The Age of Substitutability

What do we do when the mercury runs out?

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Two conflicting views dominate our perception of man's long-term future. The "catastrophists" believe that the earth's resources will soon be exhausted and that this will lead to the collapse of society. The "cornucopians" argue that most of the essential raw materials are in infinite supply: that as society exhausts one raw material, it will turn to lower-grade, inexhaustible substitutes. Eventually, society will subsist on renewable resources and on elements, such as iron and aluminum, that are practically inexhaustible. According to this view, society will settle into a steady state of substitution and recycling. This asymptotic society we call the Age of Substitutability. In this article we examine these questions; although much of what we say must be regarded as tentative and speculative, we expound these views in the hope that they will stimulate further study.

We are cornucopian, even in this era of dwindling resources and in spite of dire predictions (*1, 2*). We came to this position some 25 years ago, after reading Darwin's *The Next Million Years* (*3*). Darwin insisted, as do some present-day forecasters and systems modelers, that short-term forecasting was impossible [as well as disconcerting for the forecaster, who presumably would live to see his forecasts tested against fact]. But very long range forecasting, in which fluctuations in human experience are blips on an underlying statistical state, could be done in the same sense that statistical mechanics predicts the future of a big ensemble. Darwin asserted that over the very long term, man's fate, on the average, was predestined by the Malthusian disequilibrium: man procreates in a finite world. Man's continual scramble for finite resources condemns him to eternal social instability, violence, and brutishness.

Darwin realized, as do all neo-Malthusians, that there was no panacea; no solution could work unless population leveled off. But even this was not enough: as resources dwindled, the pressures on what remained would grow. Darwin also recognized, as did H. G. Wells some 40 years earlier (*4*), that an inexhaustible source of energy would be necessary—perhaps even sufficient—to rescue man from the resource catastrophe. Most of the materials that man uses, such as iron and aluminum, are found in nature in an oxidized state. To reduce these oxides, to extract iron or change alumina to aluminum, requires energy (more accurately, free energy). Thus, man's economic transaction with nature involves expenditure of free energy, and as his high-grade resources dwindle, he expends more energy. Darwin saw only one possible inexhaustible source of energy: nuclear fusion. Here we disagree: there are other inexhaustible sources of energy (notably the breeder reactor, and possibly solar energy) that, if developed, would allow man to avoid the hopeless future Darwin predicted.

The Principle of Infinite Substitutability

The catastrophists, when discussing a particular resource such as aluminum, usually say that when all our bauxite has been used, we shall have to live without aluminum. Thus, according to Meadows *et al.* (*1*, p. 71), "The effect of exponential growth is to reduce the probable period of availability of aluminum, for example, from 100 years to 31 years." This cannot be correct. As geologist Frasché said in 1962 (*5*), "Total exhaustion of any mineral resource will never occur: Minerals and rocks that are unexploited will always remain in the earth's crust. The basic problem is how to avoid reaching a point where the cost of exploiting those mineral deposits which remain will be so costly, because of depth, size, or grade, that we cannot produce what we need without completely disrupting our social and economic structures."

We can conceive of depletion of resources and substitution in three stages. Stage 1, which almost surely will persist for the next 30 to 50 years, is a continuation of present patterns of use of the nonrenewable resources. During stage 2, when society still would depend on reduced carbon and hydrogen found in nature—that is, coal—there would be little oil and gas, and people would begin to turn away from widespread use of a few of the nonferrous metals and toward much greater use of alloy steels, aluminum, magnesium, and titanium. Stage 2 might last several hundred years. Finally in stage 3, the Age of Substitutability, all the fossil fuel would be exhausted; society would be based almost exclusively on materials that are virtually unlimited. It is our basic contention that, insofar as limits to mineral resources can be discerned, the condition of life in stage 3 would not be drastically different from our present condition: we have the physical possibility of living in the Age of Substitutability and not "completely disrupting our social and economic structures." To reach this state without immense social disruption will, however, require unprecedented foresight and planning.

A convenient way to place the matter in perspective is to examine the "chemical" composition of one molecule of "demandite," the average nonrenewable resource humans use. We take the total number of moles of each element that is extracted from the earth, the sea, and the air, and from this compute the average mole fractional composition of the average nonrenewable resource. Similarly, we can define the average metal, "avalloy." We exclude renewable resources: agricultural products, wood, and water. In Tables 1 and 2, we give the chemical formulas and other properties of demandite and avalloy for 1968 (*6*).

Now let us compare the composition of these average materials with the average composition of the earth's crust, the sea, and the air (Table 3). Actually, the resource situation is even better than this comparison implies because many elements, including the majority of those most used in demandite, may be obtained in much higher concentration in sources other than average rocks; these are summarized in Table 4.

The data in Tables 3 and 4 show that of the 13 most widely used elements, only extractable CH_x and phosphorus are not essentially inexhaustible; whereas oxidized carbon and hydrogen are very common, extractable CH_x is rare—only 25 to 30 parts per million (ppm) in the first kilom-

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eter of the earth's crust. Yet extractable CH_x dominates demandite: 80 percent of U.S. demandite and 67 percent of world demandite is CH_x. Thus, when we speak of exhausting our resources, by far the most important scarce resource is extractable CH_x. Since energy can reduce CO_2 and H_2O to CH_x, we can paraphrase the basic point in both Wells's and Darwin's Malthusianism: the primary resource shortage is one of reduced CH_x or its equivalent, energy. Shortages of almost all other minerals are of second order compared to shortages of CH_x.

The central position of reduced carbon, or of reducing agents, is seen also when we examine the chemical composition of avalloy. Iron atoms constitute about 86 percent of U.S. avalloy, aluminum atoms 8 percent: these two inexhaustible metals constitute 94 percent of the total. Extracting iron from its oxides by presently used processes requires reduced carbon, and this accounts for about 12 percent of all coal used in the United States. Although avalloy itself is made largely from iron and aluminum, producing it requires reduced carbon, which is a rare material, or some other source of energy.

We now state the principle of "infinite" substitutability: With three notable exceptions—phosphorus, a few trace elements for agriculture, and energy-producing fossil fuels (CH_x)—society can subsist on inexhaustible or near-inexhaustible minerals with relatively little loss of living standard. Society would then be based largely on glass, plastic, wood, cement, iron, aluminum, and magnesium: whether it would be anything like our present society depends on how much of the ultimate raw material—energy—we can produce and how much energy will cost, both economically and environmentally.

To give substance to so broad a claim it is necessary to examine in detail, not simply in principle, exactly how people could live without a particular finite resource. We do not do this here; instead, we quote from previous work on the subject by Goeller (*7*).

Certainly there are no substitutes for the elements required to sustain life. The most important of these are H, O, C, and N; next come Ca, P, Cl, K, S, Na, and Mg, which constitute less than 1 percent of the total in living things. Besides these there are at least 13 required trace elements: F, Si, V, Cr, Mn, Fe, Co, Cu, Zn, Se, Mo, Sn, and I. Modern agriculture requires large amounts of Ca, N, K, and P, plus relatively small quantities of some of the trace elements. Of the major life-sustaining elements, only phosphorus is not on our list of inexhaustible elements. The average natural abundance of phosphorus in rocks is about 1000 ppm; if society eventually had to depend on average phosphorus, the costs of agriculture might become intolerably high. However, high-grade resources of phosphorus are very large: the present resource-to-demand ratio is 500 years for world reserves and an additional 800 years for potential resources. In addition, even though speculative resources are poorly known, they are regarded as very large (but considerably smaller than fixed nitrogen from air or potash from seawater). Nevertheless, phosphorus can hardly be regarded as inexhaustible. This led Wells *et al.* (*8*) many years ago to imply that ultimately we shall have to recycle bones as fertilizer, and we are in no position to refute this view.

With regard to the trace elements that are present in soil and are needed only at low concentrations, modern agriculture slowly depletes these elements. In the near term, shortages can undoubtedly be supplied from inorganic sources; in the long run, we shall undoubtedly be forced to return agricultural and animal wastes to the soil, particularly for the trace elements with limited resources, such as copper, zinc, and cobalt.

Beyond these nonsubstitutable elements, we use many rather scarce metals because of their special properties: copper because it is a good electrical conductor; nickel, chromium, and niobium because they con-

Table 1. Properties of demandite, the average nonrenewable resource used in 1968. Values apply only to new metal from ore. Data are derived, with some modifications, from (*6*). The composition of demandite, in mole fractions, is for the United States

$(CH_{2.14})_{.8022}$ $(SiO_2)_{.1115}$ $(CaCO_3)_{.0453}$ $Fe_{.0110}$
$Al_{.0011}$ $(Cu, Zn, Pb)_{.0004}$ $Mg_{.0004}$
$N_{.0076}$ $O_{.0053}$ $Na_{.0053}$ $Cl_{.0053}$
$S_{.0023}$ $P_{.0008}$ $K_{.0007}$ $X_{.0008}$

and for the world

$(CH_{1.71})_{.6660}$ $(SiO_2)_{.2117}$ $(CaCO_3)_{.0815}$ $Fe_{.0145}$
$Al_{.0007}$ $(Cu, Zn, Pb)_{.0004}$ $Mg_{.0004}$
$N_{.0068}$ $O_{.0045}$ $Na_{.0045}$ $Cl_{.0045}$
$S_{.0023}$ $P_{.0007}$ $K_{.0007}$ $X_{.0008}$

where X represents all other chemical elements; highest in order of demand are Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, and Zr; for all others the demand is < 100,000 tons a year (world) or 30,000 tons a year (United States).

Property	United States	World
Total quantity ($\times 10^6$ tons)	3,360	17,300
Total value ($ million)	42,200	158,500
Average unit value ($/ton)	12.55	9.16
Average energy used for recovery (kwh/ton)	1,140	800
Total quantity ($\times 10^6$ ton moles)	140.4	551.3
Average molecular weight	23.9	31.4
Per capita consumption (tons)	17	5
Per capita energy and energy rate		
(kwh)	18,800	3,800
(kw)	2.14	0.43

Table 2. Properties of avalloy, the average virgin metal used in 1968. Values apply only to new metal from ore. Data are derived from (*6*). The composition of avalloy, in mole fractions, is for the United States

$Fe_{.8570}$ $Mn_{.0119}$ $Si_{.0105}$ $Cr_{.0050}$ $Ni_{.0015}$ $X_{.0003}$ $Al_{.0822}$
$Cu_{.0138}$ $Zn_{.0123}$ $Pb_{.0025}$ $Sn_{.0003}$ $Mg_{.0021}$ $Ti_{.0002}$ $Y_{.0004}$

and for the world

$Fe_{.8983}$ $Mn_{.0176}$ $Si_{.0071}$ $Cr_{.0045}$ $Ni_{.0009}$ $X_{.0002}$ $Al_{.0447}$
$Cu_{.0135}$ $Zn_{.0097}$ $Pb_{.0020}$ $Sn_{.0003}$ $Mg_{.0009}$ $Ti_{.0001}$ $Y_{.0002}$

where X includes all other ferrous metals, and Y all other nonferrous metals.

Property	United States	World
Total quantity ($\times 10^6$ tons)	85.6	424.3
Total value ($ million)	16,050	75,775
Average unit value ($/ton)	187.50	178.60
Average value ($/ton of Fe, Si, Al, Ti, and Mg in avalloy	154.95	145.40
Average energy used for recovery (kwh/ton)	12,300	11,100
Average molecular weight	53.7	54.8
Per capita consumption (tons)	0.43	0.12
Per capita energy and energy rate		
(kwh)	5,290	1,340
(kw)	0.60	0.15

fer corrosion resistance and high-temperature strength onto iron; and mercury because it is a metallic liquid at room temperature. Goeller has studied in some detail the extent to which one might substitute for cadmium (*9*), zinc, lead, copper, tin, and mercury (*10*), the main conclusion being that for most of their uses, substitutes derived from inexhaustible or nearly inexhaustible materials are available. To illustrate, we summarize some of the results for mercury.

The Case of Mercury

The average annual consumption of mercury by use and form in the United States, 1964–1973, is given in Table 5. About 2250 tons of mercury were used each year during this period. Suppose we had no mercury—could we survive? Obviously, yes. To persuade ourselves of this we need only demonstrate, for each present use of mercury, a plausible alternative that does not require mercury. These alternatives are listed in Table 5. For example, the largest use of mercury (34 percent or 769 tons per year) is for caustic chlorine production. The diaphragm cell is an alternative that was in wide use before the mercury cell was introduced, and still accounts for 70 percent of the U.S. production of caustic. Diaphragm cells require relatively common materials such as concrete for the cell body, asbestos (which itself is made of calcium and magnesium silicates) for diaphragms, and copper and graphite for electrodes.

Acceptable alternatives are now known for all the major uses of mercury, except possibly for high-performance electric batteries (which would require other scarce materials such as cadmium and silver) or electric switches (*11*). For minor uses, such as in pharmaceuticals, or odd laboratory uses, which amount to <1 to 5 percent each of the total, alternatives have not been sought very seriously because the amount of mercury required is small. We can hardly imagine society collapsing, or even being seriously impeded in the long run, if we have to do without mercurial pharmaceuticals or mercury batteries.

Other Metals

Suppose we played the same game of what-do-we-do-when-the-high-grade-ores-run-out for copper, silver, zinc, tin, and other minor metals. Would the aggregate additional cost—in both energy and dollars—of the substitutes or of the materials themselves be intolerable? To be more specific, let us estimate how much the aggregate unit cost of these metals could rise without causing the cost of avalloy to rise more than twofold.

We can look at the matter by again examining the chemical composition of avalloy. Ninety-five percent of avalloy consists of iron, aluminum, silicon, magnesium, and titanium. These account for 95 percent of the energy per ton of avalloy and 80 percent of the cost per ton. All these materials are in infinite supply, and their ultimate unit cost, in either energy or dollars, can hardly exceed today's unit cost by more than a factor of 2, as shown in Table 6. The remaining 5 percent of avalloy consists mainly of Cu, Zn, Mn, Cr, Pb, Ni, and Sn; these represent about 20 percent of the total value of avalloy (Table 2). At present, extraction from ore represents only about one-half the total cost of the latter metals. The aggregate cost of this group of metals that is sensitive to the grade of ore therefore is not more than 10 percent of the total unit price of avalloy. Thus, even if the price of these materials increased five- to tenfold, the unit price of avalloy would only double.

This is almost surely an overestimate, since we have not allowed for substitution. For example, in 1968 copper accounted for 12 percent of the total cost of avalloy in the United States. But electrical copper is, in the long run, almost entirely replaceable by aluminum, and structural copper and brass are largely replaceable by steel, aluminum, titanium, and plastic. Moreover, manganese (in sea floor manganese nodules) and nickel (in the peridotites) are

Table 3. Average mole fractional composition of the earth.

Crust (topmost kilometer on continents)

(CH_x)(extractable)$_{.00004}$		(CH_x)(unextractable)*$_{.0083}$		C(oxidized)$_{.0153}$
$O_{.5907}$	$Si_{.1943}$	H(other)$_{.0658}$	$Al_{.0507}$	$Ca_{.0175}$
$Na_{.0142}$	$Fe_{.0132}$	$K_{.0123}$	$Mg_{.0120}$	$Ti_{.0016}$
$Cl_{.0014}$	$S_{.0009}$	$F_{.0007}$	$P_{.0004}$	$Mn_{.0003}$
$X_{.0004}$				

where X is all other elements, and for which X =

$Ba_{.000072}$	$Sr_{.000064}$	$V_{.000040}$	$Zr_{.000034}$	(Cu, Zn, Pb)$_{.000032}$
$N_{.000027}$	$Rb_{.000027}$	$Cr_{.000026}$	Rare earths$_{.000024}$	(Co, Ni)$_{.000022}$
Other$_{.000021}$				

Seawater (except for water)

$Cl_{.4859}$	$Na_{.4180}$	$Mg_{.0485}$	$S_{.0255}$	$Ca_{.0091}$	$K_{.0088}$
$C_{.0021}$	$Br_{.0007}$	$P_{.000002}$	$Si_{.0001}$	(Fe, Al, Ti)$_{.0000005}$	Other$_{.0009}$

Air (excluding variable amounts of CO_2 and H_2O)

$N_{.7805}$	$O_{.2100}$	$Ar_{.0093}$	$Ne_{.0002}$	(He, Kr, Xe)$_{<<.0001}$

*(CH_x)(unextractable) represents the very large amount of hydrocarbon in the topmost kilometer of shale. Almost all of this is too dilute to extract with a positive energy balance and therefore cannot be used as a source of energy. In principle, it might be used as a source of CH_x for petrochemicals.

Table 4. Present or future nearly inexhaustible resources for the most extensively used elements. The last column gives R/D, the resource-to-demand ratio in 1968. As demand grows, these values will be reduced; however, we anticipate that population must eventually level off, which will result in an ultimate leveling off of demands for energy and nonrenewable resources.

Element	Resource	Maximum amount in best resource (%)	World resource (tons)	R/D (years)
CH_x (extractable)	Coal, oil, gas	<75	1×10^{13}	2,500
C (oxidized)	Limestone	12	2×10^{15}	4×10^{6}
Si	Sand, sandstone	45	1.2×10^{16}	5×10^{6}
Ca	Limestone	40	5×10^{15}	4×10^{6}
H	Water	11	1.7×10^{17}	$\sim 10^{10}$
Fe	Basalt*, laterite	10	1.8×10^{15}	4.5×10^{6}
N	Air	80	4.5×10^{15}	1×10^{8}
Na	Rock salt, seawater	39	1.6×10^{16}	3×10^{8}
O	Air	20	1.1×10^{15}	3.5×10^{7}
S	Gypsum, seawater	23	1.1×10^{15}	3×10^{7}
Cl	Rock salt, seawater	61	2.9×10^{16}	4×10^{8}
P	Phosphate rock	14	1.6×10^{10}	1,300
K	Sylvite, seawater	52	5.7×10^{14}	4×10^{7}
Al	Clay (kaolin)	21	1.7×10^{15}	2×10^{8}
Mg	Seawater	0.012	2×10^{15}	4×10^{8}
Mn	Sea floor nodules	30	1×10^{11}	13,000
Ar	Air	1	5×10^{13}	2×10^{8}
Br	Seawater		1×10^{14}	6×10^{8}
Ni	Peridotite	0.2	6×10^{11}	1.4×10^{6}

*It must be noted that no process now exists for obtaining iron from basalt, or nickel from the ultrabasic rock peridotite; however, given a century for development of such processes, the likelihood for success seems quite high.

in nearly infinite supply: it is hard to see how the latter two metals can ever cost more than ten times their present price.

Some substitutes can be identified for the remaining elements—Zn, Cr, Pb, and Sn. Galvanized iron (which uses zinc) can, in good measure, be replaced by plastic-bonded steel; tin plate in cans can be largely replaced by plastic or glass. However, no very good substitute for Cr in stainless steel is presently known. Ultimately, this may force society to substitute titanium (which is in nearly infinite supply) for most uses that are now served by stainless steel. Nevertheless, the remaining elements—Zn, Cr, Pb, and Sn—could increase in cost by a very large factor, and the price of avalloy would still remain within a factor of 2 of its present real cost. This is true also of the remaining nonmetals, the metal oxides, the refractory metals, and the nonferrous by-product metals. Thus we arrive at our basic observation: avalloy and demandite (with the extremely important exception of CH_x) are so heavily dominated by elements derived from infinite sources or elements for which substitutes are available that their unit price is relatively insensitive to depletion of mineral resources. The tentative conclusion to be drawn is that, in principle, our social and economic structures are unlikely, in the long run, to be disrupted because we shall have to exploit lower-grade mineral resources—provided always that we find an adequate inexhaustible source of relatively cheap energy to substitute for CH_x. We put this hypothesis forward, realizing that it is in sharp opposition to the currently fashionable neo-Malthusianism; but we believe the neo-Malthusians have been misled by their habit of lumping all resources together without regard to their importance, ultimate abundance, or substitutability.

Although we can conclude from a global viewpoint that the cost of avalloy in the Age of Substitutability will not be more than two to three times its present price, there will be specific sectors of the economy that are likely to be hit severely. A point requiring additional study is the possibility that some material used in rather small quantity has extremely high leverage on a strategic industry, and that collapse of that industry, or even a drastic increase in the cost of the material, would rock the entire economy. An example might be helium, if we are forced to obtain it from air. If superconducting magnets forever required liquid helium, and if fusion absolutely required superconducting magnets, then a drastic rise in the price of helium might cause a corresponding rise in the cost of energy. However, if the cost of fusion energy exceeds that of solar energy or energy from breeders, then society will choose solar plants or breeders, not fusion, for its primary inexhaustible source of energy. Thus, we cannot accept the view that helium is absolutely essential for the long-term future of our industrial society (*12*).

Table 5. Average annual consumption of mercury in the United States, 1964–1973.

Uses	Substitutes	Metric tons	Percentage of total
Caustic chlorine production			
Inventory for new facilities*	Diaphragm cells	306	13.5
Makeup†		463	20.5
Subtotal		769	34.0
Electrical (mainly batteries)	$Zn\text{-}MnO_2$-graphite dry cell	598	26.5
Industrial and control instruments	‡	252	11.2
Biocidal paints	Plastic paints, copper oxide paint	299	13.2
Dental amalgams	Metal powders, porcelain, plastics	99	4.4
Agriculture§	Organic biocides	88	3.9
Catalysts	Ethylene process for polyvinyl chloride manufacture	54	2.4
Laboratory use	†	57	2.5
Pulp and paper manufacture‖	Organic biocides	17	0.8
Pharmaceuticals	Sulfur drugs, iodine, and others	17	0.8
Amalgamation‖	Gold recovery by cyanide process	6	0.3
Total		2256	100.0

*Includes small quantities for other uses. †Required to replace that lost in process. ‡Substitution may be based on alternative physical properties and may include bimetallic couples, aneroid barometers, and so forth. Liquid gallium and sodium-potassium alloys may be substitutes at room temperature but not at subzero temperature. §Use of methyl mercury on seed grains has been banned by the U.S. Department of Agriculture; banning of other uses may follow. ‖These uses of mercury were discontinued in the United States in 1971. Other significant uses included mercury fulminate detonators and felt manufacture; both were discontinued decades ago.

Table 6. Energy requirements for the production of abundant metals and copper. Gross energy is estimated at 40 percent thermal efficiency for generation of electricity. The last column gives the ratio of the energy required to extract a ton of metal for low-grade compared to high-grade ores.

Metal	Source	Gross energy (kilowatt-hours per ton of metal)	E_L/E_H
Magnesium ingot	Seawater	100,000	1
Aluminum ingot	Bauxite	56,000	1
	Clay	72,600	1.28
Raw steel	Magnetic taconites	10,100	1
	Iron laterites	11,900	1.17 (with carbon) $\sim$ 2 (with electrolytic hydrogen)
Titanium ingot	Rutile	138,900	1
	Ilmenite	164,700	1.18
	Titanium-rich soils	227,000	1.63
Refined copper	Porphyry ore, 1 percent Cu	14,000	1
	Porphyry ore, 0.3 percent Cu	27,300	1.95

Recycling

As prices for materials increase, there will be stronger incentives to recycle, to bring the empty bottles back. The remelt energy required to put scrap metal back into productive use is very much less than the energy needed to reduce and refine ores. For magnesium the remelt energy is 1.5 percent of the energy required to win the metal from ore; for aluminum it is 3 to 4 percent; and for titanium it is 30 percent. One must recognize that recycling cannot provide the total answer, since the recovery in each recycle is never 100 percent; in fact, unless recycling is very efficient, it will not make very much difference. If the recovery of copper, say, is 90 percent per cycle, then recycling reduces the required amount of virgin copper to be added to the system each year by a factor of $(1 - 0.9)^{-1} = 10$. But if recovery is only 40 percent per cycle, this factor is reduced to only 1.7.

Recycling is simplified by human intervention. If materials are not recycled, they become diluted and dissipated in the environment: their entropy increases. Thus, when an intelligent being sorts used material into separate bins, he diminishes the entropy of the original waste material.

However, such a macroscopic Maxwell's demon does not change the entropy of mixing appreciably unless he prevents useful materials from becoming dissolved as individual molecules, which then can be widely dispersed in soils or in the oceans.

The Energy Budget

As we exhaust the high-grade materials and have to use lower-grade ones, the energy required to recover our needed materials will grow. Yet, because the composition of avalloy is so dominated by essentially inexhaustible iron and aluminum, the energy required to extract a ton of metal will not grow nearly as much as one might think. Although Frasché was correct that "The extraction of mineral raw materials from low-grade rock is a problem in the application of energy—at a price" (*5*, p. 18), he should have added that the total mass of useful minerals that have a finite resource base is small. Therefore, the effect of their depletion on the entire energy system is less than Frasché's statement might imply.

Of course, even the elements in nearly infinite supply will take more energy to extract as we go from ores to more common rocks. The energy requirements for production and recycling of the abundant metals—Mg, Al, Fe, Ti—and Cu were estimated by Bravard *et al.* (*13*) and are summarized in Table 6. In Table 6 we compare E_L, the amount of energy required to extract a ton of metal from low-grade, essentially inexhaustible ores, with E_H, the energy required to extract the metal from high-grade ores.

It is remarkable that the estimated energy required to produce these metals from essentially inexhaustible sources is in every case not more than about 60 percent higher than the energy required to win the metals from high-grade ores. Even when all the reduced carbon is gone, the ratio for iron—by far the most important metal—is $< \sim 2.0$ (*14*).

Extraction of useful metal from ore involves two separate steps: (i) mining and beneficiation of the ore and (ii) reduction and refining of the metal from the beneficiated ore. Generally the second step requires considerably more energy and expense than the first; for example, to mine and beneficiate 1 ton of iron from presently used magnetic taconite ores requires about 5 percent as much energy as is required for the total production of steel from ore. Thus, the overall energy required is not very sensitive to the grade of ore until the ore becomes extremely dilute, and this will never happen for the inexhaustible metals.

In 1968 the metal industry consumed 8.5 percent of the total energy used in the United States; some 90 percent of this was expended in the production of Fe, Al, Mg, Ti, and Cu. The per capita annual energy expenditure for metal production came to about 8000 kilowatt-hours per person or 0.91 kilowatt per person. However, when only new metal from ores is considered, the primary metal industry accounts for 5.7 percent of total U.S. energy consumption; in this case, per capita energy use is reduced to 5300 kwh per person. In the Age of Substitutability (assuming electrolytic hydrogen, rather than carbon, is used), it seems fair to double the energy expended for these metals—to 10,600 kwh or a rate of 1.2 kw per person—assuming that the amount of metal used per capita and the composition of avalloy remain as they now are (*15*). Even in the Age of Substitutability, the amount of energy required per unit of metal to provide avalloy is hardly twice (rather than 10 or 100 times) that used in the present era. This is because the dominant metals—iron, aluminum, and magnesium—can be extracted from essentially inexhaustible resources, which demand relatively small additional amounts of energy for the extraction.

We have tried to estimate how much the per capita energy budget for producing demandite and desalted water for agriculture

Table 7. Possible annual energy budget for demandite, avalloy, and agriculture in stage 3. All values are kilowatts per capita, unless otherwise noted. World values are taken as half of U.S. values for industry and equal to U.S. values for agriculture.

	United States		World	
	Present	Stage 3	Present	Stage 3
Population (× 10⁶)	200	300	3600	10,000
Industry				
Avalloy*	0.60	1.20	0.15	0.60
Inorganic chemicals	0.86	1.12	0.13	0.56
Cement, stone, clay, and glass	0.21	0.27	0.08	0.14
Petroleum refining and petrochemicals	0.47		0.07	
Reduced carbon and hydrogen (petrochemicals)		0.24		0.12
Total demandite	2.14	2.83	0.43	1.42
Agriculture				
With desalted water		1.70		1.70
Without desalted water	0.87	0.87	0.68	0.87
Total, industry and agriculture (with desalted water in stage 3)	3.01	4.53	1.11	3.12
Total, all other uses	8	10.5	0.4	4.4
Total energy use	11†	15	1.5	7.5
Increase in stage 3				
Industry		0.69		0.98
Agriculture		0.83		1.02
Total		1.52		2.00

*Only new metal from ore is considered; total metal ≃ 1.5 times new metal. †The total in the United States in 1968 was 9.6 kw per person.

Table 8. Annual fuel and metal ore spoils today and in stages 2 and 3. At present, coal, oil, and gas are available; half of the coal is strip-mined and half is mined underground. At the peak of stage 1, oil and gas are gone; 80 percent of the coal is strip-mined and 20 percent is mined underground. In stage 2, strippable coal is gone and all coal is mined underground. In stage 3, all the coal is gone; all energy is from nonfossil fuel resources.

Period	Population (× 10⁶)	Energy (kilowatts per person)	Spoils (tons per person) Coal	Breeders	Avalloy	Total	Total annual spoils (× 10⁹ tons)
United States							
Stage 1							
Present	215	11	25		1.3	26.3	5.6
Peak	250	13	100		~ 2	102	26
Stage 2	275	14	10		~ 3	13	3.6
Stage 3	300	15		0.6	4	4.6	1.4
World							
Stage 1							
Present	4,000	1.5	7		0.4	7.4	29.6
Peak	6,000	3	35		~ 1	36	216
Stage 2	8,000	5	5		~ 1.5	6.5	44
Stage 3	10,000	7.5		0.3	2	2.3	23

would increase in stage 3, although we realize that these estimates are speculative and require more study. In Table 7 we summarize these estimates. We also estimate what these values might be in stage 3, if it is assumed that the per capita use of demandite remains constant but that agriculture requires 100 gallons of desalted water per person per day.

The most striking speculation that we make in Table 7 is that the increase in energy required in stage 3 for nonrenewable resources and desalted water is about 2 kw per person. Adding 2 kw for other uses, we arrive at an estimate that the U.S. per capita energy for all uses in stage 3 might increase from its present 11 kw to 15 kw, and the world per capita use from 1.5 to 7.5 kw. If the world's population grows to 10×10^9, and the entire world reaches half the projected U.S. per capita energy expenditure, the world's total production of energy would amount to about 75×10^9 kw. This is 12 times the present worldwide man-made energy, but still represents only 0.1 percent of the solar energy absorbed and reradiated by the earth.

We shall not dwell on the environmental, technical, and institutional implications of so large a production of energy, since these matters have been discussed elsewhere by many authors (*16*). The main conclusions that we can draw are the following.

1) All fossil fuels, at this rate of energy expenditure, would be consumed within 100 years.

2) The fission breeder, fusion (if feasible), or solar energy, in principle, could carry this energy budget essentially forever.

3) The climatic changes caused by so large a release of energy cannot be predicted with our present knowledge of climatology, although the average increase in world temperature, assuming no changes in albedo, would be about 0.1°C. Whether the effect of such energy output on climate will ever be predictable, even in principle, remains moot.

4) It seems likely that if fission breeders are the basis for the stage 3 energy supply, large institutional changes will be called for so that man can live comfortably with fission, on the scale envisioned here. Thus, if the entire 75×10^9 kw were provided by fission breeders, with each reactor operating at 5×10^6 kw (of heat), the world would have to accommodate 15×10^3 reactors. If each reactor lasted 30 years, then 500 reactors would, in the asymptotic state, be retired each year. This amounts to about ten reactors being built each week. Is this credible? Will we have the land, the waste disposal areas, and the capacity to deal with diversion and with transport of radioactivity on such a large scale?

Although technological fixes (*17*) will ease these problems—for example, cluster siting would make diversion more difficult (*18*)—one can see the point of those such as Mesarovic and Pestel (*2*), who argue that a much more appropriate asymptotic per capita energy demand is the value that now characterizes much of Western Europe: about 4 kw per person. However, we estimated (Table 7) that, in stage 3, loss of CH_x would require an additional 2 kw per person for demandite and agriculture. Since transport, space heating, and cooling would also require more energy in stage 3, we estimate that to achieve the Pestel-Mesarovic world might require perhaps 7 to 8 kw per person, and that the problems enumerated above can hardly be avoided.

Mine Wastes

The catastrophists often point out that as we exhaust our higher-grade resources and mine lower-grade rock, mine wastes will lead to disaster. But our analysis points to a rather different outcome. Since CH_x is by far the largest component of demandite, most of the waste from mining is associated with extraction of coal—8 tons of spoil per ton of coal mined in the United States. Thus, in stage 3, when we no longer mine coal, the mine spoil per person associated with other sources of energy (breeders, fusion, and solar) will be much less than the mine spoil now associated with our energy system (*16*).

As for the mine wastes per ton of avalloy, these can never increase much more than threefold because avalloy is dominated by iron, and high-grade taconite iron ore is only three times as rich as inexhaustible laterite ore. Moreover, the total waste from avalloy mining is only 5 percent of that from coal mining: a threefold increase in avalloy mining waste would still be small compared to the waste from coal mining.

Table 8 gives our estimates for mining spoil at present and in the Age of Substitutability, for the United States and the world. At a per capita energy budget of 7.5 kw in stage 3 the yearly mine spoil per person is 2.4 tons compared to the present 7.4 tons. Thus, one can argue that the world population could increase threefold before the mine wastes in stage 3 equal present mine wastes.

We have not attempted to estimate other pollutants in stage 3. However, since the bulk of air pollution (CO_2, CO, SO_2, trace elements, and fly ash) is the result of burning fossil fuel, there should be less air pollution in stage 3 than at present.

Although our estimates are reassuring, on the average, we are reluctant to leave an impression of facile optimism. The environmental impacts in specific places and specific situations might well be more serious than we have implied.

Conclusions

Most of what we contend is speculation. Yet, there is one aspect of the future which seems to be "scenario-proof": contrary to the assertions of the neo-Malthusians, depletion of mineral resources per se need not create catastrophe, provided man finds an inexhaustible, nonpolluting source of energy. The main problem is how to go from our present state, stage 1, where we have ample CH_x and other resource materials, to stage 3, the Age of Substitutability, without incurring drastic social instabilities. Will we have the capacity and foresight to plan and execute the transition without such instabilities?

It is very well to say that, in principle, substitutes can be found, that even without CH_x our per capita energy budget will not be much greater than it is now. But even factors of 2 in energy budget or price, although they seem small in the long run, can over the short term or in local situations cause great social dislocation.

What is at issue is the effectiveness of the marketplace in forcing a rational resource policy. Over the long term, the marketplace forces substitutions and the use of lower-grade ores. But the marketplace has a high discount rate: in technological changes that require many years, the marketplace as it now operates invariably seeks out paths that optimize short-term advantage. Such paths may waste resources in the long run. The situation is well illustrated by the light water breeder reactor (LWBR) and the light water reactor (LWR). Over a 30-year period, a 1000-megawatt-electric LWR with no recycling requires about 5000 tons of uranium; an LWBR of the same size may require about 1500 tons of uranium. On the other hand, almost all of the LWBR inventory must be invested during the first few years, whereas the LWR uses its uranium rather uniformly over its lifetime. Thus if one judges the relative economic costs on a very short write-off, the LWR wins; if the write-off is 30 years or longer, the LWBR wins. From the viewpoint of husbanding resources, over the long term the LWBR is better than the LWR; over the short term LWR is better.

Recycling faces the same dilemma. How can one use the marketplace to encourage recycling when, in the short run, it pays not to recycle? Is it possible for the marketplace to be modified, perhaps by government fiat, to reduce its discount rate, to take a longer, resource-dominated position?

Our technical message is clear: dwindling mineral resources in the aggregate, with the exception of reduced carbon and hydrogen, are per se unlikely to cause Malthusian catastrophe. But the exception is critically important; man must develop an alternative energy source. Moreover, the incentive to keep the price of prime energy as low as possible is immense. In the Age of Substitutability energy is the ultimate raw material. The living standard will almost surely depend primarily on the cost of prime energy. We therefore urge moving as vigorously as possible, not only to develop satisfactory inexhaustible energy sources—the breeder, fusion, solar and geothermal power—but to keep the program sufficiently broad so that we can determine, perhaps within 50 years, the cheapest inexhaustible energy source.

Our social message is less clear and certainly less optimistic. Although we see during the Age of Substitutability no insuperable technical bars to living a decent rather than a brutish life (assuming, of course, a stable population), whether in fact this will happen is far from certain. As Heilbroner (*19*) has pointed out, local shortages, which in the course of history are destined to be viewed as transitory, can and do cause large social and political instability. Heilbroner's "wars of redistribution," pitting the overpopulated have-nots against the underpopulated haves, could collapse society long before our carbon runs out. That the Age of Substitutability will, in principle, be autarkic, since mankind will no longer depend on reduced carbon (which is located in a few places), is little solace for governments or peoples today who look upon shortages of coming decades as threatening our entire social structure. We do not argue that the Age of Substitutability will be an easily achieved technological heaven-on-earth. Rather we urge attention to those institutional deficiencies that now prevent us from passing through stage 2 of our human voyage without causing the boat to capsize. The landfall, if we arrive at stage 3, should be surprisingly better than the catastrophists have predicted.

References and Notes

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11. A convenient small battery that does not use scarce materials and lasts a long time is an obvious target for research. However, if such a battery were never developed, we could revert to standard miniaturized dry cells (based on zinc and manganese) with only slight inconvenience. It must be remembered that in a 25-g cell used to power a portable computer, there are only 10 g of mercury. Even if the price of mercury rises 100-fold, the overall cost of the computer would rise by $12 if we elected to stay with the mercury battery instead of converting to shorter-lived, cheaper Zn-Mn dry cells. In the longer term, a substitute for the lead battery also may be needed.
12. Other examples of elements with finite resources that may have very high leverage are silver, which is used in photography; tungsten, in tool-making; lead and antimony, in storage batteries; beryllium, in beryllium-copper alloys; and perhaps manganese, in steel-making. More study is needed to identify other such critical situations.
13. J. C. Bravard, H. B. Flora II, C. Portal, *Energy Expenditures Associated with the Production and Recycle of Metals* (ORNL-NSF-EP-24, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1972).
14. Could we imagine charcoal from wood, used to reduce iron ore until 150 years ago, replacing coke today? Is this practical?
15. Even if copper is replaced by aluminum, the energy per ton of avalloy changes by less than 10 percent.
16. For example, see A. M. Weinberg and R. P. Hammond, *Am. Sci.* **58** (No. 4), 414 (1970).
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Chemicals from Coal

By-products of conversion of coal to clean fuels will offer new options to the maker of chemicals.

Arthur M. Squires

Coal maintained its historic role in the chemical industry until the close of World War II (*1*). By 1950, however, new procedures and new products were firmly established as prime opportunities for growth: to give examples, ammonia from methane, synthetic rubbers, polyethylene, and aromatic feedstocks from petroleum. The United States abandoned ammonia and methanol from coal in the mid-1950's. By now, the shift to petrochemicals is almost complete. The role of by-product coke ovens is greatly diminished: they supply only 10 percent of the U.S. benzene market and 2 percent of the phenol. Petrochemicals now take 10 percent of the U.S. oil and gas supply, and have expanded at 7 percent per year in recent years.

When and where will petrochemicals give way, as they eventually must, to a revival of chemicals from coal?

A return to coal will be slow. The historic shift to petrochemicals was fast not only because oil and especially gas (*2*) were often cheaper than coal but also because processing equipment for the cleaner, fluid fuels is far cheaper. The equipment can conveniently reach large rates of production from individual processing units (*3*). Historic coal conversions did not develop beyond unit sizes that are far too small to be congenial now. Much development effort lies before the question, When and where? A better question might be, What among many R & D opportunities can pay off soonest?

Chemicals as By-products

Coal chemicals were mostly by-products of two carbonization procedures, one to supply town gas (*4*), and another, coke for steelmaking. Even ammonia synthesis depended upon gasification of the coke by-product of town gas manufacture (*5*). Viewed broadly, petrochemicals are by-products of the production and delivery of gas and oil for use as fuels.

One factor conducive to preeminence of

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