Where Have All the Metals Gone?

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Preface

This book is an interpretation and a simplification for a general audience of recently published metals and minerals-fuels depletion research by Dr. Richard A. Arndt and myself.* While teaching a university course on energy, I became uneasy about the methods authors of books and journal articles on energy were using to estimate the future availability of mineral fuels (crude oil, natural gas, and coal). Some were extrapolating present production rates into the far distant future while others assumed that recent exponential growth in production rates would continue into the far distant future. Both methods are obviously wrong. Some authors have more realistically assumed that production-rate growth must eventually slow, stop, and then production rate will begin to decline as the mineral becomes harder to extract from the earth, i.e., as more energy and materials are required and more environmental degradation occurs in the extraction process.

But even in the realistic projections it was usually not obvious how the authors had arrived at their predictions. Some had used reserves estimates to delimit the amount of the mineral that would eventually be extracted. Since reserves estimates are notoriously variable depending on the methods of estimation, time of estimation, and the estimator; I was not satisfied with this approach either. It appeared to me that the best method is to fit the yearly production-rate data with mathematical functions of time that have the kind of behavior that realism requires, namely that the production rate must rapidly rise (probably exponentially), eventually peak, and then fall (but probably not so rapidly as the original rise) asymptotically until the mineral is effectively depleted. It was not clear to me then that anyone had actually fitted production-rate data by means of standard statistical least-square-fit procedures, although Hubbert had for crude oil and natural gas. Being of independent minds, my colleague, Dr. Richard A. Arndt, and I used his highly refined computer least-square-fit code to fit United States oil and gas production-rate data.

The results of the oil and gas fits whetted our appetites and thus led us to fit United States metals production-rates data and finally the world metals and mineral fuels production-rates data.

Having originally had very little knowledge about minerals depletion, we were greatly surprised to find that approximately three-fourths of the metals have apparently already peaked in production rate in the United States and one-fourth of the world metals have peaked. On the other hand, neither oil nor gas have peaked for either the United States or the world, although oil and gas will peak very soon for the United States.

Some minerals specialists have regularly warned, beginning at east twenty-five years ago, that the United States was rapidly approaching a minerals-depletion crisis. The United States public has finally been shocked into accepting this fact for oil and gas, thanks to some timely help from the Arabian oil producers. The fact that the United States is in a much more severe, in terms of production rates, metals “crisis” than it is in a mineral-fuels crisis has not yet registered with the average citizen. And there does not appear to be a sudden shocker on the horizon to apprise the American public of this fact because the world metals producers are not so strongly bound to concerted action by religion, conflict, or geography as are the world oil producers. So perhaps it would be more faithful to the English language to use the term “metals-depletion problem” instead of “metals crisis” at least until the general public recognizes the severity of the problem.

There is perhaps another reason, besides the one given above, why the metals-depletion problem has not registered in the public mind as much as the mineral-fuels depletion problem has. The crucial importance of energy to all motions and transformations of matter, including mining and processing of metals, and the lack of a wide variety of mineral fuels and other presently available energy substitutes make the early stages of mineral-fuels depletion much more traumatic than similar stages of metals depletion.

The current economic malaise in the United States, which must be strongly linked to decreasing production rates of metals in the United States, would not be easily connected in the public mind to the metals-depletion problem even if the public knew about the problem. I hope that this book will make some small contribution toward making the general public aware of the metals-depletion problem and that some public spirited economists or economic geologists will spend some effort at ferreting out, in terms the layman can understand, the connections between the metals depletion problem and the economic difficulties.

The author is grateful for the constant encouragement and help of Dr. Madan Gupta and for the help of Dr. Selim Sancactar in collecting the data.

* The mathematical details of the theory involved and the data used in carrying out this research are in *Depletion of United States and World Mineral Resources*. An abbreviated version of this research is available in paperback form, *The Metals and Mineral Fuels Crises, Facts and Predictions*. Both are published by University Publications, Blacksburg VA.

L. David Roper

Chapter 1. The Minerals Crisis

If this cycle continues long enough, basic resources will come into such short supply that rising costs will make their use in additional production unprofitable, industrial expansion will cease, and we shall have reached the limit of growth. If this limit is reached unexpectedly, irreparable injury will have been done to the social order. – S. H. Ordway, Jr., *Resources and the American Dream*, The Ronald Press Co., New York, 1953.

DEPLETION DEBATE

About two decades ago a quiet, but very important, controversy concerning the amount of crude oil available for extraction in the United States began among geologists.[1] A few, notably Hubbert[2], warned that the United States was dangerously near the inevitable peak in oil production while most held to the conventional minerals platitude that, if prices are allowed to continually rise, the amount available for extraction will continually rise.

Hubbert presented quantitative predictions for U. S. crude oil production that have proved to be quite accurate. Others besides Hubbert also sounded alarms concerning minerals depletion. For example, Steidle[3] wrote in 1952

> It appears unlikely, therefore, that domestic petroleum products will a major factor in the overall energy supply 50 years hence or even 25 years hence.

and

> In times of national emergency it would seem politically unwise to place much dependence on the importation of oil from Asia.

and

> Domestic resources of the principal alloying elements in steel production will have reached a state of serious near-depletion in another 50 years, with the exception of silicon and molybdenum.

In Chapter 4 are presented the recent crude oil and natural gas predictions of Arndt and Roper[4] which are very similar to, although slightly more optimistic than, Hubbert's original predictions. Hubbert warned us twenty years ago of the impending energy crisis, but we failed to listen.

Now a similar controversy is underway concerning depletion of metals and other nonfuel minerals. For example, Cook[5] states

> Depletion of geologic resources is real.

and

> There is no endlessly retreating interface between ore and almost-ore which some optimists have described.

and

> … without a substantial energy surplus that can be allocated to their exploitation, the nonenergy mineral resources do not exist, no matter how much mineral is in the ground.

On the other side, which seems to be populated mostly by economists rather than geologists, Page[6], for example, states

> There are no physical limits in resource extraction equivalent to 100 percent thermal efficiency in energy production.

and

> The relative cost of minerals has remained roughly constant, and has not increased over the past eighty years as a consequence of diminishing returns. And new economically exploitable reserves are being discovered all the time.

This book contains a condensed version of the recent predictions[7] concerning the depletion of metals and mineral fuels in the United States made by Arndt and Roper[4]. Only the reasonably certain U.S. predictions are included here. Also, the predictions labeled “pessimistic” in Arndt and Roper are redone into what might be called “optimistic” predictions.

Before presenting the Arndt and Roper metals and mineral-fuels depletion predictions in the next three chapters, a brief discussion of minerals depletion is in order. There are two underlying basic irrefutible facts:

1. The earth (or any portion of the earth) is a finite source of any mineral.
2. As an increasing amount of any mineral is extracted from the earth it becomes steadily more difficult to extract the remainder. By “more difficult” is meant that more materials and energy are required and more environmental degradation occurs.

In the elaboration of fact (2) above is where the controversy over minerals depletion lies. Some claim that technology will always come up with more energy and new techniques to mine less rich ores, including eventually the ocean and ordinary rocks. For example, Maddox[8] states

> The crust of the earth is much more lavishly supplied with minerals (than the oceans). Sheer physical exhaustion of the resources of spaceship earth is obviously an exceedingly remote possibility.

and

> …the contributions which science and technology have made in recent years to the improvement of natural resources have meant that nations no longer need to fear that their survival will be threatened by a lack of essential raw materials.

These people, whom Cook[5] calls “continuous creationists,” do not seem to realize that “new techniques” simply means more energy and materials and that the restrictions of the laws of thermodynamics apply.

A mining engineer's new idea for a more efficient way to mine an ore came about because much energy-matter investment was made in printing, in other informational exchange, and in the rearrangement of the energy-matter of his mind. If all of the energy utilized in these processes were obtained from mineral fuels, then there is a foreseeable limit to new ideas for new technology. Of course, we know that a small fraction of the energy came from the sun through photosyntheses processes in the crops that are primary and secondary (plant->animal->man) foods for man. However, in our modern technological society most of the energy now comes from mineral fuels. And, of course, bringing the engineer's idea to fruition will usually require an enormous amount of energy-matter investment.

When you pin the continuous creationists down with the argument given above, they counter that nuclear energy[9] will take over when mineral fuels bow out. There are tremendous problems associated with using nuclear fission reactors for power production, not the least of which is the public fear of the unknown. Even if these tremendous problems are “solved,” it is clear that there is not enough uranium-235 available in the earth to regard uranium fission energy as a long-term solution. So the hope is for breeder fission reactors and nuclear fusion reactors to supply the needed energy[9]. It is not clear that the many severe problems with breeder reactors can be satisfactorily managed; however, if they can be, this energy source will provide a huge amount of energy by utilizing the uranium-238, and perhaps thorium, available in the earth's crust. The long-range planners regard breeder reactors as the necessary link between mineral fuels and eventual-fusion reactors. Fusion reactors are far from operational; however, if and when they are “perfected,” they certainly will provide a tremendous amount of energy for use by man.

In order to be optimistic let us assume that breeder reactors and finally fusion reactors will come into operation at the appropriate times to allow the present exponential growth (~5 percent per year) in world energy use to continue. Figure 1 shows the world energy use rate versus time for this assumption. We see that about the year 2070 the world rate of energy use from earth resources would be one percent of the power (energy per time) supplied to the surface of the earth by the sun (26.5 Q/yr = 26.5×10^{18} BTU/yr).[10] It appears certain that this level of eventual heat production from earth energy sources will drastically effect the earth's weather[11]. Thus, we can view this as an upper limit for eventual energy production from earth sources, although other environmental considerations will surely halt addition to the "heat burden" long before the one-percent limit. (Some would propose that we escape this limit by learning to control the weather on a global scale[11]. The chance of this occurring within the next century seems to be very small.) We must either soon begin to reduce the rate of growth of energy use or quickly learn to use solar energy for individual and industrial consumption (Solar energy that hits the earth, of course, does not add to the heat burden.) That is, we must use a considerable amount of the remaining mineral fuels to develop systems for utilizing solar energy that hits the earth if we expect growth in energy use to continue for more than another century.

Figure 1

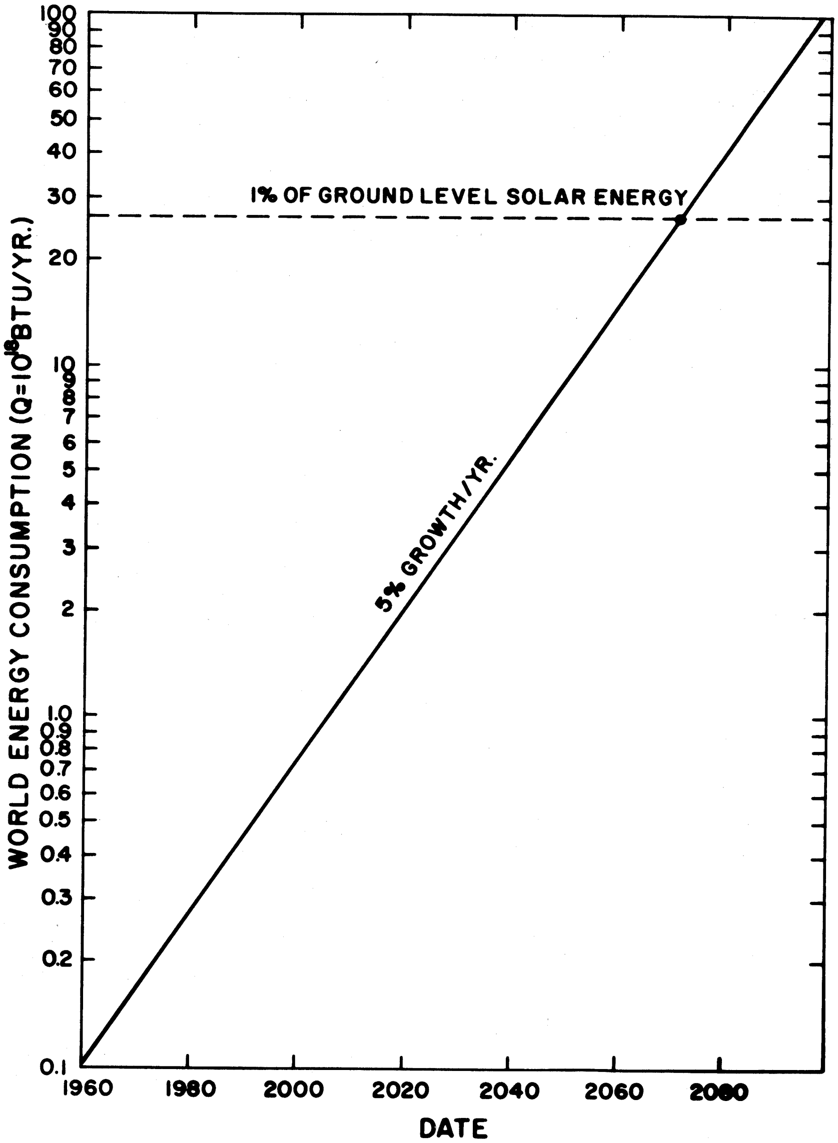


Figure 1. World energy use rate versus time for exponential growth.

But, of course, the growth cannot continue indefinitely; it can be shown by extrapolating Figure 1 that a continued exponential growth in energy use at the present growth rate would reach the amount of power supplied to the surface of the earth by the sun by about the year 2165. Of course, we cannot expect to utilize for industrial purposes more than a fraction of one percent of the sun's energy that reaches the earth's surface. So, long before 2165 a leveling off must occur. That is sufficiently far in the future that we probably should not worry too much about it; we have enough worries in converting from mineral fuels to solar energy!

So the continuous creationists are wrong. Energy considerations alone are enough to put severe limits on ore mining and processing. And there are other limits besides energy limits that restrict the mining and processing of mineral ores. Environmental degradation and the huge materials investment required will probably impose equal or more restrictive limitations on mining and ore processing compared to those imposed by limited energy.

There is no doubt that the current exponential growth of world production of many minerals must soon stop. Those interested in the world minerals-depletion situation should consult the recent book by Arndt and Roper[4].

MINERALS DEPLETION

Here we shall restrict our attention to the minerals-depletion situation of the United States. We shall see that apparently about three-fourths of the metals of the metals have already passed their production peak in the U.S. In order to be able to discuss the U.S. situation we need to consider the dynamics of depletion.

Common sense tells one the kind of long-term "average" production-rate behavior to expect for any mineral. Components of both technology and sociology play a role in that behavior.

1. In the *earliest stage* the mineral is relatively readily available, but the technology for its extraction and society's need for it are undeveloped. Therefore, the production rate will increase slowly at first. However, as the extracted mineral enters into the mainstream of the society its presence will generate more demand for it and thereby generate more advanced extraction technology. Thus, it is reasonable to assume that the production rate at earliest times will be some *increasing* function of the *amount already extracted* at that time.
2. At the *latest stage* when the mineral is almost completely depleted the principal limitation on the production rate will be the amount left to be extracted at that time. That is, the production rate at latest times will be some *decreasing* function of the *amount left to be extracted* at that time.
3. At *intermediate times* one, therefore, expects the following behavior: After rising slowly at earliest times, the production rate should begin to accelerate, and later decelerate until it peaks at some time. Then the rate will begin to decline in a similar, but not necessarily symmetrical, fashion.

Of course, in reality the long-term average behavior described above will not *precisely* describe the production-rate behavior for a particular mineral. There are short-term social phenomena, such as wars and depressions, that can and often do cause rather large fluctuations in the production rate. (A detailed study of the correlations of these mineral-production fluctuations with specific social phenomena would be interesting. We have not attempted this study in our work.) There are two situations that could exist:

1. The short-term fluctuations have little or no effect on the long-term background behavior.
2. The short-term fluctuations are evidence of changes in long-term social phenomena or of new mineral technology (e.g., substitution of another mineral for it in its major use).

Also, one would think that after a mineral has become an integral part of a society's modus operandi that the society will make a large effort to keep its production rate up after it begins to decline. This will cause the production-rate curve to be asymmetrically skewed toward large times; we shall see later that most nearly depleted United States minerals have such skewed production-rate curves. Arndt and Roper[4] fitted the U.S. and world metals and mineral-fuels production-rate data with several mathematical functions, some symmetric and some asymmetric about the production peak, that have the properties described above. Since the quality of the mathematical fits depends upon the quality of the data, we attempted to obtain the most reliable production-rate data. The details of the data and the fits are presented in our more technical work[4]. We shall focus here only on the results of the U.S. fits that yielded the most certain predictions. The fits predict the future production of the mineral. This prediction method is called the "production-history projections" method[5]. There are other depletion prediction methods, but according to Cook[5],

> The production-history method of forecasting depletion may be a better guide to national policy than are the geologic-economic methods, for it yields a direct and continuous forecast of supply rates. In addition, its errors will fall on the side of prudence rather than on the side of flatulent optimism.

There is, *a priori,* no way to tell how much asymmetry will occur in the production rates of those minerals which have not yet reached their production peak. Therefore, we do not expect the production-history projections method to give very precise predictions for those minerals which have not yet reached their production peak. This includes about one-fourth of the U.S. metals and about three-fourths of the world metals[4]. However, in the next chapter we shall see that most U.S. metals that are highly depleted show similar amounts of asymmetry. In Chapter 3 we shall use this amount of asymmetry to make what we shall call "optimistic" predictions and we shall use symmetric fits to make what we shall call "pessimistic" predictions for the moderately depleted U.S. metals. In Chapter 4 we shall do the same for U.S. mineral fuels.

It is convenient to condense the predictions for each mineral in terms of the following "depletion parameters":

1. The date when production peaks (t_p = peak date).
2. The date when the mineral is one-half extracted ($t_{1/2}$ = half date).
3. The percent already extracted by 1975.
4. The total amount to be eventually extracted (Q_∞).

The peak date is probably the most important parameter because *it is the traumatic event* that signals the end to exponential growth in production. For the reader who wants a quick answer for the depletion situations of the various U.S. metals and mineral fuels, Table 6 and Figure 25 in Chapter 5 give the depletion parameters defined above.

Although only production-rate data were used in making the predictions that follow, it is useful to compare the predictions with mineral-reserves and resources estimates at different dates. One should realize, however, that[5]

> It is not at all certain that ultimate recovery will extend to the limit of possible reserves.

Also, there are many methods for calculating reserves and resources that yield vastly different numbers. The most complete set of United States and world reserves estimates are given by Frasché[12] for 1960. However, with some effort one can collect a fairly complete, more recent, set of reserves and resources estimates from Brobst and Pratt[13]. Both sets are given in Table 1. We indicate these Table 1 values by the symbol • for reserves and by the symbol ⊗ for identified resources in the "amount left" graphs in the next three chapters. (See Table 1 for the definitions of these terms.)

Also, in the discussions of individual minerals in the next three chapters, we shall refer to the percentages imported and recycled for U.S. consumption (the production shortfall). (By "recycle" we also include materials taken from stockpiles.) These values are extracted or estimated from data given in Brobst and Pratt[13]. A table and graph of these values are given in Chapter 5 (Table 7 and Figure 26).

TABLE 1
United States reserves and identified resources.

R. = **reserves,** I.R. = **identified resources.***

Mineral	Frasché (1960) (reserves)	Brobst and Pratt	Type and date	
Antimony	50×10^3 S.T.	100×10^9 S.T.	I.R.	1972
Arsenic	2.5×10^6 S.T. (As_2O_3)	1.3×10^6 S.T. (As_2O_3)	I.R.	1972
Asbestos	1×10^6 S.T.	3.7×10^6 S.T.	I.R.	1972
Bauxite	50×10^6 L.T.	36×10^6 L.T.	R.	1972
Barite	100×10^6 S.T.	99×10^6 S.T.	I.R.	1972
Beryllium	10×10^3 S.T. (Beryl)	60.3×10^3 S.T. (Beryl)	I.R.	1972
Bismuth	15×10^3 S.T.	13.2×10^3 S.T.	R.	1970
Cadmium	100×10^6 1b.	650×10^6 1b.	I.R.	1972
Chromite	500×10^3 S.T.	0	R.	1972
Coal	—	1.58×10^{12} S.T.	I.R.	1971
Cobalt	50×10^3 S.T.	842×10^3 S.T.	I.R.	1972
Copper	32.5×10^6 S.T.	76×10^6 S.T.	I.R.	1972
Fluorine	15×10^6 S.T. (Fluorspar)	25×10^6 S.T. (Fluorspar)	I.R.	1972
Gold	50×10^6 T.O.	82×10^6 T.O.	R.	1972
Iron Ore	5.5×10^9 L.T.	9.0×10^9 L.T.	R.	1970
Lead	7.7×10^6 S.T.	39.2×10^6 S.T.	R.	1968
Manganese	1×10^6 S.T. (ore >35% Mn)	0 (ore >35% Mn)	R.	1972
Mercury	300×10^3 76 lb. flasks	490×10^3 76 lb. flasks	I.R.	1972
Molybdenum	3.0×10^9 lb.	35.1×10^9 lb.	I.R.	1972

Nickel	400×10^3 S.T.	—	—	—
Niobium-Tantalum Oxide	50×10^3 S.T. (Nb only)	$110X10^3$ S.T.	I.R.	1972
Phosphate Rock	15×10^9 S.T.	12×10^9 S.T.	I.R.	1972
Platinum Group	150×10^3 T.O. (Pt only)	3×10^6 T.O.	I.R.	1970
Selenium	—	4.8×10^9 1b.	I.R.	1972
Silver	750×10^6 T.O.	1.44×10^9 T.O.	R.	1968
Sulfur	125×10^6 L.T.	200×10^6 L.T.	I.R.	1972
Tellurium	—	63.9×10^6 1b.	I.R.	1972
Thallium	—	266 S.T.	R.	1972
Thorium Oxide	—	153×10^3 S.T.	I.R.	1972
Tin	5×10^3 L.T.	41,535 L.T.	R.	1972
Titanium, Ilmenite	64×10^6 S.T.	100×10^6 S.T.	R.	1970
Titanium, Rutile	combined with Ilmenite	500×10^3 S.T.	R.	1970
Tungsten	147×10^3 S.T. 60% WO_3	250×10^3 S.T. 60% WO_3	R.	1972
Uranium Oxide	—	273×10^3 S.T.	I.R.	1971
Vanadium	680×10^3 S.T.	115×10^3 S.T.	R.	1970
Zinc	25×10^6 S.T.	45×10^6 S.T.	I.R.	1972
Zirconium	12×10^6 S.T.	10.8×10^6 S.T.	I.R.	1972

**Reserves:* Identified deposits from which minerals can be extracted profitably with existing technology and under present economic conditions.

Identified resrouces: Specific, identified mineral deposits that may or may not be evaluated as to extent and grade, and whose contained minerals may or may not be profitably recoverable with existing technology and economic conditions.

Chapter 2. Highly Depleted United States Metals

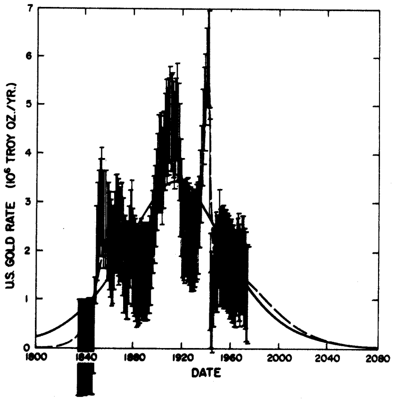
Domestic resources *of* the principal alloying elements in steel production will have reached a state *of* serious near-depletion in another 50 years, with the exception of silicon and molybdenum. —E. Steidl, *Mineral Forecast 2000 A.D.,* Pennsylvania State College, State College, Pa., 1952.

There are about one dozen metals that are depleted enough in the United States to show whether there is any asymmetry in their production rates. That is, each has gone far enough past its production peak such that one can test to see if the best fit to the data is by means of a peaked mathematical function that is skewed toward large times rather than by a symmetric peaked function. We shall discuss each metal separately and then make some general comments about all of them. Note that some of the comments in the caption of the first graph (gold) apply to many of the remaining graphs in this book.

GOLD

The only highly depleted metal that is symmetrical is gold, as shown in Figure 2. The short-term fluctuations are quite large, so our prediction for future gold production is not touted as an accurate year-by-year prediction, but rather as a prediction of “average” or “background” production. The 1960 and 1972 reserves estimates are indicated by • and are in fairly good agreement with our curve. *There is little room for doubt that gold is very near total depletion in the United States.* The U.S. now imports or obtains from private holdings about 75 percent of the gold it consumes. Gold can, with difficulty, be replaced by other metals in most of its uses. However, it does hold a unique place in men's minds as a monetary standard.

Peak date — Half date — 1916, 90% gone in 1975.



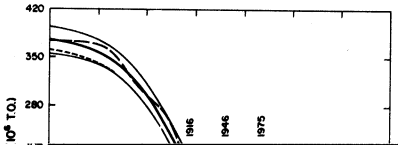
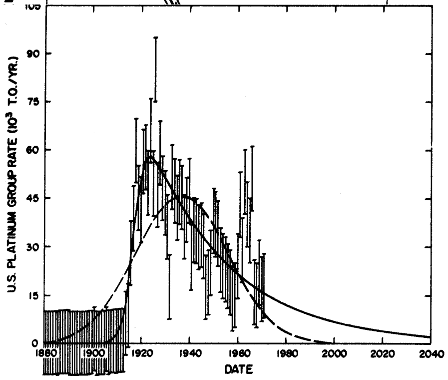


Figure 2. Gold production data, fits and predictions. In this and the next two chapters the graphs of production rates have produetion-rate data points with error bars. The error bars are technical devices used to make the fits, as explained in Arndt and Roper[4]. The reader can regard them as a measure of the average deviations of the data points from the smooth curve that is fitted to the data points. Also, in the graphs ot “amount left”, a curve is often flanked by lighter error curves calculated using the data error bars. Also, in the graphs a solid curve is usually our preferred fit and a dashed or dotted curve is an alternate fit. Here, for gold, the solid curve is the symmetric fit, the dashed curve is a fit using a sum of four peaked functions, and the dotted curve is an attempt at an asymmetric fit.

PLATINUM GROUP



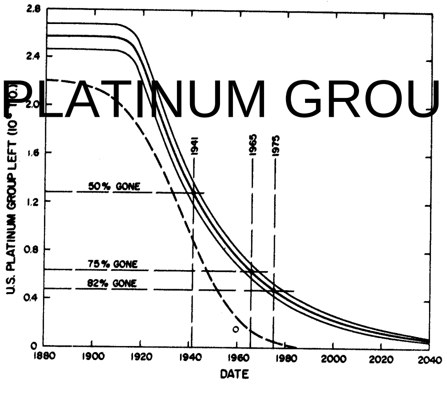
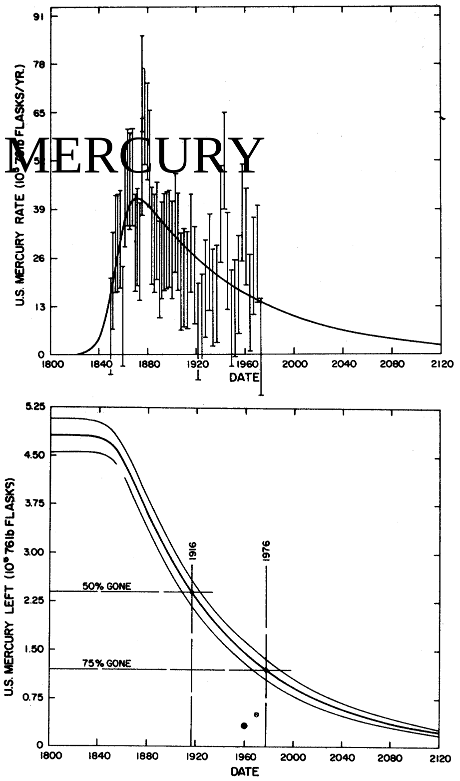


Figure 3 shows the depletion situation for the platinum group (platinum, palladium, iridium, osmium, rhodium, and ruthenium). Platinum group shares with mercury the largest asymmetry of all the U. S. metals. As seen in the figure there are large fluctuations in the production rate. The 1960 *platinum-only* reserves estimate is indicated by o, but the 1970 identified resources (see Table 1) estimate of 3×10^6 troy ounces is too large to be put on the graph. Despite this disagreement between our prediction and the recent identified-resources estimate, *there is little room for doubt that the platinum group of metals is very near total depletion in the United States.* The U. S. now imports about 78 percent and recycles 20 percent of the platinum-group metals that it consumes. These metals are essential in the chemical and electrical industries.

Peak date—1923, Half date—1941, 82% gone in 1975.

Figure 3. Platinum group production data, fits and predictions. The solid curve is the asymmetric fit and the dashed curve is the symmetric fit.

MERCURY

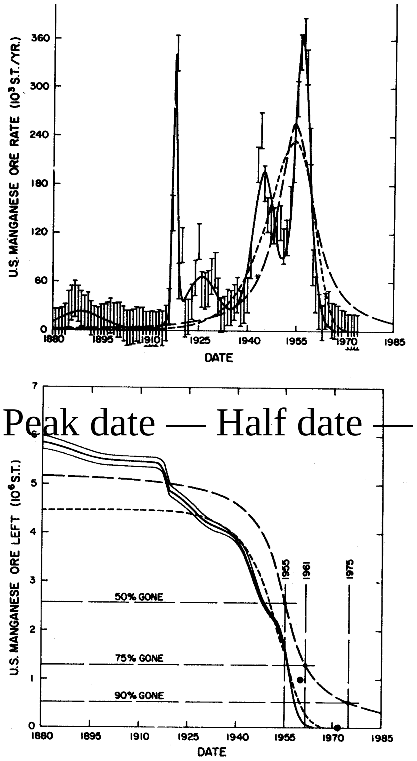


The mercury depletion situation is shown in Figure 4. Despite the many fluctuations in mercury production, there is obviously an average decreasing production rate. Mercury shares with platinum group the largest asymmetry of all the U. S. metals. The 1960 reserves estimate (●) and the 1972 identified-resources estimate (⊗) are both considerably less than our "amount left" values. *There is little room for doubt that mercury is already highly depleted in the U.S.* The U.S. now imports about 47 percent and recycles 17 percent of the mercury it consumes. This liquid metal is essential in the chemical and electrical industries.

Peak date—1870, Half date—1916, 75% gone in 1975.

Figure 4. Mercury production data, fit and prediction. Not every point is plotted because they are too close together.

MANGANESE ORE

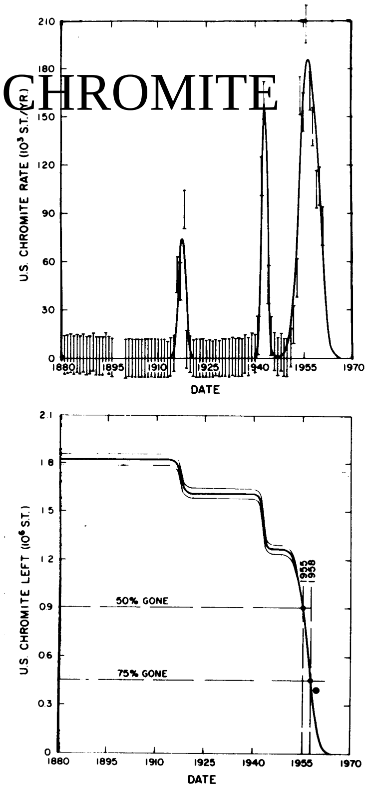


U. S. manganese ore is highly depleted, as shown in Figure 5. The huge fluctuations in manganese-ore production indicate that there may be sporadic production peaks in the future, although in recent years the production rate has been essentially zero. The 1960 and 1972 reserves estimates (•) lie between the two curves. *The U. S. now imports 100 percent of the manganese it consumes.* There is no substitute for manganese in the manufacturing of steel.

Peak date — Half date — 1955, 90% gone in 1975.

Figure 5. Manganese ore production data, fits and predictions. The solid curve is a 5-peak fit to the sporadic peaks, the dashed curve is a symmetric fit, and the dotted curve is an asymmetric fit. The latter is a better fit than the symmetric fit, but we use the symmetric fit for our prediction since it is more optimistic.

CHROMITE



U.S. chromite is highly depleted, as shown in Figure 6. The sporadic production peaks indicate that future production peaks may occur. The 1960 reserves estimate (•) is about twice as large as our “amount left” value whereas the 1972 zero reserves estimate agrees with our value. *The U. S. now imports 100 percent of the chromium it consumes.* No adequate substitutes are available for many of the uses of chromium.

Peak date—Half date—1955, 100% gone in 1975

Figure 6. Chromite production data, fit and prediction for a 3-peak fit.

SILVER

As shown in Figure 7, *silver is well* over *half depleted in the U. S.* The amount of asymmetry is about the same as for cadmium, lead, and zinc, but much less than for mercury and platinum group. The 1960 and 1968 reserves estimates (●) are less than our “amount left” values for those dates. Approximately 70 percent of the silver consumed in the U.S. is now imported (25 percent) or obtained from private holdings (45 percent). Silver is an indispensible industrial metal.

Peak date—1908, Half date—1938, 70% gone in 1975.

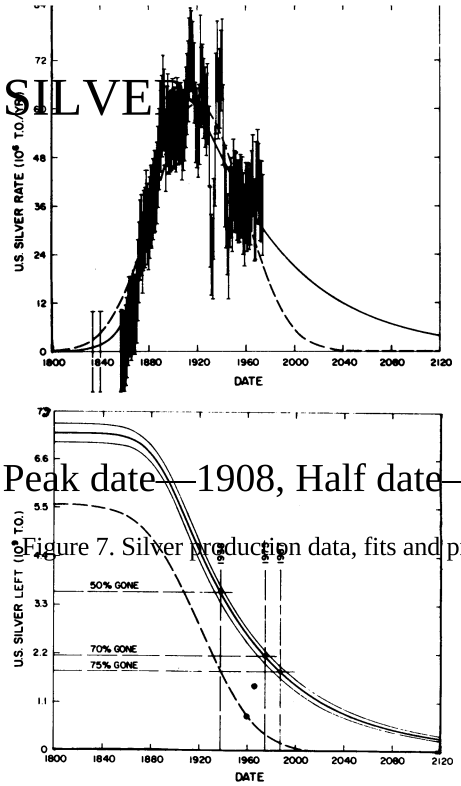


Figure 7. Silver production data, fits and predictions.

LEAD

The U.S. lead situation is shown in Figure 8. The amount of asymmetry is about the same as for silver, cadmium, and zinc, but much less than for mercury and platinum group. Our "amount left" value is considerably higher than the 1960 reserves estimate (•) but somewhat lower than the 1968 reserves estimate (•). About 43 percent of the lead consumed in the U. S. is now recycled lead and about 20 percent is imported. Lead is the fifth ranking metal of trade and consumption after iron, aluminum, copper, and zinc.

Peak date—1925, Half date—1958, 60% gone in 1975.

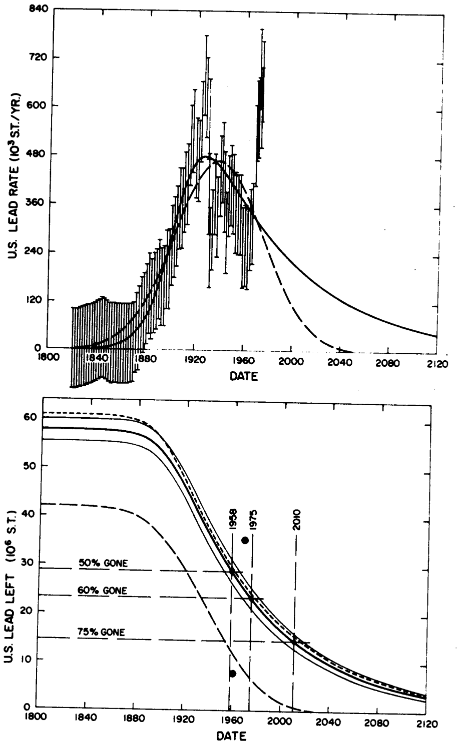
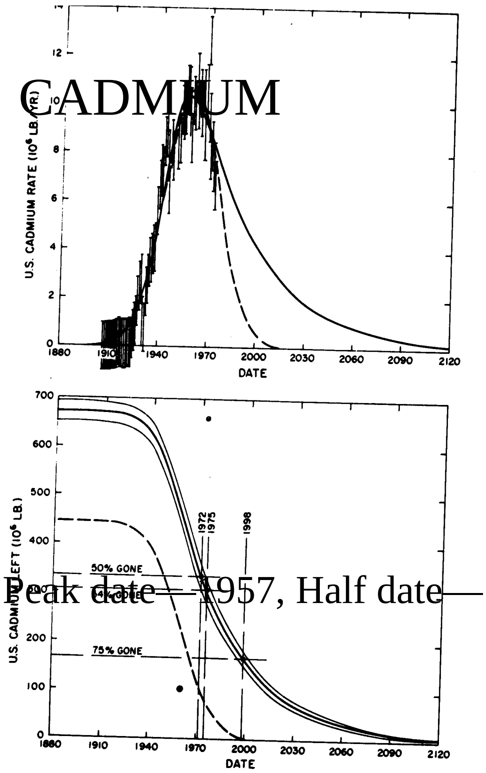


Figure 8. Lead production data, fits and predictions. Not every data point is plotted because they are too close together. The best fit is asymmetric (solid curve). We also show the asymmetric fit to a slightly different set of data (dotted curve). The differences between these two conflicting sets of data are not significant for our purposes. For comparison we show a less probable symmetric fit (dashed curve). We expect that the recent large rise in production rate due to the large discoveries in the Missouri-Kansas area will be followed soon by a drop as that area is depleted. Our curve will probably get shifted toward larger asymmetry as the next few years go by.

CADMIUM

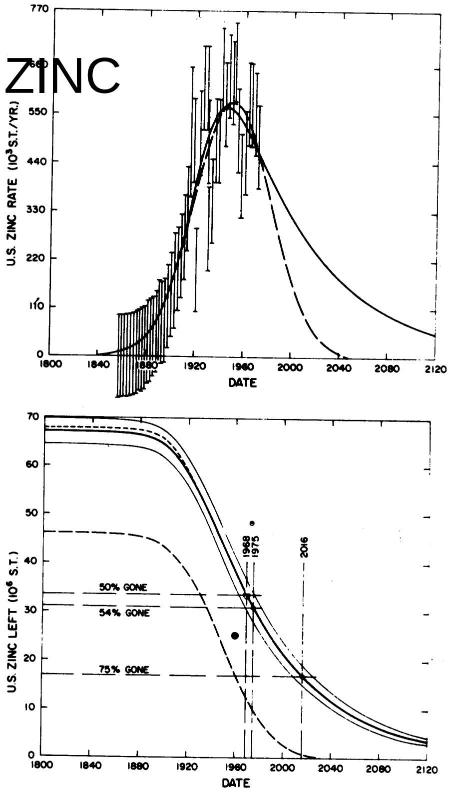


It appears, as shown in Figure 9, that cadmium is slightly over half depleted. It seems unlikely that the production peak is a short-term effect, although this possibility is not ruled out. The amount of asymmetry is about the same as for silver, lead, and zinc, but much less than for mercury and platinum group. The 1960 reserves estimate (•) is considerably below our "amount left" value and the 1972 identified-resources estimate (⊗) is considerably above our "amount left" value. *About 64 percent of the cadmium consumed in the U. S. is imported.* Its main use is as a corrosion-resistant coating for steel, in direct competition with more abundant zinc.

Peak date—1957, Half date—1972, 54% gone in 1976.

Figure 9. Cadium production data, fits and predictions. The asymmetric fit (solid curve) is not quite as good a fit as is the symmetric fit (dashed curve); however we choose the asymmetric fit for our predictions because it is more optimistic.

ZINC



As shown in Figure 10, zinc appears to be slightly over half depleted. It seems unlikely that the production peak is a short-term effect, although this possibility is not completely ruled out. The amount of asymmetry is about the same as for silver, cadmium, and zinc, but much less than for mercury and platinum group. Our "amount left" values are in reasonable agreement with the 1960 reserves estimate (•) and the 1972 identified-resources estimate (⊗). *About 50 percent of the zinc consumed in the U. S. is imported.* There is no satisfactory substitute for the large amounts of zinc used as a corrosion-resistant coating for iron and steel.

Peak date—1943, Half date—1968, 54% gone in 1975.

Figure 10. Zinc production data, fits and predictions. Not every data point is plotted because they are too close together. The best fit is asymmetric (solid curve). We also show the asymmetric fit to a slightly different set of data (dotted curve). The differences between the two conflicting sets of data are insignificant for our purposes. For comparison we show a less probable symmetric fit (dashed curve).

In Arndt and Roper[4] tin, beryl, and niobium-tantalum are also shown to be highly depleted. We do not discuss them here for the following reasons:

Tin: We could find no production-rate data after 1967 for tin; it was then headed upward on one of its many sporadic production peaks. *The U.S. now imports about 80 percent and recycles 20 percent of the tin it consumes*. Although substitutes are available for tinplate, tin alloys are "indispensable" in many modern applications.

Beryl: We could find no production-rate data for 1964-67 and after 1969 for beryl (a beryllium, aluminum and silicon oxide). The recent data that are available show a rapidly falling production rate. However, according to Brobst and Pratt[l3], a new type of ore is beginning to be mined in the U.S., so that now only 45 *percent of beryl consumed in the U.S. is imported,* whereas recently almost all of it was imported. Beryllium finds its greatest use in the aircraft and nuclear energy industries.

Niobium-tantalum: We could find no production-rate data after 1959 for niobium-tantalum. According to Brobst and Pratt[13] *present production in the U.S. is essentially zero; therefore all current consumption is imported.* Niobium is widely used to produce special steels.

We would urge those readers who know where one can obtain the missing data for tin, beryl, niobium-tantalum, and other U.S. minerals that are not published in the standard data references to inform the author.

Table 2 contains the depletion parameters (defined in Chapter 1) for the metals that are highly depleted in the U.S. and for which we found sufficient data to make predictions.

All of these metals except gold have asymmetric production peaks. In making the asymmetric fits there is a single parameter n that defines the asymmetry in the mathematical equation[4]. The second column of Table 2 gives the value of n for each metal. (No values are given for manganese ore and chromite because they consist of numerous sporadic production peaks with no smooth background.)

TABLE 2

Depletion parameters for highly depleted United States metals.

Metal	n=asymmetry parameter	t_p=peak date	$t_{1/2}$=half date	% gone in 1975	Q_∞=amount available
Gold	1	1916	1916	90	381×10^6 troy oz.
Platinum Group	14.9+6.4	1923	1941	82	2.57×10^6 troy oz.
Mercury	14+12	1870	1916	75	4.82×10^6 76 lb. flasks
Manganese Ore	—	1955	1955	90	5.35×10^6 short tons
Chromite	—	1955	1955	100	1.82×10^6 short tons
Silver	6.1+1.9	1908	1938	70	7.2×10^9 troy oz.
Lead	6.4+3.1	1925	1958	60	57.8×10^6 short tons
Cadmium	5.0+2.2	1957	1972	54	672×10^6 lb. ~0
Zinc	4.7+2.6	1943	1968	54	67.1×10^6 short tons

Symmetry of Production Peaks:

There appear to be three classes of asymmetry as shown in Table 3. Perhaps the large asymmetry for platinum group and mercury is connected with the fact that they both peaked so early in the development of the country. The four moderately asymmetric metals yield an average n value of 5.6 with a 0.8 standard deviation. It seems reasonable to assume that this moderate asymmetry should be more prevalent than either no asymmetry or high asymmetry. Therefore, in the next two chapters, which deal with metals and mineral fuels that are so near their production peak that one cannot yet discern the amount of asymmetry, we shall develop predictions for both symmetric production peaks and moderately asymmetric (n=5) production peaks. These predictions will be labeled “pessimistic” and “optimistic” as shown in Table 3.

TABLE 3
Asymmetry Classes

Asymmetry Parameter (n)	Name	Prediction Label
≈1	asymmetric	pessimistic
≈5	moderately asymmetric	optimistic
≈16	highly asymmetric	—

Summary:

In this chapter we have seen that many metals that are very important to the United States industrial economy are highly depleted in the U.S. There is no doubt that this fact is currently having, and will have even more in the future, drastic effects on the United States economy and political stance. It is no spiritual conversion that has recently caused staunch big-business-oriented conservative politicians in the U.S. to embrace world political leaders of opposite ideologies. They know that *the United States cannot remain a leading industrial state, let alone a growing industrial state, without enormous imports of these metals from many other nations of the world*

Chapter 3. Moderately Depleted United States Metals

The end of expansion, if unexpected and involuntary, would mean the reversal of a major facet of our faith; it would mean mass discouragement and unemployment; it would mean revolution and dictatorship. — S. H. Ordway, Jr., *Resources and the American Dream,* The Ronald Press Co., New York, 1953.

We saw in the last chapter that about a dozen metals are highly depleted in the United States; that is, they are over seventy percent depleted or are far enough past their production peaks such that the amount of asymmetry of the peak can be determined. Of the seven metals for which the asymmetry could be ascertained, four had similar moderate asymmetries.

Now we want to discuss the remaining metals which have either not yet peaked or are too near their peak for detecting any asymmetry. Three (copper, magnesium, and molybdenum) appear to be far from peaking; we refer the reader to Arndt and Roper[4] for somewhat uncertain predictions for them. For antimony we were not able to obtain a good set of data[4], so we do not include it here. The remaining nine for which we found data appear to be very near peaking. In Arndt and Roper[4] the future production of all of these is predicted by means of symmetric production peaks. We call such predictions “pessimistic” predictions.

It appears reasonable to assume that most of these nine metals will eventually show an asymmetry in their production peaks similar to the production peaks of the highly-depleted metals considered in the last chapter. There we found that four out of seven had moderate asymmetries while two had high asymmetries and one (gold) was symmetric (see Table 3). So, we shall assume that a more realistic prediction can be obtained for the nine moderately-depleted metals considered in this chapter by fixing their asymmetries at n=5. We call these predictions “optimistic” predictions.

We shall see that some of the depletion parameters defined in Chapter 1 can be quite different for the two different predictions. However, the most important depletion parameter, the peak date, varies the least of any of the parameters. It varies from one year to fifteen years between the two predictions for the nine metals.

We shall discuss each metal separately and then make some general comments about all of them.

TUNGSTEN ORE

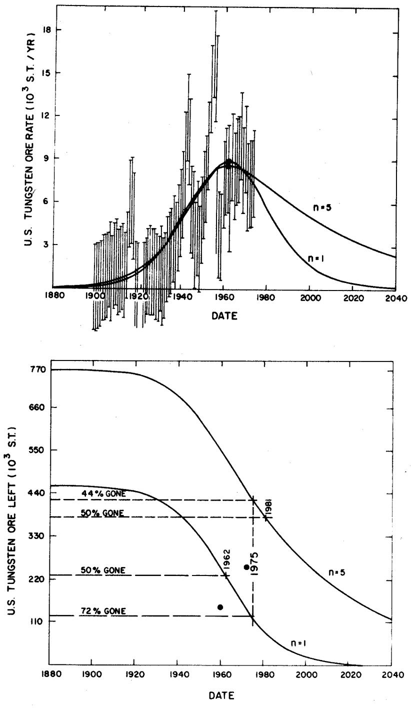


Figure 11 shows the tungsten ore (60%WO_3) pessimistic and optimistic (n=5) predictions. The two peak dates differ by only one year. It appears unlikely that the fall in production since the mid-1950's is a short-term effect. However, large fluctuations at future times of national emergencies seem probable. The 1960 reserves estimate (•) is less than both of our "amount left" values while the 1972 reserves estimate (•) lies between the two curves. *The U.S. imports about 25 percent of the tungsten it consumes.* Some adequate substitutes are available for some of the uses of tungsten.

Peak date—1961-1962

Figure 11. Tungsten ore production data, fits and predictions for symmetric and asymmetric (n=5) fits.

SELENIUM

Figure 12 shows our dubious predictions for selenium. We consider them as dubious because the data are so meager and the fluctuations are so large. The two peak dates differ by only two years. The 1972 identified-resources estimate (4.8 × 10^9 lb.) is about two hundred times our "amount left" value. *The U.S. imports 37 percent of the selenium it consumes.* Its greatest use now is in decolorizing glass, but it may soon be an important component of fertilizer.

Peak date—1962-1964

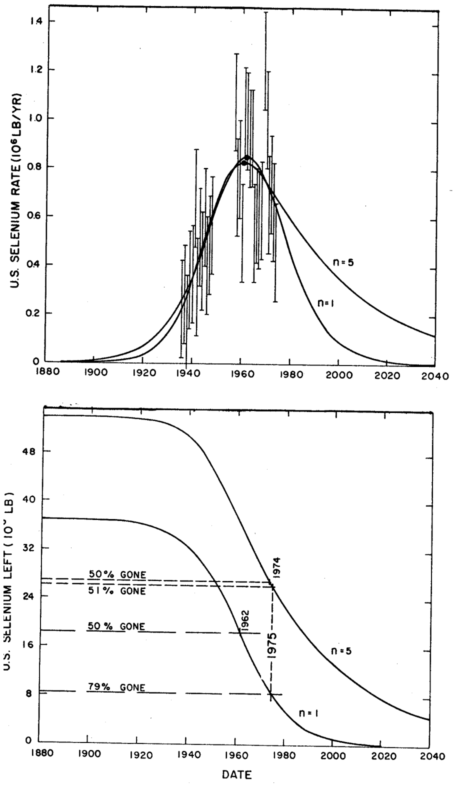


Figure 12. Selenium production data, fits and predictions for symmetric and asymmetric (n=5) fits.

TELLURIUM

Our predictions for tellurium are in Figure 13. The data are meager, but it appears that tellurium has already peaked. The two peak dates differ by only one year. The 1972 identified-resources estimate (63.9 × 10^6 lb) is about ten times our “amount left” value. *The U. S. imports 32 percent of the tellurium it consumes.* The main use of tellurium is to increase the machinability of metals. Selenium and lead can be substituted for tellurium in many of its uses.

Peak date—1964-1965

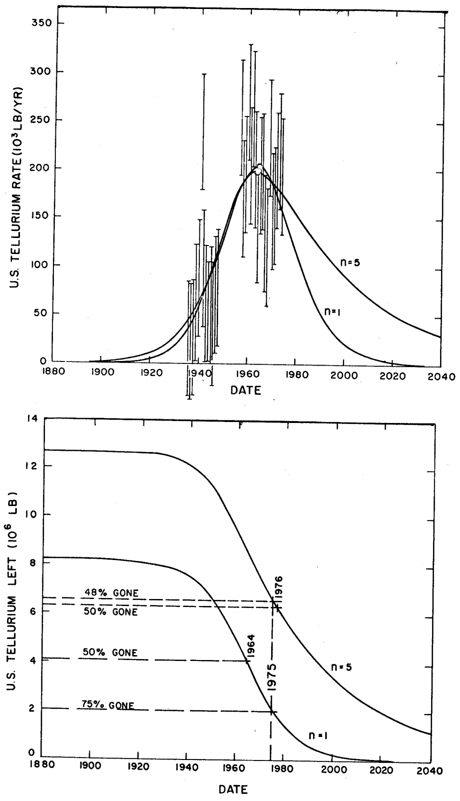
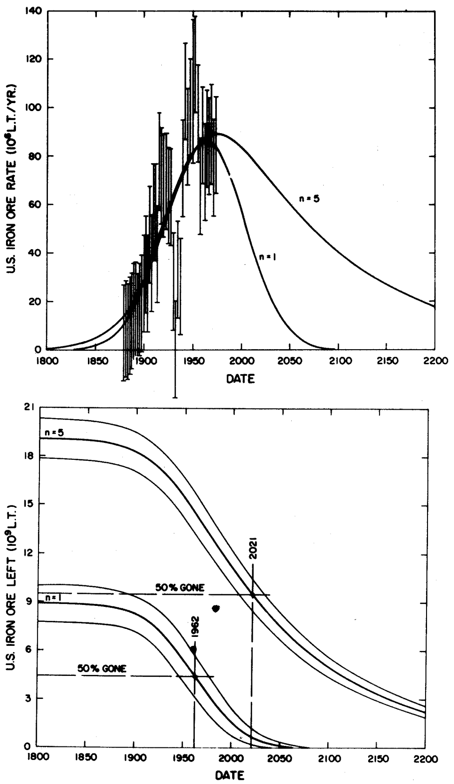


Figure 13. Tellurium production data, fits and predictions for symmetric and asymmetric (n=5) fits.



IRON ORE

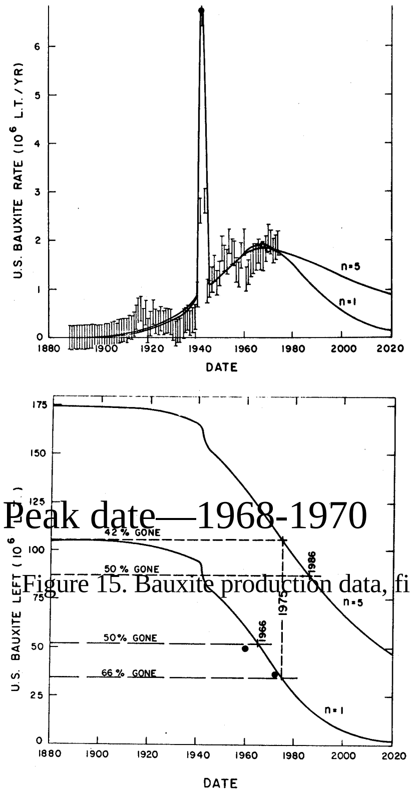
The predictions for iron ore are shown in Figure 14. The two peak dates differ by twelve years. The recent peaking could be a large fluctuation like that which occurred in the 1920's. However, the 1960 and 1970 reserves estimates (•) lie between the "amount left" curves for our two predictions. *The U. S. imports about 33 percent and recycles about 30 percent of the iron ore it consumes.*

Peak date—1962-1974

Figure 14. Iron ore production data, fits and predictions for symmetric and asymmetric (n=5) fits. Not every data point is plotted because they are too close together.

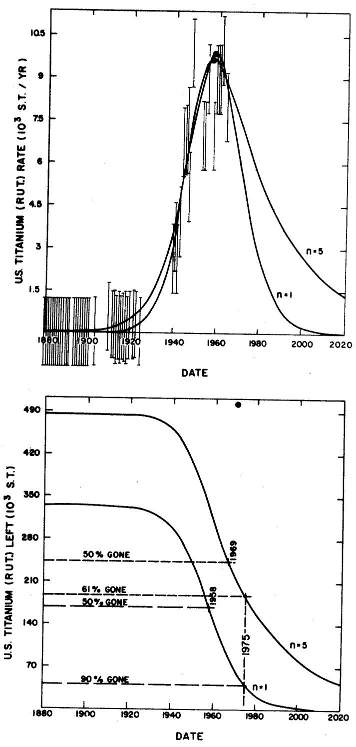
BAUXITE

From our fits in Figure 15 it appears that bauxite (a mixture of aluminous minerals, mainly aluminum hydroxides) production has recently peaked. However, the huge increase (factor of seven) in bauxite production during World War II indicates that there may be special occasions in the future when urgent demand will cause large transient production peaks. The two peak dates differ by only two years. The 1960 and 1972 reserves estimates (3) are less than both “amount left” curves. *The U.S. imports 88 percent of the bauxite it consumes.* There are some inadequate substitutes for some uses of aluminum.



Peak date—1968-1970

Figure 15. Bauxite production data, fits and predictions for symmetric and asymmetric (n=5) fits.



TITANIUM, RUTILE

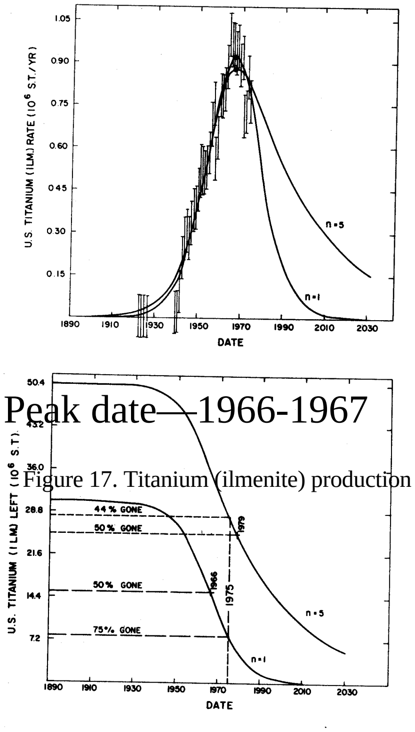
In Figure 16, it appears that rutile (TiO_2) has already peaked; however, we could be observing short-term fluctuations. The 1970 reserves estimate (•) is about twice our optimistic "amount left" value. *The U. S. now imports 100 percent of the rutile that it consumes.* Rutile has unique uses as pigment and welding-rod coatings. Titanium has unique corrosion and strength characteristics that make it highly desirable for oceanographic and aerospace usages.

Peak date—1958-1959

Figure 16. Titanium (rutile) production data, fits and predictions for symmetric and asymmetric (n=5) fits.

TITANIUM, ILMENITE

In Figure 17 it appears that ilmenite ($FeTiO_2$) has already peaked. It seems unlikely that the drop in production since the mid-1960's could be a short-term fluctuation. However, the 1970 reserves estimate (100×10^6 S.T.) is about 3.5 times our optimistic “amount left” value. *The U. S. imports about 25 percent of the ilmenite that it consumes.*



Peak date—1966-1967

Figure 17. Titanium (ilmenite) production data, fits and predictions for symmetric and asymmetric (n=5) fits.

VANADIUM

Figure 18 shows our predictions for vanadium. The two peak datesdiffer by four years. The 1960 reserves estimate (680 $\times 10^3$ S.T.) is about twice our optimistic “amount left” value; however, the 1970 reserves estimate (•) is about one-half our optimistic “amount left” value. U.S. production of vanadium about equals consumption. Vanadium is extensively used in steel, in the aerospace industry, and in the chemical industry.

Peak date—1968-1972

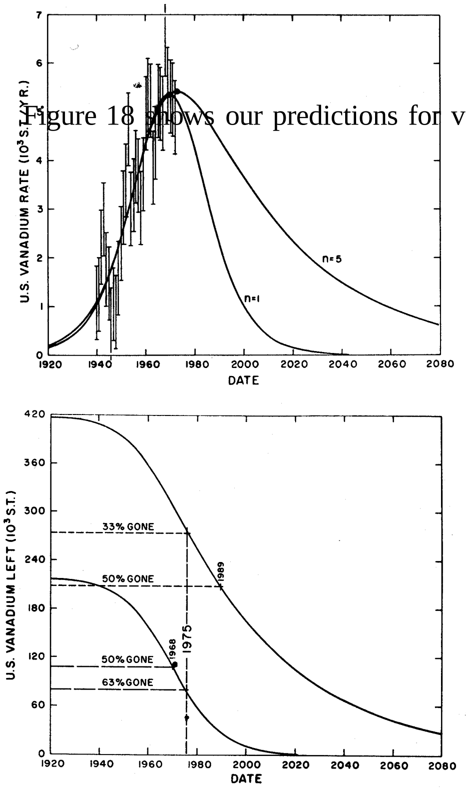


Figure 18. Vanadium production data, fits and predictions for symmetric and asymmetric (n=5) fits.

NICKEL

Our prediction for nickel is given in Figure 19. The two peak dates differ by fifteen years. The 1960 reserves estimate (•) is less than both of our “amount left” values. *The U. S. imports 68 percent and recycles 20 percent of the nickel it consumes.* Nickel is indispensible in steel, alloys, and electroplating.

Peak date—1962-1987

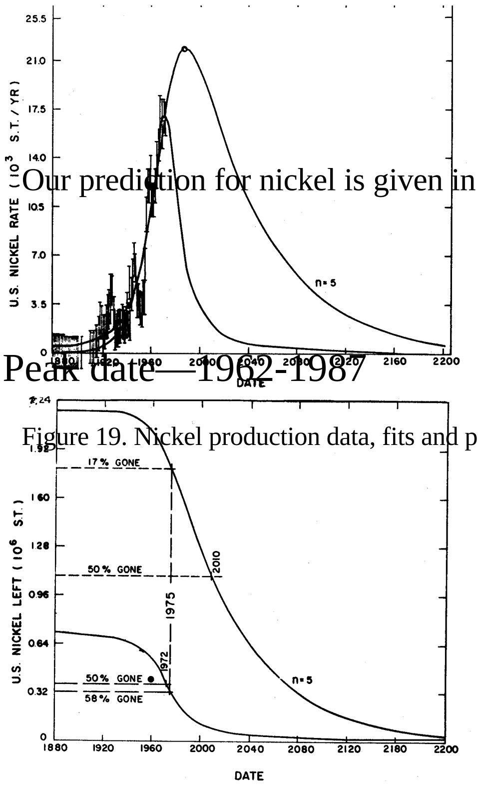


Figure 19. Nickel production data, fits and predictions for symmetric and asymmetric (n=5) fits.

In Table 4 are given the depletion parameters (defined in Chapter 1) for the metals that are moderately depleted in the U.S. and for which we found sufficient data to make predictions.

TABLE 4

Depletion parameters for moderately depleted United States metals

	Pessimistic Prediction*				Optimistic Prediction*			
Metal	t_p	$t_{1/2}$	% gone in 1975	Q_∞	t_p	$t_{1/2}$	% gone in 1975	Q_∞
Bauxite	1968	1966	66	110×10^6 L.T.	1970	1986	42	181×10^6 L.T.
Iron Ore	1962	1962	62	8.92×10^9 L.T.	1974	2021	29	19×109 L.T.
Nickel	1962	1972	58	754×10^3 S.T.	1987	2010	17	2.18×10^6 S.T.
Selenium	1962	1962	79	37×10^6 1b.	1964	1974	51	54×10^6 1b.
Tellurium	1964	1964	75	8.3×10^3 1b.	1965	1976	48	12.7×10^6 1b.
Titanium (Ilm.)	1966	1966	75	30×10^6 S.T.	1967	1979	44	50×10^6 S.T.
Titanium (Rut.)	1958	1958	90	320×10^3 S.T.	1959	1967	61	485×10^3 S.T.
Tungsten Ore	1962	1962	72	472×10^3 S.T.	1961	1981	44	759×10^3 S.T.
Vanadium	1968	1968	69	220×10^3 S.T.	1972	1989	33	418×10^3 S.T.

*See Table 3 for the definitions of these terms.

From a perusal of Figures 11 through 17 we conclude that one of the following statements must be true: Either

1. there are unusual rather long-term socio-technical forces that are temporarily depressing U.S. production of all of these six metals, or
2. all of these metals are moderately depleted, i.e., they have recently peaked, or
3. some of the metals (perhaps selenium, tellurium, and titanium) are experiencing large fluctuations and the remainder are moderately depleted.

The reserves and identified-resources estimates support statement 3, but prudence dictates that statement 2 should be adopted for planning purposes.

Chapter 4. Depletion of United States Mineral Fuels

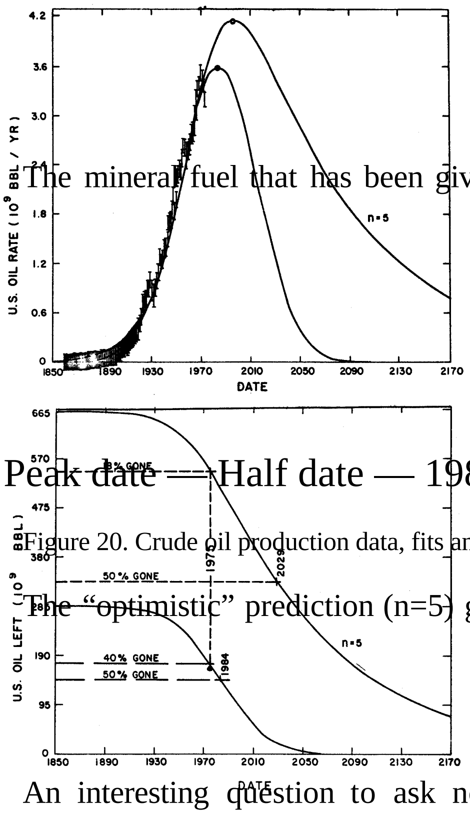
It is logical to believe, therefore, that the transition from a mineral fuel economy to one relying upon other sources will be a gradual process occurring in an orderly fashion over the next hundred years, as a result of technical developments and economic pressure. -E. Steidle, *Mineral Forecast 2000 A.D.,* Pennsylvania State College, State College, PA., 1952.

The metals are in a severe state of depletion in the United States— that is the message of the last two chapters. Surely the U.S. mineral fuels must be in a similar situation. Not so! *We shall see below that crude oil and natural gas are very near their production peaks, but coal is far from peaking.* However, indications are that coal production rate will rise rapidly to a peak in about seventy years. None of these mineral fuels are past peaking, whereas we concluded in the last two chapters that about sixteen metals are past peaking with about a dozen of them far past peaking.

Since none of the mineral fuels have peaked yet, we can only conjecture on the extent of asymmetry to expect for the production curves of the mineral fuels. Hubbert[2] assumed that they are symmetric. We shall also make such "pessimistic" predictions, but we shall, in addition, assume an asymmetry similar to that of the highly depleted metals (n=asymmetry parameter=5) to obtain an "optimistic" prediction.

CRUDE OIL

The mineral fuel that has been given the most attention in the popular press is crude oil. There have been many predictions of when we will "run out" of crude oil. A more definable prediction to make is the date when crude-oil production will peak. The oil-production data given in Figure 20 show a recent sharp peak very similar to the sharp peak that occurred at about 1929. Our analysis indicates that both of these sharp peaks are short-term fluctuations, but that U.S. crude oil will peak very soon.



Peak date — Half date — 1984, 40% gone in 1975.

Figure 20. Crude oil production data, fits and predictions for symmetric and asymmetric (n=5) fits.

The "optimistic" prediction (n=5) given in Figure 20 is a much poorer fit to the data than is the "pessimistic" prediction, because of a poorer fit to the early-time data. Also, the National Academy of Sciences 1975 reserves estimate[14] (•) agrees with the pessimistic prediction. It is reasonable to conclude that the pessimistic prediction is probably nearer the truth than is the optimistic prediction.

An interesting question to ask now is: How early could the production-history prediction method have predicted the production peak? To test for this, we fitted data only up to a specific date (data-cutoff date) according to the procedure described by Arndt and Roper[4].

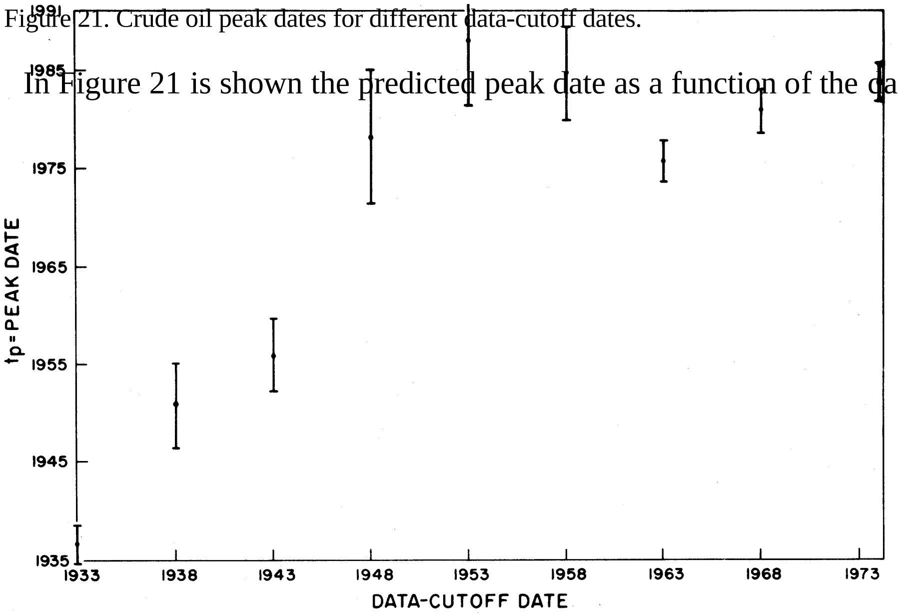


Figure 21. Crude oil peak dates for different data-cutoff dates.

In Figure 21 is shown the predicted peak date as a function of the data-cutoff date. It is seen that the predicted peak date was too small until about 1950. After that date the predicted peak date was fairly stable with increasing data-cutoff date; it varied only by about ten years between 1947 and 1974. This result gives us confidence that our peak-date prediction is fairly accurate. Also, it tells us that Hubbert[2] could have made his unheeded oil-depletion prediction much earlier than 1956. (This method of testing for peak-date stability could be profitably used for other U.S. and world minerals, which is the subject of further work in progress.)

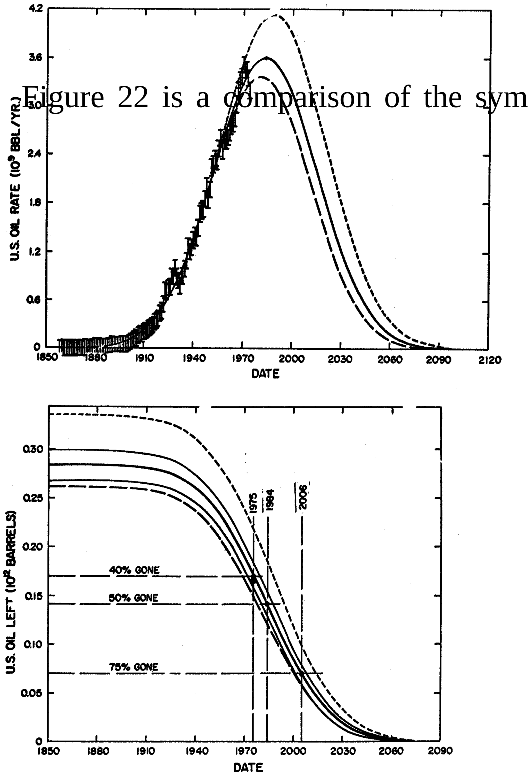


Figure 22 is a comparison of the symmetric predictions for data cutoff dates of 1953 (dotted curve), 1963 (dashed curve), and 1974 (solid curve). The National Academy of Sciences 1975 reserves estimated (•) is also shown.

We feel that our prediction will turn out to be fairly accurate for U.S. crude oil. There may occur some asymmetry, but we expect that it will not be very large. It is important to point out that, even if there is some asymmetry, it would change the peak date very little. *A major factor in the "energy crisis" in which the United States is now imbedded is the fact that crude oil is very near its production peak.*

Figure 22. Crude oil symmetric predictions for data-cutoff dates of 1953 (dotted curve), 1963 (dashed curve) and 1974 (solid curve).

One interesting general question to ask for this very important mineral, or for any other mineral, is: Could the United States decide to rapidly reduce its crude-oil production rate to, say, half the present production rate and then tail-off the production rate at a much slower deceleration than our Figure 22 shows, in order to have a slower transition from crude oil to other energy sources, or is the shape of the curve in Figure 22 an inexorable socio-technical "law"?

NATURAL GAS

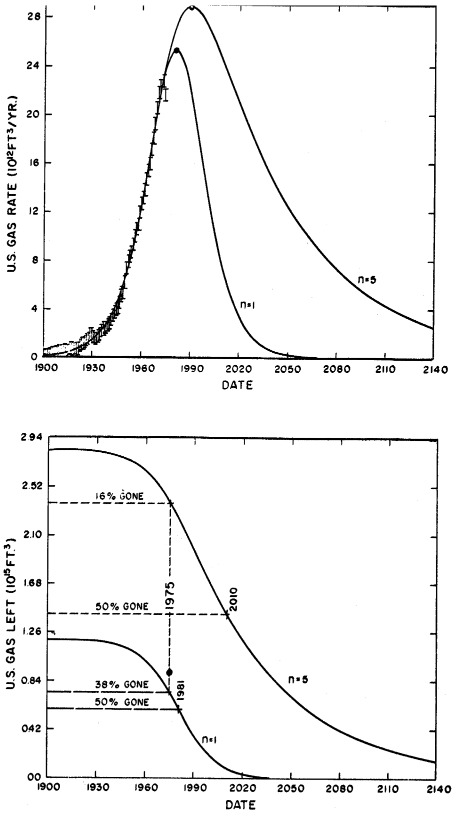
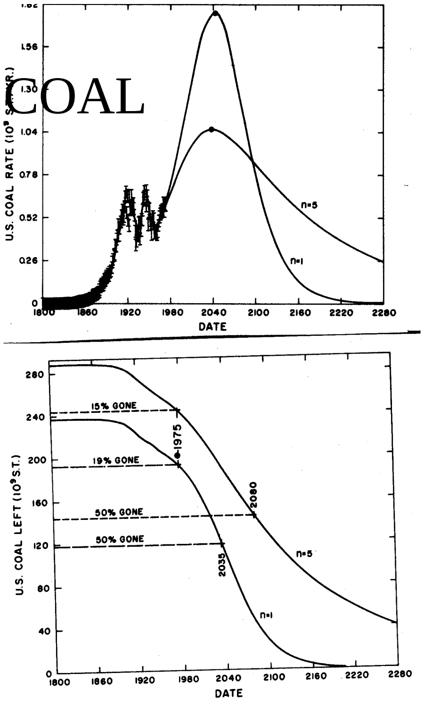


Figure 23 shows our pessimistic (n=1) and optimistic (n=5) adictions for natural gas for the United States. The two fits are almost equally good. The National Academy of Sciences 1975 reserves estimate[14] (•) is only slightly larger than the pessimistic prediction and is much smaller than the optimistic prediction. Indlications are that we should not expect very much asymmetry in the production peak.

Peak date — Half date — 1981, 38% gone in 1975.

Figure 23. Natural gas production data, fits and predictions for symmetric and asymmetric (n=5) fits.

COAL



United States coal production is difficult to predict. In this book we have shied away from any predictions for metals that are far from depletion. However, since coal is perhaps a middle-term hope as an energy source for the United States, one should make an effort to predict coal production. Figure 24 shows our pessimistic (n=1) and optimistic (n=5) predictions for coal. We previously saw for crude oil and natural gas that n=5 was not a particularly good asymmetry parameter for those mineral fuels. We can conjure no rational reason why n= 5 should be a good asymmetry parameter for coal, since the formation of coal deposits is not analogous to the formation of the four metal ore deposits which had n~5 as their asymmetry parameters. A more rational expectation is that coal's asymmetry should be similar to that of crude oil and natural gas, i.e., probably n≈1. Indeed, Parker's 1975 estimate[15] (•) of economically recoverable United States coal is in good agreement with our n=1 prediction. However, the identified-resources estimate (1.58×10^{12} S.T.) given in Brobst and Pratt[13] is seven to eight times the value of either of our predictions. We feel that our pessimistic iprediction is about the best prediction one can obtain at this date.

Peak date—2044, 19% gone in 1975

Figure 24. Coal production data, fits and predictions for symmetric and asymmetric (n=5) fits.

Summary

Table 5 contains a list of the depletion parameters (defined in Chapter 1) for the mineral fuels in the United States. As explained above, we feel that the pessimistic predictions are likelier to be near the truth than the optimistic predictions. In either case we see from Table 4 that, even if we could escape the "energy crisis" that is in force because we are near the peaks of oil and gas production by quickly switching to coal as our energy source, indications are that we would have only about sixty years before a new "energy crisis" would be upon us when coal peaks in production. *Coal is probably not the "Messiah" that it is claimed to be by many people.*

TABLE 5

Depletion parameters for United States mineral fuels

	Pessimistic Predictions				Optimistic Predictions			
Mineral	t_p	$t_{1/2}$	% gone in 1975	Q_∞	t_p	$t_{1/2}$	% gone in 1975	Q_∞
Crude Oil	1984	1984	40	284×10^9 bbl	1995	2029	18	662×10^9 bbl
Natural Gas	1981	1981	38	1.20×10^{15} ft^3	1989	2010	16	2.84×10^{15} ft^3
Coal	2044	2035	19	237×10^9 S.T.	2040	2080	15	288×10^9 S.T.

Chapter 5. Overview of United States Metals and Mineral-Fuels Depletion

It is obviously untrue that this is a race for the survival of mankind. The human race survives changes in its way of life. The price of failure to recognize the probabilities and to revise our faith, in time, could be the end of a culture.—S. H. Ordway, Jr., *Resources and the American Dream,* The Ronald Press Co., New York, 1953.

One often reads or hears the shibboleth that the United States enjoys a high standard of living because of her superior political and economic systems. As probably in any shibboleth, there is an element of truth in it. However, one cannot study the nonrenewable and renewable resources capacity that the United States has enjoyed without realizing the unique position this nation has occupied. There were seemingly endless forests that provided abundant food, fuel, and fiber. Petroleum oozed from the earth inviting humans to probe deeper for more, and much more there was. Deposits of many other minerals were also easily available. The climate and soil were very suitable for cultivation. One could argue that no other political or economic systems except laissez-faire could have evolved, because of the vast untapped regions and resources that beckoned when people felt crowded.

But now we are beginning to realize that the resources cornucopia rearly is not limitless. That realization began decades ago, and has already caused significant changes in the U.S. political and economic systems. As the realization increases we probably can expect even nore fundamental changes.

Our concern in this book is chiefly with the metals and secondly vith the mineral fuels. Just what is their overall depletion situation? Table 6 and Figure 25 show the depletion parameters (defined in Chapter 1) that we have determined for most metals and mineral fuels. We expect, for reasons explained in previous chapters, that a small fraction of these are perhaps too pessimistic.

TABLE 6

United States metals and mineral fuels depletion parameters.

Uncertainty level (column two) of 1 indicates the highest certainty and of 4 indicates the highest uncertainty.

		Pessimistic Prediction:				Optimistic Prediction:			
Resource	Uncertainty Level	t_p	$t_{1/2}$	% gone in 1975	Q_∞	t_p	$t_{1/2}$	% gone in 1975	Q_∞
Antimony	4	2000	1978	48	180×10^{3} S.T.		————		
Bauxite	3	1968	1966	66	110×10^{6} L.T.	1970	1986	42	181×10^{6} L .T.
Cadmium	2	1957	1972	54	672×10^{6} 1b		—Same—		
Chromite	2	1955	1955	100	1.82×10^{6} S.T.		————		
Copper	3	2020	2017	20	46.6×10^{6} S.T.		————		
Gold	1	1916	1916	90	381×10^{6} T.O.		—Same—		
Iron Ore	2	1962	1962	62	8.92×10^{9} L.T.	1974	2021	29	19×10^{9} L.T.
Lead	3	1925	1958	60	57.8×10^{6} S.T.		—Same—		
Magnesium	4	2004	2004	20	27×10^{6} S.T.		————		
Manganese Ore	2	1955	1955	90	5.35×10^{6} S.T.		————		
Mercury	1	1870	1916	75	4.82×10^{6} (76 lb)		—Same—		
Molybdenum	4	2020	2020	10	25.1×10^{9} 1b		————		
Nickel	3	1972	1972	58	754×10^{3} S.T.	1987	2010	17	2.18×10^{6} S .T.
Niobium-Tantalum	3	1957	1957	100	1.34×10^{6} 1b		————		
Platinum Group	1	1923	1941	82	2.57×10^{6} T.O.		—Same—		
Selenium	2	1962	1962	79	37×10^{6}1b	1964	1974	51	54×10^{6}1b
Silver	1	1908	1938	70	7.2×10^{9} T.O.		—Same—		
Tellurium	2	1964	1964	75	8.3×10^{3} 1b	1965	1976	48	12.7×10^{6} 1b
Titanium(Ilm.)	2	1966	1966	75	30×10^{6} S.T.	1967	1979	44	50×10^{6} S.T.
Titanium (Rut.)	3	1958	1958	90	320×10^{3} S.T.	1959	1967	61	485×10^{3} S.T.
Tungsten Ore	3	1962	1962	72	472×10^{3} S.T.	1961	1981	44	759×10^{3} S.T.
Vanadium	3	1968	1968	69	220×10^{3} S.T.	1972	1989	33	418×10^{3} S.T.
Zinc	2	1943	1968	54	67.1×10^{6} S.T.		—Same—		
Crude Oil	3	1984	1984	40	284×10^{9} bbl	1995	2029	18	662×10^{9} bbl
Natural Gas	3	1981	1981	38	1.20×10^{15} ft^{3}	1989	2010	16	2.84×10^{15} ft^{3}
Coal	4	2040	2035	19	237×10^{9} S.T.	2044	2080	15	288×10^{9} S.T.

In Figure 25 are shown the peak dates for the metals and mineral fuels. The peak date is probably the most important depletion parameter since it is the date when *production ceases to rise and begins to fall*; undoubtedly a *traumatic event* for a society, particularly when the peak dates for several important minerals occur over a time span of a few decades. We see from Figure 26 that the precious metals (silver, gold, and platinum group), along with lead, peaked in the two-decade period of 1905-1925. One wonders what connection there may have been between this fact and the Great Depression that began in the late 1920's. According to Figure 25 we have just passed through another, probably more mportant, two-decade period (1955-1975) in which several important metals (including manganese, chromite, tungsten, bauxite, and iron ore) appear to have peaked. Question: What connection does this fact have with the current economic difficulties in the U.S. and what does it forebode for the immediate and long-term future of the U.S.?

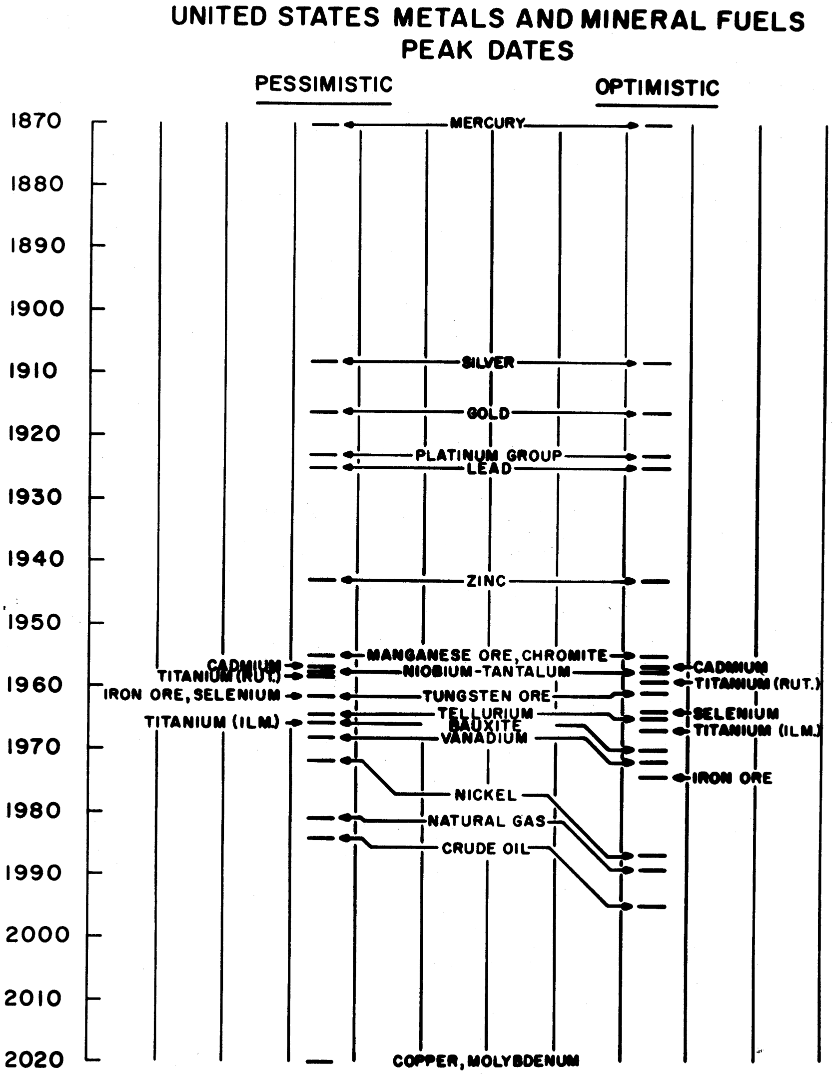


Figure 25. Peak dates for metals and mineral fuels.

There are other indicators besides our predictions that show the dire minerals depletion position of the United States. In Table 7 are given approximate percentages for various minerals of U.S. to world production, U.S. imports to U.S. consumption, U.S. recycling to U.S. consumption, and U.S. imports and recycling to U.S. consumption. (We include in "recycling" the use of materials from stockpiles.)

TABLE 7

United States Mineral Production and Consumption Percentages

(See footnote 16.)

Mineral	%of World Production	% imported	% recycled*	% imported or recycled*
Antimony	1	30	55	85
Arsenic	—	89	0	89
Asbestos	3	85	0	85
Barite	22	40	0	40
Bauxite	3	88	0**	88
Beryl	—	45	1	46
Bismuth	11	50	0	50
Cadmium	27	54	6	60
Chromite	0	97	3	100
Coal	18	-10	0	-10
Cobalt	5	80	20	100
Copper	23	6	40	46
Crude Oil	15	40	0	40
Fluorine	6	80	0	80
Gold	4	15	60	75
Helium	98	0	0	0
Iron Ore	11	33	30	63
Lead	14	20	43	63
Manganese Ore	0	—	—	100
Mercury	6	47	17	64
Mica Sheet	0	—	—	100
Molybdenum	67	-55	0	-55
NaturalGas	47	5	0	5
Nickel	3	68	20	88
Niobium-Tantalum	0	100	0	100
Peat	0.2	35	0	35
Phosphate Rock	40	-29	0	-29
Platinum Group	0.5	78	20	98
Selenium	26	37	3	40
Silver	17	25	45	70
Tellurium	48	32	13	45
Thorium	14	0	0	0
Tin	0	80	20	100
Titanium (Ilm.)	19	25	0	25
Titanium (Rut.)	0	100	0	100
Tungsten	8	25	0	25
Uranium Oxide	55	0	—	—
Vanadium	22	0	0	0
Zinc	9	50	5	55
Zirconium	16	42	4	46

*Including amounts released from private, government, and industry holdings.
**Used for other purpose besides metal production. No attempt is made to include metal recycling.

The U.S. minerals depletion position can be quickly grasped by observing Figure 26 in which the percentages of U.S. imports and recycling to U.S. consumption are shown. Over twenty of the minerals are at the fifty percent level or higher, while less than twenty are below fifty percent, including the three that are exported (shown as open bars in the figure). Less than ten are below the twenty-five percent mark and only three are exported (net). Also, almost all of these minerals-import percentages are increasing.

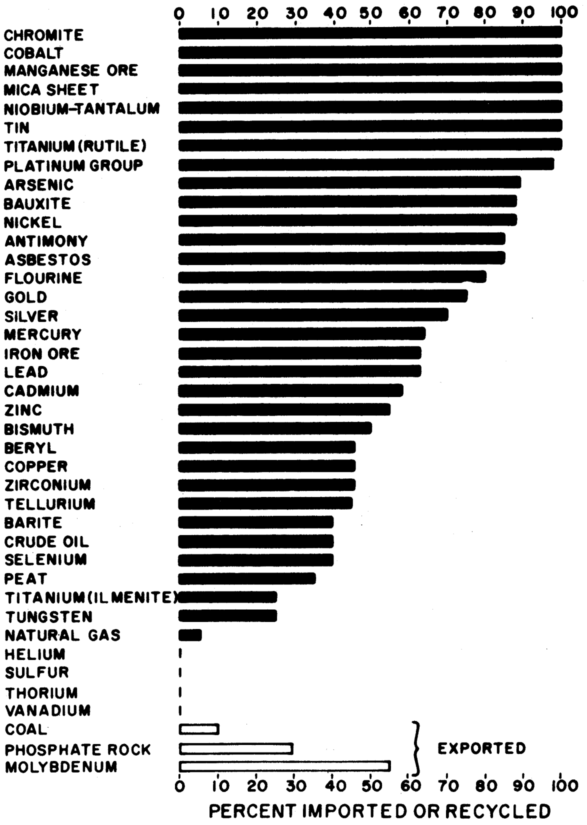


Figure 26. Percentages of U.S. minerals imports and recycling to consumption.

Adding the minerals situation to the fact that U.S. agriculture is very near its asymptopic limit of farm output as a function of ergy input[17], one can only surmise that the economic (and, therefore, political) position of the United States relative to the rest of the world will continue to decline in the future. Our best hope is that we can muster the requisite equanimity required to accept this fact without attempting to use our accumulated military prowess to maintain our historical preimminent position in the world.

Chapter 6. Possible Futures for the United States

No one has yet given extended thought to items it would be desirable to curtail. Limitations of industrial expansion and consumption can obviate the day of reckoning and will help us all to reevaluate the quality of the Good Life. -S. H. Ordway, Jr., *Resources and the American Dream,* The Ronald Press Co., New York, 1953.

Our main point of emphasis in discussing possible futures for the United States is in devising possible ways for the U.S. to meet the challenge of diminishing domestic sources for minerals to be used for energy and material needs. Because of the central importance of energy, the first question to be asked is: Where will we get energy *and how* will energy production change with time?

Energy*:* We showed in Chapter 1 that growth in world energy use from sources other than the sun's energy that presently strikes the earth must level off to zero in about a century from now, if we do not wish to drastically affect the world's weather. It must level off sooner in the U.S. So we are talking about a huge increase in energy use over the next century, but not about an indefinite growth in energy use. (See Lapp's prediction[18] of how the growth will subside.) It will not be easy for us to adjust to diminishing growth, let alone eventual zero growth.

The most stable energy scenario is one in which many variedsources are approximately equally developed, so that the nation is not subject to unpleasant surprises when the main source of supply goes “sour” in some way. We are facing just such unpleasantness now because we have relied too much on petroleum as our major energy source. We should have learned from this experience not to place our hope in one source again. Yet most of the federal energy-research funds have been and are being funneled into nuclear-energy research. A wiser course would be to channel approximately equal effort and resources into research and development in direct solar energy and waste-derived energy, geothermal and wind energy, petroleum and coal, along with nuclear energy. It appears fairly certain that if we continue to emphasize mainly nuclear energy, or even both nuclear energy and coal, we will sentence our descendants to future “energy crises”. This appears to be the most likely prospect, since the political tendency seems to be to look for single or a few large sources to supply our energy, rather than a large number of small sources. However, I would suggest a more rational, stability-enhancing energy development program:

1. Use some of the remaining petroleum energy to develop mass-produced wind electric generators, solar heating systems, solar electric cells, and methane gas generators (using organic wastes) to be used in individual homes, apartment houses, public buildings, and factories.
2. Design the national electric power grids to accept as well asdistribute power at each point in the grid, so that the many wind, solar cell, and methane-powered electric generators can “store” their produced energy by “loaning” it to someone else in the grid that needs it at the time of production.
3. Develop coal energy with maximum environmentalrestoration and protection and extreme safety and health precautions for the workers so that public opinion will support coal as a source of energy over the long haul. (This energy will add to the earth's heat burden.)
4. Slowly and carefully develop nuclear power, making every effort to *assure the public* of its safety (eliminate insurance liability limits for nuclear accidents, develop safe storage for radioactive wastes before starting to accumulate large amounts of waste, develop and test emergency procedures before proceeding with large-scale power-plant development, develop and test security for nuclear materials before producing them in large amounts, etc.). (This energy will add to the earth's heat burden.)
5. Develop large-scale solar power stations on earth to be incorporated into the power grid.
6. Carefully develop, where possible and with extreme environmental precautions, large-scale geothermal power stations to be incorporated into the power grid. (This energy will add to the atmosphere's heat burden.)
7. Carefully develop, where possible and with extreme environmental precautions, large scale wind power stations to be incorporated into the power grid.

8. Legislate extreme energy conservation measures[19] in manufacturing processes and in design of manufactured products.
9. Develop multihybrid electric cars, buses, trucks, and tractors whose batteries or other energy storage devices can be recharged by an onboard small highly efficient engine, by onboard solar cells, by regenerative braking, or by external electric power sources.
10. Experiment with solar power stations in space. These stations may be able to transmit some energy back to earth, but their greatest use may be for space colonization. Any energy that they transmit to the earth will add to the earth's heat burden. (The only way that population and economic growth can continue past another century or two is by man colonizing the solar system[20].)

This multifaceted energy system described above can be summarized by three characteristics:

1. Maximum use of the solar energy that impinges on the earth, since it does not add to the earth's heat burden. Probably not more than a fraction of a percent of this energy can be utilized.
2. A constant power level from heat-burdening power sources (coal, nuclear, geothermal, space solar) that is much less than one percent of the solar energy that impinges on the earth.
3. A power grid with independent individual and large-scale components that can continue to function when some “energy crisis” occurs in a component of the system. For example, when power lines are severed or large power plants have troubles, the individual small generators partially carry the load; or when a major nuclear accident occurs and all nuclear plants must be closed for inspection, coal and solar power stations increase their share of the load.

Proponents of “all apples in the nuclear barrel” instead of a multifaceted system argue that there is not time to develop all of the systems if we are going to maintain our rate of energy growth. They further argue that we must maintain our rate of energy growth or we will have social upheaval because of the lack of jobs and the concomitant lack of the material for human survival**. We have shown in Chapter 1 that the rate of energy growth must approach zero within the next century. It is not too soon to begin the decline; the sooner we begin the decline the less sudden the decline will be and the easier will be our adjustment to it. We must soon learn how to distribute the necessary material resources among the populace without depending on growth in energy and material usage on earth.** (Of course, growth could continue by humans colonizing some other part of the solar system[20].)

Materials*:* So much for energy. What should we do as the metals and other minerals require huge amounts of energy and materials investment in order to mine the remaining dregs? There is little choice: We have to develop efficient recycling, a small amount of which is already occurring (see Table 7).

There are large energy and materials costs to recycling; it would take an enormous amount of energy and materials investment to achieve near total recycling. The metals that are dispersed as “dust” in machining, wearing, and rusting and other chemical reactions are usually lost to further use. According to a recent report[21] the amount of recycling will be very difficult to get above 60 percent. Let us be generous and assume that we shall manage to recycle 90 percent of all metals. Assume that at some future time we shall completely use all of the metals that are available in the course of one year. At a 90 percent recycling rate, ten years later only 35 percent of the original amount will be left for use and twenty years later only 12 percent will be left. Even this unrealistically generous recycling rate leads to rapid disappearance of mineral resources. If we insist on continued industrial growth leading to huge increases in uses of minerals we shall very soon face the problem of equal or greater rapid decline in minerals use. It would be much more desirable to intentionally and gradually slow down the rate of minerals usage growth now to give us more time to adjust to minerals depletion. Is such a course of action possible or is there a sociotechnical law that mandates a rapid rise followed by a rapid fall in minerals usage?

I would not counsel despair. It will be an exciting humanistic and technological challenge to work toward developing a society that simultaneously maximizes personal independence, societal stability, and harmony with the rest of nature.

Population*:* We have mentioned the need for gradually slowing energy and minerals usage growth to zero within the next century. This would not seem such a formidable task if world population were constant or even if world population growth could be gradually diminished over the next century. There are no indications in the world population statistics that such diminishment will occur. As shown in Figure 27, world population[22] is currently growing at least exponentially (a straight line in the figure) and is extrapolated to continue such growth to the year 2000.

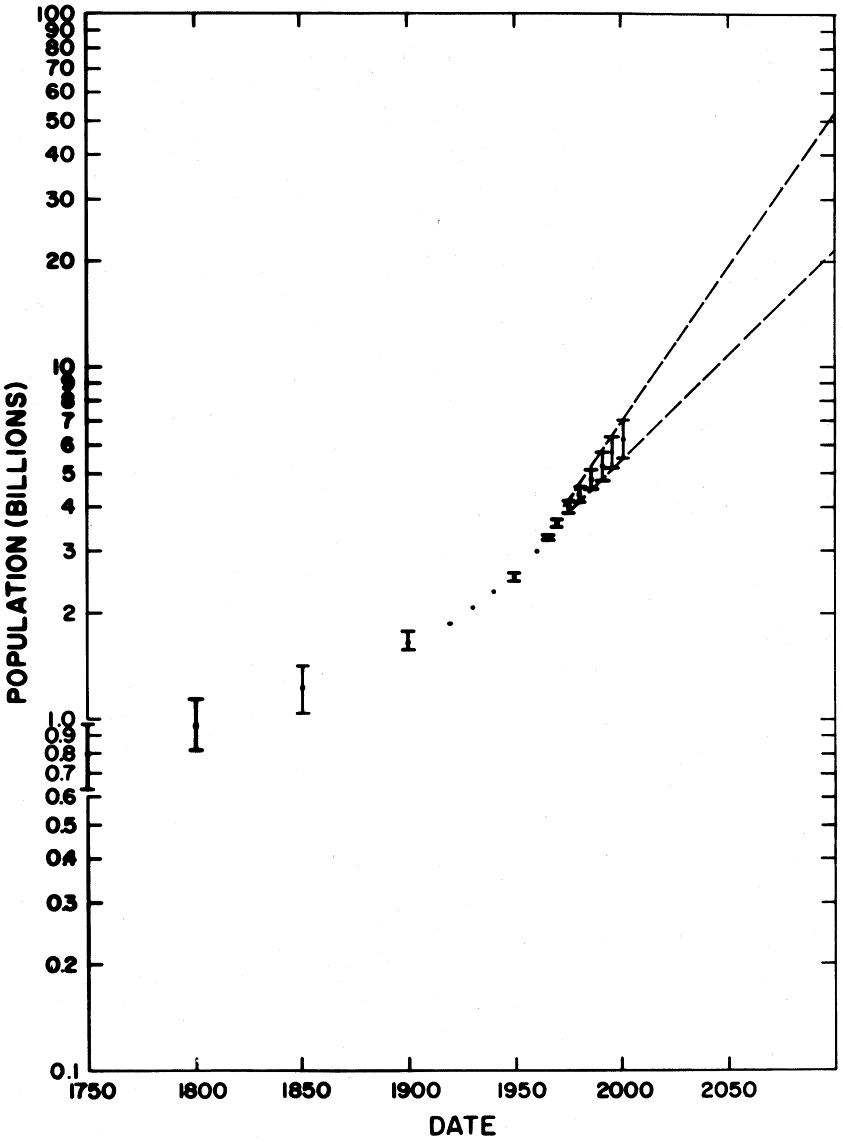


Figure 27. World population for exponential growth extrapolation.

Further exponential extrapolation of the present growth rate yields one person per square meter (149×10^{12} people) by about the year 2550. It is obvious that the growth rate has to considerably slow down in the next few centuries. However, to solve our energy and minerals problems we need *to slow down population growth in the next century.* Poleman[23] claims that world population will mimic the slowing of the U.S. population as material abundance enables adequate per capita health facilities, social security, and education.

The United Nations[22] has projected possible growth decline from 1975 to 2050 as shown by the data points in Figure 28. One of the functions used by Arndt and Roper[4] for world metal fits can be used to fit the world population data. The results are shown in Figure 28.

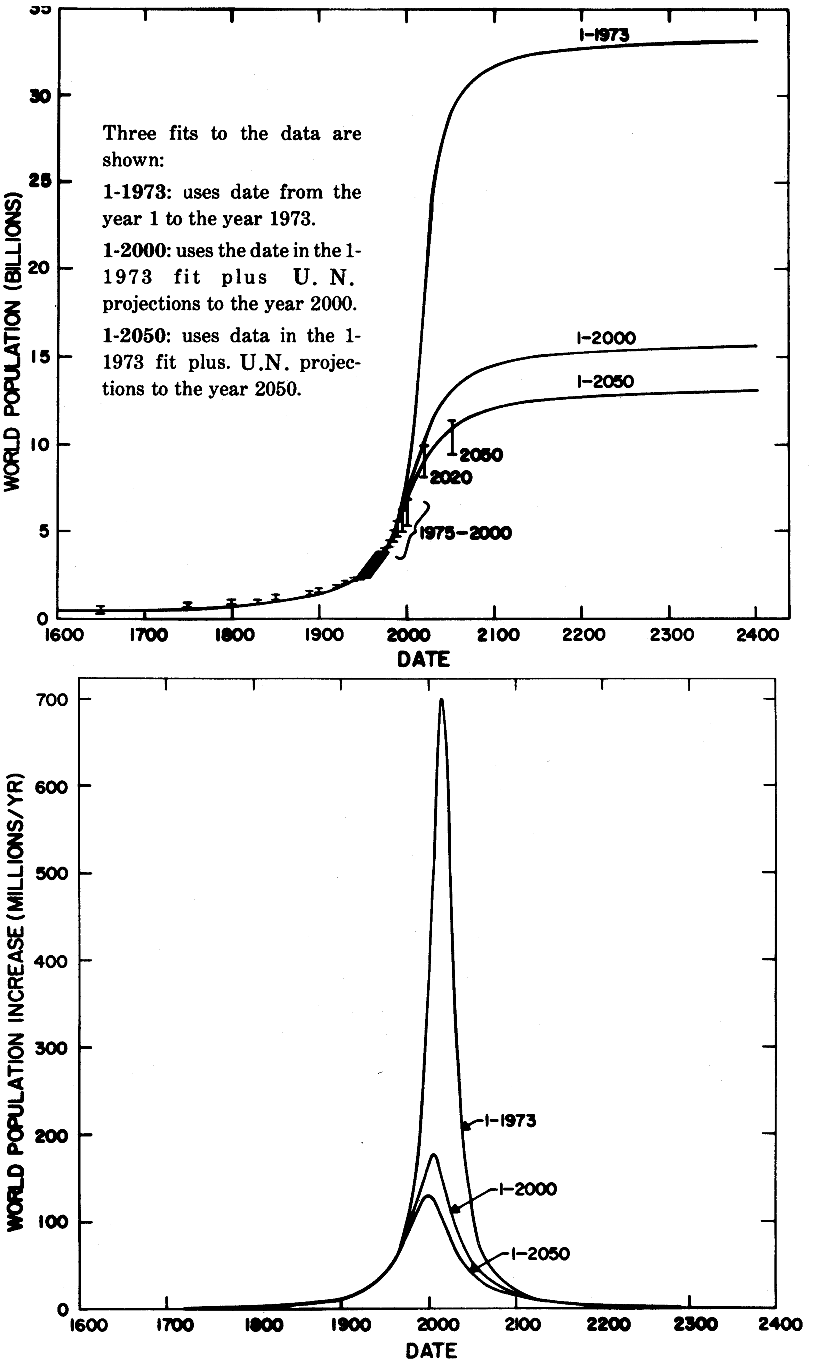


Figure 28. Fits to world population.

(The function behaves at early times like the "doomsday" function that von Foerster et. al.[24] used to fit world population data.) Bogue[25] argues that such an optimistic population growth decline as shown in Figure 28 is realistic. Brown[26] outlines how it can be achieved. The bestguess would appear to be that world population growth will achieve the necessary abatement, perhaps catastrophically in some fries, due to lack of food and/or energy and/or materials rather due to material abundance.

The United States is more fortunate; we are apparently already reaching zero population growth[23] in a pleasant way. However, energy- and materials-usage growth is continuing unabated even though our production rates are declining. We are importing the shortfall from those countries that need those materials in order to have the pleasant form of zero population growth that we are approaching. The best guess would appear to be that the U.S. and developed countries will, with some slight trauma, learn to adjust to constant energy use and to minerals depletion rather quickly when the realization of its necessity becomes well known.

I leave you with one final unanswered question: Will the rest of world, with their many nuclear weapons that we are so generously helping them to obtain (directly or indirectly), let the developed countries remain free from the severe trauma that some of the world seems destined to experience?

References

1. By “available amount” is meant the amount that man finally deems worthwhile to extract. As the energy, material investment, and environmental degradation for further extraction of a given mineral increases, society gradually decides that there are other pursuits more worth the expenditure, even though there still may be huge amounts of the mineral left somewhere in the earth's crust.

2. M. King Hubbert. 1956. Nuclear Energy and Fossil Fuels: American Petroleum Institute, Drilling and Production Practice, 7-25. Hubbert describes this early work and his later work in an article in the reference given in footnote 9 below.

3. E. Steidle. 1952. *Mineral Forecast 2000 A.D.,* The Pennsylvania State College, State College, Pa.

4. R. A. Arndt and L. D. Roper. 1976. *Depletion of United States and World Mineral Resources,* University Publication, Box 47, Blacksburg, Virginia 24060. An abbreviated version of this work, which omits the data tables and mathematics of depletion theory, is available: *The Metals and Mineral Fuels Crises: Facts and Predictions.*

5. E. Cook. 1975. *Tech. Rev.* 77, No. 7, p. 15.

6. R. W. Page. 1973. *Models of Doom: A Critique of the Limits to Growth,* ed. by H. S. D. Cole, C. Freeman, M. Jahoda, and K. L. R. Pavitt, Universe Books, N.Y., p. 33.

7. Geologists usually prefer the word “projections” which implies somewhat uncertain predictions, rather than “predictions.” We use the word “predictions” and then assign levels of uncertainty to the predictions.

8. J. Maddox. 1972. *The Doomsday Syndrome,* McGraw-Hill Book Co., N.Y.

9. Several excellent articles on many aspects of energy, including nuclear energy, are collected in L. C. Ruedisili and M. W. Firebaugh. 1975. *Perspectives on Energy: Issues, Ideas, and Environmental Dilemmas* Oxford Univ. Press, N.Y.

10. See p. 41 of the reference given in footnote 9.

11. L. C. Cole. 1969. *Bioscience, 19,* 989. Also, see F. J. Dyson. 1975. *Bull. of Atom. Sci,* (June), p. 23 for an optimistic view of man eventually

controlling the earth's weather.

12. D. F. Frasché. 1962. *Mineral Resources, A Report to the Committee on Natural Resources of the National Academy of Sciences—National Research Council,* Pub. 1000-C, Nat. Acad. of Sci.—Nat. Res. Counc., Wash., D. C.

13. D. A. Brobst and W. P. Pratt, Ed. 1973. *Geological Survey Professional Paper 820, U. S.* Gov, Printing Off., Wash., D. C.

14. National Academy of Sciences—National Research Council. 1975. News Report XXV, No. 2, February.

15. A. Parker. 1975. *Energy Policy, (March),* p. 58.

16. These data are taken or calculated from the reference given in footnote 13 and from *Mineral Facts and Problems,* 1970 edition, Bureau of Mines Bul. 650, U.S. Gov. Printing Off., Wash., D C. Some of the values given may be as much as ten percent incorrect, because of lack of recent data and different methods of calculation.

17. See p. 50 of the reference given in footnote 9.

18. See p. 17 of the reference given in footnote 9.

19. D. Hayes. 1976. *Energy: The Case for Conservation.* Worldwatch Institute, Wash., D. C.

20. G. K. O'Neill. 1974. *Phys. Today,* 27, No. 9 (Sept.), p. 32; E. Burgess, 1976. Astronomy, **4**, No. 1 (January), p. 18.

21. National Advisory Council for Development Cooperation—Netherands. 1975. Report No. 53, “Recommendations on the Future Availability of Metallic Minerals,” The Hague, Netherlands.

22. Population data and projections are taken from United Nations Statistical Yearbook. 1949-1974. United Nations, N.Y.; P.S. Putnam. 1953. *Energy in the Future,* D. Van Nostrand, N.Y.; H. Kahn and A. J. Wiener. 1967. *The Year 2000,* Macmillan, N.Y.; J. D. Durand. 1967. *Proc. of Amer. Phil. Soc.,* 111, No.3, 136; P. R. Ehrlich and A. H. Ehrlich. 1970. *Population Resources Environment, V,* Appendix 2, W. H. Freeman and Co., San Francisco.

23.T. T. Poleman. 1975. *Science,* 188, 510.

24. H. von Foerster, P. M. Mora, and L. W. Amiot. 1960. *Science,* 132, 1291 see also S. von Hoerner. 1975. J. *Brit. Plan. Soc.,* 28, 691.

25. D. J. Bogue. 1967. *The Public Interest,* No. 7 (Spring), 11.

26. L. R. Brown. 1974. *In the Human Interest, W. W.* Norton and Co., N.Y.