Infinite Resources: The Ultimate Strategy

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In this article we examine from a long-range point of view the question of possible exhaustion of nonrenewable resources, excluding energy resources. Much has been written on the subject, from the Cassandra prophecies of national subjugation to foreign owners of cobalt and chromium mines (*1*) to the carefree forecasts of some economists—and some technologists—who contend that the market or new technology will take care of everything (*2*).

We dealt with some aspects of this subject in an earlier article (*3*) that provided a rather optimistic outlook on nonrenewable resources except for fossil fuels. In the present article we compare world resources with future demands, discuss the significance of properties of materials rather than materials per se, and examine the importance of timely and vigorous research and development to ensure the use of lower grade and alternative ores and substitute materials for those resources most likely to become scarce and expensive. We base our analysis on three assumptions:

1) That nonrenewable resources are useful because of their physical and chemical properties and are not an end in themselves, and that the appropriate goal is to ensure a supply of plentiful materials with desired properties at reasonable cost.

2) That, by the year 2100, the world population will have risen to a steady-state level of about 8.5 billion people who aspire to a standard of living removed from squalor and hunger, and that this goal depends in part on the availability of materials.

3) That there are certain elements that are in essentially infinite supply, others that are near infinite or could be made so by advances in technology, and a third class of elements that are certain to eventually be in stringent short supply if a world with 8.5 billion people is to achieve and maintain a moderately industrialized civilization.

Summary. By projecting global population growth and demand for nonrenewable materials over the next century, it appears unlikely that the world will run short of any element before about 2050. This provides considerable time to develop new technology to economically exploit lower grade and alternative ores to bring some 30 elements into essentially infinite supply, and to use these elements in developing substitutes to satisfy the requirements of modern civilized societies.

Much of what we conclude is based on that most treacherous of reasoning tools: extrapolation of recent experience. But our final conclusions depend on the validity of the extrapolations only insofar as they move an end point backward or forward in time by some decades.

There are two additional assumptions implicit in what we say. First, that science and technology are capable of altering the human condition in unforeseeable ways and that many of the technical solutions which are now but dimly perceived will prove to be realistic. Second, that world societies will continue to develop along current lines, and not change, for example, to an overwhelming spiritual orientation that eschews material goods and material well-being as important societal goals.

With these assumptions in mind, we believe that, with a few exceptions, the world contains plentiful retrievable resources that can supply mankind with the necessary materials for the very long term, and that these resources can probably be extracted and converted to useful forms indefinitely with acceptable environmental consequences and within the boundaries of foreseeable economic constraints. The principal requirements to achieve this goal are reasonably stable political conditions, a continuing supply of energy, continuing availability of capital, and, most importantly, vigorous and successful research in the field of materials.

Of course, a mineral resource can never totally run out, since its price will increase significantly as the end of economic resources approaches. A supply will always exist in moderate amounts for essential applications for which there is no substitute material.

Anatomy of a Crisis

The 1970's were a very unsettled decade with regard to energy and materials. The success of the Organization of Petroleum Exporting Countries (OPEC) in controlling oil supplies and achieving astonishing oil price increases resulted in major perturbations of the world economy that included a series of recessions. The effect of the oil crisis on other nonrenewable resources was significant, and it raised serious concerns about the possibility of other cartels (as for bauxite and copper) being formed and about the potential for cutoff of supplies of materials produced predominantly in one or a few countries (such as cobalt in Zaire and Zambia and chromite, platinum, and gold in South Africa). In fact, the "Zairian cobalt crisis" of 1978 and 1979, although more perceived than real, set off a worldwide scramble to build large stocks of many materials, resulting in rapidly escalating prices. None of the feared cartels was successful, and, mainly as a result of the most recent recession, demand, production, and prices of many materials have fallen to the lowest levels in more than a decade.

It may be useful at this point to examine the cobalt crisis in greater detail. After a long series of problems Zaire, producer of over half the world's cobalt supply of about 30,000 metric tons per year, reduced allotments to customers by 30 percent in early 1978 (*4*). When mine operations were disrupted for a number of months after the rebel invasion in mid-May 1978, world supply was thought to be drastically cut and cobalt prices rose rapidly from about $11 to $25 per kilogram, with spot prices as high as $120 per kilogram by the end of 1978, brought on mainly by panic buying. In the ensuing years, however, world production has remained relatively con-

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stant, but U.S. domestic consumption of cobalt has fallen by nearly one half. Part of this drastic reduction is the result of the recent recession, but part is due to substitution, where possible, away from cobalt.

Since there are as yet few commercially available substitutes for cobalt in superalloys used mainly in gas turbine jet engines, demand for cobalt for this use has remained fairly constant. The same holds for cobalt catalysts, since no adequate substitutes are currently available. But ceramic (ferrite) magnets were fully developed at the time of the cobalt crisis and have rapidly replaced cobalt alloy magnets; the same trend is even more pronounced for cobalt use in salts and driers for paints, where manganese and lead are partially adequate substitutes. Finally, the use of cobalt in metal-cutting and mining tools at first increased and then declined rapidly as substitutes became available. (Even when substitutes are already available, it may take several years to retool to effectively use them.) The cobalt crisis has also led to intensive development of substitutes for the longer term. One example is in the development of new nickel-iron-aluminum alloys that may soon compete strongly for high-temperature service with cobalt-containing superalloys (*5*).

On the basis of constant production and demand, the world's terrestrial reserve to (current) demand ratio for cobalt is 80 years and the total resource to demand ratio is 180 years (*6*). In addition, the ratio for cobalt in sea-floor manganese nodules is 7500 years (*6*). Therefore, there appears to be no imminent world shortage of cobalt, and there is much time for further development of substitutes. The economic importance of cobalt, for example, is small. The total value of cobalt metal during the crisis was never more than 2×10^{-4} of world or U.S. gross national product (GNP). In fact, the total value of currently used nonenergy, nonrenewable resources mostly as beneficiated ore is only 1.2 percent of world GNP and 2.4 percent of U.S. domestic GNP.

The cobalt crisis was not atypical: a crisis was perceived in the supply of a mineral resource that will not be exhausted in the near future but that is perceived to be crucial to modern technological society and its economy. We believe that, in the case of cobalt and other materials, the marketplace provides a good regulating mechanism—even though sudden changes in the supply picture may drive prices up or down in swings far greater than the substantive situation warrants—and that substitute materials will be developed and enter the market when they become competitive. Nevertheless, it is obvious that the cobalt resource of many million tons cannot last forever, and will be exhausted in the foreseeable future if demand should increase significantly. At that point we have options of mining sea-floor nodules or using substitutes developed in the interim.

Table 1. Projected growth of world population. Values are millions of persons.

Year	DC's	LDC's	World total
1975	1127	2849	3976
2000	1331	4562	5893
2025	1455	5909	7364
2050	1501	6696	8197
2075	1522	6924	8446
2100	1525	6975	8500

The Asymptotic Demand Model

In this section we consider what the world demand for materials may be through the year 2100; in subsequent sections we compare the derived demands with currently known reserves and resources. We realize that no one can make accurate projections so far ahead, but we do believe it feasible to establish trends. To do so we need to know how the world population can be expected to grow and how that population may use nonrenewable materials.

For our model we use Keyfitz's (*7*) latest world population projections through 2075. His projections are based on anticipated limited population growth in the developed countries (DC's) and rapid expansion of population in the less-developed countries (LDC's) over the next 50 to 75 years, followed by a marked slowing of growth in the latter half of the next century. Since our model is for the period through 2100 we have assumed only very minor population growth between 2075 and 2100 to a final steady-state level of 8.5 billion by 2100 (Table 1).

Having postulated an asymptotic behavior for population growth, we proceed to make certain assumptions about the long-term demand for primary materials. For the world as a whole we accept as a starting point the projection by the U.S. Bureau of Mines (BOM) that world per capita demand will grow at 2 or 3 percent for most materials annually through 2000 (*8*). We think this may be high, but in the absence of more reliable analyses we go with it nevertheless. Beyond 2000, we assume that per capita demand in the DC's will remain constant; that is, their per capita demand asymptote will have been reached. Under this assumption we do not believe that the quality of life in the DC's—or, later, in the LDC's—need be in any way inferior to present levels. As the quality of raw materials declines, a slow rise in prices places more emphasis on conservation, recycling, miniaturization, and durability of products.

Since the BOM has not provided a demand breakdown between DC's and LDC's in its projections, we developed our own in the following way. Data for six important metals—copper, zinc, lead, nickel, tin, and aluminum—show that the LDC's now consume, on average, 15 percent of total world demand (*9*). On a per capita basis, the average LDC demand is currently about 6 percent of DC demand. We assume that these values are fairly representative of all the elements. Our model further assumes that by 2100 per capita demand in the LDC's will have grown asymptotically, on average, to 50 percent of current per capita demand in the DC's. By way of illustration, this means that the average per capita demand in the LDC's will be equivalent to that in Greece today (assuming that per capita demand is directly related to the per capita GNP). We do not believe it likely under present economic conditions for the LDC's to do any better than this, especially as long as their population growth rates remain so high. By 2100 there will still be considerable variation in demand among the LDC's. Other factors, such as capital formation and energy demands, are also pertinent, and we will review them in a later section.

This brings us to the main theme of our article: what will happen to the world's material resources? Will we run out of the stuff of which our civilization is made? What material strategy should we follow in view of the asymptotic population and demand projections?

The Supply Situation

The BOM, in cooperation with the U.S. Geological Survey (USGS), subdivides reserves and resources, both discovered and undiscovered (*10*), into various categories. These agencies give detailed definitions for each category. For example, measured and indicated reserves are materials in well-measured ore deposits that can be recovered at current prices with proven technology; the quantities are generally known to within 20 percent. All other reserve and resource categories involve materials that are either more costly to exploit or of less certain extent. With time, reserve and resource estimates continually change. Reserves and resources decrease as they are mined and increase through successful exploration and development of improved technology. They continually change, as well, as mineral commodity prices go up or down. Reserves (and current mine and plant capacities) are a measure of shorter term availability; total resources, even though less well known, are a measure of availability over the longer term.

If we consider only the current estimates of total resources and compare them with the integrated demand to the year 2100 obtained from our asymptotic demand model, we obtain a projected percentage depletion in 2100 for each element (Table 2). In this exercise we find that a number of elements would be completely depleted before 2100.

However, history has shown that as geological exploration proceeds and as process R & D provides new technology to utilize low-grade conventional ores or formerly useless nonconventional minerals, resources have always expanded. We see no reason why such expansion should cease. In fact, for some elements the USGS has given quite large estimates for speculative resources (*11*), which, together with current total reserves and resources, we call extended resources.

Such extension of current resource estimates must be done cautiously, however. For example, the occurrence of tin

Table 2. Present values and year 2100 estimates of world demand, resources, and resource depletion for various elements. Abbreviations: NA,

Element	World demand				Estimated current resources (MT)	Depletion of resources by 2100 (%)	Extended resources (MT)*	Depletion of current and extended resources by 2100 (%)	Comment
	1978 (MT)	Growth per year, 1978 to 2000 (%)	2100 (MT)	Cumulative, 1982 to 2100 (MT)					
Iron	4.8E8	2.7	1.9E9	1.6E11	2.0E11	86	3.1E11	55	Larger extended resources in taconites containing 15 to 25 percent iron
Calcium	4.8E8	2.5	1.9E9	1.6E11	∞	0	NA		∞ in limestone, gypsum, and seawater
Nitrogen	1.4E8	5.7	1.1E9	8.7E10	∞	0	NA		∞ in atmosphere
Oxygen	9.3E7	4.0	4.9E8	4.1E10	∞	0	NA		∞ in atmosphere
Sodium	7.7E7	3.5	3.7E8	3.1E10	∞	0	NA		∞ in rock salt, seawater
Sulfur	5.3E7	4.6	3.2E8	2.7E10	6.3E9	421	∞	0	∞ in gypsum and anhydrite; near economical
Chlorine	3.3E7	5.2	2.3E8	1.9E10	∞	0	NA		∞ in rock salt, seawater
Hydrogen	2.4E7	6.3	1.9E8	1.6E10	FF		∞	0	∞ in water; electrolysis energy–intensive, economical in places
Potassium	2.2E7	3.6	1.1E8	9.0E9	1.2E11	7	∞	0	∞ in seawater, feldspars
Phosphorus	1.7E7	5.0	1.1E8	9.4E9	1.8E10	53	3.4E10	28	Larger extended resources in low-grade phosphate rock
Aluminum	1.7E7	5.2	1.2E8	9.8E9	8.0E9	122	∞	0	∞ in clays, anorthosite
Gallium	1.2E1	6.6	1.3E2	1.1E2	9.3E3	5	∞	0	∞ in clays
Manganese	8.7E6	3.3	4.0E7	3.4E9	2.8E9	120	1.9E10	18	Extended resources mainly in nodules on the sea floor
Copper	8.1E6	3.6	4.0E7	3.3E9	1.6E9	206			Moderate amount in manganese nodules
Arsenic	3.0E4	1.7	9.8E5	8.3E6	1.0E7	82	2.0E7	42	Much of extended resources in organic-rich shales
Selenium	1.6E3	3.5	7.9E3	6.6E5	4.1E5	161			
Tellurium	3.4E2	1.1	9.7E2	8.3E4	1.1E5	78			
Zinc	6.4E6	2.0	2.2E7	1.9E9	3.3E8	581	5.1E9	37	Extended resources average 4 percent zinc, mainly as zinc sulfide
Cadmium	1.7E4	2.0	5.9E4	5.0E6	1.2E6	400			
Germanium	6.9E1	4.0	3.7E2	3.1E4	8.6E3	366			
Indium	5.3E1	3.5	2.5E2	2.1E4	3.1E3	681			
Thallium	1.0E1	0.0	2.3E1	2.0E3	7.3E2	267			
Magnesium	5.1E6	2.1	1.8E7	1.5E9	∞	0	NA		∞ in seawater
Barium	3.6E6	1.1	1.0E7	8.7E8	5.2E8	169	1.1E9	79	
Lead	3.2E6	2.9	1.4E7	1.1E9	2.9E8	395	1.5E9	75	
Antimony	6.7E4	2.2	2.5E5	2.1E7	5.2E6	402			
Bismuth	4.4E3	1.7	1.4E4	1.2E6	1.9E5	656			
Chromium	3.2E6	3.3	1.5E7	1.2E9	1.0E10	12			99 percent in South Africa and Zimbabwe, possibly in ultramafic rock
Silicon	2.6E6	3.7	1.3E7	1.1E9	∞	0			∞ in sand, sandstone, and quartzite
Fluorine (CaF_2)	2.0E6	3.5	9.7E6	8.1E8	7.8E7	191			Most of fluorine in phosphate rock; lost if not recovered as by-product
Phosphate rock					3.4E8		6.5E8	124	
Argon	1.9E6	9.0	2.8E7	2.3E9	∞	0			∞ in atmosphere; also neon, krypton, xenon, but not helium

*Estimates mainly from Brobst and Pratt (*11*).

and mercury is so geologically specific that it appears unlikely that significant alternative resources will be found. Resource expansion for such cases will be less extensive and will depend to a large extent on using ores of ever lower grades. However, large expansions are feasible even for these elements if considerably higher prices can be accepted. For example, in 1964 BOM estimated domestic mercury resources to be only 1600 metric tons at $2900 per ton (*12*), but 50,000 metric tons at $43,500 per ton. Over the past 25 years the price of mercury has varied over a wide range from $3500 per metric ton in 1976 to $16,600 per ton in 1965, or a range of $4000 to $34,000 per ton in 1978 dollars.

Over the longer term such price increases are probably allowable for many uses. First, improved technology and economies of scale will tend to hold costs down. Second, the material costs of many final products are only a small part of the total cost; in such cases large increases in material costs result in only moderate increases in consumer product costs.

Longer Term Supply-Demand Comparison

Table 2 summarizes for all the currently useful chemical elements our estimates of annual and cumulative demands in the year 2100. It also gives current estimates of reserves and resources (*6*) for all these elements and estimates of extended resources for some of them (*11*). The elements are arranged by decreasing current world demand, except that elements obtained solely or mainly as by-products are shown, indented, un-

not applicable; MT, metric tons; Ex = 10^x, thus 4.8E8 = 4.8×10^8).

Element	World demand				Estimated current resources (MT)	Depletion of resources by 2100 (%)	Extended resources (MT)*	Depletion of current and extended resources by 2100 (%)	Comment
	1978 (MT)	Growth per year, 1978 to 2000 (%)	2100 (MT)	Cumulative, 1982 to 2100 (MT)					
Titanium	1.7E6	3.8	8.6E6	7.2E8	7.1E8	102	2.0E9	38	Extended resources mainly in titaniferous magnetite
Nickel	7.1E5	4.0	3.8E6	3.1E8	2.1E8	152	9.0E8	35	Extended resources in manganese nodules, possibly in ultramafic rock
Boron	4.2E5	3.5	2.0E6	1.7E8	2.7E8	62			Possibly ∞ in seawater
Bromine	3.1E5	1.7	1.0E6	8.7E7	∞	0			∞ in seawater
Zirconium	3.0E5	3.3	1.4E6	1.2E8	4.0E7	289			
Hafnium	6.8E1	4.6	4.1E2	3.4E4	8.0E5	4			
Tin	2.5E5	0.9	6.9E5	5.9E7	3.7E7	159			
Molybdenum	1.0E5	4.5	6.3E5	5.2E7	2.1E7	249	1.0E9	5	Extended resources mainly in lower grade molybdenum porphyries
Rhenium	4.3E0	3.2	1.7E1	1.5E3	6.1E3	15			
Strontium	4.7E4	3.2	2.1E5	1.8E7	1.2E7	148			Possibly ∞ in seawater
Tungsten	4.0E4	3.4	1.9E5	1.6E7	6.8E6	236	1.5E8	11	Extended resources in lower grade tungsten and molybdenum ores
Vanadium	3.2E4	3.6	1.6E5	1.3E7	5.6E7	23			
Rare earths	2.4E4	6.3	2.1E5	1.7E7	3.6E7	48			
Cobalt	2.3E4	2.8	9.7E4	8.2E6	5.4E6	150	2.3E8	36	Extended resources in manganese nodules; possibly ∞ in ultramafic rock
Silver	1.2E4	1.9	4.0E4	3.4E6	7.7E5	439			
Iodine	1.2E4	3.4	5.4E4	4.5E6	4.5E6	100	∞	0	Extended resources in kelp and possibly seawater
Niobium	1.1E4	5.9	8.6E4	7.1E6	1.7E7	41			
Lithium	6.4E3	5.9	5.2E4	4.3E6	7.6E6	56			Possibly ∞ in seawater
Mercury	5.5E3	2.4	2.1E4	1.8E6	5.8E5	305			
Helium	5.0E3	3.2	2.3E4	1.9E6	4.2E6	45			Available only if recovered now from natural gas
Gold	1.4E3	1.5	4.5E3	3.8E5	6.1E4	617			
Tantalum	7.9E2	4.7	4.9E3	4.1E5	2.5E5	160			
Thorium	5.1E2	6.0	2.4E3	1.9E5	5.2E6	4			
Beryllium	3.6E2	0.3	8.7E2	7.5E4	1.1E6	7			
Yttrium	2.1E2	6.3	1.8E3	1.5E5	1.7E5	88			
Cesium	1.9E1	6.0	5.8E2	4.7E4	2.1E5	23			
Rubidium	2.1E0	0.2	4.9E0	4.2E2	3.8E3	11			Possibly ∞ in seawater
Scandium	2.7E−2	2.0	9.5E−2	8.0E0	1.4E3	< 1			
Platinum group	1.9E2	2.1	6.9E2	5.8E4	1.0E5	58			Possibly ∞ in ultramafic rock
Platinum	8.3E1	2.4	3.1E2	2.6E4	4.4E4	60			
Palladium	9.3E1	1.7	3.1E2	2.6E4	3.7E4	70			
Rhodium	4.3E0	3.2	1.9E1	1.6E3	6.1E3	27			
Ruthenium	9.8E0	2.2	3.6E1	3.0E3	9.8E3	31			
Iridium	3.3E0	2.1	1.2E1	9.8E2	2.0E3	50			
Osmium	2.2E−1	7.6	2.5E0	2.0E2	1.2E3	17			

*Estimates mainly from Brobst and Pratt (*11*).

der the element of which they are a by-product. Using these demand and supply values, we determined the percent depletion of current and extended resources of each element listed.

From Table 2 we find that a dozen elements are already economically in infinite supply with installed and proven technology. These are nitrogen, oxygen, and the noble gases (but not helium) from the atmosphere; sodium, chlorine, magnesium, and bromine from seawater; silicon from silica sand, sandstone, and quartzite; and calcium from limestone. Technology is already partially or fully developed, but not yet economic, to make an additional seven elements virtually unlimited. Included in this group are sulfur from gypsum (*13*), anhydrite, and seawater; hydrogen from coal and from water by electrolysis (*14*); reduced carbon from coal, shale oil, and ultimately from CO_2 from calcined limestone; aluminum and gallium from clay and anorthosite; iron from low-grade banded-iron formations (taconites with $\geq$ 15 percent iron), ironstones, and laterites; and potassium from seawater, leucite, and potassium feldspars. The latter two minerals are also potential sources of aluminum. Finally, we believe that, given a century for process R & D, an additional 14 elements are likely to achieve near infinite supply status. These are lithium, boron, strontium, iodine, and rubidium from seawater, and chromium, nickel, cobalt, and the six platinum metals from common ultramafic rock of the earth's mantle composition, in which these metals are inordinately enriched. We consider that R & D on the exploitations of ultramafic rock, with particular attention paid to environmental concerns, is probably one of the most important long-term process development projects possible.

It seems highly likely that, with sufficient R & D, about 33 of the 65 stable elements listed in Table 2 may be in unlimited supply by 2100. It also seems likely that present resources of many of the remaining elements can be significantly extended beyond our present projections. But with the large demand developing over the next century many elements will eventually become too scarce and expensive to use except in absolutely necessary applications, such as trace metal soil additives in agriculture (*15*) or components in special lasers. The loss of a significant portion of our materials base requires that we sustain a strong effort in materials research to develop substitutes over the next century. We are fortunate—although this is not entirely accidental—that the materials most essential to our civilization will not be exhausted for a very long time.

One shortcoming of our demand projection is the result of unqualified long-term extrapolation of the recent past. Thus, for predicted depletions greatly in excess of 100 percent (for example, gold, 645 percent; silver, 459 percent; and mercury, 818 percent), much effort will be needed to discover new conventional or alternative resources and to develop technologies to process them. Furthermore, such efforts must be augmented with timely development of more plentiful substitutes that to a large extent will be driven by market forces. However, as noted at the beginning of this article, the final conclusions from the demand extrapolations depend on the validity of these extrapolations only insofar as they move an end point backward or forward by some decades. The chief value of the tabulation of percent depletion is that it provides a rough ranking of the order in which materials can be expected to become scarce and hence of the ultimate need for new processes and substitutes. We do not claim that new process development and substitute research will be easy or cheap—only that they are not impossible, given the time available, if the requisite funds and talent are brought to bear sufficiently early.

Other Important Factors

As noted earlier, long-term availability of resources is only one factor controlling long-term supplies of nonrenewable materials. Equally important is the provision of new facilities—mines, mills, and processing plants—to meet increasing demands, the continuing availability of energy to mine and process ever leaner ores, and R & D to provide satisfactory new processes for leaner conventional and alternative ores and to ensure that substitutes are available. In addition, it is important to speculate on the relative contributions of the DC's and LDC's to such requirements. We cannot treat these questions for each item in Table 2, but we suspect that an analysis of three important metals, iron, aluminum, and copper, will shed some light.

Table 3 shows the DC-LDC demand breakdown derived from our model for iron and aluminum. We have already shown that iron and aluminum should eventually attain near infinite supply status through the use of lower grade taconites (for iron) and clays and anorthosites (for aluminum). The problem is more serious for copper: its solution depends on our ability to exploit much leaner copper ores for uses that require this element and to develop substitutes for the remainder of the projected demand.

We next address the question of capital investment requirements needed to fulfill the projections given in Table 3. We base our capital cost requirements on the BOM estimate (*16*) that for iron the integrated investment between now and 2100 will be about \$3 trillion (1982 dollars), mostly for the industrial iron and steel complex; for aluminum and copper the comparable numbers are \$0.5 trillion and \$0.3 trillion. These sums are for primary metals only. When one considers recycling (now running at 37 percent for iron, 20 percent for aluminum, and 30 percent for copper), close to another \$1 trillion may be required. Further, over the 120-year period plants will have to be replaced several times, since plant life seldom exceeds 30 to 50 years. The sum of all these costs will be on the order of \$10 trillion, including the requisite electrical generating capacity for aluminum production. We did not include in our estimate the rest of the infrastructure such as roads, ships, communication networks, and housing.

Can the world economy accumulate \$10 trillion for this investment over the next 120 years? The increased demand we postulate, especially for the LDC's, implies general economic expansion, again concentrated in the LDC's. If we assume world GNP to grow at the rate of 2 percent per year (in constant dollars), then the cumulative world GNP through 2100 amounts to \$6000 trillion. We note that during the 1960's and 1970's annual growth of GNP was 3 to 8 percent for DC's and LDC's as well as for the nonmarket economies, and that gross fixed-capital formation grew faster than that in nearly all countries (*17*). We conclude that a total investment of \$10 trillion is not unrealistic since it amounts to less than 0.2 percent of the cumulative world GNP.

Outlook for Uses of Materials

In this section we consider the future use patterns of some important materials by extrapolating from current domestic uses. Several bases are available for such an analysis: use by chemical form (metal, oxide, and so forth), use by semimanufactured form (alloy steels, nonferrous alloys, superalloys, magnet alloys), and use in various industries (transportation, machinery). Wherever possible we use the first or second categorization because they are more closely related to the properties for which substitution must ultimately be made.

Use patterns change with time. For example, early major uses of mercury were in feltmaking and in fulminate detonators; both uses have now virtually disappeared. More recently, the use of lead in paints and in vehicular antiknock fuels has been decreasing and the use of platinum metals as catalysts in antipollution devices has been increasing. It is relatively easy to predict changes in use patterns over the short term but much more difficult over the long term because many future uses depend on discoveries and inventions not yet made or even dreamed of.

As noted above, the physical and chemical properties of materials provide the principal basis on which materials are used and determine the criteria for suitable substitutes. Some uses involve structural properties such as compressive and tensile strength, ductility, and toughness. Other uses depend on electrical and magnetic properties such as conductivity and magnetic permeability. Still others depend on chemical properties such as reactivity in catalysts, low corrosivity in metals, and electrochemical properties for electroplating and in batteries. Scientific advances are now making it feasible to design materials to have desired properties (*18*) and thus to develop substitutes by using more plentiful elements in place of the limited ones.

Since the forms and uses of materials are enormous, we have limited our efforts in the analysis that follows to the major uses of any material that collectively account for about 90 percent of the total use. The rationale for this approach is based on the premise that development of substitutes for a use entailing only a few percent or less of total demand has only marginal profitability compared to substitutes for major uses.

Space does not allow a complete review of uses along with existing and potential substitutes, future resource prospects, and other factors bearing on supply and demand of all the limited elements. Therefore, we provide below the salient facts on some of the most used limited elements by way of example for the rest. We also include comments on iron and aluminum, even though they will be in unlimited supply, because of their great importance to society.

Iron. Iron is the most important and least expensive metal. Demand for iron exceeds that for all other metals combined by severalfold. Economically it has no substitute. Current resources are more than sufficient through 2100, and low-grade banded-iron formations (taconites with ≥ 15 percent iron) should last centuries more. If chromium, nickel, cobalt, and platinum are recovered from ultramafic rock, a supply of 1.5×10^{13} metric tons of iron is available as a coproduct. Millennia will pass before resort to basalt, averaging 8.5 percent iron, would be necessary. Nevertheless, mining iron is fraught with environmental consequences that must be addressed if the resource is to be exploited to its full potential.

Table 3. Demand projections for iron and aluminum, as determined from the asymptotic model. Values are millions of tons per year.

Year	DC's	LDC's	World
		Iron	
1982	455	80.3	535
2000	686	171.4	857
2020	737	374	1111
2040	764	629	1393
2060	778	883	1661
2080	785	1058	1843
2100	786	1153	1939
1982 to 2100			~ 160,000
		Aluminum	
1982	17.85	3.5	21.0
2000	41.84	10.46	52.3
2020	44.96	22.94	67.9
2040	46.63	38.47	85.1
2060	47.47	53.93	101.4
2080	47.88	64.62	112.5
2100	47.95	70.45	118.4
1982 to 2100			~ 10,000

Aluminum and magnesium. These two metals are the truly inexhaustible metals: aluminum from clay when bauxite is depleted and magnesium from seawater. Aluminum is the second most-used metal and the metal with the highest demand growth rate. Demand for magnesium is much lower; greater use should be promoted. Because aluminum resources are unlimited, by-product gallium resources are as well.

Phosphorus. Although the use of phosphates in agriculture may be reduced by advanced technologies, it will never be eliminated. Thus this element is necessary and nonsubstitutable. Current resources are more than sufficient through 2100, and lower grade resources are enormous (*19*) and probably sufficient for millennia.

Manganese. About 70 percent of manganese use is for desulfurizing and dephosphorizing steel, and no substitute of equally low cost exists. Current terrestrial resources are expected to be depleted within 100 years, but resources in seafloor nodules—six times the manganese in land resources—will last for centuries.

Copper. This metal is highly useful, but, given sufficient time to retool, is also highly substitutable. Substitution for copper in motor and generator windings will be difficult, but aluminum can readily be substituted in most other electrical applications. Iron, plastics, and ceramics can be used for pipe, structural elements, and so forth. Conventional resources may be exhausted in 60 to 70 years, but extended resources should last at least until 2100.

Zinc. The three major uses of zinc are in galvanized steel (36 percent of total use), in zinc die castings (33 percent), and in brass (12 percent). Many substitutes for zinc are already available, such as ceramics (to coat steel), magnesium (for die castings), and aluminum (in alloys). Although conventional resources are limited, extended resources are about 15 times as large and will be only 40 percent depleted by 2100. About 0.5 percent of zinc consumption is now as a trace metal in agriculture, a necessary use. The by-product elements cadmium, germanium, indium, and thallium are found mainly to exclusively in zinc ores, so their ultimate depletion is highly dependent on the extent to which they are recovered from zinc ores in the years ahead. Recovery and stockpiling may be a prudent option for such elements, which may never be mined in their own right.

Lead. Like zinc, conventional resources of lead are limited, but extended resources are much larger and will not be more than about 80 percent depleted by 2100. The use of lead as an additive in gasoline is rapidly declining (now 12 percent of total use), leaving use in storage batteries (55 percent) as the major application. Ultimately it will be necessary to develop substitute batteries with more plentiful materials such as iron and sulfur if, indeed, batteries remain necessary for transportation. Except, possibly, for solder, lead in its other applications is relatively substitutable.

Fluorine. The three major uses of fluorine are as a flux in steel production (43 percent of total use), in producing fluorocarbons (20 percent), and in the electrolyte for reducing alumina to aluminum (20 percent). No substitutes exist for the second use and it may be difficult to find substitutes for the other two. About 20 percent of current resources are in fluorspar (CaF_2) and 80 percent occur as a by-product from phosphate rock. Extended resources are about twice conventional ones and should last slightly beyond 2100 if there is a high degree of recovery from phosphate rock.

Barium. Over 90 percent of current barium use is for oil and gas well drilling muds. Current resources could be exhausted by 2060 but will probably last much longer as petroleum resources become exhausted. However, hematite (Fe_2O_3), although not quite so good in drilling muds, is a feasible substitute whose early and extensive use in lieu of barite would greatly extend barium resources.

Chromium, nickel, cobalt, and the platinum metals. Current resources of chromium and the platinum metals appear sufficient to last well beyond 2100 but are highly concentrated in South Africa and Zimbabwe; terrestrial resources of nickel and cobalt may be exhausted by about 2060, but mining of manganese nodules on the sea floor would extend resources far beyond 2100. These elements are not in any immediate jeopardy worldwide but they are not unlimited, and if it ultimately proves infeasible to develop an economic process to recover them from common ultramafic rock, substitutes will be required at some point for these very useful metals. They are highly valued for their use in superalloys, tool carbides, and steels; for their low corrosivity in stainless steels and platinum equipment (particularly at high temperatures); and for their catalytic attributes and in refractories (Cr_2O_3). Domestic problems for all these metals loom large only because we now import nearly all our requirements despite the fact that we have moderate to large near economical resources of them.

Titanium. Titanium is ninth among all the elements in terrestrial abundance, but current titanium resources are barely sufficient to last through 2100. However, use of all titaniferous magnetites would result in only 4 to 5 percent depletion of extended resources by 2100. Touted as a "wonder metal" after World War II, its demand growth has been less than phenomenal, although it is a viable if uneconomical substitute for many alloy steel uses. Over 90 percent of current titanium use is still as titania pigment in paints, rubber, and other products.

Helium. Helium resources will in theory be only half-consumed by 2100 in our analysis, but this is true only if it is extensively recovered from natural gas before the gas is burned. If it is not recovered in this way, its later recovery from the atmosphere to which it will escape will be vastly (probably 50 times) more expensive. Helium already has many uses, but it can be replaced by argon or nitrogen when chemical inertness is important and to some extent by CO_2 when heat transfer is important. However, as a nonflammable lifting gas and in cryogenics (particularly in electrical superconductors), it has, at present, no substitute.

Summary

If our projections of world demand for nonrenewable materials prove to be reasonably correct, then it seems highly likely that currently economic resources of many important elements will be in inadequate supply by 2100. At the same time, the prospects appear good that resources of more than 30 elements can be made virtually unlimited if sufficient R & D is invested.

Eventually a number of elements will undoubtedly become too scarce and expensive to use except for a few vital purposes. However, there is plenty of time before resources of any limited material become completely economically depleted in which to develop adequate substitutes by using more plentiful materials. The ability to tailor new materials to set specifications is advancing rapidly, and our capabilities in this direction should grow with time if R & D in this area is adequately supported. Although a strategy of infinite resources may be difficult to pursue in the face of global political uncertainties, success would mean that future shortages will be at most only transient events and that a stable population of 8.5 billion people will not be imperiled or impoverished by the lack of materials required for civilized life.

References and Notes

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