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Mineral Resources, Economic Growth, and World Population

We are running out not of mineral resources but of ways to avoid ill effects of high rates of exploitation.

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One of the ironies of the limits to growth thesis is that, while purporting to present counterintuitive ideas about the future of the world economy, it has accepted one of the oldest propositions of resource economics (*1–4*). In its strongest form, this apparently common sense proposition states that mineral resources will sooner or later run out, with drastic consequences for mankind. In a somewhat weaker form, it states that prices for minerals will rise sharply in the future. Much the same propositions are also put forward for energy and food supplies, but in this article we will focus on nonfuel mineral resources.

We maintain that most assessments of mineral supply, whether they are optimistic or pessimistic, are focusing on the wrong issue. We argue that while it is naive to jump from the premise that mineral resources are physically finite to the conclusion that this limits their economic availability, it is equally naive to jump from the premise that mineral resources are economically infinite to the conclusion that they could be produced in enormous volume without major social or political problems. This takes us beyond the usual studies of resource availability; such studies usually stop when the case for availability is proved, the investigators placing such implications as the effects on land use, the balance of payments, and the international distribution of income beyond the scope of their analyses. Yet we believe that these factors will prove less tractable than will the problem of supply itself.

Most of the data used in our analysis are from the United States or Canada. Not only are such data more abundant in these countries, but both the United States and Canada are high-income, resource-rich regions that provide prototypes of what one must look for elsewhere in the world. Our focus is on the next 50 to 75 years, not on some more distant future when populations will either have reached standing-room-only levels or population growth will have been completely curbed.

Mineral Supply

Although the ideas of resource scarcity and abundance are deceptively simple, difficulties arise when one tries to transfer them from the individual to society (*5–6*). In a recent study, Fischman and Landsberg pose nearly a full page of questions that indicate just how difficult the concepts are to define. Notably they ask (*7*, p. 79):

> What is a "shortage," and what is "adequacy"? Is the supply of a given mineral "adequate" only if it continues to be forthcoming in the "required" amounts at present relative prices, or at prices rising no more rapidly than has been the trend, even if that trend reflects increasing supply stringencies? What if the only means of avoiding marked price change is the initiation of unaccustomed efforts at conservation, reuse, and recycling, or the making of major investments toward technological advance? Is adequacy measured in terms of current levels of minerals exploration, evaluation, and development, or trend levels? May a mineral be considered adequate just because it can be geologically inferred to exist in sufficient quantity, even if it takes major new outlays in exploration, evaluation, and development to find this quantity and get it into production?

These questions are not relevant exclusively to minerals. There are examples of such presumably renewable resources as fish and timber that have been totally exhausted, while presumably nonrenewable resources like minerals seem to be producible almost without end. In fact, analysts who have reviewed the issue carefully have not found many conceptual differences among natural resources on the basis of their renewability (*8*). Nor have they been able to demonstrate any overall tendency toward increasing scarcity (open space and timber are exceptions) in terms of higher real costs of production (*9*). Let us therefore look at minerals more carefully to see how these general conclusions apply to them.

The literal notion of running out of mineral supplies is ridiculous. The entire planet is composed of minerals, and man can hardly mine himself out. Except for a few substances, notably crude oil and natural gas, which are discretely different from the rock masses that contain them, the quantities of mineral materials in even the upper kilometer of the earth's crust approach the infinite in size. A single cubic kilometer of average crustal rock contains 2×10^8 tons (metric as elsewhere in this article) of aluminum, over 1×10^8 tons of iron, 800,000 tons of zinc, 200,000 tons of copper. Much the same sort of calculation can be made for seawater. We are not suggesting that such dilute materials will ever be mined, but only indicating that exhaustion in a physical sense is meaningless.

Of more immediate interest is the

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fact that some of the elements that are most important to society are available in the greatest quantity. Copper and zinc are relatively rare metals. Iron and aluminum are not; together with a few other elements, they make up much of the crust of the earth, and there are thousands of square kilometers that could be considered as low-grade iron and aluminum deposits, some of which will be mined in the future. Much the same can be said about phosphorus and potassium, the two critical mineral components for fertilizers (*10*).

Further, there is a strong tendency for many mineral resources to increase in quantity as the quality that can be economically exploited goes down. In general terms this means that there are greater volumes of deposits containing 0.5 percent copper than 0.6 percent copper, and greater volumes containing 35 percent iron than 40 percent iron, and so on. This relationship holds until, at a certain grade, the increased tonnage of contained metal obtained with unit decreases in grade reaches a peak. Beyond this point it falls with further decreases in grade, but such grades are typically well below those being mined today. Exponential curves for grade of deposit plotted against tonnage of contained metal have been drawn for manganese, aluminum, titanium, nickel, lead, zinc, and columbium (*11*), and they indicate that this tendency is by no means confined to a few commodities, as is sometimes asserted (*4*, pp. 80–82). However, it does not hold for all deposits nor for small regions, so careful interpretation is required.

In short, almost every bit of evidence we have indicates the existence of vast quantities of mineral resources that could be mined and, further, that either as their price goes up or as their cost goes down (which is to say, as technology of extraction improves), the volume of mineable material increases significantly—not by a factor of 5 or 10 but by a factor of 100 or 1000.

The real question, then, is not whether resources exist but at what rate different sources of supply will become available to man in the sense of becoming economically feasible to recover. Natural materials do not become resources until they are combined with man's ingenuity. Over time the record is impressive. Mineral resources have become more and more widely available despite (and partly because of) growing rates of consumption. This, in crude form, is the modern economic view of mineral resources, or the "cornucopian" view as it has been dubbed.

Unfortunately, most descriptions of mineral resources include only the material that could be mined at today's prices and today's technology—what is properly termed "reserves"—and thus they understate the availability of these resources (*12*). The difference between reserves and resources become critically important when one is dealing with the so-called life index, the ratio of the reserves of some element to its current consumption. The resulting figure is best regarded as a sort of inventory of stock on the shelf, so to speak, but it is sometimes mistakenly taken to mean the years remaining until exhaustion. In fact, the ratio tends to remain stable over time. As shown in Table 1, mineral reserves in Canada have grown roughly in proportion to mineral production except in cases (see asbestos and natural gas in Table 1) where institutional changes have been taking place in the industry.

Let us review the situation for the world as a whole. Some data supplied by Cloud (*13*) are instructive in this respect, for contrary to his emphasis, we find them reassuring. On the basis of the data in Fig. 1 (and other information), one foresees no problem to the end of the century in the economic availability of iron, manganese, silicon, aluminum, nickel, and certain other materials, including energy minerals (taken together). These commodities include most of those upon which modern economic life is based.

But what about the generations beyond the end of the century? Is there

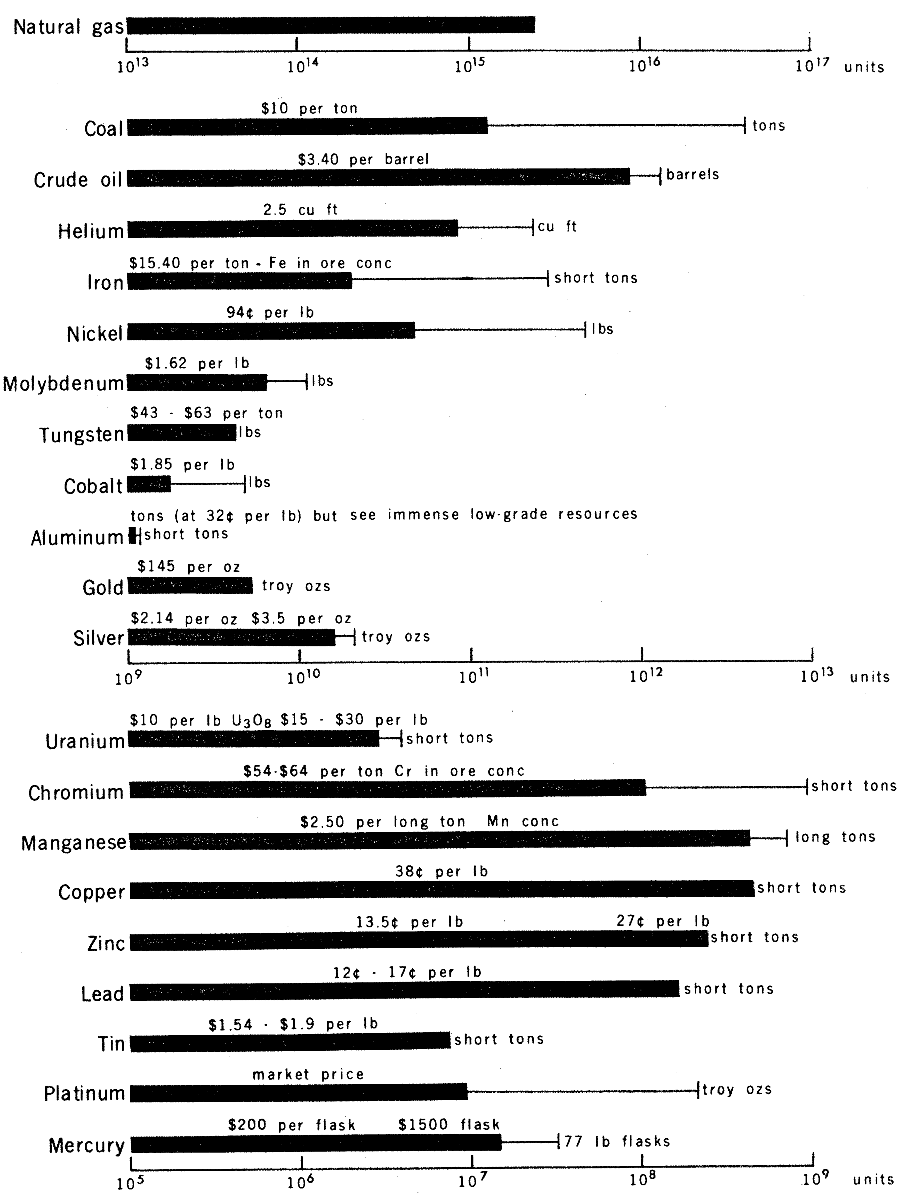

Fig. 1. Consumption of minerals throughout the world. Solid bars indicate estimated world consumption to the year 2000. Unbroken lines show current reserves at indicated prices. [From Cloud (*13*)]

enough for them too? Consider the record of the past century during which mineral supply has kept well ahead of long-term growth in mineral consumption. Why should a process of technological development that has been operating so well come suddenly to an end? New development will of course have to come more rapidly with higher rates of consumption, but it can be argued that the steepest exponential curve of all is the growth of human knowledge.

There are two main dimensions to the economies of future mineral availability:

1) Geological extensions of supply through discoveries of new deposits and of new zones in old ones.

2) Technological extensions through the ability to work lower quality or less conventional materials.

In our judgment, future increases in mineral supply are going to come more from the latter than the former dimension, and this depends almost entirely on the growth of knowledge. The distinction is important: a new discovery adds a new mine to our stock of resources; a new technology for lower-quality resources can open up deposits across the world.

Therefore, it is simply not true, as is often remarked, that average rock will never be mined. As a matter of fact, in a few cases we are already mining commodities as by-products whose average grade in the ore deposit is lower than that in the crust (titanium mined in beach sands is an example). By exploiting technology as capital rather than the ore deposit (that is, land) as capital, the very commonness of the rock may be most attractive. The more common the rock, the more freedom one has to adjust the mine to the technology, rather than the other way around. In short, through modest advances in technology mineral deposits become more rather than less available, and they can be mined in more rather than fewer regions.

Consider the case of nickel. Persistent price increases and generally rising worldwide demand for nickel are finally allowing the development of the lateritic nickel deposits, which had been known for years. These deposits are much more widespread than are the sulfide deposits typical of existing producing regions, and they are easier to mine. However, until recently there had been no commercially feasible way to extract the nickel from them. If one can judge from the success of several laterite mines in Third World nations, this is no longer a problem. As a result, world nickel reserves have been augmented manyfold and the nickel mining industry will be less concentrated geographically and industrially.

Mineral Demand

Studies published in the past few years have, without exception, indicated that increased amounts of mineral commodities are going to be demanded in the future, mainly from the already industrialized nations but also from those nations in the process of industrializing.

The most comprehensive recent set of mineral forecasts is that made by the U.S. Bureau of Mines (*14*). World demand for primary, non-energy minerals was based on contingency forecasts and gave a spread of growth rates from 3.8 to 5.6 percent per year. Demand in the United States was based on specific forecasts of population and GNP (gross national product) growth, and gave a spread of growth rates from 4.2 to 6.0 percent per year. Some specific forecasts for the United States are shown in Table 2.

Another major study of mineral demand to the year 2000 (for the United States only) was made by Resources for the Future, using an input-output model together with various assumptions of population growth and productivity change (*7*). Some of these results, which tend to be lower than those of the Bureau of Mines, are shown in Table 3.

Using a method that was apparently first developed by the International Iron and Steel Institute (IISI) (*15*), the Mineral Resources Branch of the Department of Energy, Mines and Resources in Canada has initiated still

Table 1. Mineral reserves and mineral production in Canada: selected commodities, 1955 and 1969. Data from the Department of Energy, Mines and Resources, Ottawa.

Mineral	Reserves			Production		
	1955	1969	Ratio	1955	1969	Ratio
Petroleum*	2.75	10.5	3.8	0.13	0.41	3.2
Nickel†	6.0	8.5	1.4	0.17	0.26‖	1.5
Copper†	14.5	22.9	1.6	0.33	0.61‖	1.8
Iron ore‡	5.28	33.0	6.2	0.01	0.04‖	4.0
Zinc†	20.4	34.2	1.7	0.43	1.16‖	2.7
Natural gas§	16.6	53.4	3.2	0.15	1.98	13.2
Asbestos†	86.0	1200.0	14.0	1.06	1.61	1.5

* 10^9 barrels. † 10^6 tons. ‡ 10^9 tons. § 10^{12} cubic feet. ‖ Data for 1968 used for comparison because 1969 was a strike year.

Table 2. Demand in the United States for primary refined metal in 1968 and in 2000, according to the U.S. Bureau of Mines (*14*).

Metal	Demand (tons × 10^6)			
	1968	2000		
		Low	Median	High
Copper	1.4	4.4	5.8	7.2
Lead	0.8	1.2	1.9	3.6
Zinc	1.3	1.9	2.8	3.6
Manganese	1.0	1.7	1.9	2.1
Nickel	0.15	0.35	0.42	0.50
Aluminum	3.2	15.7	23.4	31.2

Table 3. Demand in the United States for certain metals in the year 2000, according to Resources for the Future (*7*).

Metal	Demand in the year 2000 (tons × 10^6)			
	Low population		High population	
	Low growth	High growth	Low growth	High growth
Copper	2.6	3.3	2.9	3.6
Lead	1.5	2.0	1.8	2.2
Zinc	2.8	3.5	3.2	4.0
Manganese	1.9	2.4	2.2	2.6
Nickel	0.29	0.36	0.33	0.40
Aluminum	11.9	14.5	13.0	15.9

another set of projections. This method, referred to as intensity of use analysis, suggests that demands for metals in the year 2000 may be lower, at least in industrialized nations, than the projections given by most other methods. Similar results have been obtained in the study recently released on behalf of the U.S. National Commission on Materials Policy (*16*).

The intensity of use approach uses both time series and cross-sectional information. For each country, the quantity of some material consumed per unit of national product (its intensity of use) is plotted against per capita income. The IISI study showed that, as per capita income increases in an economy, the intensity of steel use first rises also, but then it peaks and begins to decline. Absolute consumption of steel continues to increase because the decline in intensity is more than overcome by the increase in GNP, but the increase in consumption is less than is forecast by trend analysis. The level of income at which the intensity peak is reached varies by country, but for most Western industrial nations is close to U.S. $2000 per capita.

When we applied this method to nonferrous metals, similar peaked patterns were observed. Figure 2 shows some indicative results for primary copper and aluminum. Data for copper in the United States and Canada were plotted for the years 1926 to 1971, long enough to demonstrate clearly the rise and subsequent decline in intensity. (Fewer data were used in the study prepared for the U.S. National Commission on Materials Policy; hence, the patterns are less clear.) Intensity of copper use in the United States fits the "ideal" shape with the maximum occurring during World War II. In Canada, there was no fixed pattern prior to 1940, but after World War II the intensity of copper use clearly began to decline, although there were fluctuations corresponding to the major postwar business cycles. The position of the Canadian curve above that for the United States probably reflects the export orientation of the Canadian economy because intensity of use is measured as shipments from refineries.

The implications of declining intensity of use can be seen by considering further the example of copper use in the United States. Figure 2 shows that the curve peaks at nearly 4 tons between U.S. $1700 and U.S. $1800 per capita (1961 dollars) in the late 1920's and again in 1940. If one ignores the distortions caused by World War II, the curve declines fairly uniformly to slightly over 2 tons at U.S. $2800 per head in 1959 to 1961, and then falls more slowly in the following decade to just below 2 tons at U.S. $3700 per head. If any decline continues, there are important implications for projections of consumption. The projections of GNP and population growth used by the Bureau of Mines indicate that a per capita income on the order of U.S. $7000 (1961 dollars) can be expected in the United States by the year 2000. At that level, consumption of copper could be, per million dollars of GNP: at 2.0 tons, 4.9×10^6 tons; at 1.5 tons, 3.7×10^6 tons; at 1.0 ton, 2.7×10^6 tons. The Bureau of Mines median contingency forecast is 5.8×10^6 tons.

The case of aluminum is more difficult. Its intensity of use curve is still rising in the United States, but the rate of increase has declined of late. The dashed lines on Fig. 2 represent three possible directions the intensity of aluminum use might take in the United States. By the end of the century, they are equivalent to consumption levels of 7.3, 16.5, and 22.2×10^6 tons, which can be compared with the Bureau of Mines median forecast of 23.4×10^6 tons.

These notes on future mineral demand only indicate that, as nations move into a postindustrial phase, their intensity of use of mineral commodities tends to decrease. The pattern for the currently less industrialized nations is less clear, and other variables would have to be studied before sound comments could be made on total world demand. However, it does not seem likely that the consumption of nonenergy minerals will continue to grow at past rates.

The Challenge to "Cornucopianism"

The idea that mineral supplies could be greatly augmented by technology has always been challenged by certain geologists. Recently, their views have been seconded by some systems analysts. Several of the conceptual and empirical aspects specifically related to minerals will be discussed briefly here (*17, 18*).

The challenge on geological evidence is based on several lines of reasoning. First, some analyses depend upon extrapolation of production trends along mathematical curves. However, production history is not based solely on the geologically available supply but also on institutional factors, such as military policies and the tariff structure. Second, other analyses are based on either individual mines or types of ore deposits that are characterized by sharp cutoffs between ore and country rock. Unquestionably, mines and such ore deposits can be exhausted, but this does not prove that world supplies are declining in an economically meaningful sense. Third, still other analyses are based on questionable ideas about the economics of discovery. While exploration costs more now than formerly, this is irrelevant. What is important is the cost per unit of information gained, and eventually of ore discovered, and this is not increasing inordinately (*19*). Moreover, it is hardly surprising that many deposits coming into production today were discovered years ago, for today's exploration is also turning up numerous deposits that will not be mined for some years.

Turning to the challenge stemming from systems analysis of the limits-to-growth type, our first comment is that it mistakes both the nature of and the evidence concerning the resource supply. Minerals are treated as if they came from a fixed stock, an approach that is not improved by the qualification that the reserve figures are perhaps off by a factor of 5 or 10. This qualification merely compounds the confusion, for we are really dealing with a flow, not a stock, and with a flow that responds to demand. True, we may have witnessed a long-term increase in the price of copper over the past 10 years, though institutional factors have obviously played a role as well. And for some commodities, perhaps tungsten, real shortages may develop (*7*, p. 93). However, such exceptions are far from proving that prices for many minerals will increase exponentially in the future under consideration here.

Our second comment is that the effectiveness of a price-cost system in altering the quantities demanded and supplied is ignored. Surely one cannot reasonably assume that mineral prices will continue to rise but that this will have no stimulating effect on exploration, technological development, and recycling (to say nothing of a damping effect on demand). However, those who challenge cornucopianism tend to ignore price effects, and let themselves open to the criticism that they did not deal with what, for all of its defects, is an effective adjustment mechanism

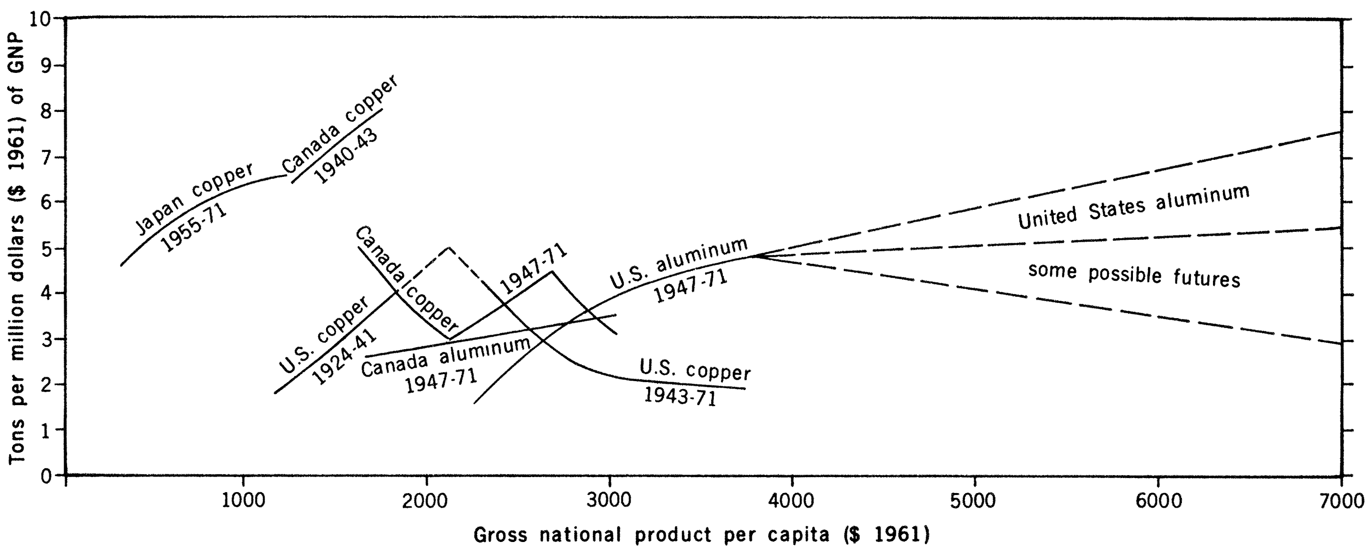

Fig. 2. Intensity of use of copper and aluminum: examples from Canada, Japan, and the United States.

(and one that can be applied whether the price derives from a market in a capitalist system or from a central bureau in a socialist system).

Finally, the challenge stemming from the nature of demand is also mistaken. While we have seen dramatically increasing demands for minerals over the past several decades, this does not mean that such increases have been or will continue to be exponential. As shown above, more sophisticated analyses suggest that relative demands decline after a point with increase in per capita income. Indeed, even though absolute increases in quantities demanded are still enormous, the relative growth is sufficiently damped that it was suggested in one study that mineral production will need to grow less fast in the future than it has grown in the recent past, exactly the opposite of most conclusions based on trend analysis (*16*, pp. 38–40).

"Cornucopianism" Saved

The foregoing combine to cast considerable doubt on the whole idea that mineral resources will limit growth. For the model itself, this creates a very weak link in the causal chain (*20*). Thus, one must ask whether we have learned anything new from recent challenges to cornucopianism? Our conclusion is that we have not, but we have forcefully been reminded to ask some important questions.

We thus maintain that minerals can be made available (at prices not greatly different from those today) to satisfy demands that are growing because of population growth, higher per capita incomes, and changing technology. In the discussion that follows we will assume that these minerals are produced and will ask about some of the implications of producing them, rather than focusing on their physical or economic availability.

Pollution

Perhaps the most widely recognized undersirable effect of higher rates of resource production and consumption is the increase in pollution that must result. In saying this, we are well aware of the major improvements being made in pollution technology that will permit mines and smelters to produce less effluent per ton of production, and transport facilities to spill less per ton-mile, for example. However, to obtain a significant improvement in the environment, such changes in pollution technology will not be sufficient. The decrease in effluents per unit of production or of consumption must more than overcome the increase in production or consumption itself. Moreover, as the scale of production increases, so will the impact of any miscalculation or accident (which are inevitable). Thus, we can either strive continually for technologies that will so reduce pollution that it will be possible to produce (and consume) safely whatever we want, or we can aim to reduce growth to make the technological task of environmental improvement less expensive and less frenzied.

There are two additional aspects of pollution that are less amenable to technological solutions: the chronic low-level exposure of the human population to pollutants that is all but inherent in an industrial world, and the possibility of triggering an ecological catastrophe.

Much pollution control practice has been based on the theory that there are "thresholds" below which health is not affected. We know now that, for many pollutants, including radioactivity and lead, thresholds do not exist. Chronic low-level exposure is important; for every additional unit of a pollutant, someone's life is shortened or days of sickness are lengthened (*21*). Since some escape of such substances cannot be avoided, the more we introduce to the environment, the less we implicitly value human life.

At the other end of the probability scale, it is conceivable that man could touch some physical or biological lever that would prove globally catastrophic. Fortunately, such problems are less likely to stem from nonfuel minerals than from energy production and consumption (*22*). Even the more difficult problems, such as acid mine drainage and smelter-based sulfur oxides, tend to be local or regional in scope rather than national or international. Nevertheless, however small the probabilities they bear close surveillance as part of the Earthwatch program originating at the 1972 United Nations Conference on the Human Environment (*23*).

Extensive Land-Use Change

In speaking of pollution we have referred to effluents added to air, water, or soil. Somewhat different, but at least as much at issue in many mining regions, are the land-use changes that will be necessary if higher rates of production are to be achieved. For example, the surface mining debate in most places is much more a question of appropriate land use than it is of pollution.

However, given that resources are irregularly distributed, the demands for efficiency and for large-scale production will dictate that resources be produced wherever they are found and by low-cost methods. Demands for land to be used for ecological preserves, recreation, and agriculture are likely to take second place to demands for land to be used in mineral production. For example, resources located in the Arctic or in other untouched areas will have to be extracted, as will deposits of common materials (sand, gravel, rock) located near urban areas. Moreover, the production goal will be to economize on manpower and materials and perhaps on energy, but at the expense of consuming, and sometimes irreparably altering, the land surface. Such tendencies will be aggravated because, as grade becomes lower, more and more mining is required to recover the same volume of valuable metal or mineral. Thus, we have the proposals for using nuclear energy to fracture underground ore bodies or to remove the overburden from ore bodies near the surface (*24*). The very scale of such an effort, coupled with the need to prevent the public from entering large areas for reasons of safety, implies enormous land-use change.

Most land-use changes under discussion here cannot be solved technologically. While the effects of some of these changes can be mitigated (by using underground quarries near urban areas, and by surface reclamation, for example), many land-use decisions are all but irreversible and "simply" involve questions of value.

Increased Energy Consumption

Another penalty for using lower grade ores will be the increase in energy consumption per unit of output because of the lower concentration of valuable material per ton. This increase will be still greater because some of the new sources will require finer crushing or will be more refractory than previously mined ores (*25*), though this effect might be offset in part by less energy being required for the actual mining of the ore (as with the laterite nickel ores described earlier).

Having recognized this problem, however, there is relatively little more one can say. If energy costs go up, as they seem likely to do, technology will turn toward cheap sources of energy and to ways of conserving energy in production. For example, the use of nuclear explosives as described in the preceding section offers a relatively inexpensive and efficient way of using energy in mining. Moreover, it seems ridiculous to point to mineral production as a cause of such global problems as changes in heat balance or climate. Mineral production is responsive to, not creative of, the demand for consumption, and by about the end of the time frame under consideration here, the world must find a way to deal with this aspect of the energy problem in the widest sense (*26*).

Instability in Human Settlements

The expansion of mining is closely associated with certain problems of human settlements. The broadest issue is that the introduction of mining can be a sociological shock. For example, some of the objections to proposals for copper mining in Puerto Rico are based on the cultural change that mining would impose on a now rural and largely self-sufficient region (*27*). Much the same objection has been raised with respect to the Inuit (Eskimo) in the Canadian North. Even less than land-use can these issues be resolved technologically. Most often they require all-or-nothing decisions based on the society's values.

Most mining communities, and all of those that cannot eventually find an alternative economic base, have a limited life. Moreover, few of them have been attractive places in which to live; in many instances they have been treated as "camps" to be abandoned as soon as the mine is closed, or they have been built as oppressive company towns. Even if mining communities are more carefully planned today, their inherent tendency to deplete their reason for existence cannot be ignored, because the result is often a depressed region with high unemployment and few services. Such problems are intensified by the cyclical nature of investment in minerals, so that there tend to be cycles, every 20 to 40 years, during which a nation is faced with waves of mine closures.

International Distribution of Income

In stating that mineral resources were unlimited, we deliberately made no distinction between the industrial and the nonindustrial areas of the world because there are enough resources for all. However, contrary to what one might expect, increased competition for minerals is likely to work against rather than for the primary producing nations. If, as we have supposed, production-consumption trends are going to continue rising, it seems excessively heroic to suppose at the same time that the future distribution of returns is going to be very different.

For one thing, the linkages between mining and other sectors of the economy are relatively weak. A mine alone, or even a mine associated with a smelter and refinery, does not confer large benefits upon a society in terms of direct or indirect employment and income—unless manufacturing industries are developed that consume the products of the mine (*28*). In fact, most development economists now believe that natural resource development usually results from activity in other sectors of the economy (or other regions of the world), and that resource development itself seldom initiates other industrial development (*29*). For example, Chilean economists have pointed out that most of that nation's rail system, extensive though it is, was designed to move copper from mine or smelter to port and has done little to stimulate development or to integrate the country.

For another thing, although a rising demand for a resource may mean that the price of the commodity can be increased, the actual amount by which it can be increased is very limited. The economic rent collectable by the producing country or organization cannot be increased indefinitely as is sometimes implied.

The Organization of the Petroleum Exporting Countries (OPEC) has succeeded in raising oil prices and national revenues. But OPEC remains a unique example, successful because of the military and commercial demand for petroleum, the difficulty of storing it, and the concentration of production in a region where the populations have a common ethnic background. Moreover, it is easier to find substitutes for other mineral commodities than it is for petroleum. Technological developments enable us to utilize lower quality, and hence more widely occurring, mineral resources (as with taconites) and also enable us to use more common materials in place of rarer ones (as with ceramics and plastics to replace metals). But such developments favor industrialized regions, which of course also fund most of the research. Therefore, while the copper and iron ore producing nations, for example, seek to gain more revenue, it is an open question how far they can reproduce the OPEC model.

For much the same reasons, there is unlikely to be any great shift of political power because of the irregular distribution of mineral resources. When more powerful nations desire resources that are located outside their own borders, they will find ways to obtain them. In some cases this may be a matter of their using crude 19th century imperialistic techniques. In other cases, they may apply their own national laws extraterritorially or impose direct sanctions on the countries that have the resources. However, political power over resource suppliers will most commonly be exercised through the subtler means of economic domination. While by no means uniformly imperialistic, such measures as direct foreign investment, special trading arrangements, and bilateral aid, when used by powerful nations or blocs of any economic system, do tend to induce more acquiescent behavior among resource-supplying satellite countries. As several recent white papers indicate, this sort of approach is common, and could prove to be a significantly destabilizing force in international relations.

Conclusions

World population and world income can grow at any likely rate for the next 50 to 75 years, probably for longer, and mineral supplies will continue to keep pace with demand. Not, however, without environmental costs, without affecting Third World development, and, perhaps most important, without ignoring critical questions of power. In what might be termed the revisionist form of the limits to growth thesis, Aurelio Peccei and Alexander King, cofounders of the Club of Rome, seem to be saying that the forecasts of doom themselves are unimportant but they symbolize critical problems of the nature and uses of power in the modern world (*30*):

> . . . the Club of Rome is questioning the quality of growth and its distribution around the world. . . . We know that the present structure of the world is obsolete. . . . Both private and state capitalism are stale . . . we have to develop something else.

Surely, continually increasing rates of mineral production are symptoms of this obsolete power structure, a result of the fact that, ultimately, population growth and monetary income growth lead to demands for natural resources that necessitate their being found and produced regardless of the implications. Since such higher rates of production are geologically and economically sustainable, we should choose among alternative paths of growth, and hence among alternative rates of mineral resource development, according to what we like or dislike about these implications. The key information will not be found in tables comparing reserves and consumption but in preferences and ethics.

References and Notes

1. The best-known treatment of this thesis is the Club of Rome–MIT study by Meadows *et al.* (see *2*, pp. 54–69). See also "Blueprint for survival," *Ecologist* **2**, 1 (1972). For a more technical treatment of minerals see Lovering (*3*) and Cloud (*4*, pp. 71–88). For a quasi-official U.S. government view of mineral supply, see National Materials Advisory Board, *Elements of a National Materials Policy* (Report NMAB-294, U.S. National Materials Advisory Board, Washington, D.C., 1972).
2. D. H. Meadows, D. L. Meadows, J. Randers, W. W. Behrens III, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (Potomac Associates-Universe Books, New York, 1972).
3. T. S. Lovering, in *Resources and Man: A Report by the U.S. National Academy of Sciences*, P. Cloud, Ed. (Freeman, San Francisco, 1969).
4. P. Cloud, in *Environment: Resources, Pollution and Society*, W. W. Murdoch, Ed. (Sinaves Associates, Stamford, Conn., 1971).
5. Much of this section is based on material presented in "Mineral supply as a stock," see Brooks (*6*).
6. D. B. Brooks, "Mineral supply as a stock," in *Economics of the Mineral Industries*, W. A. Vogely, Ed. (American Institute of Mining, Metallurgical and Petroleum Engineers, New York, in press). [Part of this work was published previously in *"Minerals: An Expanding or a Dwindling Resource,"* Mineral Resources Branch, Mineral Bulletin 134 (Information Canada, Ottawa, 1973)].
7. L. L. Fischman and H. H. Landsberg, in *Population, Resources and the Environment: A Report to the U.S. Commission on Population Growth and the American Future*, R. G. Ridker, Ed. (Government Printing Office, Washington, D.C., 1972). [The approach and general conclusion of this study, probably the best of its kind, are summarized by J. L. Fisher and R. G. Ridker, *Am. Econ. Rev.* **63**, 70 (May 1973)].
8. A. Scott, *Natural Resources: The Economics of Conservation* (Univ. of Toronto Press, Toronto, 1955).
9. H. J. Barnett and C. Morse, *Scarcity and Growth*, (Johns Hopkins Press for Resources for the Future, Baltimore, Md., 1963). See also the brief discussion by C. Morse, *Am. Econ. Rev.* **63**, 126 (May 1973).
10. The case of phosphorus has become something of a cause célèbre after the publication of a report which stated that phosphorus resources would be exhausted before the 21st century [Workshop on Global Ecological Problems, *Man in the Living Environment* (Institute of Ecology, Madison, Wis., 1971)]. However, if one includes only the already identified resources, there is sufficient phosphorus to refute the Institute of Ecology figure [G. D. Emigh, *Eng. Mining J.* **173**, 90 (1972)].
11. The most extensive discussion of the application of grade-tonnage relationships to mineral resources is by Musgrove who prepared an appendix to the article by Brooks (*6*).
12. The terms resources and reserves are properly defined for minerals by J. Zwartendyk, *What Is "Mineral Endowment" and How Should We Measure It?* (Mineral Resources Branch, Mineral Bulletin 126, (Information Canada, Ottawa, 1972).
13. P. Cloud, "Resource Use and Population Pressure—The Deadly Exponentials," paper presented at the Columbia University–United Nations Conference on Development and the Environment, April 1972.
14. U.S. Department of the Interior, Bureau of Mines, *Mineral Facts and Problems, 1970* (Government Printing Office, Washington, D.C., 1970).
15. Committee on Economic Studies, *Projection 85: World Steel Demand* (International Iron and Steel Institute, Brussels, Belgium, March 1972).
16. W. Malenbaum, *Material Requirements in the United States and Abroad in the Year 2000: A Research Project prepared for the National Commission on Materials Policy* (University of Pennsylvania Press, Philadelphia, 1973).
17. Meadows *et al.* (*2*) provide the best example of the challenge from the systems analysis point of view, while Lovering (*3*) and Cloud (*4*) provide the best examples of the challenge from a geological point of view. The geological challenge is criticized at length by Brooks (*6*). The limits to growth thesis has stirred considerable debate. See, for example, the Consultative Assembly of the Council of Europe, *Report on the Limits to Growth*, document 3233, January 1973), which includes articles by MM. A. Peccei and M. Siebker (who argue in favor of growth being limited) and J. Maddox (who argues against limited growth). With respect to minerals in particular, see Page (*18*, pp. 33–42).
18. W. Page, *Futures* **5**, 33 (February 1973).
19. D. A. Cranstone and H. L. Martin, *Can. Mining J.* **94**, 53 (1973).
20. This point is made forcefully by J. S. Carmen, *Comments on the Report for the Club of Rome entitled "Limits to Growth,"* (Natural Resources Division, United Nations, New York, 1972). See also Page (*18*, p. 41).
21. National Academy of Sciences–National Academy of Enginering, *Man, Materials and Environment: A Report for the National Commission on Materials Policy* (MIT Press, Cambridge, Mass., 1973), pp. 71–80.
22. Massachusetts Institute of Technology, *Study of Critical Environmental Problems* (MIT Press, Cambridge, Mass., 1970).
23. United Nations Conference on the Human Environment, Stockholm, 5 to 16 June 1972 (United Nations, New York, 1972), Section 1, Action Program.
24. D. B. Brooks and J. V. Krutilla, *Peaceful Use of Nuclear Explosives: Some Economics Aspects* (Johns Hopkins Press for Resources for the Future, Baltimore, Md., 1969).
25. P. Chapman, *New Sci.* (17 May 1973), pp. 408–410.
26. J. Holdren, in *Global Ecology*, J. Holdren and P. Ehrlich, Eds. (Harcourt Brace Jovanovich, New York, 1971).
27. *Church Panel on Copper Mining in Puerto Rico* (Colegia de Abogados, San Juan, Puerto Rico, January 1971).
28. Based on work under way in the Department of Energy, Mines and Resources, Ottawa. A brief summary of this work is available: J. E. Stahl, *Mining Eng.* **25**, 54 (1973). See also N. C. Bonsor, *1973 Proceedings of the Council of Economics of AIME* (American Institute of Mining, Metallurgical and Petroleum Engineers, New York, 1973), pp. 179–84.
29. A. O. Hirschman, *The Strategy of Economic Development* (Yale Univ. Press, New Haven, Conn., 1958). See also J. L. Spengler, Ed., *Natural Resources and Economic Growth* (Resources for the Future and Social Science Research Council, Washington, D.C., 1961).
30. Statements reported in *The Globe & Mail* (Toronto) (20 February 1973), p. B2; *ibid.* (22 February 1973), p. 4.