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THE AGE OF SUBSTITUTABILITY*

or

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 the earth's resources will soon be exhausted, and that this will lead to a collapse of society. The "cornucopians" argue that most of the essential raw materials are infinite: that as the society exhausts one raw material, it will turn to lower grade, inexhaustible substitutes. Eventually the society will subsist on renewable resources, and on those elements that are practically infinite, such as iron and aluminum. According to this view the society will settle into a steady-state of substitution and recycle. This asymptotic society we call the Age of Substitutability.

MASTER

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We are cornucopian, even in this era of dwindling "resources", with its dire predictions of the Club of Rome, of Limits to Growth, and of Mankind at the Turning Point. We came to this position some 25 years ago after reading Sir Charles Darwin's The Next Million Years. Darwin rightly insisted, as do some of the present-day forecasters and systems modelers, that short-term forecasting was impossible (as well as being uncomfortable for the forecaster, who presumably would be around when his forecasts could be tested against fact). But very long-range forecasting, in which fluctuations in human experience were blips on an underlying statistical state, could be done in the same sense that statistical mechanics predicts the future of a big ensemble. Over the very long run, Darwin asserted, 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, to violence, to brutishness.

Darwin, as all Neo-Malthusians, realized that no panacea 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, that an inexhaustible source of energy would be necessary - perhaps even sufficient - to rescue man from the resource catastrophe. Most of the minerals that man uses - iron ore, carbon dioxide, and alumina - are found in nature in an oxidized state, or more generally, in a state of relatively high entropy. To reduce these materials, i.e., to extract

iron, to convert CO_2 to cellulose, or to 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. We disagree with Darwin: there are other "inexhaustible" sources of energy (notably the breeder reactor, 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 the bauxite is gone, we will have to do without aluminum. Thus we read in Limits to Growth, "The effect of exponential growth is to reduce the probable period of availability of aluminum from 100 years to 31 years." This cannot be correct. As geologist Dean F. Frasché said in 1962, "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, due to depth, size, or grade, that we cannot produce what we need without completely disrupting our social and economic structures." Will we ever completely disrupt our social and economic structures because we run out of mineral resources? We propose in this paper to examine these questions. 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.

Actually, we can conceive of depletion of resources and substitution in three stages. Stage I is a continuation of our present patterns of use of our non-renewable resources; this almost surely will persist for the next 30 to 50 years. In Stage II, the society still would depend on reduced C and H found in nature, i.e., coal, there would be little oil and gas, and people would begin to turn away from widespread use of a few of the non-ferrous metals and toward much greater use of alloy steels (Al, Mg, and Ti). Stage II might last several hundred years. Finally in Stage III, the truly asymptotic "Age of Substitutability", all the fossil fuel would be gone; the 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 III, the Age of Substitutability, will not be drastically different from our present condition of life: we have the physical possibility of living in the Age of Substitutability without "completely disrupting our social and economic structure". To reach this state without immense social disruption will, however, require unprecedented foresight and planning.

A convenient way to place the matter into perspective is to examine the "chemical" composition of one molecule of "Demandite", the average non-renewable resource man uses, i.e., we take the total number of moles of each element that man extracts from the earth, the sea, and the air, and from this compute the average molar composition of man's "average non-renewable resource". We exclude renewable resources, agricultural products, wood, and water. Similarly, we can define the average metal

(Avalloy); the average fertilizer (Avfert); the average industrial gas (Avgas); the average industrial heavy chemical (Avchem), and the average refractory (Avrefract). In Tables I and II, and in Appendix 1, we give the chemical formulae and other properties of these average materials. All data are given for 1968.*

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 III). Actually, the resource situation is even better than this comparison implies, because the majority of most-used elements in Demandite, plus a few others, have near-infinite resources of much higher quality and concentrations in sources other than "average" rocks; these are summarized in Table IV.

The data in Tables III and IV show that of the 13 most widely used atoms, only extractable CH_x and phosphorus are not "essentially" infinite: whereas oxidized C and H are very common, extractable CH_x, the most widely used component of Demandite, is rare - only 16 ppm in the first kilometer of the earth's crust. Thus, when we speak of "running out of resources", <u>by far the most important "scarce" resource is extractable CH_x</u>. Since energy can reduce CO_2 and H_2O to CH_x (see Appendix 3), we can paraphrase the basic point of both H. G. Wells' and Darwin's Malthusianism: the primary resource shortage is one of reduced CH_x or its equivalent, energy.

*These formulae are based on the highly consistent statistics given in Mineral Facts and Problems, 1970, U. S. Bureau of Mines Bulletin 650 and modified as needed.

TABLE I: The Average Non-Renewable Resource Used by Man in 1968*
"Demandite"

United States:

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

World:

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

X represents all other chemical elements; highest in order of demand are Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, Zr; all others <100,000 tons/year (world) or 30,000 tons/year (U.S.)

	United States	World
Total Quantity, 10^6 tons	3,360	17,300
Total Value, $\$10^6$	42,200	158,500
Average Unit Value, \$/ton	12.55	9.16
Average Energy Used for Recovery, kwh/ton	1,140	800
Total Quantity, 10^6 ton mols	154.8	604.9
Average Molecular Weight	26.7	28.6
Per Capita Consumption, tons	17	5
Per Capita Energy, kwh	18,800	3,800
Per Capita Energy, kw	2.14	0.43

Source: Derived, with some modifications, from data in Mineral Facts and Problems, 1970, U. S. Bureau of Mines Bulletin 650.

*Applies to new metal from ore, only; for total metal, see Tables A1 and A2, Appendix 2.

TABLE II: The Average Metal Used by Man in 1968*
"Avalloy"

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				

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				

X includes all other ferrous metals; Y all other non-ferrous metals.

	United States	World
Total Quantity, 10^6 (tons)	85.6	424.3
Total Value, $ x 10^6	16,050	75,775
Average Unit Value, $/ton	187.50	178.60
Average Value, $/ton, of Fe, Si, Al, Ti, Mg in Avalloy	154.95	145.40
Average Energy Used for Recovery, kwh/ton	12,300	11,100
Average Molecular Weight	58.1	55.2
Per Capita Consumption, tons	0.43	0.12
Per Capita Energy, kwh	5,250	1,305
Per Capita Energy kw	0.60	0.15

Source: Derived from data in Mineral Facts and Problems, 1970, U. S. Bureau of Mines Bulletin 650.

*Applies to new metal from ore, only; for total metal, see Table A1, Appendix 2.

TABLE III: Average Composition of the Earth

Crust (Topmost Kilometer on Continents)

(CH_x)(Extractable) .00004		(CH_x)(Unextractable)* .0083		C(Oxidized) .0153
O .5884	Si .1931	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 .0039				

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
X' .000021				

Seawater (Except for Water)

Cl .4886	Na .4200	Mg .0475	S .0253	Ca .0092
K .0090	C .0001	P .000003	(Si, Fe, Al, Ti) .0000006	
Other .0003				

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 amounts 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 IV: Present or Future Near-Infinite Resources for the Most Extensively Used Elements

Element	Resource	Maximum % in Resource	World Resource (Tons)	R/D Ratio* Years
CH_x(Extractable)	Coal, Oil, Gas	>75	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}	$\sim 10^{9}$
Fe	Basalt**	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	.012	2×10^{15}	4×10^{8}
Mn	Seafloor 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}

*We realize that as demand grows, these values will be reduced; however, we also anticipate that population must eventually level off, followed by an ultimate leveling off of demands for energy and non-renewable resources.

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

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 Avalloy, aluminum atoms, 8 percent: these two "infinite" metals constitute 94 percent of the total. To extract iron from its oxide by presently-used processes requires reduced carbon, and this use accounts for about 12 percent of all coal used in the United States. Although Avalloy itself is made largely from inexhaustible Fe and Al, to produce Avalloy requires reduced carbon - which is a rare material - or some other source of energy.

Let us now state the Principle of "Infinite" Substitutability: with two notable exceptions - phosphorous and energy-producing fossil fuels, i.e, CH_x - the society can subsist with relatively little loss of living standard on infinite or near-infinite minerals. Such a civilization would be based largely on glass, plastic, wood, cement, iron, aluminum, and magnesium: whether it will be anything like our present society will depend upon 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, one must examine in detail, not simply in principle, exactly how one would propose to live without a particular "finite" resource. This we do not claim to do in this paper; rather we quote from previous work on the subject by H. E. Goeller.*

*H. E. Goeller, "An Optimistic Outlook for Mineral Resources", presented at Minnesota Forum on Scarcity and Growth, June 22-24, 1972.

Certainly there are no substitutes for the elements required to sustain life. The major "life" elements 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 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 calcium, nitrogen, potassium, and phosphorus, plus relatively small quantities of some of the trace elements. Of the major life-sustaining elements, only phosphorus is not on our list of "infinite" elements. The clarke of phosphorus is about 800 ppm; if the 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). This led H. G. Wells many years ago to suggest that ultimately we shall have to recycle bones as fertilizer; indeed, we are in no position to refute this view.

With regard to the trace elements which are present in the soils and are needed only at low concentrations, modern agriculture slowly depletes soil of these elements. In the near term, shortages can undoubtedly be supplied from inorganic sources; in the long run, we will 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 non-substitutable 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 confer corrosion resistance and high temperature strength on iron; mercury because it is a metallic liquid at room temperature. One of us has studied in some detail the extent to which one might substitute for cadmium,* zinc, lead, copper, tin, and mercury.** The main conclusion of this study is that for most of their uses, substitutes derived from infinite or near-infinite materials are available. To illustrate, we summarize some of the results in the case of mercury.

- The Case of Mercury -

The average annual consumption of mercury by use and form in the United States, 1964-1973, is given in the accompanying Table V. 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. For example, the largest use of mercury (34 percent or 770 tons per year) is for caustic chlorine production. Diaphragm cells are an alternative that were in

* W. Fulkerson and H. E. Goeller (Ed.), "Cadmium, The Dissipated Element", ORNL-NSF-EP-21, January 1973.

**H. E. Goeller, "Summary of Current World Resources, Production and Uses of Mercury and Possibilities for Recycle and Substitution", Paper presented to Ad Hoc Committee on the Rational Use of Potentially Scarce Metals, Scientific Affairs Division, North Atlantic Treaty Organization, (to be published 1976).

TABLE V: Average Annual Consumption of Mercury in the United States, 1964-1973

Uses	Substitutes	Metric Tons	% 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-MnO_2-Graphite Dry Cell	598	26.4
Industrial and Control Instruments	See Note 1	252	11.2
Biocidal Paints	Plastic Paints, Copper Oxide Paint	299	13.2
Dental Amalgams	Metal Powders, Porcelain, Plastics	99	4.4
Agriculture[3]	Organic Biocides	88	3.9
Catalysts	Ethylene Process for PVC Mfg.	54	2.4
Laboratory Use	See Note 1	57	2.5
Pulp and Paper Mfg.[2]	Organic Biocides	17	0.8
Pharmaceuticals	Sulfur Drugs, Iodine, Etc.	17	0.8
Amalgamation[2]	Gold Recovery by Cyanide Process	6	0.3
Total		2255	100.00

NOTES:

1. Substitution may be based on alternative physical properties; may include bimetallic couples aneroid barometers, etc. Liquid gallium and sodium-potassium alloys may be substitutes at room temperatures not at sub-zero temperatures.

2. These uses of mercury were discontinued in the U.S. in 1971. Large former uses included mercury fulminate detonators and felt manufacture; both have been replaced decades ago.

3. Use of methyl mercury on seed grains banned by U. S. Department of Agriculture, banning of other uses may follow.

*Includes small quantities for other uses.

wide use before mercury cells were introduced and still account for 70 percent of the U. S. production of caustic. These cells require relatively common materials such as concrete for the cell body, asbestos for diaphragms, and copper and graphite for electrodes.

As we go down our list we see that acceptable alternatives are now known for all of the major uses of mercury except possibly high-performance electric batteries (which would require other scarce materials like Cd and Ag) or electric switches.* For the minor uses such as 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 was small. We can hardly imagine the society collapsing, or even being seriously impeded in the long run if we have to do without mercurial pharmaceuticals or mercury batteries.

- Other Metals -

If we played the same game of what do we do when the high-grade ores of copper, silver, zinc, tin, etc., run out, would the aggregate additional cost, both in energy and in dollars, of the substitutes or of the materials themselves, ultimately derived from "dirt", be intolerable? To be more specific, let us estimate how much the aggregate unit cost of

*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 a slight inconvenience. It must be remembered that only 10 grams of mercury in a 25-gram cell are used to power a portable computer. Even if the price of mercury rises one hundred-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 storage battery also may be needed.

these metals could rise without causing the cost of Avalloy to rise more than two-fold.

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/ton of Avalloy, 75 percent of the cost/ton of Avalloy. All these are in infinite supply and their ultimate unit cost, either in energy or dollars, can hardly exceed today's unit cost by more than a factor of two as shown in Table VI. 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 II). At present, extraction from ore represents only about one-half the total cost of these 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 ten-fold, 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 U. S. But electrical copper is, in the long run, almost entirely replaceable by aluminum; structural copper and brass largely by steel, aluminum, titanium, and plastic. Moreover, Mn (in sea floor manganese nodules and in igneous rock) and Ni (in the peridotites) are nearly infinite: it is hard to see how the latter two metals can 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 the society to use titanium (which is in near-infinite supply) for most uses that are now served by stainless steel. Nevertheless, the remaining elements - Zn, Cr, and Sn - could increase in cost by a very large factor, and the cost of Avalloy would still remain within a factor of two of its present real cost. This is true also of the remaining non-metals, the metal oxides, the refractory metals, and the non-ferrous byproduct metals. These are discussed in Appendix 2. Thus we arrive at our basic observation: that Avalloy and indeed 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 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.

While we can conclude from a global viewpoint that the cost of Avalloy in the Age of Substitutability will not be more than 2 to 3 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 a drastic increase in cost or even collapse of that industry 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, one must realize that if the cost of fusion energy exceeds that of solar energy or energy from breeders, then the society will choose solar 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.*

- Recycle in the Age of Substitutability -

As prices for materials go up, there obviously will be stronger incentive to recycle, to bring the empty bottles back. The energy required to put scrap metal back into productive use is very much less

*Other examples of elements with finite resources that may have very high leverage are silver in photography; tungsten in tool-making; lead and antimony in storage batteries; beryllium in beryllium-copper alloys; and perhaps manganese in steel-making. Obviously more study is needed to identify other such critical situations.

than that needed to reduce and refine ores - for Mg it is 1-1/2 percent of that required to win the metal from ore; for Al it is 3 to 4 percent; for Ti it is 30 percent. One must recognize that recycle can never be a total answer, since the recovery in each recycle is never 100 percent; in fact, unless recycle is very efficient, it will not make very much difference. Thus, if the recovery of copper, say, is 0.9 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 0.4 per cycle, this factor is reduced to only 1.7.

Recycle is simplified by human intervention. If materials are not recycled, they become diluted and dissipated into 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 Demon does not change the entropy of mixing appreciably unless, by his intervention, 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 in the Age of Substitutability -

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 infinite iron and aluminum, the energy required for extracting metals will not grow nearly as much as one might think. Although Frasché is correct in stating in 1962, "the extraction of mineral raw materials from low-grade rock is a problem in the application of energy at a

price", he should have added, 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 infinite elements will take more energy to extract as we go from ores to more common rocks. The energy requirements for production and recycle of the abundant metals - Mg, Al, Fe, Ti - and Cu were estimated by J. C. Bravard, H. B. Flora, II, and C. Portal in 1972* and are summarized in Table VI. In this table 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.

Extraction of useful metal from ore consists of two separate steps: first, mining and beneficiation of the ore; and second, reduction and refining of the metal from the beneficiated ore. Generally the second step requires considerably more energy and expense than the first - e.g., to mine and beneficiate one ton of Fe 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 "infinite" metals.

*"Energy Expenditures Associated with the Production and Recycle of Metals", ORNL-NSF-EF-24.

TABLE VI: Energy Requirements for the Production of Abundant Metals and Copper

Metal	Source	Equivalent Coal Energy* (kwh/ton of Metal)	E_L/E_H
Magnesium Ingot	Seawater	100,000	1
Aluminum Ingot	Bauxite	56,600	1
	Clay	72,600	1.28
Raw Steel	Magnetic Taconites	10,100	1
	Iron Laterites	11,900	1.17 (with carbon) <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% Cu	14,000	1
	Porphyry Ore, 0.3% Cu	27,300	1.83

*At 40 percent thermal efficiency for generation of electricity

It is remarkable that the estimated energy required to produce these "infinite" 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 - is 2.0.*

We have estimated how much the per capita energy budget for producing Demandite and desalted water for agriculture would increase in Stage III. We realize that these estimates are speculative and require much more study. 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 8,000 kwh/person or 0.91 kw/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 5,250 kwh/person. In the Age of Substitutability (assuming electrolytic H_2, not C, is used), it seems fair to double the energy expended for these metals - to 10,500 khw/person/year or 1.2 kw/person - assuming that the amount of metal used per capita and the composition of Avalloy remains what it is now.** Even in the Age of Substitutability, the

* Could we imagine charcoal from wood, used in metallurgy until 150 years ago, replacing coke today? Is this practical?

**Even if Cu is replaced by Al, the energy per ton of Avalloy changes by less than 10 percent. See Appendix 3.

amount of energy required to provide metals is hardly twice (rather than ten- or one hundred-fold) per unit of metal used than in the present era. This is because the dominant metals - Fe, Al, Mg - can be extracted from inexhaustible resources which demand relatively small additional amounts of energy for their extraction.

In Table VII are summarized our estimates of the per capita expenditure of energy in the U. S. and the world (1968) for Demandite and agriculture. We also estimate what these values might be in Stage III, assuming the per capita use of Demandite remains constant, but that agriculture requires 100 gallons per person per day of desalted water. The details of the calculations that lead to the numbers in Table VII are given in Appendix 3.

The most striking speculation that we make in Table VII is that the increase in energy required in Stage III for non-renewable resources and desalted water is about 2 kw/person. Adding 2 kw for other uses, we arrive at a guess (justified in part by the considerations in Appendix 3) that the U. S. per capita energy for all uses in Stage III might increase from its present 11 kw to 15 kw, and for the world from 1.5 kw 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 world man-made energy, but still represents only 0.1 percent of the solar energy absorbed and reradiated by the earth.

TABLE VII: Possible Annual Energy Budget for Demandite, Avalloy, and Agriculture in Stage III of The Age of Substitutability (all values in kw/capita unless otherwise noted)

	United States		World	
	Present	Stage III	Present	Stage III[1]
Population x 10^6 persons	200	300	3600	10,000
Industry				
Avalloy[2]	0.60	1.20	0.15	0.60
Inorganic Chemicals	0.86	1.12	0.13	0.56
Cement, Stone, Clay, Glass	0.21	0.27	0.08	0.14
Reduced C and H (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	3.01	4.53	1.12	3.12
Total, All Other Uses	8	10.5	0.4	4.5
Total Energy Use	11[3]	15	1.5	7.5
Increase in Stage III				
Industry	--	0.69	--	0.98
Agriculture	--	0.83	--	1.02
Total	--	1.51	--	2.00

[1]World values taken as half of U. S. values for industry and equal to U. S. values for agriculture.

[2]New metal from ore, only - total metal = ~1.5 times new metal.

[3]Total in U. S., 1968 was 9.6 kw/person versus current value of 11 kw/person.

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. The main conclusions that can be drawn are:

1. All fossil fuels, at this rate of energy expenditure, would be used up 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 the climate will ever be predictable, even in principle, remains a moot question.

4. It seems likely that if fission breeders are the basis for the Age of Substitutability, 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 and 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 10 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?

Though technological fixes will ease these problems, i.e., cluster siting would make diversion more difficult, one can see the point of those such as Pestel and Mesarovic 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/person. However, in Stage III of the Age of Substitutability, we estimated (Table VII) that loss of reduced (CH_3) would require an additional 2 kw/person for Demandite and agriculture. Since transport, space heating, and cooling would also require more energy in Stage III, we guess that to achieve the Pestel-Mesarovic world might require perhaps 7 to 8 kw/person.

- Pollution in the Age of Substitutability -

The catastrophists often point out that as we exhaust our higher grade resources and mine lower grade rock, pollution will lead to disaster. But our analysis points to a rather different outcome. Most of the world's "pollution", measured in tons of waste, comes from mining. 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 in the United States. Thus in Stage III of the Age of Substitutability, 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.

As for mine wastes from Avalloy, these can never increase much more than three-fold per ton because Avalloy is dominated by iron, and high-grade taconite iron ore is only 3 times as rich as "infinite" laterite

ore. Moreover, the total waste from mining Avalloy is only 5 percent of that from coal mining: a three-fold increase in Avalloy mining waste would still be small compared to the waste from coal mining.

We present in Table VIII our estimates for mining spoil at present and in the Age of Substitutability for the U. S. and the world. These estimates are justified in Appendix 4.

From the table, one sees that at a per capita energy budget of 7.5 kw in Stage III the yearly mine spoil per person is 2.4 tons compared to 7.4 tons at present. Thus, one can argue that the world population could increase three-fold before the mine wastes equal present mine wastes.

We have not attempted to estimate other pollutants in Stage III. However, since the bulk of air pollution is the result of burning of fossil fuel (CO_2, CO, SO_2, trace elements, fly ash), air pollution in Stage III ought to be less than air pollution at present. This point, of course, requires further study.

Though 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 would undoubtedly be more serious than we have implied.

- Conclusions -

Most of what we have said is speculation. Yet, there is one aspect of the future which seem 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, non-polluting source of energy.

TABLE VIII: Annual Fuels and Metals Ore Spoils Today and in The Age of Substitutability

	Stage I			
	Present[1]	Peak[2]	Stage II[3]	Stage III[4]
United States				
Population, 10^6 persons	215	250	275	300
Energy, kw/person	11	13	14	15
Spoil from Coal, tons/person	25	100	10	--
Spoil from Breeders, tons/person	--	--	--	0.6
Spoils from Avalloy, tons/person	1.3	~2	~3	4
Total Spoils, tons/person	26.3	102	13	4.6
Total Spoils, 10^9 tons/year	5.6	25.5	3.6	1.4
World				
Population, 10^6 persons	4000	6000	8000	10,000
Energy, kw/person	1.5	3	5	7.5
Spoil from Coal, tons/person	7	35	5	--
Spoil from Breeders, tons/person	--	--	--	0.3
Spoils from Avalloy, tons/person	0.4	~1	~1.5	2
Total Spoils, tons/person	7.4	36	5.5	2.3
Total Spoils, 10^9 tons/year	29.6	216	44	23

[1]Coal, oil, and gas available; half of coal strip-mined, half mined underground.
[2]Oil and gas gone, 80 percent of coal strip-mined, 20 percent mined underground.
[3]Strippable coal gone; all coal mined underground.
[4]All coal gone; all energy from non-fossil fuel resources.

The main problem is how to go from our present state, Stage I - with plenty of CH_x and other resource materials - to Stage III, the true Age of Substitutability, without incurring drastic social instabilities. Will we have the capacity and foresight to plan and execute the transition without gross instabilities?

It is all well and good 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 factors of even two in energy budget or price, though they seem small in the long run, can, in the short run or in local situations, cause great social dislocation. This was sharply illustrated by the Arab oil embargo. Attempts to cartelize bauxite or iron ore show that a two-fold increase in price is not something the society accepts lightly.

What is at issue is the effectiveness of the marketplace in forcing a rational resource policy. To be sure, in the long run, the marketplace forces substitutions and lower grade ores to be used. 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 squander 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 MWe LWR with no recycle requires about 5000 tons of uranium; an LWBR of the same size may require perhaps 1500 tons of uranium. On the other hand, almost all of the LWBR inventory must be invested in 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 point of view of husbanding resources, over the long run LWBR is better than LWR; over the short run LWR is better.

Recycle faces the same dilemma. How can one use the marketplace to encourage recycle 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 - that dwindling mineral resources in the aggregate, with the exception of reduced carbon and hydrogen, are largely a myth. 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. What the living standard in the Age of Substitutability will be, almost surely will depend primarily on the cost of prime energy. It is on this account that we would urge getting on as vigorously as possible, not only to developing satisfactory inexhaustible energy sources - the breeder, fusion, solar, geothermal - but to keeping the program broad enough so that we can determine, perhaps within 50 years, what the cheapest inexhaustible energy source is.

Our social message is less clear and certainly less optimistic. Though we see no insuperable technical bars in the Age of Substitutability,

to living a decent, rather than a brutish, life, whether in fact this will happen, is far from certain. As Robert Heilbronner has pointed out, local shortages that in the course of history are destined to be viewed as transitory, can and do cause large social and political instability. Heilbronners's Wars of Redistribution, pitting the overpopulated have-nots against the underpopulated haves, could collapse the society long before our carbon runs out. That the Age of Substitutability is in principle autarkic, since mankind no longer depends on reduced carbon (which is located in a few places), is little solace for governments or peoples today who look upon the shortages of the next decades as threatening the entire social structure. Our purpose is not to argue that the Age of Substitutability is an easily achieved technological heaven-on-earth. It is rather to urge that we pay attention to those institutional deficiencies that now prevent us from passing through Stage II of our human voyage without causing the boat to capsize. The landfall, if we make it to Stage III, should be surprisingly better than the catastrophists have been predicting.

September 4, 1975

APPENDIX 1

This appendix is provided to give a brief explanation of how the formulae for Demandite and Avalloy were developed for Tables I and II. It also provides subsidiary formulae for Avrefract, etc. Finally, it gives further explanation on development of the crust, seawater, and air formulae of Table III and the "best resources" data of Table IV.

Demandite - The determination of a highly accurate formula for Demandite would be a formidable task and might be impossible today because of a lack of statistics. It is believed, however, that the formula presented in Table I are within a few percent of the ultimate formulae. This belief is based on the fact that the first four materials - fossil fuels, sand and gravel, limestone, and iron - account for over 97 percent by weights of the non-renewable materials used by society. We have combined carbon and hydrogen because the bulk of these elements have a common use: fuels. The different ratio of H/C for the U. S. and the world reflects greater use of oil and gas (versus coal) in the U. S. compared to the world at large. It should be noted that the amount of carbon in limestone compared to that in fossil fuels is quite small (5 percent for U. S., 11 percent for the world). Further, the formulae reflect the fact that very large amounts of oxygen are associated with silica and limestone, which is only of academic interest. Finally, the formulae for Demandite show how small, relative to all non-renewable materials used by society, the metals really are (1.3 mol percent in U. S. and 1.6 mol percent world-wide) and how this group is dominated by iron. It should be noted also that although the use of magnesium is large, less than 4 percent is used for production of metal.

Avalloy - Determination of the formulae for Avalloy is much simpler than for Demandite because statistics are much better. It should be noted, however, that the formulae embrace two opposing "errors". First, many metallic elements include non-metal uses (lead additives in gasoline, zinc and lead compounds in pigments, etc); these uses are included.

Second, recycle of metals amounts to 1 to 50 percent for specific metals; since we are concerned with resource depletion, amounts recycled have been excluded.

Subsidiary Formulae - As we have already noted, in addition to Avalloy, Demandite can also be subdivided into other groups of elements with fairly common use; we include four such groups below - Avfert (average of agricultural chemicals), Avgas (average of industrial gases), Avchem (average of major non-metal chemicals and metals used in oxidized form), and Avrefract (average of refractory elements).

Avfert (including sulfur and hydrogen - NH_3 - intermediates)

United States

$N_{.1803}$ $P_{.0284}$ $K_{.0229}$ $(S_{.0404}H_{.7280})$

World

$N_{.2638}$ $P_{.0391}$ $K_{.0384}$ $(S_{.0634}H_{.5953})$

Avgas

United States

$H_{.8138}$ $N_{.0483}$ $O_{.1026}$ $Cl_{.0342}$ $Ar_{.0810}$ $He_{.0004}$ $(Ne,Kr,Xe)_{<<.0001}$

World

$H_{.7783}$ $N_{.0613}$ $O_{.1306}$ $Cl_{.0294}$ $Ar_{.0004}$ $He_{.00001}$ $(Ne,Kr,Xe)_{<<.0001}$

Avchem

United States

$Na_{.7760}$ $S_{.1707}$ $Ba_{.0060}$ $F_{.0365}$ $B_{.0085}$ $Br_{.0020}$ $Other_{.0003}$

World

$Na_{.7634}$ $S_{.1930}$ $Ba_{.0050}$ $F_{.0305}$ $B_{.0071}$ $Br_{.0008}$ $Other_{.0002}$

Avrefract

United States

$Mg_{.8180}$ $Ti_{.1674}$ $Zr_{.0136}$ $(Be\ and\ Other)_{.0010}$

World

$Mg_{.8722}$ $Ti_{.1196}$ $Zr_{.0072}$ $(Be\ and\ Other)_{.0010}$

Average Abundance of Elements in the Earth's Crust, Sea, and Atmosphere - The average composition of the lithosphere was calculated for all rocks to 1 kilometer depth. It was assumed that in this thin layer on the continents, 30 percent of the rocks were igneous rocks, principally granitic, and that 70 percent were sedimentary rocks or metamorphic rocks derived from sedimentary rocks. It was further assumed that 81.5 percent of the latter were shale, 12 percent sandstone, 6 percent limestone and dolomite, and 0.5 percent evaporites. The crustal composition of Table III is, therefore, a weighted average of the abundances of the various elements in these diverse type rocks.

Seawater and air are highly homogeneous. In oder to provide a more satisfactory "formula" for seawater, the water content (96.5 percent) was omitted, i.e., the formula gives the composition of solids in seawater. This formula shows clearly that seawater solids are highly dominated by the first six elements which constitute 99.96 mol percent of all the solids. The residual 0.04 percent is principally non-metal elements such as boron and bromine and soluble metallic elements like lithium and rubidium. As shown, the common metals are extremely sparse - at least a thousand-fold less prevelant than in rocks. Thus, terrestrial resources appear much more desirable for these elements unless very specific ion exchange, adsorption, or similar processes are developed for removal of single or groups of these elements from seawater. Even then, pumping costs would be enormous.

The formula for air deserves only one comment, namely that the concentration of helium (5 ppm by volume or 0.65 ppm by weight) is so

low compared to concentrations in natural gas that the recovery of helium from air will be 50 or more times the cost of recovery from much of the world's natural gas; unfortunately the latter will be gone in less than 50 years.

High Quality, "Infinite" Resources for Widely Used Elements - Table IV gives "preferred" resources for the most commonly used elements in essentially infinite supply and demonstrates that for these elements, at least, recourse to less desirable, silicate bearing igneous rocks or "dirt" will never be required. The maximum concentration in the preferred resource, the total supply, and a resource to demand (R/D) ratio are then given for each element. The R/D ratios are highly academic because of their large values, but do indicate that only the best and most accessible of these resources need be used for a very long time.

In determining the quantities in the resource column of Table IV, the topmost kilometer of the earth's crust, all of the seawater in the oceans and the entire atmosphere were assumed available for ultimate exploitation. This assumption seems acceptable because the rates of exploitation, are so low ($<10^{-6}$/year) and because in such a long time frame most of the exploited materials would return to the seas and the air.

The qualifications for the world resource column of Table IV are as follows:

The topmost kilometer of crust contains about 3.8×10^{17} tons of rock; of which 1.15×10^{17} tons are igneous (including 2×10^{16} tons of basalt and 3×10^{14} tons of ultramafic rock rich in Ni, Cr, etc.),

2.2×10^{17} tons of shale (we assume only 10 percent of this is high alumina shale), 3×10^{16} tons of sand and sandstone, 1.6×10^{15} tons of limestone and dolomite, and 1.5×10^{15} tons of evaporites. The mass of the oceans is 1.5×10^{18} tons which contains about 5×10^{16} tons of solids; the mass of the atmosphere is 6×10^{15} tons. These great resources were assumed completely available for recovering all of the elements in Table IV except reduced carbon, phosphorus, and manganese; for these we have used present estimates of reserves and hypothetical and speculative resources.

When all the fossil fuels are depleted, recourse to carbon dioxide in the air and seas and in limestone may be required, as explained in Appendix 3, as a source of carbon for petrochemicals but not for fuels; these resources of carbon are indeed infinite. Similarly, when CH_x is depleted we must acquire hydrogen for use as a metal ore reductant for petrochemical production and for ammonia synthesis from other sources; we assume this will be from electrolysis of water, which incidentally provides large amounts of byproduct oxygen. Further, as shown in Table III, resources of "unextractable" CH_x are about 200 times that of coal, oil, and gas. Certainly, the bulk of this resource will remain forever unexploited because more energy is needed to extract this CH_x than is increased. However, it may be used in principle as a raw material for petrochemicals, and further study is required to compare CH_x from this source with CH_x from CO_2 and H_2 produced by water electrolysis.

It should also be noted in Table IV that some elements are recoverable from dual infinite resources, i.e., salt and gypsum from both the lithosphere and the oceans.

APPENDIX 2

The Rest of the Elements

The Rest of the Elements - To complete our appraisal of the elements, we consider, briefly, the non-metals (including the commonest metal oxides), refractory metals, and the non-ferrous byproduct elements. With regard to the non-metals, 11 of the 12 most widely used elements (iron being the sole exception) in Demandite either are non-metals or are metals used in their oxidized state (C, Si, Ca, Na, N, S, O, Cl, H, K, and P); as already noted, only CH_X and P in this group have non-infinite resources. Together, these 11 non-metals or oxidized metals account for 94.6 percent of all non-renewable materials currently used by world society, and iron accounts for an additional 4.8 percent. The remaining 70 stable elements account for the remaining 0.6 percent of the materials used by man. The major non-metals, oxidized metals, and iron accounted for 86 percent of the value of all non-renewable resources in 1968 in the pre-oil-embargo era; today this value would be 92 percent because fossil fuel prices have tripled.

Of the remaining non-metals or metals used predominantly in oxidized form (Ba, F, Ar, B, Br, Sr, the Rare Earths, I, He, Li, Y, Sc, Rb, Ne, Kr, and Xe) at least 5 (Ar, Ne, Kr, Xe, and Br) have infinite resources. The entire group accounts for a scant 0.05 percent of all non-renewable resources used by man: of these, 84 percent are barium and fluorine; 15 percent argon, boron, and bromine; and 1 percent all the rest. It is hard to see how even very large price increases for any or all of these elements could affect the world's total resource bill appreciably.

The major refractory metallic elements used by society are titanium and zirconium; in addition over 95 percent of all magnesium is used as

the oxide, as is a small fraction of consumed aluminum. The quantity and value of this group of elements is about the same as for the minor non-metals. The resources of magnesium and aluminum are infinite and of titanium and zirconium large to very large; therefore, costs for this group should never increase more than several-fold. The major present use (>90 percent) of titanium is for titania pigment; this is largely a use based on aesthetics, and it is hard to conceive that society would collapse if such needs were not fulfilled.

The final group, the non-ferrous metal byproduct elements (As, Sb, Cd, Ge, Se, Te, Ga, In, Tl, and Bi) are obtained partly or wholly as byproducts of copper, zinc, and lead. As a group they constitute only 0.0015 percent of all the non-renewable materials used by society and less than 0.1 percent of the total value of all such materials; the first three account for 99 percent of these small percentages. However, a number of the rest of this group have a very important use - as semi-conductors in communications and computers. Since copper, lead, and zinc are all metals with limited resources which we have indicated will be largely replaced in the Age of Substitutability by iron, aluminum, and magnesium, it seems prudent to recover and store these byproduct elements.

APPENDIX 3

Energy Demand in the Age of Substitutability

Energy Demand in the Age of Substitutability - Total annual energy consumption in the U. S. in 1968 was 62 x 10^{12} kwh (versus about 72 x 10^{12} kwh in 1972. This consumption divides into 25 percent for transportation, 34 percent for home and commercial use and 41 percent for industry. Generation of electricity accounted for 22.5 percent of this total energy consumption. Use of energy by industry for 5 major industrial sectors is shown in Table A1. The first four sectors (metals, inorganic chemicals, cement-stone-clay-glass, fossil fuels, other manufacturing) are based on non-renewable resources; the last (other manufacturing) is based mainly on the output from the first four.

According to Eric Hurst,* the energy input per kilocalorie of food is now nearly 7 kilocalories. Thus to grow, harvest, process, and distribute the 2,500 kilocalories of food per day necessary to feed the average American requires about 17,500 kilocalories/day, or about 7,600 kwh/person/year (0.87 kw/person). This represents about 10 percent of the total U. S. consumption. To grow this food requires about 8,000 liters of water per person/day.

It is the primary purpose of this appendix to examine how energy use by industry and agriculture may change on the road to and in the final stage of the Age of Substitutability, based on our prior discussions of future resource availability and mix. As we will show, energy increases

*Eric Hurst, "Energy Use for Food in the United States", ORNL-NSF-EP-57, October 1973.

per ton of product in the (1) inorganic chemical and (2) cement, stone, clay and glass sectors will be small, and that for metals somewhat more but certainly less than a factor of two. Because changes in the petroleum refining and related industries sector is the most complex, we start with this group.

As we have noted in the text, the major resource problem in the future is the eventual depletion of natural supplies of reduced carbon and hydrogen (CH_x) as a source of energy, a reductant for metal ores and minerals and as a raw material for petrochemical products and ammonia for fertilizer. We envision two stages on the road to Stage III of the Age of Substitutability. The first, the present stage, we believe will be completed in 30 to 50 years when world petroleum and natural gas supplies are depleted; however, it may be extended for a time if oil from high-grade shale can be massively exploited. The second stage, when coal is the sole remaining fossil fuel, may last another hundred years. In this stage coke for making iron and steel will still be available, but petrochemicals, synthetic oil and gas, and hydrogen for ammonia synthesis must come from coal. Finally, in the true Age of Substitutability when <u>all</u> fossil fuels are used up, completely new energy systems - breeder reactors, fusion, solar - must be fully developed and widely deployed. The major metal ore reductant and source of hydrogen for ammonia will undoubtedly become hydrogen from water electrolysis. The source of carbon for petrochemicals, unless substitutes displace them - and some would be very hard to do without - must become carbon dioxide from the calcination of limestone or conceivably CH_3 from shale that is too dilute to mine as a source of energy.

With regard to future sources of high temperature energy for industry, two options are now envisioned: (1) use of very high temperature gas cooled reactors with thermodynamic efficiencies approaching that available with the combustion of fossil fuels, and (2) electricity or electrolytic hydrogen with considerably lower overall thermodynamic efficiencies (30 to 40 percent). The former would not materially increase the input heat energy requirements of industry; the latter might double present requirements.

Reduction of metal ore concentrates and production of reduced carbon and ammonia will both require very large quantities of hydrogen in the Age of Substitutability. We assume this hydrogen will come from water electrolysis because we do not believe that the overall energy budget for alternative chemical systems are much better than for electrolytic decomposition of water. The free energy change for water electrolysis is 32,700 kwh/ton of H_2 (or 1,840 kwh/ton of iron reduced from Fe_2O_3 with hydrogen). An advanced electrolysis cell* could, we believe, produce hydrogen using 48,500 kwhe/ton (121,000 kwht/ton at 40 percent thermodynamic efficiency for production of electricity). We consider use of hydrogen as a metal ore reductant later, when we discuss metals. Use as a reductant for carbon dioxide is considered below.

*J. E. Mrochek and H. G. Goeller, "Generalized Capital and Operating Cost for Power Intensive and Allied Industries", ORNL-4296, December 1969.

The basic step in producing petrochemicals from carbon dioxide is to produce methane by the following reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

This step is exothermic, releasing -39 kilocalories per mole of enthalpy per mole and -27 kilocalories per mole of free energy. However, beginning with the electrolysis of water, the overall reaction is:

$$2H_2O + CO_2 \rightarrow CH_4 + 2O_2$$

which is highly endothermic and requires +191 kilocalories per mole of free energy. Methane is then converted to ethylene ($\Delta F° = 18.35$ kilocalories) or acetylene ($\Delta F° = 37.62$ kilocalories), the more usual precursors of many plastics, solvents, etc. These reactions increase the overall change in free energies to 209 and 229 kilocalories per mole, respectively, but reduce the quantity of electrolytic hydrogen needed. As with metals production (Table VII), however, the total energy actually required in these processes is generally much greater than the free energy changes.

Although such processes need further study as regards their energetics, we estimate very approximately that petrochemicals from air, water, and energy would require 2 to 5 times* more raw energy than plastics from natural gas. The energy we now use for plastics in the U. S. amounts to 0.2 percent of the total: in the Age of Substitutability this might increase to 1 percent or about 0.1 kw/person.

*The factor 2 would apply to polyethylene; the factor of 5, to polyvinyl chloride because of the energy intensive chlorine manufacture step.

The metal industry has already been discussed in the text. There we noted (Table VI) that the energy for producing metals with abundant resources (Fe, Al, Mg, and Ti) would increase not more than 30 percent (63 percent for titanium) when utilization of lower grade infinite resources is required, but before all fossil fuels are used up. When fossil fuels are gone and hydrogen becomes the main metals ore reductant, in the Age of Substitutability energy for extracting metals will, we believe, still be less than twice the present values. We also indicated (Table VII) that the mining and beneficiation energy are only small parts of the total energy required. We also anticipate that as recycle of metals improves, the relative amount of new metal from ores will decrease, and therefore the energy demand, because recycled metal needs less energy per ton. Conversely, as use of the low energy, but scarce, non-ferrous metals - Cu, Zn, Pb, and Sn - is replaced by the energy intensive, but abundant substitute metals - Al, Mg, Ti, and Fe - the energy demand will increase. However, because Avalloy is so dominated by iron and steel, iron strongly buffers energy demand. For example, if all Cu were replaced by Al, the energy per ton of modified Avalloy would increase only about 10 percent. In any event, it is hard to see how Avalloy can, in the future, ever require more than twice the present energy per ton of metal.

Energy requirements for metals in Tables A1 and A2 are given for new metal production from ores and for total production, including recycle. It should be noted that the kwh/ton for Avalloy is about the same for both cases. The kwh/ton for new metal should be higher than

recycled metal; however, the value for total metal may include many finishing operations not included in estimates for new metal.

The inorganic chemicals, and the cement, stone, clay and glass groups are based on infinite resources for nearly all the major elements or materials of the groups. Thus, as long as fossil fuels last, it is difficult to see how the energy/ton for these materials can increase significantly. When fossil fuels are gone, however, energy requirements will increase, but not double, especially since much of the energy is already used as electricity which is now generated at about 30 percent efficienty. In our study we have guessed that the energy/ton in the Age of Substitutability might increase by 30 percent.

In the cement, stone, clay and glass group, nearly half the energy consumed is for producing portland cement from clay and limestone; the remainder is used for quarrying sand and gravel, crushed stone, and clay, and for manufacturing glass, bricks, and other clay products. A major increase in energy requirements will occur for increased transportation of these low unit cost commodities as source to market distances increase, but we have not estimated how much this increase might be.

The inorganic chemicals sector is dominated by the major non-metals and oxidized metals - the seven elements (N, O, Na, Cl, S, P, and K) on lines 3 in the formulae of Demandite (Table I) - all of which have infinite resources with the possible exception of phosphorus. They are used principally in fertilizers, industrial gases, and basic chemicals such as caustic soda, soda ash, and sulfuric acid.

The energy demand for agriculture will also be higher in the Age of Substitutability. The extreme case would be agriculture based exclusively on desalted water and on use of fertilizers - fixed nitrogen, phosphates and potash. If water must be won from the sea, since 6 kwh is the minimum work required to desalt 8,000 liters of water (which in turn is the average required to grow 2,500 kilocalories/person/day of food), then 6 kwh of work, or about 20 kwh of heat, is the thermodynamic minimum per day to desalt the water now required for agriculture. This number must be multiplied by about 20 because desalting can never be done reversibly; but it could be reduced twenty-fold because with advanced farming methods we might grow a man's food with only 400 liters/day. Thus we estimate that desalted water for agriculture might require 20 kwh/person/day or 0.8 kw/person (7,300 kwh/person/year), and that the total energy required to conduct agriculture in an era of water scarcity might therefore come to about 1.7 kw/person. This is almost surely an overestimate since it is most unlikely that the bulk of the world will depend on desalted water for agriculture. Adding this to the 1.7 kw/person for industrial products* we estimate that the total per capita energy in the Age of Substitutability required for recovering non-renewables and for agriculture based on artificial fertilizer and upon desalted water comes to about 3.5 kw/person.

*This becomes 1.4 kw/person when only new metal is considered.

The data on which these estimates are based are summarized in Table A2. Assumptions have included a world population of 10×10^9 persons (300×10^6 for the U. S.), world use of energy at a level 7.5 kw/person (versus 15 for the U. S.), a world agricultural energy demand equal to that in the U. S. at that time, but a world industrial per capita energy use of only one-half of the U. S. As we have shown in Table VIII, such an estimate indicates an increase, for industry and agriculture, of 1.5 kw/person in the U. S. and 2 kw/person worldwide.

TABLE A1: Present (1968) U. S. and World Energy Demands for Non-Renewable Resource Industries and for Agriculture

	Total Quantity 10^6 tons	Total Energy 10^9 kwh	kwh/ton	kwh/capita	kw/capita
United States					
Industry					
Metals, Primary	85.6	1,050	12,300	5,250	0.60
Metals, Total	132.0	1,595	12,080	7,975	0.91
Inorganic Chemicals	84.1	1,508	17,930	7,540	0.86
Cement, Stone, Clay, Glass	1,642	368	225	1,840	0.21
Fossil Fuels	1,500	837	560	4,185	0.48
Subtotal, new metal	3,312	3,763	1,136	18,815	2.14
Subtotal, total metal	3,358	4,308	1,280	21,540	2.46
Agriculture	--	1,520	--	7,600	0.87
Total, new metal	--	5,283	--	26,415	3.01
Total, total metal	--	5,828	--	29,140	3.33
Other Manufacturing	--	2,431	--	12,150	1.38
Total, total metal	--	8,260	--	41,300	4.71
Other Energy Use	--	11,040	--	55,200	6.3
Total, all energy	--	19,300	--	96,500	10 (11 in 1973
World					
Industry					
Metals, Primary	424	4,700	11,100	1,305	0.15
Metals, Total	636	6,360	10,000	2,120	0.24
Inorganic Chemicals	221	3,962	17,930	1,100	0.13
Cement, Stone, Clay, Glass	11,670	2,626	225	730	0.08
Fossil Fuels	4,760	2,380	500	661	0.07
Subtotal, new metal	17,075	13,668	800	3,797	0.43
Subtotal, total metal	17,287	16,600	690	4,611	0.53
Agriculture	21,600	--	--	6,000	0.68
Total, new metal	38,675	--	--	9,797	1.12
Total, total metal	38,887	--	--	10,600	1.21

TABLE A2: Possible U. S. and World Energy Demands for Non-Renewable Resources and for Agriculture in The Age of Substitutability

(Populations - U. S., 300 x 10^6; World, 10,000 x 10^6)

	Total Quantity 10^6 tons	Total Energy 10^9 kwh	kwh/ton	kwh/capita	kw/capita
United States					
Industry					
Metals, Primary	128.4	3,150	24,600	10,500	1.20
Inorganic Chemicals	126.2	2,940	23,300	9,800	1.12
Cement, Stone, Clay, Glass	2,463	717	291	2,390	0.27
Carbon and Hydrogen	150	630	4,200	2,100	0.24
Subtotal, Industry	2,867	7,437	2,594	24,790	2.83
Agriculture					
Without Desalted Water	--	2,280	--	7,600	0.90
With Desalted Water	--	4,470	--	14,900	1.70
Total, Without Desalted Water	--	9,717	--	32,390	3.73
Total, With Desalted Water	--	11,907	--	39,690	4.53
World					
Industry					
Metals, Primary	2,134	52,500	24,600	5,250	0.60
Inorganic Chemicals	2,103	49,000	23,300	4,900	0.56
Cement, Stone, Clay, Glass	41,100	11,950	291	1,195	0.14
Carbon and Hydrogen	2,500	10,500	4,200	1,050	0.12
Subtotal, Industry	47,837	123,950	2,594	12,395	1.42
Agriculture					
Without Desalted Water	--	76,000	--	7,600	0.90
With Desalted Water	--	149,000	--	14,900	1.70
Total, Without Desalted Water	--	200,000	--	20,000	2.32
Total, With Desalted Water	--	273,000	--	27,300	3.12

APPENDIX 4

Pollution in the Age of Substitutability

Pollution in the Age of Substitutability - The primary environmental insult in Stage II of the Age of Substitutability will come from the mining associated with use of carbon, and, to a much smaller extent, of iron and copper. In addition, very large quantities of sand and gravel, crushed and dimension stone, gypsum, pumice, and clay are consumed by society. The aggregate of these materials is 1.6 billion tons/year in the United States or 8 tons per capita. However, the large bulk of these materials are quarried or dredged from a myriad of "county" rock quarries and sand pits, used almost as removed from the ground mainly in construction, and thus have a minimum environmental impact other than leaving many holes. Probably the greatest environmental problem associated with the use of such materials is the local dust, smoke, and thermal pollution resulting form the manufacture of portland cement. Because of their minor environmental impact, we will not discuss this class of materials further.

In Stage III of the Age of Substitutability when all the reduced carbon has disappeared, the environmental insult caused by mining should be less than today as the following estimate shows.

Each person in the U. S. now uses, annually, about 3 tons of coal; he also uses about 0.4 tons of Avalloy, a ratio of nearly 8:1. The spoils from mining coal, on the average, dominate all others: about 8 tons of rock/ton of coal (50 percent strip, 50 percent deep mining) or about 25 tons/person/year. In 30 to 50 years, when oil and gas are gone we will be stripping even more extensively and spoils will increase

considerably to as much as 100 tons/person/year. However, when all of the strippable coal is depleted, we will undoubtedly return exclusively to underground coal mining and the rock spoils will be reduced to, say, 10 tons/person/year.

At present, per ton of Avalloy used, we mine 3 tons of rock: thus the rock associated with Avalloy mining is about 1.3 tons/person/year. Even when we go to infinite sources of iron - 10 percent ores instead of 30 percent ores - the rock associated with Avalloy (4 tons/person/year) is still only one-sixth the rock now associated with extraction of coal, and about 40 percent of the coal spoils when the strippable coal is gone.

When reduced carbon is gone, and we have to depend on fission, fusion, or solar, the rock moved per capita is less. The worst case would be energy from fission breeders, though fusion based on lithium might be comparable. Consider energy from fission breeders based, let us say, on rock bearing 10 ppm of uranium and thorium. Then our projected U. S. budget of 15 kw/person corresponds to burning 6 grams uranium and thorium/person/year; this corresponds, at 10 ppm, to mining 0.6 tons of rock/person/year, rather than the 25 tons/person/year we now devote to energy. Thus, a striking characteristic of Stage III of the Age of Substitutability, as far as environment is concerned, is that the amount of waste rock handled for fuel and metals is <u>reduced</u> from about 30 tons/person/year to about 5 tons/person/year.

As for the world, in the Age of Substitutability, let us again assume 7.5 kw/person/year; for Avalloy, 0.2 ton/person/year (one-half

the current U. S. figure). Then as long as strippable coal holds out, the mine spoil would be 12 tons/person/year from coal mining, and (at 10 percent ore) 2 tons rock/person/year from Avalloy. When mining for coal has ceased, the rock handled per capita to extract Avalloy, world wide, may be as little as 15 percent of the rock handled when carbon extraction was at its maximum. The total rock handled by the whole world, assuming a population of 10^{10}, comes to 2.5×10^{10} tons/year. This is about equal to the amount of rock now handled by the world's coal mining - about 2.5×10^{10} tons/year. It would seem that the total mining activity in the Age of Substitutability may be the same as now; however, in the interim it may reach a maximum and then decline as coal resources approach depletion.

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