

RECYCLING METALS FOR THE ENVIRONMENT

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CONTENTS

INTRODUCTION	3
METALS PRODUCTION FROM PRIMARY AND SECONDARY RESOURCES	6
<i>Role of Thermodynamics and Kinetics</i>	8
<i>Ore Reserves and Economics</i>	9
<i>Environmental Impacts of Metal Production</i>	11
RECOVERING METALS FROM WASTE STREAMS	14
<i>Physical separation</i>	14
<i>Chemical separation</i>	18
<i>Industrial wastes</i>	18
<i>Chemical catalysts</i>	21
SECONDARY METAL PRODUCTION	22
RECOVERY PROCESSES	27
<i>Iron and Steel</i>	28
<i>Aluminum</i>	30

<i>Copper</i>	33
<i>Lead</i>	35
<i>Zinc</i>	36
ENVIRONMENTAL REGULATION	39
CONCLUSIONS	41
LITERATURE CITED	47

INTRODUCTION

Metals play an important part in modern societies and have historically been linked with industrial development and improved living standards. Society can draw on metal resources from Earth's crust as well as from metal discarded after use in the economy. Inefficient recovery of metals from the economy increases reliance on primary resources and can impact nature by increasing the dispersion of metals in ecosystems. Though the practice of recovering metals for their value dates back to ancient civilizations (1), today, the protection of Earth's resource endowments and ecosystems adds to the incentive for recovering metals after use.

Industrial society values metals for their many useful properties. Their strength makes them the preferred material to provide structure, as girders for buildings, rails for trains, chassis for automobiles, and containers for liquids. Metals are also uniquely suited to conduct heat (heat exchangers) and electricity (wires), functions that are indispensable to industrial economies. Finally, metals and their compounds are used for their chemical properties as catalysts for chemical reactions, additives to glass, electrodes in batteries, and many other applications. The basic and unique properties of metals, including the ability to work them into complex shapes (i.e., ductility), insure that long term demand for metals will certainly grow. Opinions on long-term metals demand range from predictions that growth in demand will pace the global economy (2) to the position that the ascent of knowledge-based industries as economic drivers, competition from other materials, greater consumption of lighter more sophisticated metal products, and more efficient use in the economy will slow the rate of future growth (3, 4).

Metals can be recycled nearly indefinitely. Unlike polymer plastics, the properties of metals can be restored fully, though not always easily, regardless of their chemical or physical form. Nevertheless, the ability to recover metals economically after use is largely a function of how they are used initially in the economy and their chemical reactivity. The success of secondary metals markets depends on the cost of retrieving and processing metals embedded in abandoned structures, discarded products, and other waste streams and its relation to primary metal prices.

Demand for scrap metals depends on industry structure and the availability of production technologies that accommodate scrap feeds to yield value added products. This complex market relies on the decisions of many independent actors including scrap dealers, brokers, dismantlers, and smelters. Figure 1 shows the flow of metal among a sample of non-ferrous metal scrap handlers in the New England region of the United States (5). The New England study concluded that 95% or more of the recycled metal remains within the scrap system. Despite this apparent high efficiency, the 5% losses compounded over decades introduce a significant amount of lost metal either bound in scrap heaps or dispersed into the environment. The model of industrial ecology emphasizes the containment and reuse of wastes generated by society as an overarching guideline for improving environmental quality. To realize this model, industry and society should work together to recover metals by recirculating metal from all secondary sources and losing a minimum amount of material from the industrial/social system (6,7).

[Figure 1 here]

The commercial success of scrap markets in the United States is evidenced by the fact that recovered metals comprise more than half of the metals input to producers. In the early 1990's, net U.S. exports of scrap metal averaged 8-10 million metric tons (MMT) and net export earnings totaled from \$1.5-3 billion annually (8). International trade in scrap metal neared 40 MMT in 1995, rising more than 65% from a low level in the early 1980's (9). Global commercial interest in secondary metals supports daily published price reports for secondary metals (10), industry standards for metal scrap (11), and comprehensive global industry surveys of primary and secondary production for individual metals (12).

Governments have historically been interested in the available supply of scrap metals particularly during wartime. In the United States, the U.S. Bureau of Mines traditionally collected information on secondary metals production and conducted research on secondary metals processing for industry. Beginning in the 1980s, the Bureau began analyzing secondary and primary metals trends in the context of other material classes, such as plastics and forest products (13,14). Since the closing of the Bureau in 1995, this function has been assumed by the U.S. Geological Survey (USGS) Minerals Information team which continues to collect and analyze data on secondary metals (15).

In the interest of containing metals once they have entered the industrial/social system, we identify barriers to this goal by describing the primary and secondary metal resources available to society, current and past levels of metals recovery, processes for isolating and processing metals

from secondary sources, and the major environmental regulations affecting secondary metals processors. We refer almost exclusively to data and examples from the United States, while emphasizing the underlying science and technology which is universal.

One hundred percent recovery to satisfy demand represents more of a goal than an attainable reality, even for precious metals where the incentive to recover value is highest. Thus, even if demand for metals were to stay level in the future, new metal would always be sought. Nonetheless, this exercise provides an incentive and a framework for examining alternatives to dispersive metals use, improving conditions for the efficient operation of secondary metals markets, identifying design changes for industrial and consumer products to provide for greater recovery, and stimulating research on industrial processes for recovering metals.

METALS PRODUCTION FROM PRIMARY AND SECONDARY RESOURCES

Metal production begins with either primary or secondary resources. Primary resources, or ores, contain relatively high concentrations of metals and are generally found at depths up to 1 kilometer beneath the surface. Secondary sources include all metals that have entered but no longer serve a purpose in the economy. For metal producers, the choice of whether to use primary or secondary sources is determined primarily by the type and capacity of existing capital equipment, quality of the feed, metal prices, and relative supply.

Metals exist in nature mostly in combination with oxygen (oxides) or sulfur (sulfides).ⁱ Ore deposits are of three types. The first class, high grade "alluvial" (such as the metal mined in the "gold rush" of California) and "massive" deposits can be subjected directly to pyrometallurgical (smelting) or hydrometallurgical (leaching) processes to produce metal. The second class consists of metal compounds mixed with relatively valueless "gangue" minerals, like silica (SiO_2) and calcium carbonate (CaCO_3), that after liberation by crushing and grinding can be removed by physical separation methods (e.g., gravity or magnetic separation, flotation) to produce high-grade concentrates for metallurgical processing. The third class includes finely dispersed minerals that cannot be separated physically from the gangue minerals and must be smelted or leached directly despite their low metal concentration. To process complex metal ores that contain several metals in varying concentrations, metals producers have developed sophisticated methods to separate and refine individual metals starting from complex mineral hosts.

Role of Thermodynamics and Kinetics

Recovering metals from primary or secondary resources generally requires chemical processing to isolate the metal in the desired chemical form. Thermodynamic principles establish the feasibility of a chemical reaction under certain operating conditions while kinetics (chemical rate, mass and heat transfer) determine the overall rate at which the reaction will proceed. For metal concentrates, recovering metal generally requires stripping metal atoms of oxygen or sulfur

ⁱ A small number of metals (e.g., boron, lithium, and magnesium) are extracted from naturally occurring brines as well as ores. Substantial amounts of vanadium are found in the residues of

atoms. Recovery of metal from scrap on the other hand generally requires removal of alloying elements or the attainment of a given alloy composition. The melting point needed to be reached for remelting and refining scrap metal is also determined by the chemical composition of the scrap which depends on the presence of alloying elements and other metals.

Determining whether the reaction will proceed depends on the available free energy of the particular reaction and the latter is a function of temperature. For example, the Ellingham diagram for oxidation-reduction reactions (Figure 2), plots the available free energy in kJ/mol of oxygen reacted against temperature for all known oxidation reactions, including that of C, CO, and H₂ and shows graphically the relative reducibility of any particular oxide. Considering the most commonly used metal, iron, which is found naturally as an oxide and is reduced by carbon or hydrogen to form metallic iron and CO, CO₂, or H₂O. Figure 2 shows that at 1200K, carbon will reduce FeO but not Cr₂O₃ which requires a higher temperature (16). Figure 2 also shows that higher temperatures generally decrease the free energy of the reduction reaction and explain the dominance of pyrometallurgy in primary metal production and recycling. Similar diagrams exist for other metallic compounds such as chlorides and also for metals in aqueous solutions.

[Figure 2 here]

Ellingham diagrams also illustrate the available options for restoring value to secondary metals sources. For example, the Ellingham diagram for chloride formation shows that it is

carboniferous materials like crude oil, coal, oil shale, and tar sands making petroleum refineries

possible to remove magnesium from aluminum alloys by exposing the molten alloy to chlorine gas. The same diagram shows that this method is only useful for magnesium, sodium, and calcium, and that other refining methods must be used to remove other alloying elements (17).

Ore Reserves and Economics

Deciding whether to mine and process a given ore body relies on the current and projected prices of the contained metals and their relation to the costs of production. The discovery of new deposits increases the global supply. Technological advances in the excavation and processing of minerals that reduce production costs can render previously neglected ore bodies economically recoverable. As a result, the quantity of ores considered as reserves changes dynamically with technological innovation as well as fluctuations in global metal prices. Table 1 shows global data for several major metals in the year 1996 according to the USGS (18). The reserve base (including resources currently uneconomic to mine) appears adequate for the near term even if humanity relies exclusively on primary resources. However, fully exploiting the reserve base would entail high environmental costs through significant emissions of carbon (19, 20) and sulfur oxides and landscape disturbance for mineral exploration and development.

Table 1. Primary metal resource consumption and reserve base

Resource (MMT)	World Mine Production 1996 (MMT/year)	Reserve base ⁱⁱ (MMT)	Reserve base/ Annual Mine Production (years)
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and coal-burning utilities primary sources.

ⁱⁱ The reserve base is defined as “that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those

<u>Ores</u>			
Iron ore	1,000	232,000	232
Bauxite	111	28,000	252
<u>Metals</u>			
Copper	10	610	61
Lead	2.8	120	43
Zinc	7.2	330	46
Magnesium	0.347	Recovered from natural brines and dolomite	
Nickel	1.1	110	100
Tin	0.190	10	53
Tungsten	0.030	3.3	110
Cobalt	0.024	9	375
Mercury	0.003	0.24	80

Secondary metal supplies fall into two general classes, new and old scrap.ⁱⁱⁱ The former refers to metal discards generated within an industrial setting, either at metals producers (home scrap) or from metals fabricators (prompt industrial scrap). Because new scrap stays within the mill or factory, the quality (i.e., chemical composition) is generally well known and homogeneous. As a result, this metal readily returns to the production loop. Old, or obsolete, scrap refers to metal collected after use in the economy in the form of discarded infrastructure, industrial equipment, or consumer goods. This scrap is more heterogeneous and often contains a mix of metals, alloys, and non-metallics. Moreover, the buildup of residual elements makes refining difficult, reducing the market value of recycled metal with each cycle of recovery. The ability to determine precise scrap concentrations constrain old scrap utilization. For example, erroneous

for grade, quality, thickness, and depth.” Not all of the resources included in the reserve base are economically recoverable currently but have reasonable potential for being so within planning horizons beyond those that assume proven technology and current economics (USGS Mineral Commodity Summaries 1997, p.195).

ⁱⁱⁱ “Purchased scrap” can refer to both new and old scrap but does not include the scrap generated and reused within metals production facilities.

estimates of bulk concentration made by extrapolating surface composition or through sampling can serve to disrupt optimal production schedules.

Environmental Impacts of Metal Production

One of the most striking environmental benefits of secondary metals production is the reduction in energy needed to produce a ton of metal. The primary reason for this phenomenon is that melting metal requires less energy than that needed for reducing naturally occurring oxides and sulfides. Figure 3 compares the energy requirement for producing a ton of aluminum, copper, and steel starting from ore or scrap (21). Steel produced from primary ore uses three and one half times more energy than steel from melted scrap. Copper from ore requires five to seven times more energy than that required for processing recycled metal as this ratio rises with decreasing ore grade. Aluminum from ore uses approximately twenty times more energy than from recycled metal.

[Figure 3 here]

In addition to conserving energy resources, metals recycling also reduces mining and beneficiation activities that disturb ecosystems. Though land used for the extraction of primary metals represents under 0.1% of Earth's terrestrial surface (22), exploration and mining activity can affect surrounding ecosystems due to necessary infrastructure and by dispersing metal compounds into the environment, either as air borne particles or as ions in aqueous solutions. Developing newly discovered resource deposits can also damage sensitive ecosystems, especially

in less developed regions where the need for foreign exchange from mineral rents overshadows domestic environmental concerns (23).

Recovery displaces metals from the US Municipal Solid Waste (MSW) stream, with almost 9 MMT (8.8 MMT in 1995) of metal discarded to MSW landfills annually in the U.S., a little under 6% of the total MSW by weight. This same tonnage of metal entered the MSW stream in 1960 and at that time accounted for over 10% of the waste stream (24). Two primary factors contributed to diminishing the fraction of metals as a fraction of the total weight: a) Substitution of plastic, paper, and aluminum (a lighter metal) for steel in consumer products; and b) The annual recovery of over 5.5 MMT of metal from MSW. This level of metal recovery represents a one hundred fold increase from the amount recovered in 1960, Figure 4.

[Figure 4 here]

Steel recovery from MSW began to rise significantly in the late 1980s. In 1995, about 31% of durable steel goods^{iv} (2.4 MMT), and 54% of steel containers and packaging (1.4 MMT) were recovered (25). Nonferrous metal recovery came mainly from aluminum cans (0.9 MMT) and lead acid batteries (0.825 MMT).^v The remaining discarded metal divides into about 6.6 MMT in durable goods and 2.2 MMT in containers and packaging.

^{iv} Durable goods refer to appliances, furniture, tires, etc.

^v Does not include recovery of industrial lead batteries.

Averting this flow of metals to landfills relies on a network of collection programs and processing facilities. In the U.S., curbside recycling programs serve roughly half of the population and include municipal collection of recyclables, centralized drop off centers, buy back centers, deposit systems, and programs to recover recyclable waste from commercial entities. To process the waste, over 300 Materials Recovery Facilities (MRF's) had the capacity to handle about 29.5 thousand metric tons (kMT) per day of partially sorted MSW in 1995 (5.7% of MSW) (26). Mixed Waste Processing facilities that process unsorted MSW handled an additional 18 kMT of waste daily (3.5%). Responding to state government mandates across the U.S. (e.g., Ohio, California) to reduce the volume of MSW, the number of these processing facilities continues to grow as does their use of automated separation equipment to replace manual sorters.

Secondary metals sources include other liquid and solid waste streams that are not considered traditional scrap but contain significant metal concentrations. Examples include metal slags, dross, and dusts from metals producers and sludges generated from metal using industries. Unlike traditional scrap recovery, the principal objective here is to reduce disposal costs and avoid regulatory liability by removing metals from voluminous wastes. For these sources, the value of the recovered metal at prevailing metal prices generally provides insufficient economic incentive to individual operators. Nonetheless, recovery from these sources amounts to substantial quantities at the national scale. For a study on the concentrations of several metals from reported US industrial waste streams and the economic feasibility of increased metal recovery see Allen and Behamanesh (27).

RECOVERING METALS FROM WASTE STREAMS

Physical separation

The first stage in the recycling of metal is its separation from other materials. The difficulty of separation increases with lower concentrations of metal in the source. Pieces of an individual metal (e.g., copper wires in cables) are easiest to recycle, while metals thinly distributed in products (e.g., copper in printed circuit boards) require additional processing steps for recovery. The largest single source of scrap metal from obsolete products comes from discarded automobiles. At the first stage, valuable components are removed from the car hulk whose value as parts far exceeds that of the contained material. After parts are stripped, the hulk is shredded to yield a ferrous and nonferrous metal fraction as well as Automotive Shredder Residue (ASR) comprised of plastic, rubber, glass, carpet, etc. The auto scrap industry is highly efficient, recycling 90-95% of the roughly 10 million automobiles discarded annually in the U.S. and producing about 11 MMT of iron and steel scrap in a typical year (28), as well as over 0.7 MMT of other metal scrap.

Separating the iron and steel from shredded automobiles takes direct advantage of their magnetic properties to isolate them from nonferrous metals and non-metallics. Advances in materials science have led to the introduction of rare earth alloy permanent magnets with high field strength (e.g., neodymium-boron-iron magnets that generate fields up 35 million gauss-oersted) that require no power to operate and have sufficiently high fields to allow for the recovery of even weakly magnetic stainless steels (29).

Technologies for recovering metals from waste streams draw extensively on experience gained with processing primary metal ores (30). Using traditional methods for the concentration of primary ores in the mineral processing industries, secondary processors employ milling and screening technologies to separate the metal fraction from mixed waste streams and facilitate further processing. Scrap processors use devices ranging from the heavy duty equipment for shredding automobiles to hammer mills that reduce the size of metal pieces combined with other wastes in the MSW stream. In some cases, the mechanical separation itself helps prepare scrap for the next processing stage by loosening coatings (e.g., vitreous enamel, tinplate) from metals. Subsequent screening helps remove non-metallic contaminants and narrows the size distribution of scrap to facilitate further processing (31).

To recover non-ferrous metals from mixed feeds, scrap processors exploit differences in physical characteristics, such as density and electromagnetic properties, for isolating metals from other materials and from one another. Immersing mixed scrap feeds in high density liquids produces a “sink” and “float” fraction that separate lighter metals such as aluminum and magnesium from heavier ones like copper and zinc. Hydroclones afford greater control in stratifying waste streams containing different metals and alloys by creating a density gradient proportional to applied centrifugal forces. Air classifiers separate metals from non-metallics, such as paper and plastic packaging, by allowing these lighter materials to be carried away by a jet of air that is too weak to carry the heavier metal components of the waste (32).

Both surface and bulk electromagnetic properties of metals can also be exploited to isolate metal waste streams. For instance, differences in surface electrostatic properties allow scrap handlers to remove plastic sheathing from copper and aluminum wire (33). The eddy current separator^{vi} produces an oscillating magnetic field that induces currents in conductors (i.e., metals) that generate a repulsive force to separate them from non-conductors (34). After removal of the ferrous fraction, conventional eddy current separators isolate nonferrous metals from non-metallics. Advanced models can sort among various nonferrous metals as well. Though primarily used for scrap recovery from shredded automobiles and MSW, these devices have been tested successfully for recovery of fine metal fragments from industrial wastes like ground slag and foundry sand.

Scrap processors use several techniques to separate metal alloys. To achieve gross separation, scrap handlers examine clean pieces of metal (e.g., drill cuttings that have not been allowed to oxidize) to distinguish between copper (red) and zinc (yellow) alloys for instance. More precise characterization is achieved by testing the alloy's reactivity when exposed to various acids. Chemical spot testing, for instance, indicates the presence of the major alloying elements in 2000 series (high copper), 5000 series (high magnesium), and 7000 series (high zinc) aluminum alloys. Scrap handlers can also examine the spectroscopic signature of metal samples thus determining alloy composition for any given sample. In 1990, spectroscopic analysis using lasers was introduced in automobile shredding operations (35). On the basis of rapid spectroscopic analysis of laser light reflected from a piece of metal, the mixed metal scrap is automatically sorted

^{vi} Patented by Thomas Edison in 1889

into streams containing aluminum, zinc, and copper alloys, as well as stainless steel and lead destined for different conveyor belts. The use of automated systems that rely on these various methods for alloy separation should increase scrap throughput as well as scrap quality and thus help society process more of the metal currently discarded.

Chemical separation

Several technologies dominate the industrial processes used to remove, or recover, metals from industrial waste streams, including contaminated soils (36). The efficiency of metals recovery in these cases depends on the metal concentration in the solution, properties of the host solvent (e.g., pH, viscosity), and the other metals and chemicals also present in the solution. Standard hydrometallurgical as well as pyrometallurgical processes are used to remove metals from some industrial wastes. Depending on the waste stream, other recovery methods may be appropriate. Chemical precipitation removes metal ions from aqueous solutions by transforming them into insoluble compounds which are then removed by physical methods. Ion exchange techniques remove metal ions from solution by exchanging them with weakly bound ions in a resin or organic liquid. Membrane technologies rely on differences in the permeability of metals and the host solution.

INDUSTRIAL WASTES U.S. federal regulations and industry adoption of waste minimization guidelines have stimulated the development of metals recovery processes for by-product sludges, flue dusts and other waste streams. Some emerging companies now specialize in the processing

of such hazardous wastes. For instance, Encycle/Texas^{vii} uses hydrometallurgical technology to separate copper, silver, nickel, lead, zinc, cadmium and chromium from the non-metallic components in wastes and ships the resulting metals and metal compounds to primary or secondary metal producers for re-use in processing (37).

INMETCO,^{viii} a major nickel and copper producer, specializes in the recovery of nickel, chromium and iron from industrial flue dusts, filter cakes, mill scales, grindings, nickel-cadmium batteries, and used catalysts using the INMETCO "High Temperature Metals Recovery Process." In 1993, the company processed over 54 kMT tons of such materials (38). This pyrometallurgical process yields a nickel-chromium-iron alloy and an environmentally inert slag. The cast metal has a typical composition of 10% nickel, 14% chromium, and 68% iron, with manganese, molybdenum, and carbon forming the balance. Typical metal recoveries range from 89% for chromium to 98% for nickel. This process has been designated by the US Environmental Protection Agency (USEPA) as the "Best Demonstrated Available Technology" for the recovery of nickel, chromium, and iron from electric arc furnace dusts, steel mill pickling wastes, plating plant wastes, and nickel cadmium batteries, Figure 5.

[Figure 5 here]

Ash from coal combustion (U.S. generation ~ 100 MMT/year) contains considerable amounts of silicon, iron, and aluminum oxides as well as other metallic oxides. The iron oxides

^{vii} A subsidiary of ASARCO, Inc.

can be separated magnetically (39). The ash can also be smelted to produce ferrosilicon and a byproduct aluminum-rich slag (40). In the 1970ís, the Electric Power Research Institute investigated two hydrometallurgical processes (the Direct Acid Leach (DAL) and Pressure Digestion-Acid Leach (PDAL)) for metals recovery from coal ash (41). Rayzman et al. (42) review the technologies developed for metals recovery from coal ash since the late 1960's.

Another relatively obscure source of secondary metal is found in the metals flows associated with Acid Mine Drainage (AMD). While contemporary mining regulations require mine owners to seal mines after their useful life, mines abandoned decades and centuries ago were simply left exposed to the elements. With time, the acidity levels in these mines rises as sulfurous material lay exposed to water and air. The high acidity levels serve to mobilize metal atoms that would otherwise remain bound in the geologic matrix. Streams and rivers in old mining regions, such as southwestern Pennsylvania in the U.S. and the ancient Lavrion silver mines in Greece, typically carry thousands of tons of metals values annually (43). These streams impact the environment by introducing abnormally high metals to surrounding and also distant ecosystems. Most technical work done to address AMD problems has the explicit objective of remediating past pollution. However, recent attempts in the U.S. and Europe have quantified the metal values available from recovering these high concentration metals streams using chemical, biological, and electrochemical technologies (44). For a review of the AMD treatment methods for remediation and recovery see Gazea et al. (45).

^{viii} A subsidiary of the International Nickel Company (INCO).

CHEMICAL CATALYSTS The value of minor metals used as chemical catalysts (e.g., molybdenum, vanadium, and cobalt) has stimulated industry to develop new methods for recovery (46,47). Typically, these methods employ hydrometallurgical techniques to leach waste materials in strong acid solutions and which are then subjected to solvent extraction or ion exchange treatment to bind metal ions with an organic agent that is later "stripped" to yield concentrated solutions of individual metals. The individual metals can then be obtained from the solutions by electrowinning or as precipitated salts of a particular metal.

Petroleum refineries use metal catalysts to remove sulfur compounds from crude oil, for "cracking" it to smaller molecules, as well as other unit operations. Several hydrometallurgical processes have been developed for recovering molybdenum, vanadium, cobalt, and nickel from petroleum catalysts (48). A typical spent catalyst contains 5-16% sulfur, 1-8% molybdenum, 1-13% vanadium, 1-3% nickel, 10-30% carbon and 20-30% aluminum in the form of alumina (Al_2O_3). These materials are recycled by four^{ix} principal processors globally. All together, they handle about 65 kMT metric tons of catalysts annually (49).

Automobile emissions control in most developed countries is achieved with the help of catalytic converters that use the platinum group metals (PGM), platinum, palladium and rhodium. In 1992, the global use of these metals in automobile catalysts amounted to 1.5 million troy ounces of platinum (34% of total global), 0.5 million ounces of palladium (13%) and 0.3 million ounces of rhodium (87%). Catalytic converters consist of a stainless steel canister containing

platinum group metals deposited on alumina with high surface area which lies on a substrate of synthetic cordierite, a ceramic material. Depending on the size of the automobile, the weight of the packed canister ranges from about 2 to 11 kg and typically contains about 1 kg of metal catalyst per metric ton of packing. Recovering PGMs is accomplished by dissolving the contained metals in a copper melt followed by conventional electrorefining of the copper, or leaching in sulfuric acid solutions followed by electrowinning. Other processes in various stages of development have been reviewed by Hoffman (50), Mishra (51), and Kuczynski et al. (52).

SECONDARY METAL PRODUCTION

Over the twentieth century, US metals consumption grew consistently until the mid 1970's, when several factors combined to reduce domestic demand, Figure 6. Though not shown in the figure, the capacity and output of secondary production plants in the U.S. grew significantly during World War II when national metal demand for armaments rose sharply and the war severely restricted world metal exploration and trade. From 1939 to 1943, secondary copper production rose almost 120% and secondary aluminum production shot up over 300% (53). Recovery rates for secondary aluminum are only now beginning to approach World War II levels. Following the energy shocks of the 1970s, metals demand failed to resume its upward trajectory due to several factors including saturated markets, other materials substituting for metals, and a shift to lighter metals, most notably aluminum (54). Since 1960, when data on secondary metals were first systematically collected, secondary metals production rose in fits and starts with an

^{ix} Gulf Chemical and Metallurgical Corp. in Texas; Taiyo Koko in Japan; CRI-MET in Louisiana;

average annual increase of about 4.9%. Primary metal production grew at less than 0.5% annually over the same period.

[Figure 6 here]

Steel dominates the metal tonnage handled by the secondary metal industry, but not the value. In 1993, iron and steel comprised 90% of the weight of the old scrap recycled in the U.S. while it represented only 42% of the metal value. In value terms, aluminum follows with 26%, copper at 15%, and gold with 10% of old scrap value (55).

Several metals that are commonly alloyed with commodity steels to improve properties (e.g., strength and machinability) follow steel through the recycling loop. For example, 75% of molybdenum (1996 US consumption 14.5 kMT) went to iron and steel producers in 1996. Depending on the fate of the steel, some of this metal will recycle in the general ferrous scrap stream. Similarly, vanadium (4.7 kMT) finds its primary use as an alloying agent for iron and steel and most recovered vanadium recycles in ferrous scrap. As a final example, though the recovery of manganese (716 kMT) as an individual metal is negligible, a considerable amount is recycled annually during recovery of ferrous scrap and iron and steel slag.

The stainless steels provide another example of iron-based alloys that draw substantial amounts of other metals for their production. These iron alloys contain chromium, nickel and

small amounts of other metals, and excel in their ability to resist corrosion, giving them longer economic life. This longevity diminishes the immediate need for replacement metal and thus displaces the need for new metal. As in the case of other specialty metals, the number of stainless steels has proliferated. However, at present only two grades of stainless represent 65% of the total world production of stainless: AISI 304 (18% chromium, 8% nickel, balance iron) and AISI 316 (16% chromium, 10% nickel, balance iron).(26) The smaller number of alloys increases the possibility of developing closed loop recycling systems.

Superalloys containing iron, cobalt, nickel, niobium, and hafnium were developed for use in high temperature corrosive environments like those found in jet engines and electric power generators. The performance of these alloys is compromised at contaminant levels as low as 1 part per million. Therefore, most superalloy recovery relies on new scrap, or tightly controlled old scrap streams originating in the aerospace sector. The same properties that make these alloys attractive for their specific applications (i.e., high melting point and the formation of oxide films to protect against corrosion) also makes difficult the use of traditional pyrometallurgical and hydrometallurgical techniques for recycling.

Table 2 shows that bulk commodity metals such as steel, copper, and aluminum have relatively high recovery percentages but reveals that the old scrap fraction is less than half of that considered as 'recycled' (56). The table also shows that the bulk use of certain metals in standard consumer products, such as lead in auto batteries and aluminum in used beverage cans (UBC's), significantly impacts recovery levels. Though recovery is expressed as a percent of current

production, metal that enters secondary markets can be as little as 90 days old for aluminum cans to 10 years for magnesium castings from automobiles and 20 or more years for steel scrap from demolished buildings. This varying time lag serves to increase the variety of scrap metals and alloys entering the system at any given time reflecting historical changes in the composition of commercial alloys.

Table 2 Apparent consumption, and new and old scrap recovery for various metals in the US, 1996

Metal	1996 U.S. App. Cons. (kMT)	New Scrap Recovery (kMT)	Old Scrap Recovery (kMT)	Comments
Steel	112,000	38,000	32,000	
Aluminum	6,300	1,700	1,400	60% old scrap from UBC's
Copper	2,700	880	400	
Lead	1,550	-	~1,000	88% from auto batteries
Zinc	1,470	240	115	55% App. Cons. to galvanizing
Magnesium	171	35	30	55% App. Cons. to aluminum
Nickel	172	55	-	46% App. Cons. to stainless steel
Tin	48.4	4.4	7.6	30% App. Cons. to tinplate
Tungsten	151	2.7		80% App. Cons. to electrical
Cobalt	8.9	1.5		42% App. Cons. to superalloys

As in the case of stainless steel and specialty steels, several nonferrous alloys use considerable amount of other metals. For instance, aluminum alloys account for 55% of magnesium consumption. Substantial amounts of zinc (55%) and tin (30%) are used to coat steel for corrosion resistance. A significant amount of zinc (20%) and tin (6%) are also alloyed to copper in brass and bronze mills. As a result, the recovery of magnesium, tin, and zinc are tied to that of steel, copper, and aluminum.

The recovery of several toxic metals depends on how they are used in products. Nickel-cadmium batteries now account for almost two thirds of the market for cadmium metal(52) and expanded recovery systems are now developing (see Figure 4). On the other hand, over 90% of the arsenic consumed in the U.S. is used for wood preservation.

The recycling of toxic metals may not be as important to the environment as ensuring that these metals do not become biologically available during or after use in the economy. Humans and animals require trace amounts of certain metals (e.g., iron, aluminum, zinc) as part of their diet, but can experience both chronic and acute adverse health effects at levels too high. Metals like arsenic, cadmium, and lead, however, are toxic in even small amounts and have no known nutritional value. For metals in solution, the ability to cause harm depends on their solubility, and their ability to leach through soils and wastes relies on the acidity and composition of the medium. Efforts to reduce human exposure, through efficient recovery or by sequestration in products, landfills, or some vitrified form, need to primarily consider the environmental transport mechanisms.

Arguments concerning the different bioavailability of lead compounds from gasoline emissions and in slag from lead acid battery recycling are central to recent debate about the environmental impact of electric cars. In the early 1970's, the use of lead for additives in gasoline reached a global peak of over 400 kMT, later falling to under 70 kMT by 1993 (57). In 1995, Lave et al. (58), argued that the expanded secondary production of lead associated with their use in electric cars would result in higher lead emissions per kilometer than peak lead emissions from

gasoline. Socolow and Thomas (59), countered that the most hazardous form of release, air emissions, from the production of 910 kMT of secondary lead at auto battery smelters summed to only 57 metric tons in 1994 in the U.S. The corresponding emission factor (tons emitted per ton produced) of $6 * 10^{-5}$ for the U.S. in 1994 exceeds those available with new processes, such as the $1 * 10^{-5}$ emission factor reported by the Boliden company of Sweden (60). The other loss of lead in the smelting process is as lead oxide dissolved in the silicate slag produced during the smelting of batteries. This slag typically contains 1-3% lead, depending on the efficiency of the slag treatment process, as described in a later section of this report. Lead oxide in the slag is rendered environmentally inert in the silicate matrix. The slag has passed the standard leachability test in the U.S., the USEPA's Toxic Characteristic Leaching Procedure (TCLP), that subjects materials to accelerated leaching. Slags that pass this test are used as road fill, as raw material for the manufacture of cement, a filter medium for wastewater treatment plants, and other uses. Thus, not only the quantity of the emissions but also the quality of their environmental threat were exaggerated in this case.

RECOVERY PROCESSES

Iron and Steel

As noted earlier, iron and steel constitute over 90% of all metal production and a similar fraction of the scrap metals market. Steel mills consume about three quarters of the scrap, and iron and steel foundries consume the remainder to produce ferrous castings.

The ability of steel plants to accept scrap inputs has been influenced by technology changes. For a good review of developments in pneumatic steelmaking in this century until the 1980ís see Pehlke (61). From the beginning of the century until the 1950's, the open hearth furnace dominated steelmaking technology. It used primarily pig iron, but could accommodate more than 50% scrap in its mix due to the use of an external heat source. The succeeding technology, the Basic Oxygen Furnace (BOF) process was introduced by Voest Alpine in Austria in 1952 as the Linz-Donawitz (LD) converter, and has undergone further developments with innovations such as the Q-BOP (bottom-injected) oxygen converter. Today BOF processes account for about 60% of US steel production. The primary feed of the BOF is molten pig iron from the blast furnace. The BOF also accepts from 10% to 30% scrap in the metal charge to the furnace. The US average is about 25% (62). It should be noted though that most scrap used in BOF's comes from the mill itself. Old scrap comprises at most half of the scrap in the charge (63).

The Electric Arc Furnace (EAF), introduced commercially for the melting of iron and steel scrap in the mid 1960s, accounts for the other 40% of US steel production. Electric arc furnaces use electricity conveyed by graphite electrodes (arcing) to melt scrap and can accommodate 100% scrap in the feed. EAF production is sensitive to the presence of residual elements like zinc, copper, chromium, and molybdenum which can cause defects in the finished steel at levels measured in tens of parts per million. Metals with low boiling points like zinc and cadmium volatilize when the charge is smelted and collect in dust filters used to treat emissions. Other residuals are more difficult to refine out, though some novel methods for removing residual

elements using flotation processes to recover aluminum, magnesium, and plastics from ferrous scrap and micro-alloying methods that make positive use of residual elements (64).

The Institute for Scrap Recycling Industries classifies more than one hundred standard grades or codes for ferrous scrap (65). The grades specify gross physical characteristics such as acceptable dimensions for individual pieces and densities for baled scrap. The presence of coated metal as well as threshold levels of residual alloying elements are also specified. The different grades of scrap distinguish between sources such as factory stampings, shredded auto bodies, and obsolete railroad equipment. The grading system has helped the industry grow through standardization and its extent indicates the heterogeneity of ferrous scrap available on the market.

New scrap supplies with known chemical composition can be introduced in a controlled manner into the EAF. However, the supply of new scrap is inelastic and tied to current production levels. Furthermore, innovations such as continuous casting and other efficiency improvements have reduced the amount of clean home scrap generated in mills and factories. Therefore, expanding EAF capacity must rely on old scrap whose supply may be essentially unlimited but whose quality ranges widely. EAF plants still use almost 95% scrap in their furnaces. However, as EAF mills seek to improve the quality and value of their products they have come to rely on augmenting the scrap charge with primary iron products such as Direct Reduced Iron (DRI) and pig iron to dilute the residual elements present in the scrap charge (66).

Aluminum

Like other metals, aluminum is used either in pure form (e.g., aluminum foil) or alloyed with other metals. The ASTM specifications for the most common aluminum alloy, Al6061, include copper (0.15-.6%), magnesium (0.8-1.2%), silicon (0.4-0.8%), zinc (<0.25%) and iron (<0.7%) (67). This alloy, used widely for aerospace, automotive, railroad and other industrial applications, offers light weight, good corrosion resistance, and excellent formability. As indicated by the above specifications, alloying contents above a certain level have a detrimental effect on the desirable properties. This makes the sorting of aluminum scrap, prior to melting, essential to avoiding difficult and costly refining procedures. Van der Donk et al. (68), report that aluminum scrap from Dutch household waste contained 0.06% copper, 0.03% zinc, 0.10% silicon, 0.50% manganese and 2.6% iron. Comparison with the ASTM specification for alloy Al6061 shows that only the iron content of the recycled household scrap is above specification.

Aluminum scrap is usually processed in a reverberatory furnace. The name "reverberatory" derives from the consideration that heat "reverberates" ("radiates" is more technically correct) from the roof and walls of the furnace onto the molten metal bath. The superheated metal is pumped through the charge well in which metal scrap and fluxing materials are charged continuously. Existing furnaces can process up to 5-6 tons per hour (t/h) of scrap. Wells et al. (69), investigated the effects of various operating parameters on the efficiency and metal recovery of an aluminum reverberatory furnace. The formed dross material (aluminum and other oxides) is skimmed periodically from the surface of the bath and can contain 20-80% aluminum. The incentives to process this byproduct material are tempered by concern over the

treatment of the generated wastes. New processes are under development to recover metal value from aluminum dross and generate benign waste products (70).

A review of techniques for reducing the level of impurities in recycled aluminum, in particular the removal of iron, is presented by van der Donk et al. (71). Techniques range from partial solidification of aluminum metal from an impure aluminum melt to the "three-layer-cell" electrolytic process, where a layer of molten aluminum ("cathode") is formed above a barium-sodium-aluminum halide layer ("electrolyte") that separates the pure metal from the third and heaviest layer of impure aluminum in the bottom of the cell ("anode"). Because of smaller scale operation and proportionately higher heat loss, the three-layer cell currently consumes 17-18 kilowatt-hours/kilogram (kWh/kg) of metal, in contrast to conventional electrowinning of aluminum that requires 13-14 kWh/kg (72).

In addition to alloying elements, aluminum scrap often includes lacquers, paints and plastic coatings. Alcan Recycling has developed a fluidized bed reactor that can remove such coatings from aluminum scrap containing up to 50% organic material. The aluminum scrap is introduced to a hot (<500°C) fluidized bed of alumina that heats the scrap and oxidizes its organic component. The reactor, in operation since 1994, can process 2-8 t/h of scrap, depending on the organic content, and recover over 98% of the metal (73). The Alcan recycling facility in Oswego, New York uses a more common technology for delacquering and melting aluminum UBC's by oxidizing the organics in a co-current flow rotary kiln followed by a melting furnace similar to that

described earlier. This plant has capacity for recycling 73 kMT (i.e., about five billion cans or slightly over 1% of U.S. aluminum consumption) per year (74).

The substantial increase in the aluminum content of automobiles has introduced several dozen alloys into aluminum automobile scrap, whose mix continues to change to accommodate new automotive designs (75). Mixed aluminum scrap from used car hulks (e.g., the 2000, 5000 and 6000 series alloys) must be separated to prevent downgrading of the secondary aluminum product. For example, the value of wrought aluminum alloys can not be recovered if melted with lower grade aluminum castings. This loss of value offers incentive for designers to optimize the compatibility of alloys used in automobiles and for industry to develop cost-effective alloy separation technologies that facilitate the highest value post-consumption recovery (76). Techniques for separating wrought and cast aluminum scrap have been developed but do not enjoy wide-scale use (77). In Europe, research centers for developing improved aluminum recycling systems have been established in Germany (78), Sweden and Luxembourg (79).

Copper

Copper is used primarily in electrical and plumbing systems and in heat exchangers. It enters the economy either as pure metal, copper alloys, or in combination with tin and zinc in bronze and brass. Recycled pure metal can be simply remelted and combined with primary electrorefined copper. Copper alloyed or physically mixed with other metals is melted either at secondary or primary smelters and cast into anodes along with the virgin metal prior to

electrorefining (80). Segregated copper alloys can also be used as raw material in bronze and brass foundries.

Secondary copper smelters feed low grade copper scrap with coke into a blast furnace to produce “black” copper that contains lead, zinc, and other impurities. Volatile elements like zinc and lead oxides are then driven off by partial oxidation to produce “blister” copper. Hanusch reports on the refining of copper scrap to remove associated metals (81). Prado and Prado discuss the treatment of copper dusts rich in lead and zinc (82).

The KALDO reactor of the Boliden corporation in Sweden uses another process for smelting low-grade copper scrap. In the Boliden process, metal scrap containing on average 40% copper, 10% zinc, and 15% iron is charged to an inclined rotating vessel. Coke is added as required and oxygen-enriched air is injected through a lance. The heat of oxidation of the iron, zinc, and lead drives off the volatile metal oxides and produces impure copper and an iron-rich slag that can be reduced to less than 0.5% copper and zinc. The copper smelter at Porto Marghera, Italy uses this process and has annual capacity of 25 kMT per year of secondary copper (83).

Much copper, as well as other metals, is discarded annually in millions of computers and other pieces of electronic equipment that end up in landfills. Discarded electronic scrap contains roughly 40% metals (e.g., copper, iron, aluminum, nickel, tin, lead) with the remainder accounted for by plastics and refractory oxides (84). Precious metals recovery gives the primary incentive

for recovering metal from electronic scrap with typical concentrations (circa late 1980s) of 770 grams/ton (g/t) for gold, 1500 g/t for silver, and 40 g/t for palladium. Copper, silver, gold, palladium, platinum and other noble metals are generally integrally distributed in circuit elements and can be recovered pyrometallurgically by smelting into liquid copper and then recovered by conventional electrorefining. To optimize value recovery, processors remove steel and aluminum structural components that would anyway be discarded in the by-product slag of the pyrometallurgical process.

The Noranda process reactor at Noranda, Quebec, recycles about 100 kMT of used electronics per year in addition to 6-700 kMT of primary copper concentrates (85). Even when used electronics are collected, as of the early 1990s the market price in the U.S. was only 50-60\$ per ton. Initial design for easy disassembly and downstream "ide-manufacturing" technologies can reduce the cost of recovery and allow for more economic recovery of metals. This is especially important as future electronic scrap waste streams may contain even smaller volumes of precious metals as industry becomes more efficient at depositing thinner layers of precious metals on electronic components.

Lead

The largest use of lead (~80%) in the U.S. total goes to automotive and industrial lead-acid batteries. About 95% of the used batteries in the U.S. and other developed nations undergo recycling. Lead batteries consist of a polypropylene case, lead lugs, electrodes (typically screens), plastic spacers between the electrodes, lead oxide paste (PbO_2 and PbSO_4) and sulfuric acid.

Improper handling of this combination of toxic metal and chemicals has consigned more than 20 former battery recycling facilities in the U.S. to the National Priorities List of the Superfund (86).

A typical lead battery weighs about 11 kg and contains 7 kg of lead and 3 kg of sulfuric acid. At a typical recycling plant, batteries are crushed or sliced and separated into three streams: lead materials (about 60% lead, 15% PbO_2 and 12% PbSO_4) (87), polypropylene scrap, and sulfuric acid, Figure 7. The lead-containing materials are smelted (i.e., heated to produce a molten bath) to produce lead bullion and a molten silicate solution containing all of the lead oxides. This slag by-product is smelted and reduced with carbonaceous material and fluxing agents in a lead blast furnace, similar to those used in the primary smelting of lead oxides. The low-lead slag produced in such furnaces is environmentally inert and is disposed in industrial landfills.

[Figure 7 here]

In another lead recycling process, used extensively in Europe, lead components are smelted at 1000°C with coke breeze and sodium carbonate flux and iron filings, used to fix sulfur by forming an iron sulfide matte, in a short fuel-fired rotary furnace. It is reported that use of bulk oxygen and other innovations can increase the production capacity of such furnaces by 40% (88). The ISASMELT furnace process, used in Australia and South Korea, introduces lead materials with lump coal into a vertical reactor containing a slag bath (89). Air and oxygen are injected in this reactor that is similar to the top blown BOF furnace used for steelmaking. During

smelting, metallic lead containing less than 0.01% antimony settles in the bottom and is periodically tapped out of the furnace. When the upper slag layer in the reactor reaches a certain depth, the slag is reduced from 40-60% lead and 5-6% antimony, to 2-4% lead and less than 1% antimony by continuous injection in the presence of coal. Most of the treated slag is then tapped out of the reactor and the cycle repeats (90). Thus, the two-reactor process used in the U.S. (reverberatory and blast furnace) is replaced by a two-stage process in a single reactor.

Zinc

The foremost use of zinc today (55% of total US consumption) is as a corrosion-inhibiting coating on steel products (i.e., galvanizing) (91). Therefore, much of the recycled zinc originates in the remelting of steel scrap in the EAF and the waste materials of the zinc coating process (ash and dross). Other uses of zinc include brass and bronze alloys (~20%), zinc alloys (13%) and chemicals (10%).

The high temperature of the EAF process results in the volatilization of zinc and some iron, and the production of a very fine EAF dust that may contain anywhere from a few percent up to thirty percent zinc, depending on the feed to the furnace. Typically, the EAF operation produces 10-15 kg of dust per ton of steel produced that also contains 20-40% iron, 1-4% lead, 0.5%-3% chlorine and 0.1-0.5% fluorine (92). The predominant process used for smelting high zinc recycled materials is the Waelz rotary kiln in which zinc is reduced, volatilized and recovered in the form of impure zinc oxide containing 50-60% zinc. The iron residue from the kiln can be

used along with iron scrap to produce steel in an EAF. The zinc oxide dust can be sent for further processing to a zinc-lead blast furnace (Imperial Smelting Process) or to a primary zinc plant where it is dissolved in sulfuric acid along with the primary zinc oxides.

A number of other pyrometallurgical processes have been developed for the treatment of EAF dusts, including the Flame Reactor process of Horsehead Resources (93,94). The University of British Columbia and Chaparral Steel have developed a hydrometallurgical process that recovers pure zinc hydroxide-zinc carbonate materials as well as lead, copper and cadmium from EAF dust (95). Other emerging hydrometallurgical processes such as the Ezinex (96), and the Zincex (97), processes leach the EAF dust and separate the metal ions by cementation (i.e., displacing one metal in solution by another), solvent extraction, and electrowinning. By the mid 1990s, US capacity for EAF dust recovery of zinc exceeded 95 kMT (98).

Industrial iron wastes that contain relatively small amounts of zinc (e.g. 0.1-2%) can also be smelted in secondary iron blast furnaces to produce "pig" iron suitable for some foundry operations and a zinc oxide dust that can be recycled to a primary zinc plant. The DK Recycling plant in Duisburg, Germany, processes nearly 380 kMT per year of iron wastes in a process that consists of agglomerating these feed materials by sintering and then smelting them in a blast furnace (99).

Though not used for commercial recovery, we here mention the use of above ground plants to recover metals including zinc, i.e., phytoremediation (100). Interest in remediating

metals-contaminated soils has spurred research into using plants that possess a high tolerance for metals and “hyperaccumulate” metals from the soil. Though this novel technique is used overwhelmingly to reduce metals concentrations in soils, some species are able to accumulate as much as 0.4% of zinc or nickel in the dried plant matter and a considerably higher fraction in the plant ash sometimes yielding a metals content equivalent to a low-grade ore. Baker and Brooks review the use terrestrial plants for accumulating metals from soils (101).

ENVIRONMENTAL REGULATION

Federal, state, and local environmental regulations affect the secondary metals industry like any other. Government regulates the air emissions coming from secondary smelters and stormwater runoff emissions from open scrap yards. Regulatory waste classifications also determine the transport, handling, treatment and disposal options available for metals loaded wastes (102).

The Clean Air Act (CAA) mandates the use of Best Available Technology for secondary smelters to control for criteria air pollutants.^x The 1990 amendments to CAA require Maximum Achievable Control Technologies to reduce hazardous emissions and directly affect operations at EAF mills, integrated steel mills, and secondary smelters of aluminum and lead. The Clean Water Act (CWA) controls for environmental discharges of toxic pollutants including the metals copper,

^x Carbon Monoxide , Particulates (PM10), Sulfur Dioxide, Ozone, Lead, and Nitrogen Dioxide

lead, zinc, and their compounds, as well as organic materials commonly found in scrap, such as machining oils and polychlorinated biphenyls (PCBs).

The most comprehensive solid waste regulation, the Resource Conservation and Recovery Act (RCRA), regulates the generators and transporters of wastes with rigid requirements for treatment and disposal. The Hazardous and Solid Waste Amendments to RCRA define "Solid Waste" to include recyclable materials thus placing the full regulatory burden of waste disposal on scrap handlers. Many metals-loaded wastes exhibit one of USEPA's conditions (i.e., ignitability, corrosivity, reactivity, or toxicity) for being considered hazardous waste (subtitle C). Due to its indiscriminacy, this regulatory designation impedes the collection, transport and recovery of metal wastes without improving environmental protection. Responding to outside criticism, the USEPA initiated efforts in the early 1990's to reform RCRA and to facilitate greater national metal (and other material) recovery (103). For instance, the economic recovery of metal from discarded consumer products like nickel-cadmium batteries and mercury thermostats require central processing facilities and must thus contend with regulations on inter-state waste transport. In the mid 1990s, USEPA issued the Universal Waste Rule (104), to reduce regulatory requirements for metals waste such as these and stimulate investment in recovery facilities. The economic success of facilities that have begun to introduce these wastes into their process stream will be essential to greater closure of the metal system.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA/"Superfund") affects the secondary metals industry by holding liable "Potentially

Responsible Parties that generate, transport, or treat metal wastes associated with a Superfund site. The Basel convention agreement designed to limit the unchecked flow of hazardous waste from rich to poor countries also has the effect of subjecting international scrap trade to a new regulatory regime. While regulations have been effective in controlling air and water emissions from point sources, much remains to be done to promulgate legal definitions in sweeping regulatory packages such as these that serve to protect the environment as well as encourage the optimal metals recovery (105).

CONCLUSIONS

The preceding analysis offers some perspective on the economic, technical, and regulatory factors affecting secondary metals recovery in the U.S. Comprehensive analysis of the metals system to identify leaks and potential recovery opportunities would require a description such as that shown in Figure 8 for each metal. Attaching values to some of the lines shown in the figure can be achieved using available data. For many of the other lines shown, efforts to attach numbers are complicated by the search for data that are hard to come by, the need to account for the metals content of alloys, and trade. Estimates of the quantity of metal dissipated from the industrial system need to consider the nature of the products that incorporate the metal, production losses, and losses from corrosion and wear over time. Despite the difficulty, many excellent studies have been carried out for individual metals (106,107), though much room remains for systematic analysis.

[Figure 8 here]

The metal incorporated into infrastructure and products can be considered as valuable inventory and is prevented from returning to the production stream. Much potentially recoverable metal also lies in obsolete scrap heaps for which market forces have been hitherto insufficient to enable economic recovery. For instance, the accumulation of discarded ferrous scrap alone in the U.S. was estimated to be nearly 700 MMT by the late 1980ís (108).

Secondary sources include recycled metal scrap that remains within industry and metal contained in consumer products. Metals producers have returned process scrap to the production stream since antiquity. In the past decades however, this recovery has become more efficient and has included clean scrap generated within downstream industries. Metals recovery systems have also developed for some consumer products (e.g., discarded lead-acid batteries, autos bodies) with recovery rates approaching one hundred percent. Metal recovery from products benefit from increased industry adoption of design for recyclability (e.g., reducing the number of alloys used, alloy compatibility, easy disassembly) guidelines by manufacturers. Improved instrumentation and sorting systems enable scrap processors to reduce the degradation of properties and increase the throughput of scrap. Secondary smelters contribute by developing blending technologies that minimize the loss of metal to metallurgical byproducts like slag, and the loss of value in metal alloys.

More dilute metals waste streams remain largely unexploited. Over 60% of the metal discarded in MSW and the metals values in many industrial waste streams go unrecovered. Metals used in small amounts for specialized applications not requiring bulk are not easily retrieved from products or individual waste streams. However, in several instances, industry has found it profitable to capture opportunities to collect metal wastes from disparate sources to profitably recover metal values. These initiatives typically involve large capital investments in centralized facilities and must take advantage of economies of scale to collect and process metal waste streams. The profitability of such facilities depends on market forces which are shaped by the regulatory environment, collection infrastructure, and capital costs.

Reducing human exposure to highly toxic metals depends on continued diligence in controlling emissions from metals producers and from their use in non-dissipative products. Major dispersive uses of toxic metal in applications such as herbicides and gasoline additives have been phased out in the U.S. over the last several decades by legislative decree. In other instances, research has enabled substitutes to replace toxic metals in consumer and industrial applications. Recovery of the toxic metals bound in products relies on regulatory incentives, the development of a suitable collection infrastructure, and available process technologies. These factors combine to determine the economics of secondary metals recovery from disparate sources. Alternatively, the potential environmental impact of toxic metals can be reduced by their disposition in an inert form.

Metals will remain an integral part of future industrial society due to their unique and valuable properties. Decades of increased productivity and more efficient technologies for metals production and use has diminished the share claimed by the primary and secondary metals industries in the US national economy. Nonetheless, metals appear in every rung in the ladder of value addition in the manufacturing base and are ubiquitous in the everyday activities and industrial backbone that supports modern economies. Because of the centrality of metals in industrial and consumer artifacts, improving resource efficiency and reducing losses in the metals sector cannot help but influence positive environmental change throughout the fabric of industrial society.

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Figure Captions

Figure 1. The spaghetti diagram indicates the flows of metals among a sample of metals processors in New England. The arrows indicate the direction of the flow, while the number of lines indicate the magnitude. (After Sagar & Frosch, 1997)

Figure 2. Ellingham Diagram for Oxides.

Figure 3. Comparison of Energy Inputs for Various Metals: Primary v. Secondary Production

Figure 4. Generation and recovery of ferrous and non ferrous metal from US Municipal Solid Waste 1960-1993

Figure 5. Flowsheet of the High Temperature Metals Recovery Process, INMETCO, Ellwood City, PA.

Figure 6. US Metal production from primary and secondary sources: 1900-1995.

Figure 7. Flowsheet for battery recycling plant, East Penn Manufacturing Company, Lyons, PA. (After Leiby, et al.)

Figure 8. Generic template for assessing materials flows for individual metals.

Literature Cited

1. Wilson AJ, 1994. *The Living Rock: The Story of Metals Since Earliest Times and Their Impact on Developing Civilization*, Woodhead Publishing Ltd., Cambridge, UK.
2. Williamson D. 1997. Into the Next Millennium: The Long Bull Market in Metals and Minerals. Paper presented at the Society for Mining, Metallurgy, and Exploration Annual Meeting, Denver, Colorado, February 24-27, 1997.
3. Tilton JE. (ed.). 1990. *World Metal Demand: Trends and Prospects, Resources for the Future*, Washington, DC.
4. Williams RH, Larson, ED, Ross MH. 1987, Materials, Affluence and Industrial Energy Use. *Annual Review of Energy and Environment* (12):99-144.
5. Sagar AD, Frosch RA. 1997. A Perspective on Industrial Ecology and Its Application to a Metals-industry Ecosystem. *Journal of Cleaner Production* 5(1-2):39-45.
6. Allenby BR. 1992. Industrial Ecology: The Materials Scientist in an Environmentally Constrained World. *Materials Research Bulletin* 17(3):46-51.
7. Tibbs H. 1992, Industrial Ecology: An Environmental Agenda for Industry, *Whole Earth Review*, Winter 1992. Pp. 4-19.
8. Sibley SF, Butterman WC, and Staff. 1995. Metals Recycling in the United States. *Resources, Conservation, and Recycling* 15:259-267.
9. Wulff SW. 1997. Scrap Supply for Steelmakers: Observations from the USA Experience. Paper presented at the Third ASM International Conference on the Recycling of Metals, Barcelona Spain, June 11-13, 1997.

-
10. Daily prices for secondary metals are published in the daily newspaper *American Metals Market*.
 11. Institute of Scrap Recycling Industries. Annual. *Scrap Specifications Circular: Guidelines for Nonferrous Scrap, Ferrous Scrap, Glass Cullet, Paper Stock, Plastic Scrap*, Institute of Scrap Recycling Industries, Washington, DC.
 12. Comprehensive industry surveys for individual metals are available from Roskill Information Services, Ltd., 2 Clapham Road, London SW9 0JA, UK.
 13. Rogich DG, and Staff. 1993. *Materials Use, Economic Growth, and the Environment*, Presented at the International Recycling Congress and REC'93 Trade Fair, U.S. Bureau of Mines, Washington, DC.
 14. U.S. Bureau of Mines. 1990. *The New Materials Society: Volume I-III*. U.S. Government Printing Office, Washington, DC.
 15. Biviano M, Sullivan D, Wagner L. 1997. *Materials Flow Studies, Total Materials Consumption ñ An Estimation Methodology and Example Using Lead*. US Geological Survey, Minerals Information Office, Presented at the 8th International Symposium on Raw Materials, Federal Institute for Geosciences and Natural Resources, Hannover, Germany.
 16. Evans JW, De Jonghe LC. 1991. *The Production of Inorganic Materials*. p. 58 Macmillan Publishing. New York, NY.
 17. Butterwick L, Smith GDW. 1986. Aluminum Recovery From Consumer Waste, Part I Technology Review. *Conservation and Recycling* 9(3):281-292.
 18. U.S. Geological Survey. 1997. *Mineral Commodity Summaries*. U.S. Government Printing Office. Washington, DC.

-
19. Forrest D, Szekely J. 1991. Global Warming and the Primary Metals Industry. *JOM* 43(12):23-30.
 20. Themelis NJ, Wernick IK. 1997. Metal Production and Greenhouse Gases. pp. 595-610 in the Proceedings of The Julian Szekely Memorial Symposium on Materials Processing, Cambridge, MA October 6-8, 1997. Available from The Minerals, Metals, and Materials Society (TMS), Warrendale, PA.
 21. Chapman PF, Roberts F. 1983. *Metal Resources and Energy*, p. 138. Butterworths. Boston, MA.
 22. Barney GO. 1980. *The Global 2000 Report to the President of the United States*, Pergamon, New York.
 23. Hodges CA. 1995. Mineral Resources, Environmental Issues, and Land Use. *Science* 268:1305-12.
 24. U.S. Environmental Protection Agency. 1997. Characterization of Municipal Solid Waste in the United States: 1996 Update, Final Report. EPA Report No. 530-R-97-015.
 25. Ibid.
 26. Governmental Advisory Associates. 1995. *The Materials Recycling and Processing Industry in the United States: 1995-96 Yearbook, Atlas, and Directory*. Governmental Advisory Associates, Washington, DC.
 27. Allen DT, Behamanesh N. 1994. Wastes as Raw Materials. pp. 68-96 in *The Greening of Industrial Ecosystems*. eds. Allenby BR and Richards DJ. National Academy Press, Washington, DC.
 28. Anon. 1995. *JOM* 47(5):4.

-
29. Veasey TJ. 1997, Overview Of Metals Recycling By Physical Separation Methods, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 211(E1):61-4
30. Veasey TJ, Wilson RJ, Squires DM. 1993. *The Physical Separation and Recovery of Metals From Wastes: Process Engineering For The Chemical, Metals And Minerals Industries, Vol. 1.* Gordon and Breach, Amsterdam, NL.
31. Vesilind PA, Rimer AE. 1981. *Unit Operations in Resource Recovery Engineering.* Prentice Hall, Englewood Cliffs, NJ.
32. Wakesberg S. 1994. The Air Knife: What Is It and What It Means To Can Recycling. *Scrap Processing and Recycling* July/August 1994, pp. 97-99.
33. Borsecnik J. 1995. Carpco Resolving Separation Anxiety. *Scrap Processing and Recycling*, January/February 1995, pp. 108-113.
34. Norrgran DA, Wernham JA. 1991. Recycling and Secondary Recovery Applications Using An-Eddy-Current Separator, *Minerals & Metallurgical Processing* 8(4):184-187.
35. Sateer HP. 1995. The Laser Scrap Sorting Technique: New Developments and First Operational Experience. pp. 57-64 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from The Minerals, Metals, and Materials Society, Warrendale, PA.
36. Smith LA, Means J, Barth E. 1995. *Recycling and Reuse of Industrial Wastes.* Battelle Memorial Institute, Battelle, Columbus, OH.
37. Ramachandran V, Gilbert SR, Gardenas RI, Zwierzykowski M. 1993. Recycling Metal-bearing Hazardous Waste. pp. 131-141 in *Extraction and Processing for Treatment and*

Minimization of Wastes, eds. Hager et al. Available from The Minerals, Metals, and Materials Society, Warrendale, PA.

38. Hanewald RH, Onuska JC, Schweers ME. 1995. Recycling Nickel, Chromium and Iron Catalysts by the High Temperature Metals Recovery Process. pp. 371-9 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from The Minerals, Metals, and Materials Society, Warrendale, PA.

39. Nowack Z. 1978. Recovery of Minerals and Elements from Ash. In Torrey S. ed. *Coal Ash Utilization: Fly Ash, Bottom Ash, and Slag*. Noyes Data Corporation, Park Ridge, NJ.

40. Ayres RU, Ayres LW. 1996. *Industrial Ecology: Towards Closing the Materials Cycle*. p. 266. Edward Elgar Publishing Ltd., Cheltenham, UK.

41. Cannon RM, Gilliam TM, Watson JS. 1981. *Evaluating Potential Processes for Recovery of Metals from Coal Ash*. (CS-92). Electric Power Research Institute, Palo Alto, CA.

42. Rayzman VL, Shcherban SA, Dworkin RS. 1997. Technology For Chemical-Metallurgical Coal Ash Utilization. *Energy & Fuels* 11(4): 761-773.

43. Kontopoulos A., Xenidis A, Komnitsas A, Papassiopi N. 1996. Environmental Characterization and Monitoring of the Wastes in Lavrion. Fourth International Symposium on Environmental Issues and Waste Management in Energy and Minerals Production, Cagliari, Italy, Oct. 7-11, 1996.

44. Concurrent Technologies Corporation. 1996. *Recovering Metal Values From Acid Mine Drainage: Market and Technology Analyses*. Prepared for the Southern Alleghenies Conservancy, Bedford, PA. Available on web at <<http://ctcnet.net/sac/ctc001.htm>>

-
45. Gazea B, Adam K, Kontopoulos A. 1996. A review of passive systems for the treatment of acid mine drainage. *Minerals Engineering* 9(1):23-42.
46. Inoue K, Zhang P. 1995. Separation and Recovery of Rare Metals From Spent Hydrodesulfurization Catalysts by Solvent Extraction. pp. 393-404 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from The Minerals, Metals, and Materials Society, Warrendale, PA.
47. Gaballah I, Djona M, Mugica JC, Solozabal R. 1995. Low Temperature Selective Chlorination of Used catalysts for the Recovery of Transition and/or Refractory Metals. *Ibid*, pp. 405-424.
48. Llanos ZR, Deering WG. 1995. Processes for the Recovery of Metals from Spent Hydroprocessing Catalysts. *Ibid*, pp. 425-448.
49. Case A, Garretson G, Wiewiorowski E. 1995. Ten Years of Catalyst Recycling. *Ibid*. pp. 449-468.
50. Hoffman JE. 1988. Recovering Platinum-Group Metals from Auto-Catalysts. *JOM* 40(6):40-44.
51. Mishra RK. 1993. Review of Platinum Group Metals Recovery from Automobile Catalytic Converters. p. 449-474 in Proceedings of the International Precious Metals Institute: Precious Metals '93. ed. RK Mishra Proceedings of the International Precious Metals Institute, Newport RI.
52. Kuczynski RJ, Atkinson GB, Dolinar WJ. 1995. Recovery of Platinum Group Metals From Automobile Catalysts-Pilot Plant Operation. pp. 527-544 in Proceedings of the Third

-
- International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from The Minerals, Metals, and Materials Society, Warrendale, PA.
53. U.S. Bureau of the Census, 1975, *Historical Statistics of the United States, Colonial Times to 1970*, U.S. Government Printing Office, Washington, DC.
54. Wernick IK. 1996. Consuming Materials: The American Way. *Technological Forecasting and Social Change* 53(1):111-122.
55. Sibley SF, Butterman WC, and Staff. 1995. Metals Recycling in the United States, *Resources, Conservation, and Recycling*, 15:259-267.
56. U.S. Geological Survey. 1997. *Mineral Commodity Summaries*. U.S. Government Printing Office, Washington, DC.
57. Socolow R, Thomas V. 1997. The Industrial Ecology of Lead and Electric Vehicles. *Journal of Industrial Ecology* 1(1):13-36.
58. Lave LB, Hendrickson CT, McMichael FC. 1995. Environmental Implications of Electric Cars. *Science* 268:993-5.
59. Ibid.
60. Karlsson S. 1996. Can Metals be Used Sustainably? The Example of Lead. Annual Report, Institute of Physical Resource Theory, Chalmers University of Technology and Goteborg University, AFR report no. 121. Swedish Environmental Protection Agency, Stockholm Sweden.
61. Pehlke RD. 1980. Steelmaking-The Jet Age. *Metallurgical Transactions B* 11B:539-562.
62. *Kirk-Othmer Encyclopedia of Chemical Technology, Fourth edition*. 1996. Volume 20, p. 1097.

-
63. Foster RJ. 1994. Recycling in the Major Metal Industries: Trends, Developments, and Regulatory Impacts. U.S. Bureau of Mines Information Circular/1994, Report no. PB94-203585, U.S. Department of Interior.
64. McManus GJ. 1997. Getting the Full Value Out of Scrap. *Iron and Steel Engineer* 74(10):58-9.
65. Institute of Scrap Recycling Industries. Annual. *Scrap Specifications Circular: Guidelines for Nonferrous Scrap, Ferrous Scrap, Glass Cullet, Paper Stock, Plastic Scrap*, Institute of Scrap Recycling Industries, Washington, DC.
66. Kiser K. 1994. Ferrous Scrap Substitutes: A Growing Piece of the Mill Mix. *Scrap Processing and Recycling* 51(6):40-48.
67. ASME/ASTM Boiler and Pressure Vessel Code, Section II, Part B: Non-ferrous Materials, ASME, NY, SB308/308M, 1992.
68. Van der Donk HM, Nijhof GH, Castelijns CAM. 1995. The Removal of Iron from Molten Aluminum. pp. 651-661 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from TMS Warrendale, PA.
69. Wells PA, Andreas RE, Fox TM. 1995. Metal Recovery Enhancement Using Taguchi Style Experimentation. Ibid pp. 269-281.
70. Kemeny FL, Sosinsky DJ, Schmitt RJ. 1992. Development of a dc Plasma-Arc Furnace for Processing Aluminum Dross. pp. 1147-1153 in *Light Metals 1992* Proceedings of the 121st TMS Annual Meeting Mar 1-5 1992 San Diego, CA. The Minerals, Metals & Materials Society (TMS) Warrendale, PA.

-
71. See van der Donk above
72. Moore JJ. 1990. *Chemical Metallurgy*. p. 324-325. Butterworths, Boston, MA.
73. Tremblay F, Litaline M, Stephens D. 1995. The Alcan Fluidized Decoater. p. 19-30 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
74. Newberry V, Jenkins RF. 1995. Advanced Technology Delacquering and Melting. Ibid. pp. 685-702.
75. Sanders RE, Wood CL. 1993. Aluminum Automotive Recycling and Materials Selection Issues. Society of Automotive Engineers Technical paper no. 930493. Presented at the SAE International Congress and Exposition Detroit, MI, March 1-5, 1993.
76. Sanders RE, Wood CL. 1993. Design for Aluminum Recycling: Coordination of Material Specifications Among Designers Can Raise Scrap Value and Facilitate Recycling. *Automotive Engineering* 101:65-68.
77. Montagna D, Makar HV (US Bureau of Mines). 1982. Method for wrought and cast aluminum separation. US Patent no. 4,330,090.
78. Rossel H. 1995. VAW Recycling Center pp. 663-675 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
79. Charlier PC, Sjorberg HG. 1995. Recycling of Aluminum from Post-consumer Beverage Cartons. Ibid. pp. 676-683
80. Gockmann K. 1992. Recycling of Copper. *CIM Bulletin* 85:150-6.

-
81. Hanusch K, Bussmann H. 1995. Behavior and Removal of Associated Metals in the Secondary Metallurgy of Copper. pp. 171-188 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
82. Prado F, Prado FL. 1995. Secondary Copper Smelter Dusts: An Economical and Environmentally Friendly Reclamation. *Ibid.* pp. 831-840.
83. Hendlund L. 1995. Flexible Recycling with Boliden Technology. *Ibid.* pp. 155-162
84. Hoffmann JE. 1992. Recovering Precious Metals From Electronic Scrap. *JOM* 44:43-8.
85. Veldhuizen H, Sippel R. 1994. Mining Discarded Electronics. *UNEP Industry and Environment* July-September 1994, pp. 8-11.
86. Royer M, Selvakumar A, Gaire R. 1992. Control Technologies for Remediation of Contaminated Soil and Waste Deposits at Superfund Lead Battery Recycling Sites. *J. Air and Water Management* 42(7):970.
87. Chavez F, Morales RD, Romero A, Guerrero A. 1995. Optimizing Rotary Furnace Smelting of Battery Residue. pp. 337-347 in Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
88. Suttie AB. 1995. Lead Recycling via Rotary Furnaces. *Ibid.* pp. 329-336.
89. Wright S, Jahanshahi S, Errington WJ. 1994. Reduction of Battery Paste Slags with Graphite. pp. 11 in Processing for Treatment and Minimization of Wastes, ed. Hager et al. Available from TMS, Warrendale, PA.

-
90. Brew RBM, Fountain CR, Pritchard J. 1991. ISASMELT for Secondary Lead Smelting. pp. 170-181 in *Lead '90*, Lead Development Association, London.
91. Diaz G, Martin D, Lombera C. 1995. Zinc Recycling by the Modified Zincex Process. pp. 623-638 in *Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials*. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
92. Zunkel AD. 1995. EAF Dust as an Electrolytic Zinc Resource. *Ibid* pp. 579-588.
93. Bounds CO, Pusateri JF. 1990. EAF Dust Processing in the Flame Reactor Process. pp. 511-528 in *Lead-Zinc '90*. Mackey TS, Prengaman RD (eds.) TMS, Warrendale, PA.
94. Wu L, Themelis NJ. 1992. The Flash Reduction of Electric Arc Furnace Dusts. *JOM* 44(4):35-39.
95. Dreisinger DB, Peters E, Morgan G. 1990. The Hydrometallurgical Treatment of Carbon Steel EAF Dusts by the UBC-Chapparral Process. *Hydrometallurgy* 25(2):137-152.
96. Olper M. 1995. Zinc Extraction from EAF Dust with Ezinex Process. pp. 563-578. *Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials*. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.
97. See Diaz et al. above.
98. See Sibley et al. above.
99. Moore CM. 1995 Pigs from Iron-Containing Dusts and Sludges. pp. 589-602 in *Proceedings of the Third International Symposium on the Recycling of Metals and Engineered Materials*. Queneau PB and Peterson RD eds. Available from TMS, Warrendale, PA.

-
100. Brown SL, Chaney RL, Angle JS, Baker AJM. 1995. Zinc and Cadmium Uptake by Hyperaccumulator *Thalpi caerulescens* Grown in Nutrient Solution. *Soil Science Society of America Journal* 59(1):125-33
101. Baker AJM, Brooks RR. 1989. Terrestrial Higher Plants Which Hyperaccumulate Metallic Elements - A Review of their Distribution, Ecology, and Phytochemistry. *Biorecovery* 1:81-126.
102. For a review of the impact of federal environmental regulation on the secondary metals industry see Foster RJ. 1994. Recycling in the Major Metal Industries: Trends, Developments, and Regulatory Impacts. U.S. Bureau of Mines Information Circular/1994, Report no. PB94-203585, U.S. Department of Interior.
103. United States Environmental Protection Agency Office of Solid Waste and Emergency Response. 1995. *Summary of OSW's RCRA regulatory reform analysis: preliminary results*. U.S. Environmental Protection Agency. Washington, DC.
104. Code of Federal Regulations (CFR) 40 part 273.
105. Frosch RA, 1996, Toward the End of Waste: Reflections on a New Ecology for Industry, *Daedalus* 125(3):199-212.
106. Thomas V, Spiro T. 1994. Emissions and Exposure to Metals: Cadmium and Lead, pp. 297-318 in *Industrial Ecology and Global Change*. Socolow R, Andrews C, Berkhout F, and Thomas V, eds. Cambridge University Press, New York, NY.
107. See Ayres and Ayres above.
108. Frosch RA, Gallopoulos NE. 1989. Strategies for Manufacturing. *Scientific American*, September 1989, pp. 144-152.