have been largely handmaidens to finance and industry, and revert to the longer view of LYELL and DARWIN, with a recognition that geological history has a present and future, as well as a past, to that extent may the role of geology again become one of intellectual leadership, the principal results of which could be a major cultural change in what people think rather than in how they live.

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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 von den Gesetzen der Thermodynamik bestimmt wird. Es kostet Energie, um die auf der 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 zurückgeführt werden, das kostet wiederum Energie. Die verfügbare Energie nimmt überall ab, und einmal geschaffene Ordnung gerät wieder in Unordnung — das heißt, die Entropie des Systems nimmt ständig zu. Die Industrie ist jedoch abhängig von einem niedrigen 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 niedrige Entropie der einzige realistische Wertmaßstab, und der wirkliche Wertzuwachs ist nur 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 un-

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

bedingt 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, over-industrialized 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 receuillir et concentrer l'énergie, qu'elle soit solaire ou

atomique, ou provienne de combustibles fossiles ou d'autres sources. Plus les minéraux recherchés sont dispersés et plus est côuteuse l'énergie pour leur donner une ordonnance.

Or l'énergie disponible ne peut être utilisée qu'une seule fois. Et les matériaux ordonnancés des économies industrielles se dégradent avec le temps. Ils peuvent être remis partiellement en état et recyclés, mais pour cela il faut de nouveau de l'énergie. Partout l'énergie disponible se dégrade et l'ordre devient désordre; -malgré toutes les jongleries possibles l'entropie augmente toujours.

L'industrie dépend clairement d'états de basse entropie tant en ce qui concerne les matériaux que l'énergie, tandis que plus pauvres sont les minerais, plus élevée est l'énergie à mettre en jeu pour en extraire les métaux, avec toujours augmentation à la fois de l'entropie et de la degradation des milieux.

A l'exception de ce que nous apprécions pour leur valeur intrinsèque — la beauté, le loisir, l'amour ou l'or — la basse entropie est la seule chose de réelle valeur. Son prix est réglé par le marché, et sa valeur augmente au fur et à mesure que l'entropie s'accroît. Ceux qui en disposent seraient insensés de la vendre à bas prix ou en quantité supérieure à ce qu'exige leur propre niveau de vie. Pour cette raison, et à cause des contraintes physiques liées à la disponibilité en états de basse entropie, la récente crise d'énergie n'est, en ce qui concerne les matières premières et l'énergie, que la première d'une série de crises auxquelles il faut s'attendre aussi longtemps que se poursoit la marche actuelle des étènements.

Dans les sociétés industrielles modernes, les approvisionnement en basse entropie s'effectuent plus ou moins conformément à la théorie de la concurrence des marchés. Cependant la rationalité de cette théorie se ressent de l'accentuation croissante de la polarisation, à l'échelle du monde, en nations riches, surindustrialisées, à ressources de base décroissantes, et en nations pauvres, sous-industrialisées, mais fournisseurs de resources-naturelles. De plus cette théorie ne tient pas compte de notre postérité, et ce, en face d'une densité de population et d'un taux de la consommation par tête d'habitant en augmentation continue.

Nous avons donc besoin de nouvelles normes sociales, économiques et écologiques qui conduisent au contrôle de la population, à la conservation et à la répartition des états de basse entropie à travers les générations pour assurer à notre postérité les options qui leur riviennent de droit comme une constituante importante, mais encore muette, de la collectivité que nous appelons l'Humanité.

Краткое содержание

Минеральные ресурсы и источники энергии являются основной нашей экономической системы, подчиненной законам термодинамики. Для введения в эту систему рассеянных по Земле минеральных ресурсов требуется энергия. Для получения энергии необходимы ресурсы.

Имеющийся источник энергии можно использовать только один раз. Некую часть этого материала можно частично снова употребить, но для этого требуется затрата энергии.

Количество имеющихся источников энергии повсеместно уменьшается и созданный порядок нарушается, т.е. энтропия системы неуклонно возрастает. Индустриальное общество требует, как у материала, как и у энергии очень низкого уровня энтропии.

Чем беднее руды, тем больше затрачивается энергии для получения из них металлов, причем как энтропия, так и загрязнение окружающей среды неизменно увеличивается.

Оставив в стороне предметы, дорогие нам из-за их идеальной ценности, мы видим, что единственным реальным мерилом ценностей оказывается низкое состояние энтропии, а истинный прирост ценности измеряется только по более высокому уровню энтропии: Поэтому безответственно продавать вещи, повышающие энтропию дешево, или же создавать их в избытке. Т.к. наша современная торговля с этим фактом не считается, то энергетический кризис,

появляющейся в наше время, является только предвестником ряда кризисов, как энергии, так и ресурсов.

Распределение низкой степени энтропии в современном индустриальном обществе идет более или менее по принципу конкуренции рынков. Но в этой саморегулирующей системе постепенно, с увеличивающейся полярностью: с одной стороны богатые индустриальные государства с уменьшающимися минеральными ресурсами, с другой — нации с низким уровнем индустриализации, порядок нарушается. Сторонники свободного рынка не думают о завтрешнем дне, не принимают во внимание увелечение прироста населения и возрастающего спроса на предметы потребления. Нам необходимы новые социальные, экономические и экологические нормы, которые смогли бы и удержать в должных рамках популяцию, и сохранить окружающую среду и создать для будущих поколений состояние низкой энтропии. Наши потомки в праве предъявить к нам такие требования.

Introduction

The science of thermodynamics, conceived in the mind of the brilliant but then obscure French engineer Nicolas Leonard Sadi-Carnot, almost perished with him in 1832, when, at the age of 36, he fell before the great cholera pandemic then sweeping western Europe. He left behind, in addition to copious notes, a single publication, issued eight years previously, by curious coincidence in the very year of the birth of William Thomson — the same who was to become the great Lord Kelvin and, together with R. J. E. Clausius, H. L. F. von Helmholz, and others, to soften the tragedy of Carnot's early death with the discovery, nearly two decades later, that he had laid the foundations for a new science.

The key concept of thermodynamics is the intuitively obvious fact that it takes energy to make things happen. One of the important things that thermodynamics adds is the recognition that the direction of motion of the things that happen is from higher to lower levels of available energy and that, in the process, such energy is irreversibly transformed to unavailable states. If, for instance, we know the sum of the so-called Gibbs free energies on either side of a chemically feasible reaction, we can say in which direction the reaction will move or bring about a reversal of the thermodynamically expectable direction of reaction by adding sufficient energy to the low side. That is what plants do when they use light quanta to create energy-rich carbohydrates and oxygen from carbon dioxide and water to drive the biosphere. And that is what men do when they use external sources of energy to mine and beneficiate minerals in order to extract the useful elements with which they pursue their own special form of extra-biological or, more precisely, exosomatic evolution.

This important concept is embodied in the Second Law of Thermodynamics, sometimes referred to as the Entropy Law, or poetically, as "Time's Arrow". The importance of this law, which applies without known or likely exception to all natural systems, is that it specifies that, throughout the universe, available energy is eventually converted to bound states with a consequent increase in disorder, as when coal is burned to produce heat, gases, and ash or a star explodes to form an array of heavy elements. Such conversions and increases in disorder are summarized in the term entropy, and the Second Law specifies that entropy everywhere increases with time. In an open or partially open system, energy from outside may replenish local sources in such a way that entropy appears to be locally decreased. This process is illustrated by the previously mentioned utilization of solar energy in plants to produce low-entropy substances that cause organisms to appear, while living, as if they were negentropic.

Earth itself, although, for all practical purposes a closed system as far as materials are concerned, is, fortunately for its biosphere, open as regards the receipt of solar energy. Its daily quota of solar radiation, although it too is inevitably dissipated into unavailable forms, may be partially and temporarily stored for later use in plants, fossil fuels, and the hydrosphere.

Throughout the first four milliards of years (years $\times$ 10^9) of biological evolution, the conversion of solar energy through photosynthesis, abetted by small amounts of energy from chemosynthesis, was sufficient to drive the global ecosystem. The arrival of *Homo sapiens* introduced a new and perturbing element. Man's discovery that he could make tools and weapons of metals that could be obtained from rocks by raising their temperatures sufficiently at once greatly increased his energy demands and initiated his uniquely exosomatic style of evolution, culminating in the industrial revolution that has now swept much of the world.

The industrial revolution, as all know, sprang from the minds of the likes of THOMAS SAVERY, THOMAS NEWCOMEN, ABRAHAM DARBY and sons, and JAMES WATT. But the impelling force behind it, the material foundation of industrial economics, or political economy at it is sometimes called, is geological — the minerals and mineral fuels from which are obtained most of the industrial materials as well as the energy that drives the system.

Here is where entropy becomes critical. All of these minerals, without exception, are produced, beneficiated, and transformed into low-entropy products at a cost in available energy. All of the energy utilized is concentrated and brought to focus on useful work at a cost in materials. All of this energy is also irreversibly transformed into unavailable, high-entropy states. All of the low-entropy metals and other mineral products utilized become disordered high-entropy waste with time. They can only be restored to states useful to man, recycled that is, with further inputs of energy. Entropy inexorably increases.

This transformation of low-entropy materials into high-entropy junk and pollution is the ultimate product of the economic process. That self-evident conclusion, repeatedly stressed by the great Romanian-American economist NICHOLAS GEORGESCU-ROEGEN (e.g. 1971, 1976), has been received with deafening silence by the self-styled "mainstream economists" (SAMUELSON, 1973) who, with their baffling numerological exercises continue to mesmerize the leaders of western industrial society. Indeed one of their current *enfants terribles* has gone so far as to claim that "the world can, in effect, get along without natural resources" (SOLOW, 1974).

Why is it that "mainstream" and Marxian economists alike, including gifted statisticians and systems analysts, seem to ignore or deny the importance of natural resources — in particular of geological resources?

Some aspects of the industrial ecosystem

I suspect that there may be three main reasons why mineral resources are omitted or downplayed in the prevalent economic calculus. First is that mineral raw materials *per se* comprise only a small fraction of the gross national product (the GNP). Second is the economic passion for quantitative rigor, such that the greatest accolades in the profession are reserved for the most elegant mathematics, whereas the variables of the real world are hard to treat in a way that is both quantitatively rigorous and useful. And third is the fact that all of economics traces itself back to DAVID RICARDO and ADAM SMITH, for whom the resource of preeminent value was land.

Indeed, the index of what may be the most widely used textbook of economics in North America (SAMUELSON, 1973, 9th ed.) has no entry either for mineral or for mineral resources. A brief footnote on page 50 of that book concedes that resources such as minerals may have "some of the properties of capital goods", but at the few places where "natural resources" are mentioned, they are considered as or implied to be primarily "land".

Now land is surely a natural resource. It covers 30% of the earth (if we include ice) and we must have it. But advanced societies today are all industrial societies, and the guts of industrial society are minerals and mineral fuels primarily from beneath the land.

The industrialization of Europe, and subsequently of other parts of the europeanized world, brought with it surcease from much drudgery, lengthened life spans, increased leisure time, and unprecedented cultural opportunities to larger numbers of people than ever before. In many ways it has been the most civilizing influence since silver from the mines of Laurium ignited and sustained for a time the Athenian age of enlightenment. Indeed it has been the most civilizing influence ever, for it abolished many forms of slavery and compulsory servitude and permitted a larger fraction of the world than ever before to live in relative comfort, in improved health, to advanced years.

Modern industrial societies are, without exception, high-technology growth-societies. They are organized toward ever increasing production as a central goal, with high and increasing degrees of specialization, mechanization, automation, and urbanization as distinctive manifestations. In addition to certain advantages, such processes also give rise to dis-amenities on a large scale, not only within the industrialized world but throughout the world — to an unprecedented growth and crowding of populations, to the degrading of much human input from individual, self-fulfilling work to machine-tending or work-brigade drudgery, to ever-widening gaps between rich and poor, to an alarming dependence of industrialized peoples on vulnerable supply systems, and to a growing isolation of man from nature simultaneously with a growing unfavorable impact of man on nature. Industrial society thus exhibits not only civilizing but also degrading aspects.

The productive capacity of industrial society, moreover, let me repeat, is utterly dependent on natural resources, mainly geological. It needs minerals and fibers for making things and energy to drive the system, including both mineral fuels and the food products that energize the brains and muscles that design and serve production lines. If you happen to be one of those who questions the fundamental importance of mineral raw materials, reflect for a moment on Fig. 1. This summarizes the flow of materials and energy in an industrial society. Percentages indicated at three places on this diagram refer to fractions

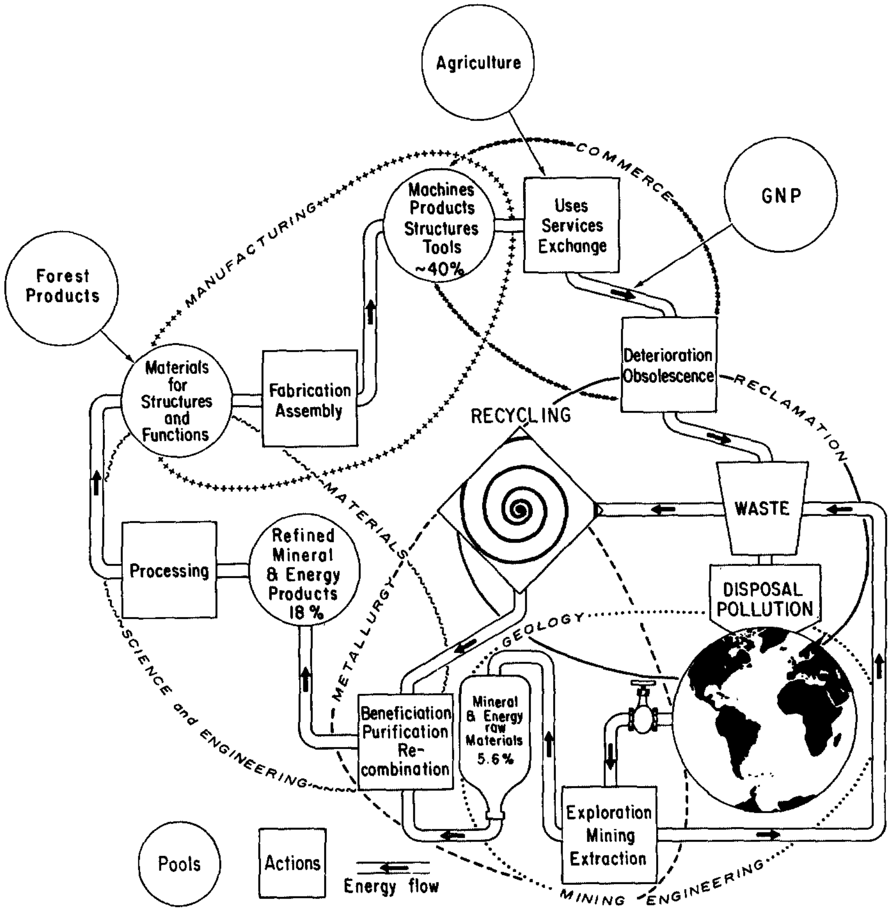

Fig. 1. Flow of materials and energy in an industrial society (percentages given are of 1975 GNP for the U.S.).

of the 1975 GNP for the United States. The fact that mineral and energy raw materials, including imports, represent less than 6% of that economic sacred cow, causes most economists to consider them unimportant. But notice that beneficiation, purification, and recombination enhance their value to a full 18% of the GNP in the form of refined mineral and energy products; and that further processing and material inputs scales this up to around 40% at the level of machines, products, structures, and tools. In a profound sense, therefore, mineral raw materials, including mineral fuels, underpin all the rest of industrial economy and, as Fig. 1 suggests, threaten to be the bottleneck to its further advance. After all, even fields and forests need mineral fertilizers, and even bankers, lawyers, economists, and other workers with words and figures need material goods, transportation, places to live and work, and increasingly, high speed computers whose performance depends on stuff like gold, germanium, and gadolinium.

What is involved in sustaining that which is good in industrial society and in making a smooth transition to the future? A change in attitude, for one thing, on the part of both rich and poor — involving the realization that the society to come must in some way preserve and enhance the civilizing aspects of industrial society, while reducing and eventually eliminating its dehumanizing effects and moving toward a less-intensively industrialized and more diversified condition.

Let us, therefore, take a hard look at the material basis of current industrial societies. And let us also examine the dangerous but widespread illusion that there are no limits to continued material growth, that mankind can somehow continue to consume and disperse the world's capital stock of raw materials forever without a day of entropic reckoning, that the gap between rich and poor can somehow be narrowed or even closed without major revision of present outlooks and norms. Let us consider too some of the steps that might be taken to smooth the transition from the world's current societal structure into a more humanistic, more durable, more equitable one.

Although the world society to come, whatever its name, nature, and economics, can arise only from our present mix of societies, the theory of competitive markets, seen by "mainstream economists" as the driving force of "free" or mixed economies, makes no provision for it. For, in addition to its exclusion of the various common propperty assets such as air, water, and scenery, and its assumption that all participants are fully informed and free to choose, the probable needs of posterity, like those of other external constituencies, are excluded from the theory of competitive markets.

This discounting of posterity as, in effect, an externality, like the environment, remains one of the most decriable aspects of current economic theory, brushed aside from the time of ADAM SMITH onward with the cold caveat that "every individual... intends only his own gain" (SMITH, 1776, quoted in SAMUELSON, 1973, p. 840). A ray of hope, however, can be gleaned from the fact that SAMUELSON (1973, p. 884) devotes two whole paragraphs of his popular "Economics" to the idea that there is something in the human sense of justice that calls for constituencies now marginal to or outside the economic system to be brought within it in some way. Although he does not say so, the largest and most voiceless of these constituencies is posterity. The only way in which the interests of posterity can be represented within the present sector of the economic system is for those now living to pay attention to the consequences of their actions for the yet unborn — at the very least to avoid the foreclosure of options that should be left open for the future.

Among the options that should not be foreclosed to posterity, but which are threatened by the excessive abundance of consumers and the greediness of the affluent among them, is the option of having access to a reasonable quantity and diversity of Earth's mineral bounty. Is it not at least conceivable that the new wave of ethical consciousness will create a place in the economic system not only for thoughts of immediate personal or corporate gain but also for truly long-range and global concerns?

Entropy, economics, and mineral production

The occasional economic assessments of mineral potential that have been made are too simplistic. There is a geological parallel to Borgstrom's passionate plea to "Those economic analysts who... take refuge in an abstract verbal world far removed from the stark realities of our globe and its staggering food needs" (Borgstrom, 1969, p. 73). A comparable set of analysts is all too prone to overlook or minimize geological variables and technological limitations in the stubborn faith that market forces will provide whatever warning, inducement, or corrective action may be needed to avert or promptly restore interruptions in the flow of minerals sought. No matter how tough a nut we have to crack or how dim the technological prospects of opening that particular nut, the economist among us always postulates a nut-cracker.

Brooks and Andrews (1974), for instance, drawing attention to the plausible but misleading conclusion that "The entire planet is composed of minerals", state that "The literal notion of running out of mineral supplies is ridiculous". Under a loose and useless definition of "supplies" that, of course, is correct, and it serves to bolster the meretricious notion of economic and technological omnipotence. But no one ever suggested we'd run out of ordinary rock-forming minerals, or that metals couldn't be recycled to some extent (although that is of only marginal help where demand is doubling at the rates it is), or even that some materials will not find substitutes. Goeller and Weinberg (1975) follow their ringing defense of cornucopianism with the concession that they see "no insuperable technical bars to living a decent rather than a brutish life", *provided*, of course, that we speak of "a *stable population*" (emphasis added).

Therein lies the crux of the matter. Neither industrial nor world populations are stable, and, what is worse, world population shows little sign of becoming so, least of all at supportable levels. Although the U.S., as an example of an industrial society, seems to be headed in that direction at the moment, the inertial effects of its age structure assure that its population will continue to grow willy-nilly for another 45 to 70 years. What is more to the point, no industrial society can divorce its fate from that of the larger, more rapidly growing world. On the 200th anniversary of its independence, the real population of the U.S. (allowing for census oversights) was near 220 million and that of the world exceeded 4 milliards. Official United Nations projections show that world population is currently increasing at a rate that yields a doubling time of 42 years — or as little as 20 to 23 years in a number of poor countries. The world can barely support its current population even at existing preponderantly deprived levels. What are the prospects that it can support double that population in the year 2020, particularly on a comfortable and sustained level? Or that world population will stabilize before then? Or that starvation and instability of the global economic system will not lead to social chaos?

Growth of world population is a trend that must be dealt with, either by altering it or by seeking to meet the staggering demands for materials that will be created by the housing, feeding, transportation, and employment of the increased numbers. Without dramatic economies and advances in recycling, it will not be possible to meet such demands at decent levels on the projected time scale except by improbably massive infusions of new virgin raw materials.

What would this entail? Few economists besides GEORGESCU-ROEGEN seem to understand that the really basic limiting factor in resource production, apart from a breakdown of society itself, is not likely to be currency so much as it is energy and the added materials required to produce this energy. We see the entropy law at work. The mining, extraction, and beneficiation of ores to produce metals represents an increase in order at a cost in available energy — for example about 16% of all energy used in the U.S. in 1975 for a domestic mineral production that fell 25% short of demand. Energy required, moreover, increases exponentially as the grade of ore decreases to some grade at which there is an inflection in the rate of energy demand such that it ascends toward the vertical at lower grades. This is clearly explained in papers by PAGE and CREASEY (1975), COOK (1976), HAYES (1976), and SKINNER (1976), including the problem of metals needed for energy production.

Fig. 2 illustrates the problem. It shows how, as the grade of ore decreases toward the left beyond certain critical values, energy costs climb dramatically. This, in effect establishes *cutoff grades* — concentrations below which ores of a given type will not yield metals at tolerable prices and existing technologies. Nor is it easy to foresee what technologies might drastically reduce such energy demands. Energy requirements of course, include not only those of actually producing and beneficiating the ores, but also those of transportation to the market, and a suitable fraction of the energy costs of all plant equipment and facilities involved in production, beneficiation, and transportation. The 16% of the U.S. energy budget that presently goes for mineral production will increase substantially as we seek to reduce our dependence on foreign sources. As the price of energy itself goes up, the hard-currency cost of non-energy mineral procurement will also increase, and with consequent braking effects on the economy.

This follows inexorably from the entropy law and the decreasing grades of new primary ores. Economics enters only to the extent that the growing energy investment is reflected in rising prices that, in turn, will stimulate the geological search for higher grades of ore and the technological search for substitute materials and technologies. A question to consider is why we must wait for "mainstream economics" to tell us what appropriate expertise can foresee now, albeit dimly, when the lead times needed for the development and introduction of uncertain new materials and technologies are so long as to introduce stresses the economy could do better without. The world already has an authentic energy crisis, but there is more to come. Any attempt to maintain present trends at projected levels will, within a few decades, precipitate a train of new crises, not only in energy, but in a variety of materials as well, not to mention environmental feedbacks of increasing gravity.

Even the hoary economic fallacy that decreasing grades of ore are compensated for by increasing volume, the so-called arithmetic-geometric, or grade-tonnage ratio, has now been laid to rest as far as metal production is concerned for the very ores (porphyry copper) that gave rise to this concept initially. A comprehensive study of grades and volumes by SINGER and others (1975) shows that this is not true for copper ores in general, and that, in particular, "large-tonnage very low grade deposits in the porphyry class ... are ... very rare".

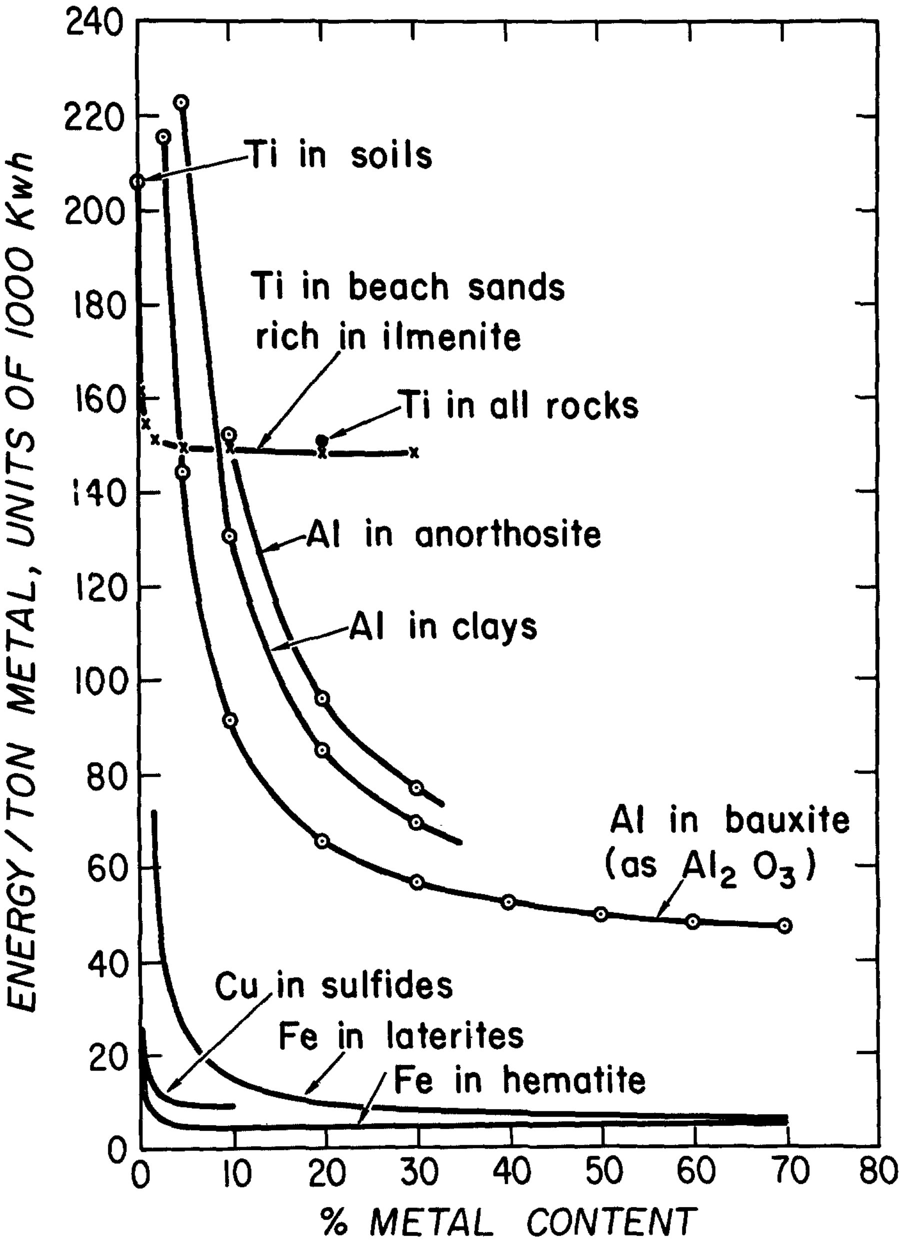

Fig. 2. Energy costs of metal production (simplified from PAGE and CREASEY, 1975).

The point is not that economics is not critical, but that an economic philosophy rooted in the concept of ever increasing material growth as the basic ingredient has dominated the affairs of industrial societies of all political shades to the point of conceptual bankruptcy, whereas considerations other than econometric are equally important and in some instances should be overriding. It is time to balance the decision-making process by introducing a better mix of economic considerations and viewpoints, including geological ones, and by paying comparable attention to other factors, including the long range values of economy in the use of most materials.

Mineral reserves, resources, total stock

Granted that the ability to foresee the consequences of our actions makes us responsible for them, why worry about posterity if the whole earth is made of minerals? Isn't it then all one big mineral deposit? Indeed that is implied by the suggestion, often made by the geologically naive, that, as grade of ore decreases, we will turn to mining "common rock". Like many other reassuring oversimplicities, there is not only an element of truth but also food for dangerous complacency in this one. Indeed, to the extent we obtain lead and zinc from limestone and copper from sandstone, we mine "common rock" now. But the idea is misleading to the nongeological public in the same sense that the idea of an earth made up of minerals, while substantially true in a literal sense, is, in the context of BROOKS and ANDREWS, simply mischievous nonsense. The zinc-rich limestones and copper-bearing sandstones are, in fact, very unusual rocks. It is the uncommon features of a rock that make it mineable. It is the local concentration of elements beyond, and usually far beyond, their normal abundance in Earth's crust to commercially exploitable levels that we designate a mineral deposit. Even if the whole earth were accessible to us, which it is not, we would have to stand somewhere while we mined it and we would have to dispose of the volumetrically preponderant waste minerals that must be moved or broken down to get at elements sought. Other factors also would prevent the mining out of the entire earth or a significant part of it — above all energy accounting, but also considerations of public health, safety, and environmental quality.

Consider Earth's accessible mineral heritage. On the unimpeachable premise that man is unlikely to recover minerals from below the outer 10 to 40 kilometers that comprise Earth's outer crust (except at those rare places where mantle rock is at or near the surface) we can think of the entire quantity of an element within that crust as the total stock of the element. Reserves and ultimate resources represent small fractions of this total stock. It is easy to estimate the *total stock* of an element from available data. Multiply the known mass of the crust by the analytically estimated crustal abundance of the element of interest and that's it. *Reserves,* being those quantities of commercially exploitable grades that have been proved to exist by physical exploration, are also not difficult to estimate. Just get the numbers from all mines in a nation or the world and add them up. What we would most like to get at, however, are reasonably reliable figures for ultimately recoverable or *potential resources* that could provide a basis for strategic intermediate and long range planning.

This is more difficult, but it can be done within very broad limits. For instance, SKINNER and BARTON (1973) estimate on geochemical grounds that most of the world's ore deposits are to be found in the upper 2 to 3 kilometers (e.g. STRONG, 1976). Viewed in the context of 4.6 milliards of years of Earth history, a new theory of metallogenic provinces and epochs related to times and types of plate motions and events within plates is emerging. Such reseach could be one of our best sources of strategic planning information and it should be strongly encouraged and supported.

Meanwhile crustal abundances provide some clues for at least informed guesses about the likely limits of potential resources, as suggested by McKELVEY (1973 and earlier). Resources that may some day become reserves are orders of magnitude less than crustal abundances, but they have some relation to them. In the case of copper, for instance, I have roughly estimated (CLOUD, 1975), using abundance data and optimistic assumptions that, of the roughly 10^{15} metric tons in Earth's crust, no more than perhaps ten times present reserves might eventually be recovered (perhaps 1 to 10 billions tons). And ERICKSON (1973) and SKINNER (1976) have derived similar maximal ultimate resource estimates for other metals in roughly the same range of differences in magnitude from total stock. All of these estimates far exceed those of individual U.S. Bureau of Mines commodity specialists made on different grounds; although, for diverse reasons, none warrant complacency. Moreover, in considering such estimates, it should be kept in mind that production down to the low grade levels involved would have enormous adverse environmental consequences.

ERIKSON's estimates, quoted in Table 1, are based on his "rule-of-thumb" that the potential recoverable resource in metric tons for most elements can be obtained by multiplying abundance in parts per million by 2.45×10^6, along with other nongeological assumptions. As he realizes, this leads to absurdities such as resource/reserve ratios for by-product elements such as tellurium, bismuth, and antimony that are much smaller than likely production or even less than unity. Low resource/reserve ratios for other metals are more cause for concern, but, generally speaking, the estimation of potential mineral resources is a very inexact science.

Ultimate supply involves so many variables that we can make reasonably reliable (although still rough) estimates only for a few commodities that are either so abundant and widely distributed that potential resources approach that part of the total stock that occurs in the outer crust, or that occur in regular and predictable patterns. Only iron, aluminum, magnesium, the rock silicates, and few others are abundant enough to be considered in this light, and their extraction too runs into energy barriers. Coal, oil, natural gas, and, to some extent, the abundant metals mentioned, occur in regular and predictable ways.

Estimates of ultimate reserves of such commodities are likely to agree within an order of magnitude or less. Virtually all of the information except trace-element content and potential environmental impact that strategic planners need to have about coal in the United States, for instance, is condensed into a single slender book by AVERITT (1975) — summarizing a beautiful example of planning for posterity by the U.S. Geological Survey. The many estimates of ultimately recoverable oil and gas, despite much dispute, agree within a remarkably narrow range. As energy resources are the subject of a preceding paper in this symposium volume by M. K. HUBBERT, however. I will pass on to the non-energy minerals.

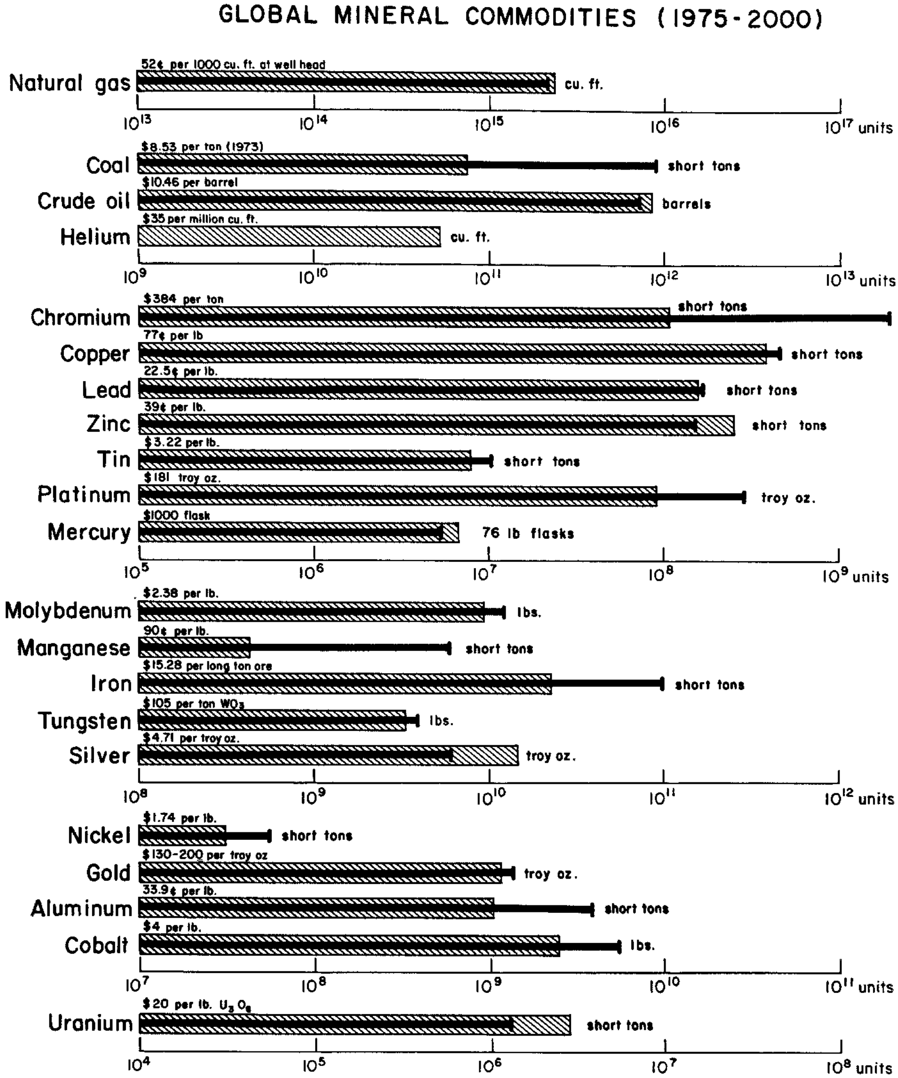

Fig 3. Reserves of 20 key global mineral commodities compared with projected cumulative demand to the year 2000 (data from U.S. Bureau of Mines 1976 a, 1976 b). Shaded bars represent projected cumulative demand through 1999. Median lines show largest, most recent reserve estimates. Prices in 1975 dollars. Scale is logarithmic, unit quantities and scales vary as indicated and all lines begin at zero to left of diagram. See Table 1 for more optimistic resource estimates.

Estimates of potential non-energy resources are given in reports by the U.S. Bureau of Mines (1976 a, 1976 b) and the U.S. Geological Survey (1973, and in USBM, 1976 a). Data on world reserves and estimated resources from these reports are summarized in terms of adequacy to meet projected demands through

LIFETIMES OF GLOBAL MINERAL COMMODITIES

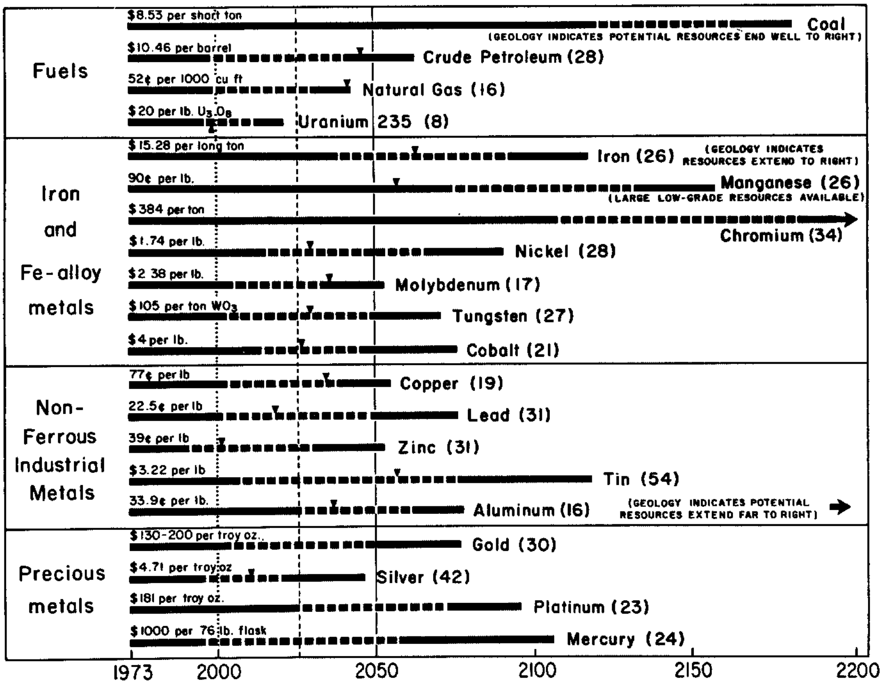

Fig. 4. Apparent lifetimes of reserves of 20 key global mineral commodities compared with lifetimes of hypothetical reserves 5 and 10 times as great and with potential resource estimates of U.S. Bureau of Mines (data from U.S. Bureau of Mines 1976 a, 1976 b). Solid bars at left are for known reserves. Short-dash lines in middle are for 5× known reserves. Solid lines at right are for 10× known reserves. Solid triangles denote lifetimes implied by U.S.B.M. resource estimates. Bracketed numbers at right are years for projected doubling of demand. Prices in 1975 dollars.

the year 2000 in Fig. 3 — in which the solid bars represent reserves and the shaded boxes demands. Wherever the solid bar ends within the shaded box, known reserves are insufficient. In Fig. 4, projected lifetimes of established global reserves at projected rates of demand are shown by the solid bars at the left, while extension of lifetimes by hypothetical reserves 5 and 10 times as great are shown by the dotted bars in the center and solid bars at the right. Lifetimes indicated by U.S. Bureau of Mines estimates of expected resources are indicated by small triangles above the bars. Additional notation indicates where geological evidence strongly implies potential resources to the right of scale. Except for South Africa, Australia, Canada, and the USSR, similar data for the domestic reserves and resources of individual industrial or industrializing nations is much less favorable.

Table 1 compares reserves and estimated potential resources cited in Bureau of Mines reports (1976 a, 1976 b) used in compiling Fig. 4 with the previously mentioned calculations by Erickson (1973) of ultimate global and U.S. resources

Element	UNITED STATES						WORLD					
	Reserves metric tons × 10^6		Potential Resources metric tons × 10^6		Ratio Resources/Reserves		Reserves metric tons × 10^6		Potential Resources metric tons × 10^6		Ratio Resources/Reserves	
	USBM 1976	Erickson 1973	USBM 1976	Erickson 1973	USBM 1976	Erickson 1973	USBM 1976	Erickson 1973	USBM 1976	Erickson 1973	USBM 1976	Erickson 1973
Aluminium	9.07	8.1	45	203,000	4.96	24,000	3,480	1,160	5,720	3,519,000	1.64	3,000
Antimony	.091	.1	.093	1.1	1.02	11	4.14	3.6	5.06	19	1.22	5.0
Beryllium	.025	.073	.073	3.7	2.92	50	.38	.016	1.105	64	2.91	4,000
Chromium	none	1.8	5.17	189	—	387	1,693	696	4,383	3,260	2.59	47
Cobalt	none	.025	.764	44	—	1,760	2.45	2.14	4.28	763	1.75	360
Copper	81.6	77.8	372	122	4.56	1.6	408	200	1,860	2,120	4.56	10
Gold	.0034	.002	.0068	.0086	2.0	4.1	.037	.011	.054	.15	1.46	14
Iron	3,600	1,800	89,900	118,000	25	65	86,900	87,000	689,000	2,035,000	7.93	23
Lead	53.5	31.8	108	31.8	2.02	1.0	150	.54	299	550	1.99	1,000
Manganese	none	1.0	66.77	2,450	—	2,450	1,814	630	3,266	42,000	1.80	67
Mercury	.016	.013—.028	.031	.20	1.94	15—6.8	.17	.11	.604	3.4	3.55	30
Molybdenum	2.96	2.83	15.92	2.7	5.38	1.0	5.99	2.0	28.62	46.6	4.78	23
Nickel	.181	.18	13.8	149	76.2	830	45.3	68	90.8	2,590	2.00	38
Phosphorus	2,268	931	6,350	2,940	2.80	3.0	16,068	15,000	76,107	51,000	4.74	34
Selenium	.035	.025	.157	.14	4.49	6.0	.168	.695	.628	2.5	3.74	36
Silver	.043	.05	.162	.16	3.77	3.2	.17	0.16	.642	2.75	3.78	18
Tantalum	none	.0015	.0015	5.6	—	4,000	.0676	.274	.261	97	3.86	354
Thorium	0.13	.54	.27	16.7	2.08	31	.71	1	1.83	288	2.58	288
Tin	.043	small	.198	3.9	4.60	small	10.1	5.8	37.6	68	3.72	12
Tungsten	.108	.079	.435	2.9	4.03	37	1.78	1.2	5.17	51	2.90	42
Uranium	.242	.27	.395	5.4	1.63	20	.967	.83	1.691	93	1.75	112
Vanadium	.104	.115	9.104	294	87.5	2,560	9.707	10	56	5,100	5.77	500
Zinc	27	31.6	45	198	1.67	6.3	135	81	245	3,400	1.81	42

Table 1. Global reserves of 23 key metals compared with two sets of independently estimated ultimate potential resources of same.

and his reserve figures for 23 metals. Data for the U.S. in this table illustrate the situation for that part of the industrialized world which has become resource-poor as a result of long or rapid economic development and is thus vulnerable to cartel actions and other economic constraints on the part of supplier nations. This table also illustrates the range from conservative to optimistic resource estimates.

Although U.S. Bureau of Mines resource estimates used in Fig. 4 and Table 1 are appropriately conservative, they do suggest where some supply problems may arise later in this century or early in the 21st. Where ERICKSON's much larger resource estimates, best taken as outside limits, yield low resource/reserve ratios, it would seem wise to prepare for recurrent and worsening global shortages during and following the 21st century if observed growth trends continue. And, to the extent U.S. ratios are typical for the industrial world, near to intermediate term difficulty may be in store with respect to supplies of copper, gold, lead, mercury, molybdenum, silver, tin, zinc, and perhaps even antimony and phosphorus. Nor is any provision made in the projected mineral lifetimes for expected increases in demand on the part of third world countries — not for lack of recognition but for lack of data. With respect to that matter, I can only say "beware". In it lies the potential for much friction, exacerbated by the fact that the rich, industrialized, high-consuming nations are increasingly resource-poor, whereas many of the poor, non-industrialized or less industrialized supplier nations are both relatively resource-rich and understandably eager to narrow the gap between themselves and the currently rich.

After, and probably well before ERICKSON's outside limits are exceeded, if present trends continue, industrial societies, regardless of how vast their energy sources, will be confronted with severe geochemical and thermodynamic constraints on the addition of new virgin metals. Those constraints will require adapting societal technology to one that can subsist on recycled materials plus rock silicates and the geochemically abundant metals. They, plus coal, solar energy, and perhaps geothermal and fusion energy, will comprise the material and energy foundations of the future, hopefully more equitable world society.

What to do

The important qualifier to all warnings issued is that they apply only to a continuation of present trends. There is no law of nature or man that says these trends have to be continued. Yet the eventually disastrous notion of growth *per se* as an intrinsic good is deeply imbedded in the current folklore of nations and societies. It served us well at one time and the inertial forces to keep it going are great. But growth both of populations and of material overconsumption by the already affluent could be slowed down and even reversed if there were a general recognition of the need and a will to do so. Therein lies the best hope for the future.

Although economists, almost as of one voice, cried foul when DONELLA MEADOWS and associates (1972) employed computerized, aggregative, analytical, albeit simplified, models of the same sort used in their own econometric exercises to produce an arithmomorphic statement of the geologically and ecologically obvious and familiar conclusion that there are limits to growth, that was five years ago. All informed people, even including some but by no means all economists, now agree that economic growth in a material sense cannot continue forever on a finite Earth. Indeed some establishment figures are now themselves mouthing words and phrases that not long ago were being branded as irresponsible. The only point at issue is when and how this cancerous growth of populations and overconsumption will come to an end — whether it will terminate with a bang, a whimper, or a cheer. Will mankind plunge blindly ahead, aware only on the one hand of his growing hunger and on the other of the Dow-Jones average or some comparable index until society collapses or goes into a declining state of fluctuating disequilibrium? Or will he use those superb computers we carry around on our shoulders to change course and speed before reaching the point of no return; to find means other than crude growth for the enhancement of the human condition?

The possibilities of amelioration are many, and the best mix for a given society will vary with its circumstances and preferences, but three actions are essential. The third of the world that consumes 90 percent of its resources must limit its consumption as well as its populations, lest if foul its nest and incur the justifiable wrath of posterity and neighbor alike. The two-thirds of the world that consumes the remaining 10 percent of the world's resources must limit its populations and soon, lest its standard of living fall even lower. And the global population must eventually decrease to one that is indefinitely supportable at decent levels within the physical limitations of our planet and the working of natural laws. If these things happen, and if the world can somehow bypass the fission economy, remain at peace, feed its teeming milliards through the crisis years ahead, and move toward a more equitable distribution of its goods, the main steps in the transition to a hopeful future will have been achieved. If they do not, our descendants might as well go first class where they can, for we will have booked reservations for them in a disintegrating system.

That would not mean the end of the world to be sure, or even of *Homo sapiens*. Geologists know that the cycle of materials goes on and that species evolve and have an amazing capacity to adapt, even to the most austere circumstances. It may have been the fate of my generation to have lived through the high water mark of industrial civilization. But it is also within the power of generations now living to initiate the new trends that could best assure lives of quality to those who will inherit this planet — the only one we know anywhere in the universe that is suitable for natural occupancy by live members of our species.

The things we do or decline to do over the next few decades will brighten or prejudice the future of all mankind. Collectively we can be the masters of our fate. But no one or no few can manage for all the rest. In fact the world cannot have guns and butter too. And time is of the essence.

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