The Industrial Materials of Man

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INTRODUCTION

It has been noted in previous lectures that man is given choice in defining both the meaning of progress and the standard of living. The conscious exercise of these choices may mark the beginning of a new era in man's development, more profound in its effects than the transition of man from a hunter to an agriculturist, or from an agriculturist to a technologist. The population and energy statistics, previously considered, emphasize that these choices must be well publicized and given priority consideration.

This lecture reviews the current and potential demands of man for the common materials of this earth. The facts which will be presented underline the urgency of the need for new thinking and new decision-making. As with our demands for energy, the requirements for many industrial materials are increasing at an exponential rate and are leading to a rapid depletion of the resources of the world. Just as the first law of thermodynamics tells us that energy can be neither created nor destroyed, the law of conservation of matter states that matter can be neither created nor destroyed.

These two fundamental laws appear to have been overlooked or deliberately forgotten in man's pursuit of material progress. The result in terms of energy is the discharge of enormous quantities of low-grade energy into the environment with its consequent undesirable effects. In the production of materials it has led us to neglect the solid, liquid and gaseous wastes which are generated by the production industries and has caused us to accept, as individuals, the use of the word "consumer" instead of "purchaser" to describe our economic role in society. However, as Dr. Spilhaus has so eloquently reminded us, "There is no such person as a consumer...we consume nothing, whether it be the food we eat, the automobiles we drive or the hardware in our houses". It is appropriate, therefore, to remember the applicability of the law of conservation of matter and to realize that most of the materials which are produced create waste and are themselves eventually considered as waste. Unlike energy, however, the wastes might be partially recovered and re-used.

These are some of the thoughts which should be borne in mind in considering the current and future requirements for industrial materials. It is also conceivable that energy restrictions may in fact provide the first check on both the utilization and re-use of materials. In this brief review, these aspects cannot be emphasized and it will be necessary to confine our attention to a statistical review of our material requirements. The wider implications, indicated here, will need to be left to the reader's thoughtful consideration.

THE INDUSTRIAL MATERIALS

Industrial (or raw) materials are all those materials which have made the creation of modern industry and modern life possible and which are now necessary for the continuation of its existence at the current level of sophistication. Four main classes may be defined, comprising plastics, wood, non-metallic minerals, and metals.

The source of most plastics is the fossil hydrocarbons. The consumption and requirements for fossil hydrocarbons have already been considered in terms of their energy generation potential. It is probably sufficient to note that since only a small fraction of the production of these hydrocarbons is used for plastics, the hydrocarbon supply is adequate for this purpose. If the bulk of our fossil fuels were not burned to generate energy, the supply would provide enough raw material for plastics and polymers to last for centuries or even millenia. Even after the petroleum and natural gas deposits are depleted it will be possible to use raw material from coal, shale, plants and even carbon dioxide from the atmosphere to provide plastics, since the higher costs of manufacturing the raw materials from these last sources would not unduly affect the final cost of the plastic. Much of the cost in manufacture of plastics is in converting the raw materials to the finished product. It can therefore be assumed that there are no serious problems of depletion and it can be optimistically postulated that plastics could supersede other materials as economic and scientific events dictate. The only predictable checks to the increased utilization of plastics are those imposed by economic considerations and availability of sources of energy.

Non-metallic minerals are also plentiful with some important exceptions. One very important exception is phosphorus in the form of phosphate, which as a fertilizer, at 17 million tons per year in 1970, makes up 1/3 of the total fertilizer used in the world. A large fraction of the world's food depends upon the availability of this mineral and increasingly so as the green revolution takes hold. Normal reserves will, however, only last a few more decades and the United Nations has classified the depletion of this mineral as being highly critical. Some other non-metals in short supply are industrial diamonds, mica, and helium. These and other non-metals, which may not be of vital significance in today's economy, may prove to be essential for future technology. For example, helium has important applications in cryogenics which in the production of superconductors could make the transmission of electricity over long distances possible. Thus, this future utility, which would make the pollution-free distribution of energy feasible and partially solve the energy problem, may not be possible unless future resources are found or current resources are conserved.

Wood and metals and their by-products are, however, the two main forms of material which have been and will continue to be of utmost importance in the development and utilization of technology. These two classes therefore deserve individual and detailed evaluation.

WOOD

Wood is a product of photosynthesis and is therefore a renewable resource - if the rate of removal by cutting, fires, and decay does not exceed the rate of growth, wood will always be available to mankind. The total amount of commercial standing timber in different areas and countries of the world and its rate of removal are given in Tables 1 and 2. The type of wood is mainly coniferous in the north and broadleaf towards the equator. It is interesting to note that North and South America together with the U.S.S.R. have more than two-thirds of the total reserves. Table 1 shows that the industrially advanced areas use most of the wood for industrial

TABLE 1: RESERVES OF TIMBER AND REMOVALS IN THE WORLD, 1968.[1]

Area	Standing Reserves (km^3)	Total Removals (km^3/year)	Industrial Wood (km^3/year)	Fuel Wood (km^3/year)
South America	110	.230	.070	.160
U.S.S.R.	80	.380	.280	.100
North America	63	.476	.400	.076
Asia	35	.425	.125	.300
Africa	30	.245	.025	.220
Europe	12	.320	.220	.100
Pacific	6	.012	.007	.005
TOTAL	336	2.100	1.150	.960

TABLE 2: STANDING TIMBER AND REMOVALS FOR SOME COUNTRIES, 1968.[2]

Country	Standing Reserves (million m^3)	Removal Rate (million m^3/year)
Canada	33,000	95.7
U.S.A.	30,000	298
Mexico	500	11.5
Brazil	60,000	120
China	7,500	134
India	2,100	17
U.K.	108	3.2
France	1,000	43
Sweden	2,100	45
W. Germany	1,000	27
Spain	200	14
Egypt	0.6	0.14

purposes and very little as fuel. The opposite is true for the underdeveloped areas. The total coal equivalent of the wood used as fuel is about 300 million tons and thus wood is still the principal fuel for a large part of mankind.

1,2 Source for: Standing reserves; FAO, U.N., World Forest Inventory 1963.
Removal rate; United Nations Statistical Yearbooks

In both tables it may be noted that the forests are concentrated in the sparsely inhabited areas of the world. Areas with large and ancient populations have for the most part destroyed their forests. Thus, India, Europe and most of China have very little forest left. Clearly forest products must move across international boundaries in the future and efforts must be made, and are being made, to reforest areas.

Industrially, wood is used both for construction and for other products such as wood pulp, newsprint and paperboard.

The total quantity of wood pulp produced is approximately 100 million tons of dry product per year. Many pulp producers practise forest farming and plant fast-growing trees which are harvested approximately every 10 years. The statement by some environmentalists that 17 trees of a forest are cut for every ton of pulp produced does not indicate therefore a depletion of the mature forests.

Production of newsprint amounts to approximately 20 million tons per year and is increasing at an annual rate of 4%. About half of this total quantity is produced in Canada, 90% of which is exported, most of it to the U.S.A.

Approximately 100 million tons per year of paperboard and other papers are produced with an annual increment of approximately 6%. These products often involve considerable use of recycled paper and paperboard.

From these figures it would seem that the supply of wood is adequate and may even satisfy a much higher demand. Shortages will develop only in high quality trees such as the rare redwoods of California and the hardwoods.

The need is for good forest management. It is well known that timber removal creates deserts in hot and temperate climates and leads to erosion. In cold climates large removals increase the reflection of sunlight by snow and can have considerable effects upon the climate. The importance of forests and trees has now been recognized and there are many schemes for reforestation across the world. Noteworthy are the attempts by the Chinese to reforest denuded areas of China, to decrease soil erosion and to improve the fertility of neighbouring soils.

The possibilities for recycling, substitution and economizing in the use of wood seem to be promising. Great amounts of paper that are now used for packaging are being recycled and this operation is now receiving support by legislation and subsidies in a number of countries. In terms of substitution, wood for construction may be replaced by stone or cement, which are plentiful and provide an additional bonus of beauty, fire resistance and strength. It is possible too that we might even see some legislation to limit the extravagant use of paper.

At this point we might again note that although the resources appear to be adequate, the processes for their utilization demand energy and create pollution problems. Any tendency towards extravagance should therefore be checked.

METALS

Metals, the bones of industry, are the materials, in the main, that are in the shortest supply. They are non-renewable - there are alternative sources of energy to take the place of fossil fuels, but with many metals no such alternatives are in sight. This class of materials therefore demands special consideration and it is appropriate to consider not only the formation of mineral bodies but the methods of exploration for new mineral bodies and the possibility of yet untapped resources from the oceans.

Formation of Mineral Bodies

Common rock contains all the metals in very small concentrations. When molten rock, or "magma", from inside the Earth is forced through the cracks in the crust, it goes through a slow process of cooling by conduction. During this process, some dissolved minerals tend to move and concentrate as a result of temperature gradients, or they might be thrown out of solution as the rock freezes. Subsequent movements of the crust may bring these mineral concentrations to or near the surface where they can be detected and used. About 85% of the mineral deposits were formed in this way.

Weathering by rain, ice and wind can also concentrate and disperse minerals. Gold placers in river beds are created in this way and 10 to 15% of the mineral bodies are formed by this process. Hydrothermal processes in which minerals are carried or deposited by steam from the inside of the Earth also perform a minor role in the formation of ore bodies.

The ore bodies are relatively small, unlike coal and petroleum deposits, and locating them is becoming increasingly difficult. Only the largest iron deposits, and those of other metals in accessible areas that have surface showings, can be located easily.

Methods of Locating Ore Bodies

In order to gain some appreciation of the validity of future estimates and projections, it is appropriate to briefly consider the general methods of geological surveys and methods of locating mineral bodies. The main methods now in use are:

1) Geological and geochemical surveys:

A general examination of the types of rocks and chemical analysis of rock and soil samples would indicate the promising areas where ore bodies might be found. The analysis of ground and surface waters and an examination of their bacterial content has also been found to be helpful.

2) Gravity:

Ore bodies which have a density higher than the surrounding matter will create local variations in the force of gravity. This effect, detectable as differences in gravity of the order of parts per million, can be measured using modern instruments.

3) Magnetometer:

Magnetic ore bodies cause changes in the magnitude and direction of the earth's magnetic field. Such ore bodies as the Kingston iron ore deposit are readily located by airborne magnetometers.

4) Electro-magnetic field:

An electro-magnetic field with its magnetic component horizontal is set up over an area. A conducting mineral body under the surface bends the field lines from the horizontal and the magnitude and extent of the deflection indicates the size of the conducting body.

5) Ground conductivity:

Metallic ore bodies conduct electricity better than average rock and if a potential difference (A.C. or D.C.) is applied between pairs of points the areas of high conductivity can be located. The effect, of course, may be due to the presence of other conductors, for example, wet soil. This method is therefore used in conjunction with others in the final analysis.

6) Spectrum analysis:

Changes in the spectrum of light reflected from the surface of the ground or water areas is being used and investigated to determine the location of potential ore bodies.

All of these methods may be used to locate mineral bodies. Aerial and even satellite surveying can now be employed, but confirmation and precise evaluation of a potential ore body require a ground survey. This involves drilling to determine the grade and tonnage of the deposit. It should be noted, however, that a geological survey at the location, coupled with drilling, remains the only certain method for exploration of mineral deposits at depths greater than approximately 100 ft. from the surface.

If methods of detection effective at greater depths could be developed the supply of metals for man might be increased, since the tops of nearly all the ore bodies which have been found are no more than 100 ft. from the surface. Thus, at present most of the easily mineable bodies have been located and it would seem that the day of the successful lone prospector is past since the deeper ore bodies can be located only at considerable expense.

The existence of considerable reserves at great depths below the earth's surface is yet unproven, but the possibility unfortunately encourages extravagance and unjustified optimism.

Minerals in Common Rock

The average abundance, or "Clarke" of various minerals in common rock is shown in Table 3, and compared with the abundance in commercial ores. It will be noted that the concentration of aluminum and iron in common rock is relatively high, and these materials could be extracted from common rock when the more profitable ore deposits are depleted. It is also most fortunate that titanium is relatively abundant in common rock since it can take the place of stainless steel when nickel and chromium resources are depleted. On the other hand, common rock contains very little chromium, zinc, nickel, copper, tungsten, tin, lead and mercury - these are from 200 to 10,000 times less abundant in common rock than in commercial ores. Some rocks contain a higher "Clarke" than others, and this will be of interest when mining of common rock is contemplated.

Metal Production Rates

Figures 1, 2 and 3 show the world extraction rate from ore for the principal industrial metals over a period of years. In all cases, the final production rate is somewhat inflated by the amount of recycled metal employed. It is said, for example, that 70% of the copper ever mined is still in use or in circulation.

Iron, the principal metal, is extracted at about 400 million tons per year, with a linear increase of 17 million tons per year. Manganese, aluminum, copper, zinc and lead, at an extraction rate of a few million tons per year, reflect a different pattern of production and consumption.

Aluminum, from the status of being a curiosity from which medals were struck, has established itself in 80 years as one of the most versatile metals. Its utility and competitive cost are reflected by the fact that the production rate is increasing more rapidly than that for any other metal. It is produced by electrolysis from the relatively abundant mineral, bauxite.

The demand for copper, the metal of electrical engineering, is by

TABLE 3: CONCENTRATION OF MINERALS IN COMMON ROCK AND IN ORES.
(All figures in parts per million by weight)

Mineral	A In common rock[a] (continental crust)	B In commercial ores[b]	Ratio B/A
Aluminum	83,000	270,000	3.2
Iron	48,000	250,000	5
Sodium	28,000	-	-
Potassium	26,000	-	-
Magnesium	21,000	100,000	5
Titanium	5,300	100,000	20
Manganese	1,000	20,000	20
Zirconium	185	-	-
Vanadium	120	5,000	42
Zinc	81	40,000	500
Chromium	77	15,000	200
Nickel	61	15,000	250
Copper	50	10,000	200
Lithium	22	800	40
Niobium	20	900	45
Cobalt	18	700	40
Lead	13	30,000	2,300
Thorium	6.8	1,000	150
Tantalum	2.3	20,000	9,000
Uranium	2.2	2,000	900
Tin	1.6	10,000	6,200
Tungsten	1.2	5,000	4,000
Molybdenum	1.1	2,500	2,200
Cadmium	.15	200	1,300
Mercury	.08	2,000	25,000
Silver	.065	100	1,500
Platinum	.028	10	350
Gold	.0035	15	4,000
Bismuth	.003	100	33,000

[a] Lee, Tan and Yao, Chi-lung, 'Abundance of Chemical Elements in the Earth's Crust and its Major Tectonic Units', *Internat. Geol. Rev.*, vol. 12, no. 7, pp. 778-86, 1970.

[b] U.S. Department of the Interior, *United States Mineral Resources*, Geol. Surv. Prof. Pap. 820 (1973).

contrast levelling off. In transmission lines it is being replaced by aluminum which, although it has half the electrical conductivity of copper by weight, is superior on a volume basis. In other applications, plastics, aluminum and coated steel have replaced the more expensive copper product.

Many of the other metals, although not produced in great quantity, are currently considered essential to our industrialized society. Among these are manganese in steel making, lead for batteries and gasoline, and chromium and nickel for the production of alloys. Tin, a soft, low-melting-point metal, is essential in solder and bearings and is now finding use in superconductors. Regrettably 60% of the tin mined has been used for the manufacture of tin cans and is now irretrievably lost. Tungsten, the hardest of all the metals, is of course employed for the production of tools for cutting other metals, and is thus a small but vital link in this industrial society.

It is an interesting fact that the proportions of different metals produced have remained nearly constant over long periods of time. Thus, in the U.S. for each ton (2000 lbs.) of steel, 40 lbs. of copper, 37 lbs. of lead, 27 lbs. of zinc and 4 lbs. of tin are used. This constancy in the proportion reflects the definite composition of alloys and the complementary use of metals in many applications. It also points to the inflexibility (inelasticity) in the demand for metals. Some variation in the proportion is to be expected however as substitutes, perhaps of plastic origin, are introduced.

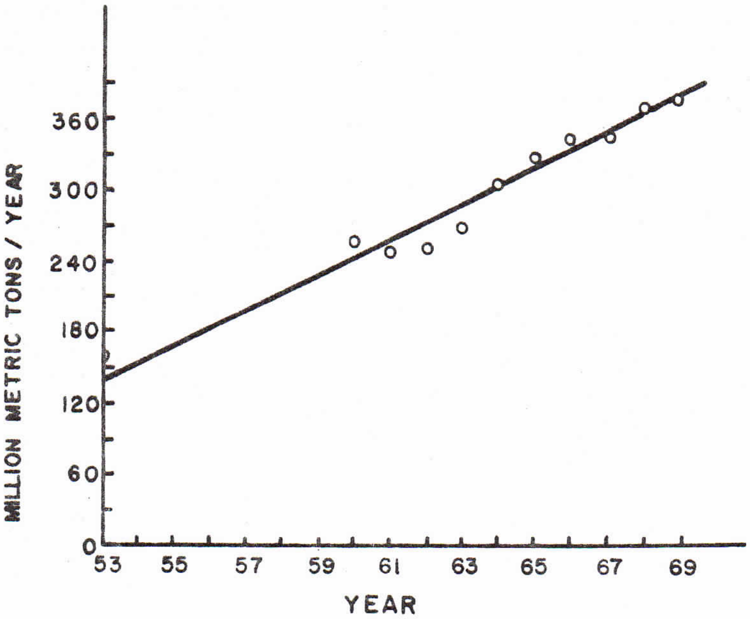

FIGURE 1 WORLD PRODUCTION OF IRON FROM ORE
(Source: *United Nations Statistical Yearbook*)

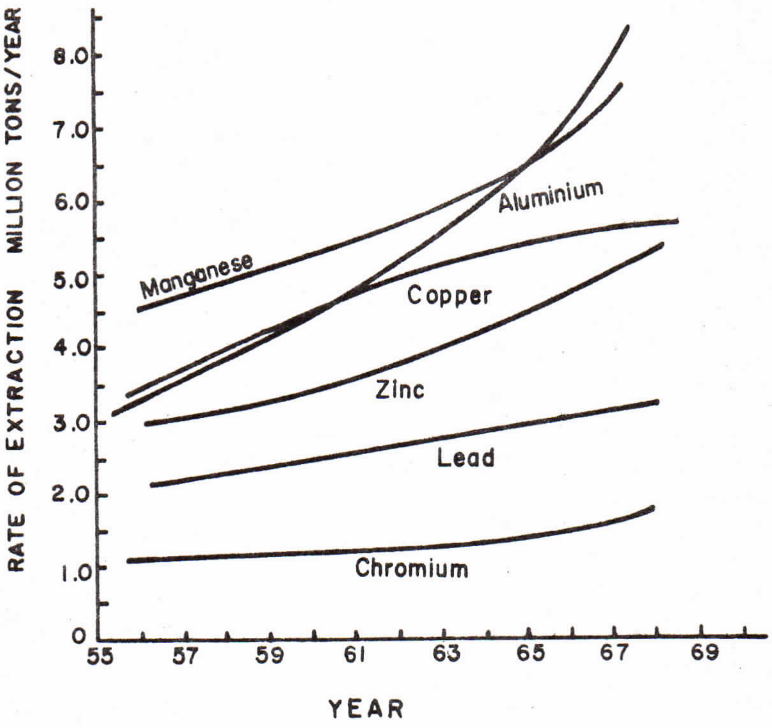

FIGURE 2 WORLD PRODUCTION OF VARIOUS METALS
(Source: *United Nations Statistical Yearbook*)

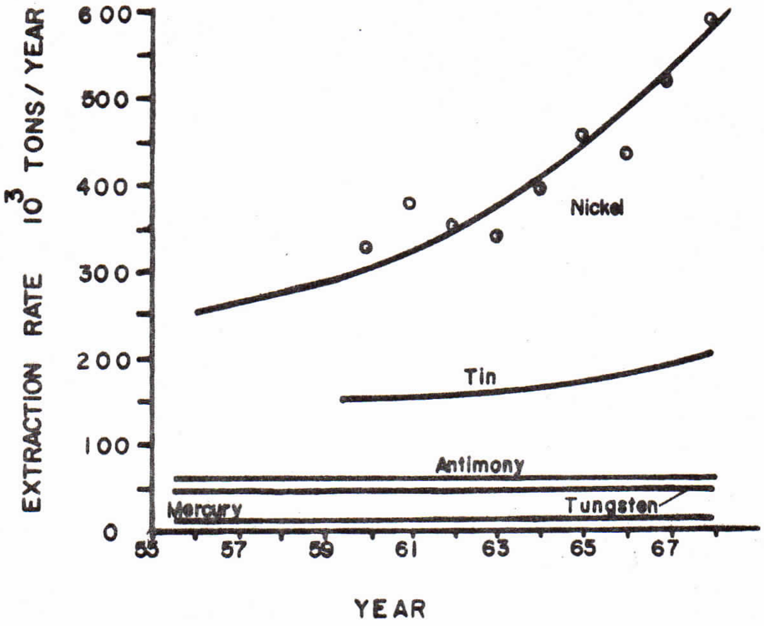

FIGURE 3 WORLD PRODUCTION OF VARIOUS METALS
(Source: *United Nations Statistical Yearbook*)

As previously noted, another approximate relationship exists between energy use in tons of coal equivalent per year and the total cumulative quantity of steel in the world, which currently stands at approximately 7 billion tons. Apparently energy and metals are consumed in proportion to the amount of equipment and structures in use. Unfortunately, the metal reserves in nature do not exist in the same proportions observed in their practical utilization. It is interesting to reflect upon what would happen if a group of metals became unavailable. Would adequate substitutes be found or would the whole system be deflated, perhaps to the point of collapse? The widespread depletion of metal and energy reserves is such that answers to such questions must be sought with some urgency in order to plan for substitutions and alternative manufacturing processes.

Metal Reserves

It has been previously noted that the reserves of ores cannot be precisely estimated, although it would be fair to assume that most of the readily detectable and mineable bodies have now been discovered. However, the precise size of the metal reserves is unimportant. Of overriding importance is the lifetime of the reserves, which is affected more by the exponential increase in consumption than by any errors, however gross, in the estimates of the reserves themselves. The truth of this statement is reflected by the data of Table 4, which shows the known reserves of most industrial metals.

The second column of this table gives the lifetime of the reserves assuming the present rate of use continues, whereas the fifth column reports the lifetime assuming the present growth rate continues. The lifetimes reported in column 6 have been estimated on the basis of five times the presently known reserves with the present growth rate continuing. It will be noted that with exponential growth the increase in reserves by a factor of 5 in most cases only results in approximately doubling the lifetime of the reserve. The location of reserves and the main producers of metals are of considerable future political and economic interest. This information is reported in columns 7 and 8.

The reported reserves are those that have been measured and estimated and cover a range of all grades but exclude the very poorest. The total known and potential reserves may be several times larger, possibly from two to six times or more, depending on the particular metal and on the ore grades included. Large areas of the planet still remain to be searched thoroughly. Established ore-bearing areas will undoubtedly be reviewed more thoroughly, particularly with respect to the occurrence of ores at greater depth. New understanding of geophysics and geology will help to focus the search on the most promising areas. The reported figures are, however, the best available to the public at the present time and are sufficient to indicate future concerns.

Column 5, for example, shows that if no new deposits are found, the world will run out of most metals in from 10 to 50 years. The same result will occur in between 30 and 100 years even if 5 times the current ore quantities are discovered. These depletion times assume, however, that economic growth will continue at the present rates, but depletion would set in much earlier if the underdeveloped countries were to industrialize. It thus seems highly probable that most of the world will run out of essential metals, as ore, some time during the 21st century.

Since the ore bodies and rates of consumption are not uniformly distributed throughout the world, the effects of depletion would affect some countries first. In Europe, for example, the depletion of the local reserves has already occurred, and in the U.S. it is now beginning. Consequently Europe, the U.S. and Japan are obtaining their metals from the Third World. It is clear that the rich nations depend very heavily upon the poor for their high standard of living.

Only three countries appear to have the range of reserves necessary for complete independence. Of these only the U.S.S.R. has sufficient quantities of most metals, large energy resources and the military power to defend them to enable this country to maintain a high level of industry and living for the next one to three centuries. Brazil also has large reserves of many metals, but lacks an energy supply, except for wood and hydro power. Brazil is also an underdeveloped country without military power, and may be forced to trade its inheritance. Canada, in contrast, has large known and potential reserves of metals and energy, although it lacks a few important metals. Canada could thus independently maintain a high level of industry and life for several centuries with the current population. Like Brazil it is not a military power, but unlike Brazil it is not forced to trade its resources in order to develop an industrial status. It is difficult to see, however, how Canada can preserve its resources in a have-not world even if it were determined to do so.

The approaching depletion of metals and fuels is likely to give rise to more problems than those of simple stagnation and the possibility of the collapse of industry. It can be envisaged that in the last desperate effort to hold on to the remaining resources the industrial countries might try to dominate, once again, the Third World and antagonize each other in doing so. It has been suggested that the case of tin may be an ominous example of things to come - 72% of the reserves of this relatively

TABLE 1: KNOWN RESERVES OF METALS AND THEIR EXPECTED DURATION[1,3]

Metal	Known Global Reserves (metric tons)	Duration at present rate of use (years)	Average Projected rate of growth (% per year)	Duration with average growth (years)	Same as Column 4 but with 5 times known reserves	Areas or Countries with largest reserves (% of total)	Prime Producers (% of total)
Aluminum	1.06×10^9	100	6.4	31	55	Australia (33) Guinea (20) Jamaica (10)	Jamaica (19) Surinam (12)
Chromium	7.05×10^8	420	2.6	95	154	S. Africa (75)	U.S.S.R. (30) Turkey (10)
Cobalt	2.2×10^6	110	1.5	60	148	Congo (31) Zambia (16)	Congo (51)
Copper	280×10^6	36	4.6	21	48	U.S.A. (28) Chile (19)	U.S.A. (20) U.S.S.R. (15) Zambia (13)
Gold	10^4	11	4.1	9	29	S. Africa (40)	S. Africa (77) Canada (6)
Iron	9×10^{10}	240	1.8	93	173	U.S.S.R. (33) S. America (18) Canada (14)	U.S.S.R. (25) U.S.A. (14)
Lead	83×10^6	26	2.0	21	64	U.S.A. (39)	U.S.S.R. (13) Australia (13) Canada (11)
Manganese	7.3×10^8	97	2.9	46	94	S. Africa (38) U.S.S.R. (25)	U.S.S.R. (34) Brazil (13) S. Africa (13)

Mercury	115×10^3 tons	13	2.6	13	41	Spain Italy	(30) (21)	Spain Italy U.S.S.R.	(22) (21) (18)
Molybdenum	4.9×10^6	79	4.5	34	65	U.S.A. U.S.S.R.	(58) (20)	U.S.A. Canada	(64) (14)
Nickel	67×10^6	150	3.4	53	96	Cuba NewCaledonia U.S.S.R. Canada	(25) (22) (14) (14)	Canada NewCaledonia U.S.S.R.	(42) (28) (16)
Platiuum Group[2]	12×10^3	130	3.8	47	85	South Africa U.S.S.R.	(47) (47)	U.S.S.R.	(59)
Silver	1.55×10^5	16	2.7	13	42	U.S.S.R. China U.S.A.	(36) (24)	Canada Mexico Peru	(20) (17) (16)
Tin	4.3×10^6	17	1.1	15	61	Thailand Malaysia Indonesia	(33) (14) (13)	Malaysia Bolivia Thailand	(41) (16) (13)
Tungsten	1.32×10^6	40	2.5	28	72	China U.S.S.R. U.S.A.	(25) (19) (14)	China U.S.S.R. U.S.A.	(32) (18) (12)
Zinc	112×10^6	23	2.9	18	50	U.S.A. Canada	(27) (20)	Canada U.S.S.R. U.S.A.	(23) (11) (8)

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[1] Sources: *The Limits to Growth* and *Mineral Facts and Problems.*

[2] These metals are platinum, palladium, iridium, osmium, rhodium and ruthenium.

[3] More recent publications give a more optimistic picture of mineral resources.

scarce essential metal available to the Western nations are to be found in Southeast Asia. Only future revelations will discount or prove a possible connection between tin reserves and the Vietnam conflict.

The commonsense and obvious way to prevent all these future calamities is to gain time for thought and action by restricting the use of the scarce metals to the most essential functions. Unfortunately at present the only control mechanism available is the free market price system, but this only responds to events that are expected in the next decade and has little influence on long-term events. This is clearly then an area for international action by all governments, and such action may indeed come as a result of the growing awareness of the future resource problems.

To some extent the action is being delayed by the optimists who quite rightly emphasize that the dire predictions of the past have proven to be incorrect as technology or new resources were developed. In recent times the sulphur shortage scare has provided evidence for this confident conclusion. However, while in the past conclusions were drawn in considerable ignorance of the possibilities, today there is very much more knowledge on which to base predictions, so that the comparison is not valid.

MINING AND EXTRACTION OF METALS FROM LOW-GRADE ORES, COMMON ROCK AND SEAWATER

It is often stated, particularly by those with a background in economics,that as the richer ore deposits become depleted metals will be obtained from poorer ore deposits, common rock and seawater. They postulate that improvements in technology, and the economy of ultra-large operations in technical achievements to reduce the cost of power, will make these sources economically satisfactory for many years to come.

The economy of scale has been well established, but in view of the large plants now in operation it is doubtful whether a further increase in scale would significantly reduce the extraction charges. The prospects for energy have already been considered and the optimistic forecast of abundant low cost energy has been challenged. An appraisal of these new potential sources of metals is therefore needed in order to completely evaluate the confident optimist's belief that developing technology will be adequate insurance against metal depletion.

Extraction of Metals from Low-Grade Ores

Barnett and Morse in their book *Scarcity and Growth*, conclude that the confident optimist's beliefs are correct. However, their analysis is based on the assumption that there are vast quantities of metal in the lower-grade ores so that there can be no question of supply but only of cost. This critical assumption of vast quantities of metals contained in the poorer ores cannot be justified. On the contrary the available evidence points in the opposite direction, in that the poorer ores contain a smaller fraction of the total metal and that the rich deposits by contrast contain the largest fraction.

This disturbing fact is revealed by a study of the mercury and porphyry copper ores in the United States. These studies encompassed the eight major deposits of copper known in 1950 and most of the known deposits of mercury. The results are shown in graphical form in Figures 4 and 5. In both cases it will be noted that the resources of metal contained in the downgrade ores are marginal. Thus, for example, when the copper has been extracted from the current .6% grade ore, over 60% of the copper contained in all the ores will have been utilised. While it may not be possible to generalise the conclusions drawn from these two cases, they do give weight to the probability that other metallic ores exhibit a similar relationship.

The significance of this is underscored when it is realised that most of the metals are to be found in a few rich deposits in widely isolated areas of the world. Once these are depleted there can be no hope that they will be replaced by other large deposits of high or low-grade ores. The U.S., for example, has no significant deposits, even those of poor grade, for tin, tungsten and nickel.

The variation in quantity of ore versus the grade in the prophyry copper ores were studied by Lasky who discovered that the following relationship was obeyed:

$$G = K_1 - K_2 \ln Q$$

where G is the ore grade in % metal, Q is the amount of ore and K_1 and K_2 are constants peculiar to the ore type. This formula is also known as the A/G ratio (arithmetic/geometric). It has been found to hold for some other deposits similar to the porphyry coppers, "in which small quantities of ore are scattered through great volumes of shattered rock". The formula is applicable to the range of grades between 1 to 2% metal and therefore is not applicable to very rich deposits or to very low-grade ores approaching in value the "Clarke" in average rock. Lasky's formula may also not be applied to ores containing mercury, zinc, gold, silver, tungsten, antimony and the rare elements.

In spite of these restrictions the formula is useful in exploring the question of mineral abundance. On semi-logarithmic paper with G plotted on the linear axis and Q on the logarithmic axis, the relationship

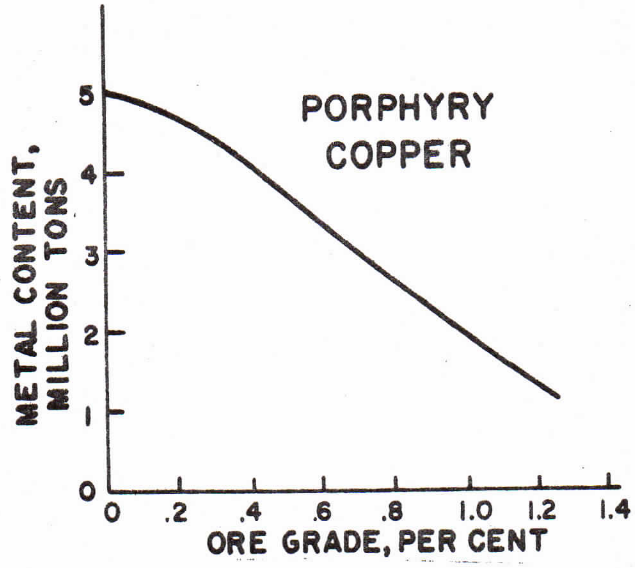

FIGURE 4 CUMULATIVE METAL VS. GRADE FOR PORPHYRY COPPER ORES IN THE UNITED STATES. (Data from *Resources and Man*)

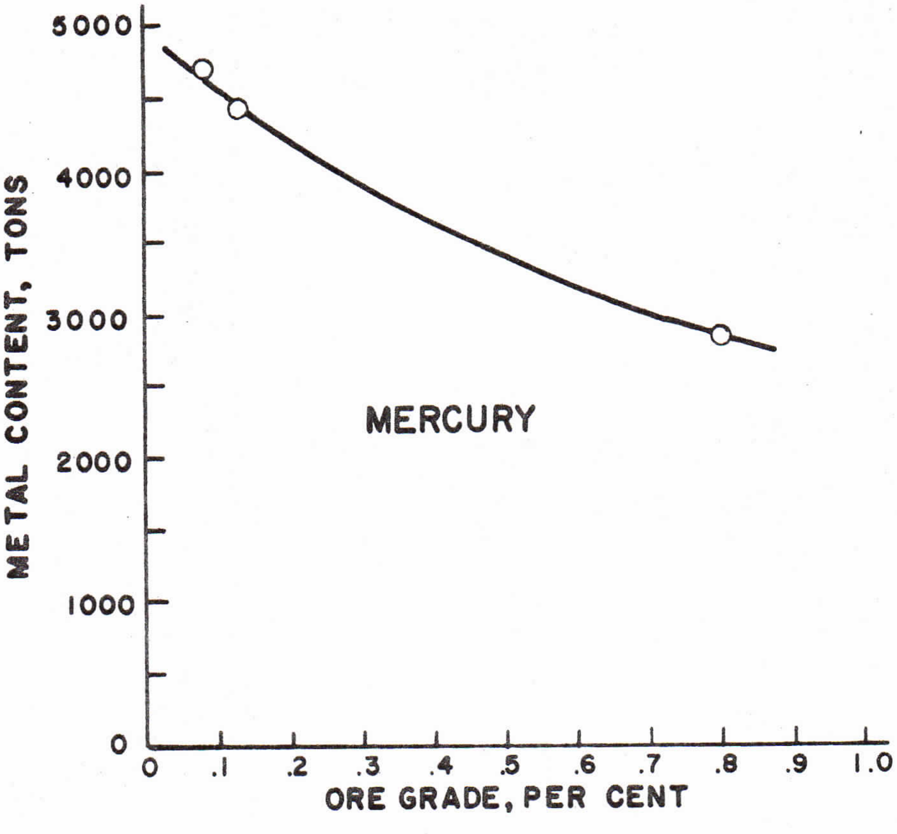

FIGURE 5 CUMULATIVE METAL VS. GRADE FOR MERCURY ORES IN THE UNITED STATES (Data from *Resources and Man*)

is clearly linear. K_2 is the slope of the line and the greater its value the greater the tonnage of ore at the lower grades. It will be noted that the curve cuts the Q axis at G = 0, from which an upper limit to the total quantity of ore may be found as being:

$$Q = e^{K_1/K_2}$$

The actual quantity will be less than this since a cut-off point is reached for economic reasons before the grade becomes zero.

The quantity of ore between two grades G_1 and G_2 may be found by integration as being given by:

$$\Delta Q = e^{K_1/K_2} \left(e^{-G_2/K_2} - e^{-G_1/K_2}\right)$$

The quantity of metal can be obtained by further integration to provide the relationship:

$$M = K_2\, e^{-G_2/K_2} (G_2 + K_2) - K_2\, e^{-G_1/K_2} (G_1 + K_2)$$

Mining Common Rock

Would it be possible to obtain our metals from common rock when the rich mineral deposits are depleted? This will of course depend on the cost of extraction. The rare metals Cr, Zn, Ni, Cu, W, Sn, Pb and Hg make up together 560 parts per million (Table 3). Extensive basaltic rocks may be found where the corresponding sum is 1000 parts per million or a kilogram per ton of rock. It will be more economical to mine all these elements together from the same rock.

Because of the low concentration of these minerals, chemical methods of separation must be used. The rock must be dissolved in acid (1 part rock, 2 parts acid) which can be used only once. From then on various techniques may be used to remove the metals. The acids must be of the more expensive type (HCl, HNO_3, HF). Thus the total cost of obtaining one kilogram of these metals (i.e. per ton of rock) will range from \$100 to \$500. The same quantity of metal costs about one dollar now. At such a cost most present uses of these metals will have to be discontinued.

The question is: Are there any uses that are so essential as to justify these high costs? There are such uses where the quantities involved are small, e.g., catalysts and other scientific uses. Some other essential uses will require larger quantities, e.g., tin for solder and superconductors, copper for electrical applications and in walls of future fusion reactors, etc. High production costs may therefore force man to abandon some of his more essential industries.

Instead of mining rock directly it has been suggested that man find indirect ways of obtaining his metals. For example, there are some plants and bacteria which tend to concentrate specific elements. It may be possible to cultivate the type that could concentrate a given metal. At the present time these ideas are interesting curiosities rather than distinct possibilities.

Minerals from seawater

Many minerals are dissolved in seawater. Table 5 shows the concentration of a few elements. Considering the large volume of the oceans the absolute quantities of these minerals are enormous even at very small concentrations. Some of these minerals, such as magnesium, potassium and lithium, are already being obtained from salt water, particularly from salt lakes of high salinity. A few more might be obtained in future but the prospects for getting such essential elements as copper, tin, zinc, lead, etc. do not seem promising because of their very small concentrations. Some promise may lie in the ability of some types of plants to concentrate certain elements. The Japanese have succeeded in developing sea plants that concentrate iodine by a factor of a million. It is not clear though whether similar success may be expected with the much needed metals.

TABLE 5: CONCENTRATION OF SELECTED ELEMENTS IN SEAWATER

Element	Concentration (parts per million)
Chlorine	20,000
Sodium	11,000
Magnesium	1,430
Potassium	400
Bromine	68
Lithium	.2
Rubidium	.12
Iodine	.06
Zinc	.01
Tin	.004
Copper	.004
Gold	.00004

Minerals from the Seabed

Lying at the bottom of the oceans in concentrations of a few pounds per square foot there are hundreds of billions of tons of potato-shaped "manganese nodules". The Pacific Ocean is richest of all the seas in terms of quantity and composition of nodules; a typical composition and total reserves of the major constituents are shown in Table 6. For these metals the seabed reserves are obviously much greater than those of the land.

Considerable experimentation with collection methods is being carried out in various parts of the world, but it is believed that the costs of recovery from the seabed will greatly exceed costs of mining on land. It is important to remember, however, that when land reserves are depleted, metals from the sea will be considered cheap when one considers the alternatives.

In addition to the nodules, metalliferous muds have been discovered, e.g. in the Red Sea. Little is known at present about the composition and the extent of these muds.

Mining the ocean bottom will pose more problems than are immediately obvious. Pollution is one of them. Fine muds, brought up to the surface, can give rise to fine suspensions which could spread out over wide areas and take centuries to resettle. In doing so they could block out the sunlight and thus cause plankton life to disappear.

TABLE 6: COMPOSITION AND RESERVES OF METALS IN "MANGANESE NODULES" IN THE PACIFIC OCEAN

Metal	Weight % of "nodule"[a]	Total reserves in Pacific Ocean (billion tons)	Total known land reserves (billion tons)
Manganese	33	360	.7
Iron	18	196	-
Aluminum	3	33	-
Nickel	1.1	12	.067
Copper	.8	8.7	.3
Cobalt	.5	5.5	.002
Lead	.2	2.2	.08
Zinc	-	1	.1
Other	44	-	-

[a] From *Mining in Canada*, July 1970.

Answer to Depletion

In order to prolong the life of the existing supplies of the rarer metals a number of steps could be taken. All frivolous uses of such metals (e.g. tin cans) should be eliminated and only the more essential ones kept. This could be achieved completely by international governmental action, but action even within one country could dramatize the problem and precipitate action elsewhere. In the meantime an intensified search for plentiful substitutes should be carried out. Recycling of the used quantities would ensure the lengthening of the lifetime of these resources.

A more thorough search of the planet and development of techniques to search to greater depths and to mine the ocean bottom could also increase supplies and provide time in which substitutes could be sought. In some cases (tin, lead, copper, zinc, silver, gold and tungsten) supplies are so limited that appropriate actions should be taken immediately.

Substitutes for Scarce Materials

It is commonly believed that when a resource that serves man in some way becomes unavailable, another one can always be found to take its place. Everyday life provides countless examples. Even if the resource is unique in some way and the function it serves is critical for man, the optimistic belief persists: "Science will come up with something" or "the infinite ingenuity of man will find a way"; and even if nothing can be found there may be some inconvenience but no serious threat to progress and ever greater prosperity.

Thus today's concern about the problems that man faces in his dependence on non-renewable resources is not shared by all or even by the majority. The man in the street and most economists are equally optimistic that science and technology can solve these problems when they arise. But this optimism is not shared by scientists and technologists who have a more intimate knowledge of the problems and of the limitations of science and technology.

Consider the role that the metals play in modern technology. There are only a few of them and each has some unique basic physical property which, as yet, cannot be created artificially in materials other than metals or their alloys. Such unique properties have made important activities, even entire industries, possible for man. Indeed, some metals have a combination of unique properties which render them most valuable and indispensable in their uses.

The combination of all those properties and the resulting uses have made it possible to create our high performance technology which, coupled with other resources, has in turn made modern life possible. This did not have to be so. It was a lucky accident that the essential building blocks were there. If some such basic building block becomes unavailable and the edifice is threatened, nature does not guarantee an alternative merely because one is needed. And even if it did, much time and work would be needed to incorporate it into the edifice. The loss of a few important resources could have a crippling effect on modern industry. The same could happen if a larger number of minor resources were lost. And since deficiencies do not act in isolation but tend to reinforce each other, the combined effect can be much greater than the sum of the individual effects. Thus the performance of our technological system could be lowered sufficiently to threaten everything that depends on it, including not only our style of life but also our numbers.

What possible substitutes are there for our essential metals? First we should look to metals that are more plentiful. This substitution, when possible, will extend the life of our industrial activities, but in the long run, for the heavily used metals, there are only three ultimate substitutes which exist in practically infinite quantities: iron, aluminum and titanium. There is also magnesium, whose usefulness is limited because of its high reactivity, but which may be used in alloys. Sodium and potassium, also very abundant, have some limited uses, but as metals they are nearly useless. It may also be possible to use non-metals in alloys.

It should be kept in mind that the problem of substitution in the future will not be the same as in the past. The excellent substitutes of the past came from that same group of metals that now face depletion. Thus in the past there was an expansion of choice and substitution was optional; in the future there will be a contraction of choice and substitution will be forced. On the positive side must be added the greater knowledge that man may have in the future, which will help him to utilize what he has in better ways.

RECYCLING

Although man consumes materials it should be remembered that those materials are not destroyed. They merely change form. Over 20 tons of materials from the earth's crust are utilised for the benefit of a single individual on this continent, but except for the amount which is recycled or indefinitely preserved, this entire amount very rapidly appears as waste in gaseous, liquid or solid form.

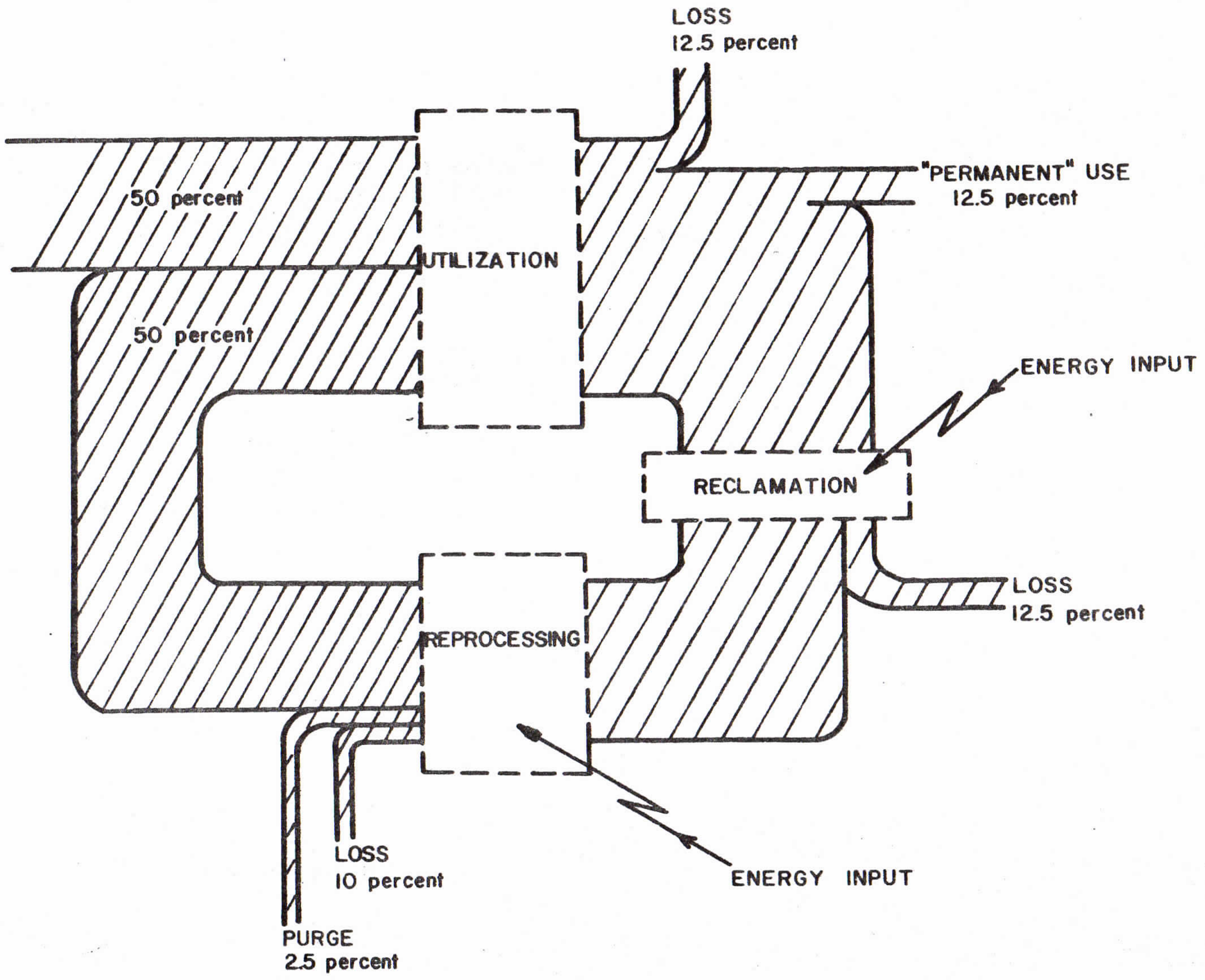

FIGURE 6 THE RECYCLING PROCEDURE, SHOWING INEVITABLE LOSSES AND ENERGY REQUIREMENTS.

As indicated in Figure 6, wastes can be reclaimed and recycled at every stage in the production - utilization chain. It might be inferred, even from this diagram, that the recycling process becomes more effective as the cycle is shortened; this also leads to a decrease in the overall pollution effects.

The recycling of materials is not a new concept. Industries practise recycling of materials at the production stage whenever it can be shown to be both practical and economical. In the plastics and glass industry most of the trimmings and scrap during the manufacturing stage are immediately recycled. The metal industries have traditionally exerted every effort to recycle material. Thus, for example it is said that at least 70 percent of the copper produced in the world is still being utilized, and twice as much lead is recovered as is mined. Nevertheless, there are both inevitable and preventable losses of such magnitude that the reclamation of materials will become of increasing significance in the future.

The reclamation and recycling of materials on a large scale will need to be shown to be economically justified unless these processes are demanded or encouraged by legislation. At best, the process of recycling will merely serve, however, to reduce the rate at which the resources are utilized. Self-sufficiency by the introduction of recycling procedures is not possible. This point is illustrated in Figure 6.

In constructing Figure 6 the most fortunate circumstances have been presumed. Losses in the utilization of a typical material have been set at only 12.5 percent and the long term use of the material has been assumed to result in a similar figure. Immediately, therefore, the amount which can be readily reclaimed is reduced to 75 percent of the material utilized. Losses in the reclamation system have also been set at a low figure of 12.5 percent, whereas with current technology losses of 50 percent could be incurred. Finally, in the reprocessing step a further physical loss is unavoidable. This has been set at 10 percent, and might be deliberately increased by a purge stream to reduce the accumulation of undesirable materials in the total cycle. Thus in this simple analysis it is seen that for many materials and with favourable circumstances the recycled stream may only contribute an amount of material equal in amount to that produced from virgin resources.

To put recycling into perspective we need to conclude that although this process will extend the useful life of our resources, and serve to reduce pollution levels created by the preceding production process, even the universal introduction of recycling processes will merely postpone the

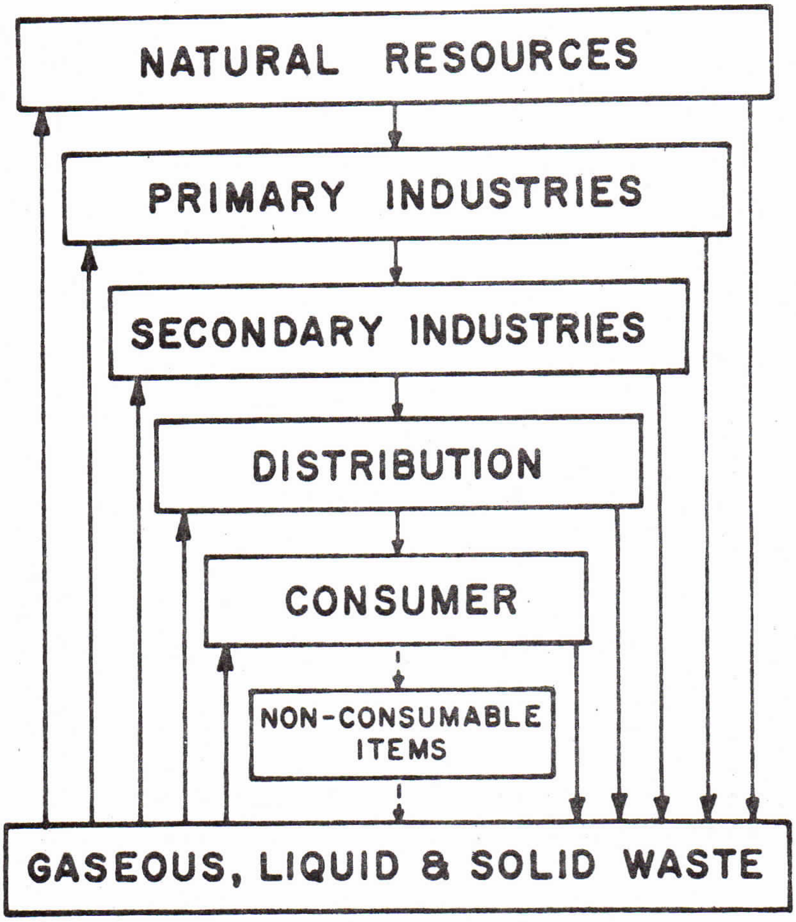

FIGURE 7 THE RESOURCES, WASTE AND RECYCLE RELATIONSHIP.

exhaustion of the current rich resource deposits by thirty to fifty years. This is, however, not an argument for continued extravagance and waste since this extension of the current resources could provide the critical time needed for the development of new technology and in particular could greatly reduce the energy consumption for materials production, both now and in the future.

STUDY OF COMPLEX RESOURCE PROBLEMS - USE OF MATHEMATICAL MODELS

All the resources are used in conjunction with each other and an individual resource cannot be isolated and studied independently from the rest of the total technological system. Complex interrelationships exist which so far have precluded any thorough understanding or any projection of the course of technology into the future. Only simple projections into the very near future could be made with the laws of chance and those of supply and demand exercising control.

From the world of science and in particular from the descriptions of physics a new means of analysis and projection has been developed. It has been found that phenomena cannot only be understood, sometimes thoroughly, but also controlled by the understanding provided by mathematical description in the form of a "mathematical model". It is pertinent to enquire whether similar methods can be devised to represent the more complex industrial and social systems.

Three major difficulties were immediately apparent. The first was to determine the laws of the system and to represent them in mathematical form. The second was to solve the resulting mathematical model and the third was to discover how to apply action and affect the system. Up to about 1965 the second difficulty was the absolute stumbling block. The mathematical model, where it could be formulated, was too complex to solve. But with the coming of the fast computer, the "supercomputer", this block was removed. Models could then be written and solved for complex systems with highly coupled components. Many of the restrictions on the model required in order to obtain solutions by the old analytical techniques, were removed. Thus the class of problems that could be solved was widened greatly. In engineering the development of a large-scale mathematical model is now a routine matter. The computer has also invaded the wider field of complex mixed systems involving both physical and social processes and many problems have already been solved.

An initial attempt to formulate and solve the problem of resources for the whole planet was made at the Massachussetts Institute of Technology. The principal components of the system were judged to be the following: population, non-renewable resources (metals and fuels), capital investment (and its fraction going to produce food), and pollution. The interactions between the components were partly known and partly assumed. Equations were written for the system and the model was solved by the computer.

Figure 8 shows what may happen if the present course of mankind continues into the future: resources will be depleted in the next century and the world will return to a mostly agricultural mode of life. (The quality of life in Figure 8 has been defined as a function of food, material standard of living, and absence of pollution and crowding.) With more resources made available, the model shows that pollution may increase to great levels so that a catastrophic collapse could result. These and other results have been publicized widely by the Club of Rome, the sponsors of the project, and much interest has been aroused.

This interest, at times highly critical, is the most important result of the project, since it has and will continue to accelerate the study of the important problems of mankind. More accurate models will be forthcoming and the information that could lead to timely action will become more convincing. As to whether action will be taken, one might be inclined to be pessimistic and cynical in view of our past history and current attitudes.

In the authors' opinion, however, there is no precedent for the changes which are about to occur. These, when seen in historical perspective, might appear as a sudden discontinuity in man's development, but will mark the impact of the education and information explosion. As with all exponential processes, the growth of information and education has been deceivingly subtle but is now at such a level that a further doubling could engulf the population of the world. The generation gap, work specialization and the tendency to overeducate or overtrain may indeed be merely uncomfortable symptoms of the imminence of this explosion.

Perhaps our definitions of progress and standard of living will, as a result, undergo such dramatic changes that we need have no fear that demands will outstrip our resources or cause intolerable pollution levels.

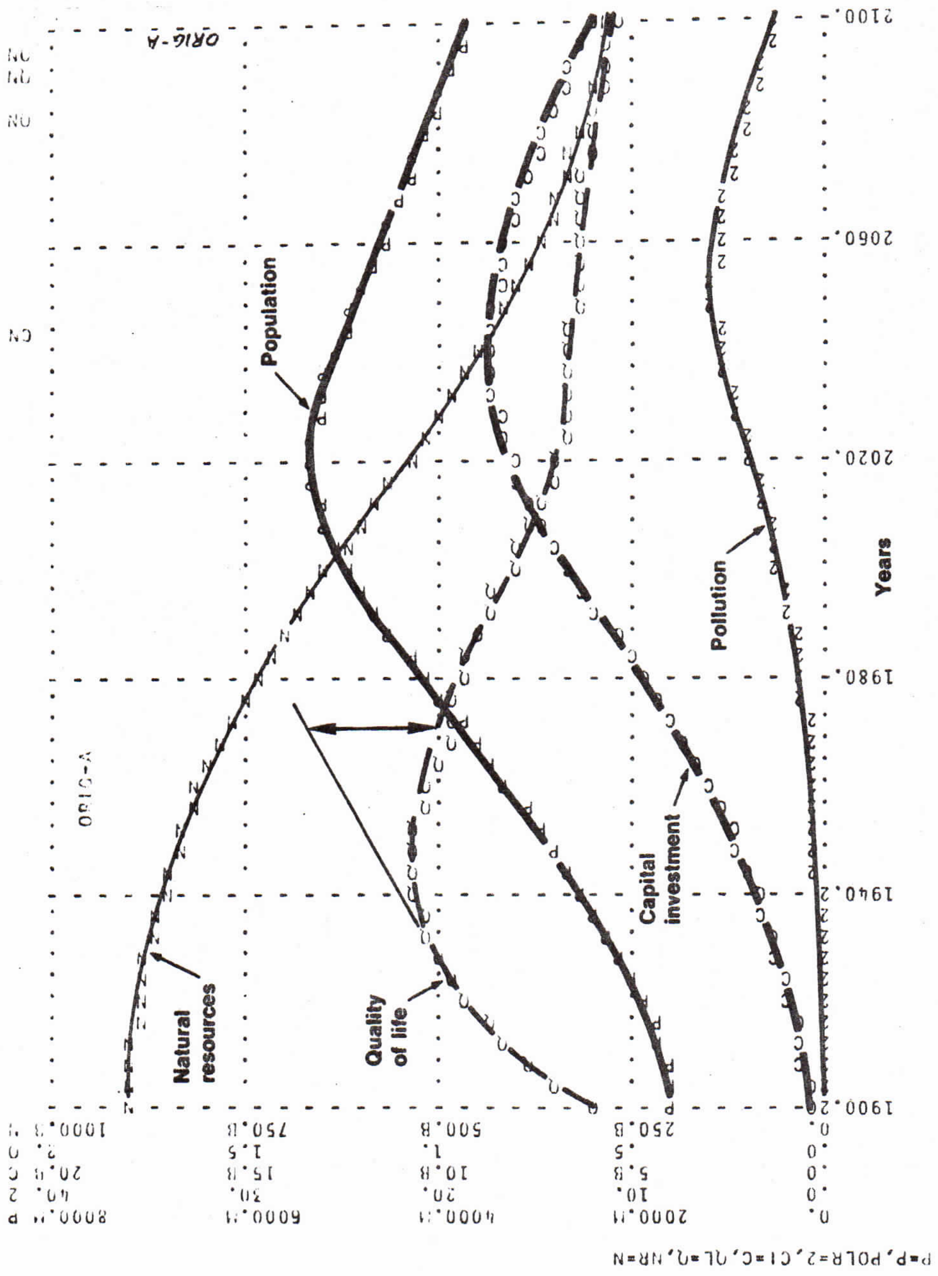

FIGURE 8 BASIC BEHAVIOUR OF FORRESTER'S WORLD MODEL, SHOWING THE MODE IN WHICH INDUSTRIALIZATION AND POPULATION ARE SUPPRESSED BY FALLING NATURAL RESOURCES (from Forrester, *World Dynamics*. Copyright 1971 by Wright-Allen Press, Cambridge, Mass. 02142).

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