all the electric power produced in the United States at the present time were generated by nuclear-fission power plants, the fuel consumed and fission products produced per year would be only of the order of 100 metric tons.

With this in view the Committee reviewed the likely means of waste disposal, of which two were regarded with special favor: (1) in the salt mines or domes, preferably in solid form, and (2) in the form of heavy liquids in permeable sedimentary rocks in the bottoms of synclinal basins. It was pointed out, however, that none of the existing A. E. C. installations, and few of the proposed power plants, had been located at suitable waste-disposal sites, and it was suggested that eventually consideration should be given to locating power plants and waste-processing plants at suitable waste-disposal sites with either a regrouping of power distribution with respect to these sites, or else developing means for long-distance transmission of power to centers of consumption.

After five years, the Committee summarized its observations and recommendations in the following letter addressed to John A. McCone, Chairman of the Atomic Energy Commission:

NATIONAL ACADEMY OF SCIENCES

NATIONAL RESEARCH COUNCIL

DIVISION OF EARTH SCIENCES
2101 CONSTITUTION AVENUE, WASHINGTON 25, D.C.

June 21, 1960

Mr. John A. McCone, Chairman
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear Mr. McCone:

On February 28, 1955, arrangements were formalized between the Atomic Energy Commission and the National Academy of Sciences-National Research Council to provide advisory services on geological and geophysical problems related to the disposal of radioactive wastes on continental areas. Your Academy-Research Council Committee on Waste Disposal has been active for some 5 years, has held an important conference attended by about 75 scientists and engineers, has closely followed the results of research on disposal problems, and has held numerous meetings, both at AEC installations and elsewhere.

Early in its deliberations, the Committee reached the conclusion which was later stated on page 3 of the report of April 1957 that no system of waste disposal can be considered safe in which the wastes are not completely isolated from all living things for the period during which they are dangerous. This period for high-level wastes containing the long-lived isotopes of Cs^{137} and Sr^{90} is at least 600 years. After an extensive review of possible disposal methods which would satisfy the stringent conditions of safety set forth above, your Committee, in light of the technology then existing, favored the following:

1. Disposal within chambers excavated or dissolved in rock salt.
2. Deep disposal in sands or other porous and permeable rocks near the lowest parts of synclinal basins.

While it is possible that other safe disposal methods may be developed, your Committee still regards these as the most promising methods, and feels that no worthwhile advantage will be gained by further delay in stating its appraisal of the present situation, namely:

> No existing AEC installation which generates either high-level or intermediate-level wastes appears to have a satisfactory geological location for the safe local disposal of such waste products; neither does any of the present waste-disposal practices that have come to the attention of the Committee satisfy its criterion for safe disposal of such wastes.

The Committee's recommendations are as follows:

1. The Committee regards it as urgent that action be taken for the establishment of waste-disposal facilities at suitable geological sites where the accumulated wastes of the existing installations can be processed and safely disposed of.
2. Your Committee further recommends that approved plans for the safe disposal of radioactive wastes be made a prerequisite for the approval of the site of any future installation by the AEC or under its jurisdiction.
3. In particular, your Committee recommends that the Commission consider concentrating its chemical processing activities at a minimum number of sites located at satisfactory places for the disposal of radioactive wastes.

Sincerely yours,

H. H. Hess
Chairman

Committee Members

John N. Adkins	William B. Heroy	Charles V. Theis
William E. Benson	M. King Hubbert	William Thurston,
John C. Frye	Richard J. Russell	Secretary

This was prompted by the fact that the Committee did not feel that the budget for waste disposal was commensurate with the magnitude of the problem. The investigations were further hindered by a hope on the part of A. E. C. personnel that a suitable waste-disposal site could be found at or near each present installation.

It is here recommended that a much broader view of this problem be adopted, and that a budgetary increase for this purpose, amounting possibly to several fold, be allowed.

Energy from Fusion

Energy is obtained from fusion when hydrogen, or its heavy isotope deuterium, is combined into helium. The process is illustrated in Figure 59, showing three deuterium atoms combined to form one atom of Helium-4 plus one proton and one neutron with a release of energy of 9.61×10^{-19} kilowatt-hours of energy in the form of heat. Since the ratio of deuterium atoms to hydrogen atoms in water is about 1/6500, and the deuterium can be separated at an energy cost which is a fraction of 1 per cent of the energy potentially obtainable from fusion, we may estimate about how much energy could be obtained from various amounts of sea water. This has been done in Table 12.

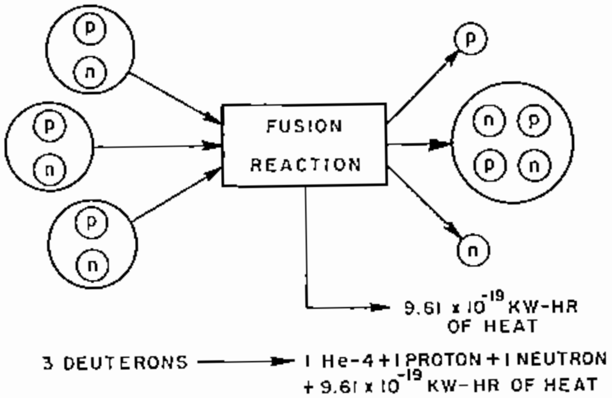

Figure 59. Possible Method of Producing Power by Fusion

The energy obtainable from 1 gram of water is about 3.30 kilowatt-hours of heat, or a little less than the heat of combustion of a pound of coal. The energy from 1 cubic meter of water is equivalent to that of 1,870 barrels of crude oil, and that from

TABLE 12

Energy Obtainable From Sea Water By Fusion

Volume of Water	Energy (kw-hrs heat)	Equivalent Coal or Oil
1 cm^3	3.30	0.9 lb coal
1 m^3	3.30×10^6	433 tons of coal or 1870 bbls of oil
1 km^3	3.30×10^{15}	4.33×10^{11} tons of coal or 1870×10^9 bbls of oil
0.67 km^3	2.20×10^{15}	1250×10^9 bbls of oil (estimated initial world oil reserves)
8.2 km^3	27×10^{15}	Total World Supply of Fossil Fuels

1 cubic kilometer to $1,870 \times 10^9$ barrels of crude oil, or to 1-1/2 times the crude-oil reserves of the world.

These circumstances, including the abundance of water on the earth, and the fact that the end-product is common helium which is nonradioactive, make the achievement of controlled fusion potentially one of the most important goals in the history of mankind.

This problem was reviewed at the conference on energy by James L. Tuck of the Los Alamos Laboratory. His report was one of tempered optimism. A great deal of essential fundamental knowledge is being acquired which, within a decade or two if not earlier, may permit solution of the problem of controlled fusion.

One point on which Mr. Tuck made a very strong plea was the prevention of present wastage of helium. Helium is absolutely essential in the cryogenic work to produce strong magnetic fields by means of superconductivity, and such fields appear to be indispensable as a container for fusion reactions.

A much more complete review of the problem of obtaining controlled fusion is given under the heading, "The Goals and the Problems," on pages 228-243 of "Research on Power from Fusion and Other Major Activities in the A. E. C. Programs," A. E. C. Semi-Annual Report, January-June, 1958.

It may be well to stress that in the reaction shown in Figure 59, one neutron is produced with each atom of Helium-4. Since neutrons not only produce fissioning in fissile isotopes, but render many other elements artifically radioactive, a fusion power plant may be difficult to operate on that account. Certainly very heavy shielding will be required, and to accomplish this it might prove desirable to locate such plants at a considerable depth underground.

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CHAPTER VII

OUTLOOK AND RECOMMENDATIONS

Recapitulation

From the review which we have just made it should be clear that our modern industrial civilization is distinguished from all prior civilizations, and from all contemporary civilizations in the so-called underdeveloped areas of the world, in its dependence upon enormous quantities of energy obtained from sources other than the contemporary biologic channel, and upon correspondingly large quantities of other mineral products, particularly the ores of the industrial metals. We have also seen that, although this development has had its beginning in the remote prehistoric past, most of it has taken place within the last two centuries, and principally since the year 1900.

Rates of Growth

We have seen how the progressive manipulation of the world's energy flux by the human species and, more recently, the tapping of the large stores of energy contained in the fossil fuels have continuously upset the plant and animal ecological equilibria, and almost always in the direction of increase of the human population. Consequently, during the last century or two—the period of history with which we are most familiar--the pattern of change which we have observed, and in which we have participated, has been of almost continual growth--growth of the world population at an increasing rate which has now reached 2 per cent per year, growth of the United States population from the first census in 1790 until 1860 at 3 per cent per year, growth in the world rate of industrial energy consumption for nearly a century at 4 per cent per year, and of United States consumption at 7 per cent per year.

Yet when reviewed in historical perspective, we have seen that these recent developments have had no precedents in human history, and that the rates of growth we have been witnessing, instead of being the "normal" order of things, are in fact the most abnormal in human history--the usual, or normal, state of affairs being one in which the magnitudes of various human activities have been subject to an almost imperceptible rate of change.

That such rates of growth are essentially ephemeral, and cannot be continued into the future indefinitely, can be seen by noting that the earth on which we live is finite in magnitude; whereas no physical quantity, whether the human population, the rate of energy consumption, or the rate of production of a material resource such as a metal, can continue to increase at a fixed exponential rate without soon exceeding all physical bounds.

For example, during most of the nineteenth century the rate of production of pig iron in the United States increased at 6.4 per cent per year. At such a rate of growth the production rate doubled in 11 years and increased 10-fold in 36 years. By 1900 the production rate had reached 15.4 million metric tons of pig iron per year. With eight more 10-fold increases the rate of pig iron production would be increased by 100 millionfold, or to 15.4×10^{14} metric tons of pig iron per year. At a steady rate of increase of 6.4 per cent per year this would take place during eight 36-year periods, or in 288 years.

The figure of 15.4×10^{14} metric tons is approximately the estimated total iron content (at 4.7 per cent average iron content by weight) of the rocks of the United States to a depth of 2,000 meters, or 1.2 miles. It is manifestly a physical impossibility to continue the nineteenth-century rate of growth until production rates anywhere near this magnitude have been reached. The growth rates not only must decline, but in all instances where exhaustible resources are concerned they must eventually become zero and then negative, as is shown in Figure 17.

For a renewable resource, such as water power, instead of the quantity of energy involved having some definite amount, it is the power which is finite. The growth curve with which we are then concerned is the amount of this power that is brought under control and converted to human uses as a function of time. Such a curve would be that of installed water-power capacity. This must start at zero; and then, after a period of growth, it must eventually level off asymptotic to some maximum amount, which may approach but cannot exceed the water power naturally available in a given area. This is the type of growth represented by the logistic growth curve of Figure 55.

Then we have the growth curves of biologic populations, of which that of the human population is only a particular example. Since the normal ecologic state is one in which biologic populations are nearly constant, or else oscillate with nearly constant amplitudes, as is the case with annual plants and insects, it follows that any rapid departure from this state must be due to some major disturbance.

It is well known, and has been shown experimentally in detail by Raymond Pearl (1925), that when a population sample of any biologic species is isolated from its ecological system and placed in a favorable artificial environment, this population will increase spontaneously at an exponential, or geometrical, rate. However, because of the finite size of the space in which this experiment must be performed, the geometrical rate of increase can continue only for a limited number of doublings before the rate of increase begins to slacken, and decreases ultimately to zero. The population itself increases in the manner of the S-shaped logistic growth curves shown in Figures 22 and 23, a type of growth which is described analytically by equation (7). In fact, the name "logistic curve" was first given to this type of curve, and its basic theory derived by the Belgian mathematician, P.-F. Verhulst (1838; 1845; 1847), in a series of celebrated memoirs on the law of population increase.

In case the food supply, rather than space, is a limiting factor, the population may reach a maximum and then decline and stabilize at some lower level. Or, of course, if the food supply fails it can decline to zero.

In a natural ecological environment (Lotka, 1925), conditions are much more complex. In a near-equilibrium state populations tend to remain nearly constant or to change very slowly with time. However, in response to some major disturbance <u>all</u> populations of the complex undergo rapid change (Figure 60). Some increase by a positive logistic growth to some higher number than before; others decrease and level off at some lower number; some may even become extinct.

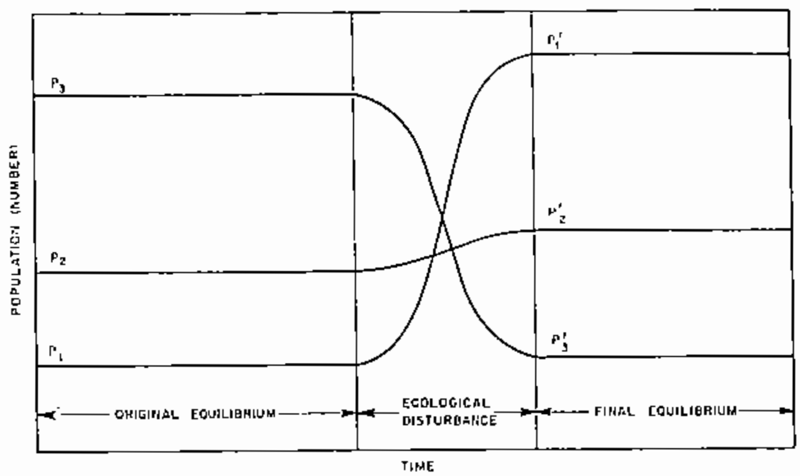

Figure 60. Population Changes Due to Ecological Disturbance

The significance of this to our present inquiry is that the whole biologic complex of the earth is at present in the midst of one of the greatest ecological upheavals known in geological history. The various biological populations are about mid-range in their transitions from their earlier near-equilibrium states to new equilibria at markedly different levels. In this transition some populations, notably that of man, are increasing; others, including most of the familiar wild animals and most native plants, are decreasing; some have already become extinct.

Because the earth is of finite magnitude, it is unavoidable that the present abnormal rate of increase of the human population must eventually slow down and ultimately become zero or even negative. The population itself may level off asymptotic to some maximum number, or it may overshoot and stabilize at a lower, more nearly optimum figure. Or, in the event of a general cultural degeneration, it may be forced back to some level that could be sustained by the industry of a more primitive culture.

The alternatives faced by the human population at the time of the inevitable cessation of growth, as was pointed out by Frank Notestein during an informal panel discussion at Northwestern University on the occasion of its Centennial Celebration in 1951, are the following:

When the population growth ceases, the birth rate and the death rate (number of births per thousand per year, and number of deaths per thousand per year) must become equal. From the point of view of one who has to be a member of the population at that time, the question might be asked: What would be a desirable condition under which to live? Notestein suggested that a high standard of public health might be a major attribute of a desirable condition for existence.

However, a high standard of public health implies a long expectancy of life, which in the United States and Western Europe at present is about 70 years. With a life expectancy of 70 years, and an equilibrium birth rate and death rate, 1/70th of the population would have to be replaced per year, which, on a per-thousand basis, would be 1000/70, or a death rate and birth rate of about 14 per thousand per year.

In case this low birth rate should be unacceptable to the population, and its members insisted upon breeding at the biological rate of 40-50 per thousand per year, then the death rate would have to rise to the same figure. As a result the life expectancy would be reduced to 20-25 years, characteristic of a very low state of the public health. Hence, such a population could choose to have either a high standard of public health or a high birth rate, but it could not have both.

Nonfuel Mineral Resources

We have discussed in detail in the present report the nature of the supplies of the fossil fuels, and have shown that they can be expected to serve as principal sources of industrial energy only for a period of about 300-400 years. During this period petroleum and natural gas will be the earliest of the fossil fuels to approach depletion, with their span of greatest usefulness lasting less than a century. We have not made a corresponding review of mineral resources other than energy, since this is the subject of a companion report by Dean F. Frasché (1962). Nevertheless, since our modern industrial complex depends upon large supplies of both energy and nonfuel minerals, mention of the latter needs to be made in our appraisal of our present position and possible future evolution.

Like the fuels, the nonfuel mineral resources are distributed over the earth in a highly inequitable manner. The principal industrial minerals until now have been coal and iron ores, and the world's regions of industrialization have been limited to the areas of the northern hemisphere, where large quantities of coal and iron ores have occurred in proximity to one another. In countries like Brazil, which has large reserves of iron ore but almost no coal, significant industrialization has so far been impossible. Brazilian iron ores have been transported to the United States and other industrial centers where coal is available.

The mining of metallic ores customarily proceeds from deposits of highest grade, and, as these are exhausted, either mining must cease or else ores of progressively lower grades must be produced. In the United States the high-grade iron ores (50 per cent iron content or better) of the Lake Superior region have already been largely exhausted and mining of the lower-grade (30 per cent iron content) taconite ores is proceeding. The average grade of the copper ores mined in the United States has been declining for some decades, and today ores with a copper content as low as 17 pounds per ton, or 0.8 per cent, are being mined. A century ago most copper producers required ores with an average copper content of not less than 10 per cent; today the world average is 1.5 per cent (Pehrson, 1962, p. 25).

The mine production of lead in the United States reached a peak rate of 684,000 short tons per year in 1925 and 1926, and by 1960 this rate had declined to 244,000 tons, or to 36 per cent of the peak rate. Similarly, the United States production of zinc reached two peaks of about 775,000 short tons per year each, the first in 1926 and the second in 1942 during the war. By 1960 the production rate had dropped to 432,000 tons per year, or to 56 per cent of the peak rate.

The approximate world situation as of 1956 for six of the principal industrial metals--aluminum, iron, zinc, copper, lead and tin--is shown in Table 13. This is taken from a table by Elmer Walter Pehrson (1959, p. 3) of the United States Bureau of Mines, but is based on work by the German mineral economist, Ferdinand Friedensburg. In the first two columns the average percentage content and the total content of each metal in the upper 2,000 meters of the lithosphere are shown. In the following columns data for each metal are given on: (1) the estimated exploitable reserves by present methods, (2) the ratio of exploitable reserves to the total amount of the metal in the ground, (3) the 1956 rate of production, and (4) the number of years supply of exploitable reserves at the 1956 rate of production.

TABLE 13

Quantitative Comparisons of Theoretical Resources and Exploitable Reserves In The Earth's Crust With 1956 World Production, For Selected Metals[a]

(Pehrson's Table 1)

Element	Theoretical Availability[b]		Estimated Exploitable Reserve, billion (10^9) metric tons	Ratio, Exploitable to Theoretical, One to:	1956 World Production, metric tons	Years of Supply in Exploitable Reserve[c]
	Average Content, per cent	Total Resource, billion (10^9) metric tons				
Aluminum	7.48	58,366,000	2.0	29,000,000	3,500,000	570
Iron	4.7	36,674,000	50.0	700,000	200,000,000	250
Zinc	0.017	133,000	0.07	2,000,000	3,100,000	23
Copper	0.01	78,000	0.10	800,000	3,500,000	29
Lead	0.003	23,000	0.04	600,000	2,100,000	19
Tin	0.0005	4,000	0.007	600,000	200,000	35

[a]Based largely on the study by Ferdinand Friedensburg, "The Future Supply of Metals," Zeitschrift für Erzbergbau und Metallhüttenwesen, Dec. 1957, pp. 573-576.

[b]Content of lithosphere to a depth of 2,000 meters; estimated gross weight 780×10^{15} metric tons.

[c]At 1956 rate of production.

It is significant that for only two of the metals, aluminum and iron, is the number of years supply of estimated exploitable reserves larger than 100 years. The years of supply of the other four metals range from 19 to 35 years. The ratios of the total content of each metal to the estimated exploitable reserves range, however, from 600,000 to 29 million.

These data emphasize two basic facts of the mineral industry:

1. The estimated world supply of metallic ores of grades now capable of utilization for most minerals is measurable at present rates of production in decades rather than in centuries.

2. The total amount of each metal occurring within minable depths is, on the average, the order of a million times larger than the amount of metal contained in currently exploitable grades of ore.

In principle, it is possible to mine and extract the metals from rocks having much lower metallic contents than present ores, but to do so would require much higher expenditures of energy per unit produced than is required at present, and would also require a much more sophisticated technology, particularly in the direction of large-scale industrial chemistry.

Mineral Requirements to Industrialize Undeveloped Areas.

A problem closely related to that of the mineral and energy requirements of the presently industrialized areas of the world is the question of how much larger these requirements would be if the world were to be industrialized to the extent that has now been reached in the United States. An approximate answer can be given to this question by noting that the United States, with 6 per cent of the world's present population, consumes approximately 30 per cent of the world's total current production of minerals. Let $\underline{M}_1$ be the present rate of mineral production, and $\underline{M}_2$ the rate that would be required to give the total world population the same per capita mineral consumption as that in the United States. Let $\underline{P}$ be the world population, and $\underline{C}$ the United States per capita consumption.

[a] Based largely on the study by Ferdinand Friedensburg, "The Future Supply of Metals," Zeitschrift für Erzbergbau und Metallhüttenwesen, Dec. 1957, pp. 573-576.

[b] Content of lithosphere to a depth of 2,000 meters; estimated gross weight 780 × 10^{15} metric tons.

[c] At 1956 rate of production.

Then the per capita consumption for both the United States and the world would be

$$C = \frac{0.3\ M_1}{0.06\ P} = \frac{M_2}{P}.$$

Solving this for $\underline{M_2}$ then gives

$$M_2 = 5\ M_1\ .$$

In other words, if the whole world were industrialized to the same level as is the United States, the annual drain on the world's mineral resources would be about five times what it now is.

This neglects the fact, however, that before any area can reach the per capita energy and mineral consumption rate of the United States, it must first build up its industry to that level. Were the whole world to have done this, the minerals and energy required would have been about five times the present cumulative production of the world. At such a world rate of consumption the middle 80 per cent of the world's supply of crude oil and natural gas would be consumed during a period of about 15-20 years, and the corresponding period for coal would be reduced from about 350 years to less than a century. Moreover, the presently estimated world supply of the ores of most industrial metals, producible by present technology, would have been exhausted well before such a level of industrialization could have been reached.

Hence, so long as the world depends on the fossil fuels as its principal source of industrial energy, there appears to be little ground for the humanitarian hope of significantly improving the standard of living by industrialization of the underdeveloped areas of the world. For the same reason, there is not very much promise that the activities of the highly industrialized areas can be maintained at anything like present levels for more than a few centuries, and there are possibilities that shortages may develop before the end of the present century.

Necessity of Nuclear Energy.

If a world-wide industrial collapse due to the exhaustion of the fossil fuels and the high-grade ores of metals within the next few centuries is to be forestalled, there appears to be no possible way of accomplishing this except by a newer and larger supply of energy suitable to the requirements of large-scale industrial operations. We have already observed that, while solar power is of this magnitude, it does not offer much promise of concentration such as to provide the power for large electric-power networks. Water power is of a lesser magnitude, but still large and capable of providing power in the hundreds-of-megawatts range in many parts of the world. It still, however, is not large enough, and besides it requires prior industrialization before it can be developed and used.

The only remaining source of energy that does have the proper magnitude and does lend itself to large industrial uses is nuclear. We have already seen that the supplies of uranium and thorium in the United States alone, occurring in concentration of 50 grams or more per metric ton of rock within a depth of 2,000 meters, have an energy content at least hundreds of times, and possibly thousands of times, greater than that of all the fossil fuels in the world. We have noted further that the energy content of 1 metric ton of such rock is equal to that of 150 tons of coal or 650 barrels of oil. Therefore, even if the extraction of this uranium or thorium should require energy equal to a few tons of coal or barrels of oil per ton of rock, the net amount of energy obtainable per ton of rock should still be many times greater than that from an equivalent mass of any fossil fuel.

The resources of fission energy, uranium and thorium, and of fusion energy, deuterium or heavy hydrogen, are quite as exhaustible as the fossil fuels, but the quantities are so large that it is doubtful if any significant diminution of the total reserves could be effected by industrial uses within the next thousand years. Hence, for all present purposes, nuclear energy may be regarded as being essentially inexhaustible in terms of human usage.

With such quantities of energy available, it then would become both possible and practical to work the lower and lower grades of metallic ores, and in so doing to begin to realize a part of the potential million-fold increase in reserves indicated in Table 13, thus forestalling the otherwise imminent shortages of many of the industrial metals. With a source of energy of this magnitude, and the additional quantities of metals which would thus become available, the dream of improving the standards of living of all the races of man no longer appears so visionary.

Time Perspective

The present state of human affairs can perhaps more clearly be seen in terms of a time perspective, minus and plus, of some thousands of years with respect to the present, as depicted in Figure 61. On such a scale the phenomena of present interest--the growth in the rate of consumption of energy, the growth of the human population, and the rise in the standard of living as indicated by the increase in the per capita rate in energy consumption--are all seen to be represented by curves which are near zero and rising almost imperceptibly until the last few centuries. Then, after an initial gradual increase, each curve, as the present is approached, rises almost vertically to magnitudes many times greater than ever before.

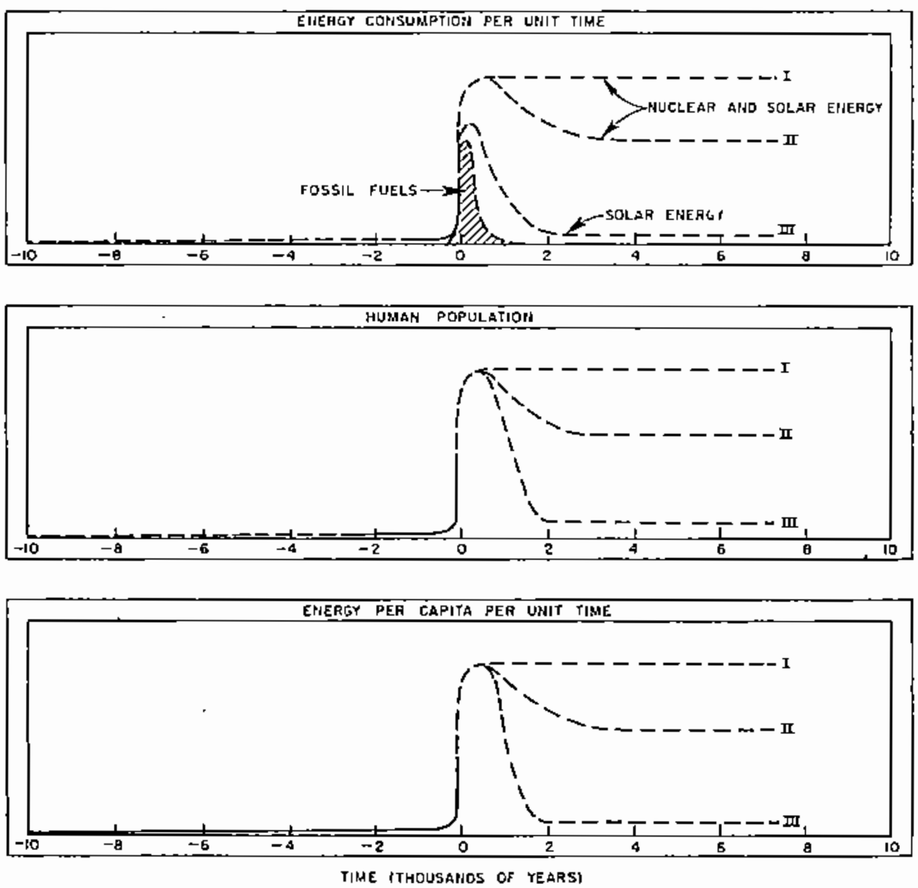

Figure 61. Human Affairs in Time Perspective

On this time scale the consumption of fossil fuels is seen to rise sharply from zero and almost as sharply to descend, with the total duration of the period of consumption representing but a brief interval of the total period of human history.

As to the future, if we disallow imminent annihilation by nuclear warfare, three distinct possibilities appear to exist. These are represented on the graphs as Courses I, II and III. One possibility, shown as Course I, is that we may be able to maintain our present scientific and technological culture, using the fossil fuels as an essential intermediate step in the transition to ultimate dependence upon the large-scale use of nuclear energy. Should this be successfully accomplished there appear to be no physical reasons why we should not be able to level our activities off asymptotically to some maximum level which could be maintained for many centuries.

There is also a possibility, indicated as Course II, that we may not succeed in overcoming the cultural lag between our inherited folkways and our present requirements in time to prevent a serious overshooting of the world population above a manageable magnitude. After a temporary state of chaos we might still be able to stabilize our population and the magnitude of our industrial activities at some lower and more nearly optimum level which could be maintained for a long period of time.

Finally, there is the possibility, indicated as Course III, that we could go into a state of confusion and chaos, including nuclear warfare, from which we might never be able to recover. In that case we could suffer a cultural decline and return to our former agrarian and handicraft level of culture. At what level the population would become stabilized in this event it is not possible to state with any assurance, but since modern medicines and techniques of public health are a by-product of our present culture, and not otherwise possible, it appears doubtful whether a population nearly as large as that of the present could be sustained.

Which of these three possibilities may be the one actually realized depends largely upon the foresight that can be exercised with respect to the guidance of human affairs, and in large measure on whether the cultural lag can be sufficiently reduced between the inhibitory sacred-cow behavior patterns which we have inherited from our recent past and the action requirements which are necessitated by the socio-industrial complex with which we have to deal. If such impediments can be overcome it is entirely possible that, with only minor extensions of our present knowledge of the physics, chemistry, biology and geology of the world in which we live, we shall be able to make the transition to a stabilized industrial civilization with a decent standard of living and a high standard of health for all the world's human inhabitants. If we are unable to make this transition, and if we do permit ourselves to go into a cultural decline, then, as Brown, Bonner, and Weir (1957, p. 151) have pointed out, it is doubtful whether we shall ever be able to arise again.

Recommendations

If our future evolution is to follow one of the more desirable paths--one characterized by a high per capita utilization of energy, a general state of individual well-being, and a high standard of public health--then it is clear that a number of essential steps must be taken, some sequentially and others in parallel. Among the more important of these are the following:

I. The growth of the world's population must be brought under control.

While this is a problem of formidable magnitude, it is not intrinsically more difficult than the control of disease, in which the medical profession has already achieved marked success. The present flare-up of the world population is in fact the consequence of this success. Until comparatively recently, as we have noted, the world population was almost stationary. The birth rate and death rate were nearly equal but also near the biological maximum of 40-50 per thousand per year, with a life expectancy of 20-25 years.

During the last few centuries, and particularly during the last few decades, the death rate, world-wide, has been dropped spectacularly to a present average value of about 20 per thousand, while the birth rates of most of the world's population have been but little reduced. The difference between the birth rate and the death rate is a direct measure of the rate of population growth.

If the desirable objectives mentioned above are to be achieved, it is essential that the death rate and birth rate must be equalized at a low level compatible with a high standard of public health (about 15 per thousand). If this is not done, assuredly they will eventually become equalized at a level corresponding to a low standard of public health.

This is partly a problem in physiological and medical research and partly a problem in applied sociology and anthropology. As a measure of what can be accomplished when the problem is faced forthrightly, we have the recent experience of the Japanese (Cook, 1959). Here, we have a nation with a population half that of the United States which has deliberately dropped its birth rate during the ten-year period 1947-1957 from 34.3 to 19.2 per thousand, the most rapid decrease known in history.

II. New sources of energy must be developed.

As sources of energy for the world's future needs, the fossil fuels are exhaustible, solar power cannot practicably be concentrated, and water power, though large, is inadequate. This leaves us ultimately with only nuclear energy as a source which is both adaptable to large-scale power generation and of sufficient magnitude to meet the world's potential requirements.

Fossil Fuels. Since the fossil fuels are adequate to meet the limited needs of the presently industrialized areas of the world for the next few centuries, there is obviously no immediate emergency as to energy supplies for these areas. Neither, however, are there grounds for complacency, because most of the areas of the world are not industrialized and, so long as we depend upon the fossil fuels, are not likely to become so.

Among the fossil fuels themselves, because petroleum and natural gas are the least abundant and coal the most abundant, it is evident that in the comparatively near future a transition must be begun from crude oil and natural gas to the more abundant reserves of oil shale and tar sand, and ultimately to coal, for our supplies of liquid and gaseous fuels. This transition, utilizing the large research establishments of the petroleum industry, will probably be made in an orderly manner as rapidly as new sources of liquid and gaseous fuels are required, and no additional research effort in this field appears to be needed.

In the coal industry proper, however, there is need for increased integrated research in all phases of production, processing, and transportation. Research of this kind would particularly benefit by a reorientation in which coal is regarded as an energy and organic-chemical raw material rather than as just a fuel, much as crude oil is regarded by the petroleum industry.

Although coal represents nearly 80 per cent of the energy reserves of the fossil fuels in the United States, it has been a depressed industry, largely because of a displacement by oil and gas, since World War I. One of the largest bottlenecks in present coal utilization arises from the prohibitive costs of railroad transportation. Promise of eliminating this bottleneck is now afforded by the recent successful developments in the transportation of coal in the form of a coal-water slurry by pipeline at a greatly reduced cost. The present impediment to this form of transportation is the lack of the right of eminent domain for coal pipelines. The granting of this right by means of the legislation proposed by President John F. Kennedy in his letter of March 20, 1962, to both houses of Congress, is highly recommended.

A needed restriction in the uses of coal should also be mentioned. Of all the coal reserves in the United States only a small fraction is suitable for the manufacture of metallurgical coke, which is particularly essential for the smelting of iron ore. Much of the coking coal has already been indiscriminately mined and burned as fuel. A control is needed whereby only noncoking coals are burned as fuels, reserving the more valuable coking coals for the metallurgical industry.

Nuclear Energy. The eventual dependence upon nuclear energy as the principal source of industrial power in areas which now have abundant fossil fuels, and the immediate needs in other areas, makes it essential that research and development in this field should be vigorously pursued. With regard to fission energy, there are two very important problems. The first is the development of power reactors based upon complete or nearly complete breeding. This will permit the utilization not only of common uranium-238 but also of thorium-232. More importantly, it will make it economical to consider rocks with uranium and thorium contents as low as 50 grams per metric ton as practically utilizable ores, and so will enormously enhance the magnitude of the reserves of nuclear fuels.

The second problem associated with fission reactors is that of safe disposal of the highly dangerous radioactive fission-product wastes. These wastes, some of which are dangerous for the order of a thousand years, must be completely isolated from the biological environment for their periods of danger. Up to the present, the work in this field has not been pursued with a vigor commensurate with its importance. It is recommended that the budgetary support for such work be increased considerably--possibly several fold--over the average of the last few years.

The control of the fusion reaction--deuterium to helium--possibly represents the greatest energy goal now known. The problem is one of very great difficulty and may never be solved. Nevertheless, what is most needed at this stage of development is systematic, long-range, fundamental research of the type now being pursued, rather than some kind of a crash program. Continuation of this research at about the present level is recommended.

Synthesis of Chemical Fuels. Automotive vehicles for both highway and air transportation are dependent for their energy supply upon the energy stored chemically in the form principally of liquid fuels, and, so far as can now be seen, will continue to be so. Heretofore these fuels have been obtained almost solely from the fossil fuels in which the energy was originally stored by photosynthesis. On the other hand, it has long been known to be possible to manufacture simpler but equally useful fuels by means of the schematic chemical reaction

$$\text{Energy} + CO_2 + H_2O \rightarrow \text{Fuel} + O_2.$$

This has not been done because the energy required for the reaction would have to be obtained by burning already synthesized fossil fuels.

With the advent of nuclear energy this situation is drastically changed. Here, with an almost unlimited supply of energy potentially available, it would be a comparatively simple matter to synthesize any desirable quantity of liquid and gaseous fuels from common inorganic substances such as water and limestone. Were this eventually to be done, our remaining fossil fuels, comprising already synthesized complex organic molecules, could be more effectively used as the raw material for an increasingly versatile chemical industry.

III. Eventual dependence upon low-grade deposits for our principal supplies of industrial metals, and of other nonfuel mineral products, must be anticipated.

Since this has been covered in a companion report on "Mineral Resources" by Dean F. Frasché, it will not be further discussed here. It is mentioned only to emphasize the fact that the nonfuel mineral resources, together with the energy resources and the population problem, constitute a triumvirate of perhaps the foremost problems now confronting the human race.

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