

**METALS RECYCLING:
ECONOMIC & ENVIRONMENTAL
IMPLICATIONS**

by

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METALS RECYCLING: ECONOMIC & ENVIRONMENTAL IMPLICATIONS

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Abstract

We are in a period of economic transition. The "cowboy economy" of the past is obsolescent, if not obsolete. Environmental services are no longer free goods, and this fact is driving major changes. Recycling is the wave of the (immediate) future. The potential savings in terms of energy and capital have long been obvious. The savings in terms of reduced environmental impact are less obvious but increasingly important.

The obstacle to greater use recycling has been the fact that economies of scale still favor large primary mining and smelting complexes over (necessarily) smaller and less centralized recyclers. But this advantage is declining over time as the inventory of potentially recyclable metals in industrialized society grows to the point that efficient collection and logistic systems, and efficient markets, justify significant investments in recycling.

Increasing energy and other resource costs, together with increasing costs of waste disposal, will favor this shift in any case. But government policies, driven by unemployment and environmental concerns, taken together, may accelerate the shift by gradually reducing taxes on labor and increasing taxes on extractive resource use.

Background: The Present Situation

Economic development in the developing countries over the next half century, at recent growth rates, combined with unavoidable population growth, would require a many-fold (more or less) increase in the consumption of natural resources. But materials consumed by the industrial economic system do not physically disappear. They are merely transformed to less useful — or harmful — forms. In some cases (as with fuels) they are considerably transformed by combination with atmospheric oxygen. In other cases (such as solvents and packaging materials) they are discarded in more or less the same form as they are used. In the case of metals, the subject of this paper, they are chemically degraded and, in some cases, physically dissipated.

Enormous quantities of metal ores are extracted from the earth's crust. *Table I* shows world production of *concentrated* (or selected) metal ores and metals.¹ The rate of extraction is increasing rapidly (*Figure 1*). Annual production (i.e., extraction) of just three metal ores — copper, gold and iron — in the US in 1994 was about 2.5 tonnes per capita, not including overburden left at the mine [Adriaanse *et al* 1997]. Consumption levels in Europe are similar, although a higher percentage is imported (and more is exported).

Every substance extracted from the earth's crust is now a potential waste. With the exception of metals that are currently being recycled, in most cases it soon becomes an actual waste. This was not always true. Until the relatively recent past, metals were never discarded. They were too scarce and too valuable. During the last two centuries, and especially the last half century, things have changed radically. Today dissipative use and waste is virtually the norm, not only for paper and plastics, but even for silver, gold and platinum. For instance, chromium chemicals are used for leather tanning, algicides, metal plating and wood preservatives. Chromite is used as a refractory. Copper chemicals are used in wood preservatives and fungicides (especially in vineyards). Tetraethyl lead is still used as a fuel additive in many countries (including Europe); lead is also a major ingredient of metal protective paints, and solder. Zinc — normally contaminated by cadmium — is used for protective metal plating (galvanizing), batteries, paints and pigments, insecticides and in tire manufacturing.

Essentially all of the uses of arsenic -- a by-product of copper mining and smelting -- are both toxic and dissipative. The major uses are for herbicides, pesticides and wood preservatives. Similarly, almost all the existing uses of cadmium, which is generally found in zinc ores and extracted at the refinery, are inherently dissipative. These uses include electroplating, bearing alloys, pigments, and stabilizers for PVC. Much the same thing can be said of mercury, whose end uses include chlorine production, gold mining, fluorescent lights, small batteries, dentistry, thermometers, electrical switches, pesticides and pharmaceuticals. Even the "noble" metals are being dissipated: silver is used in photographic film, gold is used in micro-electronic circuitry, platinum and palladium are used in catalytic converters for reducing pollution from motor vehicles.

The only exceptions worth mentioning to the dominance of dissipative uses are in jewelry, coinage and long lived structural materials, especially steel and its alloys, aluminum and copper. Metals used for structural purposes are also relatively easy to recycle. Secondary production from new and old scrap in the US and recycling rates as a percentage of apparent consumption are summarized for the US in *Table II*. The fraction of metal obtained each year from secondary sources has risen fairly sharply between 1987 and 1991 in the case of aluminum (from 30% to 40%) and lead (from 56% to 69%, due to the ban on using lead in gasoline, a dissipative use) but has fluctuated or remained roughly constant in the other cases.

This modest increase is attributable to two factors reasons. One is that inventories of

recyclable metals in use have accumulated over time, and specialized technologies and markets for them have developed. The other reason is that the mining, beneficiation and smelting of primary metal ores is inherently dirty and energy-intensive. Moreover, the lower the grade of ore, the dirtier and more energy intensive the recovery process. Even though modern technology permits the capture of most toxic waste pollutants from the concentration and reduction processes, these materials must still be disposed of somehow.

There is a further complication: many compounds of most important metals other than iron and aluminum — including arsenic, cadmium, copper, zinc, lead, nickel, chromium, manganese, cobalt, vanadium, selenium and tin, as well as mercury — are quite toxic to animals and plants. The extreme toxicity of lead, arsenic, cadmium, and mercury is well-known. But salts of copper, zinc, chromium, tin, bismuth and thallium are also toxic enough to have found medical or agricultural uses as insecticides, fungicides, algicides, rodenticides and so on.

A number of very toxic minor metals are by-products of copper, zinc and lead mining *Table III*. (Lead itself is one of the most toxic). These include arsenic, bismuth, cadmium, cobalt, selenium, silver, tellurium and thallium. While many of these metals are recovered for use in other commercial products, the products in question — from pesticides, herbicides, fungicides and wood preservatives to pigments and batteries — are almost entirely dissipated in use or discarded after use.

Mining and Metallurgical Wastes and Pollution

The principal driver of change in the mining and metallurgical processing sectors in coming decades will be environmental problems. Of this there is little doubt. Regarding mining operations, it is primarily the tonnage of material handled and processed, and secondarily the technology used for concentration (beneficiation) of the ore that are of importance environmentally. Iron ore is produced in large quantities mainly because iron itself is used in large quantities: according to the US Bureau of Mines, approximately 900 MMT/y (million metric tonnes) of concentrated ore was shipped in 1991, not including about 325 MMT of gangue, plus comparable quantities of overburden left on site. See *Table IV*. The world's biggest iron ore producer (and consumer) is the former USSR (now the Community of Independent States, or CIS), followed by Brazil, Australia and China. The average ore grade (world) is about 58% (Fe), which means that 525 MMT of Fe was contained in the ore that was shipped. Most of this was converted first into pig iron in blast furnaces, and subsequently into finished (cast or wrought) iron or steel.

Since iron ore is a mixture of iron oxides, mainly Fe_2O_3 , the mass differential (375 MMT) consists mostly of oxygen, which combines with the carbon in coke producing carbon monoxide and carbon dioxide. A relatively small amount of other mineral impurities (mainly silica) is removed in the smelting process and, combined with limestone, producing a harmless mineral product, slag. In the US, blast furnaces consumed 57.4 MMT of ores in 1991, producing 13.3 MMT of slag. Assuming the same ratio worldwide, global iron slag production for 1991 was about 210 MMT. In the OECD countries slag is increasingly sold as a useful by-product for paving and other purposes. However old-style slag heaps are still a problem in some parts of the world.

Most blast furnaces use coke from coal.² Coking is probably the dirtiest process in the ferrous metal sector. Thanks to large investments in pollution control technology, modern coking plants in the industrial world now emit only small amounts of pollutants to the environment. However facilities built under communist regimes, such as those in eastern

Europe, CIS (former USSR) and China, are still typically almost uncontrolled. They emit significant amounts of particulates, carbon monoxide, benzene, xylene, toluene and other aromatics, ammonia and hydrogen sulfide. No specific data is available for the countries where environmental controls are weak. However Chinese authorities acknowledge that energy consumption in Chinese coking ovens ranges from 40% to 100% more than non-Chinese averages [Zhenping 1994, Table 1]. Much of this excess energy loss is directly translated into pollutant emissions. Apart from coke ovens, environmental controls are primarily needed to minimize the discharge waterborne acidic wastes or sludges, from "pickling" sheet or strip.

Aluminum, like iron, is obtained from ores of relatively high grade. The mining itself is a surface (open pit) operation, since the bauxite, the only commercial source of aluminum, is normally found in a thin layer. Almost all of it is found in the tropics. Overburden is removed by means of draglines and left on site. About 2.2 tons of crude bauxite ore yields one ton of dehydrated alumina (Al_2O_3), by means of the so-called Bayer process. This process consumes large amounts of lime and caustic soda, and generates a caustic waste called "red mud" (because of its iron-content) which is usually left in ponds near the alumina plant. Red mud is useless, corrosive and can pollute ground water, especially in wet climates.

The reduction of alumina to pure aluminum metal is done by electrolysis, and is invariably sited near a cheap source of electric power. About two tons of alumina and 0.5 tons of carbon anodes (made from petroleum coke), plus a small amount of aluminum fluoride, are needed to produce one tonne of aluminum metal; the mass differential is converted into carbon monoxide and carbon dioxide, plus some toxic fluorides. (The latter are dangerous if not rigorously controlled). Aluminum smelting is normally done in remote places mainly to exploit cheap electric power, but also to minimize the exposure of local populations to fluoride pollution. In general the aluminum industry is moving away from western Europe and North America. Recent smelting facilities have been built in Australia (using coal as a source of energy), Brazil and China.

Environmental problems associated with end use consumption and disposal of iron steel and aluminum are primarily due to the wide variety of "small" uses. Scrap from demolished structures, pipelines, worn-out rails and rolling stock, obsolete machinery, junk cars or the like is easily aggregated and recycled via electric furnaces. It is much less easy to recover metal economically from cans, bottle caps, wire products, aluminum foil, fasteners (e.g. nails), razor blades, mattress springs and so forth. These tend to be mixed with other kinds of waste (household refuse) or to be scattered over the landscape as litter. In this context, aluminum cans and bottle caps constitute by far the most serious eyesore since aluminum is highly corrosion resistant, whereas small iron or carbon steel objects eventually rust away.

Except for iron and aluminum, the quantities of solid mining and milling wastes produced by mining for metal ores is typically much greater than the quantities of processed metals, as indicated in *Table IV* above. See also *Figure 2*. For example, zinc ore averages 4.4%, lead ore 3%, nickel ore 2%, copper ore averages 0.9%; uranium ore averages 0.002%, gold ore and platinum ore around 0.0003%. To produce a ton of pure metal, on the (world) average, it is necessary to process 22 tons of zinc ore, 30 tons of lead ore, 45 tons of nickel ore, 110 tons of copper ore, 50,000 tons of uranium ore and 330,000 tons of gold or platinum ore.

These ores must be extracted, concentrated — perhaps in several stages — and finally smelted. In the US, gold mining accounts for nearly as much mine waste as copper mining (which is number one on the list). To be precise: domestic copper mining in the US generated 316 million metric tons of gangue (plus 600 million tons of overburden) and yielded 2 million tons of copper in 1994. By contrast, domestic gold mining generated 217 million tons of gangue (plus 587 million tons of overburden) but yielded just 326 tons of gold [Adriaanse *et al* 1997 p. 57].

In all of these cases concentration wastes, normally left near the mine, are very significant in absolute magnitude. In some cases, the concentration process is extremely dirty. Usually the ores are finely ground, screened, and then the useful fraction is separated from the waste fraction (gangue) by a chemico-physical process known as "froth flotation". Chemicals are added to the finely ground ore. These chemicals adhere preferentially to the surfaces of the desirable mineral fraction, encouraging clumping and coagulation and allowing the clumps to be captured in a chemical foam. The ore concentrate is then removed but the chemicals are simply left behind in huge impoundments near the mines. In dry climates (such as Arizona and Chile) probably no great harm results, but in wetter climates — as in Africa — there may be serious leaching into groundwater.

Most non-ferrous metals (copper, zinc, lead, nickel) are geochemically quite different from iron and aluminum (*Table II*). Technically, they are mostly sulfur-lovers, or "chalcophiles", meaning that they are typically found in nature as complex sulfides³ rather than oxides. Major metal co-product groups are also shown in *Table II*. Thus a copper, zinc, lead or nickel smelting operation will normally yield tailings slags, ashes flue dust, or sludges that are rich in some of the other metals, as well as by-product metals such as antimony, arsenic, bismuth, cadmium, selenium, tellurium, silver and gold. These may or may not be highly desirable in themselves (as silver or gold are). Several of these metals are not worth enough to justify highly efficient recovery methods. Thus significant quantities of minor metals are discarded or lost in refinery operations, mainly as smoke, dust and slag.

Prior to the actual smelting stage — which is very similar to iron smelting — most sulfide ore concentrates (including Cu, Zn, Pb and Ni) are first converted to oxides by heating in the presence of air to drive off the sulfur as SO₂, along with volatile metallic contaminants such as arsenic. This was one of the dirtiest of all industrial processes in the past, and there are still some old copper mining/smelting districts where literally nothing will grow, due to heavy arsenic contamination combined with erosion of denuded slopes. For example, the large copper-nickel refineries in the Sudbury district of Ontario has emitted as much as 2.7 million tons of sulfur oxides annually, causing severe damage to forest over 720 square miles (about 1850 km²) and lesser damage over a much larger area. Certain valleys in Tennessee and Montana in the U.S., and parts of the Kola peninsula of northern Russia, are among the other well-known examples.

Modern practice in the non-ferrous metals sector is to recover the sulfur as sulfuric acid. In fact, recovered sulfur is now a significant fraction of total sulfur supply in some countries (12% in the U.S.) But this is a recent development. Even twenty years ago (1974) the US Bureau of Mines estimated that only 30% of the sulfur content of copper ore smelted in the U.S., and 43% of the sulfur in lead ore was recovered as sulfuric acid [USBM 1975]. Recovery from zinc ore was 81%. The remainder was driven off into the air as SO₂. The sulfur recovery rate in non-ferrous smelting in the U.S. today is 95% [USBM 1994]. This is also true for copper smelters located in Western Europe and Japan, where emissions regulations are tight.

However, sulfur recovery in major exporting countries is much lower. A study done in 1989 estimated sulfur control indices for major exporting countries as follows: Australia (0%), Philippines (0%), Peru (0%), Chile (14%), Canada (26%), South Africa (39%), Zambia (70%) and Zaire (76%) [Chapman 1989, Table 3]. The average level of control for all exporting countries was estimated to be 32% [ibid]. Based on very sketchy information, to be sure, it is likely that emissions control for non-ferrous metal smelters in the former USSR and China is still very low if not zero. The health situation among residents of metallurgical districts in Russia and the former USSR is known to be catastrophic [Feshbach and Friendly 1992; Feshbach 1994, 1995].

Another kind of pollution problem arises in gold (and silver) mining. Modern large-scale gold mining operations use a process known as "heap leaching" using sodium or potassium cyanide as an agent to concentrate the gold ore. The cyanides remain in impoundments which can (and sometimes do) leak into groundwater. However an older and much more dangerous process was once standard practice, namely the use of mercury to amalgamate gold particles in low-grade ores (4-20 ppm). The gold-mercury amalgam is then heated, which vaporizes the mercury and leaves the gold. The vaporized mercury is probably oxidized in the atmosphere, but it ultimately condenses on soil or vegetation, washes into the rivers, and is taken up by plankton and aquatic food chains in the most toxic form, namely methyl mercury (CH_3Hg), which is biologically concentrated by fish and birds and is the cause of "Minimata disease".

This process was extensively used for gold and silver mining in the past, leaving large areas — such as the famous Potosi mines of Bolivia — as virtually uninhabitable "moonscapes". The mercury amalgamation process is still being used by small-scale illicit gold miners in the Amazon basin (known as "garimpos") who account for roughly half of Brazil's gold production. Illicit gold mining is not limited to the Amazon basin, of course, but occurs in remote regions of many less developed countries, especially Africa. There is evidence that gold mining is now one of the major uses of mercury, and causes of mercury pollution, in the world (after chlorine manufacture).

The same is true of other classic pollutants, such as leather tanning, and electroplating. Leather tanning, an extremely dirty industry, which uses large quantities of toxic chromic acid, has been moving rapidly out of Europe and North America, where strict pollution standards are required. Brazil and India are the two chief "beneficiaries" of this particular shift. (Shoe manufacturing is a rapidly growing industry in both countries). However, the bulk of the chromium chemicals — not to mention organic wastes — ends up in the rivers. Electroplating is another industry dominated by small firms that use toxic heavy metals — especially chromium and cadmium — much of which ends up in the rivers. Tough environmental controls in western countries are rarely enforced in the developing countries. The rapid growth of light manufacturing in Asia and Latin America is sure to increase pollution from such sources.

Tables V and VI show estimated air emissions data for a number of heavy metals, in comparison with natural rates of mobilization. While the data are incomplete, it seems clear that mobilization of toxic metals from anthropogenic sources — at least in Europe — already far exceeds mobilization from natural sources. A similar table for waterborne emissions would show comparable results.

What Direction is Forward?

The prospect of increasing the output of mines and primary smelters — together with all the associated energy consumption, wastes and emissions by an order of magnitude — is obviously inconsistent with long-term ecological sustainability. As it happens, resource economists have satisfied themselves that, despite growing consumption, scarcity is not yet a serious problem for most metals. Costs of most raw materials have actually declined during the past century, in real terms [e.g. Barnett and Morse 1962; Smith 1979]. Technological progress may continue to compensate, to some extent, for declining ore quality — the visible symptom of gradual exhaustion.

Costs per unit output, may continue to decline, but at a slower and slower rate. Eventually the cost of further marginal gains in the efficiency of discovery, extraction and

refining of raw materials must rise. At some point in the future, the value of the exergy embodied in low grade ores or mineral fuel deposits in the earth's will no longer economically justify the expenditure of solar exergy needed to extract and refine them. At that point, if it occurs, the material cycle on earth will necessarily have to be "closed" for that material. (It can never be closed for all materials, since recycling can never be 100% efficient).

Indeed, there is no denying that the countries that the industrialized countries — even the US — are now largely dependent on imported ores of many metals (not to mention petroleum) from a shrinking list of potential mineral exporters. Meanwhile growing demand from Japan, the east Asian "tigers" and China will increase the competition among importers. Thus, while this may seem to be good news for the established mining industry, there is a growing likelihood that resource supply constraints will make such a radical "growth" trajectory impossible.

It follows that ecologically sustainable economic development at the global level, in the long run, will require comparably massive reductions in primary metals (and energy) use per capita and per dollar (or Deutsche mark or yen) of economic output. In short, the goal for governments, especially in the OECD countries, must be to increase the productivity of all physical resources by something like an order of magnitude, within the next half century. For this reason, among other reasons, it is important to accelerate the closing of the materials cycle, as indicated in *Figure 3*, starting with metals.

Closing the materials cycle is particularly important for the toxic non-ferrous metals, such as arsenic, bismuth, cadmium, copper, lead, mercury, plutonium, silver, thallium, uranium and zinc, as well as some ferrous metals (e.g. chromium and nickel). Of these, the artificial element plutonium is by far the most dangerous. It is carcinogenic and toxic to an extreme degree, as well as being fissionable and hence usable for nuclear explosives. Many people now believe that the various risks associated with use of plutonium (or even uranium, from which plutonium is manufactured) are too great to justify its use in nuclear power production. In any case, the closing of the global uranium-plutonium cycle is extremely urgent. However, this subject cannot be realistically discussed without also discussing the entire question of nuclear armaments and their disposition.

Following uranium-plutonium on the list in terms of urgency would be lead, mercury and those toxic metals (arsenic, bismuth, cadmium, thallium) that are by-products of copper, lead or zinc mining and refining. These metals are widely used in chemical products such as pesticides, pigments and stabilizers, mainly because there is a steady low-cost supply and no constraint on such use. Finally, copper, chromium, manganese, nickel, silver, tin and zinc constitute lesser but significant problems worthy of consideration.

One of the problems is that these metals are being dispersed into the environment at very low concentrations that make later recovery for recycling impracticable in most cases, but that nevertheless constitute a threat to the health of humans and other species. With regard to metallic emissions, it has already been pointed out that anthropogenic airborne emissions currently exceed natural sources by large factors, even on a global basis (*Tables V and VI*).

However, if the problem of toxic buildup were not enough, there are other unsustainable features of the present materials system. One is the fact that the industrial world is increasingly import-dependent for critical materials, since economically recoverable deposits in the industrial countries are being depleted faster than in the rest-of-the-world. Another problem is that ore grades are gradually declining, worldwide, as high grade deposits are exhausted. In the 19th century, copper was being mined from deposits with 10% ore grade. Today the world average is about 0.9%. Much the same situation applies to a number of other non-ferrous metals, including gold, silver, uranium and tin. This means that more and more tons of inert materials must be physically moved, crushed, screened and later dumped, to yield

a concentrated fraction. The concentrates must then be smelted or otherwise refined to produce a ton of salable product. Moving and handling requires energy, so that *ceteris paribus*, energy requirements for primary production must be expected to rise over time.

It would be futile to advocate such a far-reaching re-structuring of human economic activity without specifying feasible strategies and paths to accomplish the goal. In remainder of this paper I adopt two complementary perspectives. The first is the engineering/technological perspective, as exemplified by the approach known as Industrial Ecology (IE). The major focus of IE in the present context is to identify unexploited opportunities for metals recovery and recycling. Technical feasibility is the primary criterion for initial consideration.

The other perspective is that of resource and environmental economics. Economics is sometimes characterized as the discipline concerned with production and allocation of useful goods and services from "scarce" resources. To most economists, by long tradition and habit, capital and labor are the only scarce resources usually considered. But land, fresh water, clean air, benign climate, ecological balance and many — if not all — renewable natural resources can certainly be characterized as scarce. In some of these cases there are no markets at all, so that market prices do not exist, but in many such cases evidence of approaching scarcity are unmistakable. In some cases — notably clean air, topsoil, ground water, and biodiversity — a significant cause of deterioration is pollution from industrial processes and dissipative consumption of toxic substances. But these resources also provide essential services to man. It is appropriate for economists to consider how the productivity of *all* resources, including renewable and environmental resources, can be increased. This problem is becoming urgent, especially in the most industrialized countries and regions.

Thus, it is important to identify and analyze current and potential opportunities for increasing resource productivity by using economic and regulatory policy levers e.g. using tax strategies and/or exchangeable consumption or emissions permits to change the relative prices of factors of production. The purpose of this would be to induce absolute demand reduction or use substitution and/or to induce emissions reduction by inducing process change, source substitution, re-use and recycling. There may be a need to ban certain uses of metals outright (as in the case of tetraethyl lead as a gasoline additive or cadmium as a stabilizer for PVC).

It is also important to identify profitable opportunities for the private sector to reduce its consumption of virgin metals, by increased recovery and recycling, "waste mining", remanufacturing, dematerialization and substitution of renewable and non-metals for metals. (The substitution of glass fibers for copper wire is one example of the latter that is already well advanced. Another possible future example might be the use of high temperature ceramics for gas turbine engines in place of superalloys.)

Technical (IE) Aspects

There are two basic technological strategies for closing the materials cycle. The first of these (the main subject of this paper) is a composite that might be termed the 4R strategy: repair, re-use, remanufacturing and recycling. Obviously all of these tend to reduce the need for virgin materials, and (indirectly) all of the environmental damage and energy consumption associated with the extraction and processing of virgin materials, including their toxic byproducts.

A second generic technological strategy for closing the materials cycle is "waste mining" or WM. It comprises the use of mining and ore beneficiation technologies to utilization of waste streams from (currently) unreplaceable resources as alternative sources of other needed

materials. This strategy simultaneously reducing (1) the environmental damage due to the primary waste stream, (2) the rate of exhaustion of the second resource, and (3) the environmental damage due to mining the second resource. The WM strategy is potentially important, especially in the context of recovering light metals from coal ash. However, the technology is underdeveloped and the economics are not yet attractive. Hence, I do not consider it further in this paper.

The 4R strategy can be more fully described in terms of its elements, namely:

- *Re-use* of a discarded metal product, as such, but in a less demanding application. For instance, partially worn bearings or obsolete computer chips have been re-used in yachts and electronic games, respectively.
- *Repair* of a discarded metal product, for subsequent re-use. For instance automobiles, are often repaired to allow further use. (Unfortunately, modern technology and sophisticated composite materials often makes repair more difficult than it was in the past, although products may last longer without repair). More commonly, discarded motor vehicles and other equipment are commonly dismantled to recover valuable unworn components that can be used to repair equipment that is still in active use.
- *Remanufacture* of a discarded metal product (such as a pump, engine or motor), by replacing worn parts such as bearings, gaskets, piston rings or wearing surfaces but retaining structural components that retain their integrity. The remanufacturing option is gaining in popularity, since it offers a means of upgrading certain components (e.g. of computers, telecommunications equipment or copying machines) without discarding the whole unit.
- *Recycling* of scrap from demolition wastes, the carcasses discarded motor vehicles or other piece of equipment. The process involves manual removal of valuable metal items (like stainless steel, copper wire or tube, or catalytic convertor), removal of non-metal items, shredding, mechanical sorting and gravity, centrifugal or magnetic separation of ferrous from non-ferrous and non-metallic elements. The next step is either remelting in a reverberatory furnace for recasting, or return to a blast furnace feed for more complete re-purification.

Thanks to economies of scale and cheap energy, re-use and remanufacturing are not important economic activities at present. (See "Economic Perspective" discussed in the next section). However, they — along with recycling — will inevitably grow in importance, for several reasons. One is the acute and increasing shortage of landfill sites for solid wastes in the most industrialized regions. This induces governments to tax and regulate waste disposal and to introduce measures to force original equipment manufacturers (OEMs) to take back old equipment for ultimate disposal or re-use. Remanufactured refrigerators, A/C units, kitchen appliances, cars (or engines), tires, and PCs can offer a good low-priced alternative to new equipment for low income workers in the rich countries, or they could fill an important economic niche in some of the developing countries.⁴

A second reason for expecting growth in this area is that primary metal processing and reduction activities are inherently quite dirty. While the mining sector has been largely exempted from the intensive environmental regulation that downstream industries have already experienced, this relative immunity from regulation cannot continue indefinitely. Most large-scale mining and metallurgical firms headquartered in industrialized countries are already

being forced to apply similar standards to their operations in developing countries. Small and medium sized operations will eventually have to follow suit. This trend toward internalizing the environmental costs of primary metallurgical operations will, in turn, improve the relative economic attractiveness of secondary activities and the 4R strategy.

Every ton of metal that is re-used, remanufactured or recycled — or avoided by dematerialization — replaces a ton that would otherwise have to be mined and smelted, with all of the intermediate energy and material requirements associated with those activities. This is already very significant for iron and aluminum. Each ton of iron recycled saves 12.6 tons of overburden (coal and iron mining), 2.8 tons of iron ore, 0.8 tons of coal (exclusive of its use as fuel), and a variety of other inputs. It also eliminates at least a ton of CO₂ pollution and significant additional pollution of air and water from coking, pickling and other associated activities. See *Figure 4*.

In the case of non-ferrous metals, the indirect savings are much larger, of course. A ton of non-ferrous metals recycled in the US saves 78 tons of overburden, 77 tons of gangue, 0.32 tons of explosives, 0.75 tons of flotation chemicals, 0.50 tons of smelter slag (a waste, unlike iron slag), and 3.06 tons of CO₂ emissions. To the extent that the smelting is carried out in less regulated countries outside North America and Europe, recycling or remanufacturing also saves 1.0 tons of SO₂ that would otherwise be emitted into the air. (N.B. sulfur is recovered as sulfuric acid, which is subsequently used for the increasingly important heap-leaching process in North America, but this is not being done extensively elsewhere). See *Figure 5*. A third factor is also increasingly important from an IE viewpoint. It is the fact that the gross supply of many minor metals, especially some of the most toxic ones like arsenic and cadmium (Table II), is not determined by direct demand *per se* but by the demand for more important metals such as copper and zinc, with which they are normally associated as minor by-products of ore processing and smelting. Thus, the more copper is recycled, the less need be mined, thus reducing the aggregate arsenic supply. Similarly, the more zinc is recycled, the less cadmium will be produced to pollute the soil or find harmless uses for.⁵

Economic Perspective

As I mentioned earlier, scrap metals have been collected and recycled since ancient times. In what Boulding has called the "cowboy economy" of ancient and prehistoric times land was relatively plentiful and building materials, wood and most renewable resources were essentially free for the taking [Boulding 1966]. However metals or metal alloys (in reduced form) such as iron or bronze — not to mention silver and gold — were extremely scarce and therefore valuable.⁶ More recently the relative scarcity has been gradually relieved by the application of industrial technology and the relative value of metals has, accordingly, fallen. Today many metals are used wastefully, some are dissipated.

Yet, looking ahead to the more distant future "spaceship economy", land and even renewable resources are becoming scarce. Natural resource supply constraints will inevitably drive prices up. Energy will become more costly. It is fairly obvious that impending scarcity will discourage less essential uses of metals, especially dissipative ("one time") uses that do not permit recovery, re-use or recycling. On the other hand, the increasing complexity of both industrial materials and products has made recycling and re-use more difficult in many cases. This is a particularly acute problem in the case of complex machinery and especially electronic products.

But to create conditions for easier repair, renovation and (at the end of the life-cycle) easier disassembly the need is to induce manufacturers to design their products differently in

the first place. (This is called "design for environment" or DFE). One way to achieve this is to increase vertical integration of the manufacturing process, either by means of direct ownership or by forcing the firm at the end of the manufacturing value-added chain, or even the retailer, to take responsibility for the use and disposal of the product. The immediate incentive -- apart from the threat of regulation -- is that firms realize that they are more and more likely to be held liable for future environmental harm or health problems associated with their products (or wastes), even if those products were made by another firm, are later misused, or if the potential for harm was not known when the product was originally designed and produced, or if the waste was properly disposed of under then-current rules. To see why, it is probably sufficient to cite asbestos insulation, Love Canal, and silicone breast implants.

In the long run this trend toward increasing responsibility and liability will gradually shift manufacturers away from their current orientation (selling products to consumers) to selling the services of their products, while retaining ownership and/or responsibility for those products. An intermediate step, already contemplated by the European Union, is legislation to force manufacturers to "take back" products they have previously made. One can think of this as the first step in a necessary evolutionary development, namely to "convert" every possible product into a service. More precisely, it means selling the service of the product, rather than the product itself.

The key result of this evolutionary change would be that firms begin to think of their products as assets to be conserved. This would automatically result in greater emphasis on re-use, repair and remanufacturing as means of saving energy and conserving value-added embodied in products.

However, re-use and repair have been declining, nonetheless, partly because products are becoming more complex (making repair difficult), partly because manufacturers would prefer to sell replacements for complete units rather than parts, and partly because the more easily repairable breakdowns are gradually being eliminated by improved design and higher quality. Also, more and more products are being imported from manufacturers far away (e.g. in Asia) who cannot be reached by local regulators or through the local courts.

Most important, perhaps, re-use, repair and remanufacturing are inherently more labor-intensive than primary manufacturing. This is because they cannot exploit the great economies of scale and of experience (learning-by-doing) that have benefitted primary production. Mass production typically requires less than 1 percent of the labor hours per unit output, as compared to custom or "job shop" production. While there is some potential in the long run for using mechanization for purposes of dismantling and remanufacturing used equipment, it is obvious that batch sizes for repair, dismantling or remanufacturing will always be much smaller -- and inventory requirements correspondingly larger -- than is the case for primary production. One study has estimated that reconditioning and remanufacturing in general require roughly half of the energy input, but twice the labor input per physical unit of output, as compared to manufacturing from all-new materials [Stahel 1982, 1986].

This situation constitutes something of a dilemma for modern society. On the one hand, mass production has contributed tremendously to economic prosperity by bringing costs and prices of manufactured goods down, thus increasing market size and driving economic growth. Henry Ford is widely credited with increasing wages in order to allow workers to become potential customers. The so-called 'Salter Cycle' -- probably misnamed -- is a positive feedback loop between lower costs, lower prices, increased demand (income elasticity of demand) and larger scale of production, which again permits lower costs, lower prices, etc. See *Figure 6*. The visible consequence of this cycle -- apart from growth itself -- is increased labor productivity. That is, more output of manufactured goods for less labor. In any case, from 20 percent to 50 percent of the economic growth of major industrial countries in the

post-WW II era has been credited to scale effects in manufacturing [Denison 1962, 1967, 1979, 1985; Usui 1988]. Economies of scale are also the primary mechanism for the benefits of reducing trade barriers.

On the other hand, mass production results in massive waste of resources, *precisely because re-use, remanufacturing and recycling are not economically justified in most cases*. Yet, resource conservation is the route that society must follow, to secure a healthy environment for our children and their children. The problem is to generate economic growth in the sense of increased output of *services* without destroying the very engine of growth itself, which seems to depend on economies of scale.

The resolution of this apparent contradiction between resource conservation and growth, is for firms to learn how to reduce costs by saving on materials and energy, rather than by saving on labor. The "new" growth engine would then look like *Figure 7*. An obvious benefit of this approach would be to reduce unemployment, which should make the idea quite interesting to politicians.

I hesitate to say it in this audience, but to create the economic conditions for this industrial transformation it will be necessary for governments to alter the tax system radically, although it must also be done gradually. At present, most taxes are charged to labor, or to value added, which is either labor (from the employers perspective) or aggregate consumption (from the consumers's perspective). This has pushed the effective price of labor (to employers) too high, while depressing consumption of services. Meanwhile, resources and energy are seriously under-taxed and under-priced. To reduce the relative price of labor, it is necessary to shift the tax burden (gradually) onto resource consumption.

Conclusions

It is not easy to produce a neat set of conclusions from this overview. Perhaps the principal one is that the world is changing. We are in a transition between the "cowboy economy" of the 19th century and the future "spaceship economy" of the latter part of the 21st century. In the cowboy economy economic growth was largely driven by the exploitation of cheap and readily available extractive resources, and use (or misuse) of the environment was a free good. This attitude still prevails in parts of the world, but to see its consequences a tour of the mining and metallurgical areas of the former USSR and present day China would be an eye opener. The spaceship economy, by contrast, will be one in which all resources — including the environment — are scarce and must be treated as depreciable assets.

The major implication for the metals industries is that recycling is the growth sector of the near future. In the distant past metals were recovered and reused as much as possible, of course, but seldom recycled as such. This was because, until recently, efficient recycling on a small scale was less profitable than mining and smelting. Environmental considerations strongly and increasingly favor recycling, of course. The fact that recycling uses less energy than primary production has long been obvious.

Economies of scale are a central concern, as I have pointed out. In the past they were unfavorable to recyclers. However, economies of scale are becoming applicable to the recycling industries, as the inventory of recyclable materials in our industrial society has reached a critical level, and efficient markets for secondary materials have evolved. In turn, specialized recycling technologies have also emerged. The result is exemplified by the profitability of the steel "minimills".

In the more distant future, remanufacturing will gradually become more important than

recycling. The reason is that manufactured products are assets and remanufacturing conserves more of the value added by manufacturing, especially in complex materials and subsystems. Again, however, economies of scale currently favor recycling over remanufacturing. This will only change gradually as end-use service providers introduce more efficient "reverse logistics" systems to return used vehicles, appliances and other equipment for routine maintenance and upgrading or back to their manufacturers. Such systems will evolve first in the industrialized countries, partly because the necessary infrastructure is already largely in place and partly because other means of disposal are increasingly unacceptable.

Government policy driven in part by other concerns, will accelerate the coming changes. There is ample evidence that extractive resources have been underprice in the past, thanks to explicit and implicit subsidies. One of the major subsidies to extraction has been the treatment of the so-called assimilative capacity of the environment as a free good. When the environment's capacity to assimilate wastes was essentially infinite (the "cowboy economy") this did not matter much. Today it does matter. There is growing pressure to eliminate this sort of hidden subsidy. On the other hand, there is growing evidence that labor — which carries almost all of the tax burden of government — is overpriced. The result is a growing unemployment problem, at least in Europe. Thus governments are likely to begin to reallocate the tax burden away from labor and onto extractive resources. This process will be slow, but the pressures in this direction are powerful.

What does all this mean for existing mining and smelting industries? There is no immediate crisis, but the long term outlook is for these sectors to decline. Yet their capital assets and their technologies may have other applications. For instance, there is some potential for "waste mining", to recover valuable but scarce materials, as I have hinted. Mining firms that have hitherto specialized in taking ores and minerals out of the ground may find it possible to utilize some of their old mines and technologies to put suitably treated solid wastes — such as incinerator ash, flue gas desulfurization sludge, or other industrial waste treatment sludges — back into the ground for long term storage. Similarly, there is some potential for old blast furnaces to be used in other ways, although this is not the place for a discussion of the pros and cons of these possibilities. In general, however, the large-scale metallurgical industries should be recycling themselves into medium scale metals recyclers.

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Endnotes

1. The quantities of ore removed from the earth are normally much larger, but physical separation techniques leave much of the excess material at the mine, where it is piled up into small mountains, but not put back into the ground. For instance, copper ores mined in the western part of the US contain less than 0.4% copper, whereas concentrates delivered to refineries average 20% copper. Thus, for every tonne of concentrate, at least 50 tonnes of crude ore were dug up and processed (by flotation ponds) at the mine. For 1 tonne of refined copper 250 tonnes of ore are processed. In some cases the quantities of ore processed are much larger. For example, roughly 140 000 tonnes of ore must be processed to yield 1 tonne of platinum group metals.
2. There is one major exception, a relatively new blast furnace in the Amazon basin of Brazil (Carajas) financed by the World Bank, using charcoal from wood. In principle this might be regarded as a "renewable resource" but in practice it is virgin tropical forest that is being consumed and the land that is cleared is not being replanted, but used for cattle raising.
3. Nickel is mined in both forms. The large Canadian deposits, for instance, are sulfides. However, the so-called lateritic ores found in tropical countries are oxidized.
4. Actually, since remanufacturing will always be more labor-intensive than original equipment manufacturing (OEM), it is inherently a very suitable activity for border regions with excess labor, such as Mexico's "maquiladora" zone, Eastern Europe or North Africa. (As these countries develop, of course, the "border regions" will shift too).
5. Luckily, more and more arsenic is being used to make gallium arsenide for the electronics industry, thus reducing the supply available for pesticides and wood preservatives. Again, it is fortunate that nickel-cadmium batteries are now taking up most of the available supply. These batteries can be recovered and recycled, although this is not yet happening on a significant scale.
6. Copper, lead, zinc and tin (and their alloys, such as brass, bronze and pewter) melt at temperatures at or below 1000°C., which can be reached with a small forced air furnace using bellows. However, all of these metals are intrinsically scarce on the earth's crust and such high quality ores as there were had mostly been exhausted in Europe before the 18th century. The scarcity of wrought iron and steel was due to a technological limitation: prior to Huntsman's "crucible process" in the late 18th century, steel could only be made by repeated heating and hammer forging (like a Damascus or Japanese sword). It was then impossible to achieve continuous furnace temperatures high enough (c. 1550°C.) to liquefy pure iron (or steel) and maintain it in liquid form long enough to pour or mold. The Huntsman process produced enough steel for cutlery, cutting tools, pistols and clockwork, but not much more. The quantity constraint on steel-making was not fully relieved until the Bessemer convertor was introduced in the 1850s.

Table I: World production of metal ores 1993 (MMT)

		<i>Gross weight of ore MMT</i>	<i>Metal content %</i>	<i>Net weight of metal MMT</i>	<i>Mine & mill waste MMT</i>
Aluminum		106	19	19.8	86
Chromium		10	30	3.0	7
Copper	a	> 2 500	0.4	9.4	> 2 490
Gold	b	≈ 466	0.0005	.002	≈ 466
Iron		989	52	517.0	472
Lead	a	> 45	6.5	2.9	> 42
Manganese		22	33	7.2	15
Nickel	a	> 130	0.7	.9	> 129
Platinum group	b	≈ 50	0.0005	.0002	≈ 50
Uranium (1978)	c	1 900	0.002	.04	1 900
Zinc	a	> 219	3.2	6.9	> 212

Source: Calculated from data in US Bureau of Mines, Minerals Yearbook 1993.

- a. Extrapolated from US data on ore treated and sold vs marketable product for 1993, using same implied ore grade.*
- b. Based on ore grades mentioned in text for mines in South Africa only.*
- c. Based on data from Barney 1980. No current data available.*

Table II: U.S. recycling statistics & apparent consumption for selected metals, 1987-1991

Year	Quantity (kMT)			Apparent consumption ⁴	Recycle % of apparent consumption
	Recycled metal ¹				
	New scrap ²	Old scrap ³	Total		
ALUMINUM⁵					
1987	1134	852	1986	6603	30%
1988	1077	1045	2122	6450	33%
1989	1043	1011	2054	6000	34%
1990	1034	1359	2393	6298	38%
1991	979	1522	2501	6214	40%
COPPER					
1987	716.122	497.937	1214.059	2912.929	42%
1988	788.712	518.179	1306.891	3002.257	44%
1989	760.894	547.561	1308.455	2945.209	44%
1990	773.873	535.656	1309.529	2942.311	45%
1991	679.882	533.338	1213.220	2782.942	44%
LEAD					
1987	52.535	657.532	710.067	1259.029	56%
1988	45.274	691.127	736.401	1274.477	58%
1989	49.612	841.729	891.341	1382.250	64%
1990	48.104	874.093	922.197	1345.344	69%
1991	54.172	829.563	883.735	1280.586	69%
NICKEL⁶					
1987			32.331	155.781	21%
1988			41.039	159.019	26%
1989			39.784	135.218	29%
1990			33.716	145.556	23%
1991			32.520	128.048	25%
TIN					
1987	4.604	11.462	16.066	59.458	27%
1988	3.925	11.350	15.275	60.955	25%
1989	2.795	11.545	14.34	47.285	30%
1990	4.035	13.200	17.235	53.430	32%
ZINC					
1987	270	82	352	1324	27%
1988	240	97	337	1340	25%
1989	230	117	347	1311	26%
1990	232	109	341	1239	28%
1991	233	120	353	1134	31%

Source: [USBulMiner 1991, "Recycling-Nonferrous Metals", Tables 1 & 2]

1. Recycled metal is metal recovered from reported purchased new plus old scrap supply.

2. New scrap is scrap resulting from the manufacturing process, including metal & alloy production.

3. Old scrap is scrap resulting from consumer products.

4. Apparent consumption is production plus net imports plus stock change. Apparent consumption is calculated on a contained weight basis.

5. Recycle quantity is the calculated metallic recovery from aluminum-base scrap, estimated for full industry coverage.

6. Nickel scrap is nickel contained in ferrous & non-ferrous scrap receipts.

Table III: By-product and co-product groups

<i>By-product groups</i>			
Copper	Zinc	Lead	Platinum
antimony	antimony	antimony	iridium
arsenic	cadmium	bismuth	osmium
cobalt	gallium		palladium
gold	germanium		rhodium
rhenium	indium		ruthenium
selenium		selenium	
silver	silver	silver	
tellurium	thallium	tellurium	
Niobium	Zirconium	Nickel	Lithium
tantalum	hafnium	cobalt	rubidium
		manganese	
<i>Co-product groups</i>			
	Brine	Rare Earths	
	sodium	yttrium	
	potassium	europium	
	boron	erbium	
	magnesium	terbium	
	chlorine	dysprosium	
	bromine	ytterbium	

Table IV: Production & waste allocation for primary U.S. metal production 1988 & 1993 (1000 metric tons)

	<i>US domestic mine production</i>						<i>US domestic concentrate production</i>						<i>US primary metal production (domestic & foreign ores)</i>					
	<i>Total material handled</i>		<i>Ore treated or sold</i>		<i>Overburden</i>		<i>Production (metal content)</i>		<i>production (gross weight) (d)</i>		<i>Concentration wastes</i>		<i>Concentrate consumption (gross weight)(d)</i>		<i>Primary production total</i>		<i>Smelting/refining losses</i>	
	A		B		A-B				C		B-C		D		E		D-E	
	1988	1993	1988	1993	1988	1993	1988	1993	1988	1993	1988	1993	1988	1993	1988	1993	1988	1993
Bauxite/Aluminum	8246	5610 e,g	1107	753 e,g	7140	4857												
			9139	11917 f					4575	3695	4564	8222	7730	7242	3944	3695	3786	3547
Copper	523446	706997	218631	436083	304814	270914	341	1801	5364	7206	213267	428877	5794	7023	1406	1704	4388	5319
Gold	536146	1027281	117934	254404	418212	772877	0.201	0.331	0.201	0.331	117934	254404	392	305	0.138	0.243	392	305
Lead	9707	4344	6450	4202	3257	142	385	355	481	444	5969	3758	490	381	392	305	98	76
Molybdenum	127006	115667 b,g	72212	65765 g	54794	49902	43	39	172	157	72040	65608	103	91	26	23	77	68
Platinum group	34189	57097	11396	19032 c	22793	38064	0.005	0.008	0.005	0.008	11396	19032	0.0003	0.0002	0.0003	0.0002	0	0
Silver	48444	47977 c,g	15876	15723 g	32568	32254	1.661	1.645	1.661	1.645	15874	15721	2	2	1.718	1.712	0	0
Zinc	21149	6298 h	9106	5606 h	12043	692	244	488	432	869	8674	4737	429	428	241	240	188	187
Uranium oxide(a)	22000	22000	15200	15200	6800	6800			20	20	15180	15180	20	20	5	5	15	15
NF Total	1330333	1993270	467912	816768	862420	1176502			11046	12392	464898	815540	14960	15491	6016	5974	8944	9517
Iron	300278	284068	197766	102271	102512	181797			57515	55661	140251	46610	83694	76793	49242	52321	34452	24472
TOTAL	1630611	2277338	665678	919039	964932	1358299			68561	68053	605149	862150	98654	92284	55258	58295	43396	33989

- NOTES: (a) 1980 data
 (b) Assumes 3:1 ratio material handled to ore - as with gold/silver
 (c) Zinc data from page 1159 has been subtracted from "other" on page 59 of Minerals Yearbook 1989 to construct approximate platinum data.
 (d) Where direct figures for gross weight of concentrate were unavailable, they were calculated by applying reasonable concentration ratios to the metal content.
 (e) Bauxite at US Mines. Included in total of "ore treated".
 (f) Crude bauxite ore, dry equivalent. Includes net imports. Not included in "ore treated" total.
 (g) 1993 estimate derived from 1988 data by applying 1988 ratio of material handled to ore treated to 1993 data.
 (h) Zinc data from detail "other" to avoid double counting.

Source: Calculated from data in US Bureau of Mines, Minerals Yearbooks, 1988,1989, 1993.

Table V: Worldwide Atmospheric Emissions of Trace Metals (1000 tonnes per year)

<i>Element</i>	<i>Energy Production</i>	<i>Smelting, Refining & Manufacturing</i>	<i>Manufacturing Processes</i>	<i>Commercial Uses, Waste Incineration & Transportation</i>	<i>Total Anthropogenic Contributions</i>	<i>Total Contributions by Natural Activities</i>
Antimony	1.3	1.5	—	0.7	3.5	2.6
Arsenic	2.2	12.4	2.0	2.3	19.0	12.0
Cadmium	0.8	5.4	0.6	0.8	7.6	1.4
Chromium	12.7	—	17.0	0.8	31.0	43.0
Copper	8.0	23.6	2.0	1.6	35.0	6.1
Lead	12.7	49.1	15.7	254.9	332.0	28.0
Manganese	12.1	3.2	14.7	8.3	38.0	12.0
Mercury	2.3	0.1	—	1.2	3.6	317.0
Nickel	42.0	4.8	4.5	0.4	52.0	2.5
Selenium	3.9	2.3	—	0.1	6.3	3.0
Thallium	1.1	—	4.0	—	5.1	29.0
Tin	3.3	1.1	—	0.8	5.1	10.0
Vanadium	84.0	0.1	0.7	1.2	86.0	28.0
Zinc	16.8	72.5	33.4	9.2	132.0	45.0

Source: [Nriagu 1990]

Table V: Indicators of unsustainability (ratios)

<i>Metal</i>	<i>Anthropogenic flow to natural flow</i>		<i>Cumulative extraction to topsoil inventory Azar et al 1994</i>
	<i>Galloway et al 1982</i>	<i>Azar et al 1994</i>	
Antimony (Sb)	38	6.0	—
Arsenic (As)	4	0.33	—
Cadmium (Cd)	20	3.9	3.0
Chromium (Cr)	2	4.6	2.6
Copper (Cu)	14	24.0	23.0
Lead (Pb)	333	12.0	19.0
Mercury (Hg)	—	6.5	17.0
Nickel (Ni)	4	4.8	2.0
Selenium (Se)	5	2.0	—
Vanadium (V)	3	0.32	—
Zinc (Z)	23	8.3	6.9

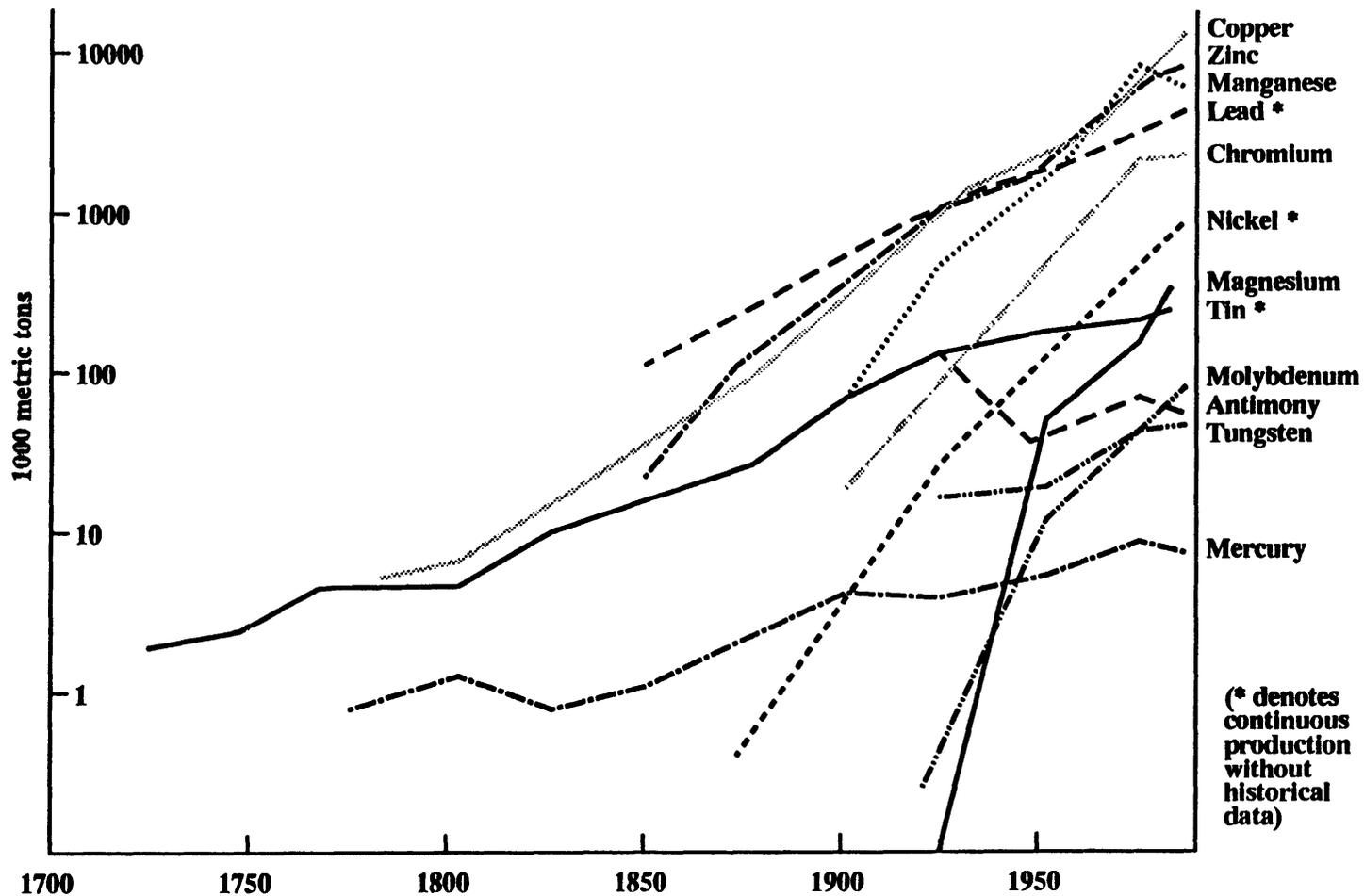


Figure 1. Annual worldwide production of selected metals, 1700–1983
Data source: Pacyna 1986.

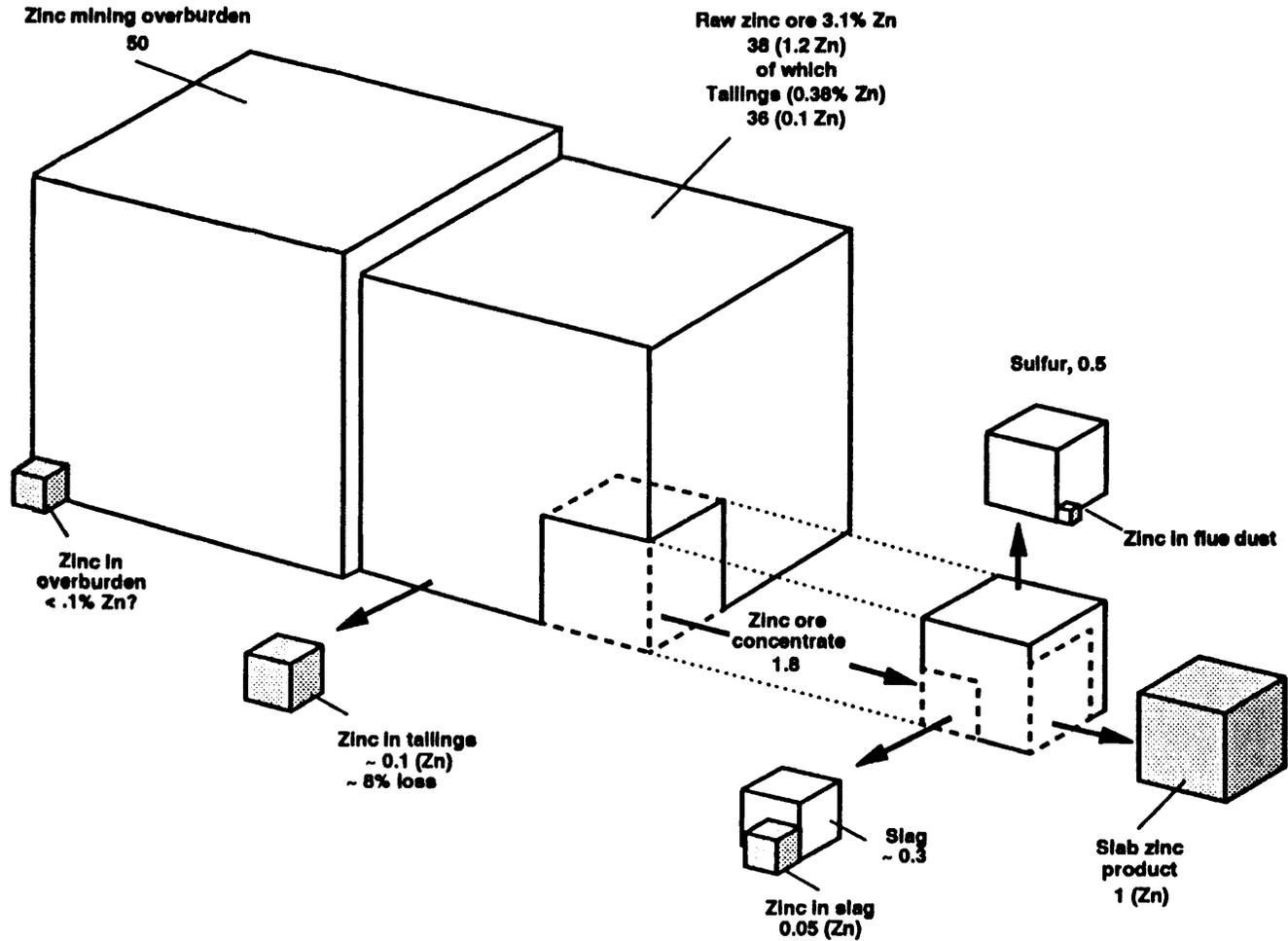


Figure 2. Zinc flow in mining & processing of zinc ores to produce 1 unit of slab zinc

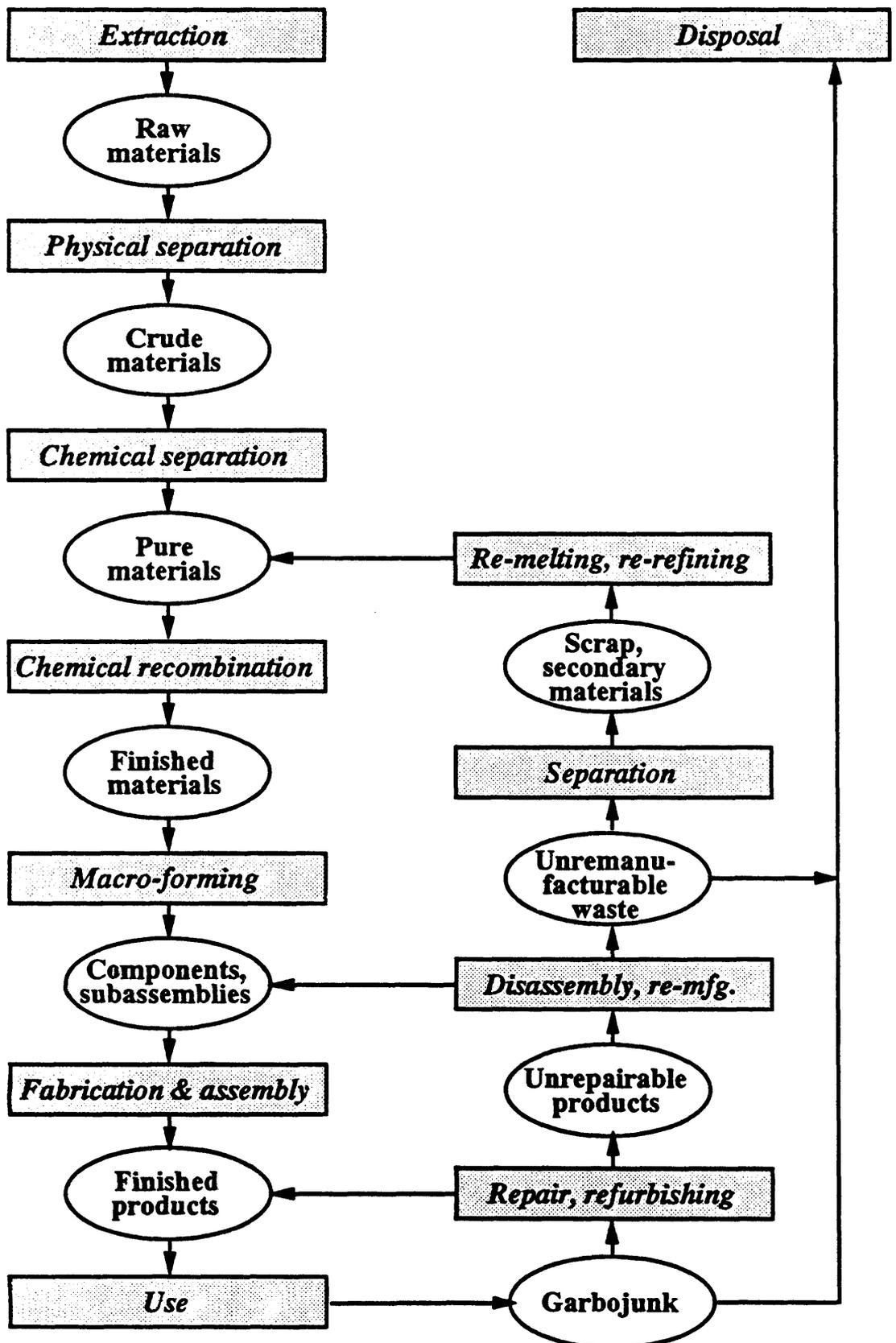


Figure 3. *The materials cycle*

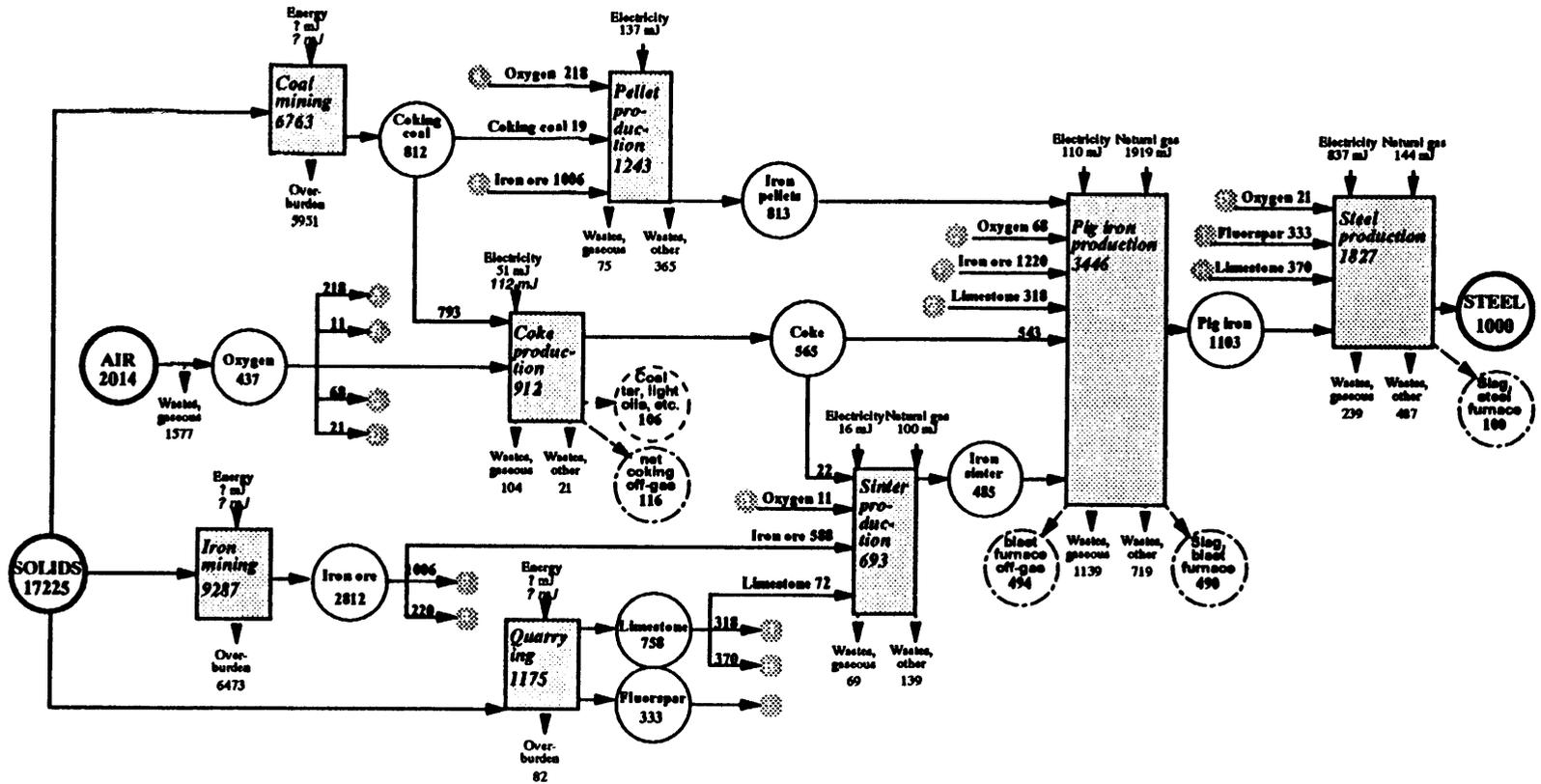


Figure 4. Materials flow; 1 MT of Steel produced without recycling

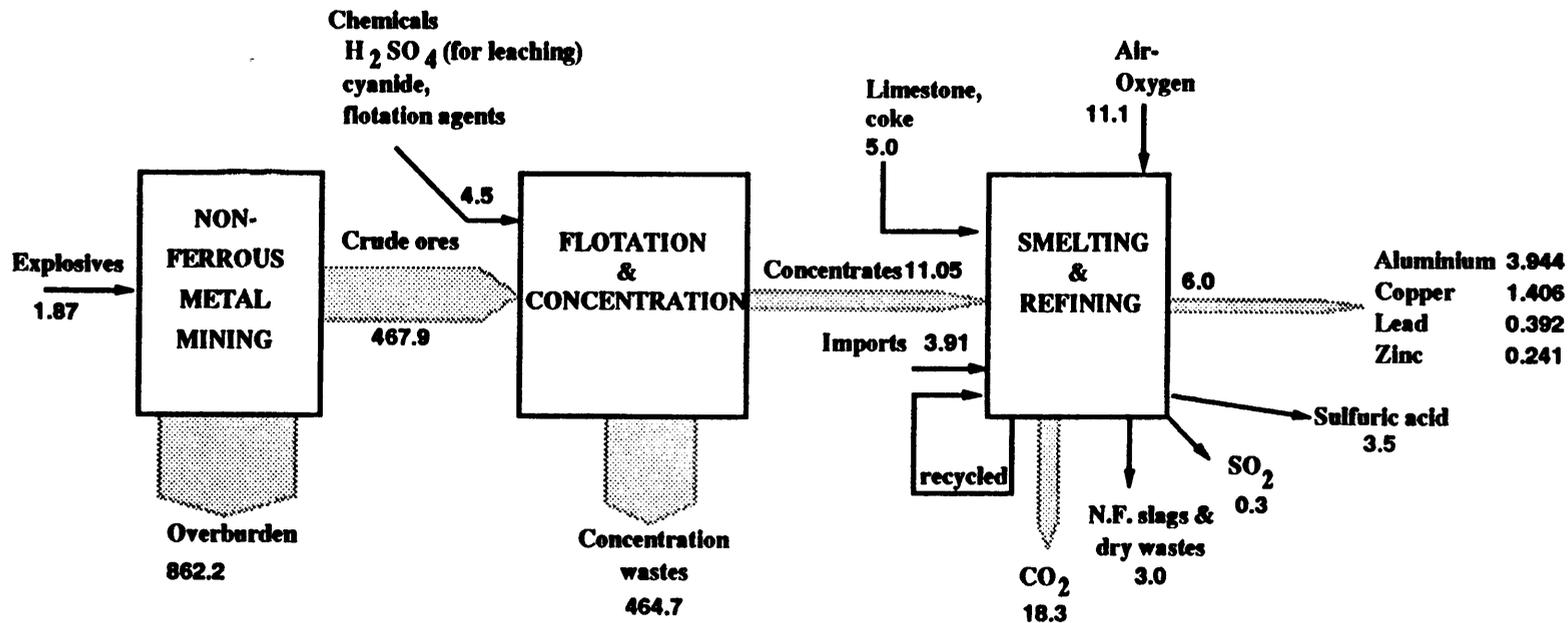


Figure 5. Mass flows in the U.S. non-ferrous metals sector, 1988 (MMT)

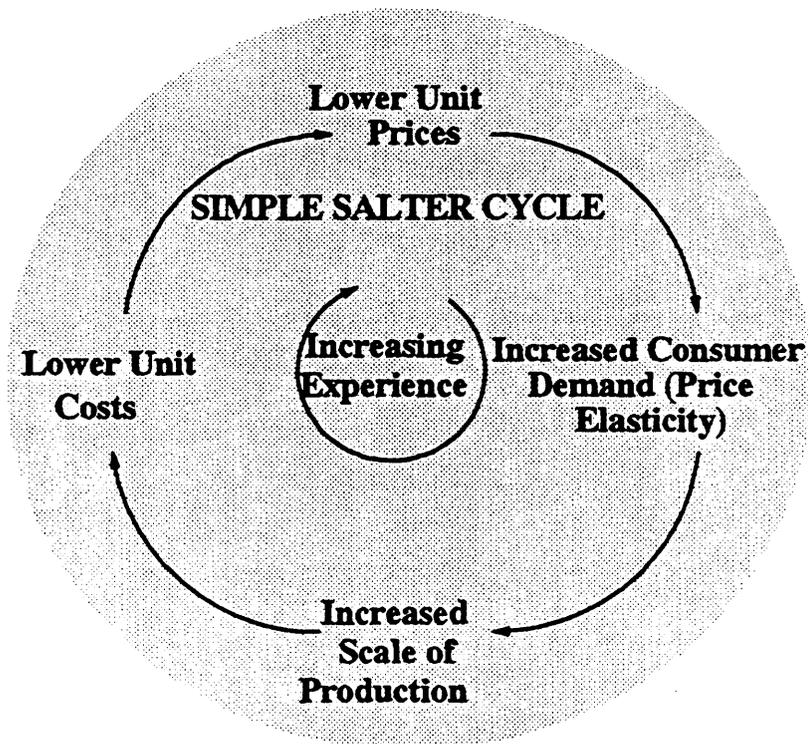


Figure 6. Simple Salter Cycle

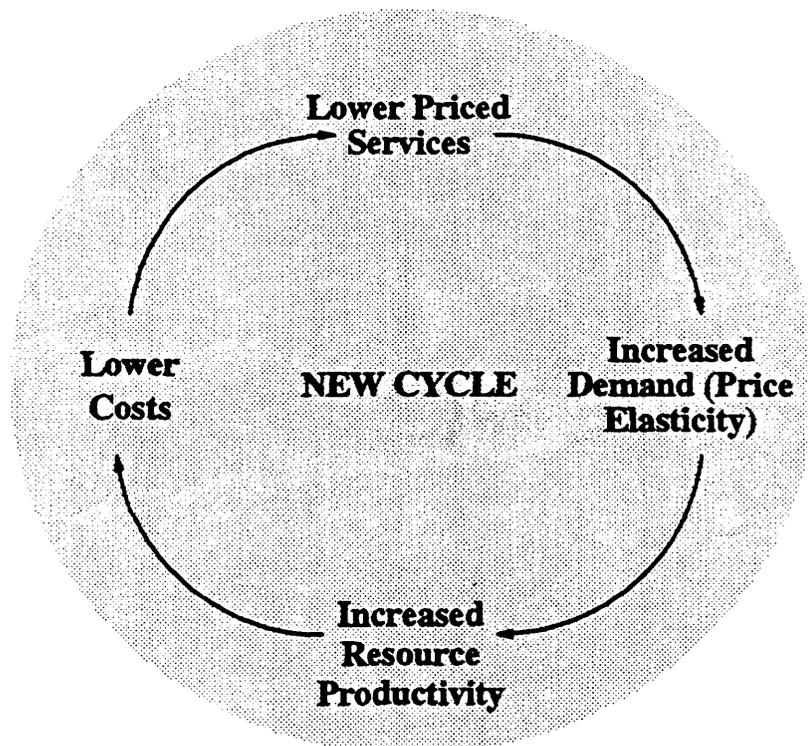


Figure 7. A New Cycle