Earth Resources

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The earth with all its biological inhabitants, including man himself is a complex evolving system which normally exists in a state of stable dynamic equilibrium. This global system is open with respect to the flow of energy (see Fig. 5), most of which comes initially from the sun and is eventually lost to outer space; but it is closed with respect to matter, the amount of which is fixed, with only the state and distribution changing. Energy flowing through the system drives a complex array of interdependent material cycles, including among others: the hydrologic cycle, the rock cycle, and the various biogeochemical cycles and food chains of the biosphere. Under equilibrium conditions each of these cycles involves a continual recirculation of some part of the earth's finite supply of basic material resources. Collectively they comprise a global ecosystem that is the product of some 4.5×10^9 years of gradual evolution, during which, whenever some fundamental change disrupted the stable equilibrium of the system, the system reacted (in accordance with Le Châtelier's Principle) in such a way as to minimize the effects of that change and to achieve a new and different state of stable dynamic equilibrium. It is only within the short span of the last few centuries that mankind has emerged as the dominant source of profound change and instability in this system. The human species has become singularly unsuccessful in devising ways of circumventing the controls which normally tend to maintain a steady state in the ecosphere, and now the effects of human intervention are increasing at an accelerating pace.

Growth at a steady or increasing rate, in the human population, in the per capita consumption of nonrenewable earth resources, and in the degree of human disruption of long established natural ecosystems, has been the hallmark of man's recent and rapid emergence as the dominant species on the face of the earth. This growth, and the rapid changes which are a natural consequence of it, have had such a pervasive influence on the collective human experience of contemporary man and his recent ancestors that they have come to be regarded as the normal course of events on a stable earth whose biological inhabitants are in a state of equilibrium with their environment. This has fostered the popular notion that growth is synonymous with progress and that further improvements in the quality of life will be contingent upon steady or increasing rates of growth. This in spite of the self-evident fact that growth at a steady or increasing rate cannot be sustained indefinitely within the physical limits of a finite earth. It must come to an end soon; but how soon, and in what way?

Growth at a fixed or increasing rate is perceptually deceiving. The periodic doublings of the quantities involved lead unexpectedly to explosive increases, the implications of which are elegantly illustrated in the simple riddle that was cited in The Limits to Growth:

> Suppose you own a pond on which a water lilly is growing. The lily plant grows at a fixed rate, doubling in size each day. If the plant were allowed to grow without interference it would completely cover the surface of the pond in thirty days, choking off the other forms of life in the water. For a long time the lily plant seems small, and so you decide not to worry about cutting it back until it covers half the pond. On what day would that be?
>
> On the twenty-ninth day, of course. You then will have one day to save your pond.

The emergence and contemporary rapid growth of a global technological society, with all its concurrent ecological disturbances, including that of the human species itself, has only been made possible because of man's collective ingenuity of devising ways of capturing an ever-increasing proportion of the energy available at the earth's surface, and in using this energy to exploit an ever-larger proportion of earth's store of natural resources and to overcome the constraints that are imposed on the human species by the long-established natural ecosystems of which it is a part. Initially, the growth in human energy consumption and technology was very slow indeed. The ancestors of the present human species, from about 5,000,000 years ago, when they began to walk upright, until about 500,000 years ago, when the first of them began to use fire, had access to a per capita daily energy supply of only some 2200 kilogram-calories (approximately 2.5 kilowatt-hours) which was derived exclusively from the food they ate. In some of the "underdeveloped" parts of the world the average daily per capita consumption of energy reamins close to this level, but in the more highly industralized "developed" countries it has risen rapidly to about 200 kilowatt-hours, and in some regions within these countries it is many times as high. Man first began to cultivate crops and to use domesticated animals about 10,000 years ago. He learned to use fire to smelt and work metals not long afterwards, and the power of the wind and of running water were first harnessed only a few thousand years ago, but the meteoric rise of our modern technological society did not begin until the developing technology of the industrial revolution, some two hundred years ago, made possible the large-scale exploitation of the earth's fossil-fuel resources. This development marked the threshold of our current ecological crisis. A positive feedback relationship developed between growth in technology and growth in production of fossil fuels. The availability of large supplies of energy fostered rapid growth in technology which, in turn, provided ready access to even larger supplies of energy that fuelled further growth. This relationship is responsible for the ensuing explosion in rates of technological development, of nonrenewable mineral resource consumption, and of environmental deterioration, as well as for mankind's growing dependence on the continuation of this growth for its very well-being. The full impact of the threat posed by this explosive growth only appears in all its enormity when viewed from the perspective of geologic time and the relationships of human history to the history of the earth (Fig. 1).

TIME

The very essence of the problem is man's perception of time. Our understanding of time and the changes that are now overtaking us is clouded by the normal scale of our observation of these phenomena -- the personal experiences of the individual spread over the short span of his individual life. To perceive more it is necessary to adopt a different perspective, at a different scale of observation -- one that encompasses the whole earth and all of its history, including that small part in which mankind plays its role. This change in perspective can have important consequences in shaping our perception of the nature of the world and man's place in it.

If we imagine that it is midnight on December 31, 1975 and that we are looking back through earth history using a compressed scale of time in which one year of earth histroy corresponds with one second in our lifetimes (Figure 1), the normal lifespan of a human being lasts about one minute, and the industrial revolution -- taking the introduction of the steam engine as its beginning -- started four minutes ago. The earth came into being almost 140 years ago, but the race of man itself has been on the earth for only one month. Man began using stone implements about two weeks ago, and fire during the last week. Mining and agricultural activities have been underway since 9:00 p.m. and some of these were recorded iin man's first writings at about 10:30 p.m. It has been half an hour since man began harnessing the power of the wind; and the systematic exploitation of the earth's fossil fuel resources has been underway for 15 minutes; but petroleum production did not begin until 2 minutes ago, and 90 percent of the world's petroleum resources can be expected to have been exhausted within one minute from now. The use of electrical energy has grown to its present level of pre-eminence in less than two minutes and may be expected to continue to grow at about the same rate. The contribution from nuclear power has only been with us for 18 seconds, and is small but growing very rapidly. The profound changes of the last few minutes are but a token indication of what can be expected in the immediate future.

MINERAL RESOURCES

A clear distinction between mineral resources and mineral reserves is fundamental to any appraisal of the world's future supplies of mineral commodities or fossil fuels (Figure 2a). Mineral resources comprise all those discrete concentrations of naturally occurring materials in or on the earth from which it now is, or may some day become, economically feasible to extract one or more mineral commodities; whereas mineral reserves consist only of those specific portions of the earth's mineral resources which actually have been "discovered", and for which it has been demonstrated, on the basis of geologic evidence and supporting engineering measurements, that one or more mineral or energy commodities can be extracted economically, under present social and political conditions, using the technology that is available now. Accordingly, conclusions about the limits to growth that are based on appraisals of mineral reserves alone may be misleading. Mineral reserves are variable quantities. They change in maginitude not only because they become depleted through exploitation, but also because they are augmented by new engineering measurements, new geological discoveries, and new developments in technology, and either augmented or reduced by changing social, political and economic conditions. Mineral resources, on the other hand, are fixed quantities that include, in addition to reserves, other known and specifically identifiable mineral concentrations that may not be exploitable under existing conditions, but may become exploitable, as well as still other undiscovered concentrations that are now or may become exploitable, but whose existence can only be inferred from geological reasoning.

Estimates of the finite magnitudes of the earth's mineral resources depend on two fundamentally different kinds of information: geological appraisals of what is actually available at various levels of concentration in different parts of the earth; and technologic and economic forecasts of what part of this material it eventually may become feasible to exploit. The geologic appraisals can be made relatively objective, but the technologic and economic forecasts become largely matters of personal judgement as one looks further into the future.

The geochemical reservoir from which most economically exploitable mineral concentrations are extracted is the earth's crust. Some elements, such as aluminum and iron, have a high average abundance and relatively uniform distribution in the crust; others, like mercury, have an extremely low average abundance in the crust and in most common rock types. Accordingly, the level of concentration necessary to produce an orebody varies widely from one element to another; and, on this basis, the industrial metals can be grouped into three main categories for purposes of assessing global mineral resources: (1) elements of high crustal abundance ($>$1000 ppm) such as iron and aluminum; (2) elements of intermediate crustal abundance (1000 - 10 ppm), such as copper, cobalt, nickel, chromium, zinc, and lead; and (3) elements of low crustal abundance ($<$10 ppm) such as mercury, tungsten, tantalum, silver, tin, and molybdenum. Iron, copper and mercury provide examples of the world resources for each of these categories.

Iron

Iron is one of the most abundant elements in the crust of the earth. It comprises 5.8 percent (1.4 x 10^{18} metric tons) of the total crustal mass of 24 x 10^{18} metric tons. The upper part of the continental crust contains on the average 3.5 percent iron; and basalts which are among the most common rocks at the earth's surface, have an average content of 8.6 percent iron. The concentration of iron in ores which are mined today varies between 25 and 65 percent - between 7 and 19 times the average level in the upper part of the continental crust or between 3 and 8 times that for basalts. However, in these ores iron is bound to oxygen in minerals such as hematite, geothite and magnetite, whereas in normal rocks most of the iron occurs in silicate and sulfide minerals.

The critical factor in determining whether an iron-rich deposit constitutes an ore, and therefore, in measuring iron-ore reserves, is not just the amount of the metal in the deposit, but the unit cost of producing pig-iron made from the deposit. During the last twenty years many low-grade deposits have proven to be more economical to beneficiate than higher grade deposits containing 55 to 60 percent iron, and much of the iron production added since 1954 has been based on low-grade deposits.

The annual world production of iron ore has been growing exponentially (Figure 3) since at least 1850; and during the last few decades the rate of growth has been steady at about 4.8 percent per year (Figure 4). The cumulative world iron ore production during the 122-year period from 1850 to 1971 was 20 x 10^9 metric tons, of which 11 x 10^9 metric tons were produced in the 22-year period from 1950 to 1971. We might take comfort in the knowledge that the total known world reserves are 13 times, and the total estimated world resources 27 times the cumulative production since 1850; except for the fact that if the exponential growth in annual production were to continue at the current rate, the total world resources, as estimated by the United Nations in 1970, would be depleted by 2052. If these resources were increased by a factor of 10, to 7820 x 10^9 metric tons, the time of depletion would only be extended 47 years to 2099. Moreover, if the calculation is repeated using quantities of iron rather than iron ore, it can be shown that in order to maintain the current rate of growth in production for another 395 years it would be necessary to mine a mass of rock equivalent in volume and grade to the entire crust of the earth!

Copper

Average abundances of copper in common types of rocks and sediments are listed in Table 1. From these the average abundance of copper in the upper continental crust can be estimated at 24 ppm (24 x 10^{-4} percent). The lower crust probably contains about twice as much copper. The oceanic crust which comprises about one-third of the total volume of the volume of the earth's crust is, because of its basaltic character, appreciably higher in copper (85 ppm) than the continental crust.

Table 1

Average abundance of copper

	ppm
Magmatic rocks:	
Granites, granodiorites, quartz diorites	13
Diorites, andesites	53
Gabbros, basalts	90
Sediments and sedimentary rocks	
Graywackes	20 - 50
Sandstones	6 - 33
Shales and clays	35
Bituminous shales and clays	95
Deep sea clays:	
Atlantic	114
Indian Ocean	199
South Pacific	259
North Pacific	433
Limestones	6

The copper content of ores which are mined at present ranges from a few percent to a lower limit of about 0.3 percent (3000 ppm), which is 125 times the average abundance in the upper continental crust. Unlike the situation for iron, there is no continuous gradation between the copper content of common rocks and that of copper ores. The majority of minable ores are local enrichments of copper produced by the activity of hot vapours and fluids which have concentrated copper sulfide minerals in volcanic and sedimentary formations. Three types of deposits account for 86 percent of the present copper production: (1) disseminated or porphyry copper ores (50 percent); (2) sedimentary copper ores (23 percent); (3) volcanic-sedimentary copper ores (13 percent).

The established and probable reserves of copper in the world have been estimated at 308.5×10^6 tons. Growth in the annual production of copper since 1922 is shown in Figure 3. From 1950 to 1972 the production has grown exponentially at a rate of 4.5 percent per year (Figure 4). The cumulative production between 1922 and 1972 was 150×10^6 metric tons. Thus, the 1972 reserves are twice as large as the cumulative production within the last 50 years. If the exponential growth of production were to continue at the current rate, the reserves, as known in 1972, would be depleted in 1997. A doubling of the reserves would prolong this period until 2008; an increase by a factor of ten, until 2040. If the annual production could be kept constant at the present level (6.8×10^6 tons/year), the reserves, as estimated in 1972, would be exhausted in 2017. In reality, the production of copper will neither grow exponentially nor remain constant, but, as new reserves are establihsed, will follow a curve with a maximum, as shown in Figure 2 (curve 3).

It follows from these considerations that a shortage of copper can be expected in the near future unless the resources are enlarged appreciably. This could occur through the discovery of new deposits of conventional types of ores or by development of potential ores. Intensified prospecting, mainly in the areas of disseminated copper ores, has increased the world reserves from 195 x 10^6 of Cu in 1966 to 308.5 x 10^6 of Cu in 1972. Disseminated copper ores are associated with Mesozoic to Tertiary circum-Pacific volcanism. Additional ores of this type might be discovered in the younger mountain belts where the volcanic and related rocks have not yet been thoroughly studied. Additional sedimentary and volcanic-sedimentary ores might be found in the Precambrian shields of Southern and Central Africa, Canada, Australia and the Asian parts of USSR. One important potential source of copper ores is the manganese nodules which occur at the bottom of the Atlantic, the Indian and the Pacific Ocean, in water depths greater than 3000 m. Manganese nodules containing 1.5 to 2.0 percent copper occur in a broad band in the Pacific south of the Hawaiian Islands.

There is little prospect of finding large volumes of common rock types with copper contents just below the present economic limit, but well above the very low average crustal abundance. One could contemplate the possibility of always being able to find ways to mine progressively leaner ores in ever increasing volumes, in order to maintain an annual rate of growth in production of 4.5 percent per year (Figure 4), the total amount of copper (1.51 x 10^{15} metric tons) distributed throughout the whole of the earth's crust, would have to be extracted by the year 2330.

Mercury

The average abundance of mercury in magmatic and metamorphic rocks of the upper continental crust of the earth is 30 ppb, whereas in sedimentary rocks it is 330 ppb Hg. Mercury is one of the volatile elements which have accumulated in the upper levels of the earth's crust by the progressive degassing of the lower crust and upper mantle. Mercury ores are impregnations of various porous rocks with cinnabar (HgS) and metallic mercury. Minable ores contain mercury concentrations in the range between 10 percent and a few tenths of a percent. All known mercury deposits occur at shallow depths and mostly in young mountain belts characterized by geologically recent volcanic and igneous intrusive activity. Some are in the volcanic and intrusive igneous rocks themselves, and the sources of the liquids or vapours that deposited the ores were apparently magmatic; whereas other mercury deposits, although located in volcanic belts, occur in sedimentary rocks and may result from a concentration of mercury that was dispersed in the sedimentary rocks.

The annual world production of mercury since 1948 is shown in Figure 8. In the period from 1948 to 1958 the annual production increased exponentially at a rate of 7.7 percent per year. After 1958 the rate of increase in production dropped to 0.93 percent per year, even though during this period the price of mercury increased by a factor of more than three. The cumulative production of mercury from 1922 to 1972 was 320 x 10^3 tons. According to estimates of the U.S. Bureau of Mines, proved and probable reserves of mercury amount to 201 x 10^3 tons, which is equal to the cumulative production within the last 24 years. The slowing down of the growth rate of the annual production appears to be due to a progressive depletion of known mercury deposits and a lack of major new discoveries.

Unless new reserves can be found, there will be an almost immediate shortage of mercury. The mercury in ores is enriched by a factor of 10^4 relative to the average content in sedimentary rocks, and there is a very large gap between the mercury content of ores and the average concentration of mercury in common rocks.

The industrial use of mercury - mainly in the course of soda fabrication by electrolysis - has produced local enrichments of mercury from industrial wastes in natural waters, soils and sewage muds. Incidents of poisoning of humans and animals due to mercury pollution from industrial wastes have occurred in Japan, Pakistan, Guatemala and Sweden; and man-made mercury deposits are forming from industrial wastes at the bottom of some rivers. Rhine River muds in the Federal Republic of Germany contain up to 18,000 ppb mercury; and muds of the Wupper River contain 47,000 ppb of mercury at Sohngen and 38,000 ppb at its confluence with the Rhine.

ENERGY RESOURCES

Large-scale development of the earth's mineral resources depends upon the availability of abundant supplies of energy.

The earth's energy resources differ fundamentally from its mineral resources because the earth is essentially an open system with respect to energy (Figure 5), whereas with respect to minerals it is a closed system, the amount of matter being substantially fixed, with only the state and distribution changing. Energy flowing through this system drives various material cycles, of which the hydrologic cycle is a prime example. An essentially fixed rate of supply of solar radiation provides the energy for the evaporation of surface waters and for the atmospheric circulation and precipitation that is the ultimate source of man's domestic, industrial and agricultural water supplies and hydroelectric power. This continuous flow of solar radiation into the earth's surface environment, which provides the energy input for the entire biosphere including all agricultural production, has been the dominant factor, through geologic time, in the development of all soils, all fossil fuels, and many important classes of mineral deposits.

The solar radiation intercepted by the earth ($174,000 \times 10^{12}$ watts) is the principal source of energy in the earth's surface environment (Figure 5), and is almost four orders of magnitude greater than the thermal energy conducted and convected to the earth's surface from its interior (32×10^{12} watts), which is, in turn, an order of magnitude greater than the tidal power dissipation from the combined kinetic and potential energy of the earth-moon-sun system (3×10^{12} watts). About 30 percent of the total incident solar radiation, the earth's albedo, is directly reflected and scattered into outer space and exerts negligible influence on terrestrial activities. About 47 percent is absorbed directly by the earth's atmosphere, its bodies of water, and its land surface, and is converted directly into heat. About 23 percent is consumed in the evaporation, precipitation and circulation of water in the hydrologic cycle, and some of this can be converted into water power. Less than one percent is dissipated in maintaining the atmosphere and oceanic circulation, which results from absorption of heat; and a small part of this can be converted into power. Only some 40 x 10^{12} watts, about 0.02 percent of the total incident solar radiation, is absorbed by plants and transformed into chemical energy by the process of photosynthesis which converts solar energy, carbon dioxide and water into free oxygen and the reduced organic carbon that is the main source of energy for the rest of the biosphere. Almost all of this organic carbon is recycled back into the atmosphere within a few tens of years by respiration and decay; but, ever since photosynthesis began more than 3 billion years ago, a gradually increasing amount has become preserved by burial in the sediments of the earth's crust, whilst a proportionately increasing amount of oxygen accumulated in the atmosphere. Most of the fossil organic carbon is so widely dispersed that it is most unlikely to ever become a technologically and economically feasible source of energy for mankind. Sedimentary rocks have an average content of about 0.5 percent of organic carbon. Of the 12 x 10^{15} metric tons of carbon held in this sedimentary reservoir, an estimated 0.06 percent (7 x 10^{12} metric tons) is concentrated locally in deposits of coal, oil and natural gas that may one day be economically exploited as fossil fuels. These fossil fuel resources, which have been the basis for the emergence of a global technological civilization, result from the gradual conversion and storage over tens or even hundreds of millions of years, of an almost infinitesmally small component of the total solar energy flux at the earth's surface. Since at least 1860, consumption of these nonrenewable resources has been growing at an annual rate of between 1.5 and 4.4 percent which means that the annual production doubles at intervals of from 16 to 46 years.

The world's ultimate recoverable reserves of coal can be estimated with some confidence because coal is a sedimaentary deposit, comprising plant materials that accumulated in fresh or brackish water swamps and were buried and transformed physically and chemically to form layers that are of relatively constant thickness and are intercalated with other distinctive types of sedimentary rocks. Averitt has estimated that the total amount of coal occurring throughout the world in beds 12 inches (30.5 cm) or more thick that are generally 4,000 feet (1219 m) or less below the surface is about 15.3 x 10^{12} metric tons, and that from a long-term point of view only about 50 percent of the coal present (7.6 x 10^{13} metric tons) can actually be recovered. Hubbert has suggested that even with this reservation there may still be a sense of unreality about the estimate in terms of the potential for actually exploiting beds as thin as 12 inches which are at depths as great as 4,000 feet. Accordingly, he has suggested that 2 x 10^{12} metric tons would be a more realistic estimate of total world resources of coal, and has used both of these estimates to construct curves showing the complete cycle of world coal production (Figure 6). Although the details of the shapes of the curves are somewhat arbitrary, the curves are subject to certain fundamental constraints. The initial parts represent the actual history of changing rates in world production of coal, and the total area subtended by the cruve must be equal to the total world coal resources, because this area is the integral of rate of production with respect to time. (The scale in the figure is shown by the block in the upper righthand corner). Moreover, the rate of production can be expected to continue to increase only until lack of new resources curtails further growth, at which point production rates begin to level off and then decrease to zero as the resources finally become exhausted. Assuming, for implicity, that the curves will be symmetrical and that there will be no abrupt departures from the current pattern of growth in rate of production, the peak production for the higher estimate of 7.6 x 10^{12} metric tons would occur about 225 years from now in the year 2200, whereas that for the smaller estimate of 2 x 10^{12} metric tons would occur 125 years from now in the year 2100. If the peak rates of production should be higher than those shown, they will occur earlier. If the supply of coal is to last longer, the peak rates of production will have to be kept to a lower level - growth in production will have to be purposely curtailed.

The prognosis for world production of crude oil is similar to that for coal. Oil and natural gas are fluid hydrocarbons that are generated by slow thermal alteration of organic matter trapped in deeply buried sediments. As fluids, they migrate through the pore spaces of the rock in a water environment until trapped beneath some less permeable rock structure. The development of an oil or gas pool is contingent on a whole series of favourable conditions during the evolution of a sedimentary basin: abundant source rocks rich in organic matter, an appropriate history of burial and heating of the source rocks, suitable reservoir rocks and an effective seal for the entrapment of the hydrocarbons after they have migrated from the source rocks, and preservation of the oil or gas pools once they have formed. Thus, it is probably not surprising that oil and gas pools are very unevenly distributed among the various sedimentary basins over the world and that the occurence of hydrocarbons is very difficult to predict.

The size-frequency distribution of oil and gas pools, and perhaps many types of mineral deposits as well, is approximately log-normal. A very large proportion of the world's known petroleum reserves is concentrated in a few pools, mainly in a small area in the Middle East, whereas the remainder is widely dsitributed among thousands of smaller pools throughout the world. Accordingly, attempts at predicting the petroleum resources in unexplored frontier areas are fraught with uncertainty. Nevertheless, there is a surprising level of agreement among various estimates of ultimate world production of crude oil. There appears to be a convergence toward an estimate of 2000 x 10^9 barrels or slightly less. The implication of such a figure to the complete cycle of world crude-oil production is shown in Figure 7. The world crude oil production rate can be expected to reach a peak of about 40 x 10^9 bbls per year at about the year 1995 and then begin to decline. It is noteworthy that according to this prediction the middle 80 percent of the total production will occur within a span of about 56 years, well within the normal lifetime of one human being, and that ninety percent of the world's total initial resources of crude oil will be exhausted within the lifetimes of many people living today.

Natural gas and crude oil are genetically related and the ultimate amount of natural gas that can be produced may be estimated on the basis of the observed ratio of gas to oil that has been discovered to date, about 6400 ft^3 per barrel.

In addition to coal, normal petroleum liquids and natural gas, the other principal classes of fossil fuels are the so-called tar or heavy-oil sands and the oil shales. The best known and probably the largest of the heavy-oil or bitumen-impregnated sands occur in western Canada and contain an estimated 250 x 10^9 barrels of potentially recoverable oil. The crude oil in these deposits is too viscous to be produced as a fluid and must be partially extracted as a synthetic crude oil, either in conjunction with large-scale mining or in situ methods. Unlike the tar sands, which contain viscous hydrocarbon fluids, the oil shales contain solid hydrocarbons, which upon destructive distillation yield substantial amounts of oil. The extractable oil content ranges up to 100 U.S. gallons per short ton (340 liters per metric ton) and the extimated world supply of oil from oil shales is very large, but large-scale production must await more favourable economic conditions and technological improvements in combating the environmental impact of the mining and extraction processes.

The exploitation of the fossil fuels, considered from the perspective of a span of history encompassing some thousands of years before and after the present (Figure 8), is a transitory or ephemeral event, but nonetheless, an event which has exercised the most drastic influence on the human species during its entire biologic history.

The remaining sources of energy suitable for our industrial civilization are principally the following :

1. Direct use of solar radiation
2. Indirect uses of solar radiation
   (a) water power
   (b) wind power
   (c) photosynthesis
3. Geothermal power
4. Tidal power
5. Nuclear power
   (a) fission
   (b) fusion

The largest concentration of solar radiation reaching the earth's surface occur in desert regions within about 35° of latitude north and south of the equator. At about 35° latitude, the thermal power density of solar radiation incident upon the earth's surface ranges from about 300 to 650 calories per cm^2 per day, from winter to summer. The winter minimum of 300 calories per cm^2 per day when averaged over 24 hours represents a mean power density of 145 watts per m^2. If 10 percent of this could be converted to electrical power by photovoltaic cells or other means, the area required to generate 350,000 megawatts - the approximate electric power capacity of the United States at present - would be roughly 25,000 km^2. This is equivalent to the area of a square 160 kms or 100 miles to the side. Thus, the generation of electric power from direct solar radiation offers the prospect of a very large supply of energy with a minimal environmental impact.

The long-term history in the development of water power should be represented by a logistic type of growth curve. 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 of about 3×10^{12} watts when all available world potential is being utilized. This rate could be maintained provided that the climate does not change and also that some method can be devised for removing the sediment which treatens to fill most large reservoirs within a few centuries. Only 8.5 percent of the world's ultimate hydroelectric potential is developed at present, and this principally in the highly industrialized regions.

Wind power is essentially limited to comparatively small units and is suitable for special local uses but does not offer much promise of competing with other sources of large-scale electric power.

Forests, which are one means of using photosynthesis to capture solar energy for man's use, represented the principal energy source for our civilization until they were displaced by the fossil fuels toward the end of the last century. If an efficiency of 1 percent in the capture of solar energy could be achieved through improvements in forest management and the technology for converting plant materials to more useful forms of energy such as methanol, an annual energy harvest could make substantial contributions toward meeting the world's energy needs.

Geothermal energy can be obtained from any mass of rock in which temperatures are significantly higher than in the earth's surface environment, provided that the rock is sufficiently pervious so that circulating water can be used to extract the heat. Usually, only low temperature rocks are within easy reach, and the heat extracted can, at best, be used for central heating; but locally there exist, at moderate depths, large volumes of rock that have been heated by volcanic activity or related processes, and economically significant quantities of energy may be obtained from them if they are permeable enough. Steam produced by water circulating through these rocks can be piped to the surface and used to drive steam turbines for electrical power generation. However, because the heated rocks are limited in quantity and have finite heat contents, the amount of energy that can be extracted by circulating water through them is limited. The production of geothermal power involves the "mining" and eventual depletion of temporarily stored quantities of volcanic heat. White has estimated that the stored thermal energy in the world's major geothermal areas to depths of 10 km amounts to about 4×10^{20} thermal joules. With a 0.25 conversion factor this would yield an average of about 58,000 megawatts for 50 years, equivalent to approximately 2 percent of the world's potential water power.

Tidal power is essentially hydroelectric power obtainable by damming the entrance to a bay or estuary in a region with tides of large amplitude. An inventory of the world's most favourable tidal-power sites gives an estimate of a total potential power capacity of about 63,000 megawatts, approximately equal to the world's potential geothermal power, but unlike the latter, a renewable resource.

The last major source of industrial power is that of the atomic nuclei. This may be obtained by two contrasting types of nuclear reactions: (1) the fissioning of heavy atomic isotopes, initially uranium-235; and (2) the fusing of isotopes of hydrogen into helium. In the fission process, two stages are possible. The first consists of power reactors whcih are dependent almost solely on the rare isotope, uranium-235, which represents only 0.7 percent of natural uranium. The second process is that of breeding whereby either the common isotope of uranium, uranium-238, or alternatively thorium, is placed in a reactor initially fuelled by uranium-235. In response to neutron bombardment, uranium-238 is converted into plutonium-239, or thorium-232 into uranium-233, both of which are fissionable. Thus, by means of a breeder reactor, in principle, all of the natural uranium or thorium can be converted into fissionable reactor fuel.

The energy released by the fissioning of a gram of uranium-235, of plutonium-239, or uranium-233 is 8.2×10^{10} joules, the approximate equivalent of the heat of combustion of 2.7 metric tons of bituminous coal or 13.4 barrels of crude oi. Uranium-235 is sufficiently scarce that, without the breeder reactor, the time span of large-scle nuclear power production would probably be less than a century. With complete breeding, however, it becomes possible to consume all of the natural uranium and thorium and also to consume all of the natural uranium and thorium and also to utilize low-grade sources, including extensive deposits of uranium-rich shales available for mining at shallow depths. However, such mining could lead to serious environmental problems.

The fusion of hydrogen, using the heavy isotope, deuterium, can yield 7.95×10^{9} joules of thermal energy from 1 liter of water, or the equivalent of 1,300 billion barrels of crude oil from $1 km^3$ if sea water. Although fusion has only been achieved by man in an uncontrolled or explosive manner in the thermonuclear or hydrogen bomb, there is hope that controlled fusion will be achieved within the next few decades.

The principal problem in the generation of power by nuclear fission is the development of means for economical and safe management and disposal of the fission products. These consist of a wide spectrum of radioactive isotopes, all of which are dangerous until they have decayed to the very low levels of tolerance prescribed for biological safety. For the short-lived fission products a period of tens of years is required; for the long-lived isotopes the corresponding period is hundreds and possibly even a thousand years. With the eventual exponential growth of nuclear power plants the hazards of radioactive waste management will become a major environmental problem and a security problem quite unlide any mankind has face heretofore.

As to the future of the world's energy economy, the fossil fuels are short-lived; nuclear power is potentially large but also hazardous; water power is large but inadequate; and geothermal and tidal power are inadequate; however, the largest source of energy available to the earth, the solar radiation, offers the hope of an abundant supply with a minimum of impact on the environment.

POPULATION AND THE ENVIRONMENT

Even the most preliminary examination of the realtionships between the finite size of the world's mineral resources, on one hand, and established rates of growth in mineral consumption, on the other, reinforces the notion that there are indeed physical limits to the continued rapid growth of our modern industrial civilization, and that the present episode of exponential growth can be only a transitory epoch of a few centuries duration within the totality of human history.

Changes of climate, and of sea-level; volcanic eruptions and earthquakes may test man's ability to adapt to his changing physical environment; but only marginally can he control them; and moreover, man's activity on the globe is now so great that he himself is the cause of major geological change. There is convincing evidence to show that the erosion rate of the land has been doubled or trebled by man's activities. With a rising world population, more and more of the earth's surface will be occupied, and by 2000 A.D. man will probably have occupied twice the present area. Increased erosion removes fertile soil from the farmlands, and produces sediment which clogs the stream and hydroelectric reservoirs (at a rate of 1 million acre-feet or 1 billion cubic meters per year in the U.S.A.), and carries pollutants. Because such processes are normally slow they tend to be ignored; but if man is to survive he will have to heed the warnings.

Finally, and perhaps most vitally, comes the question of water supply. The water resources of the globe are naturally recycled, but nevertheless they are finite. So far it is only by the expenditure of large quantities of energy that sea-water can be made drinkable; and today man puts some pollutants into water which it may never be possible to remove. Throughout the developed world water is being pumped from underground sources at a greater rate than those sources are being replenished. A scarce resource is being mined. Thus every city in the world depends upon ground water has its record of falling water levels. Not only is this a problem because it represents a progression which cannot continue indefinitely, but in coastal areas, as for example in Holland and in New York, salt water is drawn in which contaminates the supply. In addition, in his efforts to dispose of the enormous quantities of refuse which his civilization gernerates, man fills quarries with garbage, discharges poisonous chemicals on to farm land, and noxious effluents into streams. Eventually this finds its way into drinking water. Whilst this is a problem which is becoming fully appreciated, the geological situations in which such disposal is safe, and in which unsafe, receives too little attention.

CONCLUSIONS

Mankind is on the threshold of a transition from a brief abnormal interlude of exponential growth to a much longer period characterized by rates of change so slow as to be regarded essentially as a period of nongrowth. Although the impending period of transition to very low growth rates poses no insuperable physical or biological difficulties, those aspects of our current economic and social thinking which are based on the premise that current rates of growth can be sustained indefinitely must be revised. Failure to respond promptly and rationally to these impending changes could lead to a global ecological crisis in which human beings will be the main victims.

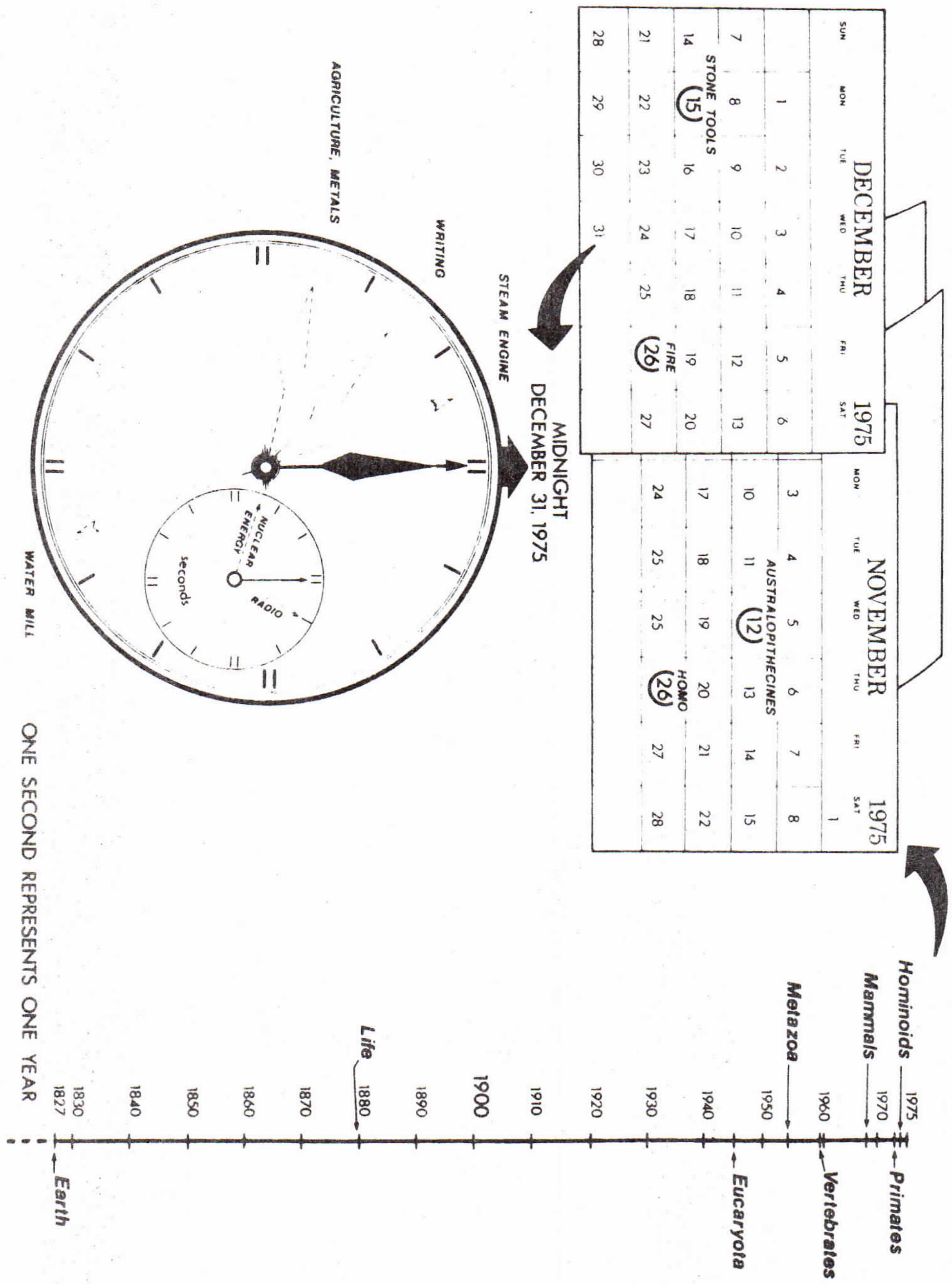

Figure 1. The emergence of man's global technological civilization viewed from the perspectives of earth history. Various benchmarks in the evolution of the earth and our modern technological civilization are portrayed as they would appear to an observer who is looking back through time from midnight on December 31st, 1975, and using a reduced time scale in which one second equals one year.

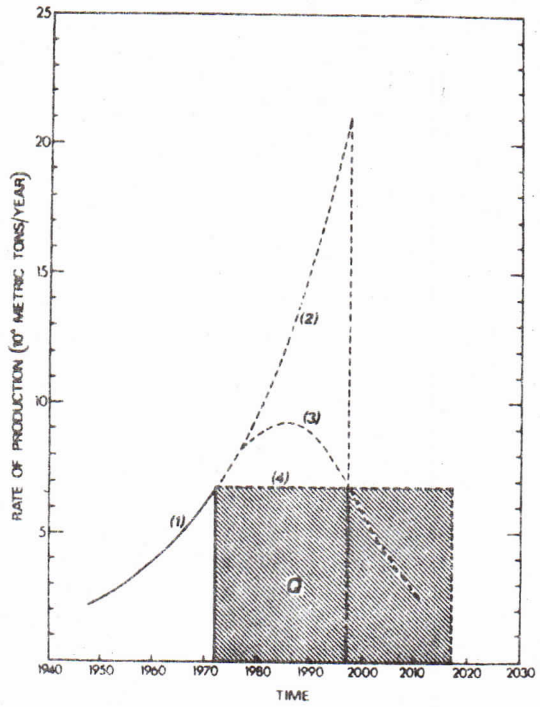

Figure 2. Growth in annual production of a mineral resource toward the fixed limits of a finite supply. The example is based on estimated and probable world reserves for copper in 1972. The rate of growth in production from 1950 to 1972 was 4.5 percent (Figure 4) and is represented by curve 1. If this rate of growth were to continue (curve 2) the reserves would be exhausted in 1997, but if the rate growth were to rise to a maximum between 1980 and 1990 and then decline exponentially (curve 3) complete exhaustion of reserves would occur sometime after 2020. With a constant annual production at the 1972 rate (6.8 x 10^6 metric tons) the reserves would last until 2017.

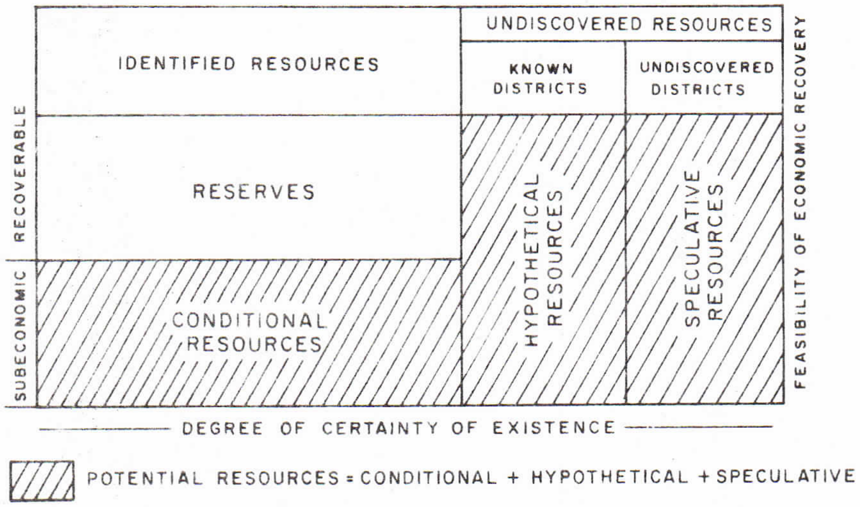

Figure 2a. Mineral resources comprise all those discrete concentrations of naturally occurring materials in or on the earth from which it now is, or may some day become, economically feasible to extract one or more mineral commodities; whereas mineral reserves consist only of those specific portions of the earth's mineral resources which actually have been "discovered", and for which it has been demonstrated, on the basis of geologic evidence and supporting engineering measurements, that one or more mineral or energy commodities can be extracted economically, under present social and political conditions, using the technology that is available now.

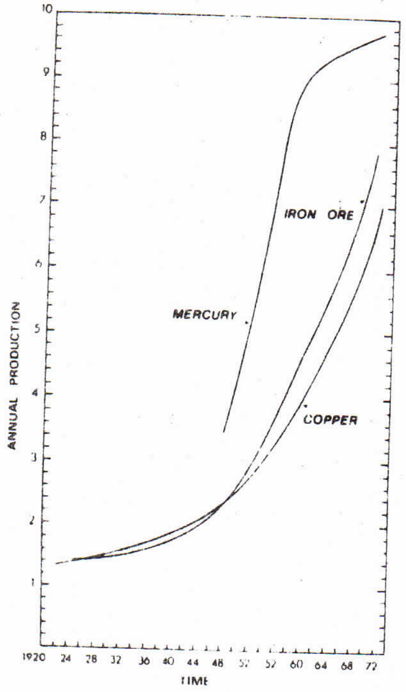

Figure 3. World production of iron ore, copper, and mercury between 1922 and 1972.

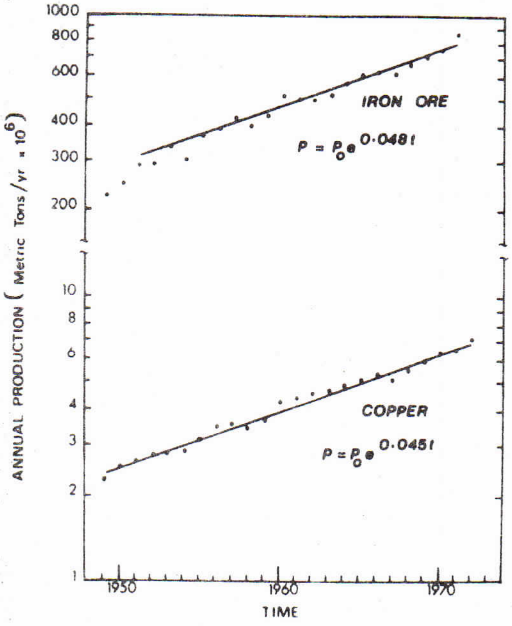

Figure 4. World production of iron ore and copper between 1949 and 1972 (after Figure 3); semi-logarithmic scale; annual rate of growth is given by the slope of the straight line drawn through the data points.

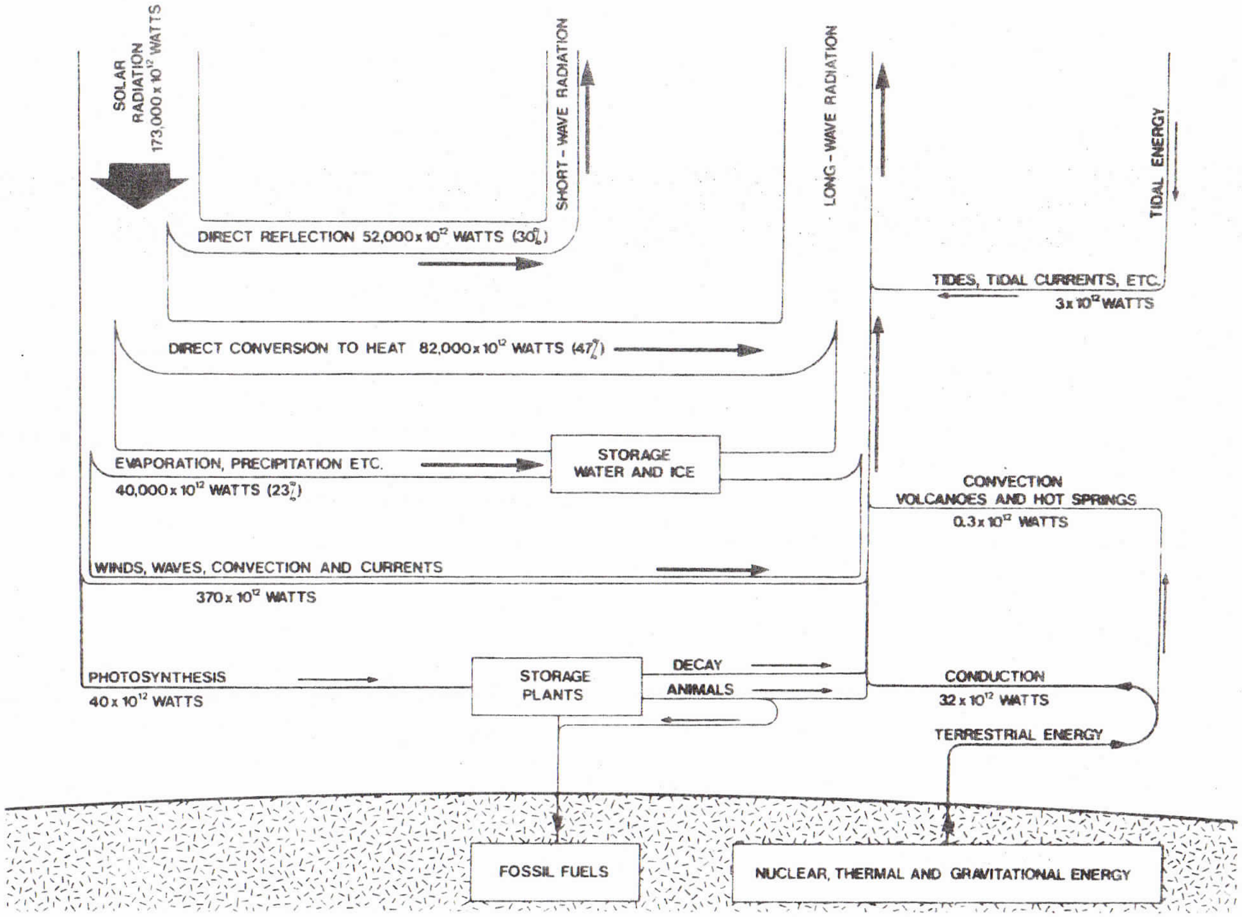

Figure 5. World energy flow sheet.

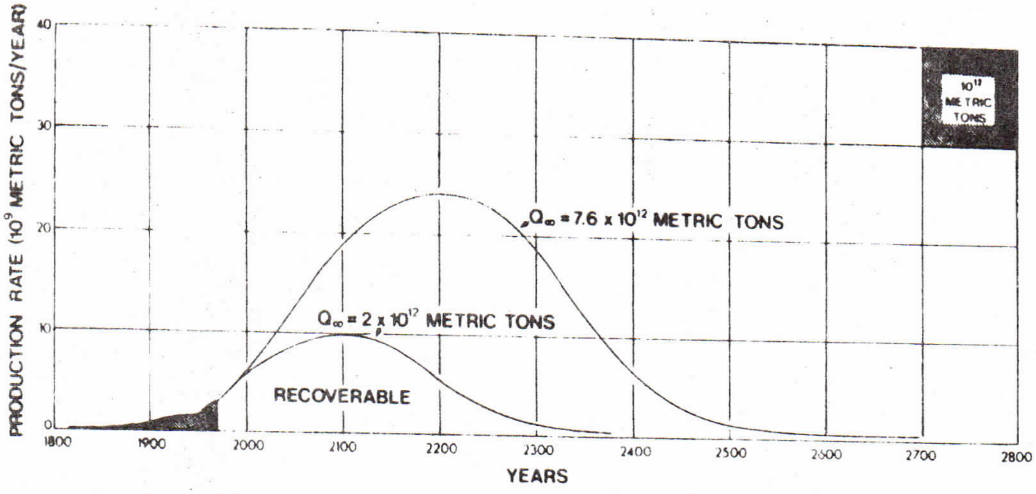

Figure 6. Complete cycle of world coal production.

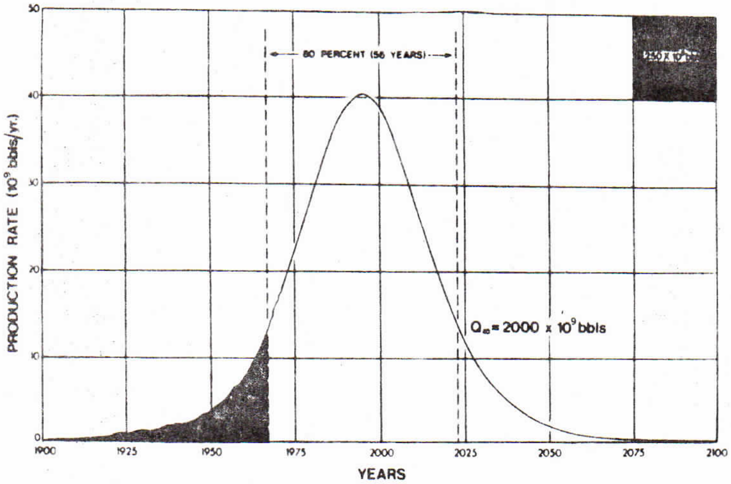

Figure 7. Complete cycle of world crude-oil production.

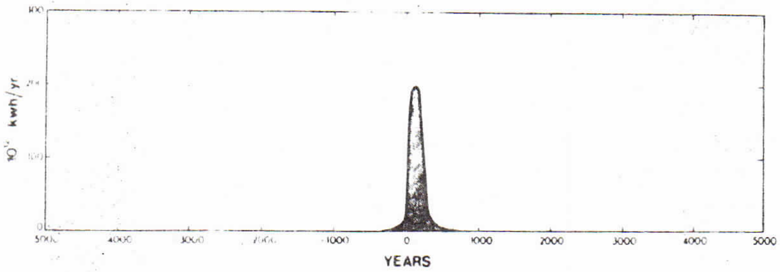

Figure 8. Epoch of fossil fuel exploitation viewed in the perspective of human history from 5000 years in the past to 5000 years in the future.