GEOLOGISCHE RUNDAU 66 (NO. 3, 1977): 654-678.

AUFSÄTZE

Role of Geology in Transition to a Mature Industrial Society

By M. King Hubbert, Washington, D.C. *)

With 18 figures

Zusammenfassung

Als Resultat der Zunahme naturwissenschaftlicher Erkenntnis und gleichzeitiger Entwicklung der Technik beobachten wir ein exponentielles Wachstum bei allen unsere Gesellschaften bestimmenden Faktoren.

Analysiert man diese Situation, so läßt sich leicht beweisen, daß die Erde von sich aus das Wachstum einer biologischen oder industriellen Aktivität nicht länger als einige Zehner von Verdoppelungen verträgt und daß der größte Teil der möglichen Verdoppelung sich bereits ereignet hat. Im biologischen Fall sind retardierende Einflüsse zu erwarten; sie haben gewöhnlich den Charakter von (a) Begrenztheit der Nahrung und (b) des Lebensraumes, (c) Verunreinigung oder (d) Jäger-Beute-Beziehungen.

Für das industrielle Wachstum, sei es von Autos oder von Kraftwerken, müssen analoge Faktoren der Begrenzung wirksam werden.

Unser industrielles Wachstum beruhte bisher auf Mineralressourcen und fossilen Brennstoffen. In wenigen hundert Jahren werden diese Vorräte erschöpft sein. Die Entwicklung der menschlichen Gesellschaft muß in einen Zustand des ökologischen Gleichgewichts übergehen, wobei eine gewaltig ergiebige Energiequelle Voraussetzung ist. Der Übergang von unserem Zustand in Vergangenheit und Gegenwart in den Zustand der nahen Zukunft kann in kontrollierter Weise vonstatten gehen. Es ist aber ebensogut möglich, daß er sich in Form einer Katastrophe ereignet. Es ist so gut wie sicher, daß die menschliche Spezies im letzteren Fall zu einer primitiven Form der Existenz mit niedrigem Energieverbrauch zurückkehren müßte, einer Form des Lebens, die der unserer Vorfahren vor wenigen Generationen nicht unähnlich wäre.

Ich stelle die These auf, daß die geologische Wissenschaft während ihrer Geschichte bezüglich der Probleme der menschlichen Gesellschaft zwei grundsätzlich verschiedene Phasen durchgemacht hat. Die erste Phase dauerte von 1785 bis 1885 und ist mit den Namen von Hutton, Lyell und Darwin verbunden. Sie war verantwortlich für eine der größten intellektuellen Revolutionen oder Fortschritte der menschlichen Erkenntnis in der Geschichte der Naturwissenschaften. Die zweite Phase währte im wesentlichen während der letzten hundert Jahre und war hauptsächlich von utilitaristischem Charakter. Geologen haben während dieser Periode gründlich zum industriellen Wachstum beigetragen, indem sie die Mineral- und Brennstoffressourcen entdeckten, die dieses Wachstum anheizten. Sie taten dies aber als Handlanger von Handel und Industrie, wobei sie nur selten den zugrunde liegenden Kanon der zeitgenössischen Kultur des exponentiellen Wachstums in Frage stellten oder ablehnten.

Für die dritte Periode, in die wir jetzt eintreten, besteht die Hoffnung, daß der wesentliche Beitrag der Geologie wieder ein intellektueller werden kann. Der Übergang von der zweiten zur dritten Phase verlangt indessen eine ebenso entschiedene Abkehr von den Dogmen der heute geltenden sozialen und ökonomischen Theorien, wie sie für Lyell und Darwin bezüglich der Dogmen der Religion ihrer Zeit erforderlich war.

Falls die geologische Theorie erneuert werden kann zu einer Betrachtung der terrestrischen Entwicklung in physikalischer, chemischer und biologischer Hinsicht, und falls es gelingt, zu begreifen, daß die geologische Geschichte statt mit dem Pleistozän zu enden ebenso eine Gegenwart und eine Zukunft hat wie eine Vergangenheit, dann könnte es sein, daß Geologen wieder in die Lage kommen, eine intellektuell führende Rolle zu spielen.

---

*) Anschrift des Verfassers: Dr. M. King Hubbert, 5208 Westwood Drive, Washington, D.C. 20016, U.S.A.

Abstract

As a result of the increasing scientific knowledge and parallel development of technology, we are witnissing an exponential growth of all factors that determine the shape of society.

Analysis of this situation makes it easy to prove, that the Earth is no longer, spontaneously, capable of sustaining an idustrial or biological growth of more than a few powers of ten and that the major part of this feasible increase has already been attained.

In the biological case, retarding effects are expected.

They are normally characterised by

a) limitation of nutrition

b) limitation of living space

c) pollution, or

d) predator-prey relations.

In case of the industrial growth, be it through automobiles or power stations, analogous limiting factors must also be of the same effectivness.

Up-to-now, our industrial growth has been depending on mineral resources and fossil fuels. These will be exhausted in a few hundreds of years. In this case, the development of human societies will have to pass into a state of ecological balance, provided that a powerful energy source is used. This passage from our past and present state into the near future may, under controlable conditions, be prosperous. It may as well take a catastrophic form. In the latter case, it is almost sure, that the human species must return to a primitive state of low energy consumption — a form of life not unsimilar to that of our ancestors.

Regarding the problems of human societies, I propose that the geological sciences, have passed during their history through two fundamental different stages. The first of these lasted from 1785 to 1885 and was connected with the names of Hutton, Lyell, and Darwin. It was responsible for one of the greatest intellectual revolutions, or forward steps of human knowledge, in the history of natural science. The second stage held out, essentially, during the last hundred years and had an utalitarian character. Geologists have, during this period, basically contributed to the industrial growth by discovering mineral and fuel resources that enhanced this growth. They carried this out, as a cat's paw for trade and industry, whereby they seldom discussed or questionad the fundamental canon of the contemporary culture of exponential growth.

As for the third stage in which we are now entering, it is hoped that the essential contribution of geology should be once more an intellectual one. The transition from the second stage to the third one requires, in the meantime, a renunciation of the prevailing dogmas of economic and social theories as it was the case for Lyell and Darwin with the religious dogmas of their time.

In case that the geological theory can be renovated into a consideration of the terrestial evolution with regard to physical, chemical and biological aspects and if it would be managed to conceive that the geological history, instead of ending with the

Pleistocene, has a present and a future as well, it would then be possible for geologi to play again a leading intellectual role.

Résumé

De l'augmentation du savoir scientifique et du développement parallèle de technique résultent — nous en sommes les témoins — la croissance exponentielle d touts les facteurs déterminant la forme des sociétés humaines.

L'analyse de cette situation montre clairement que la Terre ne peut pas suppor une croissance industrielle ou biologique dépassant quelques exposants de dix et qu la majeure partie de cette croissance possible est déjà réalisée.

Du côté biologique, on peut s'attendre à des effets ralentissants normalem caractérisés par

a) la limitation de la nourriture,
b) la limitation de l'espace vital,
c) la pollution,
d) les relations ravisseur — proie.

Dans le cas de la croissance industrielle, qu'il s'agisse d'automobiles ou d'usine électriques, des facteurs limitatifs analogues doivent avoir la même efficience.

Jusqu'à aujourd'hui la croissance de nos industries a été dépendante des ressourc minérales et des combustibles fossiles. Ceux-ci seront épuisés dans quelques centaine d'années. Le développement des sociétés humaines aura donc à passer à un éta d'équilibre écologique, dans lequel toute source d'énergie sera épuisée. Cett transition de notre état passé et présent dans le proche avenir pourrait sous de conditions controllées être prospère. Mais il n'est point exclu qu'elle prenne une forme catastrophique. L'espèce humaine s'en retournerait à une vie primitive caracterisée par une faible consommation d'énergie, comparable à la vie de nos ancêtres.

En ce qui concerne les problemes des sociétés humaines, il me paraît que les scienc géologiques ont vécu deux âges fondamentalement différents au cours de leur histoire Le premier, de 1785 à 1885, peut être évoqué par les noms de Hutton, Lyell e Darwin. On lui doit une des plus grandes révolutions intellectuelles ou une forte progression de la connaissance humaine dans les sciences naturelles. Le deuxième comprend presque les cent dernières années, et revêt un caractère utilitaire. Les géologue pendant cette période, ont contribué fondamentalement au développement industriel en découvrant les ressources en minérais et combustibles qui lui sont indispensables ils étaient des agents au service du commerce et de l'industrie, et rarement ils ont mis en question ou refusé le canon fondamental de la culture contemporaine, la croissanc exponentielle.

Quant au troisième âge dans lequel nous entrons aujourd'hui, il faut espérer que l contribution essentielle de la géologie sera de nouveau une contribution intellectuelle Les transformations nécessaires des sociétés humaines demandent de surmonter le dogmes encore dominants des théories économiques et sociales, effort aussi grand que celui de Lyell et Darwin qui avaint à se libérer des dogmes réligieux de leur temps.

Pour autant que la pensée géologique soit renouvelée dans une reconsideration d l'évolution terrestre sous les differents aspects de la phsyique, de la chimie et de l biologie, dans une conception ou l'histoire géologique ne se termine pas avec l Pleistocène, mais va se poursuivant à travers le présent au futur, les géologues pourron jouer de nouveau un rôle intellectuel de premier rang.

Краткое содержание

В результате накопления сведений по естествознанию и одновременного развития техники отмечается рост по геометрической прогрессии факторов управляющих всем нашим обществом.

Анализ такого условия указывает на то, что Земля наша, при дальнейшем росте биологической и индустриальной активности, вынесет не более пары десятков удвоений их, и что во многих отраслях допустимое удвоение уже достигнуто. В биологической среде следует уже ожидать появления затормаживающих влияний, которые сказываются обычно в: а) органичении питания; б) органичении жизненного пространства, в) в загрязнении среды и г) в нарушении взаимоотношений «охотник-дичь».

Также и в случае индустриального роста — будет-ли это автомобиль, или электространция — должны проявиться аналогичные факторы органичения роста.

Наш индустриальный рост жиздется до сих пор на минеральных ресурсах и ископаемых горючих. В течение нескольких сот лет запасы эти истощатся. Развитие человечества должно достичь состояния экологического равновесия, но предпосылкой последнего является наличие гигантского источника энергии. Переход человечества от прошлого и настоящего в ближайшее будущее может проходить урегулировано по плану. Но не исключена возможность, что такой переход ознаменуется и катастрофой. Вероятнее всего в этом случае роду человеческому придется вернуться к примитовной форме существования, не многим отличающемуся от такового наших предков несколько поколений тому назад.

Автор утверждает, что науки о Земле за время их развития прошли — относительно проблемы развития общества — два диаметрально противоположных периода. Первый длился от 1785 до 1885 года и связан с такими гениальными учеными, как Hutton, Lyell и Darwin. Этот период подготовил великую индустриальную революцию и успехи человеческого познания в истории естествознания. Второй период охватывает примерно последние 100 лет и носит утилитарный характер. Геологи этого периода много сделали для роста индустрии, открыв минеральные и энергетические ресурсы, ускоряющие его. Но, вместо того, чтобы играть руководящую роль при решении этих серьёзных социально-экономических проблем, геологи превратились в слуг индустрии и торговли, и очень редко ставили под сомнение канон, лежащий в основе роста современной цивилизации по геометрической прогрессии, или же отбрасывали его.

Есть надежда, что в третьем периоде, в который мы теперь вступаем, вклад геологов снова будет носить в значительной мере интеллектуальный характер. Переход от второго к третьему периоду требует такого же решительного отхода от догм социальных и экономических теорий, принятых сегодня, как и в свое время поступили Lyell и Darwin, отбросив догмы религии.

Если геологическую теорию можно ещё обновить, рассматривая развитие Земли с физической, химической и биологической точки зрения, и если удасться усвоить, что геологическая истоpя не заканчивается плейстоценом, но имеет и настоящее и будущее, а также и прошедшее, то геологи должны стать ведущей интеллектуальной силой, с мнением которой принуждены будут считаться все другие.

Introduction

The social importance of any science is roughly commensurate with the effect it has upon either what people think or how they live. Geology in this respect has already gone through two distinct phases and is now entering upon a third. In terms of their influence upon what people think, two scientific developments since the fifteenth century are outstanding. The first is the mechanical-astronomical revolution that occurred during the two centuries from 1500 to 1700 with which the names of Copernicus (1473—1543), Galileo (1564—1642), Kepler (1571—1630), and Newton (1642—1727) are associated as principal contributors. During this period the Ptolemaic geocentric universe with its Aristotelian mechanics and associated theological dogmas was displaced by the heliocentric solar system and the development by Galileo and perfection by

Newton of a valid system of mechanics which became the theoretical foundation for the subsequent flowering of physical science.

The second intellectual revolution, and one of comparable importance, was the geological-biological revolution that occurred principally during the century 1785 to 1885 to which James Hutton (1726—1793), Charles Lyell (1797 to 1875), and Charles Darwin (1809—1882) were principal contributors. During this period the views of the learned world regarding the earth, its biological inhabitants, and its history were changed profoundly and irreversibly. The view of the earth with a presumed Biblical history of only some 6,000 years, whose plant and animal inhabitants were Divinely created, held almost universally at the beginning of this period, was transformed to that of an earth with a history, deciphered from the rocks themselves, of at least hundreds of millions of years duration, which was populated by plants and animals that had evolved by natural selection from ever more primitive ancestors. Man, by this view, instead of being God's highest and most favored creation, was reduced to being a direct biological descendant, in common with all other members of the animal kingdom, from the long animal evolutionary chain.

The second major phase in the history of geological science, that encompassing approximately the last century, has induced few significant changes in what people think, but has contributed profoundly to changes in the way people live and what they do. This is the period during which the world's industrial societies, based upon the fossil fuels and mineral resources, have principally arisen, and to this geologists, by systematically discovering the earth's deposits of the ores of metals, and of the fossil fuels, have been major contributors.

This has been a period of exponential industrial growth and of ecological disturbances unprecedented in human history. It is also a period that is intrinsically irreversible and ephemeral, and one which has now almost run its course. This, in turn, will almost inevitably precipitate geologists into a new role, that of providing intellectual guidance to a world society in a state of confusion over the impossibility of sustaining the state of growth of the last two centuries, and the problems associated with the progressive depletion of the earth's resources of fossil fuels and of its ores of industrial metals.

In order to understand the nature of this new phase and its challenges it is necessary that we be informed with regard to the major developments of the last few centuries in the context of the vastly longer span of human and geologic history, both past and future. Broadly, this is a problem of matter and energy.

As regards materials, the earth is an essentially closed system composed of the 92 naturally occurring chemical elements, all but a minute fraction of which are nonradioactive and hence obey the rules of conservation and nontransmutability of classical chemistry. As regards energy, the earth is an open system into whose surface environment there occurs a continuous influx, degradation, and efflux of energy. As a consequence, the mobile materials of the earth's surface undergo either continuous or intermittent circulation.

Energy System of the Earth's Surface

The nature of this energy system of the earth's surface is illustrated in Fig. 1. Here the horizontal bar near the bottom of the chart represents the earth's surface, beneath which at minable and drillable depths there occur certain large stores of energy, the fossil fuels, geothermal energy, and nuclear energy resources. The energy of these stores is measurable in units of energy such as the joule.

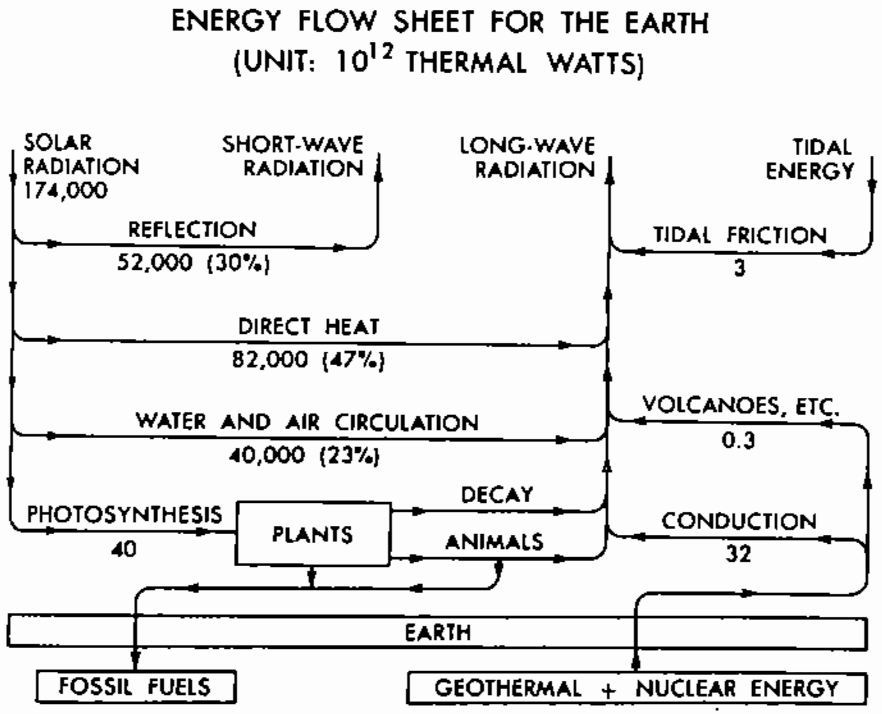

Fig. 1. Energy flow sheet for the earth's surface environment (Hubbert, 1974, Fig. 1).

The upper part of the diagram is an energy flow sheet showing the rates of the energy fluxes. These rates are not measurable in units of energy but in units of power of which the International unit is the watt, or 1 joule/second. For the earth fluxes of energy the unit used in Fig. 1 is 10^{12} watts.

The energy influxes into the earth's surface environment are from three sources: (1) the solar radiation intercepted by the earth's diametral plane, (2) the heat conducted and convected to the earth's surface from its interior, and (3) tidal energy from the earth-moon-sun system. The magnitude of the three influxes in the unit of 10^{12} watts are:

Solar radiation	174,000
Geothermal	32
Tidal	3

It is thus seen that the magnitude of the solar influx is about 5,000 times the sum of the other two.

Of the total solar influx, about 30 percent, the earth's albedo, is reflected into outer space as visible short-wavelength radiation; about 47 percent warms the atmosphere, the oceans, and the ground and degrades into heat at the temperature of the environment; 23 percent circulates the atmosphere and the oceans and drives the hydrologic cycle. Finally a very small fraction, 40×10^{12} watts, drives the process of photosynthesis whereby CO_2 and H_2O are synthesized into carbohydrates and other more complex compounds and solar energy is stored chemically, according to the equation,

$$\text{Radiant energy} + CO_2 + H_2O \rightarrow [CH_2O] + O_2,$$

where $[CH_2O]$ is the unit building block of a series of carbohydrates of increasing complexity.

The photosynthetic component of the solar influx, though small, is of exceptional importance because it is the sole source of physiological energy for the entire plant and animal kingdoms. By the reverse reaction to photosynthesis,

$$O_2 + [CH_2O] \rightarrow CO_2 + H_2O + \text{heat},$$

the stored energy is eventually released as heat, and the plant and animal materials revert to CO_2 and H_2O.

This is an almost steady state, except for a minute fraction of the plant and animal material which becomes deposited in peat bogs and other oxygen-deficient environments where the oxidation reaction is impossible. When these become buried by sedimentary sands, limes, and muds they become preserved and eventually are transformed into fossil fuels.

All others of these energy fluxes, after a series of degradations, eventually end as heat at the local ambient temperature after which they leave the earth as long-wavelength thermal radiation.

Time Span of Geologic History

These processes also need to be considered in the context of the time span of geologic history. In Fig. 2, geologic history is represented graphically by a series of bar charts, with the right-hand end in each case representing the present. The uppermost chart represents the 4.5 billion (10^9) years since the solar system was formed. The oldest rocks whose ages have so far been reported occur in Greenland with a radioactively determined age of 3.8 billion years. The oldest organisms are fossil microbes found in cherts in South Africa with an age of about 3.2 billion years. Hence, life must have originated more than 3.2 billion years ago. Organic evolution has been occurring ever since, but without an extensive fossil record until the beginning of the Cambrian Period, 570 million years ago. The second chart is an enlargement of the last 570 million years of the first; the third chart is an enlargement of the last 65 million years, the Cenozoic Era, of the second; and the fourth chart of the last 3 million years, the Quaternary Period, of the third.

With regard to the fossil fuels, the oldest known commercial gas field occurs in Australia in rocks of late Precambrian age. Oil and gas deposits are found in the central United States and elsewhere in rocks of all geologic ages from the Cambrian to the last million years in the sediments of the Mississipppi River delta in coastal Louisiana. Coal deposits are more recent, the earliest major deposits being those in western Europe, Britain, eastern United States and other countries of the Pennsylvanian or Carboniferous Period, about 300 million years ago. Younger, mostly subbituminous coals, of Mesozoic age occur in the western United States and elsewhere. Still younger lignites or brown coals of Cenozoic age are widespread; and finally peat deposits, the first stage in coal formation, are being formed at present.

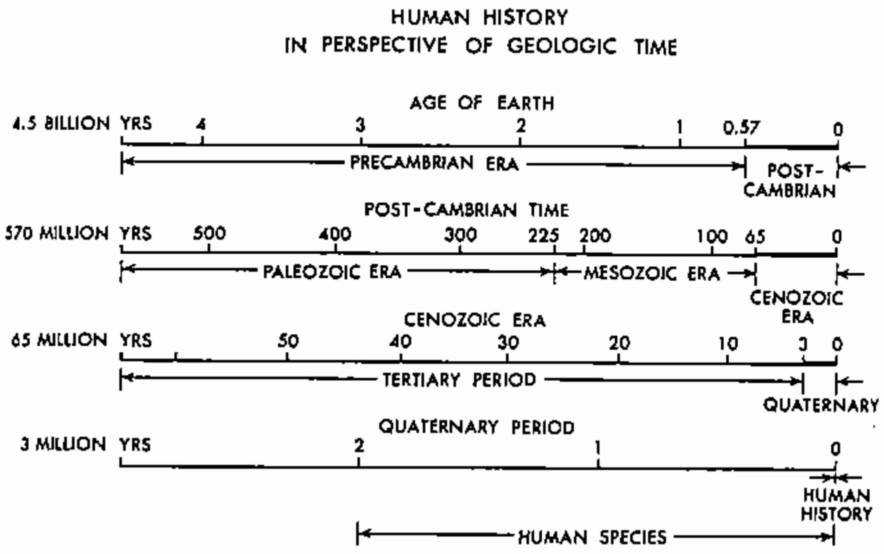

Fig. 2. Time scales for the history of the earth (Hubbert, 1974, Fig. 2).

Thus the world's present suppply of fossil fuels has been accumulating during some 600 million years of geologic history. At the same rate of accumulation negligible additions will accrue within the next few thousand years so that during the period of their depletion the fossil fuels may be regarded as a fixed initial stockpile which can only diminish as exploitation proceeds.

The last bar in Fig. 2, the last 3 million years, is of especial present interest because that is the period, according to recent discoveries by the Leakeys and others in Africa, when the ancestors of modern man had begun to walk upright and to use stone weapons and tools. The narrow vertical line at the right end of the last bar represents the last 5,000 years of human history.

During this period the ancestors of modern man distinguished themselves from all other species by their inventiveness in capturing an ever-larger fraction of the ambivent energy supply and converting it to human uses. This included the use of tools and weapons, the development of clothing and housing, the control of fire about a million years ago, the domestication of plants and animals about 8,000 to 10,000 years ago, the smelting of nonferrous metals about 5,000 and of iron about 3,500 years ago. The principal energy supply used was biological, food and firewood.

Some 3,500 years ago the Egyptians tapped a nonbiological channel of Fig. 1 by using windpower for sailing ships on the Nile; the Romans tapped another channel by using waterpower for grist mills.

One final remark about these charts is in order. They all give the false impression that geological and human history ends with the present. Actually, there will probably be more billions of years of geological history in the future and present events are just as much a part of geological history as events of the distant past. Man is the dominant animal now, as were the dinosaurs during the Mesozoic Era, and there is no reason to expect this to be more than a temporary episode in the totality of geologic history.

Exploitation of the Fossil Fuels

Although the human population increased in density and spread geographically, until about a millenium ago the energy utilized per capita remained small, only about twice that of energy from food. Release from this constraint was not possible until the large stores of energy from the fossil fuels began to be exploited. This occurred about nine centuries ago when coal mining as a continuous enterprise was begun at Newcastle in northeast England. This spread rapidly to the other coal fields of Britain and into western Europe. The uses initially were for heat but were soon extended to metallurgy. Then, in 1712 the Newcomen steam engine was developed, and shortly afterwards the method of making coke as a substitute for charcoal for the smelting of iron was developed. From that time until recent decades coal became the principal energy source for the world's industrialization.

Only scattered statistics of early coal mining are available and it is difficult to assemble annual production statistics earlier than about 1860. However, by 1860 the annual production had reached 138 million metric tons, and from earlier statistics it can be determined that during the preceding 800 years the annual production must have increased at a rate of about 2 percent per year, with a doubling period averaging about 34 years, and with cumulative production by 1860 amounting to 7 billion metric tons.

The annual production of coal from 1860 to 1970 is shown graphically in Fig. 3. From 1860 to about World War I production increased at a steady rate of about 4.2 percent per year, with a doubling period of 16.5 years. Between World War I and the end of World War II the growth rate slowed down to less than 1 percent per year. Then, since 1946, growth has resumed at a rate of about 3 percent per year.

What is most impressive about this is the contrast between the magnitude of coal production during the last century and that previously. In fact, of all of the coal mined during the last nine centuries somewhat more than one-half has been mined since 1940.

Production of the second major fossil fuel, crude oil, began much more recently than coal. As a continuous industrial enterprise oil production began in 1857 in Rumania and two years later in 1859 in the United States. World annual production of crude oil from 1880 to 1970 is shown in Fig. 4. This is an almost unbroken exponential growth curve at an average annual rate of 7 percent per year with a doubling period of 10 years. At this rate of growth the cumulative production also doubles every 10 years, so that the amount of oil produced during the decade between 1960 and 1970 is almost exactly equal to all the oil produced from 1860 to 1960.

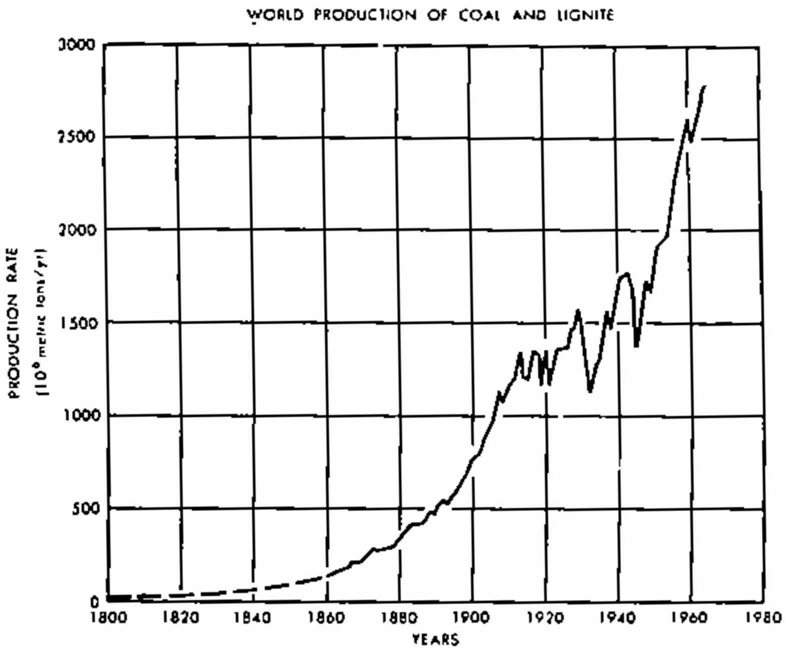

Fig. 3. World production of coal and lignite (Hubbert, 1974, Fig. 3).

Figs. 5 and 6, respectively, show the production of coal and of crude oil in the United States. A small amount of coal was mined in Virginia during Colonial times, but significant production did not occur before about 1820. From that time until about 1910 the production rate increased exponentially at an average rate of 6.7 percent per year with a doubling period of 10.4 years. After 1920 the rate fluctuated about an average figure of 500 million metric tons per year.

Shown separately in Fig. 5 is the annual production of anthracite in the United States. Anthracite is mined in the eastern Appalachian Mountains in two small areas in Pennsylvania and Virginia. Because anthracite is almost pure carbon and smokeless it was used as the principal fuel in the cities of the eastern seaboard of the United States during most of the last century. However, because of its limited resources, we see from the graph that the annual production increased exponentially for half a century, then slowed down until it reached a maximum rate in 1919. Thereafter, with minor fluctuations, it has declined negative exponentially until it has now almost reached zero. This illustrates what will herein be referred to as a complete cycle of production of a nonrenewable resource. For any nonrenewable resource the curve of annual production, plotted as a function of time, begins at zero, then increases, usually at an exponential rate, after which it reaches one or more maxima and finally, as the resource approaches depletion, declines negative exponentially back to zero.

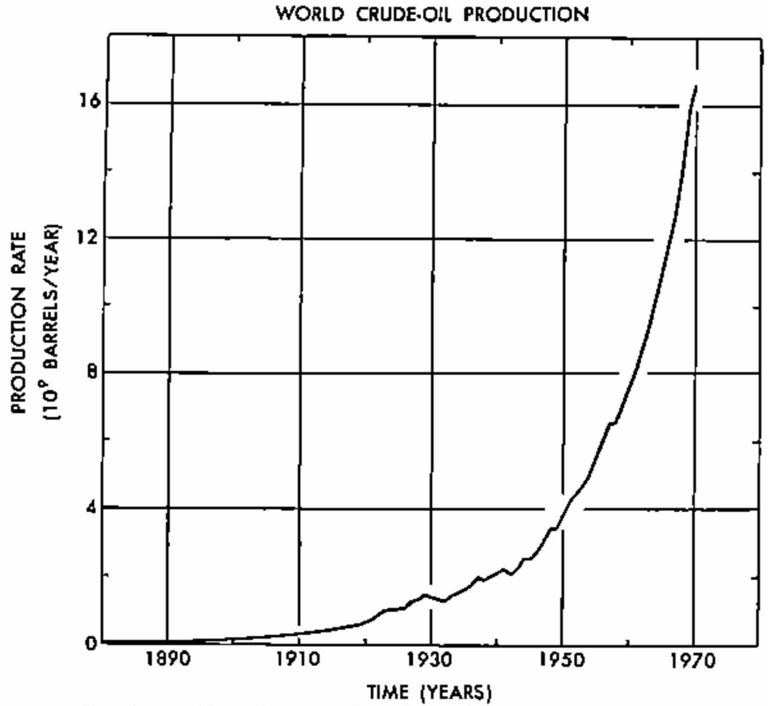

Fig. 4. World production of crude oil (Hubbert, 1974, Fig. 5).

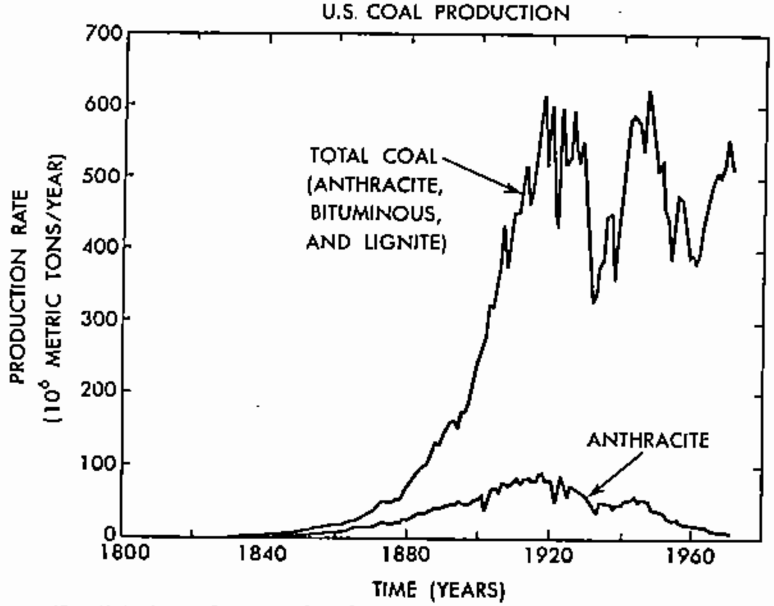

Fig. 5. U.S. production of coal and lignite (Hubbert, 1974, Fig. 9).

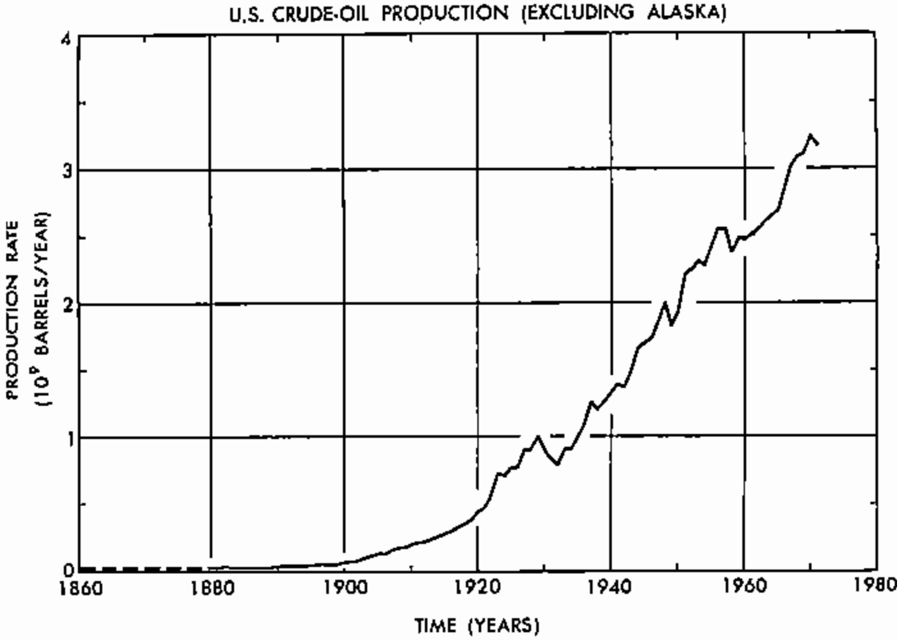

Fig. 6. U.S. production of crude oil (Hubbert, 1974, Fig. 11).

Mathematical Properties of Complete-Cycle Curve

An idealization of such a complete cycle is shown in Fig. 7. A fundamental mathematical property of such a curve is the following. If a narrow vertical rectangle with a base Δt on the time axis be erected to the production-rate curve, the altitude of this rectangle will be the production rate P. But

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

where ΔQ is the quantity of the resource produced during the time Δt. Hence the area of the rectangle will be

$$P\Delta t = \Delta Q.$$

Passing to the limit, for an infinitesimal element of time dt, the quantity produced during time dt would be

$$dQ = Pdt$$

and the cumulative production from the beginning to any later time t_1 would be

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

which would be represented graphically by the area beneath the curve from $t = 0$ to $t = t_1$. Then for the complete cycle, the ultimate production Q_∞, as t increases without limit, would be the total area under the complete-cycle curve, or

$$Q_\infty = \int_0^\infty Pdt.$$

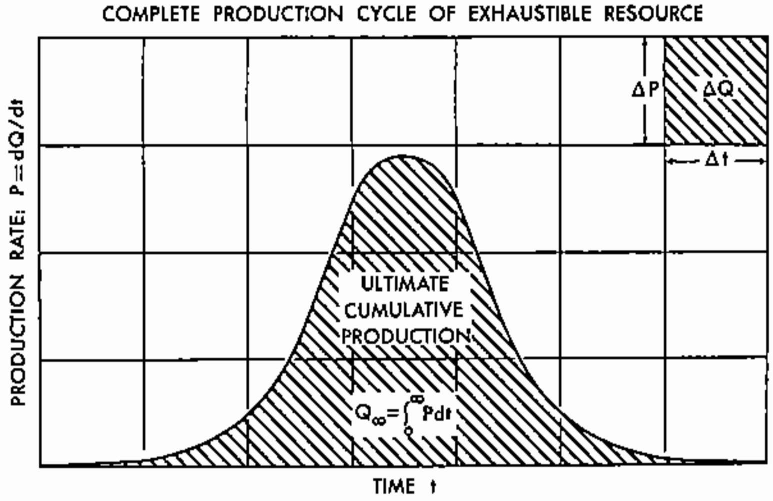

Fig. 7. Mathematical properties of a complete-cycle curve for the production of an exhaustible resource (Hubbert, 1974, Fig. 18).

When any such curve is plotted graphically a scale relating the quantity Q to the geometrical area is provided by the vertical and horizontal scales chosen for P and t. For the vertical scale a production interval ΔP will correspond to the geometrical interval Δy, and for the horizontal scale, Δt will correspond to the geometrical interval of length Δx. Then the area of one grid rectangle on the graph, $\Delta x \Delta y$, will correspond to

$$\Delta P \times \Delta t = \Delta Q.$$

That is, if a constant rate of production ΔP is sustained during the time Δt the cumulative production ΔQ would be graphically represented by one $\Delta P = \Delta t$ grid rectangle.

If, after an early stage in the production cycle, the magnitude of Q_∞ can be estimated from geological or other data, then the total number of grid squares under the curve for its complete cycle will be

$$n = Q_\infty / \Delta Q.$$

and the complete-cycle curve must be drawn subject to this constraint.

This provides a powerful method of analysis in that it exercises a constraint upon the otherwise unbridled use of the imagination. Without this constraint how would one estimate the future of the world crude-oil production shown in Fig. 4?

Complete Cycle for Coal Production

Let us now apply this technique for estimating the future of the world coal-production curve shown in Fig. 3. Geologically, coal is an easy resource to estimate because it is solid and occurs in strata which are continuous over extensive areas, and frequently crop out on the surface. The principal coal-bearing basins of the world are known and published estimates of the amount of coal in the various countries exist. Paul Averitt (1969) of the U.S. Geological Survey has recently compiled these estimates for coal and lignite to depths of 1,200 meters and in some cases to 1,800 meters, and occurring in seams of 0.3 meters or more in thickness. His results, expressed in metric tons of recoverable coal initially present, assuming a recovery of one-half the coal underground, are given in a graphical form in Fig. 8 for the principal geographical and political areas of the world. The total initial recoverable coal of the world he estimated to amount to 7.6×10^{12} metric tons.

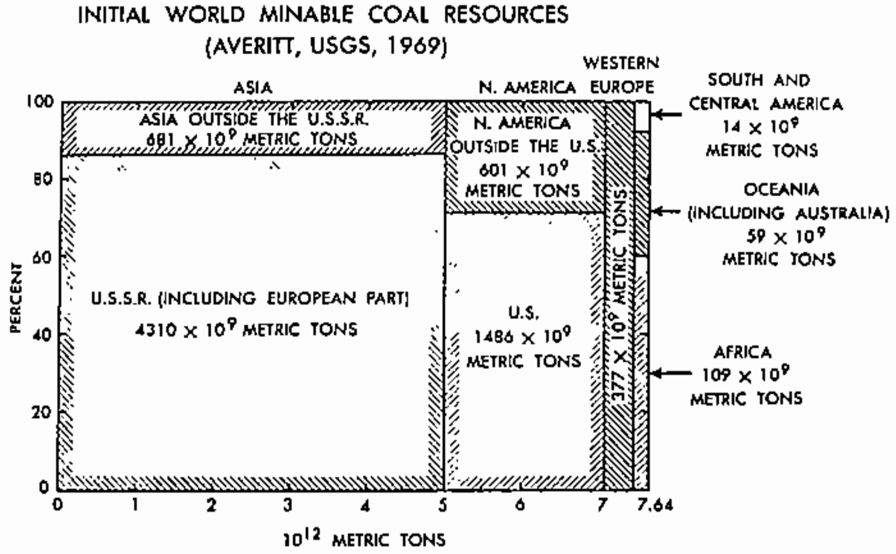

Fig. 8. Averitt estimate of initial quantities of recoverable coal in major geographical regions of the world (Hubbert, 1974, Fig. 19).

Even if this figure were strictly accurate it may be misleading because it may not be practical to mine beds of coal 0.3 meter thick occurring at depths as great as 1 kilometer. Consequently, a few years ago Averitt (1972) made a new estimate of the recoverable coal in the United States occurring at depths of not more than 300 meters and in seams of not less than 0.7 meter thick for anthracite and bituminous coal, and 1.5 meters thick for subbituminous coal and lignite. This resulted in a reduction from his earlier figure of $1{,}486 \times 10^9$ metric tons for the United States to only 390×10^9 metric tons — a reduction of 74 percent. Assuming that approximately the same reduction would be valid for the rest of the world, the world total of 7.6×10^{12} metric tons shown in Fig. 8 would be reduced to 2×10^{12}.

Using these two values for Q_∞ for coal, we construct the two complete cycles for world coal production shown in Fig. 9. In this figure, one grid square has the dimensions of

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

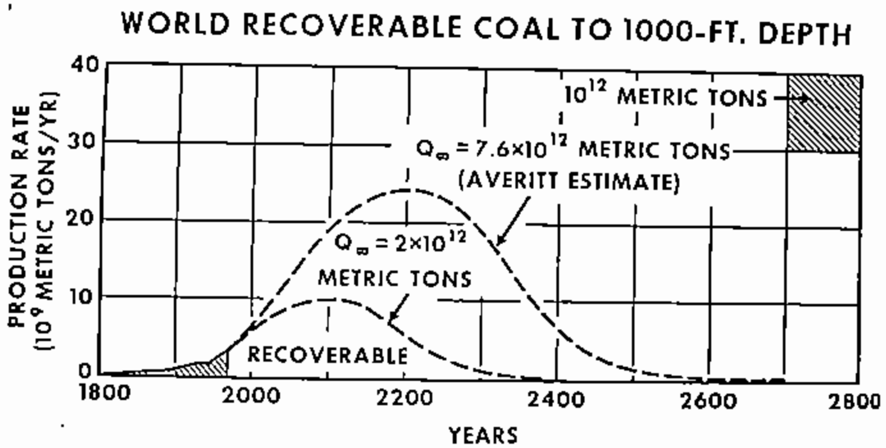

Fig. 9. Two complete cycles of world coal production based on Averitt's high and low estimates for ultimate cumulative production (Hubbert, 1974, Fig. 21).

Therefore, for Averitt's larger and more unrealistic figure of 7.6 × 10^{10} metric tons for Q_∞, the total area beneath the curve would be 7.6 grid squares; for the smaller figure of 2 × 10^{12} metric tons, the area would be but 2 grid squares.

The two complete-cycles curves of Fig. 9 are constructed accordingly. The curve for the larger figure assumes an 8-fold increase in the present rate of production and that for the smaller figure only a 4-fold increase before the decline begins. What emerges from this is a significant time scale. For the larger estimate for Q_∞, the maximum production rate would probably occur about the year 2200; for the smaller estimate about the year 2100. Also of interest is the time required to produce the middle 80 percent of Q_∞. For the larger estimate this would be approximately the four centuries from the year 2000 to 2400; for the smaller estimate, only about 2 centuries. Hence, if a single figure were sought concerning about how long coal can serve as major source of energy for the world, that figure would be about 300 years, or possibly less.

Estimations of Petroleum Resources

In 1956 (Hubbert, 1956) the foregoing method was used to estimate the time scale of petroleum production in the United States. At that time it had been 97 years since oil was originally discovered in Pennsylvania, and the production rate had been increasing, with only minor reversals, ever since. The production rate by 1955 had reached 2.5 × 10^9 barrels per year, and cumulative production amounted to 52.4 × 10^9 barrels. Published estimates by leaders of the petroleum industry for Q_∞ fell principally within the range of (150—200) × 10^9 barrels.

These were the generally accepted figures by members of the U.S. petroleum industry, but their intuitive interpretation was that if only about 50 billion barrels of oil had been produced in a century, and if future production would be 2 to 3 times this amount, it was most unlikely that an oil shortage could occur before the year 2000.

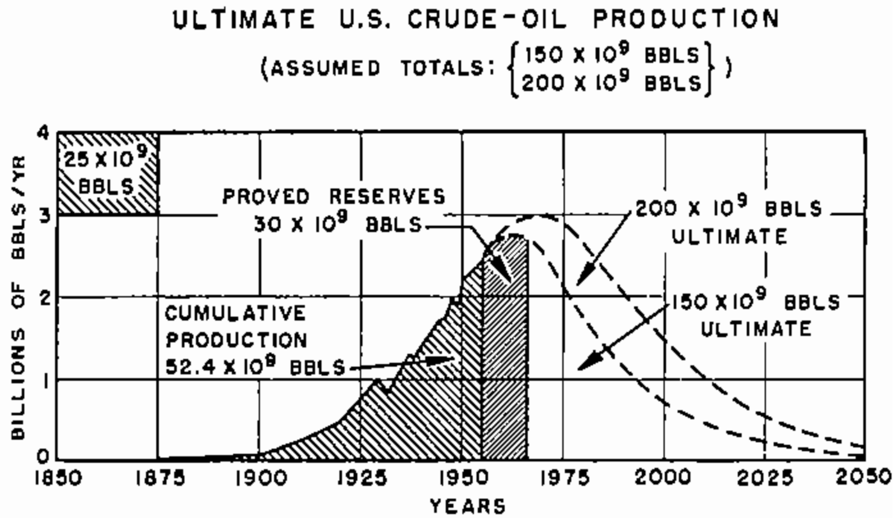

Fig. 10. Hubbert 1956 estimates of future U.S. crude-oil production (Hubbert, 1956, Fig. 21).

A graphical interpretation of these figures made at that time is shown in Fig. 10. Here, 1 grid square represents 1 billion barrels per year times 25 years, or 25 billion barrels. Hence, for the lower estimate of 150 billion barrels for Q_∞, the total area beneath the complete-cycle curve would be 6 squares; for the higher estimate of 200 billion barrels, 8 squares. The two curves shown in Fig. 10 were drawn accordingly. For the lower figure, the maximum production rate was estimated to occur by about 1966; for the higher estimate, about 5 years later, or about 1971. Hence, if the value for Q_∞ should fall within the range of 150—200 billion barrels, as all available information indicated, the peak in U.S. oil production should occur within 10 to 15 years after 1956, or between 1966 and 1971, not some time in the twenty-first century.

It actually occurred in 1970.

The weakness of this method of estimation of petroleum results from the fact that the amount of petroleum still to be discovered is a difficult quantity to estimate. However, in a primary region such as the United States, which is in a mature state of petroleum development, various methods exist for making such estimates, based upon the cumulative evidence of exploratory drilling and discovery. One of these is based upon the average quantity of oil discovered by unit of depth of exploratory drilling as a function of cumulative depth of drilling.

Initially, when undiscovered oil accumulations are at their maximum number, there is a high probability that any given well will discover oil. However, as more and more discoveries are made, the number of remaining accumulations steadily diminishes. These may also be small in size and of increasing depth, and hence more difficult to discover.

All petroleum exploration techniques — surface and subsurface geology, geophysical methods, and physical well-logging techniques — are designed to

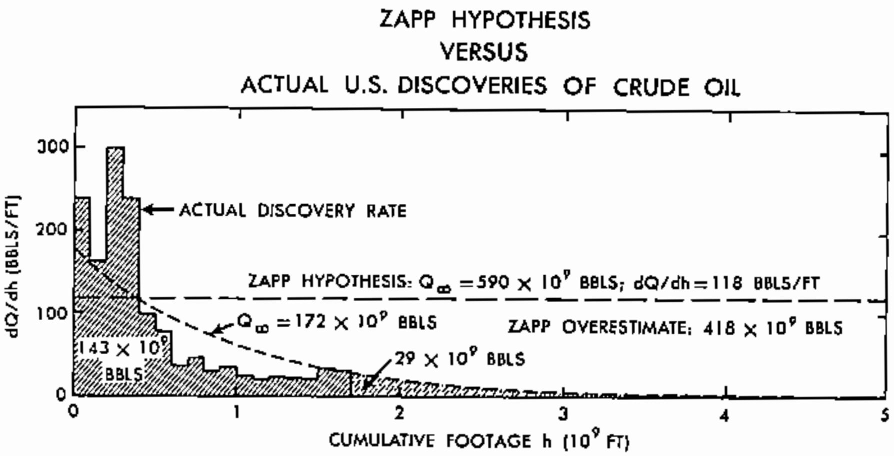

Fig. 11. U.S. crude-oil discoveries per foot of exploratory drilling versus cumulative depth of drilling (HUBBERT, 1974, Fig. 50).

maximize the probability of discovery as compared with that of random drilling. Nevertheless, it is expectable that in general the discoveries per unit depth of exploratory drilling, as a function of cumulative depth of drilling, will undergo an approximately negative exponential decline as the difficulties of discovery of the ever-scarcer remaining accumulations increase.

Such a record for the United States for the 1.7×10^9 feet of exploratory drilling from 1860 to 1972 is shown in Fig. 11. The figure of 1.7×10^9 feet of exploratory drilling divides conveniently into 17 units of 10^8 feet each. For each of these units the total amount of oil discovered, and the average discoveries per foot are shown. Despite the primitive state of petroleum exploration during the drilling of the first unit, which required the 60-year period from 1860 to 1920, the discovery rate per foot was high, 240 bbl/ft. The highest discovery rate of 300 barrels per foot occurred during the third unit. Then followed a steep decline to an average of only 30 barrels per foot for the 17th unit.

The negative exponential curve that most nearly fits these data is also shown in Fig. 11. This declines at an average rate of 10.6 percent per each 10^8-ft unit. Cumulative discoveries for the first 17 units amounted to 143 billion barrels. Extrapolation on the assumption that the future rate of decline will be about the same as that of the past gives an estimate of 29 billion barrels for future discoveries, or a total for Q_∞ for the conterminous United States and its adjacent continental shelves of 172 billion barrels. Other independent methods of estimation have given about 170 billion barrels, a figure near the middle of the range of estimates of 150—200 billion barrels current in 1956.

The complete cycle of oil production for the conterminous United States based upon a figure of 170 billion barrels for Q_∞ is shown in Fig. 12. The maximum of the mathematically smoothed curve occurred about 1968 but the actual maximum production rate occurred as an eccentric spike two years later in 1970. The production rate has been declining ever since.

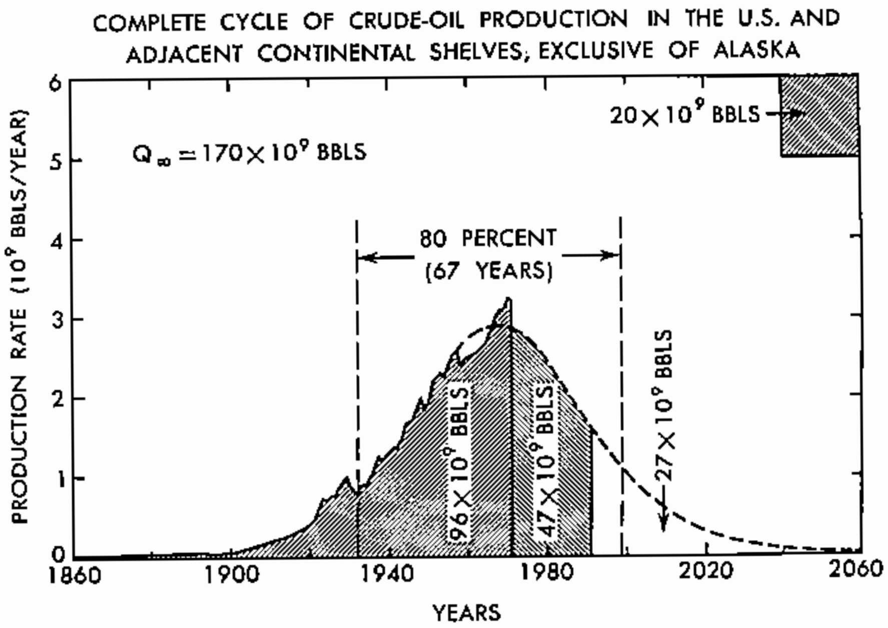

Fig. 12. Estimate in 1972 of complete cycle of crude-oil production in conterminous United States and adjacent continental shelves (HUBBERT, 1974, Fig. 51).

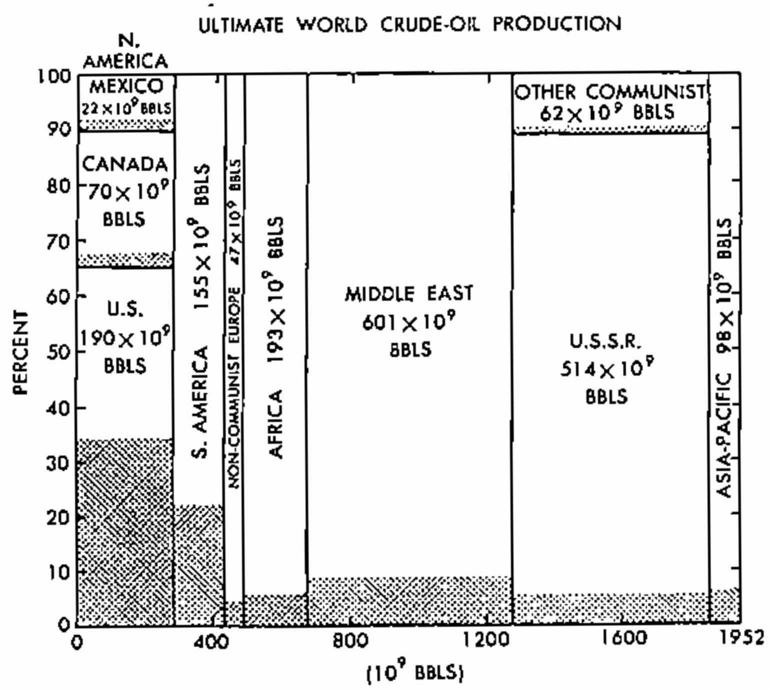

Fig. 13. Jodry estimates of ultimate crude-oil production and degree of depletion by 1971, for major regions of the world (HUBBERT, 1974, Fig. 67).

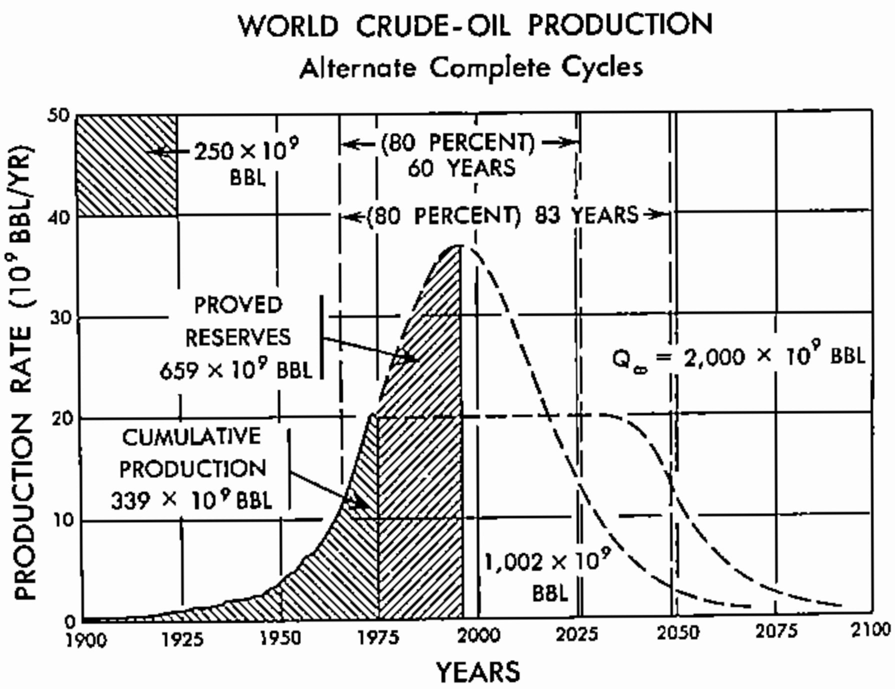

Fig. 14. Two alternative complete cycles of world crude-oil production.

The time span of this curve is also significant. The middle 80 percent of Q_∞ will be produced during the 67-year period between 1932 and 1999. Thus, such is the brevity of the epoch of crude-oil exploitation that children born during the 1930-decade will see the United States consume most of its oil during their lifetimes.

The estimated oil resources of the major geographic and political areas of the world, and their degree of exhaustion, are shown in Fig. 13. These are estimates made by Richard L. Jodry, Senior Research Scientist of Sun Oil Company, which resulted from a staff study of several years duration encompassing every potential oil-producing region on the earth. These estimates are also close to an average of the results of fifteen or more other estimates published within the last 20 years by various oil geologists with international oil companys. What is most conspicuous is that the largest future oil resources of the world are those of the Middle East and the U.S.S.R. North America represents only about 15 percent of the estimated world ultimate production.

Two alternative complete cycles of world crude oil production are given in Fig. 14, based upon a figure of 2,000 billion barrels for the ultimate cumulative production Q_∞. Should the world rate of production proceed in an orderly manner, as indicated by the first curve, the maximum production rate approaching 40 billion barrels per year would be reached by about 1995, and the time for the middle 80 percent to be produced would be about 60 years. However, it is possible, though unlikely, that oil production could be stabilized near the present level, as represented by the second curve in Fig. 14. In that case the crestal region of the first curve would be translated to its back slope. This would extend the span of the middle 80 percent to about 80 years. In any case, children born during the last decade will probably see the world consume most of its petroleum during their lifetimes.

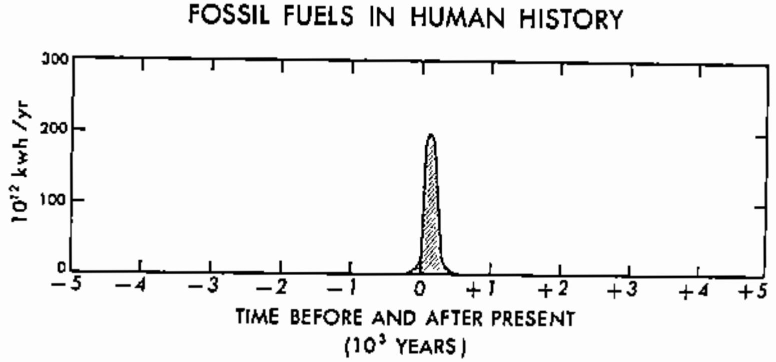

Fig. 15. Complete cycle of world fossil-fuel production seen on a time scale from 5,000 years in the past to 5,000 years in the future (Hubbert, 1974, Fig. 69).

Fossil Fuels in Human History

To better appreciate the era of the fossil-fuel exploitation in the perspective of a longer span of human history, consider Fig. 15, in which the complete-cycle curve for energy from all the fossil fuels has been plotted on a time scale extending from 5,000 years in the past to 5,000 years in the future. The obelisk-like column in the middle of this span, with an 80-percent width of about 300 years, represents the episode of the fossil fuels in human history. Yet this has been the basis for the industrial growth, principally during the last century, for the mining and smelting of the world's accumulations of metallic ores, which are essential elements in the development of the world's state of industrialization. As an event in geological history, we may well ask which is the more remarkable geological phenomenon, for the earth by natural processes to accumulate the stores of coal and oil during 600 million years, or for a single animal species to destroy them within a span of three centuries?

Other Sources of Energy

Space here does not permit the discussion of other sources of energy except summarily. Of the stores of energy within the earth, geothermal energy is large in magnitude but the problems of extraction are also formidable except for the case of shallow accumulations of volcanic heat producing dry steam. At present the largest geothermal installation in the world is that of The Geysers in California with a capacity of about 500 megawatts of electric power. Total world installations amount to about 1,300 megawatts which is only slightly more than one large modern power plant.

The extraction of geothermal heat is in effect a mining process. It is not accurately known how long the energy at The Geysers can be withdrawn at the present rate, but it is probable that the period will be measured in decades rather than in centuries. The total world outlook for such power at present appears to be much smaller than the world's current rate of consumption of energy from the fossil fuels.

Nuclear power obtained from the fissioning of uranium-235 is now a *fait accompli* and 1,000-megawatt nuclear power plants are proliferating around the world. However, the scarcity of uranium, the intrinsic industrial hazards of such concentrations of energy, the waste-disposal problem, and finally the vulnerability of such installations to terroristic activities or legal warfare together are making nuclear power appear far less attractive as a solution of the world's power problem than it was originally thought to be.

This leaves us with the renewable sources of power, which are only two, solar and tidal. Of these, tidal power is attractive in special cases, but the world total of potential tidal power is only a few percent of that of water power.

Solar power is available directly from solar radiation and indirectly from water power, wind power, the power of ocean waves and currents, and that obtainable from thermal gradients in ocean waters, and finally that from photosynthesis. Referring to Fig. 1, the largest source of power on earth, past, present, or future, is that from solar radiation. This is equivalent to all the fossil fuels about every 21 days, and it is amenable to large-scale utilization by means of presently available technology. Hence, if while the fossil fuels are still available, the world should direct its technological efforts in this direction, there is every promise that its energy and power needs for the future could be satisfied from this source.

Metals

Complementary to its energy requirements, are the requirements for metals by the industrial world. Metals and energy in their utilization differ from one another in one fundamental respect. Energy, during its utilization, undergoes a series of degradations until it reaches the final form of heat at the ambient temperature. After that it leaves the earth entirely by thermal radiation. Metals, on the other hand, as is shown in Fig. 16, are usually extracted from geologically concentrated ore bodies. After being mined, the metallic elements are extracted by smelting and then placed into industrial usage. Following that, one fraction of the metal is retrieved as scrap and recycled back into industrial use. A second fraction, however, becomes irretrievably dispersed. For example, lead is obtained from the ore galena or PbS. It is used as a metal for cable sheathing and plumbing, and chemically in lead-acid storage batteries, in paints, and in tetraethyl lead added to motor fuels. The metallic lead and that in storage batteries is retrieved and reused; the lead in paint and in motor fuels is irretrievably dispersed. Thus, although the metals remain on the earth, their transformation from concentrated ore deposits to a state of wide dispersion is unidirectional and irreversible. Ore deposits are just as exhaustible as accumulations of petroleum.

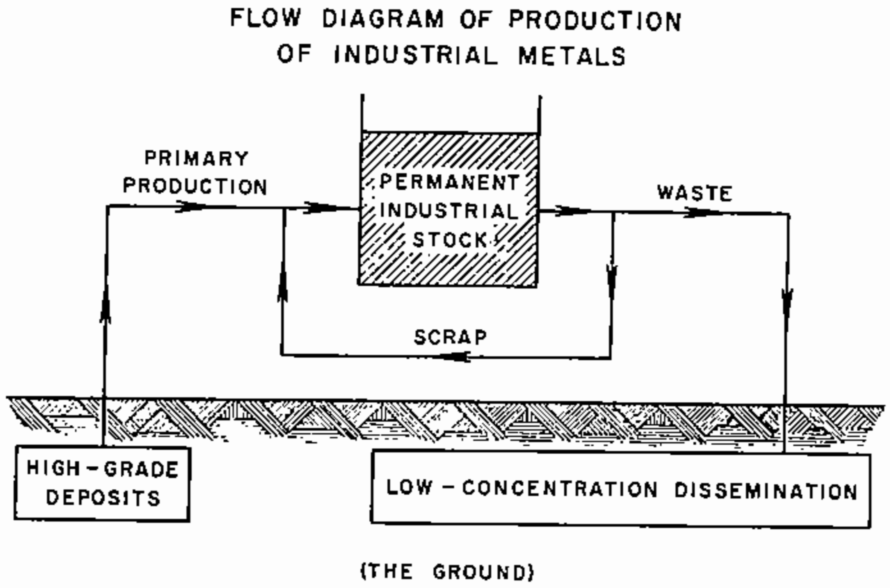

Fig. 16. Flow sheet of production of an industrial metal.

Although the smelting of nonferrous metals began in Anatolia about 5,000 years ago, and of iron about 1,500 years later, the preponderance of metal mining has occurred during the last century. In fact, the quantity of every metal produced during the last half century exceeds the cumulative production of that metal during all preceding history.

The brevity of this recent period of exponential growth in metal production, and the shortage of the resources of the ores of various metals, has been made eloquently clear by W. von Engelhardt (1976) in his paper, „Raubbau an den Erzvorräten". Of the nine principal industrial metals, for only three, iron, chromium, and manganese, are a five-fold increase in the known world reserves sufficient to sustain current rates of production for more than 100 years. Thus, in parallel with the limitations of the fossil fuels, the world also faces an impending shortage within decades of most of the industrial metals.

Exponential Growth

Before concluding, it is important that consideration be given to the phenomenon of exponential growth. During the last century or two the dominant characteristic of the industrial world has been an exponential growth in the rates of production of the primary energy and raw materials, and of finished products. These growth rates during most of the 19th century were commonly in the range of 4 to 8 percent per year, with doubling periods within the range of 7 to 18 years. In parallel with, and as a consequence of this, there has occurred

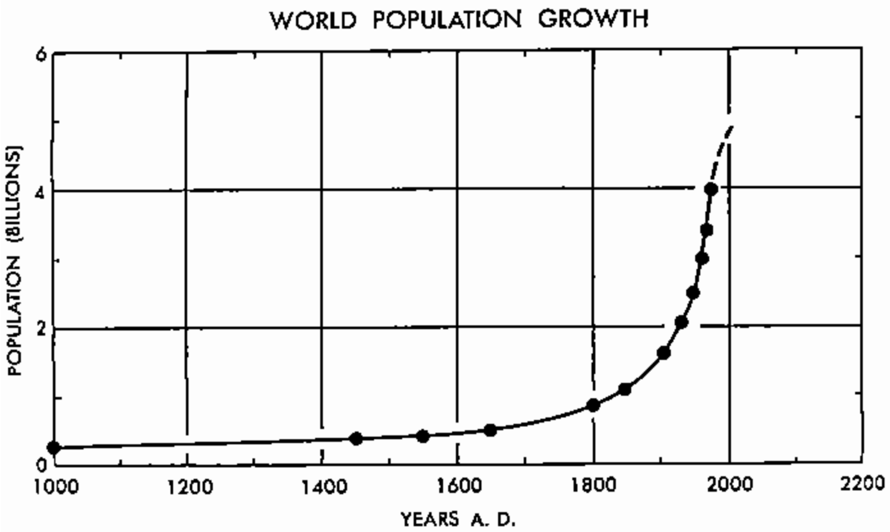

Fig. 17. Growth of human population from year 1000 A.D. to present.

one of the greatest and most rapid ecological disturbances, including the hum population, ever known.

The abnormality of this state of affairs can only be appreciated when we review the events of the last few centuries against the background of a much longer period of history. The growth of the human population since the year 1000 is shown in Fig. 17. Note the extremely slow rate of growth until about the year 1500 and then the gradual acceleration. By 1650 it is estimated the human population had reached about 500 million. By about 1800 this had doubled, reaching 1 billion. By 1933 it had reached 2 billion and by about 1973, 4 billion. At the present rate of growth it is due to double again in about 35 years.

The anomalous nature of this recent population growth can be appreciated if we ask what must have been the average period of doubling during the last million years. The maximum possible growth would have occurred if the population 1 million years ago had been the biological minimum of 2. Then the maximum possible number of doublings required to reach the present population of about 4.2 billion would have been 31. For 31 doublings in 1 million years, the average length of the doubling period would have been 32,000 years.

Similar arithmetic applied to any exponential growth phenomenon shows that such a growth can only be sustained for a few tens of doublings before restraints in the form of resource exhaustion, crowding, and environmental contamination become effective and growth must cease. The world is now entering this stage. When viewed upon a time scale from 5,000 years in the past to 5,000 years in the future, as shown in Fig. 18, it is seen that the events of the immediate past and future represent a disturbed period of rapid change of about 3 cenuries duration between a past, comprising all preceding history, and a future of very slow rates of change.

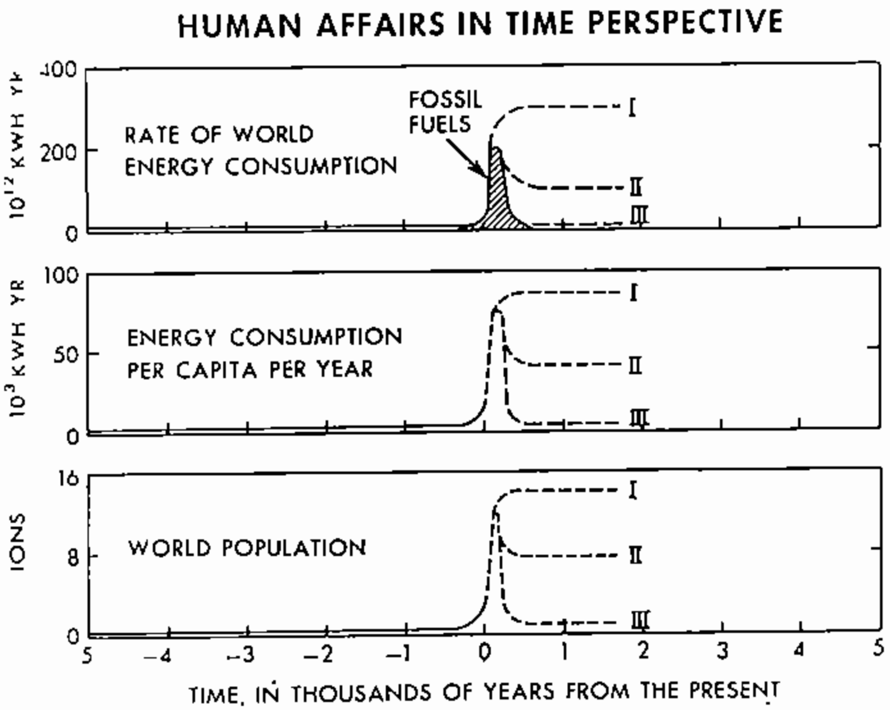

Fig. 18. The present state of human affairs seen against a background of history from 5,000 years in the past to 5,000 years in the future.

However, it has been during the last century that the industrial societies of the world have made the transition from a simple handicraft society to that of the modern industrial and commercial complexity. It is also during this period that most of the industrial world's institutions — its legal system, its financial structure, and its social organizaion — have evolved, all in an atmosphere of continued exponential growth. In short, we have developed what amounts to an exponential-growth culture, but a culture which is ill adapted to cope with the problems of nongrowth.

Challenge to Geologists for Intellectual Leadership

In the face of this impending cultural crisis, if a major catastrophic solution is to be avoided, it is imperative that the predicament the world has reached be understood. Only with such prior understanding are rational actions compatible with the facts likely to be undertaken. Therein lies the challenge to geologists. The knowledge essential to competent intellectual leadership in the impending difficult situation is preeminently geological — a knowledge of the earth's history and the evolution of its organisms, a knowledge of the earth's mineral and energy resources. Hence, provided that geologists can divest themselves of their preoccupations of the second phase of the history of geology when they have been largely handmaidens to finance and industry, and revert to th longer view of Lyell and Darwin, with a recognition that geological histor has a present and future, as well as a past, to that extent may the role of geolog again become one of intellectual leadership, the principal results of which coul be a major cultural change in what people think rather than in how they live.

References Cited

Averitt, Paul: Coal resources of the United States, January 1, 1967. — U.S. Geologica Survey Bulletin, 1275, 116 p., 1969.

—: Citation in Theodor, P. K., Schweinfurth, S. P., and Dungan, D. C., 1972, Energ resources of the United States. — U.S. Geological Survey Circular, 650, 3—4, 197

von Engelhardt, W.: Raubbau an den Erzvorräten. — Bild der Wissenschaft, No. 1 78—84, 1976.

Hubbert, M. King: Nuclear energy and the fossil fuels. — Dallas, American Petroleu Institute, Drilling and Production Practice (1956, 7—25, 1956.

—: U.S. energy resources, a review as of 1972, Pt. I, in: A national fuels and energ policy study. — U.S. 93 d Congress, 2 d Session, Senate Committee on Interi and Insular Affairs, Serial no. 93—40 (92—75), Washington, U.S. Governme Printing Office no. 527002419, 267 p., 1974.

Entropy, materials, and posterity

By Preston Cloud, Santa Barbara *)

With 4 figures and 1 table

Dedicated with appreciation to Nicholas Georgescu-Roegen,
distinguished economist, realist among cornucopians

Zusammenfassung

Rohstoffe und Energie sind die Grundlagen unseres ökonomischen Systems, das vo den Gesetzen der Thermodynamik bestimmt wird. Es kostet Energie, um die auf d Erde verteilten Rohstoffe diesem System zuzuführen. Andererseits braucht man Rohstoffe, um die Energie nutzbar zu machen.

Die verfügbare Energie kann nur einmal genutzt werden und das Material verbraucht sich. Verbrauchtes Material kann teilweise zur weiteren Nutzung zurückgeführ werden, das kostet wiederum Energie. Die verfügbare Energie nimmt überall ab, und einmal geschaffene Ordnung gerät wieder in Unordnung — das heißt, die Entropi des Systems nimmt ständig zu. Die Industrie ist jedoch abhängig von einem niedrige Entropiezustand sowohl der Materie als auch der Energie.

Je ärmer die Erze sind, um so höher wird die Energie sein, um sie in Metalle umzuwandeln, wobei die Entropie und die Belastung der Umwelt ständig zunimmt.

Außer den Dingen, die wir wegen höherer ideeller Werte schätzen, ist eine niedrig Entropie der einzige realistische Wertmaßstab, und der wirkliche Wertzuwachs ist nu an einer höheren Entropie zu messen. Es ist unverantwortlich, Dinge, die eine höhere Entropie bedingen, billiger zu verkaufen oder in größerer Menge zu erzeugen, als unbedingt notwendig ist. Da wir dies heute in unserem Handeln nicht berücksichtigen, ist die derzeitige Energiekrise nur der Anfang einer Folge von Krisen, die Energie und Rohstoffe betreffen, solange wir nicht umdenken.

Die Verteilung von niedriger Entropie in einer modernen Industriegesellschaft wird mehr oder weniger nach dem Prinzip der konkurrierenden Märkte erreicht. Das selbstregulierende System gerät jedoch mit zunehmender Polarisierung in reiche Industrienationen mit abnehmenden Ressourcen und armen Nationen mit geringer Industrialisierung in Unordnung. Dieses Prinzip berücksichtigt auch nicht die Nachwelt, vor allem wenn die Bevölkerungsdichte stetig zunimmt und die Konsumbedürfnisse anwachsen. Es sind neue soziale, ökonomische und ökologische Normen notwendig, die zur Populationskontrolle, zur Erhaltung der Umwelt und zu einem Zustand niedriger Entropie für zukünftige Generationen führen. Die nach uns kommenden Menschen haben ein Anrecht darauf.

Abstract

Materials and energy are the interdependent feedstocks of economic systems, and thermodynamics is their moderator. It costs energy to transform the dispersed minerals of Earth's crust into ordered materials and structures. And it costs materials to collect and focus the energy to perform work — be it from solar, fossil fuel, nuclear, or other sources. The greater the dispersal of minerals sought, the more energy is required to collect them into ordered states.

But available energy can be used once only. And the ordered materials of industrial economies become disordered with time. They may be partially reordered and recycled, but only at further costs in energy. Available energy everywhere degrades to bound states and order to disorder — for though entropy may be juggled it always increases. Yet industry is utterly dependent on low entropy states of matter and energy, while decreasing grades of ore require ever higher inputs of energy to convert them to metals, with ever increasing growth both of entropy and environmental hazard.

Except as we may prize a thing for its intrinsic qualities — beauty, leisure, love, or gold — low-entropy is the only thing of real value. It is worth whatever the market will bear, and it becomes more valuable as entropy increases. It would be foolish of suppliers to sell it more cheaply or in larger amounts than their own enjoyment of life requires, whatever form it may take. For this reason, and because of physical constraints on the availability of all low-entropy states, the recent energy crises is only the first of a sequence of crises to be expected in energy and materials as long as current trends continue.

The apportioning of low-entropy states in a modern industrial society is achieved more or less according to the theory of competitive markets. But the rational powers of this theory suffer as the world grows increasingly polarized into rich, overindustrialized nations with diminishing resource bases and poor, supplier nations with little industry. The theory also discounts posterity, the more so as population density and percapita rates of consumption continue to grow. A new social, economic, and ecologic norm that leads to population control, conservation, and an apportionment of low-entropy states across the generations is needed to assure to posterity the options that properly belong to it as an important but voiceless constituency of the collectivity we call mankind.

Résumé

Matériaux et énergie sont les sources des systèmes économiques et sont régis par les lois de la thermodynamique. Il faut de l'énergie pour transformer les ressources minérales dispersées dans la croûte terrestre en matériaux et structures ordonnancées. Et il faut des matériaux pour recueillir et concentrer l'énergie, qu'elle soit solaire ou

---

*) Author adress: Preston Cloud, U.S. Geological Survey and Department of Geological Sciences, University of California, Santa Barbara CA 93106, U.S.A.