

Flow Studies for Recycling Metal Commodities in the United States

Edited by Scott F. Sibley

Circular 1196–A–M

**U.S. Department of the Interior
U.S. Geological Survey**

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U.S. Geological Survey
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Foreword

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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Gold Recycling in the United States in 1998

By Earle B. Amey

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CONVERSION FACTORS

Most measurements in this report are in metric units, but troy ounces are used in some discussions because international gold prices are reported per troy ounce. Conversion factors are provided below.

Multiply	By	To obtain
<i>Length</i>		
meter (m)	3.281	foot
<i>Mass</i>		
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram
<i>Other</i>		
gram per metric ton (g/t)	0.0292	troy ounce per short ton

Gold Recycling in the United States in 1998

By Earle B. Amey

ABSTRACT

In 1998, 175 metric tons (t) of refined gold was recovered by U.S. refiners from old and new scrap. The overall recycling rate was 29 percent when scrap consumption was compared with apparent domestic supply. Sources of old scrap included discarded jewelry, dental materials, plating solutions, and electronic equipment. A very high old scrap recycling efficiency of 96 percent was reached in 1998, the supply of old scrap peaked, gold prices were at an 18-year low, and substantial amounts of old scrap were exported. U.S. net exports of old scrap had a gold content of 28 t.

INTRODUCTION

This report describes trends in consumption, loss, and recycling of gold-containing materials in the United States in 1998, as depicted in the U.S. gold materials flow diagram (fig. 1). The purpose of the materials flow study was to illustrate the extent to which gold was being recycled and to identify recycling trends.

Because of its high value, gold has been recycled through the ages. Modern jewelry that incorporates recycled gold could contain atoms of gold from an earring worn by Helen of Troy or a nugget of gold used in the 4th millennium B.C. to barter for ingots of crude copper at a Mediterranean seaport. Gold's high recycling rate is further illustrated by the fact that most of the gold ever mined can be accounted for (Lucas, 1993). Of an estimated 125,000 metric tons (t) of gold mined from historical times through 1998, only about 15 percent is thought to have been lost or used in dissipative industrial processes or to be otherwise unaccounted for or unrecoverable. Of the remaining 106,000 t, an estimated 34,000 t is in official stocks held by central banks, and about 72,000 t is privately held as coin, bullion, and jewelry (Amey, 1999). The total amount of gold ever mined is equivalent in volume to an 18-meter cube (Green, 1993, p. 4).

It has been said that gold is forever; its high intrinsic and monetary value dictates that, in time, most of it will be recycled. In 1998, 175 t of refined gold was recovered by domestic refiners from old and new scrap. The value of this refined gold was about \$1.7 billion, when it was calculated on the basis of the average gold price for 1998 of \$295.24 per troy ounce (see appendix). The overall recycling rate was 29 per-

cent when scrap consumption was compared with apparent domestic supply (table 1). This percentage is on the low side of the range of 20–70 percent estimated for gold recycling during the past 50 years. Gold recycling, however, cannot be viewed strictly from the U.S. market. International political and economic events that may influence the gold commodity market may be outweighed by developments perceived to favor gold as a medium of exchange.

In 1998, secondary unrefined gold-bearing materials valued by the U.S. Census Bureau in excess of \$370 million were exported, principally for refining to commercial-grade gold bullion. These materials are designated in figure 1 as old scrap exported, which had a gold content of 40 t. The principal recipient nations were Canada and the United Kingdom. Old scrap imported by domestic refiners during 1998, and originating in Canada, the Dominican Republic, Mexico, and elsewhere, had a gold content of 12 t and was valued at over \$100 million. Thus, the value of the 28 t of gold in net exports of old scrap in 1998 was about \$270 million.

GLOBAL GEOLOGIC OCCURRENCE OF GOLD

Estimates of gold's abundance in the Earth's crust range from 3 to 4 parts per billion (ppb) gold (Lucas, 1985). This abundance is equivalent to about 1 gram of gold in 300 t of rock. Although data were sparse, gold was more abundant in mafic than in felsic igneous rocks and in sandstone than in other sedimentary rocks. Much of the gold that has been mined came from quartz veins or from alluvial deposits in streams. As these easily accessible sources became increasingly rare, gold mining shifted to bulk ores of lesser grades. South Africa has about half of all world gold resources, and Brazil and the United States have about 10 percent each (Amey, 1999). If the South African deposits are considered to be paleoplacers, alluvial deposits account for somewhat more than half of the world's gold resources (Simons and Prinz, 1973, p. 266).

Native gold is fairly insoluble in almost all surficial environments and is unaffected during weathering and decomposition of rocks. Hence, it occurs in extremely small amounts in freshwater, about 0.03 ppb, and even less in seawater, 0.011 ppb (Simons and Prinz, 1973, p. 266). In environments where humic or other acids exist, gold can become soluble, forming nuggets when it precipitates.

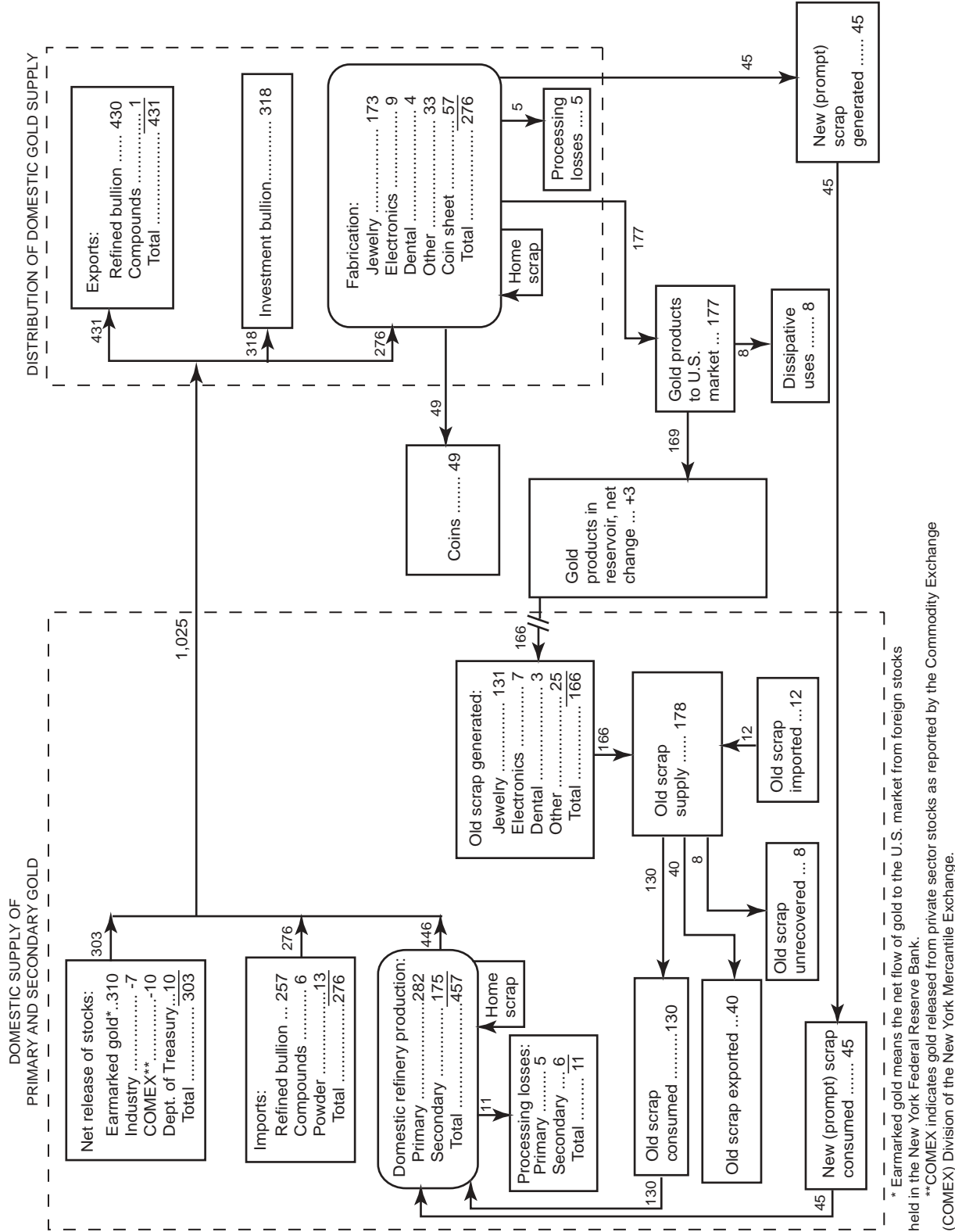


Figure 1. U.S. gold materials flow in 1998. Values are in metric tons of contained gold. Sources of data are described in the section titled "Sources of Gold Scrap."

Table 1. Salient statistics for U.S. gold scrap in 1998.
[Values in metric tons of contained gold, unless otherwise specified]

Old scrap:	
Generated ¹	166
Consumed ²	130
Value of old scrap consumed	\$1.234 billion
Recycling efficiency ³	96 percent
Supply ⁴	178
Unrecovered ⁵	8
New scrap consumed ⁶	45
New-to-old-scrap ratio ⁷	25:75
Recycling rate ⁸	29 percent
U.S. net exports of scrap ⁹	28
Value of U.S. net exports of scrap	\$272 million

¹Gold content of products theoretically becoming obsolete in the United States in 1998. Dissipative uses were excluded.

²Gold content of products that were recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁴Old scrap generated plus old scrap imported.

⁵Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁶Including prompt industrial scrap but excluding home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of the gold apparent supply that is scrap on an annual basis. It is defined as (consumption of old scrap plus consumption of new scrap) divided by apparent supply (see appendix), measured in weight and expressed as a percentage.

⁹Trade in scrap is assumed to be principally in old scrap. Net exports are exports of old scrap minus imports of old scrap.

GOLD PRODUCTION PROCESSES

Gold ores can be classified into two groups: (1) free milling ores from which native gold is recovered by crushing, gravity separation, amalgamation, and leaching processes, such as cyanidation, and (2) refractory ores, such as tellurides and other auriferous sulfides, that yield gold after complex oxidizing processes (Roskill Information Services, 1995, p. 1). Many gold mining operations recover gold from cyanide leach solutions by precipitation with carbon in the pulp. The activated carbon collects gold from the cyanided pulp until the pulp contains 300 to 400 troy ounces of gold per metric ton of carbon. Gold with accompanying silver is desorbed or stripped from the carbon with a strong alkaline cyanide-alcohol solution. The precious metals are recovered from the strip solutions by electrodeposition on a stainless-steel-wool cathode. The cathode deposit is refined into a doré, a gold-silver bullion of variable composition, which is sent to a refiner.

Gold is refined by chlorination in the molten state (Miller process) and by electrolysis (Wohlwill process). Generally, gold bullion made by the Miller process is 996 to 997 fine

(99.6 to 99.7 percent), and bullion made by the Wohlwill process is 999.5 to 999.8 fine (99.95 to 99.98 percent) (Lucas, 1985). Gold purity is expressed as fineness in parts per thousand or, in the case of gold alloys, in karats (parts per 24).

When gold is associated with copper ores, it travels with the base metal through concentration and smelting to the refining stage. It is eventually separated from the anode slimes, which accumulate in electrolytic copper refining cells, and is recovered as gold bullion in the precious-metals refinery (Lucas, 1985).

GOLD MARKET PRICES AND USE PATTERNS

The dollar price for gold decreased throughout 1998. The Engelhard Corporation's industries quotation (listed weekly in *Platt's Metals Week*) showed that the daily price of gold ranged from a low of nearly \$275 per troy ounce on August 28, 1998, to a high of about \$314 on April 24. The average for the year was, to the nearest dollar, \$295. The 1997 prices ranged from about \$298 to \$368 and averaged \$332 per troy ounce (Amey, 2000, p. 33.1).

In 1998, estimated uses of gold were jewelry, which includes arts, 63 percent; coins, 21 percent; industrial, which includes electronics and other assorted uses, 15 percent; and dental, 1 percent. U.S. gold-use patterns in 1998 were similar to those of the rest of the world (Murray and others, 1998, p. 5). U.S. gold consumption by end-use sector from 1978 through 1998 is depicted in figure 2. Two significant factors increased gold use: (1) the popularity of the American Eagle gold coin produced by the U.S. Mint since 1987 and (2) seven consecutive years (1992–98) of growth in unit sales for gold jewelry in the United States. Much of the latter increase came from outside the Northeast sector, which has been the traditional heartland of the U.S. jewelry industry.

GOLD STATISTICS

Various components of the U.S. gold materials flow were studied to specify the factors affecting recycling and to identify the ultimate direction and disposition of domestic supply. Companies that supply gold to end users were regularly contacted by the U.S. Geological Survey (USGS) to update data used to estimate the total amount of gold consumed by industry. Because new suppliers become active every year, the estimates were slightly understated but were still accurate to two significant figures. Most of the data used in this report relating to production, supply, and consumption of gold were obtained from USGS publications on minerals. Most of the remaining data were obtained from company reports and industry publications.

SOURCES OF GOLD SCRAP

Sources of old scrap and new scrap are key features of the U.S. gold materials flow diagram (fig. 1). Statistical data for domestic consumption of new and old scrap in

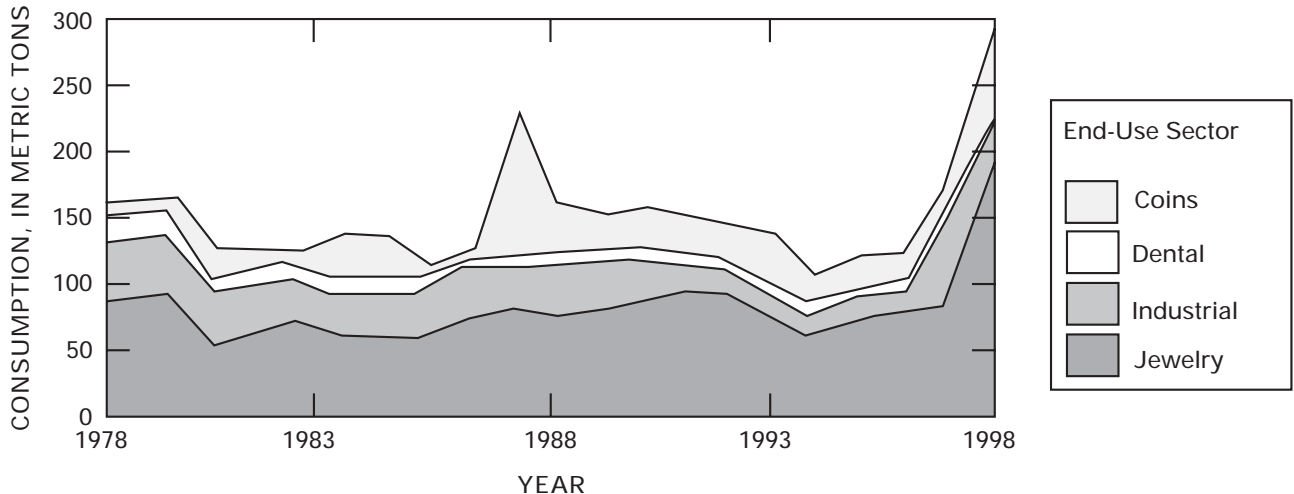


Figure 2. U.S. gold consumption by end-use sector from 1978 through 1998. Values are in metric tons of contained gold. Industrial uses include the manufacture of electronic devices.

1998 were collected by the USGS as a single quantity. The amount of new scrap was calculated by estimating that it generally is about 17 percent of the total input for the fabrication process. Gold coin cuttings, which became new scrap, were estimated to be 14 percent of the total input. Consequently, the amount of old scrap consumed may be obtained by subtracting the amount of new scrap consumed from the total scrap consumed.

Figure 1 shows that the domestic supply of primary and secondary gold consists of (1) inputs from domestic refinery production, (2) imports, and (3) the net release of gold stocks from foreign countries, U.S. industry, the U.S. Department of the Treasury, and the private sector. Statistical data for domestic refinery production were collected by the USGS as primary and secondary quantities. Statistical data for gold imports were collected by the U.S. Census Bureau (written commun.). Statistical data for the net release of gold to the U.S. market from foreign stocks were reported by the New York Federal Reserve Bank (written commun.); data on industry stocks were collected by the USGS; Government stocks were reported in the *Federal Reserve Bulletin* (1999); and private sector stocks were reported by the Commodity Exchange (COMEX) Division of the New York Mercantile Exchange (CRU International, Ltd., 1999).

Refined bullion, compounds, and powder were exported, bought as investments, or made into jewelry, electronic components, coins, and other products. More than 99 percent of the gold bullion coins were American Eagle coins, which were purchased at precious-metal dealers, brokerage companies, coin dealers, and participating banks strictly for investment. Coins are treated separately from other fabricated gold products in figure 1 to show the amount of gold held for investment purposes in 1998. Statistical data for coins were collected by the U.S. Mint (Shirley Jones-Keller,

written commun., 1999); for gold exports, by the U.S. Census Bureau (written commun.); and for jewelry, electronic components, and other products, by the USGS. Investment data were obtained by calculating what remained of the domestic gold supply after gold exports and fabricated gold products were deducted.

Data discussed in the following sections are summarized in table 1.

OLD SCRAP GENERATED

Old scrap consists of gold-containing products that have been discarded after use or after becoming obsolete. The old scrap generated in 1998 had a gold content of 166 t. The amount of gold in old scrap consumed, 130 t, amounted to 78 percent of the gold in old scrap generated and had a value of more than \$1.23 billion. Net exports of old scrap had a gold content of 28 t.

The old scrap component of the gold supply was perhaps the most difficult component to quantify. In many areas of the world, especially where the holding of gold was encouraged by tradition, secondary gold, especially that derived from relatively crude gold jewelry, changed hands both locally and internationally from purchasers to goldsmiths and back again to purchasers. This flow was often in response to variations in the gold price and usually could not be followed statistically. In addition, some old scrap was lost because, in practice, gold cannot be economically recovered from all manufactured products; recovery becomes increasingly difficult as gold-bearing electronic products become more miniaturized.

NEW SCRAP

New scrap is generated during manufacturing processes and, for the most part, remains the property of the manufacturers; it is continually recirculated. A considerable

amount of scrap is generated in manufacturing operations, but, because of strict controls over waste materials in precious-metals plants, nearly all of this home-generated scrap can be recovered. In 1998, 45 t of new scrap was consumed, which was about 25 percent of the total scrap consumed.

DISPOSITION OF GOLD SCRAP

The feature generally attributed to the metals recycling industry—high volume of comparatively low value metal—is quite unlike that of gold. Gold recycling deals with relatively low volumes of very highly valued raw material. Therefore, proper handling, accountability, and security against loss and theft during generation, collection, and distribution are important additional burdens not shared by most other metals industries. Many gold consumers have elaborate collection systems for reclaiming new gold scrap that results from the manufacture of gold products. Thus, there are very small losses. All materials that may come into contact with gold during the processing and handling are recycled. Gloves, aprons, and dust masks worn by gold workers and the dust, or sweeps, from the shops are collected and processed to get additional quantities of gold. At times, even the floors of the refineries are burned to recover gold. Similarly, a specialized field of secondary gold recovery gleans gold from defunct gold-processing operations (Lucas, 1993).

The high intrinsic value of gold scrap shipped to a refiner dictates that special precautions be taken to assure preservation of the payable gold content. For example, raw electronic scrap may be collected, disassembled, or shredded, and gold components separated from other less valuable ones before shipping to a refiner (Lucas, 1993). At the higher end of the spectrum, gold scrap created during the manufacture of jewelry will go directly to the refiner. These are only a few examples of the scrap forms that typically cross a refiner's loading dock. Each shipment can also be accompanied by documentation, ranging from title, insurance, and customs papers to licensing and transport documents that address local, State, and national environmental and other regulatory requirements.

Each refining transaction is negotiated individually between the refiner and the customer. Ordinarily, refining schedules or outlines of services, capabilities, and charges are used by refiners to establish the basis upon which the negotiations will proceed (Lucas, 1993). Included in these negotiations are lot size and character of the product to be refined. Other factors may be minimum or standard treatment charges, charges for preparation and assaying, charges or penalties for the presence of deleterious elements, and instructions regarding the basis of payment. The customer may elect to sell the material outright, may have the scrap refined and the gold prepared to contract specifications and returned (toll refining), or may elect to draw an equivalent

value of refined metal from a pool account established by the refiner.

A shipment is assigned a control number upon arrival at the refinery, then is weighed, evaluated, and subjected to a variety of preparatory processes, depending upon the shipment's character (Lucas, 1993). Preparation may include incineration, roasting or melting, and pulverizing, shredding, or grinding to produce a homogeneous product. At this point, one or more representative samples are drawn so that assays can determine the character and content of the original shipment. The refiner may combine similar lots to form large batches. These batches are sent to the refining process, which may include pyrometallurgical, hydrometallurgical, and electrochemical processes to separate gold from associated impurities.

OLD SCRAP RECYCLING EFFICIENCY

Old scrap recycling efficiency shows the relation between what was theoretically available for recycling and what was not recovered. This relation is defined as (old scrap consumed + old scrap exported) divided by (old scrap generated + old scrap imported \pm scrap stock changes), measured in weight and expressed as a percentage. The old scrap generated in 1998 was made up of jewelry and art products, industrial and electronic scrap, and dental debris. The typical content of gold in electronic scrap was about 300–400 grams per metric ton (ASM International, 1998, p. 1192). Most old scrap came from jewelry and electronic manufacturers' buy-back programs. A very high old scrap recycling efficiency of 96 percent was reached in 1998, the supply of old gold scrap peaked, gold prices were at an 18-year low, and substantial amounts of old gold scrap were exported.

INFRASTRUCTURE OF GOLD SCRAP

The historical and universal recognition of gold as a highly valuable commodity assures that virtually every conceivable recycling method will be used to recapture it from scrapped materials. Industrial gold consumers, the principal sources of supply, keep their gold-bearing scrap moving into the market on an established, routine basis for security reasons. On the other hand, private individuals may hoard or sell gold in response to the prevailing or anticipated economic or political climate. For example, a person may hoard gold coins, bars, and jewelry as a hedge against inflation or in anticipation of economic or political upheaval and may sell gold coins, bars, and jewelry in times of relative stability when alternative, dividend-paying investments may be more attractive. Most of the conditions and incentives that have encouraged high rates of gold recycling exist today and will probably exist in the future. Gold, more than any other recyclable material, continues to be a highly sought after commodity in the secondary metals market.

SCRAP COLLECTION SYSTEMS

Refiners throughout the world recover secondary gold from scrap. In the United States in the past 20 years, as much as 70 percent and as little as 25 percent of the scrap came from current manufacturing operations, and the remainder came from old scrap, such as discarded jewelry, dental materials, used plating solutions, and junked electronic equipment. A few dozen companies, out of several thousand companies and artisans, dominated the fabrication of gold into commercial products. Most of the domestic scrap was processed by refiners centered in the New York, N.Y., and Providence, R.I., areas. Other centers were in California, Florida, and Texas, although the trend in 1998 seemed to be toward a less centralized industry. Scrap dealers processed the scrap and then shipped the upgraded product to refiners and fabricators for further treatment and refining. The U.S. Department of Defense (DOD) recovered significant quantities of gold from military scrap. Other Federal agencies either participated in the DOD recovery program or had their own; all of the scrap reclaimed through these programs was sent to refiners for further processing in 1998.

Gold-bearing scrap was paid for on the basis of gold content, as determined by analytical tests. The market price for gold was paid on the day that the refined product was available for sale. Processing charges and adjustments for processing losses were deducted from the total value in settling payments. Aside from dealer-processors and refiners, there were no markets for scrap gold. The market is limited by the Federal Trade Commission requirement for karat identification of jewelry alloys, which in effect requires gold refiners to know the chemical analysis of the alloys they purchase and requires gold refiners to separate the constituents of scrap to assure meeting karat standards (Public Law 226, 1906).

TRADE

In 1998, U.S. exports of gold scrap decreased for the second straight year (to 40 t), after 5 years of increase, while imports increased for the second year in a row (to 12 t). As it had been for many years, the United States was still a net exporter of gold scrap. Prices for gold waste and scrap imported and exported in 1998 averaged \$190 and \$197 per troy ounce, respectively; the annual average price for gold was \$295 per troy ounce.

Exports of refined gold bullion were 430 t; the United Kingdom (209 t) was the principal destination, followed by Switzerland (79.6 t), Australia (47 t), and Canada (46.7 t). More than 8 percent of all gold exported was scrap. Imports for consumption of refined gold bullion in 1998 were 257 t; Canada (96.5 t) was the largest supplier, followed by Australia (62.4 t), Brazil (32.7 t), and Peru (23.1 t). More than 4 percent of all gold imports were scrap.

PROCESSING OF GOLD SCRAP

Scrap metals can be processed by either primary or secondary refiners. The latter handle only scrap, such as discarded jewelry, electronics, and dentistry products. Other types of scrap include gold-bearing slimes, solutions, and sludges; precipitates from base (lead and zinc) or precious metals recycled from smelters and refiners; and old gold coins, medals, and previously hoarded low-purity nonaccredited gold bars. Primary refiners receive doré directly from the mine in addition to gold scrap that has been amassed by collectors. Most refiners will not accept scrap lots of less than 0.5 t, and many have a 2.5-t minimum (Garino, 1994). Many small shipments are obtained from collection points throughout the Nation, and some even come from overseas. At the higher end of the spectrum of value, scrap generated during the manufacture of karat gold jewelry will go directly from the manufacturer to the smelter-refiner. Scrap originating at the jewelry manufacturer is closely monitored by the company from generation through collection, packaging, and transportation to the recovery plant.

Upon arrival at the refinery, each shipment is assigned a control number. Each scrap shipment is accurately weighed, blended, and analyzed for precious-metal content before payment is made (Lucas, 1993). It is common for a representative of the source company to be present during this step. Once the refinery owns the scrap, impurities such as lead, copper, and silver are removed from the gold by a high-temperature chlorination step (Miller process).

The purified scrap that remains after chlorination is electrorefined (Wohlwill process) to recover gold directly in what is called a fine gold cell. High-grade anodes are suspended from positive bus bars by platinum hooks, and the gold is plated out into thin sheets of pure gold called starting sheets. Gold produced in this manner is 999.75 fine or better. The sludge that remains in the cell contains platinum-group metals, which can be recovered by various methods that are usually patented by individual companies for their own use.

Products derived from secondary materials have a wide range of shapes and forms, including some bars of pure gold, sheet gold, wire, tubing, foils, leaf, casting grain, gold-plating solutions, gold-bearing organometallic liquids, and conductive inks and pastes. Probably the greatest loss in gold fabrication occurs in gold electroplating plants where fouled solutions (containing cyanides that must be labeled "toxic waste") or depleted solutions are sometimes discarded (Recycling Today, 1990, p. 69). Likewise, some old scrap is lost, because, in practice, gold cannot be economically recovered from all manufactured products.

OUTLOOK

Barring any unforeseen changes in the established pattern of world secondary supply, the quantity of gold generated from secondary sources was forecast to be about the same in 1999 as it was in 1998 (Klapwijk and others, 1999, p. 7), which is more than 20 percent of the total world gold supplied to fabricators, investors, and exporters. Developments that may increase the percentage of scrap entering the market include the following:

1. Any decline in world gold production, if not offset by refined supplies from other sources (such as central bank sales or bullion sales from the private sector), could lead to higher prices and thereby cause more material to enter the recycling stream.
2. The establishment of more efficient, centralized scrap collection and recovery centers could encourage higher rates of recycling.
3. Continued growth in the demand for gold jewelry in rapidly industrializing nations, such as those of the Far East and China, could result in increased recycling of older style jewelry as fashion tastes evolve with improved standards of living.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recycle.

doré. A gold-silver bullion of variable composition.

gold bullion. Refined gold in the shape of bars or ingots.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as post-consumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizer, are not included.

old scrap generated. Gold content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) + exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Based on the unit value of gold in materials. Values of gold in this report are calculated on the basis of the average gold price for 1998 of \$295.24 per troy ounce. Daily prices that were averaged came from the Engelhard Corporation's industries quotation (listed weekly in *Platt's Metals Week*).

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

U.S. Department of the Interior
U.S. Geological Survey

Platinum Recycling in the United States in 1998

By Henry E. Hilliard

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-B

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

1. Salient statistics for U.S. platinum scrap in 1998 B3

CONVERSION FACTORS

Most measurements in this report are in metric units, but a few terms are in customary units. Conversion factors are provided below.

Multiply	By	To obtain
<i>Length</i>		
kilometer (km)	0.6214	mile
inch (in.)	25.4	millimeter
<i>Volume</i>		
cubic foot (ft ³)	0.02832	cubic meter
<i>Mass</i>		
microgram (μg)	0.0000003527	ounce avoirdupois
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram
<i>Pressure</i>		
kilopascal (kPa)	0.1450	pound force per square inch
kilopascal (kPa)	0.009869	1 atmosphere
<i>Other</i>		
gram per metric ton (g/t)	0.0292	troy ounce per short ton

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Platinum Recycling in the United States in 1998

By Henry E. Hilliard

ABSTRACT

In the United States, catalytic converters are the major source of secondary platinum for recycling; about 25,500 kilograms of platinum-group metals from automobile catalysts was available for recycling in 1998. Other sources of platinum scrap include reforming and chemical-process catalysts. The glass industry is a small but significant source of platinum scrap. In 1998, an estimated 7,690 kilograms of platinum was recycled in the United States. The U.S. recycling efficiency for old scrap was calculated to have been 76 percent in 1998; the recycling rate was estimated at 16 percent.

INTRODUCTION

World resources of platinum appear ample for the foreseeable future. Political and economic events in the past decade, however, have raised concerns about the availability and reliability of the supply of platinum and other metals in this group. This report discusses the 1998 flow of platinum in the United States from mining, through metallurgical and chemical applications, to recycling (fig. 1, table 1). Factors influencing the rate and availability of material for recycling are described, especially areas where significant losses occurred.

Platinum-bearing scrap is a heterogeneous material that may also contain one or more of the other platinum-group metals. This report deals primarily with platinum, which was the most valuable and abundant platinum-group metal (PGM) found in scrap materials at the time of this study. The annual recycling rate for platinum, which represents the fraction of the metal's apparent supply that is scrap, was estimated at 16 percent in 1998. The balance of apparent supply was primary platinum (see appendix). This study also indicates that materials containing about 8,500 kilograms (kg) of platinum were unrecovered in 1998, representing about 14 percent of U.S. apparent consumption.

Six elements of group VIII in the periodic table of the elements have been collectively designated the platinum-group metals; they are palladium (Pd), platinum (Pt), iridium (Ir), osmium (Os), rhodium (Rh), and ruthenium (Ru). Sometimes called noble metals because of their resistance to

oxidation, these precious metals are found in the Earth's crust in very low concentrations. PGM's are conveniently separated into two subgroups; the light PGM's (those of lower atomic weight) are Ru, Rh, and Pd, and the heavy PGM's are Os, Ir, and Pt.

The PGM's are strongly siderophilic and chalcophilic; that is, they occur predominantly as pure metals and alloys and, to a much lesser extent, combined with sulfur, tellurium, and arsenic. They occur in rock-forming silicates in small to negligible amounts. For the most part, PGM's are concentrated in the early stages of magmatic differentiation and, consequently, are most abundant in magmatic mafic and ultramafic bodies and associated ore deposits. Under certain conditions, as yet imperfectly known, the PGM's are carried through the differentiation process because of their lack of affinity for the silicate minerals and are then concentrated in the products of late hydrothermal solutions (Wright and Fleischer, 1965, p. A2).

Despite their limited availability, these metals and chemical compounds containing them are extremely useful as catalysts in the automobile, chemical, and petroleum industries, as conductors in the electrical and electronic industries, in extrusion devices, in dental and medical prostheses, and in jewelry. Also, the glass industry takes advantage of platinum's high melting point, its noncontaminating behavior, and its chemical inertness and resistance to corrosion in the manufacture of high-quality optical and special glasses.

Platinum is primarily an industrial metal. There are, however, small quantities in the possession of speculators and investors. In 1998, there was strong demand for the platinum American Eagle coin, launched by the U.S. Mint in 1997. Domestic and foreign sales of this coin totaled 5,443 kg in 1998 (U.S. Mint, 1999, p. 7-13). Although Eagle coin sales were concentrated in the United States, the coin also found a market in Japan. Demand in Japan was mainly for smaller coins, weighing 0.10 or 0.25 troy ounce (troy oz), many of which were incorporated into watches and other items of jewelry. There are no reliable statistics available about the quantity of platinum held by speculators and investors. Probably stocks are held in banks and private holdings. This material, held for speculation and profitmaking, is

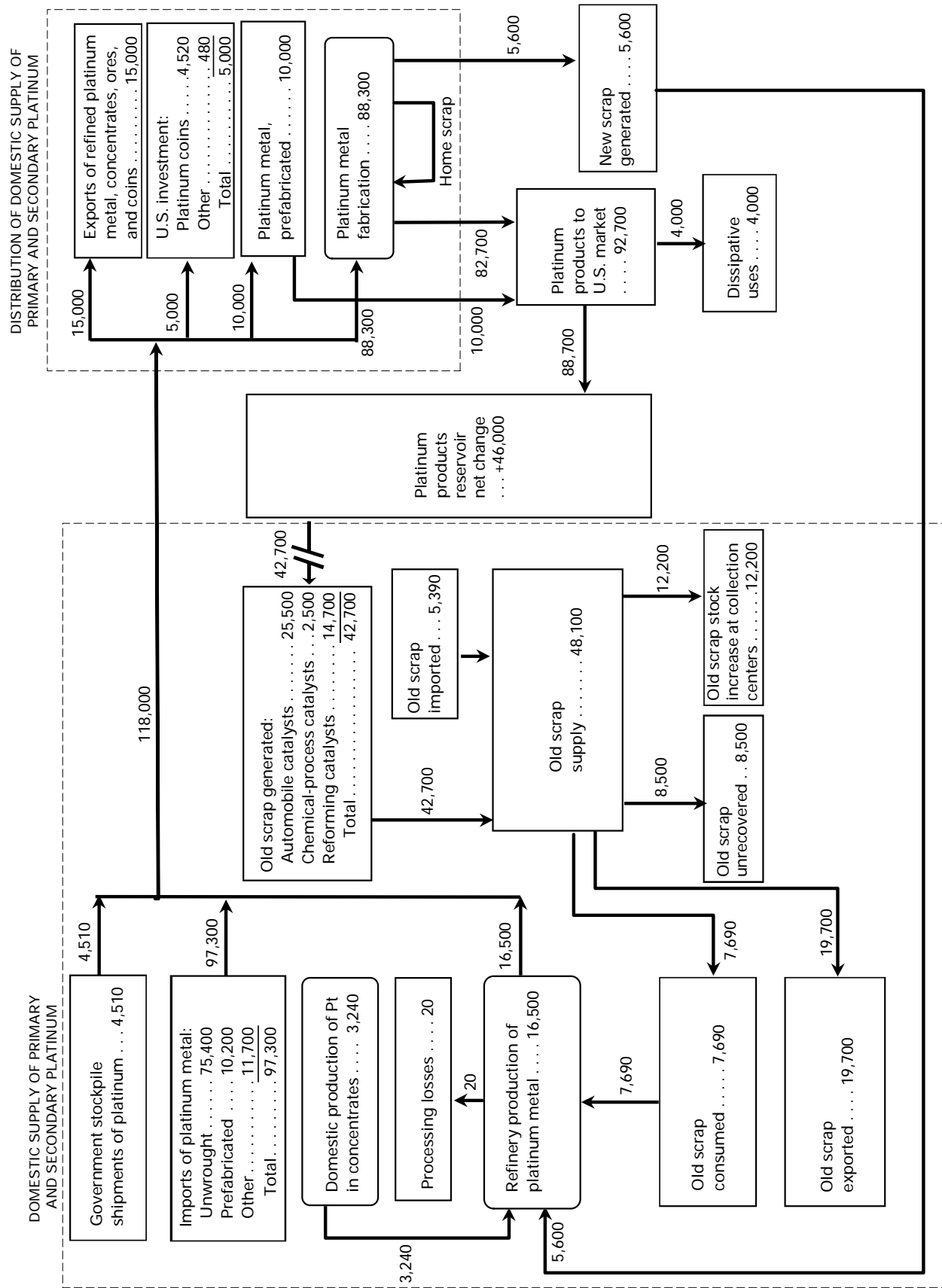


Figure 1. U.S. platinum materials flow in 1998. Values are in kilograms of contained platinum, and totals have been rounded to three significant figures. Sources of data are described in the section titled "Sources of Platinum Scrap."

put on the market infrequently, depending upon price and price outlook. The material is usually of high purity and is not likely to be found in the recycling circuit, except as home scrap during its manufacture.

SOURCES OF PGM ORE

Canada, South Africa, Russia, and the United States account for nearly all of the world’s primary production of PGM ore. The relative amounts of the individual elements in ores vary from deposit to deposit and from country to country. The ratio of platinum to palladium in ores can vary from 3:1 in the Bushveld Complex in South Africa to 1:3.5 in the Noril’sk deposit in Russia and 1:3 in the J-M Reef of the Stillwater Complex in the United States and the Sudbury Complex in Canada (Conradie, 1997).

CANADA

Small amounts of silver, gold, and PGM’s are present in most sulfide deposits of nickel. In Canada, PGM’s are mainly a byproduct of copper-nickel production. Most of the nickel ores are located in the Sudbury Complex in Ontario. The complex is a large stratiform, oval intrusion with dimensions along the axes of 50 and 23 kilometers (km). The copper-nickel deposits of the Sudbury area are peripherally located around the structure of an elliptical basin-shaped stratiform complex referred to as the Nickel Irruptive or the Sudbury Basin. The Nickel Irruptive consists of an outer part of noritic rocks and an inner part of granophyre (micropegmatite) (Cabri and Laflamme, 1976, p. 1159). The concentration of PGM’s averages about 0.9 to 1.0 gram per metric ton (g/t), with about 40 percent Pd, 40 percent Pt, and 20 percent Ir, Os, Rh, and Ru. Canada also produces nickel-copper ores with byproduct PGM’s from the entire spectrum of ultramafic and mafic complexes that occur in Manitoba, Ontario, and Quebec (Allen, 1960, p. 1–26; Page and others, 1973; Sutphin and Page, 1986, p. 2–7).

SOUTH AFRICA

South Africa is the world’s largest source of platinum. South Africa’s PGM output is derived mostly from the Bushveld Complex, with only a small amount coming from the Evander Gold Field and the Phalaborwa Complex. Currently, 10 mines are producing platinum in the Bushveld Complex (South Africa Department of Minerals and Energy, Minerals Bureau, 1997, p. 34–40). Of these, nine exploit the Merensky Reef and UG2 Chromite Layer, and one, Potgietersrust Platinum Ltd., the only open-cast operation, exploits the Platreef on the northern limb of the complex. Eight of the mines are located on the western limb of the Bushveld Complex; Atok Mine, of Lebowa Platinum Mines Ltd., is currently the only producer on the eastern limb. Beneficiation of PGM ore through milling, flotation, and smelting (to form a matte containing PGM’s, gold, silver, and the base metals cobalt, copper, and nickel) is

Table 1. Salient statistics for U.S. platinum scrap in 1998. [Values in kilograms of contained platinum, unless otherwise specified]

Old scrap:	
Generated ¹	42,700
Consumed ²	7,690
Value of old scrap consumed	\$117 million
Recycling efficiency ³	76 percent
Supply ⁴	48,100
Unrecovered ⁵	8,500
New scrap consumed ⁶	5,600
New-to-old-scrap ratio ⁷	42:58
Recycling rate ⁸	16 percent
U.S. net exports of scrap ⁹	14,310
Value of U.S. net exports of scrap	\$200 million

¹Platinum content of products theoretically becoming obsolete in the United States in 1998. Net U.S. imports of semifinished products containing platinum in 1998 are included. Dissipative uses are excluded.

²Platinum content of products that were recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁴Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁵Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁶Including prompt industrial scrap but excluding home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of the metal apparent supply that is scrap, on an annual basis.

⁹Trade in scrap is assumed to be principally in old scrap. Net exports are exports of old scrap minus imports of old scrap.

undertaken at the various mines. Further refining of the matte, including extraction of the base metals and recovery of the precious metals, takes place at refineries near Rustenburg, Brakpan, and Springs. Some matte is sent to refineries outside the country for toll refining. In 1998, South Africa produced about 117,000 kg of platinum and 57,300 kg of palladium (Hilliard, 2000b, p. 58.7).

RUSSIA

Probably more than 97 percent of Russia’s mine output of PGM’s is a byproduct of nickel-copper mining. The nickel-mining complex at Noril’sk, in northwestern Siberia, accounts for about 95 percent of total Russian production, and the mines at Pechenga on the Arctic coast account for most of the remainder. Modes of occurrence and composition of PGM’s in different types of ores vary significantly at Noril’sk. In disseminated ores, the main PGM minerals are represented by isoferroplatinum and cooperite, whereas in massive ores, very diverse palladium intermetallic compounds and tetraferroplatinum occur (Genkin and Evstigneeva, 1986, p. 1204). PGM’s are refined at the metallurgical complex in Krasnoyarsk, East Siberia. In 1998, Russia produced about 17,000 kg of platinum and 47,000 kg of palladium (Hilliard, 2000b, p. 58.7).

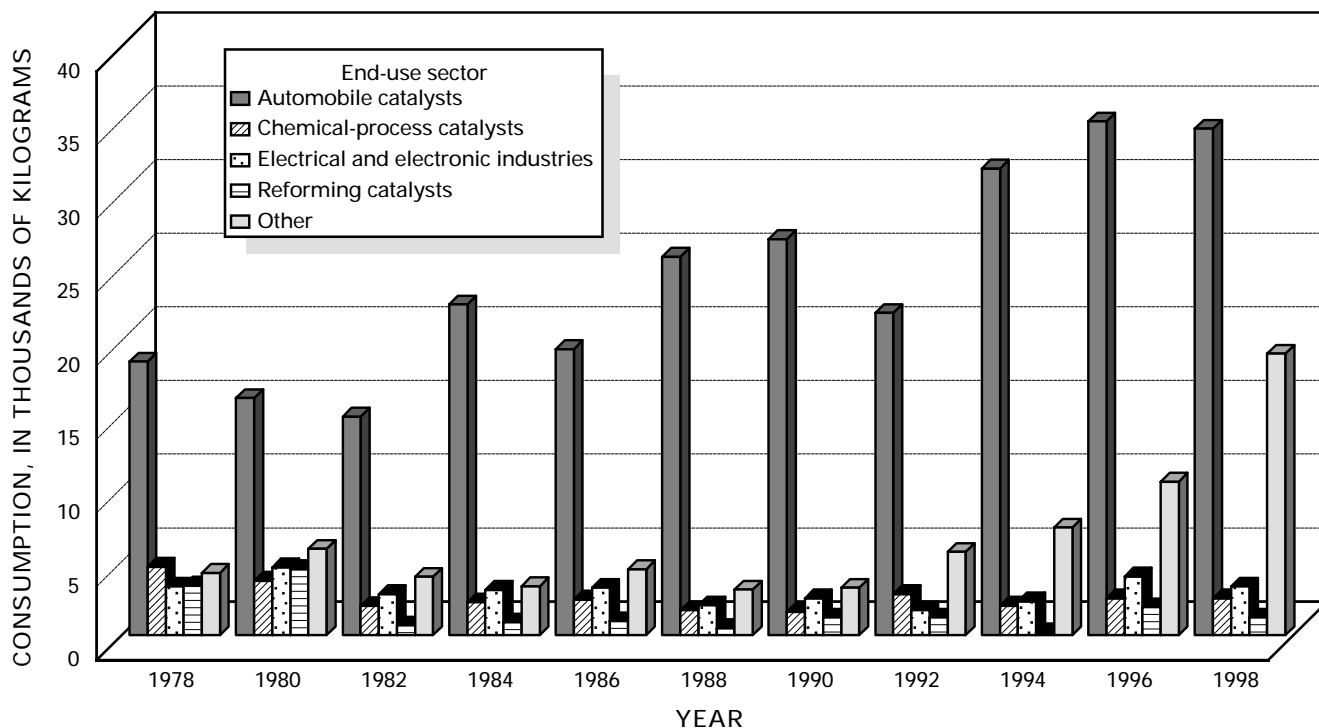


Figure 2. U.S. platinum consumption by end-use sector from 1978 to 1998.

UNITED STATES

The Stillwater Mine near Nye, Mont., is the only primary PGM producer in the United States. The Stillwater Complex is an elongated assemblage of intrusive rocks that occurs in Sweetwater County, Mont., and extends into Park and Stillwater Counties. In its annual report, the Stillwater Mining Company reported its 1998 production as 10,575 kg of palladium and 3,235 kg of platinum (Stillwater Mining Company, 1999). In 1998, the company mined 653,184 metric tons (t) of ore. In conjunction with the operation of the mine, the average throughput at the mill facility was 1,196 metric tons per operating day (t/d) with a recovery rate of 91 percent. The mill head grade was 23.7 grams (g) of combined palladium and platinum per metric ton of ore.

The Stillwater Mining Company operates a smelter and base-metals refinery (BMR) at the company's metallurgical complex in Columbus, Mont. At the smelter, concentrate is treated to produce matte containing approximately 22.3 kg of palladium and platinum per metric ton. The matte is subsequently sent to the BMR, which produces a filter cake that is about 60 percent palladium and platinum. The filter cake is sent to metal refiners in New Jersey, California, and Germany, where it is converted into palladium and platinum sponge for sale to end users.

In 1998, the Stillwater Mining Company restarted its program to process spent automobile catalysts for the recovery of PGM's. In 1998, approximately 139 t was processed in the BMR at a rate of 1 t/d. The usual procedure was to blend spent catalysts with concentrate from the mill (Stillwater Mining Company, 1999).

SOURCES OF PLATINUM SCRAP

Typical sources of platinum for secondary refining include spent automobile, reforming, and chemical-process catalysts; electronic scrap; jewelry; and used equipment from the glass industry (fig. 2). Spent automobile catalysts have emerged as the major source of secondary platinum, palladium, and rhodium. In the United States, about 25,500 kg of PGM's from automobile catalysts was available for recycling in 1998 (see p. B5).

OLD SCRAP GENERATED

Old scrap generated is defined as the platinum content of products theoretically becoming obsolete in the United States in 1998. Total platinum old scrap generated in 1998 in the United States from automobile catalysts, reforming catalysts, and chemical-process catalysts was estimated as 42,700 kg (table 1). Old scrap consumed, defined as the platinum content of products recycled, was estimated at about 18 percent of old scrap generated or 7,690 kg.

AUTOMOBILE CATALYSTS

Spent automobile catalysts have emerged as the major source of secondary platinum, palladium, and rhodium. The amount of platinum that is recovered from automobile catalytic converters depends upon the following factors: (1) the average loading of platinum in the converters, which will not be a constant, (2) the probability that vehicles from each of the previous model years will be taken out of service in the year under consideration, (3) the percentage of the vehicles that are taken out of service in that year and are scrapped,

and (4) the percentage of platinum that is recoverable from a used converter. The first of these factors can only be estimated, but industry-based statistics are available for the second factor. A value for the third factor depends upon the returns expected in the scrap market. Annual figures for automobiles scrapped are influenced by the strength or weakness of the scrap metal market. Thus, vehicles retired in years when the price of scrap is depressed may not reach the scrap yard until there is sufficient economic incentive. In the long run, however, it is likely that most vehicles withdrawn from service end up as scrap. As for the fourth factor, research has shown that the high recovery rates typical of PGM recycling in the chemical, petroleum, and electronic industries can also be achieved with automobile catalysts (Dhara, 1983).

Beginning with the 1974 model year, new automobiles sold in the United States have been equipped with catalytic converters that chemically convert polluting substances in automobile exhaust to nontoxic materials. Automobile catalysts were developed to remove carbon monoxide (CO), hydrocarbons (HC), and the oxides of nitrogen (NO_x) that cause air pollution from vehicle exhausts. Small amounts of platinum, either alone or combined with other PGM's, were used to oxidize and reduce the exhaust gases, thereby significantly lowering harmful emission levels.

The first catalytic converters used a monolithic system that incorporated palladium and platinum as the active constituents to oxidize the CO and HC. NO_x was controlled by modifications to the engine. In addition to monoliths, highly porous pelleted materials were also used. All converters now use monolithic supports because of the monolith's high geometrical surface area and low pressure drop during operation.

Since the introduction of the basic catalytic converter in 1974, the technology has advanced in response to tightening air-quality-control regulations; for example, the three-way oxidation-reduction converter (TWC) was developed. In the TWC system, all three pollutants—CO, HC, and NO_x —are converted in one reactor using a platinum-rhodium catalyst coated on a ceramic monolith. Thus, a reducing-type catalyst, based on rhodium for the reduction of NO_x , is combined with a conventional oxidation catalyst to provide three-way emission control of the pollutants. In TWC's, the platinum-to-rhodium ratio is generally about 10:1. The amount of PGM's used in the manufacture of these devices is more than the total amount consumed in all other U.S. uses combined (Roskill Information Services Ltd., 1991, p. 99).

At the beginning of the 1980's, General Motors suggested that a typical TWC might contain 1.555 g Pt, 0.622 g Pd, and 0.156 g Rh (Roskill Information Services Ltd., 1991, p. 100). The oxidizing units of early TWC's are thought to have contained platinum and palladium in the ratio of 2:1. The palladium content subsequently has risen considerably. Newer TWC's may contain about 1.8 kg (58 troy oz) PGM's per cubic meter of monolith. A catalytic converter measuring 10 centimeters (cm) in diameter by 15 cm in length would contain 2.3 g (0.074 troy oz) PGM's. A typical mean level of 1.5 g (0.048 troy oz) was suggested.

In 1998, about 200 million automobiles were in circulation in the United States, and about 17 million automobiles were scrapped. If each catalytic converter in the scrapped automobiles contained an average of 1.5 g of platinum, then about 25,500 kg of platinum was available for recycling from this source. Of the 17 million scrapped automobiles, about 12 million were recycled through shredders (Fenton, 1999, p. NN1). If it is assumed that the catalytic converters were collected from the automobiles prior to shredding, then 18,000 kg of platinum was available for recycling.

REFORMING CATALYSTS

Heterogeneous catalysts containing platinum are widely used in the petroleum-refining industry for a variety of hydrocarbon conversion processes, including reforming. The products made by these processes, such as motor fuels and aromatic hydrocarbons, are of great economic value to the United States. For example, increasing the aromatic hydrocarbon content of gasoline raises the octane rating and lessens knocking.

Catalysts in this service can be deactivated by several different mechanisms, but deactivation is primarily the result of deposition of carbonaceous materials onto the catalyst surface during hydrocarbon processing at elevated temperature. This deposit, known as coke, results in substantial deterioration in catalyst performance (Fung, 1993, p. 91–96). The catalyst activity, or its ability to convert reactants, is adversely affected by this coke deposition, and the catalyst is referred to as "spent."

The original performance of the fresh catalyst can be restored by proper regeneration to remove this coke (Kim and others, 1992, p. 39–46). Regeneration allows continued use of the same catalyst for many years. The actual loss of platinum during use by the petroleum industry is very small, and this efficient metal recovery contributes greatly to the economics of platinum use. There is a limit, however, to the number of times that a catalyst can be regenerated, and eventually the catalyst must be replaced. Many reforming and selective hydrogenation catalysts are regenerated two or more times. As a general rule, after a catalyst can no longer be regenerated to at least 75 percent of its original activity, it is reclaimed or discarded (Chang, 1998).

When the catalysts are removed from service, they are sent to a toll refiner for recovery of the metal values, which are returned to the owner. About 70 percent of the replacement market is for the bimetallic form commonly consisting of 0.3 percent platinum and 0.3 percent rhenium. Monometallic catalysts average 0.4 percent platinum (Burke, 1979). It is estimated that the amount of platinum used in catalytic reforming in 1998 was over 40,200 kg and was increasing by about 6,200 kg each year. Because PGM's are valuable, great care is exercised in monitoring all streams entering and leaving catalyst manufacturing sites to ensure that no significant amounts of material are lost. Yearly overall materials recovery rates of about 99.8 percent are attainable.

CHEMICAL-PROCESS CATALYSTS

A typical use of a PGM catalyst in a chemical process is the production of nitric acid. During the manufacture of nitric acid by the oxidation of ammonia, platinum-rhodium and platinum-palladium-rhodium alloy gauzes are used as catalysts. Traditionally, the process is carried out at temperatures of 750°C to 950°C and at pressures of 101.3 to 1,013 kilopascals. The amount of platinum lost from catalyst gauzes during nitric acid production depends upon the properties of the catalyst alloys, the operating conditions (temperature and pressure), and the technical control. The rate of platinum loss from a binary gauze consisting of 90 percent platinum and 10 percent rhodium varies from 0.05 g of platinum per metric ton of nitric acid produced in plants operated at atmospheric pressure (101.3 kilopascals) to 0.45 g of platinum for each metric ton of nitric acid produced in some high-pressure plants (Platinum Metals Review, 1999). In 1998, the United States produced 9.3 million metric tons of nitric acid (Chemical & Engineering News, 1999). With that rate of nitric acid production, about 2,300 kg of platinum is estimated to have been consumed in this process. Not all of this material was allowed to escape into the atmosphere. Various filters and "gettering" devices allowed recovery of perhaps half of the lost metal. Of the platinum that escaped, most was probably trapped in absorption towers and ended up in the nitric acid.

About 200 kg of platinum was consumed in other industrial or commercial catalytic applications.

NEW SCRAP

New scrap is defined as scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semi-finished articles that must be reworked. Typical sources of platinum new scrap are used equipment from the glass industry, jewelry, and electronic scrap (fig. 2). Platinum and platinum-rhodium alloys are basic to the glass industry and are used in a variety of glass-handling and -forming equipment. Platinum is used in these applications because of its high melting point, high-temperature strength, low oxidation rate, and noncontaminating behavior. Pure platinum is used to make stirrers and tanks and crucibles for melting glasses. Alloys of 90 percent platinum and 10 percent rhodium are used for the bushings and baskets needed in the production of glass fibers. This use represents a large application for platinum-rhodium alloys. Similarly, alloys of platinum and 10 to 40 percent rhodium are used for crucible liners, structures conveying molten glass, fiber-optics-forming devices, laser-glass melters, and stirrers for glass homogenization. Very low metal losses are experienced in these uses. Worn parts are recycled on a toll basis, and the recovered metals are returned to the industry for fabrication into new parts.

The platinum used in jewelry is theoretically available as an aboveground resource, but there is very little recycling,

apart from machining chips and grindings resulting from jewelry fabrication. The machining chips and grindings are efficiently recycled.

Precious metals in the electrical and electronic industries are dispersed in the assemblies, and until recently, little effort was made to recycle discarded scrap. Electronic scrap may contain recoverable amounts of gold, palladium, and silver but only trace levels of platinum (Hilliard and Dunning, 1983). The amount of platinum in electronic scrap may change dramatically as hard disk drives from computers manufactured after 1996 are scrapped. The first hard disk drives used 50 disks, each measuring 61 cm in diameter, to store just 5 megabytes of data. A typical modern personal computer can store 15 megabytes on a hard disk drive containing two or three disks that are only 9 cm in diameter. This efficiency was achieved by incorporating a platinum-cobalt magnetic layer on the surface of the disk to improve storage capacity. About 50 percent of the hard drives manufactured in 1998 used platinum, and it was estimated that in 2000 more than 90 percent of the hard drives used magnetic thin films containing platinum (Johnson Matthey, 1999, p. 26). It will be several years, however, before these hard drives begin appearing in scrap streams for recycling.

Almost all new PGM scrap generated is consumed. As shown in table 1, new scrap consumed in 1998 was estimated to have a platinum content of 5,600 kg, and the new-to-old-scrap ratio was 42:58.

HOME SCRAP

In every company that manufactures semifinished and final PGM products, virtually all of the scrap generated is reprocessed for precious-metals recovery. Casting scrap, such as croppings of castings, is recovered simply by adding it to melt charges. This scrap is not counted as material consumed because it is endlessly recycled and never leaves the plant. Grindings, ingot scalping, and machining chips, which are processed through toll refining, are not home scrap.

DISPOSITION OF PLATINUM SCRAP

SCRAP CONSUMPTION

Recovery of PGM's from spent automobile catalysts is growing in the United States, where a network of recycling facilities is being put in place. This growth is due to the higher PGM loadings in automobile catalysts in recent years. Nevertheless, the amount of PGM's recovered from catalysts remained only a fraction of the total amount consumed. In 1998, more than 6,000 kg of PGM's was recovered from spent automobile catalysts and other sources in the United States (Hilliard, 2000a). This represented about 8 percent of U.S. apparent consumption in 1998. More than 19,000 kg of platinum in spent automobile catalysts and other scrap materials was exported to other countries (fig. 1) where the metal values were recovered and the recovered platinum sold back to the United States.

UNRECOVERED OLD SCRAP

Only about 64 percent of the catalytic converters scrapped in the United States are being collected (Dhara, 1983). Of these scrapped converters, less than 30 percent are being processed domestically for recovery of PGM content; about 30 percent are shipped to collection centers to await more favorable economic conditions before processing; 20 percent are unrecovered. The remaining catalytic converters (20 percent) are exported to Japan and Europe for processing.

OLD SCRAP RECYCLING EFFICIENCY

Old scrap recycling efficiency shows the relation between old scrap materials recovered and reused and old scrap that is available to be recovered and reused. By definition, this relation is (the amount of old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any decrease in old scrap stocks or minus any increase in old scrap stocks). Platinum-bearing scrap materials consist mostly of spent catalysts from the automobile, chemical, and petroleum industries. In 1998, the chemical and petroleum industries recycled spent catalysts with recovery rates above 98 percent. Overall recycling efficiency for platinum was lower because of the many automobile catalysts that were not being recycled in 1998. Uncertainty in the exact value for recycling efficiency is increased because of lack of data on stocks of platinum-bearing material, but old scrap recycling efficiency is estimated at 76 percent.

INFRASTRUCTURE OF PLATINUM SCRAP SCRAP COLLECTION SYSTEMS

Anyone who owns a car manufactured in the United States after January 1, 1974, also owns a certain amount of automobile catalyst. Although spent automobile catalysts are readily available, collecting the material systematically is a complicated task. Because the catalysts are unevenly distributed, it is assumed that 20 to 40 percent of the total available catalysts will be either uncollected or unaccounted for (Dhara, 1983, p. 86). The flow of the material is unpredictable, as many factors, such as PGM prices, govern the collection effort.

The low PGM content in automobile catalysts and the nature of the monoliths used as support have required the development of specialized recovery techniques, as well as the establishment of an infrastructure of collection centers. These factors have slowed the development of an automobile catalyst recycling industry.

TRADE

In 1998, the United States imported 103,000 kg of pre-fabricated platinum, unwrought platinum, platinum scrap, and other platinum materials. The value of these imports was \$603 million. South Africa (69 percent), the United Kingdom (12 percent), and Germany (4 percent) were the major foreign sources of imports. The United States exported

14,300 kg of refined platinum and 20,447 kg of platinum in scrap, ores, and concentrates. The value of these exports was \$240 million (Hilliard, 2000b, p. 58.6). These quantities differ from those given in figure 1 because the U.S. Census Bureau reports some imports and exports as gross weight and estimates were made for the platinum content of these materials for inclusion in figure 1.

In the first half of 1998, delayed shipments from Russia caused platinum prices to rise by more than \$60 to reach a peak of \$434 per troy oz on April 14. Prices began to fall soon afterward, following news that Russian export quotas had been approved. Platinum prices declined sharply from May through October 1998 because of the economic crisis in Asia and renewed financial and political uncertainty in Russia. As a result, the price of platinum sank to a 5-year low of \$337 per troy oz in October. In 1998, the average annual price was \$372.50 per troy oz (Hilliard, 2000b, p. 58.3).

PROCESSING OF PLATINUM SCRAP

Automobile and catalyst-canister manufacturers arrange to recover in-house stainless steel and PGM-bearing scrap materials. Once a canister containing PGM's is mounted on a car that is sold, however, it is not regarded as an item for recovery by the manufacturers. Initially, each canister contains about 1.5 to 3 g of PGM's; 1 to 3 micrograms of PGM's are emitted per 1.6 kilometers from the exhaust systems of automobiles equipped with the canisters. For the present, the economic conditions of salvage through automobile scrap yards limit the amount of PGM's recovered from this source. Several processes are available for recovering platinum from spent automotive industry catalysts:

- Selective dissolution of the PGM's from ceramic support in aqua regia. Soluble chloro-complexes of platinum, palladium, and rhodium are formed, and reduction of these compounds yields crude PGM's for further refining.
- Dissolution of the catalyst support in sulfuric acid, in which PGM's are insoluble. This technique is widely used for the treatment of reforming and isomerization catalysts in which γ -alumina is the substrate but is not suitable for dissolution of the cordierite honeycomb substrates used in many automotive catalysts.
- A gas-phase volatilization in which the PGM's are selectively chlorinated to produce volatile compounds that are condensed in a cooler zone.
- Blending of the catalyst with PGM concentrate to be refined by the same process as PGM ore (Dhara, 1983, p. 89).

In the United States, A-1 Specialized Services & Supplies, Inc., Croydon, Pa., and Multimetco, Inc., Anniston, Ala., are among the leading buyers and processors of scrap catalytic converter canisters. These companies have a network of collection points across the country and pay between \$3.00 and \$17.00 per canister (International Precious Metals Institute, 2000).

OUTLOOK

The amount of platinum recovered from scrapped automobile catalysts continues to climb slowly and is expected to increase significantly in the long term because of increased demand for catalytic converters and platinum jewelry in Japan and China. Catalytic converters are the major source of platinum and other PGM's for recycling. The outer shell of the converter is recycled for its stainless steel content, and the substrate is shipped to extractors to recover platinum, palladium, and rhodium. The U.S. price of steel scrap, a key ingredient of the steelmaking process, continues to be depressed, primarily because of the import of new foreign steel (Fenton, 2000, p. 40.1). With lower steel scrap prices there is less incentive to dismantle cars as dismantlers cut back in hope of a price rebound, resulting in fewer salvage catalytic converters coming to collection centers. In many instances, the converters that find their way to collection centers are exported to countries with lower labor cost—recycling catalytic converters is a labor-intensive task—allowing for the economic recovery of the PGM's. The relatively low value of the metal content (about \$19.00 in each converter), the low concentration of PGM's (less than 0.1 weight percent), and the difficult logistics of returning the material to a central recycling location are reasons why recycling of PGM catalysts is not yet economically viable in the United States. Consequently, it is doubtful that there will be a significant increase in the reclamation of metals from automobile emissions control catalysts in the immediate future.

Significant changes are on the horizon. The U.S. automobile industry has begun to enter the automobile recycling business, which could lead to an improved infrastructure of collection centers. Pending regulations will deter catalysts from entering landfills and will redirect spent catalyst traffic from disposal to regenerating and reclamation plants. Although the number of cars being scrapped in the United States is fairly constant, new sources of material, especially from Mexico, where new air-quality regulations are being considered, could increase significantly the number of catalytic converters available. Beginning in 2001, automobile manufacturers will shift to a more palladium-intensive catalyst. It will be 5 to 6 years, however, before any change is seen in the relative amounts of various PGM's available for recycling.

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APPENDIX—DEFINITIONS

γ -alumina. An activated form of alumina, made from Bayer α -trihydrate, widely used in adsorption and catalysis, where its large surface area, pore structure, and surface chemistry play an essential role.

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

aqua regia. Royal water, usually a solution of 1 part nitric acid and 3 parts hydrochloric acid used to dissolve platinum and other precious metals.

catalyst. A substance that changes the rate of a chemical reaction but is itself not permanently changed in chemical form.

chalcophilic. Having an affinity for sulfur.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recycle.

heterogeneous catalysts. Catalysts in which phase boundaries exist between the catalysts and the reacting substances, such as a solid catalyst in a gas or liquid phase reaction.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

metal values. The amount of a specified precious metal or nonferrous scrap recovered by a refiner plus the cash value of other desirable metals recovered minus a penalty for undesired metals recovered.

monolith. [*monos*, one + *lithos*, stone] A single ceramic block coated with catalytic materials.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from

industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizer, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Based on unit value of platinum in materials.

primary platinum. Platinum derived from ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the metal apparent supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

reforming. A petroleum-refining process that uses a platinum catalyst to convert aliphatic hydrocarbons to aromatic hydrocarbons. Increasing the aromatic hydrocarbon content of gasoline raises the octane and lessens knocking

secondary platinum. Platinum derived from or contained in scrap.

siderophilic. Having an affinity for iron.

toll refining. Custom refining of metal scrap or residue (feedstock) for which the refiner is paid an agreed fee (toll) for the recovery of specified precious metals or nonferrous scrap. The refined product is returned to the owner of the feedstock.

U.S. Department of the Interior
U.S. Geological Survey

Chromium Recycling in the United States in 1998

By John F. Papp

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-C

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

1. Salient statistics for U.S. chromium scrap in 1998	C3
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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

Chromium Recycling in the United States in 1998

By John F. Papp

ABSTRACT

The purpose of this report is to illustrate the extent to which chromium was recycled in the United States in 1998 and to identify chromium-recycling trends. The major use of chromium was in the metallurgical industry to make stainless steel; substantially less chromium was used in the refractory and chemical industries. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse. In 1998, 20 percent of the U.S. apparent consumption of chromium was secondary (from recycling); the remaining 80 percent was based on net chromium commodity imports and stock adjustments. Chromite ore was not mined in the United States in 1998.

In 1998, 75,300 metric tons (t) of chromium contained in old scrap was consumed in the United States; it was valued at \$66.4 million. Old scrap generated contained 132,000 t of chromium. The old scrap recycling efficiency was 87 percent, and the recycling rate was 20 percent. About 18,000 t of chromium in old scrap was unrecovered. New scrap consumed contained 28,600 t of chromium, which yielded a new-to-old-scrap ratio of 28:72. U.S. chromium-bearing stainless steel scrap net exports were valued at \$154 million and were estimated to have contained 41,000 t of chromium.

INTRODUCTION

The chemical element chromium was discovered in 1797 by Nicolas-Louis Vauquelin, a professor of chemistry at the Paris École des Mines, which was one of the new European technical universities established to bring science education to the mining industry (Weeks and Leichester, 1968, p. 271–283). The mineral chromite, which consists primarily of chromium, aluminum, iron, magnesium, and oxygen, is a source of chromium. Chromite was first exploited for the production of pigments (Gray, 1988) and the manufacture of refractory materials.

In the United States in 1998, the major use of chromium was in the metallurgical industry to make stainless steel; substantially less chromium was used in the refractory and chemical industries. The major chromium commodities are

chromite ore, ferrochromium, and chromium chemicals, metal, and refractories. The major traded chromium commodity in the United States in 1998 was ferrochromium, which replaced chromite ore in 1983. Ferrochromium includes high-, medium-, and low-carbon ferrochromium; charge chrome is a type of high-carbon ferrochromium. Ferrochromium and ferrochromium silicon are chromium ferroalloys.

More than half of the chromium consumed in the United States in 1998 was used in stainless steel; all grades of stainless steel contain appreciable amounts of chromium. To be used in stainless steel, chromite ore is first smelted into ferrochromium. Most ore is smelted near the chromite ore mine, but some is shipped to smelters near inexpensive electrical power sources or near stainless steel producers. Ferrochromium is mixed with iron to make stainless steel.

The purpose of this report is to illustrate the extent to which chromium was recycled in the United States in 1998 (fig. 1, table 1) and to identify chromium-recycling trends. Most recycled chromium was part of stainless steel scrap, and smaller amounts were in superalloys. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse.

For the purpose of computing chromium supply from trade, the traded chromium commodities include chromite ore, chromium ferroalloys and metal, and selected chromium chemicals and pigments. On the basis of trade statistics and stainless steel scrap receipts reported by U.S. stainless steel producers, 20 percent of the 1998 chromium apparent consumption was secondary (from recycling of stainless steel scrap); the remaining 80 percent was based on net chromium commodity imports and stock adjustments. Chromite ore was not mined in the United States in 1998 (Papp, 1999).

On the basis of a different chromium material flow model, Gabler (1994, p. 18) estimated that in 1989, about 33 percent of chromium material potentially available for recycling was recycled and that the recycled material accounted for 23 percent of 1989 apparent consumption. Although the models differed for this study and Gabler's, the percentages of apparent chromium consumption from recycling were similar for 1989 (23 percent) and 1998 (20 percent).

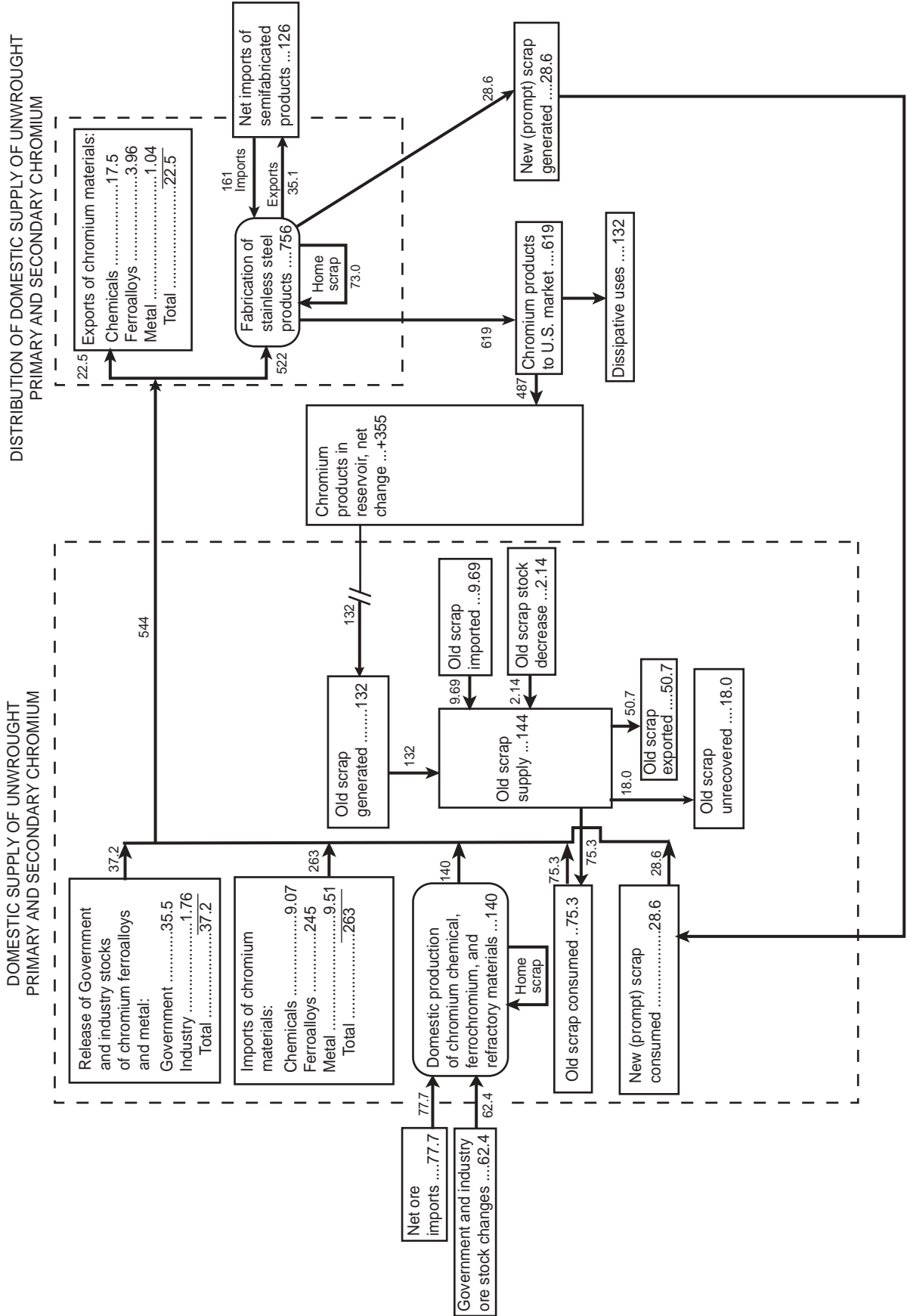


Figure 1. U.S. chromium materials flow in 1998. Values are in thousands of metric tons of contained chromium and have been rounded to three significant figures. In this study, the only chromium recycling reported was that which was a part of stainless steel scrap reuse.

Table 1. Salient statistics for U.S. chromium scrap in 1998.
[Values in thousands of metric tons of contained chromium,
unless otherwise specified]

Old scrap:	
Generated ¹	132
Consumed ²	75.3
Value of old scrap consumed ³	\$66.4 million
Recycling efficiency ⁴	87 percent
Supply ⁵	144
Unrecovered ⁶	18.0
New scrap consumed ⁷	28.6
New-to-old-scrap ratio ⁸	28:72
Recycling rate ⁹	20 percent
U.S. net exports of scrap ¹⁰	41.0
Value of U.S. net exports of scrap ¹¹	\$154 million

¹Old scrap generated in 1998 is estimated to have been the chromium content of a fraction of the net stainless steel supply in 1968, as discussed in the text section "Old Scrap Generated." The chromium fraction of stainless steel is estimated at 0.170 (Papp, 1991, p. 20). The fraction of the 1968 supply reporting to old scrap in 1998 was 0.894. The net stainless steel supply was shipments plus imports minus exports of stainless steel mill products.

²Old scrap consumed is estimated to have been the chromium contained in stainless steel scrap receipts reported by consumers in 1998 less the sum of new scrap generated and scrap imports.

³Value is estimated to have been the annual average unit value of high-carbon ferrochromium in 1998 (\$882/t of chromium or \$497/t gross weight of high-carbon ferrochromium) applied to old scrap consumed. This value is used because stainless steel scrap and ferrochromium compete as sources of chromium for the production of stainless steel (Papp, 2000).

⁴Recycling efficiency is (old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁵Old scrap supply is old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap unrecovered is old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁷New scrap (also called prompt industrial scrap) consumption is not reported. It is estimated to be the new scrap generated. See text for estimation procedure.

⁸New-to-old-scrap ratio is new scrap consumption compared with old scrap consumption, measured in weight and expressed in percentage of new plus old scrap consumption.

⁹Recycling rate is old plus new scrap consumed divided by apparent supply expressed as a percentage. Chromium apparent supply is primary domestic chromium production (from mining, which was nil for the United States in 1998) plus secondary domestic chromium production (from old plus new stainless steel scrap) plus imports minus exports plus adjustments for Government and industry stock changes. Old plus new scrap consumed is estimated to be the chromium contained in stainless steel scrap receipts reported by Fenton (2000) and updated by Duane Johnson (U.S. Geological Survey, 2000, unpub. data). Chromium apparent supply used here is the same as that reported in the U.S. Geological Survey Mineral Commodity Summaries, where it is called apparent consumption (Papp, 1999).

¹⁰U.S. net exports of scrap are chromium contained in exports minus chromium contained in imports of stainless steel scrap.

¹¹Value of U.S. net exports of scrap is the value of stainless steel scrap exports minus imports as reported by the U.S. Census Bureau on the basis of data collected by the U.S. Customs Service. Stainless steel scrap has value for reasons other than its chromium content.

In 1998, 75,300 metric tons (t) of chromium contained in old scrap was recycled in the United States; it was valued at \$66.4 million. Old scrap generated contained 132,000 t of chromium. The old scrap recycling efficiency was 87 percent, and the recycling rate was 20 percent. (See appendix for definitions.) About 18,000 t of chromium in old scrap was unrecovered. New scrap consumed contained 28,600 t of chromium, which yielded a new-to-old-scrap ratio of 28:72. The U.S. Census Bureau reported that U.S. chromium-bearing stainless steel scrap net exports were valued at \$154 million in 1998 and were estimated to have contained 41,000 t of chromium. Trade data reported by the U.S. Census Bureau are based on data collected by the U.S. Customs Service.

SOURCES OF CHROMIUM-CONTAINING SCRAP

Figure 1 shows secondary chromium material supply, distribution, and recycling in the U.S. economy in 1998. Stainless steel scrap was the major source of recycled chromium and is the only type of scrap reported in figure 1. In the United States, the average primary chromium supply distribution and usage trend in the metallurgical industry from 1983 through 1992, as measured by reported consumption, was stainless steel, 79 percent and increasing; alloy steel, 8 percent and decreasing; superalloys, 3 percent and increasing; and other uses, 10 percent (Papp, 1994, p. 68–70).

Steel production classifications include alloy steel (except stainless), carbon steel, and stainless steel. U.S. steel production by these classes is, in descending order of magnitude of production as a percentage of total averaged from 1993 through 1998, carbon steel, 88.8 percent; alloy steel, 9.17 percent; and stainless steel, 2.06 percent. In 1998, U.S. carbon steel production was 88.0 million metric tons (Mt); alloy steel, 8.60 Mt; and stainless steel, 2.01 Mt. Relative to steel production, stainless steel production is small.

In a world context, the United States accounted for 12.6 percent of world steel production and 15.2 percent of world stainless steel production on the basis of data from 1994 through 1998 (American Iron and Steel Institute, 1999; INCO Limited, 1999, p. 3). In 1998, U.S. stainless steel producers reported stainless steel scrap consumption of 1.04 Mt (Fenton, 2000, and updates by Duane Johnson, U.S. Geological Survey, 2000, unpub. data), or 51.8 percent of that year's stainless steel production. Consumption consisted of receipts of new, old, and home scrap. The chromium fraction of stainless steel is estimated at 0.170 (Papp, 1991, p. 20). The 1.04 Mt of scrap was estimated to have contained about 177,000 t of chromium valued at \$882/t and to have had a primary-chromium-material-equivalent value of \$157 million.

In 1998, reported receipts were 611,000 t of new and old stainless steel scrap, which were estimated to have contained 104,000 t of chromium. The difference between the chromium content of reported stainless steel scrap consumption and that of reported stainless steel scrap receipts was assumed to be equal to the chromium content of home scrap (73,000 t).

Chromium is used in alloy, carbon, stainless, and tool steels; cast irons; chemicals; and superalloys. Chromite is used in refractories. The amount of chromium added to carbon and alloy steel is small, and chromium is included in only a few grades. Many grades of these alloys do not have any added chromium. As a result, when recycled, these alloys are not sought for their chromium content. Stainless and tool steels and superalloys are more valuable, contain greater amounts of chromium, and contain chromium more universally than do carbon or alloy steels. These materials are sought for recycling because of their high value, their high content of desirable elements (such as nickel, cobalt, molybdenum, and chromium), and their lack of undesirable, or tramp, elements.

The carbon steel recycling rate is defined as carbon steel scrap consumption per carbon steel production on an annual basis. In the United States on average for 1994 through 1998, it exceeded the stainless steel recycling rate by about 15 percent. All grades of stainless steel contain chromium, whereas only a few grades of carbon steel contain chromium, and the quantities are small compared with those in stainless steel. Because of these circumstances, the amount of chromium contained in recycled carbon steel cannot be confidently estimated, and carbon steel recycling is not considered to contribute to chromium recycling in this study.

In the United States on average for 1994 through 1998, alloy steel was recycled at less than one-sixth the rate of stainless steel. The alloy steel recycling rate was measured by comparing the ratio of alloy steel scrap consumption to alloy steel production with the ratio of stainless steel scrap consumption to stainless steel production (AISI, 1995–99). The amount of alloy steel recycled was nearly 1 Mt in 1998. Only a few grades of alloy steel contain chromium, and the amounts are small compared with those in stainless steel. Because of these circumstances, the amount of chromium contained in recycled alloy steel cannot be confidently estimated, and alloy steel recycling is not considered to contribute to chromium recycling in this study.

Although the production of superalloys is small compared to that of stainless steel, their high value makes recycling superalloys cost effective. Nevertheless, data were not available to estimate the contribution of superalloy recycling to chromium recycling in this study.

DISSIPATED MATERIALS NOT AVAILABLE FOR RECYCLING

Dissipative uses do not result in new or old scrap generation in this model; they commonly involve dilution of the material or use in small volumes. Two broad categories of chromium products that are used dissipatively are chemicals and refractory materials; small amounts of chromium-containing steel can also be considered to be used dissipatively. For example, chromium is used in dyes and pigments that are subsequently incorporated in inks and paints. Because those inks and paints are used as thin coatings, the chromium becomes so diluted that recovery is uneconomic. Such materials leave the use cycle if incinerated or placed in a landfill.

For the purpose of estimating the amount of dissipative use, chemical and refractory material production would be a good start except that such information is company confidential and, therefore, is not available for this calculation. Because imported chromite ore was used to make chromium chemicals, chromite-containing refractory materials, and chromium ferroalloys, net chromite ore imports can be used to estimate dissipative use. Inclusion of net trade in chromium chemicals and stock change of chromite ore to refine that estimate indicates that U.S. dissipative chromium use in 1998 was 132,000 t.

Chromium ferroalloys are used to make the end-product iron and steel alloys discussed above. Some of that use is dissipative. The amount of chromite ore consumed in the United States in 1998 to make ferrochromium is the amount herein assumed to have been used dissipatively in metallurgical applications. Although there is no quantitative information about dissipative use, the assumption seems reasonable.

Because chromium ferroalloy and metal production data for 1998 were withheld, estimates made for 1997 are assumed to apply. Domestic ferrochromium production is estimated to have been reported domestic chromium ferroalloy and metal production less domestic chromium metal production. Chromium metal production in 1998 is estimated to have been 2,000 t, implying that 38,900 t of chromium contained in stainless steel was used dissipatively. That was 10.6 percent of chromium contained in the net stainless steel supply. The net stainless steel supply was material that entered the marketplace in products; it is calculated as stainless steel shipments plus net imports of stainless steel mill products. Applying this result to 1998 data indicates that 38,900 t of chromium contained in the 1998 net stainless steel supply was used dissipatively in metallurgical applications, or about 11.4 percent of chromium contained in stainless steel production. Because chromium not used dissipatively becomes old scrap supply, the above assumption further implies that 88.6 percent of the net stainless steel supply in 1998 will become old scrap.

OLD SCRAP GENERATED

Old scrap generated was estimated to be the net stainless steel supply of 30 years before 1998 adjusted for trade and dissipative use. Stainless steel is used in virtually all industry sectors. Stainless steel is stronger, more durable, and more valuable than common grades of steel. The actual lifetime of stainless steel parts depends on the specific applications, but data are lacking on the distribution of stainless steel by end use, average product life by end use, and recovered fraction by product; therefore, old scrap generated was estimated on the basis of the past domestic net stainless steel supply.

From 1994 through 1998, the United States was a net exporter of stainless steel. U.S. stainless steel ingot exports were in the range of 0.4 to 0.6 percent of domestic stainless steel production; semifinished stainless steel exports were 4 to 8 percent of that production. Stainless steel net exports in 1968 are assumed to have been balanced by stainless steel contained in net manufactured product imports. This leaves dissipative uses in 1968 to be accounted for. The same dissipative use pattern discussed above for 1997 is assumed to apply to 1968. Therefore, dissipative uses in 1968 were 10.6 percent of net stainless steel supply in 1968, leaving 89.4 percent of that supply potentially available for recycling. Thus, 89.4 percent of the 1968 net stainless steel supply is the input to old scrap generated in 1998.

Stainless steel production in 1968 contained about 221,000 t of chromium. The net stainless steel supply (that is, stainless steel shipments plus imports minus exports) contained 148,000 t of chromium, of which 89.4 percent became the estimated amount of old scrap generated in 1998, 132,000 t of chromium.

In mining terms, a “resource” is material available regardless of the economics of recovery, and a “reserve” is an economically recoverable resource—old scrap generated is a resource, and old scrap consumed is a reserve (U.S. Bureau of Mines and U.S. Geological Survey, 1980). This resource may or may not have been collected, sorted if collected, or traded if sorted. In effect, the scrap industry must undo what the wholesale and retail trade industries do—the wholesale and retail trade industries take goods concentrated at the point of production and distribute them to consumers, whereas the scrap industry takes distributed materials and concentrates them so that they can reenter the production process.

Various factors affect material collection and recycling (Aylen and Albertson, 1995). The availability of obsolete stainless steel scrap is price sensitive. In other words, when the price of scrap goes up, so does the supply of obsolete stainless steel scrap. The reason for this is that scrap collectors and processors stock obsolete stainless steel scrap until it becomes profitable for them to handle, process, and ship that material. On the basis of the resource/reserve analogy above, as price increases, resources become reserves.

Old superalloy scrap is generated when parts made of superalloy material, such as jet engine parts, are replaced. Chemicals, such as plating and metal finishing baths, are processed to extend their useful life by removing contaminants. To the extent that this processing is recycling, it produces home scrap because such renewal is done within a plant. Refractory materials, such as chromite casting sand, are processed for reuse. To the extent that this processing is recycling, it produces home scrap because such reuse is done within a plant.

Figure 2 shows the supply of chromium by material to the U.S. economy and the use of that material by end-use market sector. Figure 2A shows the distribution of chromite ore use by industry from 1978 to 1994; data are given individually for the chemical, metallurgical, and refractory industries from 1978 through 1985, but data are combined for the chemical and metallurgical industries from 1986 through 1994 to protect company proprietary data. After 1994, publication of chromite ore consumption by industry was discontinued to protect proprietary data.

As shown in figure 2A, from 1978 through 1985, consumption of chromium from chromite ore by the chemical industry declined by 7 percent; consumption by the metallurgical industry dropped by half, to 65,200 t from 132,000 t; and consumption by the refractory industry dropped more than two-thirds, to 15,400 t from more than 53,800 t. Refractory industry consumption continued to drop until it reached less than 6,000 t in 1994, when reporting was discontinued. From 1979, a peak consumption year, to 1994, the chromium contained in the reported annual chromite ore consumption dropped to just more than 100,000 t from about 300,000 t. Chromite ore was being replaced by ferrochromium as the major source of chromium for the U.S. economy. Ferrochromium is used in the metallurgical industry, which is the major source and consumer of chromium-bearing scrap.

Figure 2B shows the relative importance of the two major commercial sources of chromium in the United States during the 20 years, 1978–98. The figure shows that the dominant source of chromium for the U.S. economy shifted from chromite ore before 1981 to ferrochromium after 1983; for example, chromite ore supplied 61 percent of chromium contained in these imports in 1978, whereas ferrochromium supplied more than 67 percent of chromium in 1998.

The major end use of chromium in the metallurgical industry is the manufacture of stainless steel. Figure 2C shows the inferred distribution of chromium among major end-use market sectors, which are electrical and electronic equipment, fabricated metal products, industrial and commercial machinery, and transportation. Transportation and industrial and commercial machinery each accounted for more than 40 percent of the total; fabricated metal products and electrical and electronic equipment each accounted for under 10 percent.

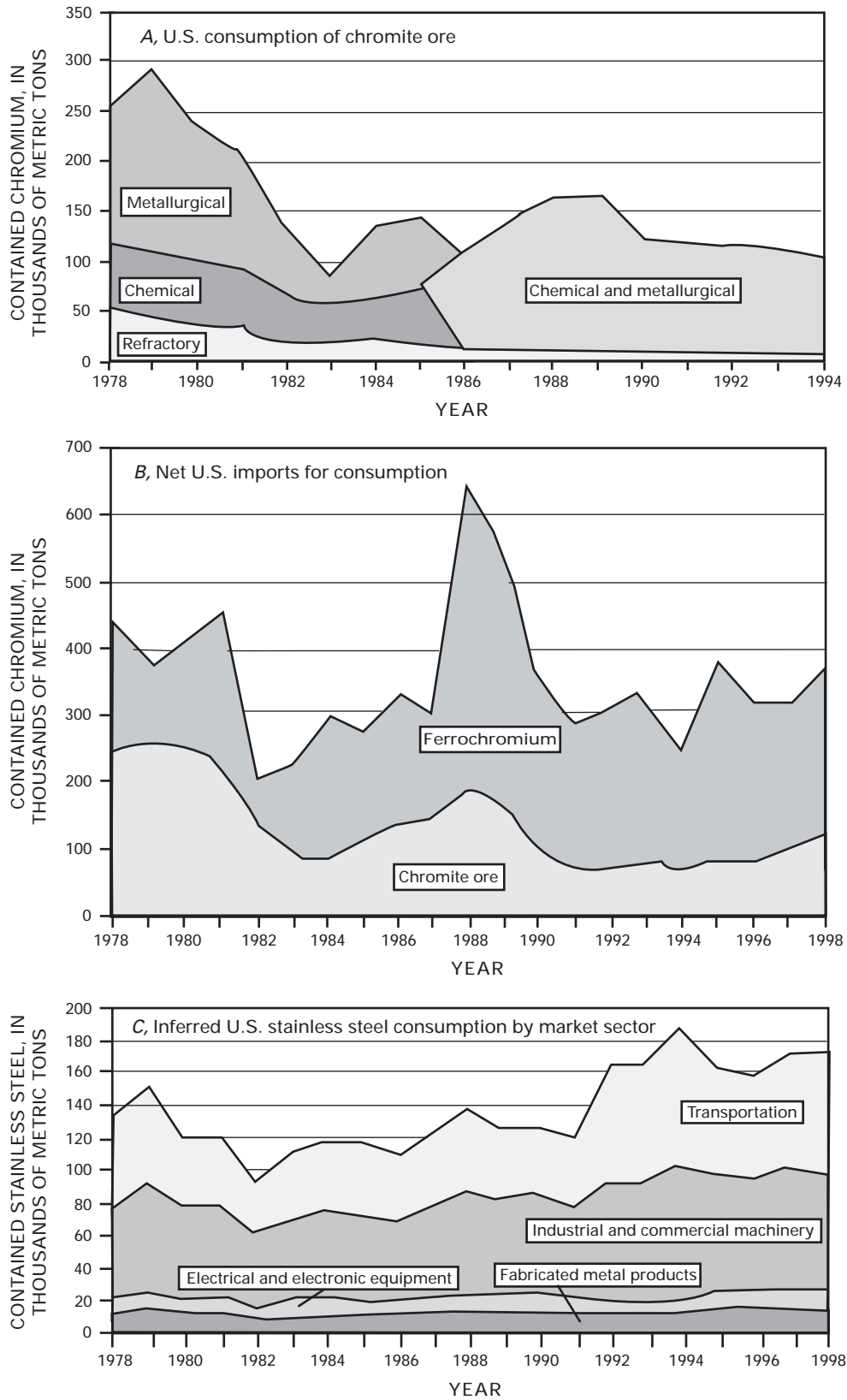


Figure 2. U.S. chromium source materials and consumption from 1978 through 1998. A, Reported U.S. consumption of chromite ore by the metallurgical, chemical, and refractory industries (data through 1994 only). B, Net U.S. imports for consumption by material. C, Inferred U.S. stainless steel consumption by market sector.

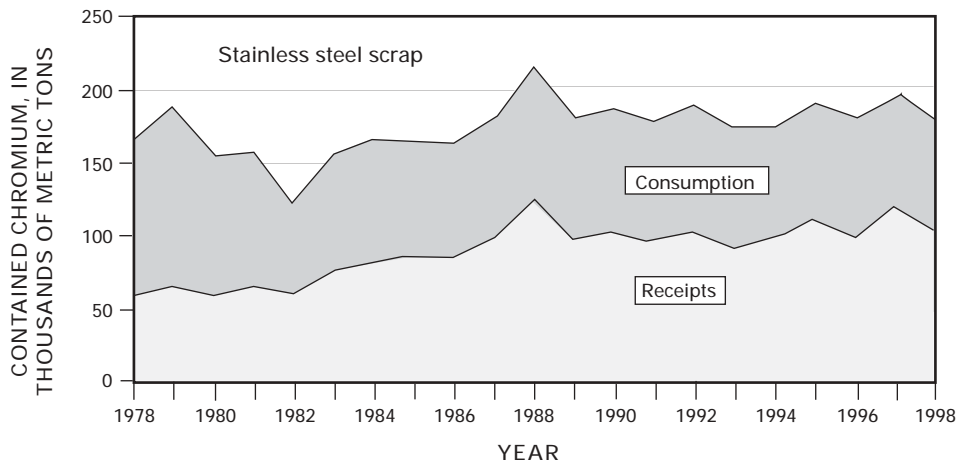


Figure 3. U.S. chromium recycling trend as indicated by reported consumption and receipts of stainless steel scrap from 1978 through 1998.

Figure 3 shows reported consumption and receipts of stainless steel scrap from 1978 through 1998. Assuming that scrap receipts are new or old scrap, one may infer that scrap receipts shown in figure 3 came from the end-use manufacturing processes shown in figure 2C or from the products of those uses. If the difference between scrap receipts and scrap consumption in figure 3 is home scrap, then the source of that scrap is the primary metals industry market sector. The figure shows a trend of increasing importance of new and old scrap, as shown by the increasing amount of scrap receipts compared with scrap consumption, during the 20-year period. Scrap receipts accounted for less than 36.8 percent of consumption in 1978 compared with 58.7 percent in 1998.

NEW SCRAP

New scrap results from steel fabrication processes. Stainless steel is either wrought or cast to make shapes, such as bars, plates, sheets, or strips, that are used to manufacture products. New scrap is valuable and is returned to the stainless steel producer through the supplier-purchaser channel or through scrap processors and dealers.

New stainless steel scrap generation is proportional to stainless steel use. Reducing the amount of new scrap generated per unit of stainless steel production increases processing efficiency. The constancy of new scrap availability in the face of continued average production growth indicates that processing efficiency has increased coincident with and proportional to the growth in production. New scrap availability is not as price sensitive as old scrap availability because it is easier to collect, sort, and return new scrap; commonly, new scrap is returned under formal contract arrangements (Friedrich Terörde, ELG Haniel Group, U.S.A., 1997, written commun.). New scrap may also be called prompt industrial scrap because it is generated when industry manufactures products that use stainless steel and is returned as it is generated; that is, promptly.

Stainless steel production has been growing; from 1950 to 1996, the compounded annual growth for the major producing countries was 6.0 percent (INCO Limited, 1997, p. 6). Annual growth of stainless steel production for these countries from 1986 through 1996 ranged in magnitude from as little as 0.04 percent to more than 14 percent.

For the secondary material flow model used in this report, new scrap generated was estimated on the basis of information from Austin van't Wout (Capricorn BV, Holland, 1998, written commun.) that 25 to 30 percent of scrap shipped by scrap suppliers to the stainless steel industry is new scrap. Thus, because scrap receipts were 58.7 percent of scrap consumption in 1998 and new scrap was 25 to 30 percent of scrap receipts (receipts by stainless steel producers being the same as shipments from scrap processors), new scrap was 14.7 to 17.6 percent of stainless steel scrap consumption, and the new-to-old-scrap ratio was 28:72.

In written communications in 1997, P.J. Probert (Hernic Ferrochrome, South Africa) and Josephine Ward (Reward Raw Materials, Inc., Carnegie, Pa., U.S.A.) discussed secondary chromium consumption. Probert reported that stainless steel scrap typically provided 35 to 40 percent of the chromium required to produce stainless steel worldwide. For austenitic grades (those requiring nickel), scrap provided 45 to 50 percent of the required chromium units. Ward estimated the lifetime of stainless steel products to range from 15 to 20 years in the United States and stainless steel scrap to comprise 50 percent reclaimed (old scrap), 35 percent revert (home scrap), and 15 percent industrial (new scrap) in the United States. This estimate suggests that 65 percent of scrap consumption is receipts. U.S. stainless steel receipts and consumption reported to the U.S. Geological Survey (USGS) indicate that receipts averaged 59 percent of stainless steel scrap consumption during 1994 through 1998. The new scrap percentage of net stainless steel scrap consumption inferred in this report from other sources is 16.2 percent.

In a study of nickel that is more recent than the studies cited in the previous paragraph, Salamon (2000) reported the lifetime of stainless steel in buildings to be 70 years; industrial plants, 35 years; and consumer products, 5 to 25 years.

Chemicals do not contribute to new scrap.

DISPOSITION OF CHROMIUM-CONTAINING SCRAP

Scrap processors collect old and new scrap, segregate it by grade, and cut it to usable size. They commonly mix scrap to meet the chemical specifications of the stainless steel consumers who use it as a feed material for their furnaces. The USGS monitors scrap consumption of the U.S. stainless steel industry. The industry reports scrap receipts and scrap consumption. Stainless steel scrap accounting procedures do not differentiate old from new scrap.

In the model presented here, the difference between old scrap supply and old scrap consumed is taken as the sum of old scrap exported, old scrap going into stocks, and unrecovered old scrap. The rate of recovery of old scrap from the general economy by scrap dealers and processors is unknown. Old scrap generated is an estimated number. Old scrap consumed is estimated to be the difference between scrap receipts (a surveyed quantity) and new scrap consumed (an estimated quantity). Unrecovered old scrap is estimated by balancing old scrap supply inputs and outputs.

In 1998, 1.04 Mt of stainless steel scrap was consumed to produce 2.01 Mt of stainless steel. In other words, the stainless steel industry consumed the equivalent of 51.8 percent of production in stainless steel scrap, an amount similar to the overall steel industry recycling performance of 58.4 percent, which is based on American Iron and Steel Institute (AISI) data averaged from 1994 through 1998 (AISI, 1999).

Individual stainless steel producers reported scrap usage ranging from 0 to 80 percent. One company reported feed consisting of 20 percent in-house (home) scrap, 30 percent primary (previously unused) materials, and 50 percent secondary materials (new plus old scrap). By using reported stainless steel scrap receipts and consumption, secondary supply could be estimated as receipts, and in-house scrap could be estimated as consumption minus receipts; by using production to estimate feed, primary supply could be estimated as production minus scrap consumption. For the U.S. stainless steel industry, this process averaged from 1994 through 1998 yields the following stainless steel scrap types as percentages of stainless steel production: 22.2 percent in-

house scrap; 46.1 percent primary materials, and 31.7 percent secondary materials.

The U.S. Environmental Protection Agency (EPA) reported the release and transfer of from 12,000 t to 42,000 t of chromium annually between 1987 and 1995 from the primary metals industry, which for chromium is the steel industry (Papp, 1994, p. 72; 1996; 1997, p. 182; 1998, p. 196). In 1991, industry started reporting recycling as part of transfers (EPA, 1993, p. 6, 144, 162). As a result, transfers increased from about one-half of releases plus transfers to about three-fourths. One could conclude that in excess of one-half of the reported 40,000 t of transfers in 1991 were recycled. In the model used here, this material would be classified as either home or new (prompt) scrap.

The above discussion of scrap disposition focuses on stainless steel scrap because it is accounted for separately from carbon steel, alloy steel, and superalloys. The chromium in stainless steel can reasonably be estimated, whereas the chromium in the other materials cannot, although brief discussions are provided above in the section, "Sources of Chromium-Containing Scrap."

OLD SCRAP RECYCLING EFFICIENCY

Old scrap recycling efficiency is defined as old scrap consumed plus old scrap exported as a percentage of old scrap generated plus old scrap imported plus old scrap stock released; it shows the relations among what is theoretically available for recycling, what is recovered, and what is not recovered. For U.S. chromium in 1998, old scrap recycling efficiency was 87 percent. As mentioned above in the section on "Old Scrap Generated," the availability of old stainless steel scrap is price sensitive. Therefore, the resource of old scrap is closely monitored and converted to commercial product when it is economically possible to do so. In an economic sense, old stainless steel scrap is being fully used consistent with the economic constraints placed upon its recycling by our economy.

INFRASTRUCTURE OF CHROMIUM-CONTAINING SCRAP

Scrap collection takes different forms on the basis of the kind and quantity of scrap. For example, scrap generated in the manufacturing process (new scrap) has value because its composition, quality, and origin are known. One recycling expense is the cost of separating materials into usable groups. Manufacturers can avoid this cost by not mixing incompatible materials, then returning the material to the metal producer for reuse. Recycling obsolete products is more labor intensive than recycling new scrap because the products are a mixture of materials that need to be segregated. For some products, high-value materials are efficiently

segregated from low-value ones. For example, automobile catalytic converters are housed in stainless steel cans. Because many automobiles are recycled, the cans are economically reclaimed and their material is reused.

Although not all stainless steel in household products is recovered, much of the stainless steel in industrial products is. The stainless steel scrap industry includes suppliers of scrap to stainless steel producers and collectors of scrap who also sort material. Functions performed by these two groups—collecting, sorting, storing, and distributing—overlap. The scrap supplier takes on the responsibility for meeting the quality requirements of stainless steel producers. Scrap collectors are among their sources of scrap (Austin van't Wout, 1998, written commun.).

The U.S. Harmonized Tariff System categorizes chromium metal import trade into waste and scrap and other; "other" includes wrought and unwrought chromium alloys. The system makes no such breakdown for chromium metal exports. Vastly more chromium is traded as part of stainless steel than is traded in chromium waste and scrap. In 1998, U.S. exports of chromium metal (including waste and scrap) were 1,038 t; in contrast, stainless steel scrap net exports (net exports are old scrap exported minus old scrap imported) of 241,000 t, gross weight, contained an estimated 41,000 t of chromium. Chromium contained in stainless steel scrap net exports was 23 percent of chromium contained in domestic stainless steel scrap consumption. Only stainless steel scrap is included in this report because it dominates the quantity of chromium recycled and because it is the material for which information is available.

PROCESSING OF SCRAP METALS

SMELTING/REFINING

In the steel industry, smelting is the process of converting iron ore into iron. Chromium plays no role in this process. In the chromium industry, smelting is the process of converting chromite ore into ferrochromium. Steelmaking, in particular stainless steelmaking, is a refining process that involves combining iron and alloying elements to convert iron into steel. Steel is iron with carbon added. Chromium is one of the alloying elements added to iron to make stainless steel. The source of chromium could be ferrochromium or stainless steel scrap. Ferrochromium is the primary supply because it comes directly from mined materials, and stainless steel scrap is the secondary material because it is recycled material. Stainless steel scrap is mixed with ferrochromium and other feed materials, melted, and refined. Because pri-

mary and secondary materials are processed together in the stainless steelmaking process, secondary material metallurgical processing losses are the same as those of primary material.

FABRICATION

Scrap generated in the fabrication industry may require processing before it is reusable. For example, only certain sized objects are permissible for materials handling and furnace feed. Large objects must be cut; small ones, agglomerated. Contaminants must be removed. Cutting operations require lubricants that may have to be cleaned off of the metal before it is reused.

OUTLOOK AND SUMMARY

Chromium is recycled as part of stainless steel recycling. Once it is reclaimed, stainless steel scrap is processed and sold to be used as a feed material in the stainless steel production process. The scrap is mixed with other feed materials, including primary materials, and is melted and refined.

The U.S. stainless steel industry in 1998 produced stainless steel scrap in excess of its needs. With a chromium recycling rate of 20 percent and old scrap recycling efficiency of 87 percent as interpreted in this model, chromium recovery from obsolete material might be improved. Figures indicate that in 1998, 18,000 t of chromium could theoretically have been obtained from unrecovered old scrap. Although furnaces in industrialized countries (probably including the United States) produced stainless steel using as much as 80 percent scrap, the U.S. market did not absorb this additional material under 1997–98 conditions of relatively strong demand. Price, of course, is a major inducement, and prices were relatively low in 1998. The 18,000 t is an estimate that could be off for several reasons—dissipative use could have been underestimated, old scrap supply could have been overestimated, or high-cost stocks may have built up in scrap yards.

New scrap recycling efficiency is high relative to that of old scrap and likely cannot be improved significantly. Recycling of stainless steel in a wide variety of products, however, is the area where attention could be focused. Some believe that greater design for recycling would aid in this effort for a more sustainable environment. In 1998, the United States had net exports of stainless steel scrap containing 41,000 t of chromium that earned the United States \$154 million. The U.S. stainless steel industry reported consuming 1.04 Mt of home, new, and old stainless steel scrap that was estimated to have contained about 177,000 t of chromium and to have had a primary-chromium-material-equivalent value of \$157 million.

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APPENDIX—DEFINITIONS

apparent consumption. Primary domestic production plus secondary domestic production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes. For chromium, there is insufficient information about recycling to distinguish between new and old scrap consumption. Chromium apparent consumption is approximated by chromium apparent supply (see definition below) where new plus old scrap production is defined as stainless steel scrap receipts as reported in the U.S. Geological Survey's Iron and Steel Scrap Survey (Fenton, 2000, and updates by Duane Johnson, 2000, unpub. data).

apparent supply. Apparent consumption calculated with secondary production equal to new plus old scrap; see *apparent consumption*.

dissipative use. A use in which a metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recover the metal.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as post-consumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizer, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary production. Chromium from ore. Because chromite ore was not mined in the United States in 1998, the primary domestic production term used in calculating apparent consumption is zero.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the metal apparent supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

secondary production. Chromium from recycling of new plus old scrap.

superalloys. Alloys developed for high-temperature conditions where stresses (tensile, thermal, vibratory, and shock) are relatively high and where resistance to oxidation is required.

value. Unit value of primary metal applied to primary metal contained in scrap. For chromium, the primary metal is ferrochromium.

U.S. Department of the Interior
U.S. Geological Survey

Zinc Recycling in the United States in 1998

By Jozef Plachy

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-D

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)

For temperature conversions from degrees Celsius ($^{\circ}\text{C}$) to degrees Fahrenheit ($^{\circ}\text{F}$), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Zinc Recycling in the United States in 1998

By Jozef Plachy

ABSTRACT

In 1998, about 426,000 metric tons (t) of zinc scrap was consumed in the United States; more than three-fourths (344,000 t) was new scrap, and the remainder (82,000 t) was old scrap. The main sources for old scrap were brass and bronze scrap, galvanizing residues, die-casting scrap, zinc sheet, and flue dust from steelworking electric arc furnaces (EAF's).

Old scrap was a small part of the supply because many uses of zinc are dissipative, long term, or not conducive to economic collection and recycling. In 1998, about 23 percent of zinc products were made for dissipative uses. The recycling efficiency of old scrap was about 19 percent.

Zinc in low concentrations is generally considered to be nontoxic. Consequently, recycling of zinc is driven primarily by the production cost of primary metal and the price of zinc and only to a lesser extent by environmental considerations. Because of the Government-mandated collection of flue dust, the only old zinc scrap that has an established system for collection and processing is EAF dust.

In recent years, new technology to dezinc galvanized steel has been developed. It should increase the relatively low recycling rate of old zinc scrap. The total zinc scrap recycling rate in 1998 was estimated to be 27 percent, although it may be higher. Future technical and economic developments will increasingly favor the recycling of zinc, thereby enhancing the sustainability of primary zinc production.

INTRODUCTION

The purpose of this report is to show trends in consumption, loss, and recycling of zinc in the United States in 1998 to illustrate the extent to which zinc was recycled (fig. 1, table 1). The flow diagram in figure 1 shows the quantity of zinc present at different stages of recycling and use. As easily minable deposits become exhausted and the costs of primary zinc production and waste disposal increase, the recycling of secondary materials plays an ever-increasing role in the sustainability of natural resources.

BACKGROUND

Zinc is a bluish-white metal with a melting point of about 420°C and a boiling point of 907°C. The low melting point permits low-temperature casting, and the low boiling point is an important factor in purifying the metal by distillation and in producing high-purity metal dust and zinc oxide. Many minerals contain zinc, but sphalerite (zinc sulfide) is by far the most common zinc mineral. Mined ore is usually concentrated to about 55 percent zinc content at the mill and shipped to smelters. Concentrates are reduced to zinc metal by electrolytic deposition from a sulfate solution or by distillation in retorts or furnaces (Jolly, 1992).

Measured in quantity produced, zinc is the fourth most important metal in the world after iron, aluminum, and copper. Although zinc was first produced in China in the 1st century A.D., it was not until the 18th century that it entered commercial production in Europe. In the early years, the principal uses of zinc were in sheet for building applications, in brass, and, to a lesser extent, in hot-dip galvanizing (immersion of steel or iron in molten zinc to form a coating to protect against corrosion).

During the 1930's, the use of zinc alloy castings became increasingly important with the rapid development of mass production, particularly of cars and appliances. By the 1940's, galvanizing became the dominant use (Jolly, 1997, p. 108). In 1998, an estimated 55 percent of zinc metal was used in galvanizing, followed by zinc-based alloys (19 percent) and brass and bronze (13 percent). The pattern of end uses of slab zinc (fig. 2) has a direct effect on the production and consumption of secondary zinc.

GLOBAL SOURCES OF ZINC ORE

Zinc was extracted from 20 mines in 7 States by 8 mining companies in 1998 (Plachy, 2000a). The United States accounted for 10 percent of world production; other leading producers were Australia, Canada, China, and Peru. The Red Dog Mine, which was operated by Cominco Alaska, Inc., produced more than one-half of the U.S. total zinc in concentrate, which amounted to 755,000 t in 1998 (Plachy, 2000b). Since the Red Dog Mine was opened in 1989, U.S. mine production has greatly exceeded the capacity of the three existing U.S. primary smelters, which totaled 234,000 t in 1998.

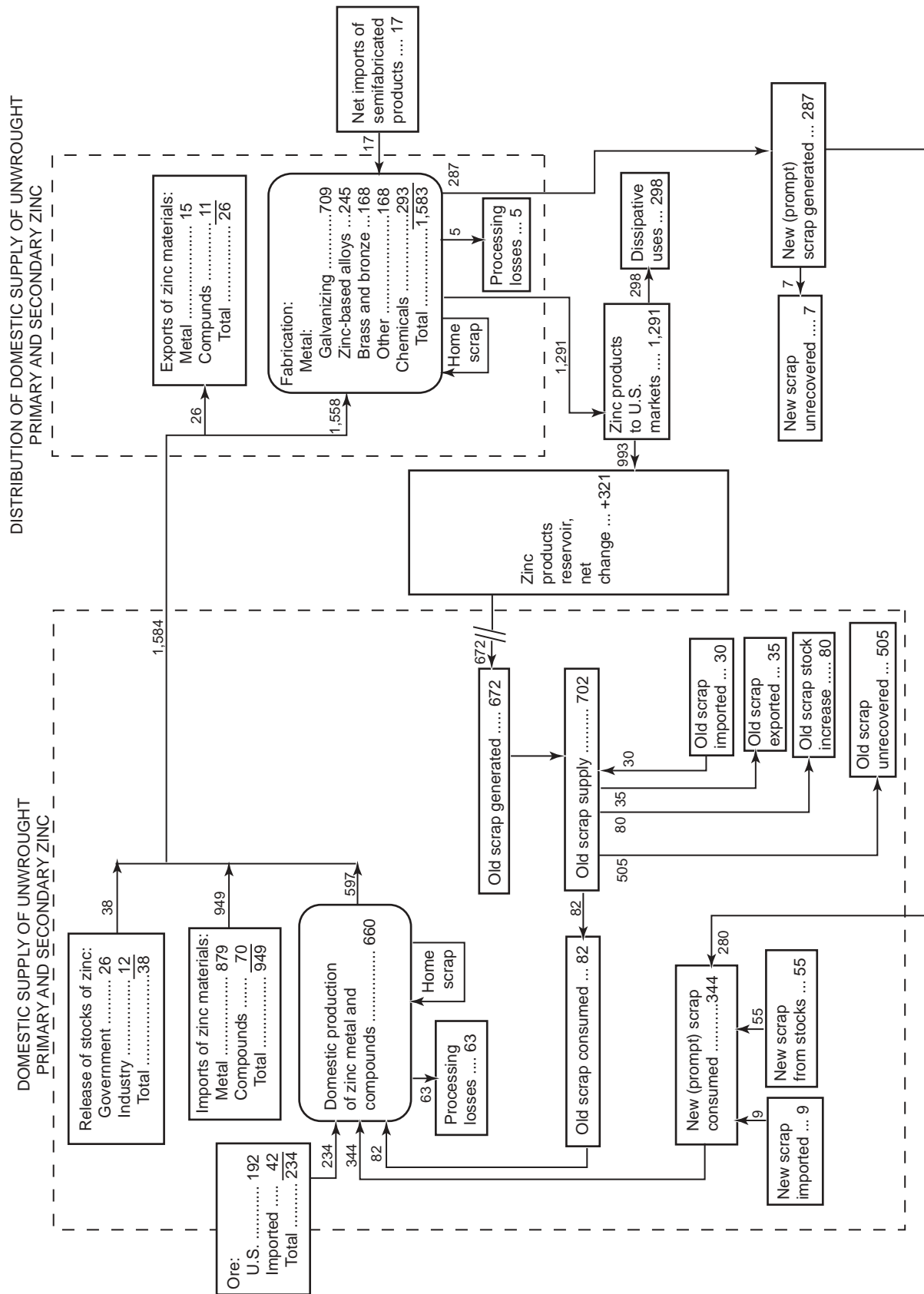


Figure 1. U.S. zinc materials flow in 1998. Values are in thousands of metric tons of contained zinc. Sources of data are described in the section titled "Sources of Zinc Scrap."

Table 1. Salient statistics for U.S. zinc scrap in 1998.

[Values in thousands of metric tons of contained zinc, unless otherwise specified]

Old scrap:	
Generated ¹	672
Consumed ²	82
Value of old scrap consumed ³	\$71 million
Recycling efficiency ⁴	19 percent
Supply ⁵	702
Unrecovered ⁶	505
New scrap consumed ⁷	344
New-to-old-scrap ratio ⁸	81:19
Recycling rate ⁹	27 percent
U.S. net exports of scrap ¹⁰	5
Value of U.S. net exports of scrap ¹¹	\$12 million

¹Zinc content of products theoretically becoming obsolete in the United States in 1998. Total consumption excludes dissipative uses.

²Zinc content of products that were recycled in 1998.

³The value of zinc scrap in 1998 was about \$865/t contained zinc.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁵Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁷Including new (prompt) industrial scrap but excluding home scrap.

⁸Ratio of quantities consumed, in percent.

⁹Fraction of the apparent metal supply that is scrap, on an annual basis.

¹⁰Trade in scrap is assumed to be principally in old scrap. Net exports are exports of old scrap minus imports of old scrap.

SOURCES OF ZINC SCRAP

A small amount of scrap is generated during the production and processing of zinc (new scrap), most of which is easily recovered and recycled. Scrap generated only at the end of the useful life of the product into which it is incorporated (old scrap) is more difficult to recover; consequently, only a small portion is recycled. Until 1993, nearly all zinc used in galvanized steel products was lost either in landfills or in slag at steel scrap processing plants.

In recent years, zinc has been recovered from flue dust, and new technology to dezinc galvanized steel has been developed. This new dezincing process should increase the relatively low recycling rate of old zinc scrap, thereby enhancing the sustainability of primary zinc production. The total zinc scrap recycling rate in 1998 was estimated to have been 27 percent (table 1). The balance of supply was primary material.

Many metallic and virtually all chemical uses of zinc are essentially dissipative. Given the long life cycles for zinc products, a large amount of metallic zinc is still in use. Apart from what is now being recovered, small amounts of zinc-containing objects still end up in slag or landfills, from which an unknown amount of zinc may be leached by acidic water. A much smaller fraction of metallic zinc is vaporized and discharged to the atmosphere.

In 1998, about 426,000 t of zinc scrap was consumed in the United States; more than three-fourths (344,000 t) was new scrap, and the remainder (82,000 t) was old scrap. The value of zinc in recycled scrap (old and new scrap consumed plus old scrap stock increase) was \$437 million in 1998. In 1990, the main sources for secondary zinc were as follows (Pocket Guide to World Zinc, 1996): brass and bronze scrap, 32 percent; galvanizing residues, 23 percent; die-casting scrap, 16 percent; zinc sheet, 10 percent; and flue dust from steelworking electric arc furnaces (EAF's), 8 percent. Percentages were probably similar in 1998. During 1998, about 795,000 t of zinc was unrecovered from old scrap or dissipated. The recycling efficiency of old scrap was about 19 percent (table 1).

Most of the data in figure 1 were collected by the U.S. Geological Survey (USGS). The domestic supply of primary and secondary zinc shown in figure 1 is estimated from monthly and annual USGS surveys of domestic producers, data on sales from the U.S. Government's National Defense Stockpile, import/export data compiled by the U.S. Census Bureau, and reported changes in producer, consumer, and merchant stocks. Reporting by producers and consumers of zinc is voluntary.

The three largest secondary zinc producers do not report consumption of secondary zinc. Consequently, data concerning fabrication, production, and consumption of new and old scrap are mostly estimates based on survey forms compiled by the USGS and various studies carried out by individuals and organizations, such as the International Lead and Zinc Study Group. The 27-percent recycling rate shown in table 1 may actually have been much higher. According to IMCO Recycling, Inc. (1999), the world's largest zinc recycler, the recycling rate for zinc in the United States could have been as high as 38 percent.

DISPOSITION OF ZINC SCRAP

Zinc in low concentrations is generally considered to be a nontoxic material. Consequently, recycling of zinc is driven primarily by the production cost of primary metal and the price of zinc and only to a lesser extent by environmental considerations. Because of the Government-mandated collection of flue dust, the only secondary zinc that has an established system for collection and processing is EAF dust. Collection of other zinc scrap is done by either public organizations or private companies.

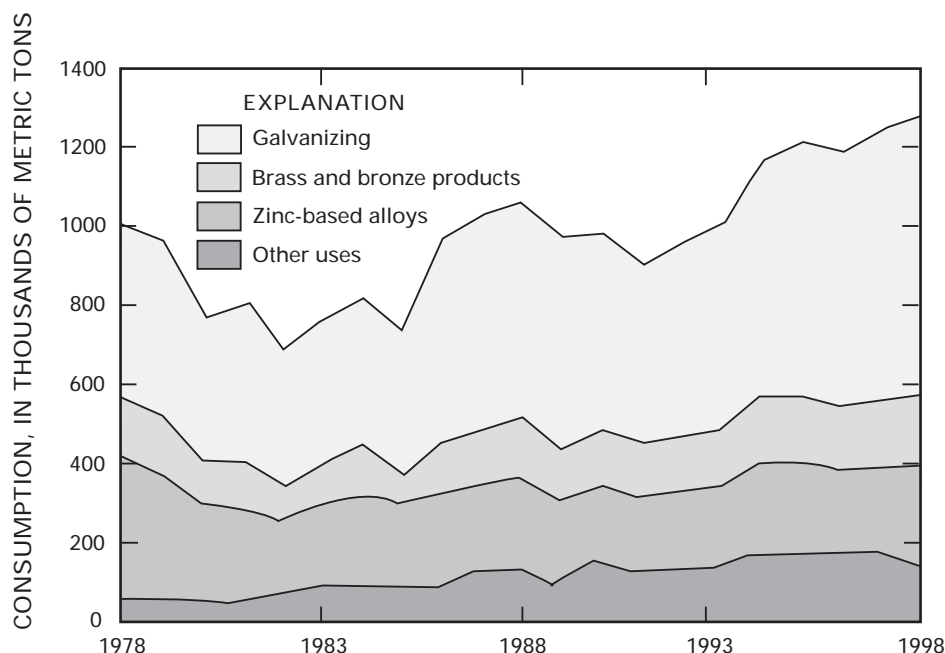


Figure 2. U.S. slab zinc consumption by end-use sector from 1978 through 1998.

OLD SCRAP

Old scrap consists of used zinc products in the form of zinc metal or alloys, which have been discarded because of wear, damage, or obsolescence. This category includes die-castings, automobile shredder scrap, engraver plates, brass and bronze products, rolled zinc from roofing and gutters, dust and sludges from ironmaking and steelmaking, and contaminated waste solutions (mine waste, rinse effluents, waste plating solutions, and contaminated surface waters). In the past, the types of old scrap that were processed were limited by the ease of collection and the narrow range of composition. Therefore, only small amounts of old scrap were recycled.

Environmental mandates that were passed in the 1980's broadened the types of old scrap collected by the recyclers by adding effluent zinc from recycling of galvanized steel scrap and zinc recovered from burning rubber tires. Despite Government-mandated efforts to protect the environment, only about 12 percent of the total zinc consumption in the United States was derived from old scrap in 1998. Old scrap was a small part of the supply because many uses of zinc are dissipative, long term, or not conducive to economic collection and recycling. In 1998, about 23 percent of zinc products were made for dissipative uses; dissipation can be either rapid (fertilizers, animal feed, fungicides, pharmaceuticals) or long term (corrosion of galvanized surfaces, rubber tire abrasion, flaking paint). Large amounts of zinc products are still in circulation because their usefulness may last 100 years. These products include zinc used in galvanizing and, in smaller quantities, in zinc-based alloys, brass, and bronze. About

68 percent of U.S. zinc products made in 1998 will eventually be available as old scrap, but only a small portion of them will be recycled.

NEW SCRAP

New or prompt scrap is defined as that generated in manufacturing processes and consumed at plants other than where generated. Although the amount of new zinc scrap generated, which is estimated to have been 287,000 t in 1998, is much smaller than the amount of old scrap generated (672,000 t), it constitutes more than three-fourths of consumed recycled zinc. Most of the new scrap is produced during fabrication before it becomes part of a product; therefore, it is easily collected for recycling. New scrap consists mostly of galvanizing residues that comprise a wide range of different materials, including ashes, flux residues, and top and bottom drosses; all have a very high content of zinc metal (Radiant Corp., 1976, p. 182).

OLD SCRAP RECYCLING EFFICIENCY

The recycling efficiency of old zinc scrap for 1998 in the United States is estimated at 19 percent; compared with the recycling efficiency of other metals, that of zinc is very low because nearly all chemical uses of zinc are virtually dissipative and because galvanized products have long life cycles before the zinc can be recovered. Like zinc alloys, including brass and bronze, galvanized steel is potentially a large source of secondary zinc. Because zinc is not a toxic metal, the increased recycling efficiency of zinc depends more on improving the technology to dezinc galvanized steel than on environmental protection requirements.

INFRASTRUCTURE OF ZINC SCRAP

Although the exact number of recycling facilities is not known, the zinc recycling industry is dominated by IMCO Recycling, Inc., and Zinc Corporation of America. Together, they treated nearly three-fourths of all U.S. secondary zinc in 1998. Most of the recycling plants were in Michigan, Pennsylvania, Tennessee, and Texas.

Because most zinc metal is used for corrosion protection of iron and steel, the largest portion of recycled zinc is supplied by steel industries either as galvanizing residues or as flue dust. Galvanizing residues contain between 90 and 95 percent zinc and 5–10 percent other metals. Depending on the steel type and the galvanizing process, between 10 and 40 percent of the total zinc consumed ends up in residues. Zinc, which is metallurgically combined with steel during galvanizing, cannot be easily separated from galvanized steel scrap. It is usually recovered from flue dust generated during reprocessing of steel scrap. This dust contains an average of 20 percent zinc, which is generally recovered as crude zinc oxide for zinc metal production.

Because the largest consumer of zinc is the steel industry, the largest consumers of galvanizing residues and flue dust are located near large steelworks. Collection of secondary zinc is usually based on long-term agreements between steel producers and secondary zinc consumers.

As is the case with galvanized steel, zinc die-cast components enter the recycling stream as a function of the number and type of products used. Old die-cast components provide high metal recovery, but the recovery of the products in which they are contained is typically low.

About one-third of U.S. consumption of zinc in 1998 came from domestic primary and secondary production. The balance was supplied by imports, mostly from Canada. Trade in zinc scrap was relatively small compared with trade in zinc concentrate and zinc metal. Most of the zinc scrap exports were shipped to Asia, primarily to Taiwan. In 1998, more than 90 percent of scrap imports came from Canada.

PROCESSING OF ZINC SCRAP

Zinc can be recycled again and again without loss of its original properties. Its low melting and boiling points make zinc relatively easy to recycle. The main sources for secondary zinc, listed in decreasing order of use, are brass and bronze scrap, galvanizing residues, die-casting scrap, zinc sheets, and flue dust from steelworking electric arc furnaces (EAF's). Processing methods for these scrap materials are described below, as is a new dezincing process that should increase the recycling of galvanized steel scrap.

BRASS AND BRONZE SCRAP

With its high value and high copper content, brass and bronze scrap is recycled almost exclusively by the brass and copper industries. Effectively, this means that zinc used in brass leaves the zinc recycling circuit and is completely recycled within the brass/copper circuit. However, it is included in the materials flow depicted in figure 1. "It is a common practice to boil secondary zinc alloys [in muffle furnaces or retorts] and evaporate zinc away from the alloying elements" (Schau, no date). The zinc vapor can be purified in a distillation column to produce refined zinc metal.

GALVANIZING RESIDUES

Because of environmental restrictions and the high content of entrained zinc metal, galvanizing residues (which comprise top and bottom drosses, skimmings, and ashes) are the second most commonly recycled zinc scrap. Most galvanizing residues are cast into slabs as discussed below, but some other processing methods are used.

Combining drosses with fluxes.—Galvanizers' drosses are metallic alloys of iron and zinc plus some unalloyed zinc and other metals, mainly aluminum, lead, and tin. The bottom dross consists mainly of iron and zinc. Because it is heavier than the molten zinc, it sinks to the bottom of the galvanizing pots. The light, top dross contains primarily zinc and aluminum with small amounts of iron, lead, and tin. Both these drosses can react with various fluxes to release the entrapped metallic zinc, which is cast into slabs for subsequent use by secondary zinc smelters.

Treating skimmings and ashes.—Skimmings and ashes are formed by oxidation on the surface of galvanizing baths when no flux is used. High-grade skims are used directly by secondary producers. Medium- and low-grade skims generally undergo an intermediate reduction-distillation-pyrometallurgical step to upgrade the zinc content before treatment, or they are leached with acid, alkaline, or ammoniacal solution to extract zinc, which is subsequently recovered as a compound by crystallization or as a salable chemical product retained in solution.

Casting galvanizing residues into slabs.—Most of the galvanizing residues are cast into slabs and fed into furnaces that are stationary, horizontal, or tilted. Most of the furnaces are fired with either natural gas or oil. Feed is placed in a retort through which a flame passes and heats up the charge to the boiling point. The fumes pass through the neck of the retort into a condenser, where they are cooled to form either metal or dust, depending on the type of condenser. Recovery efficiency is very high from simple remelting but declines as the number of processing steps increases (Edwards, 1977, p. 5).

DIE-CASTING SCRAP

New die-casting scrap is recycled directly and qualifies as home scrap. Old scrap, which includes, in particular, that from shredding of cars and domestic appliances, can be used in the production of zinc dust and zinc oxide and as a feedstock for smelters.

ZINC SHEETS

Zinc sheets are generally old scrap from roofs, cladding, gutters, and downspouts, together with some "cut-offs" from the use of new sheet. This material is the most sought after by zinc recyclers, because it can be readily used by secondary or primary zinc producers.

EAF DUST

The use of zinc for galvanizing has grown very substantially in the last 40 years, but owing to the long life of galvanized products, this source has only recently appeared in substantial quantities as scrap. After reauthorization of the Resource Conservation and Recovery Act in 1984, which substantially raised the disposal cost of EAF dust, the recycling of EAF dust is estimated to have increased to about 75 percent in 1998 from 30 percent in 1984. Inclusion of EAF dust in the hazardous waste list created a market for approximately 500,000 t per year of flue dust (Consolidated Materials Brokers, L.L.C., 1998). Zinc content ranges from about 5 percent to nearly 40 percent zinc (average about 20 percent), and the dust contains small amounts of hazardous constituents, including cadmium, chromium, and lead.

The first treatment of flue dust is usually carried out close to secondary steel plants. The predominant technology used for the recovery of zinc from EAF dust is the Waelz kiln process. The EAF dust is mixed with coal and flux and fed to the kiln, where materials roll along the inside slope. Occasionally, energy provided by coal combustion is supplemented by natural gas or oil combustion via a burner at the discharge end of the kiln. The feed is reducing and oxidizing simultaneously in the kiln, thus generating two marketable products—a mixed zinc/lead oxide and an inert iron-rich slag. Most of the crude zinc/lead oxide, which contains about 55 percent zinc, is reused by the Zinc Corporation of America at its Monaca, Pa., plant for production of zinc metal and refined oxide. Slag, which contains between 30 and 35 percent iron, is sold as road base, anti-skid agent, portland cement additive, and an aggregate in highway blacktop (Kern and Mahler, 1987, p. 8).

GALVANIZED STEEL SCRAP

Metal Recovery Technologies, Inc., installed a pilot plant in East Chicago, Ind., that converted galvanized steel

scrap into clean scrap for steelmaking and zinc solution. The new process used in this plant consisted of dissolving the zinc coating from scrap in a hot, caustic solution and recovering the zinc from the solution electrolytically. Because the electrolyte was reused, waste was minimal compared with waste caused by processing of flue dust (Argonne National Laboratory, Transportation Technology Research and Development Center, 1998).

OUTLOOK

The changes in end-use patterns of zinc and the overall increase in consumption mean that considerably increased amounts of zinc will be available for recycling, despite the long lifetime of zinc products. As with other materials, future technical and economic developments, such as efficient separation of zinc from galvanized steel, will increasingly favor the recycling of zinc.

Environmental considerations, technological advances, and the economics of primary and secondary production are the major reasons for increased recycling of all metals. In the past, only new zinc scrap was recycled. As time progressed, old scrap was recycled, and old scrap recycling efficiency began to increase. Although zinc is not a hazardous material, high concentrations of it could harm the environment. The nature of the principal uses of zinc and established recycling circuits, however, ensure that zinc is rarely an environmental threat.

Past patterns of use indicate that increasing amounts of zinc will be used for galvanizing. Therefore, the development of economically efficient recycling of galvanized scrap should increase the recycling rate of old scrap. With the growing availability of valuable secondary materials and increased efficiency of zinc recovery, the amount of zinc coming from secondary sources should increase steadily. An increase or decrease of recycling capacity will depend mainly on the relative cost of recycling and changes in regulations governing disposal of secondary zinc.

The recycling rate of zinc, however, will probably not approach that of some of the other major metals because many uses of zinc are dissipative or nonrecoverable. For example, zinc used in fertilizers or animal feed is essentially unrecoverable, and zinc in paints or in rubber products has, at best, only limited recoverability (Munford, 1998).

Despite a relatively low recycling rate, the recycling industry enhances the sustainability of zinc production by reducing the need for primary production, thereby saving energy and extending the longevity of natural resources.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

brass. An alloy of copper and zinc that may contain other elements such as aluminum, iron, manganese, nickel, tin, and lead.

bronze. An alloy of copper and tin that may contain other elements such as aluminum, silicon, and zinc.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

hot-dip galvanizing. Immersion of steel or iron in molten zinc to form a coating to protect against corrosion.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as post-consumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Based on the unit value of zinc in materials.

primary zinc. Zinc derived from ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary zinc. Zinc derived from or contained in scrap.

slab zinc. A general term for commercial zinc cast in various shapes and sizes.

U.S. Department of the Interior
U.S. Geological Survey

Magnesium Recycling in the United States in 1998

By Deborah A. Kramer

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-E

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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CONVERSION FACTORS

	Multiply	By	To obtain
metric ton (t, 1,000 kg)		1.102	short ton (2,000 pounds)
million metric tons (Mt)		1,102,000	short ton

For temperature conversions from degrees Celsius ($^{\circ}\text{C}$) to degrees Fahrenheit ($^{\circ}\text{F}$), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Magnesium Recycling in the United States in 1998

By Deborah A. Kramer

ABSTRACT

As concern for the environment has grown in recent years, the importance of recycling has become more evident. The more materials that are recycled, the fewer natural resources will be consumed and the fewer waste products will end up in landfills, the water, and the air. As one of a series of reports on metals recycling, this report discusses the 1998 flow of magnesium in the United States from extraction through its uses with particular emphasis on recycling. In 1998, the recycling efficiency for magnesium was estimated to be 33 percent—almost 60 percent of the magnesium that was recycled came from new scrap, primarily waste from die-casting operations. The principal source of old scrap was recycled aluminum beverage cans.

INTRODUCTION

Figure 1 and table 1 provide a snapshot of the U.S. magnesium recycling industry in 1998. This materials flow study shows the extent of magnesium recycling and identifies the consumption, losses, and trends in the U.S. secondary magnesium industry. In 1998, approximately 33 percent of the magnesium consumed in the United States came from recycled magnesium; almost 60 percent of this recycled magnesium was derived from new scrap.

GLOBAL GEOLOGIC OCCURRENCE OF MAGNESIUM

Magnesium is the eighth most abundant element and constitutes about 2 percent of the Earth's crust. It is the third most plentiful element dissolved in seawater with a concentration that averages 0.13 percent. Although magnesium is found in more than 60 minerals, only brucite, carnallite, dolomite, magnesite, and olivine are of commercial importance. Magnesium metal is produced from seawater, well and lake brines, and bitters, as well as from the minerals carnallite, dolomite, and magnesite (Bodenlos and Thayer, 1973).

Primary magnesium is produced in Brazil, Canada, China, France, India, Israel, Kazakhstan, Norway, Russia, Serbia and Montenegro, Ukraine, and the United States. In the study year, 1998, primary magnesium was produced in

the United States by three companies—Dow Chemical Co., Freeport, Tex., Magnesium Corp. of America (MagCorp), Rowley, Utah, and Northwest Alloys Inc., which is a subsidiary of Alcoa Inc., Addy, Wash. Dow closed its magnesium operation in November 1998.

PRODUCTION TECHNOLOGY

Magnesium is manufactured by two methods—thermic reduction of dolomite or electrolytic reduction of magnesium chloride. Two thermic processes are in use to recover magnesium metal from dolomite—the Pidgeon and the Magnetherm. Although both use the same basic chemistry, the Pidgeon process uses an external heat source, and the Magnetherm process uses heat generated by the electrical resistance of the reactants. In the Pidgeon process, dolomite and ferrosilicon are formed into briquettes and heated in a retort under a vacuum. Magnesium oxide in the dolomite reacts with the ferrosilicon to produce magnesium vapor, which is cooled, condensed, and collected in a separate section of the retort. In the Magnetherm process, calcined dolomite, ferrosilicon, and alumina are heated under a vacuum. Alumina reduces the melting point of the slag produced by the dolomite-ferrosilicon reaction to make resistance heating practical. Magnesium vapor is cooled and condensed in a condensing chamber.

Electrolytic recovery of magnesium requires a magnesium chloride feedstock that normally is prepared from seawater or brines. Two types of magnesium chloride can be made—hydrous and anhydrous. In the preparation of hydrous magnesium chloride, which was used by Dow until 1998, magnesium hydroxide is precipitated from seawater by the addition of dolomitic limestone. Adding hydrochloric acid to the magnesium hydroxide produces a neutralized magnesium chloride solution. This solution is dehydrated until it contains about 25 percent water and then is fed directly to electrolytic cells.

MagCorp uses an anhydrous magnesium chloride feed for their electrolytic cells. Solar evaporation initially concentrates the magnesium chloride brines from the Great Salt Lake. After adding calcium chloride to precipitate sulfate impurities and removing boron by solvent extraction, the brine is concentrated further and dehydrated in a spray

DISTRIBUTION OF DOMESTIC SUPPLY OF UNWROUGHT PRIMARY AND SECONDARY MAGNESIUM

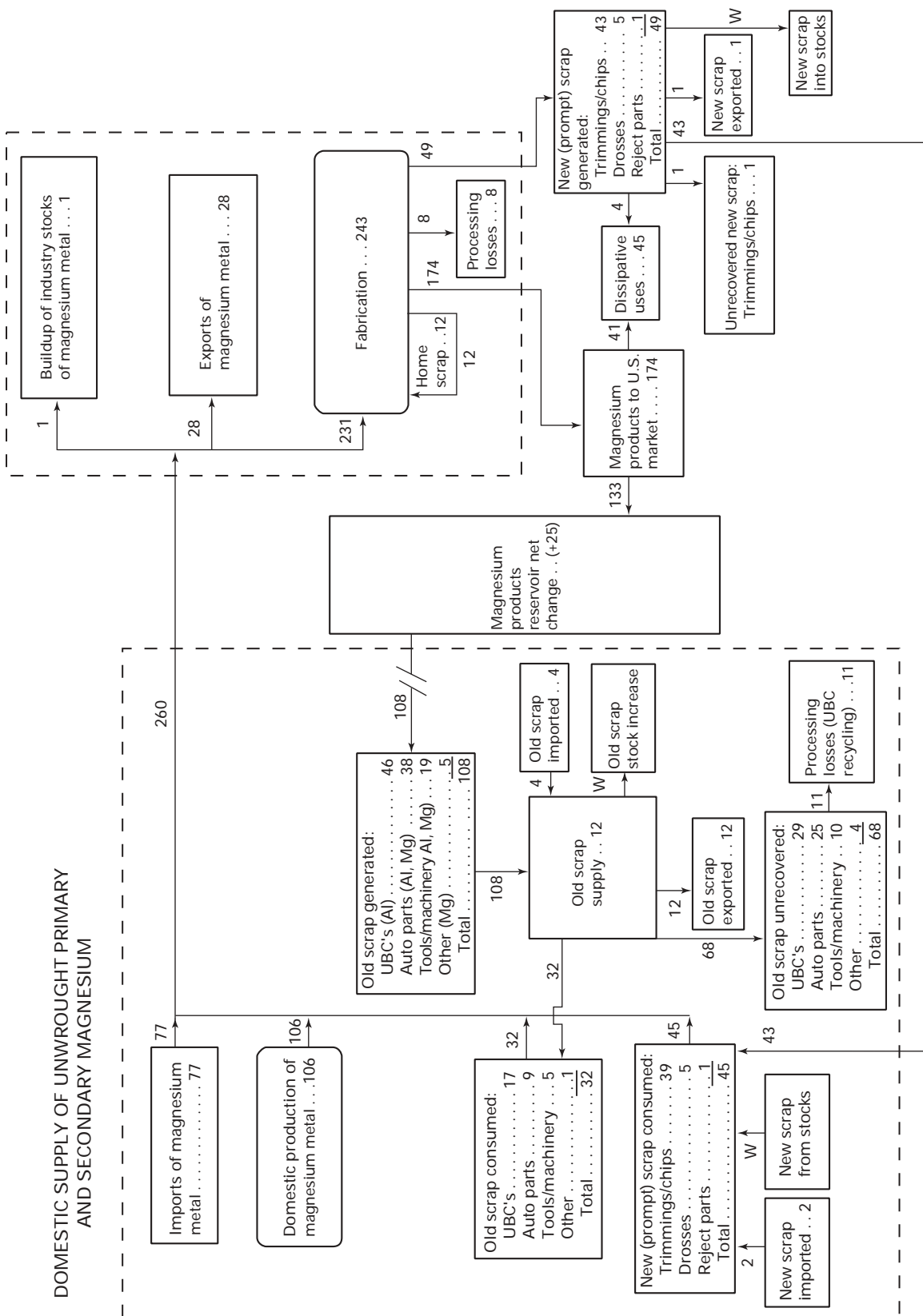


Figure 1. Magnesium recycling flow, 1998, in thousand metric tons contained magnesium. W, withheld to avoid disclosing company proprietary data; UBC is , used beverage cans.

Table 1. Salient statistics for U.S. magnesium scrap in 1998.
[Values in thousands of metric tons of contained magnesium,
unless otherwise specified]

Old scrap:	
Generated ¹	108
Consumed ²	31.8
Value of old scrap consumed	\$72.1 million
Recycling efficiency ³	39 percent
Supply ⁴	112
Unrecovered ⁵	68.2
New scrap consumed ⁶	44.6
New-to-old-scrap ratio ⁷	58:42
Recycling rate ⁸	33 percent
U.S. net exports of scrap ⁹	7.5
Value of U.S. net exports of scrap	\$22.2 million

¹Magnesium content of products theoretically becoming obsolete in the United States in 1998. It excludes dissipative uses.

²Magnesium content of products that were recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported). Changes in stocks of old scrap are withheld and not included.

⁴Old scrap generated plus old scrap imported.

⁵Old scrap supply minus old scrap consumed minus old scrap exported.

⁶Including new (prompt) industrial scrap, but excluding home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of the apparent magnesium supply that is scrap, on an annual basis.

⁹On the basis of average value in 1998, trade in scrap is assumed to be principally old scrap.

dryer. The resulting powder is purified, concentrated, prilled, and dehydrated to produce anhydrous magnesium chloride (Kaplan, 1990).

Electrolytic cells used to recover magnesium from either hydrous or anhydrous magnesium chloride differ from company to company, and most information about cell design and operating conditions usually is not disclosed. Essentially, magnesium chloride fed to an electrolytic cell is broken down into magnesium metal and chlorine gas by direct current at 700°C. Graphite electrodes suspended in the bath serve as anodes, and steel rods serve as cathodes. Several cell designs are used for producing magnesium that differ in electrode positioning and use of a diaphragm for separating the electrodes (Strelets, 1977, p. 250-264). After the current breaks down the magnesium chloride into chlorine gas and molten magnesium, the metal formed at the cathode rises to the surface of the bath where it is guided into storage wells. Metal is dipped from the wells and cast into pigs. Chlorine and hydrogen chloride gases generated at the anodes are collected from the tightly closed cell and pumped to a hydrochloric acid plant for recycling or to a plant for separating the chlorine and hydrogen chloride.

Although not yet in commercial operation, one plant in Canada, which was scheduled to open in 2001, is planning to use tailings from an asbestos mine that contain serpentinite as a raw material for magnesium metal. Recovery technology involves leaching the material, removing the impurities in several steps, and recovering magnesium by electrolysis (Brown, 1998.)

Magnesium is also recovered by recycling magnesium chloride produced in the manufacture of titanium. Titanium is recovered from titanium tetrachloride (TiCl₄) by the Kroll process, in which magnesium is used as a reducing agent. This reaction produces a pure anhydrous magnesium chloride that can then be fed to an electrolytic cell to convert it back to magnesium metal. Electrolytic cells have been developed to take advantage of this type of feed. Chlorine generated during the magnesium reduction is recycled to prepare another batch of titanium tetrachloride.

USES

The largest use of magnesium metal is as an alloying addition to aluminum to increase the hardness and corrosion resistance of the pure metal. The 5000 and 7000 series alloys of aluminum contain up to 5.5 percent and 3.5 percent magnesium, respectively. The single largest application for magnesium-containing alloys of aluminum is the aluminum beverage can, which has a magnesium content of about 4.5 percent in the lid (alloy 5181 or 5182) and about 1.1 percent in the can body (alloy 3004). Since the early 1980's, magnesium consumption in this market has grown at an average compound annual rate of 3.2 percent. If it were not for significant increases in aluminum recycling, which lower the quantity of primary magnesium needed, this rate might have been greater. More than 60 percent of aluminum beverage cans are recycled annually, which conserves the aluminum and magnesium contents of the alloys as well as the energy required to produce them (Sirdeshpande, 1990).

Magnesium and its alloys have structural uses in the forms of die-castings, gravity (sand and permanent mold) castings, and wrought products. Die-castings are the largest structural application for magnesium. U.S. automakers have recently introduced such magnesium components as clutch housings, headlamp assemblies, grille covers, instrument panels, and seat components to reduce vehicular weight. The power tool market includes magnesium castings in chain saws and lawnmower housings. Die-cast magnesium also is used in cellular phone, computer, and video camera components.

The low density of magnesium is especially important for gravity-cast military and aerospace applications. Gravity castings are essentially all produced as sand castings; permanent mold and plaster casting represent a small segment of the alloy market. Typical applications include air intakes, aircraft canopy frames, auxiliary component housings, engine frames, helicopter gear housings, and speed brakes.

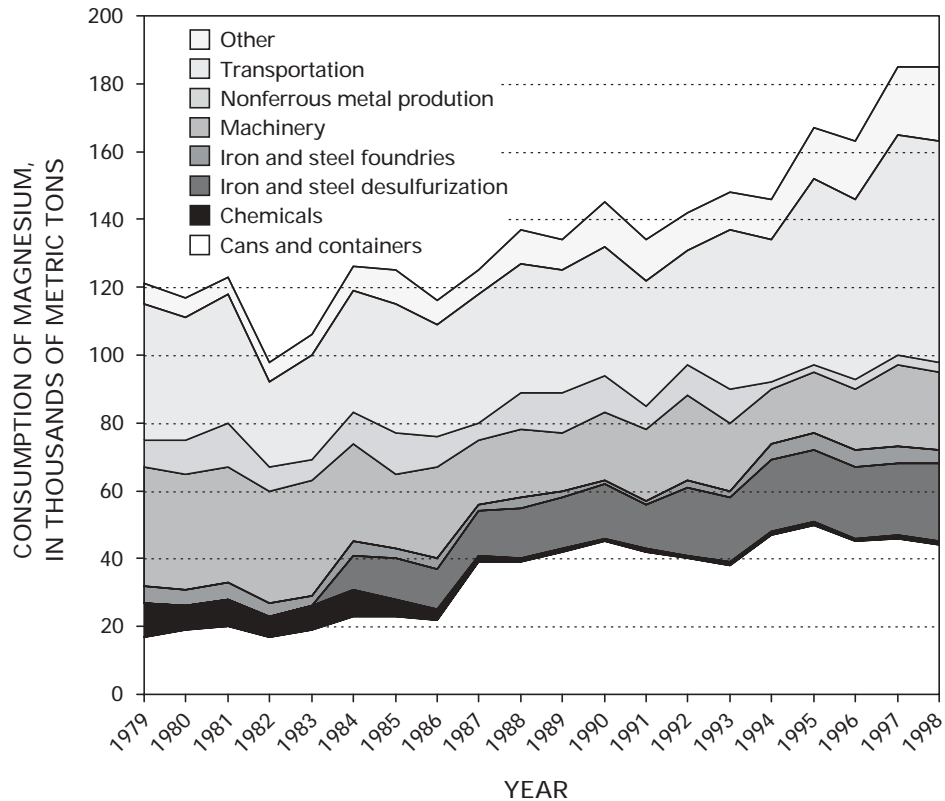


Figure 2. U.S. magnesium end-use patterns from 1978 through 1998.

Magnesium is also used in wrought form in such products as extrusions, forgings, sheet, and plate. Applications for these products range from bakery racks, hand trucks, loading ramps, and tennis rackets to aerospace assemblies, computer printer platens, concrete finishing tools, and nuclear fuel element containers.

In the iron and steel industry, magnesium is used as an external hot-metal desulfurization agent and in the production of nodular iron. Magnesium's unique affinity for sulfur allows it to be injected into molten iron, where it vaporizes and reacts to form magnesium sulfide, which floats to the surface as a readily separated phase. This affinity allows the steel producer the flexibility to use lower cost raw materials while maintaining the ability to produce the high-quality, low-sulfur product required for high-strength, low-alloy steels. The magnesium used is often derived from low-quality streams or alloy scrap, which is then ground into a coarse powder and combined with lime prior to injection in the hot metal. Lime blends have been found to provide significantly improved efficiencies based on the magnesium required.

Magnesium, in combination with ferrosilicon, is used in the production of ductile (nodular) iron because of the ability of magnesium to promote the formation of spherical (globular) graphite particles in place of the normal flake structure. This results in an iron product that has improved toughness and ductility. Two principal applications for duc-

tile iron are in the production of pipe and automotive engine and drive train components.

Magnesium is used as a catalyst for producing certain organic chemicals and petrochemicals and as a reducing agent for producing other nonferrous metals, such as beryllium, hafnium, titanium, uranium, and zirconium. Anodes of magnesium are frequently used for the cathodic protection of iron and steel, particularly in underground pipe and water tanks, as well as water heaters and marine applications. Magnesium also has smaller applications in the graphic arts (as photoengraving plates), pyrotechnics, and alloys other than aluminum.

Data for magnesium metal consumption are reported to the U.S. Geological Survey (USGS) from an annual canvass of magnesium consumers in the categories that are detailed above. These data then are extrapolated to derive end-use consumption patterns. According to extrapolations of these data by the USGS, the consumption pattern for magnesium metal in 1998 in the United States was transportation, 35 percent; cans and containers, 24 percent; iron and steel desulfurization, 13 percent; machinery, 12 percent; iron and steel foundries for nodular iron, 2 percent; nonferrous metal production, 1.5 percent; chemicals, 0.5 percent; and other uses, 12 percent. Figure 2 shows magnesium end-use data for a 20-year period.

Because of the types of applications for magnesium, it is primarily used in developed nations. According to data

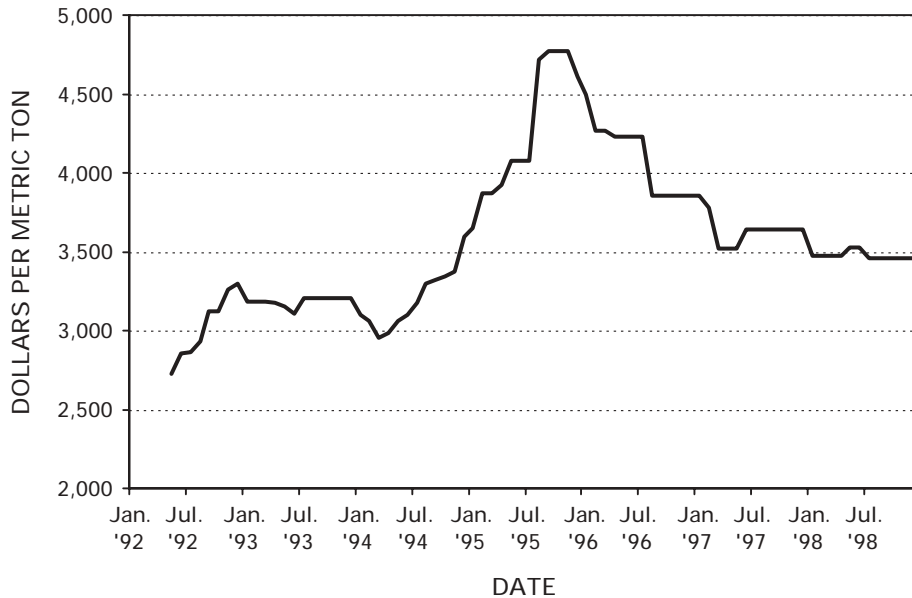


Figure 3. Average U.S. spot Western magnesium prices. (Source: Platt's Metals Week.)

published by the International Magnesium Association (1999) that detail world magnesium shipments by geographic area (excluding China and countries formed from the former Soviet Union), most magnesium was consumed in North America (58 percent) and Europe (27 percent) in 1998. Magnesium consumption in aluminum alloying and die-casting, which are the two principal end uses in all geographic areas, is about even in North America and Europe, and aluminum alloying dominates in Asia and Africa (greater than 70 percent). In South America, die-casting shipments are slightly larger than those for aluminum alloying, although this geographic area does not represent significant magnesium consumption.

PRICES

During 1998, the average U.S. spot Western price did not fluctuate significantly and was \$1.57 per pound at yearend. The price was at its highest level at the beginning of the year at \$1.65 per pound and dropped slightly throughout 1998. Figure 3 shows the trends in magnesium prices from 1992 through 1998.

The sharp increase in the magnesium price from 1994 through 1995 was caused by the institution of an investigation of magnesium dumping from China, Russia, and Ukraine, which stopped imports of magnesium from these countries into the United States during the investigation. Imports of magnesium from Canada already had been eliminated by the imposition of antidumping and countervailing duties in 1992. As demand increased during this time, the largest sources of imported magnesium were cut off, which led to a significant run-up in prices. At its highest level from September to November 1995, the magnesium price climbed to about \$2.17 per pound. Final

antidumping determinations for magnesium from China, Russia, and Ukraine were set in April 1995. Because the antidumping duty on Russian magnesium was established at 0 percent for all the large producers (as long as they imported the magnesium through specified importing companies), magnesium could again be imported from Russia, which had been the United States' largest magnesium supplier; as a result, prices declined sharply (Kramer, 1999).

SOURCES OF MAGNESIUM SCRAP

New magnesium-base scrap typically is categorized into one of four types. Type I is high-grade scrap, generally material such as gates, runners, and drippings from die-casting operations that is uncontaminated with oils. Types II, III, and IV are lower graded materials. Type II is oil-contaminated scrap, type III is dross from magnesium-processing operations, and type IV is chips and fines. The most desirable type of scrap is type I. Most of the type I scrap is generated during die-casting of magnesium alloys. This scrap is either reprocessed at the die-casting facility or sold to a scrap processor. The other types of scrap either are sold to a scrap processor or are used directly in steel desulfurization, which is a dissipative application.

Old magnesium-base scrap, or postconsumer scrap, consists of such material as automotive parts, helicopter parts, lawnmower decks, used tools, and the like. This scrap is sold to scrap processors.

In addition to magnesium-base scrap, significant quantities of magnesium are contained in aluminum alloys that also can be recycled. Although some magnesium is lost in scrap processing, a significant quantity of the magnesium is

recycled with the aluminum alloy. New aluminum-base scrap that is recycled consists, in descending order of importance, primarily of solids, borings and turnings, dross and skimmings, and other material, which includes foil and can-stock clippings. Because the main aluminum product that contains magnesium is beverage cans, the principal magnesium-containing aluminum-base scrap is can scrap skeleton from lids and can sheet clippings. This represents about one-half of the overall magnesium-containing aluminum-base scrap.

Old aluminum-base scrap consists of a variety of materials, but the most important magnesium-containing component is used aluminum beverage cans (UBC's). Because of the high recycling rate (about 63 percent in 1998), UBC's represent about three-quarters of the magnesium-containing, old aluminum-base scrap that is reprocessed. The magnesium in old and new aluminum-base scrap is not separated from the aluminum alloy when it is recycled; rather, it is retained as an alloying component. Therefore, the magnesium recycling industry consists of three main components—old and new magnesium-base scrap, UBC's, and new aluminum-base scrap. In some cases, the new and old aluminum-base scraps are recycled together, but for this analysis, they are considered separately.

Table 1 is the basis for the data shown in figure 1. Definitions of the terms used in the table are detailed in the appendix. Data on old and new magnesium-base scrap consumed are reported to the USGS annually by the magnesium consumers and are published in the USGS Minerals Yearbook series. Data on old and new aluminum-base scrap are reported to the USGS by means of a monthly survey of aluminum-scrap-processing firms; various factors are applied to the aluminum scrap to estimate the magnesium content. Trade data for magnesium waste and scrap are collected by the U.S. Census Bureau and reported in the Minerals Yearbook series.

To determine the quantity of old scrap available to be recycled, data for old scrap generated are estimated by determining the lifetimes of various magnesium-containing products, combined with the end-use data, and estimated for the year that the product was produced. For example, the average life of a magnesium-containing automobile component was estimated to be 10 years. Because the magnesium consumed in transportation was determined to be 36,000 metric tons (t) in 1989 (10 years prior to the study period of 1998), this is the quantity of material that is included in the "old scrap generated" figure, which includes magnesium contained in the magnesium- and aluminum-base alloys that are used in transportation. The average life of an aluminum beverage can is less than 1 year, so the quantity of magnesium used in beverage cans in 1997 (46,000 t) was estimated to be the quantity of old scrap generated. For machinery and tools, the lifetime is estimated to be 10 years; so the quantity of old scrap generated was estimated to be the quantity used in 1989, or 17,000 t. The "other" shown in fig-

ure 1 is material such as computer parts, magnesium engraving plates, and sporting goods. An estimated 5-year life was assumed for these products; these types of products also were assumed to represent about one-half of the total "other" end uses. Therefore, the quantity of these materials that were estimated to be available for recycling was one-half the "other" end use in 1994, or about 5,000 t.

DISPOSITION OF MAGNESIUM SCRAP

Old scrap consists of magnesium-containing products that have been discarded or have become obsolete. About 42 percent of old magnesium scrap generated is from UBC's (fig. 1). UBC's consist of aluminum alloys in which the magnesium is recycled along with the aluminum content. The second largest source of old magnesium scrap (35 percent of the total) is automobile components. These consist of magnesium- and aluminum-base alloys. As with UBC's, the magnesium content is recycled along with the aluminum content of the aluminum alloys. The magnesium-base scrap is recycled separately. Of the old scrap that was available for recycling in 1998, about 63 percent of the magnesium was unrecovered and probably ended up in landfills. A significant portion of the magnesium in aluminum-base scrap was lost to the environment, most probably in landfills as well, during processing.

RECYCLING EFFICIENCY

As shown in table 1, 39 percent of the old magnesium scrap generated is recycled, much of which comes from recycling UBC's. UBC's have a well-established collection mechanism that reaches directly to the consumer; many municipalities collect cans at the curbside, thus making recycling convenient. Making recycling easy for the consumer generally results in a high recycling rate; the UBC recycling rate in 1998 was 62.8 percent (Aluminum Association Inc., 1999a). Many of the magnesium components that are not recycled, however, are not recycled because they are used in consumer goods that do not have a well-established recycling collection mechanism. Many items, such as hand tools, are discarded in landfills when they become unusable. If the magnesium component is part of a larger item, such as an automobile, the magnesium part may not be separated when the item is recycled because it represents an insignificant portion of the total weight; therefore, the magnesium content generally is not recovered during the recycling process. The magnesium may be oxidized and become entrapped in the fines or dross from recycling and may be discarded.

Of the total magnesium supply in 1998, about 33 percent came from recycled new and old scrap. Although this rate was lower than that for such materials as iron and steel and lead, it is comparable to those of copper and nickel (Papp, 1999, p. 62.14-62.15). One factor that has a significant effect on the overall recycling rate is the quantity of

magnesium that is used in dissipative applications, which are defined as uses in which the metal is dispersed or scattered, thus making it exceptionally difficult and costly to recycle. Approximately 25 percent of the magnesium that was consumed in 1998 was used in dissipative applications, which included, in descending order of importance, iron and steel desulfurization, sacrificial anodes, chemical manufacture, and nodular iron. Inclusion of the magnesium used in these types of applications in the overall magnesium supply makes the magnesium recycling rate appear to be artificially low.

The recycling of the magnesium content in aluminum alloys is not likely to increase significantly unless more communities introduce curbside recycling programs. As the magnesium content of automobiles increases and magnesium is used in larger parts, these components will be easier to separate from the junked automobile, and the recycling rate for old scrap is likely to increase. In addition, with the production of greater numbers of magnesium alloy die-castings, more new scrap will be generated than was produced with the 1998 consumption pattern; therefore, new magnesium-base scrap recycling also is likely to increase.

INFRASTRUCTURE OF MAGNESIUM SCRAP

LOCATIONS OF FACILITIES

In 1998, three companies produced 106,000 t of primary magnesium metal. Dow recovered magnesium from seawater at a 65,000-metric-ton-per-year (t/yr) plant in Freeport, Tex., MagCorp recovered magnesium from brines from the Great Salt Lake at a 40,000-t/yr plant in Rowley, Utah, and Northwest Alloys recovered magnesium from dolomite at a 40,000-t/yr plant in Addy, Wash. Dow closed its plant in November 1998. Because each of these plants uses a different magnesium-recovery process, data on processing wastes are plant specific and cannot be generalized. Magnesium not recovered in the electrolytic process is returned to either the sea (in the case of seawater) or the solar evaporation ponds (in the case of the Great Salt Lake brines). Northwest Alloys generates significant quantities of waste from its magnesium processing. In 1997, the waste at the plant site was estimated to be about 109,000 t; additional material was in storage facilities and warehouses. Although some of the material needs to be disposed in hazardous waste landfills, Northwest Alloys was planning to treat and then market some of the material as fertilizer (Wilson, 1997). In addition, magnesium-base scrap, which includes such material as off-specification products, is generated at each of these facilities; details on the quantities of scrap recycled, however, are not available.

Magnesium-base-scrap recycling plants are located throughout the United States, but the largest percentage of capacity is located in the Midwest. Many of the magnesium-product-manufacturing capabilities are located in this area,

and the recycling plants are located near the scrap-generation facilities; in particular, the magnesium die-casting industry. Because some magnesium-base-scrap recycling plants also recycle aluminum, the magnesium recovered in the magnesium portion of the recycling operation may be used as an alloying ingredient in some secondary aluminum alloys.

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Table 2 lists information on some of the larger magnesium-base scrap recyclers. This list covers only those that recycle magnesium-base scrap, not aluminum-base scrap.

TRADE

In 1998, about 12,000 t of magnesium waste and scrap was exported, almost all of which went to Canada. The magnesium exported to Canada most likely went to Norsk Hydro Canada Inc., which had a recycling plant associated with its primary production facility in Becancour, Quebec. The average value of this scrap was about \$2,300 per metric ton. On this value basis, more than 90 percent of the scrap exported was estimated to be old scrap. Of the total quantity of magnesium and magnesium alloys that were exported in 1998, scrap represented about 37 percent, on a gross-weight basis.

Imports for consumption of magnesium waste and scrap in 1998 totaled about 6,000 t. Approximately 47 percent of this material came from Canada, 9 percent from the United Kingdom, and 8 percent from China. The average value of this material was about \$1,400 per metric ton. On the basis of the value of individual shipments during the year, 4,000 t was estimated to be old scrap, and 2,000 t, new scrap. Of the total imports for consumption of magnesium and magnesium alloys, scrap represented about 7 percent, on a contained-weight basis, in 1998.

PROCESSING OF MAGNESIUM SCRAP

STRUCTURAL MAGNESIUM-BASE PRODUCTS

In making magnesium alloy die-castings, about 50 percent of the material ends up as a finished product, and the remainder as new scrap. Of the scrap generated in the die-casting process, about 80 percent ends up as trimmings; 8 percent, as dross; 7 percent, as chips; 4.5 percent, as reject parts; and the remaining 0.5 percent, as a slurry, which is probably lost (Albright, 1993). For magnesium extrusions, about 75 percent of the magnesium ends up in the product,

Table 2. Major U.S. magnesium-base scrap processors.
[Metric tons per year. NA, Not available]

Company	City	State	Product	Type of scrap processed	Capacity
Alabama Cathodic Metals Inc.	Foley	Ala.	Magnesium ingots (mostly for aluminum alloying) and anodes.	New die-cast and old magnesium base.	¹ 17,000
Garfield Alloys Inc.	Cleveland	Ohio	Magnesium ingots, anodes, powder, and granules.	New (types II, III, IV)	13,600
Garfield Alloys Inc. 15,000 (MagReTech Inc.).	Bellevue	Ohio	NA	New (type I)-.5	
IMCO Recycling Inc.	Sapulpa	Okla.	Magnesium ingot and anodes	Dross and old magnesium base.	NA
Reactive Metals and Alloys Corp.	W. Pittsburgh	Pa.	Desulfurization reagents	Dross	NA
Rosborough Manufacturing Co. L.P.	Walkerton	Ind.	Desulfurization reagents	Chips	NA
Spectrulite	Madison	Ill.	Magnesium ingots	New die-cast	15,000

¹Closed in 2000.

and the remainder is new scrap (mostly chips), much of which is recycled internally (Barnes and Barnes, 1994). Extrapolating from data collected by the USGS and these factors, approximately one-third of the magnesium that is used to fabricate structural products (castings and wrought products) ends up as new scrap, which is either reprocessed or used directly in dissipative applications, such as steel desulfurization and sacrificial anodes.

Magnesium scrap arrives at the recycler either loose on a dump trailer or in boxes on a van-type trailer. Sorting the magnesium-base scrap correctly is crucial to producing a product that meets specifications. Because magnesium and aluminum closely resemble each other, a load of magnesium scrap may contain some aluminum scrap as well. The scrap is visually inspected, and one of the ways to separate the magnesium from the aluminum scrap is by scratching the metal with a knife. Magnesium tends to flake, whereas the softer aluminum tends to curl. After being separated from the aluminum-base scrap and any other foreign material, the magnesium scrap is sorted according to alloy.

In melting, sorted scrap is charged to a steel crucible, which is heated to 675°C. As the scrap at the bottom begins to melt, more scrap is added. The liquid magnesium at the bottom is covered with a flux or inhibitive gas to control surface burning. After any alloying elements are added, such as aluminum, manganese, or zinc, and melting is complete, molten magnesium is transferred to ingot molds by hand ladling, pumping, or tilt pouring (Wentz and Ganim, 1992).

In addition to melting, magnesium scrap may be recycled by direct grinding of the scrap into powder for iron and steel desulfurization applications. This method is limited to using only specific types of clean scrap. Drosses and other contaminated scrap are not used because they can introduce impurities into the finished product, and these types of scrap can increase the danger of fire in the direct grinding (Dahm, 2000).

USED BEVERAGE CAN RECYCLING

In UBC recycling, most of the cans are converted into body stock (AA3004) after they are melted and delacquered. Much of the magnesium remains with the recycled can, but some is lost during reprocessing. A simplified diagram of the magnesium portion of UBC recycling is shown in figure 4. Data for this figure were determined from the content and recovery rates shown in table 3 and by using a 63-percent UBC recycling rate for 1998. Because UBC scrap is recycled almost exclusively into aluminum cans, the magnesium recovered from this product can be recycled as many times as the aluminum cans are recycled.

In recycling UBC's, the UBC stream is blended with virgin material in the production of aluminum cans. The losses shown in figure 4 may come from either the UBC or the virgin material (except for those in the melting and delacquering stage); once the streams are combined, the two are indistinguishable. For convenience, these losses are shown from the old scrap component in figure 1. A more detailed discussion of UBC recycling is presented by Jenkins and Robertson (2000, p. 1007-1027).

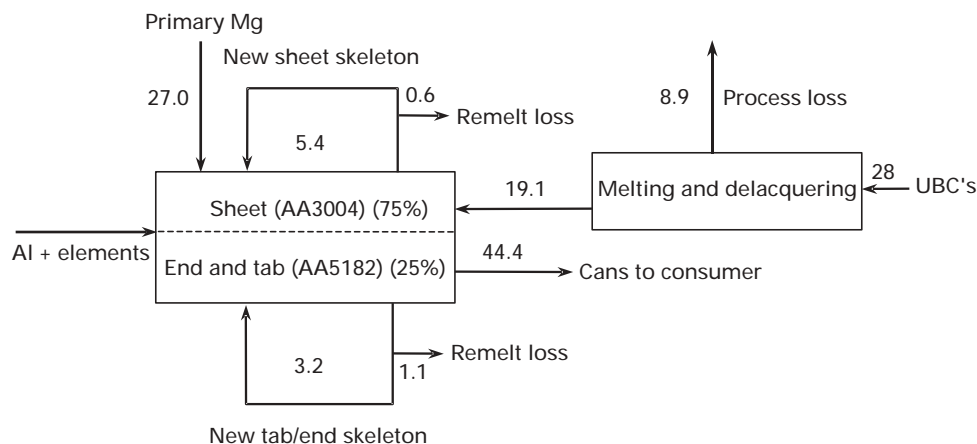


Figure 4. Simplified used beverage can processing, in thousands of metric tons of contained magnesium. UBC's. used beverage cans. Adapted from Bowman, 1983.

ALUMINUM-MAGNESIUM ALLOYS

Magnesium-containing scrap also is generated when aluminum-magnesium alloys are fabricated. The USGS estimates that most of these aluminum-magnesium alloys are used in packaging (aluminum beverage cans), transportation, and machinery applications, in descending order of use. The Aluminum Association, Inc. (1999b, p. 22-26), collects data on product form shipments by major application. In addition, the Aluminum Association completed a life-cycle study that determined the quantity of scrap generated in various fabrication operations, which included shape casting, extruding, and hot and cold rolling, in descending order of scrap generation. For aluminum shape casting, about 45 percent of the input material ends up as new scrap; for extrusion, 30 percent; for hot rolling, 17 percent; and for cold rolling, 16 percent. In addition, some material ends up as residues, which are also recycled (Aluminum Association Inc., 1998, p. 4-14 to 4-17.) Based on the above, information about the quantity of scrap generated from aluminum beverage can production, and USGS estimates of quantities of magnesium used in aluminum alloys in each application, approximately 30 percent of the magnesium in aluminum alloys becomes scrap, and 8 percent is lost to the environment.

In aluminum can production, 24.2 percent of the body stock ends up as skeleton, and 16.4 percent of the tab and end stock ends up as skeleton scrap (Bowman, 1983). Of this scrap, 100 percent is assumed to be returned to the sheet producer for reclaiming. Approximately 5 percent of the cans produced are projected to be spoilage; this material is assumed to be sent to a secondary aluminum smelter where the magnesium component most likely is lost (Sanders and others, 1990, p. 196).

Table 3. Used beverage can scrap melting data. [In percent. From Bowman, 1983]

Type	Metal recovery	Magnesium content
Body stock skeleton (AA3004, 1.05-percent Mg)	80	0.95
End and tab stock skeleton (AA5182, 4.50-percent Mg)	90	3.4
Recycled beverage cans (1.9-percent Mg)	90	1.3

TITANIUM PRODUCTION

Magnesium also can be recovered in the production of titanium. In the Kroll process to produce titanium metal, TiCl_4 is reacted with magnesium metal to form titanium metal and magnesium chloride in a batch reactor. After the titanium is separated from the magnesium chloride, the magnesium chloride can be reduced in an electrolytic cell to form magnesium metal and chlorine gas. The magnesium metal can then be reused to react with a new batch of TiCl_4 . Approximately 125 percent of the stoichiometric quantity of magnesium is needed to assure complete reduction of the TiCl_4 , and if this is recycled, then about 0.2 to 0.5 t of magnesium per metric ton of titanium produced is needed to make up for losses. Because production of magnesium is very energy intensive, recycling of magnesium may be dependent on energy costs, which vary from plant to plant (Poulsen and Sprayberry, 1992). This type of magnesium recycling is analogous to home scrap recycling. Because titanium sponge production data in the United States are withheld, data on the quantity of magnesium that is recycled in titanium plants are also withheld and, therefore, are not included in figure 1.

OUTLOOK

If magnesium use in the automobile industry continues to grow at the rapid pace that it has in the past few years, then this growth could have significant immediate and long-term effects for the magnesium recycling industry worldwide. The immediate effect would be a huge increase in the quantity of new scrap generated because about 50 percent of the weight of the input material becomes new scrap. As a result of this anticipated increase in new scrap generation, companies are planning new magnesium recycling plants or they are expanding existing capacity. The principal long-term effect is that after an automobile is junked, the magnesium-containing parts may be removed from the automobile and recycled. These additional magnesium-containing parts would result in additional quantities of old scrap as a source of supply. The projected increase in the use of magnesium in this application has prompted other countries to install additional magnesium recycling capacity. New magnesium recycling plants have been planned for Germany and Japan, and increases in capacity at existing plants were announced for Germany, Japan, and the United Kingdom (Kramer, 2001).

Potential legislation to regulate the use of sulfur hexafluoride (SF_6) may affect the magnesium industry as a whole, which includes the magnesium-recycling sector. International concern over global warming has focused attention on the long atmospheric life of SF_6 , which has about 23,800 times the global warming potential of carbon dioxide. Although the primary use of SF_6 is as a dielectric in electrical transmission and distribution systems, it is also used as a cover gas in casting molten magnesium.

Fugitive emissions of SF_6 occur from leaks in and servicing of substations and circuit breakers, especially from

older equipment. The U.S. Environmental Protection Agency (EPA) (1999) estimated that emissions from this source increased to 7.0 million metric tons (Mt) of carbon equivalents in 1997; this was a 25-percent increase from those in 1990. Estimated emissions from primary magnesium production and magnesium casting were 3.0 Mt of carbon equivalents in 1997; this was an increase of 76 percent since 1990 (EPA, 1999). In 1998, the EPA began a collaborative effort with the U.S. magnesium industry to improve manufacturing processes and gas-handling practices in an effort to reduce emissions of SF_6 (EPA, 1998). The magnesium industry itself is investigating the use of other gases as a substitute for SF_6 . For example, researchers at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) have investigated a number of alternatives that are more environmentally friendly than SF_6 , one of which is very promising. SF_6 can be replaced with the hydrofluorocarbon 1,1,1,2 tetrafluoroethane (HFC-134a) with only minor modifications to gas delivery systems. HFC-134a, which is a refrigerant gas commonly used in car air conditioners, is not toxic, corrosive, or flammable and does not contribute to ozone depletion. According to CSIRO (2000), replacing SF_6 with HFC-134a has the following advantages:

- HFC-134a has a global warming potential of only 1,300 times the global warming potential of carbon dioxide, or 18 times less than that of SF_6
- HFC-134a is only about one-third of the cost of SF_6 ; HFC-134a is more effective than SF_6 for magnesium melt protection
- HFC-134a has the ability to extinguish a magnesium fire once started, whereas SF_6 will not (Commonwealth Scientific and Industrial Research Organisation, 2000).

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Based on the unit value of zinc in materials.

primary zinc. Zinc derived from ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

U.S. Department of the Interior
U.S. Geological Survey

Lead Recycling in the United States in 1998

By Gerald R. Smith

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-F

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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CONVERSION FACTORS

Multiply	By	To obtain
<i>Length</i>		
kilometer (km)	0.6214	mile
inch (in.)	25.4	millimeter
<i>Volume</i>		
cubic foot (ft ³)	0.02832	cubic meter
<i>Mass</i>		
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram
<i>Pressure</i>		
pound force per square inch	6.895	kilopascal
atmosphere (atm)	101.3	kilopascal

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Lead Recycling in the United States in 1998

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ABSTRACT

This materials flow study includes a description of lead supply and demand factors for the United States to illustrate the extent of lead recycling and to identify recycling trends. Understanding the system of materials flow from source to ultimate disposition can assist in improving the management of the use of natural resources in a manner that is compatible with sound environmental practices. The quantity of lead recycled in 1998, as a percentage of apparent lead supply, was estimated to be about 63 percent, and recycling efficiency, to be 95 percent. Of the total lead consumed in products for the U.S. market in 1998, an estimated 10 percent was consumed in products in which the lead was not readily recyclable.

INTRODUCTION

Figure 1 and table 1 provide data on the use of lead in the United States in 1998. The sources of lead supply and the distribution of these supplies are quantified in this illustration so that specific information on recycling, including lead scrap recycling efficiency and lead scrap recycling rate (see appendix) can be determined. As an introduction prior to specific discussion of the components of figure 1, the following background on lead, including its history, important uses and use trends, geological occurrence, production processes, and market prices, is discussed.

HISTORY AND USE PATTERNS

Lead is a very corrosion-resistant, dense, ductile, and malleable blue-gray metal that has been used for at least 5,000 years. Early uses of lead included building materials, pigments for glazing ceramics, and pipes for transporting water. The castles and cathedrals of Europe contain considerable quantities of lead in decorative fixtures, roofs, pipes, and windows (Shea, 1996, p. 1). Lead scrap has represented a portion of lead supply in the United States since the 1800s. The earliest known report of consumption of lead scrap was between 1867 and 1889 when about 11,000 metric tons (t) of lead scrap was imported to the United States for unspecified uses (Kirchhoff, 1894). Actual U.S. production of lead from scrap was first reported in 1907. In the following 2 years, about 77,000 t of recycled lead was recovered (Siebenthal,

1911, p. 187). The recovery of lead from scrap increased significantly in the United States during the next 18 years, and by 1927, nearly 252,000 t of lead had been recovered from scrap; this represented an estimated 27 percent of the total refined lead consumed (Smith, 1930, p. 341). By 1980, the quantity recovered had reached 675,000 t, which was about 63 percent of the total refined lead consumed, and by 1998, it had risen to 1.12 million metric tons (Mt), which was 69 percent of consumption (Rathjen, 1981, p. 480; Smith, 2000).

Prior to the early 1900s, uses of lead in the United States were primarily for ammunition, brass, burial vault liners, ceramic glazes, leaded glass and crystal, paints or other protective coatings, pewter, and water lines and pipes. The advent of the electrical age and communications, which were accelerated by technological developments in World War I, resulted in the addition of bearing metals, cable covering, caulking lead, solders, and type metal to the list of lead uses. With the growth in production of public and private motorized vehicles and the associated use of starting-lighting-ignition (SLI) lead-acid storage batteries and terne metal for gas tanks after World War I, demand for lead increased. Most of these uses for lead continued to increase with the growth in population and the national economy. Contributing to the increase in demand for lead was the use of lead as radiation shielding in medical analysis and video display equipment and as an additive in gasoline, which peaked in the late 1970s when environmental bans on leaded gasoline were introduced.

Figures 2 and 3 show the trends in consumption of lead in the United States since 1978. By the mid-1980s, a significant shift in lead end-use patterns had taken place. The demand for lead in SLI-type batteries grew rapidly, and this growth continued into the 1990s (fig. 2). In addition, the demand for lead in non-SLI battery applications also grew. Non-SLI battery applications include motive sources of power for airport ground equipment, industrial forklifts, mining equipment, and a variety of nonroad utility vehicles, as well as stationary sources of power in uninterruptible electric power systems for hospitals and for computer and telecommunications networks, and load-leveling equipment for electric utility companies. The use of lead in nonbattery products declined as battery demand increased (fig. 3).

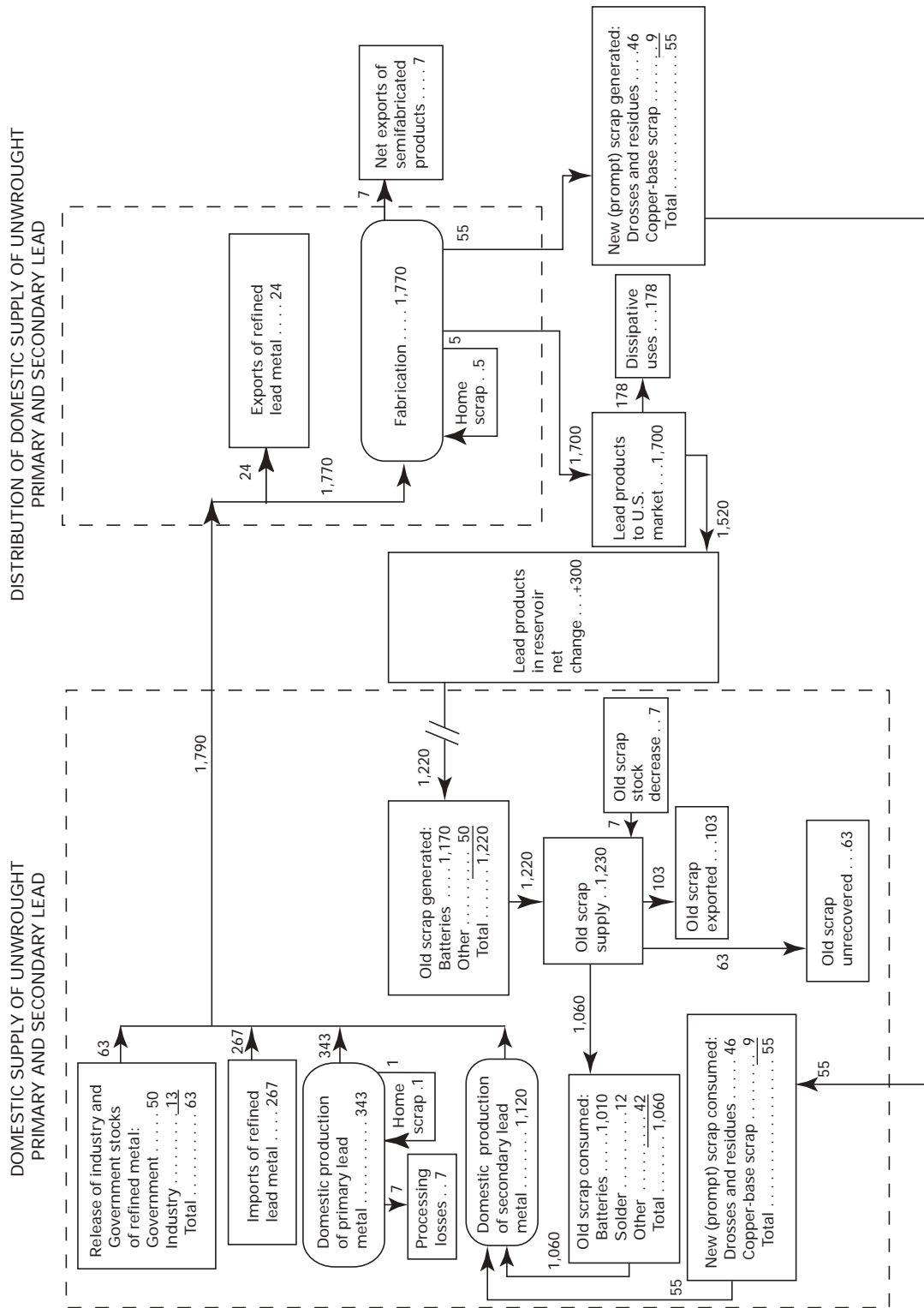


Figure 1. U.S. lead materials flow, in 1998. Values are in thousands of metric tons of contained lead and have been rounded to three significant figures.

Table 1. Salient statistics for U.S. lead scrap in 1998.

[Values in thousands of metric tons of contained lead, unless otherwise specified]

Old scrap:	
Generated ¹	1,220
Consumed ²	1,060
Value of old scrap consumed	\$263 million
Recycling efficiency ³	95 percent
Supply ⁴	1,230
Unrecovered ⁵	63
New scrap consumed ⁶	55
New-to-old-scrap ratio ⁷	5:95
Recycling rate ⁸	63 percent
U.S. net exports of scrap ⁹	103
Value of U.S. net exports of scrap	\$26.8 million

¹Lead content of products theoretically becoming obsolete in the United States in 1998. It excludes dissipative uses.

²Lead content of products that were recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁴Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁵Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁶Including prompt industrial scrap, but excluding home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of the lead apparent supply that is scrap, on an annual basis. It is defined as (consumption of old plus consumption of new scrap) divided by apparent supply (see appendix), measured in weight and expressed as a percentage.

⁹Trade in scrap is assumed to be principally old scrap. Net exports are exports of old scrap minus imports of old scrap.

Much of the decline in nonbattery use of lead was a result of the U.S. lead consumers' compliance with environmental regulations that significantly reduced or eliminated the use of lead in products that included gasoline, paints, solders, and water systems. Data for consumption of lead used as chemical additives in gasoline from 1987 through 1995 were estimated. The U.S. Environmental Protection Agency (EPA) issued a direct final rule that prohibits the use of such additives in highway vehicles effective January 1, 1996 (U.S. Environmental Protection Agency, 1996). By 1998, the total demand for all types of lead-acid storage batteries represented a record high 88 percent of apparent U.S. lead consumption. Other significant uses included ammunition (3 percent), oxides in glass and ceramics (3 percent), casting metals (2 percent), and sheet lead (1 percent). The remainder was consumed in bearing metals, brass and bronze billets, covering for cable, caulking lead, extruded products, and solders. U.S. lead consumption in 1998 was about 29 percent of total world consumption of lead. The lead end-use pattern in the remainder of the world, with

batteries being the predominant end-use sector, was similar to that of the United States (International Lead and Zinc Study Group, 1999, p. 23-34).

The domestic demand for refined lead, by industrial sector in 1998, was principally in the transportation industry as component material for batteries, fuel tanks, seals, solders, and wheel weights and in the communication, construction, electrical, and electronic industries in such products as batteries, cable covering, extruded shapes, pipes, and radiation shielding. A small amount of lead also was consumed for use by producers of ceramics, crystal glass, and specialized chemicals.

GLOBAL GEOLOGIC OCCURRENCE OF LEAD

Conventional deposits of primary lead and zinc are separable into five principal types that are based, for the most part, on differences in their geologic environments. The following definitions and descriptions of these deposits are from Briskey and Wedow (1986) and J.A. Briskey (U.S. Geological Survey, written commun., 2000).

- Volcanic-hosted submarine exhalative massive sulfide deposits comprise almost entirely pyrite and pyrrhotite (iron sulfides) with varying proportions and amounts of sphalerite (zinc sulfide), galena (lead sulfide), chalcopyrite (copper and iron sulfide), and silver-bearing minerals. Lists of minerals in this geologic section are approximately in order of decreasing abundance. The sulfide minerals typically occur as multiple stratiform lenses within submarine volcanic rocks and commonly overlie or are adjacent to discordant feeder zones that contain smaller amounts of these minerals as stringers and disseminations in altered volcanic rocks. Large examples of these deposits include those found in Canada, Cyprus, Japan, Tasmania, and Turkey.
- Sediment-hosted submarine exhalative deposits consist of stratiform basinal accumulations that comprise mainly fine-grained pyrite and (or) pyrrhotite, sphalerite, galena, sporadic barite (barium sulfate), and minor chalcopyrite interbedded with euxinic marine sediments, which include black shales, siltstones, sandstones, cherts, dolostones (calcium magnesium carbonate), and micritic limestones (calcium carbonate). Large examples of these deposits are found in Australia, Canada, Germany, and the United States (Alaska).
- Strata-bound carbonate-hosted deposits, which are commonly referred to as "Mississippi Valley type," contain mostly sphalerite, galena, pyrite, barite, fluorite (calcium fluoride), and chalcopyrite. These minerals typically fill primary and secondary voids developed in favorable beds or horizons within thick sequences of platform dolostones and limestones. Important examples of these deposits are found in the Mississippi Valley and adjacent regions of the United States, which include the Upper

Mississippi Valley, the tristate region (Kansas-Missouri-Oklahoma), southeastern Missouri, and the central and east Tennessee districts, and are found in the Alps in southern Europe, Canada, and Poland.

- Sandstone-hosted deposits typically are strata-bound and commonly are stratiform concentrations of mainly fine-to-medium crystalline galena with sporadic smaller amounts of sphalerite, pyrite, barite, fluorite, and minor chalcopyrite. These minerals usually occur as clots and disseminations that in aggregate form multiple, thin, sheetlike ore bodies within marine, terrigenous, and continental sandstones, conglomerates, grits, and siltstones. Important examples of these deposits are found in Canada, France, Morocco, and Sweden.
- Vein, replacement, and contact metasomatic deposits typically comprise coarse crystalline aggregates of pyrite, sphalerite, galena, and chalcopyrite, as well as a large number of complex base- and precious-metal sulfide minerals that include those that contain abundant arsenic and antimony. Most deposits form multiple, tabular-to-podiform, or pipe-shaped ore shoots or occur as extensive, highly irregular, branching masses. Deposits occur in clusters (districts) that are spatially and temporally related to nearby granitic plutons of granodioritic or quartz monzonitic composition. Contact metasomatic deposits are restricted mostly to the contact aureoles of the plutons. Replacement and contact metasomatic ore bodies typically replace carbonate rocks adjacent to the pluton, whereas vein deposits are usually open-space fillings in fractures in a variety of host rocks. Classic examples of these deposits are found in Germany, Japan, Mexico, Peru, and, especially, the Western United States.

LEAD PRODUCTION PROCESS AND GLOBAL PRODUCTION

The major share of the U.S. mine output of lead in 1998 was derived from production in Alaska and Missouri. Appreciable quantities were also produced from mining operations in Colorado, Idaho, and Montana. Cumulatively, during the past 200 years, 57 percent of the U.S. mine output of lead was from strata-bound carbonate-hosted deposits, and 40 percent was from vein, replacement, and contact metasomatic deposits. The remaining 3 percent was produced from volcanic-hosted submarine exhalative massive sulfide, sediment-hosted submarine exhalative, and other deposits (Long, DeYoung, and Ludington, 2000, p. 640).

Lead is processed from the mined ore to the concentrate stage through a series of conventional beneficiation steps. After the raw ore is screened, crushed, and ground at the mill, it is chemically treated in a flotation process to separate metal-containing minerals from the waste rock (tailings) and from each other. The resulting lead concentrate is then further

processed through sintering, smelting, and refining steps to produce the pure lead metal. Most of the copper, nickel, and other impurities, which include antimony, arsenic, gold, and silver, are removed from the lead in a "dross" layer that forms on the surface of the melt upon cooling.

The lead bullion product from the smelting step is then processed through several molten refining steps to remove the remaining trace impurities, which may include antimony, arsenic, bismuth, copper, silver, tellurium, and zinc; this process ultimately yields a minimum of 99.97 percent pure refined lead. This lead is then cast into various size ingots for sale to end-use consumers. In 1998, mine production of lead was reported in 44 countries; the top 5 accounted for 68 percent of the world's total production of 3.1 Mt of lead in concentrates. Australia was the largest producer with 20 percent of the world total, followed by China, 18 percent; the United States, 16 percent; Peru, 8 percent; and Canada, 6 percent.

LEAD MARKET PRICES

Refined lead prices declined throughout most of 1998. The average London Metal Exchange and North American Producer prices per pound were \$0.240 and \$0.453, respectively, which were down by \$0.043 per pound and \$0.013 per pound, respectively, compared with those of 1997. In 1998, recycled lead sold for an average \$0.483 per pound, which was down by \$0.012 per pound compared with the price in 1997 (Platt's Metals Week, 1999). The market price for whole scrap lead-acid batteries (a principal source of lead for recycling) ranged between \$0.045 and \$0.065 per pound, which translated to a lead price of \$0.09 to \$0.13 per pound assuming that the average amount of lead in such batteries is about 50 percent (Worden, 1998). Soft lead scrap from other sources averaged \$0.195 per pound (American Metal Market, 1999).

In the late 1980s and early 1990s, lead prices generally increased as the lead-producing industry continued to adjust effectively to environmental regulations imposed a few years earlier. After a brief decline, prices rose steadily from 1992 to 1996 as a result of the increasing demand in the replacement automotive battery sector. In 1997 and 1998, the price of lead showed some softness owing to 2 consecutive years of moderate temperatures in the more-populated regions of the United States that reduced the failure rate of automotive-type batteries and the subsequent need for replacement batteries.

SOURCES OF LEAD SCRAP

Sources of new and old scrap are key features of the U.S. lead materials flow diagram that is shown in figure 1. Statistical data for the various types of old and new scrap processed into refined lead metal for domestic consumption were derived from specific information provided to the U.S. Geological Survey (USGS) by the lead recycling (secondary) industries.

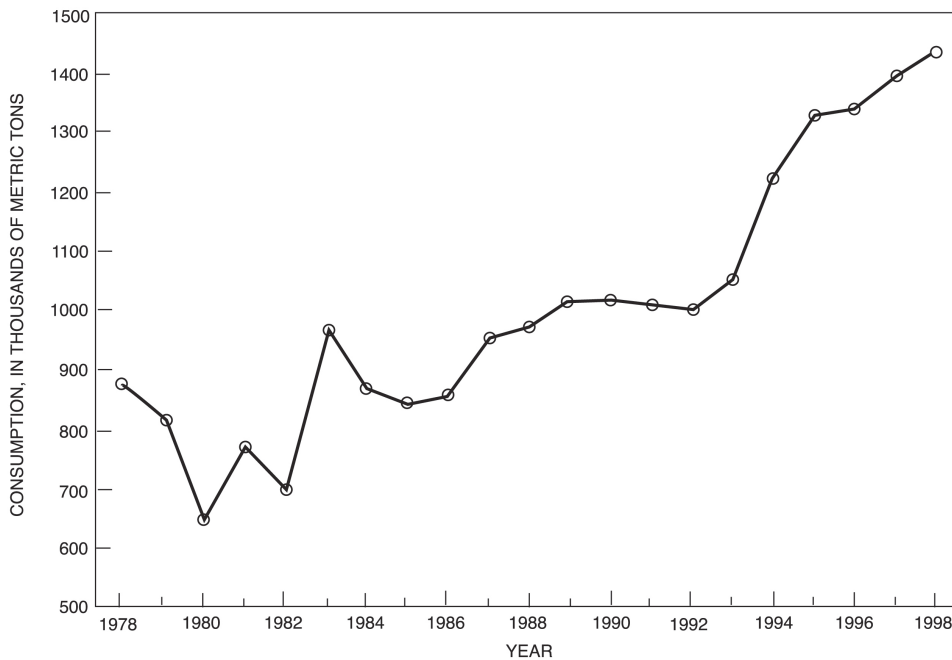


Figure 2. U.S. lead consumption in batteries from 1978 through 1998.

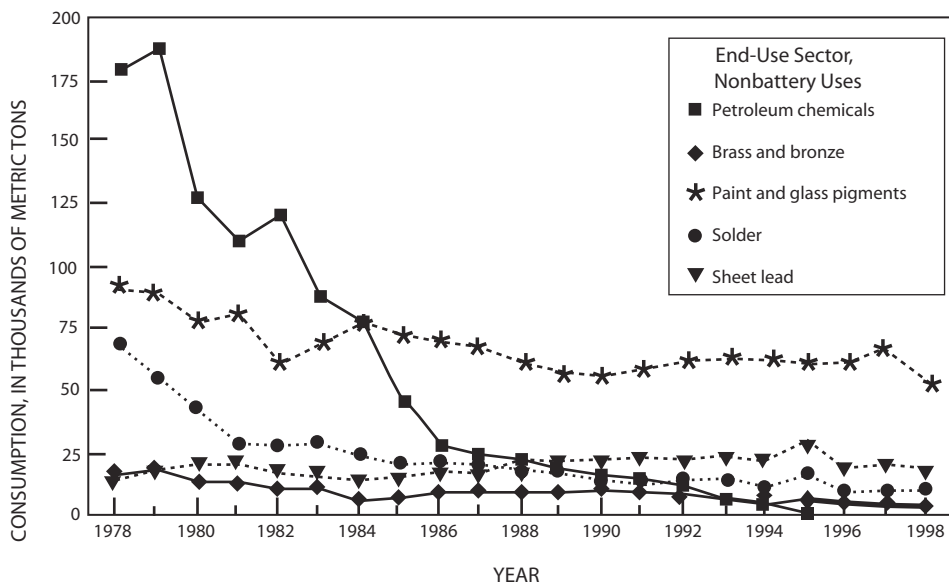


Figure 3. U.S. lead consumption by end-use sector, nonbattery uses from 1978 through 1998.

The domestic supply of primary and secondary refined lead, as shown in figure 1, consists of primary and secondary refinery production, net imports of refined lead, sales of lead from the Government stockpile, and net releases of industry stocks. Data on trade and Government stockpile sales were obtained from the U.S. Census Bureau and the U.S. Defense National Stockpile Center, respectively, through monthly reports issued by the agencies.

The salient lead scrap statistics discussed in this report for calendar year 1998 (table 1) are based primarily upon information received from lead industry producers and consumers through industry surveys submitted to the USGS. Statistics received through these surveys provided about 99 percent of the total production of refined lead reported and 96 percent of the apparent consumption of lead.

OLD SCRAP GENERATED

The key component of the lead recycling industry in the United States is the reprocessing of spent lead-acid batteries. In 1998, approximately 88 percent of these spent batteries were of the SLI automotive type, which had an average life of about 4 years; 8 percent were of the motive power type, which had an average life of 6 years; and 4 percent were of the stationary type, which had an average life of 10 years (Battery Council International, 1998, p. 3). The calculated quantity of old scrap generated in 1998 was assumed to have originated from lead consumed in the manufacture of batteries of the SLI automotive type in 1994, the motive power type in 1992, and the stationary type in 1988. An estimated 97 percent of all the old lead scrap generated in 1998 was from spent lead-acid storage batteries. The remainder was from metal sources, such as castings, sheet, solders, and miscellaneous fabricated parts.

NEW SCRAP

The quantity of refined lead recovered from new scrap was estimated from the gross weight of purchased drosses and residues reported to the USGS as a source of scrap by the lead recycling industries. An additional source of new lead scrap was that contained in copper-base alloys. New scrap consumed in 1998 was estimated to be 55,000 t, or about 5 percent of total scrap consumed.

DISPOSITION OF LEAD SCRAP

In 1998, recycled lead represented nearly 77 percent of refined lead production in the United States. The spent lead-acid battery is the dominant source of lead for reprocessing by the secondary lead industries. Thus, the efficiency with which these batteries are collected, reprocessed, and returned to the marketplace in the form of refined lead is of prime importance in maintaining the required supply of lead in the United States.

OLD SCRAP RECYCLING EFFICIENCY

Recycling efficiency shows the relation between what is theoretically available for recycling and what is and is not recovered. By definition, this relation is the amount of old scrap consumed plus old scrap exported divided by the sum of old scrap generated and old scrap imported plus or minus old scrap stock changes. Each component that is used to determine the relation is considered in terms of the recoverable metal content. The recycling efficiency of about 95 percent that was reached in 1998 is consistent with the organized infrastructure that exists in the United States for collection and recovery of lead scrap and, in particular, spent lead-acid batteries.

INFRASTRUCTURE OF LEAD SCRAP

In 1998, about 98 percent of all recycled lead was produced by 9 companies that operated 17 battery recycling plants in Alabama, California, Florida, Georgia, Indiana, Louisiana, Minnesota, Missouri, New York, Pennsylvania, Tennessee, and Texas. The geographical distribution of these plants effectively supports the complete network of spent battery sources. Secondary lead production capacity in the United States is estimated to be about 1.1 Mt per year.

BATTERY SCRAP COLLECTION SYSTEM

An estimated 60 percent to 70 percent of spent lead-acid batteries are collected for recycling each year by battery manufacturers through sales agreements with major retailers or through reverse distribution systems. The manufacturers typically collect spent batteries from retailers when delivering shipments of new lead-acid batteries. Retailers accumulate these spent batteries in exchange when customers purchase new batteries. Upon collection of the batteries from the retailer, the battery manufacturer, in turn, arranges to recover the lead content of the batteries through tolling agreements with secondary lead smelters. This lead is then returned to the manufacturer as feedstock for the production of new batteries. If the battery manufacturer also owns a secondary smelter, then the tolling step is eliminated. The remaining 30 percent to 40 percent of spent batteries are collected by scrap dealers. These dealers collect from sources other than large retailers, which include small retailers, service stations, and junk yards, and subsequently offer the batteries for sale on the open market.

TRADE

As a net exporter of lead scrap, the United States sent 103,000 t abroad in 1998; about 91 percent went to Canada. Other places that received appreciable quantities of lead scrap from the United States included Belgium, China, Hong Kong, India, Japan, Mexico, Sweden, Taiwan, and the United Arab Emirates. The exported scrap was principally in the form of battery and nonbattery metal scrap, which

included approximately 5,000 t of lead contained in whole spent batteries. The remaining scrap (about 9 percent) was exported in the form of ash and residues. Exports of lead scrap represented about 39 percent of the total exports of lead-containing materials, which included base bullion, concentrates, and wrought and unwrought lead and lead alloys.

PROCESSING OF LEAD SCRAP

SPENT BATTERY SCRAP

The processing of spent batteries is carried out in a series of steps that includes draining the battery acid, dismantling the battery by hammer mill and grinding procedures, washing and tumbling the dismantled battery to separate its component parts (generally by screening and gravity separation steps), and, finally, treating the individual component parts for recovery and reuse. In the processing of the lead-acid battery, most of its components are recovered for reuse. The lead-containing components recovered from the battery consist of lead alloy from the grids and posts, lead oxides from the electrode paste, and other lead compounds from the battery cell reactions. Typically, the lead-bearing paste is first desulfurized and combined with the lead-bearing grids and posts as a feed to a reverberatory furnace; this yields a raw lead product and a slag that contains 20 percent to 40 percent lead. The slag is fed to a blast furnace or electric reduction furnace from which the lead content is recovered as raw lead product. The raw lead products from these furnaces are then melted in refining kettles to remove residual impurities, adjusted to customer specifications, and cast into ingots for shipment. In some facilities, the grids and posts are treated separately from the paste. In such operations, a rotary furnace that produces desired alloys for new battery production directly from the used grids and posts is used.

The manner in which the sulfuric acid recovered from the batteries is treated to produce usable products, such as fertilizers, laundry detergent and paper-processing ingredients, regenerated electrolyte for use in new batteries, and a pH control solution for use in the wastewater-treatment system at the recycling facility, depends upon the particular recycling facility. The shredded polypropylene plastic battery casings are converted to plastic pellets onsite or shipped to a plastics recycler for eventual reuse in the production of new battery casings. Nonplastic components of the battery, such as rubber casing material and grid separators, may be used as reducing agents in the melting process for recovery of lead.

Loss of lead is minimal in the processing of spent batteries. Environmental regulations in place for secondary lead smelters require that the loss of lead in these operations be significantly restricted. In June 1997, the EPA issued a direct final rule that amended certain components of the existing national emission standards for hazardous air pollutants from secondary lead smelting. This direct final rule,

as amended, established standards to limit hazardous air pollutant emissions from agglomerating furnaces, dryers, fugitive dust sources, refining kettles, and smelting furnaces at lead smelters (U.S. Environmental Protection Agency, 1997).

BATTERY FABRICATION

Battery manufacturers recover essentially all the scrap, which is mostly grid and post trimmings, generated in the battery assembly process. This home scrap is collected and remelted for use in the fabrication of more grids and posts. Minimal scrap or waste is generated in the production of the electrode paste. The small quantity that is recovered is reused as home scrap.

OUTLOOK FOR LEAD RECYCLING

The recycling efficiency level of 95 percent achieved in 1998 is likely to continue into the foreseeable future. Because the recycling efficiency is, however, already quite high, any further increase will be slight. Likewise, the recycling rate of 63 percent also is expected to remain at a high level. Only a decline in the demand for lead, thus lessening the need for primary material, is likely to raise it significantly. Such factors as environmental controls on lead, rising lead demand in the replacement battery sector, and the integral and appreciable role that the secondary lead industry plays in meeting overall U.S. demand for lead will continue to support significant recycling of lead. Continued high levels of lead recycling enhance the sustainability of lead production and result in greater conservation of energy and resources.

On an international level, interest in lead recycling has been continuous and extensive. Increasing environmental concerns have prompted the institution of additional regulations on new lead production that have resulted in additional pressure and incentive to increase the recycling of lead in many countries around the world. Recycled lead now accounts for about one-half of the refined lead produced worldwide each year (International Lead and Zinc Study Group, 1995).

Forecasts for lead recycling indicate that an additional 1 Mt of secondary lead capacity will be required worldwide by 2008. The feed source for this capacity increase essentially will be that of the spent lead-acid batteries obtained from the ever-expanding number of vehicles throughout the world. In those regions where the number of vehicles is increasing to the greatest extent, however, challenges are expected to remain in achieving significant increases in recycling efficiency. Specifically, the collection of the spent automotive-type batteries and their transportation to appropriate recycling facilities will require the resolution of certain restrictions to battery recycling as outlined in the Basel Convention (International Lead and Zinc Study Group, 1998).

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old

scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Total value of old lead scrap consumed calculated on the basis of an estimated value for the lead contained in whole battery scrap plus 75 percent of the unit value of primary lead for all other forms of lead scrap. The total value of old lead scrap exports was based upon the value for the gross weight of lead scrap as reported by the U.S. Census Bureau.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinsplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinsplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

U.S. Department of the Interior
U.S. Geological Survey

Iron and Steel Recycling in the United States in 1998

By Michael D. Fenton

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-G

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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CONVERSION FACTORS

Multiply	By	To obtain
	<i>Length</i>	
kilometer (km)	0.6214	mile
	<i>Mass</i>	
kilogram (kg)	2.205	pound avoirdupois
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Iron and Steel Recycling in the United States in 1998

By Michael D. Fenton

ABSTRACT

Consumption of iron and steel scrap and the health of the scrap industry depend directly on the health of the steel-making industry. The United States, as well as most of the world, is expected to consume increasing amounts of scrap as a steadily increasing population demands more steel products. World resources of scrap should be sufficient for the foreseeable future. An estimated 75 million metric tons of scrap was generated during 1998 in the United States, and 35 million tons of old scrap and 18 million tons of new scrap were consumed. The recycling efficiency was calculated to be 52 percent, and the recycling rate was found to be 41 percent.

INTRODUCTION

Iron, which includes its refined product steel, is the most widely used of all the metals. Iron and steel products are used in many construction and industrial applications, such as appliances, bridges, buildings, containers, highways, machinery, tools, and vehicles. The recycling¹ of iron and steel scrap (ferrous scrap) is an important activity worldwide, especially in the United States where 73 million metric tons (Mt) of new, old, and home scrap was consumed in the making of new steel during 1998. Obsolete iron and steel products and the ferrous scrap generated in steel mills and steel-product manufacturing plants are collected because recycling iron and steel products by melting and recasting them into semifinished forms for use in the manufacture of new steel products is economically advantageous. The steel scrap market is mature and highly efficient. The recycling rate for steel scrap, which was defined by the Steel Recycling Institute as total scrap recovered versus total raw steel produced, has exceeded 50 percent every year since World War II and has been more than 60 percent for about two decades.

Iron and steel scrap is more than just economically beneficial to steelmakers; ferrous scrap recycling is part of wise management of iron resources. Recovery of 1 metric ton (t) of steel from scrap conserves an estimated 1,030 kilograms (kg) of iron ore, 580 kg of coal, and 50 kg of limestone.

Each year, steel recycling saves the energy equivalent required to electrically power about one-fifth of the households in the United States (about 18 million homes) for 1 year (Steel Recycling Institute, 1999). In the production of steel, 99.9 percent of scrap melted is consumed in the new steel while producing negligible environmentally undesirable waste.

This materials flow study, as summarized in figure 1, describes the materials cycle of pig iron, direct reduced iron (DRI), and scrap used in the manufacture of iron and steel products; the recycling of scrap; and the losses of iron and steel during the steelmaking and product fabrication processes during 1998. The flow diagram shows the quantities of iron present at stages of steel product manufacture, shipping, and recycling.

In a free-market economy, scrap prices react quickly to changes in supply and, especially, demand. When demand for steel mill and foundry products is low, demand for scrap is low, and prices fall. Dealers cannot influence sales of scrap if mills and foundries do not need it to charge their furnaces. Although prices of scrap depend upon the market conditions for new products, the scrap industry uses inventory to absorb price differentials; that is, inventories increase as scrap prices decrease. Prices are also influenced by technological changes in mills, processing of scrap, the use of scrap substitutes, environmental controls and other Government regulations, and export demand. During the decade prior to 1998, the average annual composite price of No. 1 Heavy Melting Steel scrap, which was an industry standard, fluctuated between \$84.67 and \$135.03 per metric ton. Ferrous scrap prices declined significantly during 1991 and 1992 as domestic and world demand for scrap decreased. The period from 1993 to 1995 was one of strengthening demand and rising prices to a peak average price of \$130.60 per ton in 1995. Prices then declined to an average of \$108.30 in 1998.

In 1998, an estimated old scrap supply of more than 78 Mt was available for recycling, and about 35 Mt valued at nearly \$3.8 billion was recycled in the United States. About 18 Mt of new scrap was consumed, and about 38 Mt was unrecovered. The old scrap recycling efficiency was 52 percent, and the recycling rate was 41 percent (table 1).

¹Definitions for selected words are found in the Appendix.

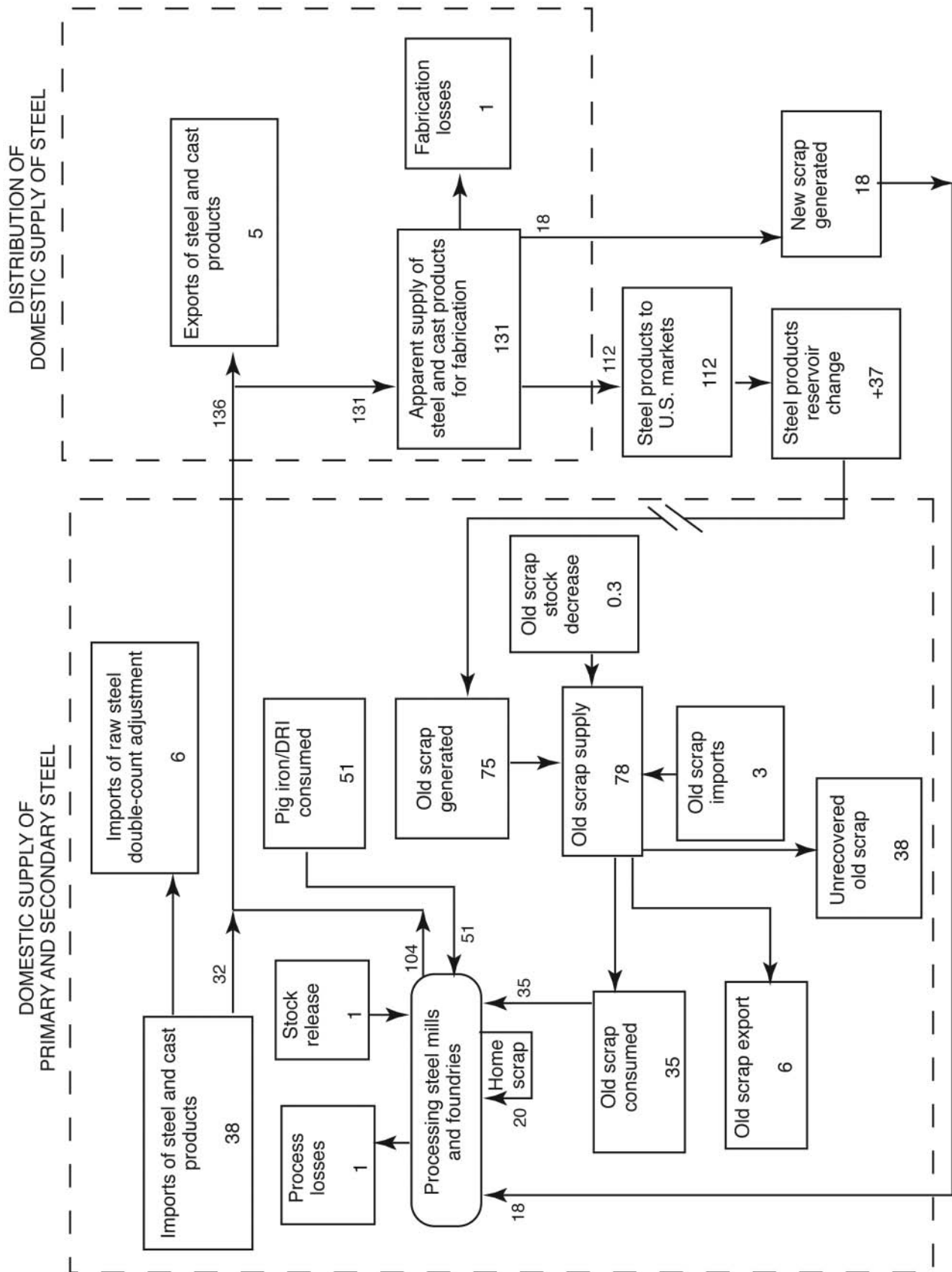


Figure 1. U.S. steel materials flow in 1998. Values are in million metric tons. DRI is direct-reduced iron.

Table 1. Salient statistics for U.S. iron and steel scrap in 1998.
[Thousand metric tons, unless otherwise specified]

Old scrap:	
Generated ¹	75,000
Consumed ²	35,000
Consumption value ³	\$3.79 billion
Recycling efficiency ⁴	52 percent
Supply ⁵	78,000
Unrecovered ⁶	38,000
New scrap consumed ⁷	18,000
New-to-old-scrap ratio ⁸	34:66
Recycling rate ⁹	41 percent
U.S. net exports of scrap ¹⁰	2,510
Value of U.S. net exports of scrap ³	\$272 million

¹Old scrap that will theoretically become obsolete in the United States in 1998. Dissipative uses are excluded.

²Old scrap recycled in 1998.

³Based on average 1998 three-city composite price (Chicago, Philadelphia, Pittsburgh) of \$108.30 per metric ton, published by American Metal Market, used to calculate values of old scrap consumed and U.S. net scrap exports.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus the old scrap imports plus old scrap stock decrease).

⁵Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap supply minus old scrap consumed plus old scrap stock decrease minus old scrap exports.

⁷Includes prompt industrial scrap but excludes home scrap.

⁸Ratio of quantities consumed, each measured in weight and expressed as a percentage of old plus new scrap consumed.

⁹Fraction of supply that is scrap on an annual basis. Old plus new scrap consumed divided by apparent supply (primary plus secondary production (old plus new scrap) plus imports minus exports plus adjustment for industry stock changes), in percent.

¹⁰Trade in scrap is assumed to be principally in old scrap.

SOURCES OF IRON

Approximately three-quarters of the iron ore used by domestic integrated steel mills to make iron and steel originated in the United States in 1998. Brazil, Canada, and Venezuela accounted for more than 90 percent of iron ore imports, which average about 15 million metric tons per year. Domestic consumption of iron ore was about 78 Mt in 1998. Almost all the ore is produced in Michigan and Minnesota from taconite, which is a low-grade ore; almost all the ore is produced in the form of pellets. In 1998, the quantity of iron ore by type consumed at U.S. iron and steel plants was pellets, 63 Mt, sinter, 11 Mt, and direct shipping ore, 900,000 t. Integrated steel mills consumed about 16 Mt of iron and steel scrap and 400,000 t of DRI in blast and basic oxygen furnaces during 1998. Minimills that use electric arc furnaces consumed about 3.4 Mt of pig iron and about 42 Mt of scrap during 1998. Thus, steel scrap comprised about 43 percent of iron units supplied for steelmaking. During 1998,

minimills also consumed about 1 Mt of DRI to improve steel quality; this was moderately higher than in previous years. About 87 percent of DRI imports, or 900,000 t, came from Venezuela.

SOURCES OF IRON AND STEEL SCRAP

Sources of different types of scrap are key features of the flow diagram (figure 1). Ferrous scrap available for recycling comprises home, old, and new scrap. Home (mill or revert) scrap is generated within the steel mill during production of iron and steel. Trimmings of mill products and defective products are collected and quickly recycled back into the steel furnace because their chemical compositions are known. The availability of home scrap has been declining as new and more-efficient methods of casting have been adopted by the industry. Old scrap includes metal articles that have been discarded after serving a useful purpose. Because of the wide variety of chemical and physical characteristics, old scrap often requires significant preparation, such as sorting, de-tinning, and de-zincing, prior to consumption in mills. New (prompt or industrial) scrap is produced from trimmings and discards during product manufacture. Statistical data for domestic consumption of home and old scrap were collected by the U.S. Geological Survey (USGS) (figure 1). Industry analysts estimate the amount of new scrap to be 15 percent of apparent consumption of steel mill products.

The domestic supplies of primary and secondary iron as shown in figure 1 consist of inputs from domestic steel mills and DRI producers, imports, and the supply of old scrap available for recycling. Statistical data were collected by the USGS, the American Iron and Steel Institute, and the U.S. Census Bureau.

HOME SCRAP

Home scrap consists of scrap that is produced in steel mills and foundries as a byproduct of their operations, as well as old plant scrap. This scrap has a known composition and is always recycled to the furnace for remelting. Home scrap generated and recycled in 1998 totaled about 20 Mt.

OLD SCRAP GENERATED

Old scrap is available for recycling. The largest source is junked automobiles followed by appliances, machinery, worn out railroad cars and tracks, demolished steel structures, and other products. Old scrap estimated as being available for recycling consisted of products in circulation that became obsolete in the United States in 1998. On the basis of the estimated average useful life of products and on the amounts of iron and steel contained in the various market classes in the appropriate prior years, the estimates of obsolescence developed by market class total 75 Mt. The weighted average product life was 19 years.

NEW SCRAP

New scrap is generated from manufacturing plants that make steel products. Scrap accumulates when steel is cut, drawn, extruded, or machined. The casting process also produces scrap as excess metal. Its chemical and physical characteristics are known, and it is usually transported quickly back to steel plants through scrap processors and dealers or directly back to the steel plant for remelting to avoid storage space and inventory control costs. The supply of new scrap is a function of industrial activity. When activity is high, more industrial scrap is generated. New scrap generated and recycled in 1998 was estimated to be 18 Mt. The new scrap-to-old-scrap ratio during 1998 was 34:66.

DISPOSITION OF IRON AND STEEL SCRAP

The U.S. steel industry reports scrap receipts and consumption to the USGS. Also, the U.S. Census Bureau reports scrap imports and exports. Apparent steel supply or consumption is the amount of steel products available within the United States. A unit of imported semifinished steel is included in finished steel shipments of companies that report to the American Iron and Steel Institute. These shipments and imports are added together to calculate apparent supply. Thus, this unit must be removed from imports to avoid double counting and overestimating of apparent consumption. In the model presented here, the starting point for ferrous scrap flow, through processing, is old scrap generated, which is the estimated 75 Mt of iron and steel that became obsolete in 1998. The old scrap supply available for recycling in the domestic steelmaking industry is 78 Mt, which is the amount of old scrap generated with 3 Mt old scrap imports added.

Some scrap is lost to the environment and is unrecoverable. Scrap that is discarded to scrap yards or abandoned in place is considered to be temporarily unrecoverable and may be recycled at some future date. In 1998, the steel industry used 35 Mt of old scrap and exported 6 Mt. Unrecovered old scrap, which is old scrap supply minus old scrap consumed minus old scrap exports, was estimated to be 37 Mt for 1998.

RECYCLING EFFICIENCY FOR OLD SCRAP

The relation between the amount of scrap that is theoretically available for recycling and what is recovered and reused is called recycling efficiency in this report. Old scrap recycling efficiency during 1998 was 52 percent. Recycling efficiency is not expected to increase significantly because ferrous scrap competes with direct reduced iron and pig iron as a raw material, both of which are readily available and tend to hold down scrap prices, thereby limiting scrap availability and recycling efficiency.

INFRASTRUCTURE OF THE IRON AND STEEL SCRAP INDUSTRY

Steel mills and foundries require ferrous scrap provided by brokers and scrap collectors and processors. Brokers bring scrap buyers and sellers together on a scrap transaction and receive a fee for this service. Consumers use brokers to procure scrap; processors use their services to market their scrap. Brokers purchase scrap without having storage or processing facilities for a particular client buyer or with the hope of finding a future buyer offering a favorable price and profit. More than 16,000 automotive dismantlers and thousands of scrap processing facilities in the United States play an integral role in the steel industry by collecting and preparing scrap for transport to steel mills that need raw materials (Steel Recycling Institute, 2000). The greatest concentration of these facilities is in the northeastern, north-central, and middle Atlantic regions because the large population uses more steel products and generates more scrap. The scrap recycling infrastructure causes the recycling rate of steel in the United States to be equal to and, in most cases, to exceed that of other industrialized countries. The rate is much higher than that of lesser developed countries.

PROCESSING OF IRON AND STEEL SCRAP

By using a variety of equipment, scrap dealers collect and process scrap into a physical form and chemical composition that steel mill furnaces can consume. The type and size of equipment they use depends on the types and volume of scrap available in the area and the requirements of their customers. The largest and most expensive piece of equipment is the shredder. The shredder can fragment vehicles and other discarded steel objects into fist-sized pieces of glass, various metals, plastic, and rubber. These materials are segregated before shipment by using air ducts, fans, flotation equipment, hand pickers, and magnets. Hydraulic shears, which have cutting knives of chromium-nickel-molybdenum alloy steel for hardness, slice heavy pieces of railroad car sides, ship plate, and structural steel into chargeable pieces. Baling presses are used to compact scrap into manageable bundles, thereby reducing scrap volume and shipping costs. Scrap dealers must carefully sort the scrap they sell, and steelmakers must be careful to purchase scrap that does not contain unacceptable levels of undesirable elements. Total scrap processing capability in the United States has been estimated to be 118 Mt (Robert Garino, Director of Commodities, Institute of Scrap Recycling Industries, Inc., written commun., January 2, 2001).

Old and new scrap consumed or recycled during 1998 was about 53 Mt. Recycled automobiles accounted for about one-sixth of the ferrous scrap recycled by the U.S. steel industry in 1998. About 16,000 automobile dismantlers and 202 shredders in the United States disassembled and shredded automobiles in 1998 (Recycling Today, 1998); appliances, bicycles, and other

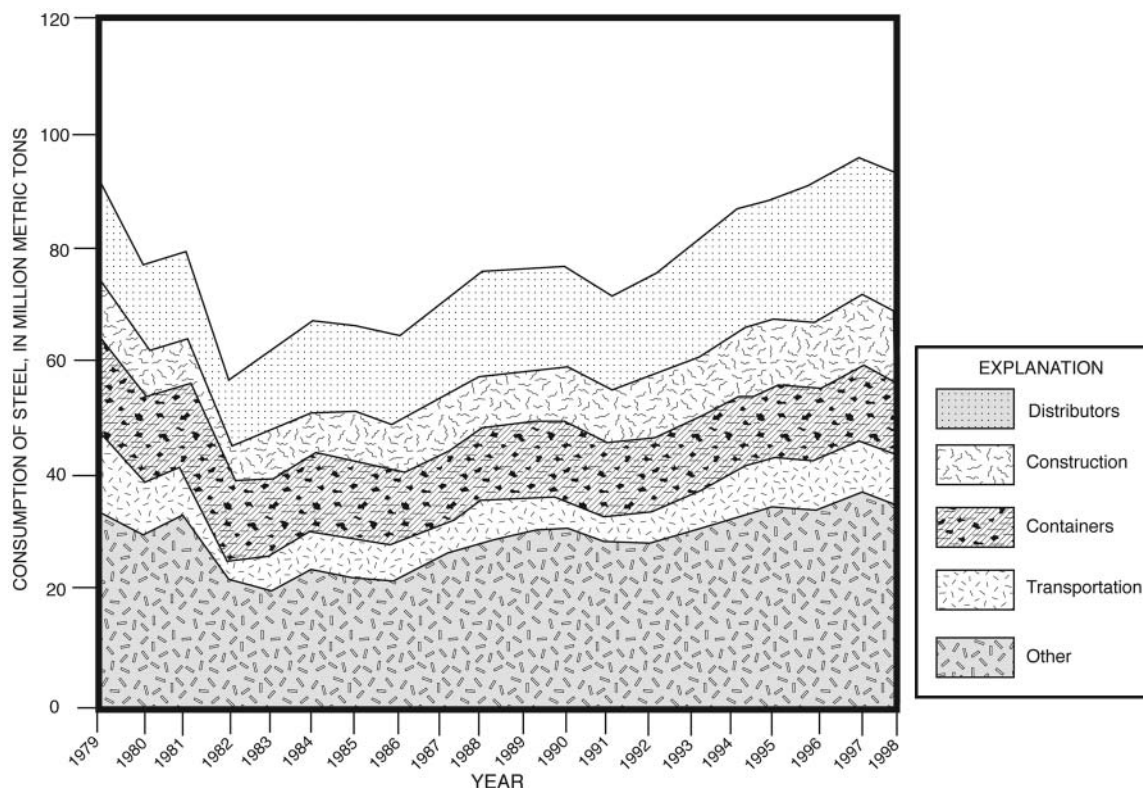


Figure 2. U.S. steel product shipments by end-use sector, from 1979 through 1998.

steel products are also shredded for recycling. More than 1,500 scrap yards process steel from construction and demolition sites by shearing, shredding, and baling. By comparing the annual tonnage of steel used to produce the new product with the tonnage of recycled product, steel recycling rates during 1998 were determined for the following: automobiles, 92 percent; construction plate and beams, 88 percent; appliances, 72 percent; steel cans, 56 percent; and other products, 64 percent (Institute of Scrap Recycling Industries, 1999).

Steel mills melt scrap in basic oxygen furnaces (BOF), electric arc furnaces (EAF), and, to a minor extent, blast furnaces. The proportion of scrap in the charge in a BOF is limited to less than 30 percent, whereas that in an EAF can be as much as 100 percent. Steel and iron foundries use scrap in EAFs and cupola furnaces. In 1998, BOFs were used to produce 55 percent of the total steel in the United States while using only 19 percent of total scrap consumed (American Iron and Steel Institute, 1998, p. 75). During the same period, EAFs produced 45 percent of total steel while using 62 percent of total scrap consumed. Scrap was also melted in blast furnaces and other types of furnaces.

Fabrication of new steel products produces new steel scrap that is relatively clean, chemically and physically, and of known chemical composition. For this reason, most scrap consumers prefer new scrap to old scrap. Preparation of new scrap is usually limited to cutting, cleaning, and baling prior to rapid transport back to the steelmaker for recycling.

SUMMARY AND OUTLOOK FOR FERROUS SCRAP RECYCLING FLOW

Consumption of ferrous scrap and the growth or decline of the scrap industry depends directly on the health of the steelmaking industry. Most regions of the world will see a marked increase in steel consumption during the next 5 years, according to the International Iron and Steel Institute (American Metal Market, 2000). In the United States, a steadily increasing population and a growing economy in the long term should assure that demand for steel products and the scrap used to make them will also increase. Steel and scrap consumption will continue to be in strong demand in the automotive and consumer appliance sectors. New highway and bridge projects supported by increased Federal funding will require structural and reinforcement bar products. The use of steel framing is increasing in the construction of multi-family developments, retirement homes, and single-family residences. Steel demand for can production, which includes aerosols, food, and paint, should remain strong in the long term. A thriving steel industry is dependent on plentiful inexpensive energy. As energy costs increase, the demand for steel pipe and tubular goods used in the oil and gas industry will increase for new drilling projects. Foundries are an important market for tin-bearing scrap from recycled cans.

Relative consumption of iron and steel scrap in four major markets (construction, containers, transportation, and distributors) from 1979 through 1998 may be inferred from shipments of steel mill products by the end-use sector as shown in figure 2. Total shipments and inferred scrap consumption in all sectors shown in the figure declined during the early 1980s, but by 1998, they regained the levels of the late 1970s. During the 20-year period, the proportion of steel containers to the total decreased from 7 to 4 percent, that of transportation decreased to 16 percent from 24 percent, and that of construction materials increased only slightly to 15 percent from 13 percent.

The EAF contribution to the total production of steel has risen dramatically, and the proportion of EAF steel produced should continue to increase, perhaps at a rate of 4 percent per year during the next 10 years (Steel Times International, 2000). The EAF may be the primary steel production method in the world by 2010 (Forster, 1999). The EAF has evolved in minimills from the small unit limited in use for specialty steel production to the large-capacity unit used to produce a wide range of steels, which includes the long product bars, structural shapes, tubulars, wire, rails, and flat product sheet and plate.

The availability of scrap and operating and capital cost advantages have made EAF growth possible. Locations of new minimills in areas of increasing population growth and manufacturing activity in the Southern States and the Western States and away from the traditional "rust belt" States have, to a large extent, satisfied demand for construction steel products and products used by the oil and gas industry. The EAF process is flexible in its raw material requirements and sources and can operate with considerable flexibility in making products depending on market requirements. Steelmaking by the EAF will continue to grow because of the capital and operating cost advantages relative to those of the BOF, the increasingly wide range of steel products that it makes, and its environmental cleanliness. The use of the EAF is the most effective way of reducing carbon dioxide emissions because of the lower energy needed to melt scrap than to smelt ore. Use of EAFs will increase as new minimills are built, and EAFs may replace operating BOFs. Ispat Inland, Inc., has been considering the replacement of one of its two BOFs with an EAF, which would create new demand for large amounts of ferrous scrap, as much as 900,000 metric tons per year (Worden, 2000). As the expansion of the EAF in the United States continues, ferrous scrap will continue to be available in sufficient quantities worldwide, but the role of the United States as the world's largest scrap supplier may diminish in importance (Katrak and others, 1999).

Ferrous scrap will remain the most important raw material used, but reduced iron in the form of DRI and hot-briquetted iron (HBI) will become a larger component in the raw materials mix for EAF steel production. Increasing availability from domestic producers of DRI and HBI will be a factor in this trend as will the increasing need for low-residual feedstock for the production of high-quality flat steel and special-bar-quality steels required to compete in the higher end markets.

E-commerce has been making progress at different rates in the steel industry as well as in many sectors of the economy. Selling scrap through e-commerce has potential, but adoption of e-commerce marketing by the ferrous scrap industry will probably be a slow evolutionary process. For e-commerce to be adopted, scrap processors, dealers, and brokers must realize the value of this new Internet technology and see potential gains in profits and efficiency.

A major problem for world and U.S. steel industries is that the world is producing too much steel. Except for North America, world steelmaking capacity is excessive relative to demand—perhaps as much as 15 percent more than can be consumed (Matthews, 2000). Companies continue to expand production by about 2 percent per year as profits decline. Excess steel production from major steelmaking nations is being imported into the United States because of its strong economy and open market system. The result has been declining domestic steel production, falling steel prices, and declining scrap demand and prices. Support seems to be increasing for consolidation among domestic steelmakers followed by the closing of inefficient plants and production reductions. Also, increased communications between scrap processors and consumers to resolve common issues of concern, such as quality control, the universality of specifications, and delivery services, will help maintain profitability for all concerned.

Recycling a large amount of scrap steel reduces the total energy needed to produce steel. Nevertheless, the steel industry uses about 3 percent of the energy consumed in the United States and more than 10 percent of that used by the industrial sector. Energy purchases represent nearly 20 percent of the total manufacturing cost of steel. Of particular concern is the recent trend toward declining availability of and higher prices for oil, gas, and electricity. To control these significant production costs, the industry will use and promote, as much as possible, new technologies to conserve energy, such as scrap preheating. Scrap preheating may increase threefold in new furnaces owing to energy conservation, shorter cycle times, and reduced operating costs (Steel Times, 2001). Another technology advance is the development of strip casting that reduces energy usage by as much as 50 percent by casting steel into its final thickness and shape with minimal further hot or cold rolling. Of immense concern to the scrap and steelmaking industries is the threat of accidental melting of radioactive scrap. Steel mills that receive ferrous scrap have been exposed to radioactive materials without warning. Such accidents can be extraordinarily expensive to steelmakers. In 2001, the Federal Government proposed releasing very low-level radioactive scrap into the recycling stream, an action that is vigorously opposed by the scrap and steelmaking industries. The Metals Industry Recycling Coalition has been trying to persuade the U.S. Department of Energy, the Nuclear Regulatory Agency, and the U.S. Congress to keep any radioactively contaminated scrap out of the commerce stream.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Manganese Recycling in the United States in 1998

By Thomas S. Jones

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-H

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

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CONVERSION FACTORS

Multiply	By	To obtain
<i>Length</i>		
kilometer (km)	0.6214	mile
inch (in.)	25.4	millimeter
<i>Volume</i>		
cubic foot (ft ³)	0.02832	cubic meter
<i>Mass</i>		
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Manganese Recycling in the United States in 1998

By Thomas S. Jones

ABSTRACT

This report describes the flow and processing of manganese within the U.S. economy in 1998 with emphasis on the extent to which manganese is recycled. Manganese was used mostly as an alloying agent in alloys in which it was a minor component. Manganese was recycled mostly within scrap of iron and steel. A small amount was recycled within used aluminum beverage cans. Very little manganese was recycled from materials being recovered specifically for their manganese content. For the United States in 1998, 218,000 metric tons of manganese was estimated to have been recycled from old scrap, of which 96 percent was from iron and steel scrap. Efficiency of recycling was estimated to be 53 percent, and the recycling rate, 37 percent. Metallurgical loss of manganese was estimated to be about 1.7 times that recycled. This loss was mostly into slags from iron and steel production from which recovery of manganese has yet to be shown economically feasible.

INTRODUCTION

The purpose of this study is to document the extent to which manganese is being recycled in the United States, to identify trends in domestic manganese recycling¹, and to determine the implications of these trends for sustainability of manganese use. The base year for the study is 1998.

Manganese (atomic number 25) is in Group 7 of the Periodic Table. In that table, its closest neighbors are, to the left, vanadium and chromium and, to the right, iron, cobalt, and nickel. Thus, it is not surprising that manganese should be considered a ferrous metal and that its major use is in iron-base alloys (steel and cast iron). Because manganese metal typically is brittle and unworkable, only a small amount can be used as an alloy in which manganese is the major component. Rather, manganese is used predominantly in alloys where it is a minor component, principally in steel and, to a lesser extent, aluminum. Manganese is essential to steel production by virtue of its sulfur-fixing, deoxidizing, and alloying properties.

In nonmetallurgical uses, the most common valences for manganese are two and four, and oxygen is the main element with which manganese is combined. Accordingly,

the mineral and commodity chemistry of manganese centers on such compounds as manganese oxide (MnO), manganese dioxide (MnO₂), manganese carbonate (MnCO₃), and manganese sulfate (MnSO₄). Pyrolusite (a mineral form of manganese dioxide), braunite (an oxysilicate), and rhodochrosite (a manganese carbonate) are among the minerals more commonly found in manganese ores. In 1998, the leading producers of ore were Australia, Brazil, China, Gabon (the leading U.S. source), India, South Africa, and Ukraine.

When a reductant (carbon) is present in the charge to a process for making iron or steel, some manganese ore is used directly. Examples include addition to the charge to an iron blast furnace and direct smelting of ore during steelmaking (Japan). For the most part, however, ore is smelted and reduced to its metallic content by carbon predominantly in submerged-arc electric furnaces but also in blast furnaces. Because manganese ores typically contain iron as well, the result of smelting is an iron-bearing ferroalloy, which is used subsequently to add manganese to liquid metal during steelmaking. The principal manganese ferroalloys and their typical components are high-carbon ferromanganese (78 percent manganese, 7 percent carbon, balance mostly iron) and silicomanganese (66 percent manganese, 17 percent silicon, 2 percent carbon). An electrolytic process is used to obtain electrolytic manganese dioxide (EMD) and most manganese metal, the two other forms in which manganese is commercially most used. The sequence of steps usually used in producing these two materials is similar—leaching manganese feed with sulfuric acid and electrodepositing EMD or metal from the leach liquor after it has been purified.

Metallurgical applications account for most domestic manganese consumption, of which 85 to 90 percent has been going to steelmaking and about 8 percent, to the manufacture of dry cell batteries. The preponderance of the manganese used domestically for making batteries is now EMD because usage of natural battery ore has declined greatly. The manufacture of manganese chemicals, such as potassium permanganate, and agricultural use of manganese in animal feed and plant fertilizer as oxide, sulfate, and oxysulfate together account for another 5 percent of use. These patterns of domestic use are typical for other industrialized countries having well-developed steel industries.

¹Definitions for select words are found in the Appendix.

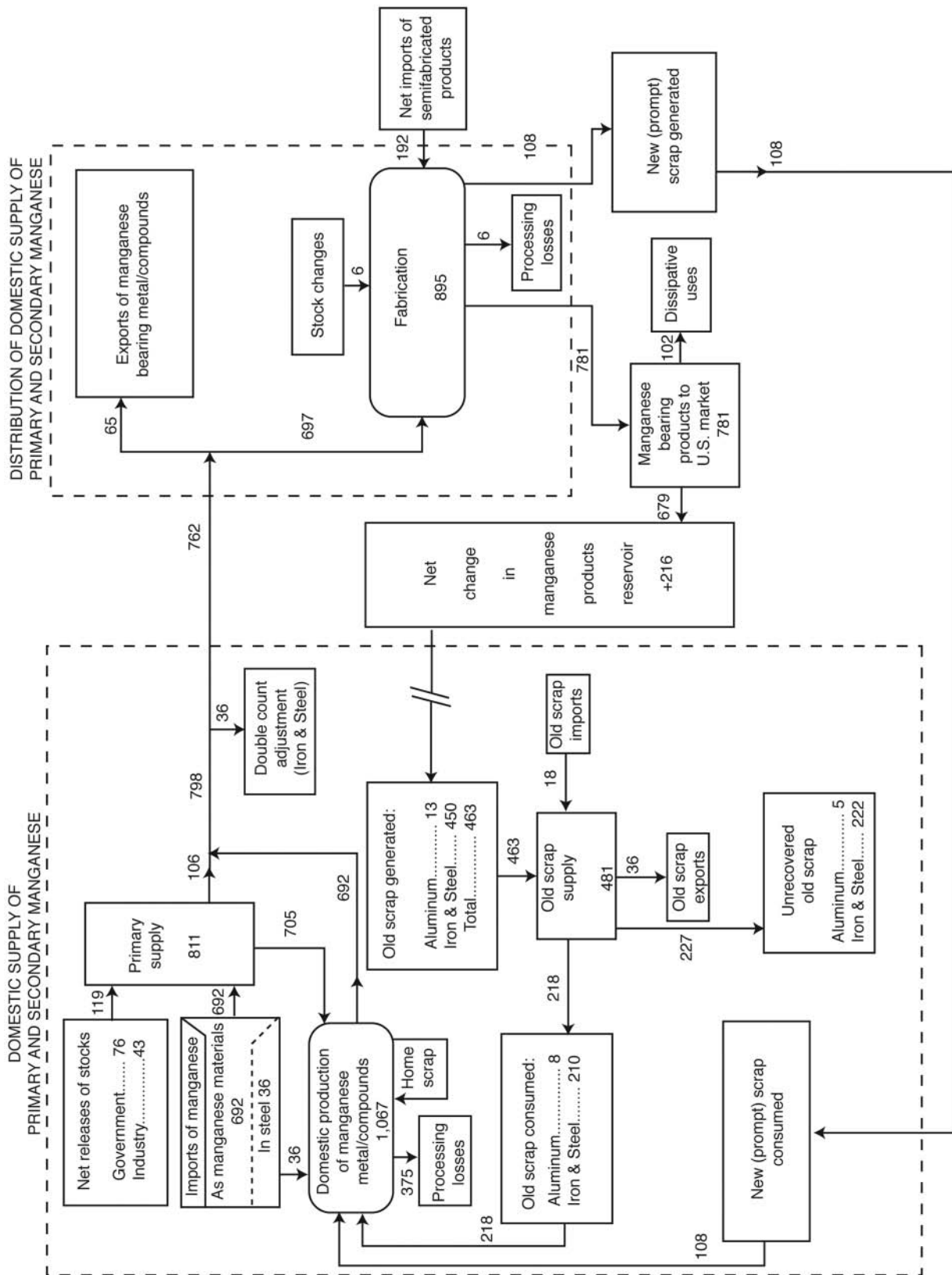


Figure 1. U.S. manganese materials flow in 1998. Values are in thousand metric tons of manganese content.

Table 1. Salient statistics for U.S. manganese-bearing in 1998.
[Values in thousand metric tons of contained manganese, unless otherwise specified]

Old scrap:	
Generated ¹	463
Consumed ²	218
Consumption value	\$120 million
Recycling efficiency ³	53 percent
Supply ⁴	481
Unrecovered ⁵	227
New scrap consumed ⁶	108
New-to-old-scrap ratio ⁷	33:67
Recycling rate ⁸	37 percent
U.S. net exports of scrap ⁹	18
Value of U.S. net exports of scrap	\$10 million

¹Old scrap that will theoretically become obsolete in the United States in 1998. Dissipative uses are excluded.

²Old scrap recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported).

⁴Old scrap generated plus old scrap imported.

⁵Old scrap supply minus old scrap consumed minus old scrap exported.

⁶Includes prompt industrial scrap but excludes home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of supply that is scrap on an annual basis. It is defined as (consumption of old scrap plus consumption of new scrap) divided by apparent supply (see appendix), measured in weight and expressed as a percentage.

⁹Trade in scrap is assumed to be principally in old scrap.

For 1998, the average price for U.S. delivery of metallurgical-grade ore was assessed at \$2.40 per metric ton unit, on the basis of cost, insurance, and freight; and the year-average free-on-board price for imported high-carbon ferromanganese was \$502 per long ton of alloy (Jones, 2000, p. 49.2-49.3). At per kilogram of contained manganese, these prices equate to 24 cents for ore and 63 cents for high-carbon ferromanganese. For 1993 through 1998, the ore prices were reasonably steady following a decline from a peak of \$3.78 per metric ton unit in 1990 (Jones, 1999). In the 1990s through 1998, the price trend for high-carbon ferromanganese had been gradually declining from a maximum of about \$650 per long ton of alloy in 1990.

The salient statistics for manganese-bearing scrap given in table 1 are based mainly on and determined by the status of recycling for iron and steel. The recycling of iron and steel scrap is the subject of another report by the U.S. Geological Survey (USGS) to which the reader is referred for details (Fenton, in press). Those aspects that deal with iron and steel scrap are given only in summary form in this report. Two of the three ratios given in table 1 are nearly the same as the ratio for manganese and iron and steel scrap—old scrap recycling efficiencies of 53 percent for manganese and 52 percent for iron and steel scrap and new-to-old-scrap

ratios of 33 to 67 for manganese and 34 to 66 for iron and steel scrap. The lower recycling rate for manganese (37 percent) than that for iron and steel scrap (41 percent) reflects the relatively large loss of manganese during metallurgical processing. Figures given in table 1 for the value of the manganese units in scrap are based on a unit value of \$560 per metric ton of manganese as estimated from foreign trade data for 1998.

The only significant metal form recovered specifically because of its manganese content was wear-resistant steel in which the manganese content typically is about 12 percent (so-called Hadfield steel). Otherwise, recovery of manganese in metal was incidental to the recycling of another metal—iron in the case of steel scrap and iron castings and aluminum in the case of used beverage cans (UBCs).

A small amount of manganese was recovered through recycling of dry cell batteries or manganese-bearing wastes generated in battery manufacture. One battery company formed a partnership with a steel company whereby more than 1,000 metric tons per year of scrap from the battery company was to be consumed in steel production (Watson, Andersen, and Holt, 1998). With a manganese content of 20 percent, this volume might be expected to contain about 200 metric tons (t) of manganese (Ferlay and Weill, 2000). Battery recycling is not considered further in this report because the quantity of manganese being recycled from batteries was relatively small and not precisely known.

SOURCES

Figure 1 is a composite derived from knowledge of the flows of manganese and manganese-bearing materials, such as iron and steel scrap and aluminum UBCs. The data for the majority of the diagram are based on the material flow relations for iron and steel scrap, in which the manganese content is taken to be 0.6 percent throughout, as suggested by Jones (1994, p. 42), for average manganese content of steel. Scrap of high-manganese Hadfield steel is not treated as a separate item. Its annual domestic production was not known but is estimated to be about 50,000 t as inferred from shipments (Kirgin, 2000). Even if it were recycled at a 75-percent rate, the manganese content of manganese steel scrap would only be about 2 percent of the estimated manganese content of the 35 million metric tons (Mt) of iron and steel scrap consumed/recycled in 1998.

The inputs to the primary supply of manganese as diagrammed in the upper left of figure 1 consist of drawdowns of industry and Government stocks of manganese materials, imports of manganese materials (dioxide, ferroalloys, metal, ores), and imports of raw steel. Of this, 4 units (4,000 t) of manganese exported as ore and 102 units of manganese destined for battery and chemical uses bypass metallurgical processing and flow directly to the output (right) side of the diagram. The balance of the primary supply goes mainly into the manufacture of ferroalloys and steel. Most of the

ferroalloys and metal were used in steelmaking, but 31 units were exported and are included within the 65 units of exports.

The principal data sources for this report are Fenton (2000b, c), Jones (2000), and the sources upon which the data in those chapters were based. Quantities for manganese end uses are obtained from data collected by means of the Manganese Ore and Products Survey of the USGS.

The types of manganese-bearing products ultimately becoming scrap and the industries in which they were used can be inferred by considering the pattern of manganese consumption. This is shown for 1979 through 1998 in figure 2, in which an estimated total of 730,000 t of manganese was used for 1997; this replaced the anomalously low total of 643,000 t published in the 1999-2001 USGS Minerals Yearbooks. Construction, machinery, and transportation have been the larger of the consuming sectors. The "All Other" category includes steel for nonspecified uses as well as a number of other minor steel categories (appliances and equipment, cans and containers, and oil and gas industries).

OLD SCRAP GENERATED

Old scrap generated was mostly iron and steel scrap. The first step in estimating this component was to assign lifetimes to various steel products as categorized in the steel shipments data published in the Annual Statistical Reports of the American Iron and Steel Institute. For iron and steel scrap, the weighted average product life was 19 years. For each product, the quantity of steel becoming obsolete in 1998 was taken to be that shipped at the beginning of its life. For example, the quantity for a product with a lifetime of 20 years was the quantity of that product shipped in 1978.

Scrap from aluminum UBCs made only a small contribution to old scrap generated. Estimation of the addition to manganese recycling from UBCs is discussed in detail in the "Processing of Manganese-Bearing Scrap" section of this report.

NEW SCRAP

New scrap consists entirely of iron and steel scrap that results from fabricating operations and is often returned directly from the fabricator to the originating steel plant. The quantity of new scrap generated is taken as being equal to 15 percent of apparent consumption of steel (Fenton, in press). Apparent consumption of steel in 1998 was 118 Mt (Fenton, 2000a). The quantity of new scrap consumed is assumed to be equal to that generated without losses or additions. As indicated in figure 1, the quantity of new scrap generated was about one-fourth of the quantity of old scrap generated.

DISPOSITION

The supply of old scrap consists of old scrap from iron and steel scrap plus a small amount of old scrap from UBCs (discussed in the section "Used Aluminum Beverage Cans"). Output from old scrap supply includes exports and unrecovered scrap with the balance going into current consumption (recycled). Import and export quantities are obtained from the trade statistics for iron and steel scrap. The quantity consumed is obtained from iron and steel scrap consumption data as provided by a USGS survey from which are deducted the amounts of consumption of home and prompt scrap. The number of manganese units in the quantity consumed was 210,000 t. The amount of unrecovered scrap is estimated to be the difference needed to obtain a balance for supply of old scrap.

Included in the right-hand part of figure 1 is the dissipative loss of 102,000 t of manganese from the manufacture and use of manganese-containing batteries and chemicals. This was the quantity obtained for 1998 from the USGS Manganese Ore and Products Survey of plants where batteries, EMD, or such manganese chemicals as manganese sulfate and potassium permanganate are made or that supplied manganese raw material that ultimately went into such items as animal feed and plant micronutrients. The battery total includes imports of manganese dioxide. The average lifetime of batteries and chemicals was assumed to be less than 1 year.

RECYCLING EFFICIENCY FOR OLD SCRAP

Recycling efficiency is the amount of scrap recovered and reused relative to the amount theoretically available to be recovered and reused. The recycling efficiency for manganese-bearing scrap is calculated to be 53 percent on the basis of the recycling of old iron and steel scrap plus a small amount of old UBC scrap.

By using a different manganese material flow model, Gabler (1995, p. 19) estimated the amount of manganese contained in old scrap that was recycled to correspond to 12 percent of the apparent consumption in 1990. The equivalent percentage is 28 percent for the flow model for 1998 shown in figure 1.

Recycling of iron and steel scrap has been going on for more than 200 years, and that of UBCs, for about 30 years. Nearly one-half of domestic steel production in 1998 was from plants based solely on the use of scrap. Recycling efficiency is expected to remain about the same for iron and steel scrap because of competition from alternative sources of iron units. The aluminum industry expects that the trend in recycling rate for UBCs will be a slow but gradual increase. For information on the recycling of iron and steel, see Fenton (in press).

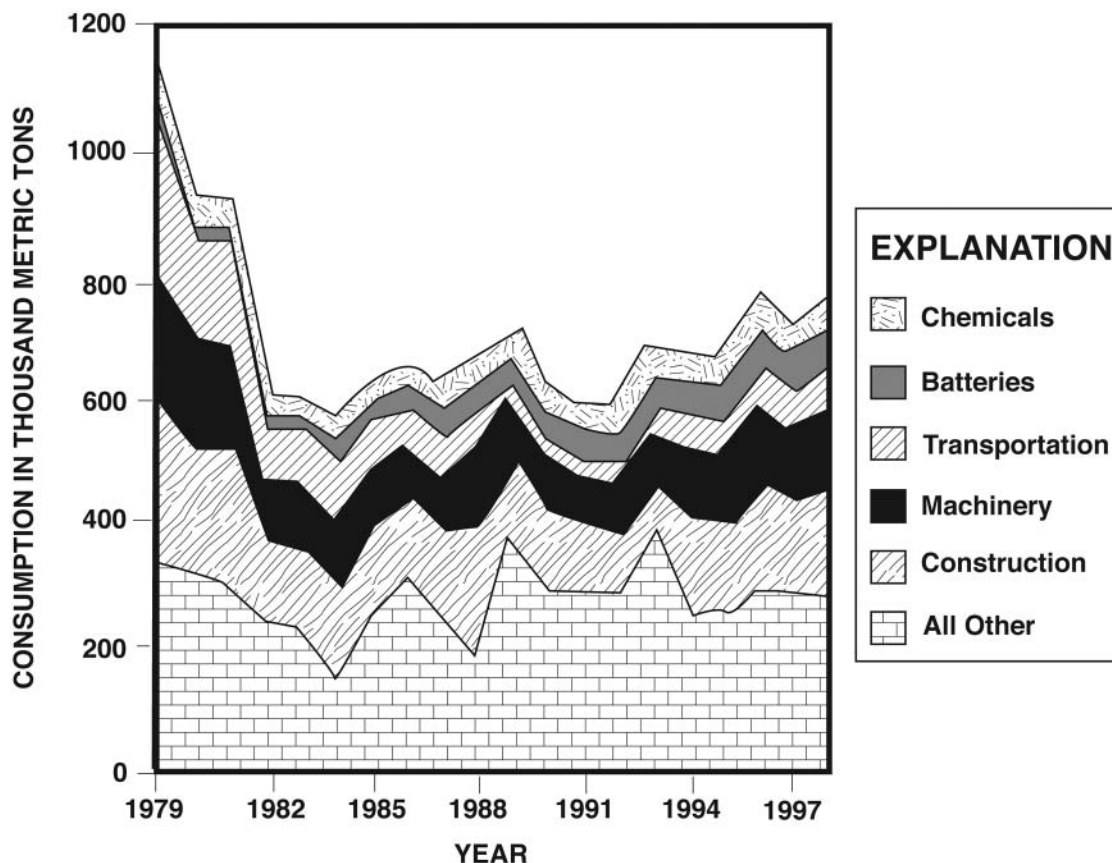


Figure 2. U.S. manganese consumption, by end-use pattern, from 1979 through 1998.

INFRASTRUCTURE

No ore with a manganese content of more than 35 percent was mined domestically in 1998. Consequently, all primary units of manganese were obtained from either imported ore or ore released from Government stockpiles.

The chief facility where manganese was smelted and/or extracted was near Marietta, Ohio, and was the only site where manganese ferroalloys were produced domestically. In 1998, this facility, which was operated by Elkem Metals Co., accounted for more than 50 percent of total U.S. consumption of manganese ore. Ownership of this facility changed in 1999 to France's Eramet; it was renamed Eramet Marietta Inc. In 2000, annual production of manganese ferroalloys there was reported to be 65,000 t of silicomanganese and 104,000 t of various grades of ferromanganese (Platt's Metals Week, 2000); manganese metal and EMD also were produced electrolytically at this site. Several other companies produced EMD—Eveready Battery Co. in Ohio, Kerr-McGee Chemical LLC in Mississippi, and Erachem Comilog, Inc. (formerly Chemetals Inc.), in Tennessee. Electrolytic metal was produced domestically at another site in Nevada (also Kerr-McGee). Subsequently, domestic production of manganese metal ended, first at Eramet Marietta in 2000 and then at Kerr-McGee in 2001.

With regard to the infrastructure of iron and steel scrap recycling [discussed by Fenton (in press) in more detail], a large amount of scrap is generated by a multitude of firms and facilities located in the northern and eastern parts of the country.

Monthly and annual reports of the USGS for Iron and Steel Scrap and for Aluminum provide details of foreign trade in scrap of these materials, especially trade of the United States. The United States historically has been a net exporter of iron and steel scrap.

In chapter 81 of the Harmonized Tariff Schedule for U.S. imports, the part that pertains to "Other base metals" contains a "Waste and scrap" subcategory (8111.00.3000) for manganese. The quantity of imports reported in this subcategory typically is about 200 t or less, most of which is from Canada. The nature of the material being reported under this subcategory is not well known and probably consists of various manganese-bearing drosses, residues, and steel and/or iron items or perhaps none of these. This material is not included within the manganese materials flow discussed in this report except that the 215 t of so-called manganese waste and scrap reported as having been imported is assigned an average manganese content of 50 percent and, on that basis, is included within total manganese imports.

PROCESSING OF MANGANESE-BEARING SCRAP

IRON AND STEEL SCRAP

Of the 811,000 t of manganese units from stocks and imports that compose primary supply, 705,000 t goes into domestic production (figure 1). Domestic production includes the sequence of manufacturing steps that produce manganese ferroalloys and/or metal, raw steel in whose manufacture domestic plus imported ferroalloys and metal are consumed, and finally steel mill shapes that are shipped to fabricators or end users. By means of a balance between the total inputs and outputs for production that relate to iron and steel, the metallurgical loss or nonutilization of manganese was calculated to be 368,000 t. This signifies a loss rate of 52 percent, which is somewhat greater than the range of 40 to 50 percent that is presumed to apply for manganese loss in steelmaking in the 1990s (Jones, 1994, p. 15). The 52-percent figure does not seem unreasonable, however, when one considers that it includes not only losses in steelmaking, but also those in the manufacture of ferroalloys and metal. Presumably, most of the manganese not ending up in product becomes a constituent of slag, at least some of which is usable.

Most of the processing of iron and steel scrap takes place prior to its arrival at the steel plant. Operations at the steel plant consist of keeping scrap segregated according to its chemical and physical characteristics and cutting up bulky home scrap into more manageable pieces. Because of the high temperatures involved, iron and steel scrap is completely melted in the steelmaking operation. Refining typically includes an oxidation step; for example, by injection of gaseous oxygen. This causes the losses of carbon to gas and of some iron, manganese, and silicon to slag. The recycling model for iron and steel shows a processing loss for iron of 1 Mt, which is presumed to carry with it a manganese loss of 6,000 t, thus raising processing losses calculated so far to 374,000 t (Fenton, in press).

Small amounts of iron and steel are unrecoverably lost through such dissipative causes as corrosion. Some old scrap can be regarded as temporarily unrecovered through its disposal in landfills or abandonment in place. The manganese units in unrecovered iron and steel scrap were estimated on the basis of the iron and steel model to be 222,000 t.

Following this model, the amount of old scrap generated (that is, the manganese content of the 75 Mt of iron and steel that became obsolete in 1998) was 450,000 t. As stated earlier in the section "Old Scrap Generated," the weighted average recycling time was 19 years. The material savings from recycling of iron and steel scrap is estimated to be

1 t of iron ore and 0.6 t of coal per metric ton of scrap recycled. The energy saved from recycling of iron and steel scrap was equivalent to that required to supply electricity to about one-fifth of domestic households (Fenton, in press).

In view of its quality and known composition, home scrap within the steel plant is assumed to be recycled within 1 year of its generation. Similarly, new scrap generated during fabricating operations is relatively clean and of known composition and requires little preparation. Consequently, prompt scrap rapidly finds its way back to steel plants. This type of scrap is usually recycled directly; for example, from an automobile plant back to the steel plant from which the steel originally came.

USED ALUMINUM BEVERAGE CANS

Some of the quantities shown in figure 1 reflect the relatively small amounts of manganese recovered by recycling of UBCs. On a weight basis, 75 percent of aluminum beverage can (ABC) bodies are made from alloy 3004, and 22 percent of lids, from alloy 5182. The nominal manganese content of alloy 3004 is 1.1 percent, and that of alloy 5182 is 0.35 percent. The conditions for UBC recycling in 1998 were taken to be the same as those that had been projected for 1997—average UBC manganese content of 0.92 percent and melt loss of 9.3 percent (Sanders and Trageser, 1990, p. 197). Melt loss is the only source of manganese loss in UBC recycling; loss of manganese is not due to burn-off or vaporization (R.E. Sanders, Jr., Technical Consultant, Aluminum Company of America, oral commun., December 4, 2000). UBCs were processed in facilities dedicated to their recycling.

The Aluminum Association estimated the net weight of new ABCs shipped in 1998 to be 3.09 billion pounds (1.4 Mt) and the rate of their recycling to be 62.8 percent (Aluminum Association, Inc., 1999). At 0.92 percent, the manganese content of the quantity shipped is approximately 12,900 t, which is assumed to be the quantity of old scrap eventually generated from this source. UBC recycling—from can shipment to use to disposal and recovery—takes place rather rapidly so that recovery is assumed to take place within the year of generation. At a recycling rate of 62.8 percent, the manganese content of the old scrap recovered (consumed) is 8,100 t. The unrecovered quantity of manganese is 4,800 (12,900 minus 8,100) t, or a rounded 5,000 t, which is only about 2 percent of total unrecovered old scrap. At a 9.3-percent melt loss rate, the loss in processing the 8,100 t of manganese recovered from UBCs in old scrap is about 750 t, or a rounded 1,000 t. Incorporation of this with the process losses mentioned in the "Iron and Steel Scrap" section increases the total processing loss of manganese to 375,000 t.

SUMMARY AND OUTLOOK

Trends in the recycling of manganese are largely determined by trends in the recycling of iron and steel, which has accounted for 85 to 90 percent of manganese consumption. Steel is the more-important industry with a production of about 10 times that for cast iron. Consequently, the majority of manganese consumption is accounted for by production of raw steel (primary shapes).

The precipitous drop in manganese consumption between 1979 and 1982, which is shown in figure 2, is attributed mainly to a large decrease in raw steel production owing to adverse economic conditions and a significant decrease in the amount of manganese used per metric ton of steel produced. This decline in unit consumption was a gain from the adoption of new steelmaking technologies in the early 1980s, such as the use of combined blowing (Jones, 1994, p. 36). After 1983, the trend in total manganese consumption has been similar to that for raw steel production (about 1.8-percent-per-year growth). Assuming no significant change in manganese unit consumption, forecasts of the International Iron and Steel Institute suggest that the annual growth rate for total manganese consumption during the coming decade will be no greater than that of the past one (Iron & Steelmaker, 1999).

Figure 2 also shows that the distribution of manganese consumption among end uses has changed little with time. For the reasonably foreseeable future, this distribution pattern will remain about the same. Manganese consumption in batteries has been growing at a faster rate (about 6 percent per year) than steel-related uses but still accounts for less than 10 percent of total demand.

Recycling of iron and steel scrap is a well-established component of domestic steel production. Supply of iron units for steel production now is about evenly divided between iron ore plus some scrap (integrated steelmaking) and all scrap except for a small proportion of direct-reduced iron [electric arc furnace (EAF) mills]. By 2000, the EAF process could be used in 47 percent of domestic steel production. Because the share of domestic steel production taken by EAF mills has been growing steadily, these mills could be the dominant process by 2010 (Stubbles, 2000). This will provide the motivation for maintaining domestic recycling of manganese-bearing iron and steel scrap.

On a much smaller scale, recycling of UBCs has reduced the primary manganese requirement for aluminum beverage cans. Recycling of household batteries, which is an activity that is in its infancy, has the potential to make a small contribution to manganese recycling. One of the original motivations for battery recycling—preventing mercury loss to the environment—has been greatly diminished because deliberate additions of mercury to the battery mix are no longer made.

From the standpoint of sustainable use of manganese, reducing manganese loss in metallurgical processing would appear to be a major subject for investigation and is always of interest as a way of cutting costs. The relations given in figure 1 indicate that almost one-half as much manganese is lost in metallurgical operations as is contained in products going into use. These relations also indicate that nearly 90 percent of metallurgical losses were compensated for by the level of scrap recycling. Efforts to recover manganese from steelmaking slags date back to at least World War II, but development of a commercially feasible method has not been achieved nor seems likely to be for the foreseeable future (Jones, 1994, p. 29). A major difficulty is that the manganese content of steelmaking slags is relatively low (typically 7 percent or less). Significant quantities of iron and steel slags are used in construction and road building and for other purposes. These usages do not constitute a use of their manganese values per se.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinsplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinsplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Columbium (Niobium) Recycling in the United States in 1998

By Larry D. Cunningham

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-I

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

Columbium (Niobium) Recycling in the United States in 1998

By Larry D. Cunningham

ABSTRACT

This report describes the flow of columbium (niobium) in the United States in 1998 with emphasis on the extent to which columbium was recycled/reused. Columbium was mostly recycled from products of columbium-bearing steels and superalloys; little was recovered from products specifically for their columbium content. In 1998, about 1,800 metric tons of columbium was recycled/reused; about 55 percent of that was derived from old scrap. The columbium recycling rate was calculated to be 22 percent, and columbium scrap recycling efficiency, 50 percent.

INTRODUCTION

As shown in figure 1, this materials flow study of columbium includes a description of columbium supply-and-demand factors for the United States in 1998 to illustrate the extent of columbium recycling¹ to identify recycling trends.

Columbium [niobium (Nb)] is a steel-gray ductile refractory metal that is used mostly as an alloying element in steels and superalloys. Columbium and niobium are synonymous names for the chemical element with atomic number 41—"columbium" was the name given in 1801, and "niobium" was the name officially designated by the International Union of Pure and Applied Chemistry in 1950. The metal conducts heat and electricity well, has a high melting point (about 2,470°C), is readily fabricated, and is highly resistant to many chemical environments.

Salient columbium statistics are based on the columbium content of steel and superalloy scrap (table 1). In 1998, about 2,900 metric tons (t) of columbium contained in old scrap was generated; about 1,000 t of columbium valued at about \$20 million was recycled/reused. The old scrap recycling efficiency was calculated to be about 50 percent, and the recycling rate was about 22 percent. Columbium contained in new scrap consumed was about 800 t.

GLOBAL GEOLOGIC OCCURRENCE OF COLUMBIUM

Columbium is almost always found in nature as an oxide in association with other minerals, but not in elemental form or as a sulfide. Columbium has an overall

crustal abundance estimated to be 20 parts per million and a strong geochemical affinity for tantalum. Pyrochlore [(Ca,Na)₂Nb₂(O,OH,F)₇] and bariopyrochlore (also known as pandaite), which is its barium analog, from Brazil and Canada have become the main sources of columbium. The minerals, which contain little tantalum, have a columbium oxide-to-tantalum oxide ratio of 200:1 or greater. The minerals are commonly found in the interior parts of alkaline igneous complexes, frequently in association with minerals of thorium, titanium, uranium, and rare-earth elements. In Brazil, the occurrences are in eluvial deposits that result from the weathering in place of carbonatites, which leaves an enriched concentration of apatite, bariopyrochlore, and magnetite. In Canada, the occurrences are in complex ring structures of carbonatite and alkaline rocks in the Precambrian Shield. Columbite and tantalite, which are similar in chemical composition and atomic structure, are the other principal columbium minerals. When columbium predominates over tantalum, the proper name for the mineral is "columbite" when the reverse is true, the proper name is "tantalite." Columbite-tantalite, which is also known as coltan in some African countries, occurs mainly as an accessory mineral disseminated in granitic rocks or in pegmatites associated with granites. Columbite-tantalite is known to exist in all continents, but most deposits with high columbium or tantalum content are small and erratically distributed. In most cases, economic mineral concentrations have been produced by weathering of pegmatites and formation of residual or placer deposits (Parker and Adams, 1973; Cunningham, 1985; Crockett and Sutphin, 1993, p. 6-7).

The largest columbium reserves and resources are located in Brazil where reserves are estimated to be more than 4 million metric tons of contained columbium in pyrochlore deposits. Canada has the second largest columbium reserves in pyrochlore deposits; the reserves are estimated to be about 140,000 t of contained columbium (Cunningham, 2002). U.S. columbium resources are of low grade, and none were considered to be economically minable in 1998.

PRODUCTION AND PRODUCTION PROCESSES

The United States, which has no columbium mining industry, must import all its columbium source materials for processing. Brazil and Canada, which are the world's largest producers of columbium minerals, together account for more

¹Definitions for select words are found in the Appendix.

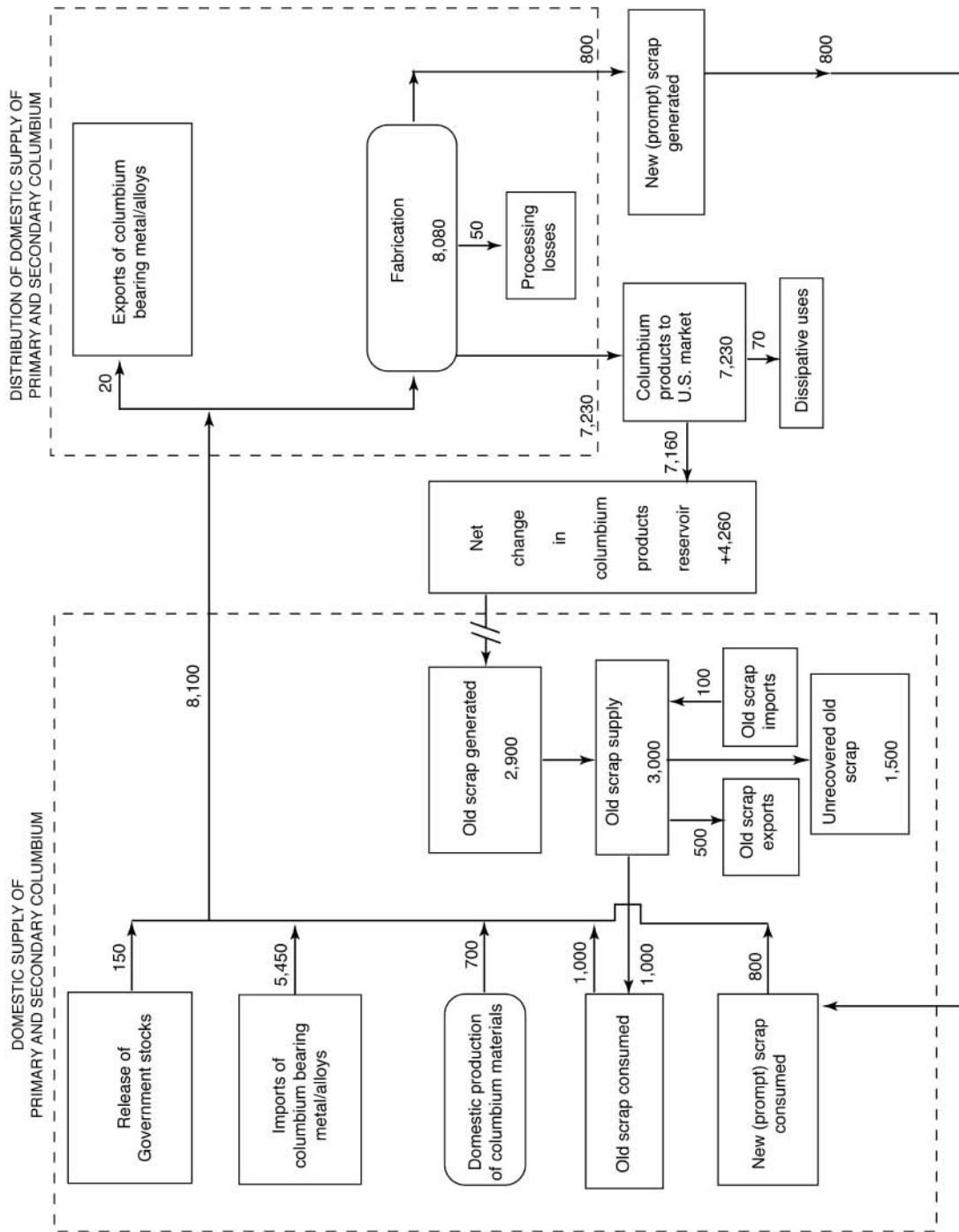


Figure 1. U.S. columbium materials flow in 1998. Values are in metric tons of contained columbium.

Table 1. Salient statistics for U.S. columbium scrap in 1998. [Values in metric tons of contained columbium, unless otherwise specified]

Old scrap:	
Generated ¹	2,900
Consumed ²	1,000
Value of old scrap consumed ³	\$20 million
Recycling efficiency ⁴	50 percent
Supply ⁵	3,000
Unrecovered ⁶	1,500
New scrap consumed ⁷	800
New-to-old-scrap ratio ⁸	44:56
Recycling rate ⁹	22 percent
U.S. net exports of scrap ¹⁰	400
Value of U.S. net exports of scrap	\$6 million

¹Columbium content of products theoretically becoming obsolete in the United States in 1998; this excludes dissipative uses.

²Columbium content of products that were recycled in 1998.

³Unit value of contained columbium in materials used in calculating total value of contained metal in scrap.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported).

⁵Old scrap generated plus old scrap imported.

⁶Old scrap generated plus old scrap imported minus old scrap consumed minus old scrap exported.

⁷Including prompt industrial scrap but excluding home scrap.

⁸Ratio of quantities consumed, in percent.

⁹Fraction of the columbium apparent supply that is scrap, on an annual basis.

¹⁰Trade in scrap is assumed to be principally in old scrap.

than 95% of total reported world production. Pyrochlore (produced in Brazil and Canada) is the columbium source material that is used to produce steelmaking-grade (regular-grade) ferrocolumbium. The remaining columbium mineral supply comes from the mining of columbite and columbite-tantalite mostly in Australia, Brazil, Nigeria, and other African countries. Brazil discontinued the export of pyrochlore in about 1981 and now exports only upgraded/value-added columbium products, most of which is steelmaking-grade ferrocolumbium. Prior to 1994, the United States converted pyrochlore from Canada into steelmaking-grade ferrocolumbium. Beginning in late 1994, however, all pyrochlore produced in Canada was being converted to steelmaking-grade ferrocolumbium in that country. Thus, the United States does not produce steelmaking-grade ferrocolumbium from pyrochlore, and the U.S. steel industry requirements for ferrocolumbium are satisfied virtually entirely by imports. Brazil's annual ferrocolumbium production capacity, which is mostly steelmaking grade, is estimated to be more than 30,000 t of contained columbium. In 1998, Brazil accounted for almost 80 percent of total U.S. columbium imports. Canada's annual capacity is estimated at about 2,200 t of contained columbium in steelmaking-grade ferrocolumbium.

Pyrochlore is mined mainly by mechanized open pit or underground methods. An open pit is used in Brazil, and an underground mining method is used in Canada. Ore with host rock is usually dislodged from a working face with explosives. After the ore has been finely ground, it is beneficiated primarily by various flotation procedures combined with magnetic separation to remove iron minerals. A chloridizing and leaching process also can be used to lower barium, lead, phosphorus, and sulfur contents. Methods used to mine other columbium-bearing ores have ranged from simple hand operations in small pegmatite mines to hydraulic monitors and dredges at placer deposits. Aluminothermy is a process used for making steelmaking-grade ferrocolumbium from pyrochlore concentrates. A mixed charge of aluminum powder, iron oxide, pyrochlore concentrates, and slagging agents is reacted in a steel cylinder. Steelmaking-grade ferrocolumbium is also produced from pyrochlore in an electric furnace by using essentially the same reactants as in the aluminothermic process. Heat input can be better controlled with the electric furnace process, and columbium recovery is generally better than the aluminothermic process. The extraction of columbium from other columbium-bearing concentrates involves dissolution with hydrofluoric acid followed by liquid-liquid extraction with methyl isobutyl ketone (MIBK). This procedure efficiently recovers columbium in a form that can then be further processed into columbium oxide. Columbium oxide is aluminothermically reduced batchwise to produce high-purity ferrocolumbium, nickel columbium, and columbium metal. In some cases, the reactions are carried out in water-cooled copper reactors to avoid contamination by refractory materials. Aluminothermically produced columbium metal is commonly purified to remove aluminum and other contaminants by remelting it in an electron-beam furnace. Several remelts may be required before the desired level of purity is reached and a ductile ingot has been produced (Cunningham, 1985; Miller, Fantel, and Buckingham, 1986, p. 8-10; Schlewitz, 1996, p. 46-49).

USES

The principal use for columbium is in the form of steelmaking-grade ferrocolumbium. Ferrocolumbium is typically available in grades that contain from 60 to 70 percent columbium. Steelmaking accounts for more than 80 percent per year of reported columbium consumption in the United States. In 1998, estimated percentages of end-uses for columbium in the United States were microalloyed steels, 66; superalloys, 19; stainless steels, 14; and other, which includes superconducting materials, 1. The end-use patterns for columbium in the remainder of the world were similar to those of the United States with microalloyed steels being the predominant end-use sector (Tantalum-Niobium International Study Center, 1999b). In the 1960s and early 1970s, two significant events increased columbium use—the introduction of columbium as an important microalloying element in

steel and the development of nickel-base alloys, which made use of columbium in alloys for jet engine components. U.S. columbium consumption during the past 20 years is shown in figure 2.

Columbium-bearing microalloyed steels are used in automobiles, buildings, bridges, oil and gas pipelines, and so forth, where the strength-to-weight and cost-per-unit-strength ratios are advantageous. In the automobile industry, the use/amount of high-strength columbium-containing steel has continued to increase despite the trend to reduce the total amount of steel in automobiles. Columbium-bearing high-strength low-alloy steels allow designers to save weight and to reduce fabrication cost.

Because of its refractory nature, appreciable amounts of columbium in the form of high-purity ferrocolumbium and nickel columbium are used in cobalt-, iron-, and nickel-base superalloys for such applications as heat-resisting and combustion equipment, jet engine components, and rocket subassemblies. Columbium in superalloys strengthens the alloy at high service temperatures, such as in aircraft engine components. Most columbium-containing superalloys contain up to 2 percent columbium; some cobalt- and nickel-based superalloys, however, contain up to 6 percent columbium.

Columbium and some of its alloys exhibit a lack of electrical resistance at very low temperatures (superconductivity) in such applications as magnetic resonance imaging

(MRI) devices for medical diagnostics. Columbium carbide is used in cemented carbides to modify the properties of the cobalt-bonded tungsten carbide-base material to impart toughness and shock resistance. It is usually used along with carbides of other metals, such as tantalum and titanium, in drill bits, shovel teeth, tool bits, and other wear-resistant components; these are small end-use sectors for columbium. Columbium oxide is the intermediate product used in the manufacture of columbium carbide, columbium metal, high-purity ferrocolumbium, and nickel columbium.

PRICES

During the 1990s, the columbium price remained stable owing to the availability of columbium from Brazil and Canada. Brazil's production of columbium concentrates, which is mostly pyrochlore, accounts for more than 85 percent of total world columbium production. As the dominant columbium producer/supplier, Brazil has maintained a marketing strategy of moderate price changes and stable supply. Events that had some impact on the columbium price during the 1990s included Brazil's expansion of its ferrocolumbium production capacity, Canada's startup of steelmaking-grade ferrocolumbium production, and initiation of sales of columbium materials from the National Defense Stockpile (Cunningham, 1999). A price for Brazilian pyrochlore has not been available since 1981, and the published price for pyrochlore produced in Canada was discontinued in early 1989.

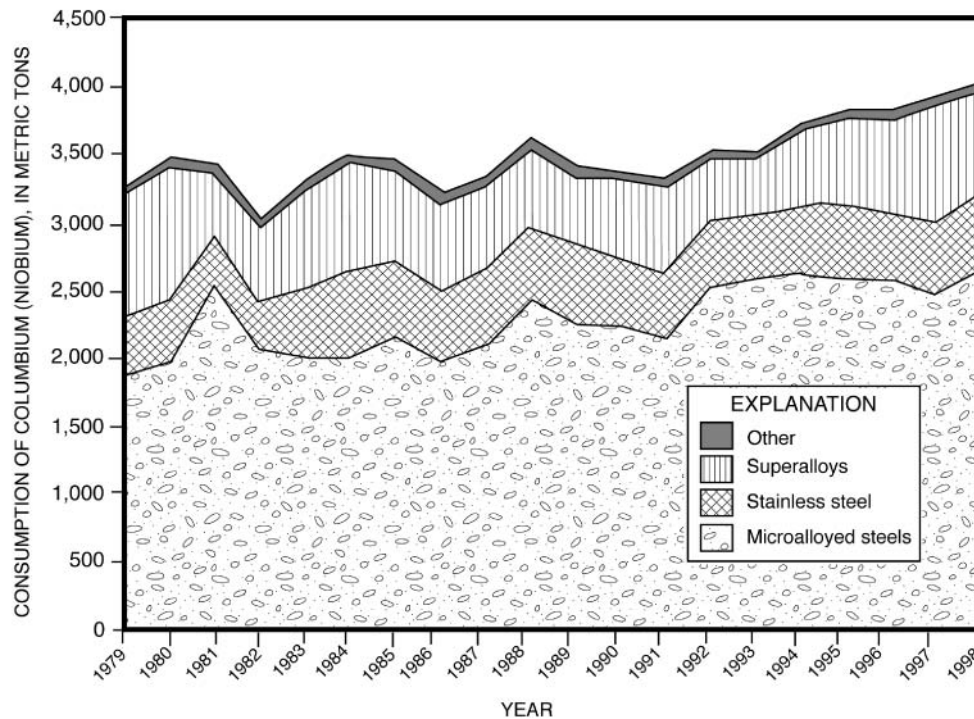


Figure 2. U.S. columbium consumption, by end-use sector, from 1979 through 1998.

The price of columbium is affected most by the availability of steelmaking-grade (regular-grade) ferrocolumbium produced from pyrochlore. In 1998, the American Metal Market published price for steelmaking-grade ferrocolumbium ranged from \$6.75 to \$7.00 per pound of contained columbium. The Metal Bulletin price for columbite ore, which is based on a minimum of 65 percent contained columbium oxide (Nb_2O_5) and tantalum oxide (Ta_2O_5), ranged from \$2.80 to \$3.20 per pound. The American Metal Market published price for high-purity (vacuum-grade) ferrocolumbium ranged from \$17.50 to \$18.00 per pound of contained columbium. Industry sources indicated that columbium metal products sold in the range of about \$24 to \$100 per pound in ingot and special shape forms, columbium oxide for master alloy production sold for about \$8.80 per pound, and nickel columbium sold at about \$18.50 per pound of contained columbium (Mining Journal, 1999; Tantalum-Niobium International Study Center, 1999a). In 1998, no price for any type of columbium scrap was published. For this report, the price for columbium contained in steel scrap was taken to be the average published price for steelmaking-grade ferrocolumbium—about \$6.90 per pound of contained columbium. The price for columbium contained in superalloy scrap was taken to be the average published price for high-purity ferrocolumbium and nickel columbium—about \$18 per pound of contained columbium.

SOURCES OF COLUMBIUM SCRAP

Columbium in the form of steelmaking-grade ferrocolumbium is used as an additive in steelmaking to improve corrosion-resistance and strength characteristics in some steels. Less than 10 percent of steel produced in the world has been estimated to benefit from the advantages of columbium addition (Tantalum-Niobium International Study Center, 1993, p. 4; Roskill Information Services, 1998, p. 110).

In steelmaking, the addition of ferrocolumbium to the steel bath is accompanied by a number of chemical and physical processes. Ferrocolumbium is heated above its melting point, and the columbium dissolves into the liquid metal. After a period of time, the columbium is dissipated throughout the entire volume of the liquid steel in the bath by mass transfer processes (Lyakishev, Tulin, and Pliner, 1984, p. 199).

Although most columbium-containing steels comprise less than 0.1 percent columbium, some stainless steels can comprise as much as 1.25 percent columbium. A major market for columbium among stainless steels is in type 347, which contains about 0.8 percent columbium. Stainless steel scrap is almost always used to produce more stainless steel. The scrap is mainly recycled as either home or purchased scrap; demand is usually a function of demand for the stainless steel itself. Columbium

mostly in the form of high-purity (vacuum-grade) ferrocolumbium and nickel columbium is added to cobalt- and nickel-base superalloys in such applications as jet engine components. The most important columbium-containing superalloy, nickel-base alloy Inconel 718, comprises about 5 percent columbium. Of the total superalloy scrap processed worldwide in 1996, about 70 percent was recycled into the same alloy; about 20 percent, downgraded; and the remaining 10 percent, sold to nickel refineries (ASM International, 1998).

Although columbium is not recovered from the scrap steel and superalloys that contain it, recycling of these scrap materials is significant, and columbium content, where applicable, can be reused. Much of the columbium recycled in steel is diluted to tolerable levels; it effectively becomes a substitute for iron or other alloy metals rather than being used for its unique properties or is oxidized and removed in processing. New columbium-bearing scrap is generated mostly from manufacturing plants that produce steel products and fabricators of parts made from superalloys. This type of scrap is usually quickly returned to steel plants and superalloy meltors for remelting. Some major sources for old columbium-bearing scrap are junked automobiles (estimated 10-year lifetime) and scrap from discarded or obsolete parts made from superalloys (estimated 20-year lifetime), such as jet engine components. In 1998, columbium scrap sources consisted of steel scrap (estimated to be about 70 percent of the total) and superalloy scrap (estimated to be about 30 percent of the total). A major end use for columbium has been in columbium-bearing high-strength low-alloy steels for oil and gas pipelines (estimated 60-year lifetime). These steels were introduced during the 1970s and will be a potential significant future source of columbium-bearing steel scrap.

DISPOSITION OF COLUMBIUM SCRAP

In 1998, the quantity of columbium recycled/reused from old scrap represented about 12 percent of domestic columbium supply. With no U.S. columbium mining industry, columbium-bearing old scrap is important to the columbium supply chain. Of the estimated 3,000 t of columbium contained in old scrap that was available for recycling in 1998, about 33 percent was used for domestic columbium supply, and about 50 percent was unrecovered. Most of the unrecovered material was in the form of steel scrap that was abandoned in place, lost to the environment, or shipped to landfills. Scrap that was abandoned or in landfills could possibly be recycled in the future.

RECYCLING EFFICIENCY

Most columbium is recycled/reused in the form of columbium-bearing steel and superalloy scrap. In 1998, a columbium recycling efficiency was estimated to have been about 50 percent compared with 52 percent for steel.

INFRASTRUCTURE

Although no columbium was mined in the United States in 1998, compounds, ferrocolumbium, metal, and other alloys were produced mostly by six companies. Cabot Performance Materials, Boyertown, Pa., had a production capability that ranged from raw material processing through to the production of columbium end products, H.C. Starck Inc., Newton, MA, was a supplier of columbium products, Kennametal, Inc., Latrobe, Pa., was a supplier of columbium carbides, Oremet-Wah Chang, Albany, Ore., and Reading Alloys, Inc., Robesonia, Pa., were major producers of high-purity columbium products, and Shieldalloy Metallurgical Corp., Newfield, N.J., was a producer of ferrocolumbium. Columbium consumption was mainly in the form of steel-making-grade ferrocolumbium by the steel industry and high-purity columbium alloys and metal by aerospace-related industries with plants in the Eastern United States, the Midwestern United States, California, and Washington.

Columbium is recycled mainly in the iron and steel and alloys-related industries. A companion report on steel recycling in this series discusses the infrastructure for the recycling of steel scrap (Fenton, in press). The largest concentration of recycling facilities is in the heavily populated northern and eastern regions of the country where steel product use and scrap generation are greatest.

The superalloy recycling industry comprises mainly superalloy processors, scrap generators, scrap dealers, and scrap consumers. Scrap is generated when superalloys are produced, cast, or wrought into semifinished products, cut or ground into finished products, and when finished products become obsolete. The scrap is collected, sorted, cleaned, sized, and certified for chemical composition by a superalloy scrap processor before it reenters the superalloy-use cycle. The numerous material flow relations among superalloy scrap generators, collectors, dealers, processors, and brokers obscure the quantities of superalloy scrap that is available for recycling, that is downgraded, and that is imported or exported. Superalloy scrap recycling facilities are located mostly in the eastern and western regions of the country where the larger concentration of superalloy producers and end users is found (Papp, 1988).

Trade in columbium scrap is relatively small, and data are not available. The U.S. International Trade Commission's Harmonized Tariff Schedule System categorizes some selected columbium materials. The system, however, categorizes columbium waste and scrap in a nonspecific tariff classification, and, in 1998, no trade figures for import or export of columbium scrap were identified. The columbium content of columbium-bearing steel and superalloy scrap imports and exports, however, was estimated to be about 100 t and 500 t, respectively, in 1998.

The United States imports most of its columbium requirements. In 1998, U.S. imports of ferrocolumbium and columbium alloys, metal, and powders totaled about 5,450 t of contained columbium and were valued at about \$83 million. Imports came mostly from Brazil and Canada. Columbium exports, mainly ferrocolumbium, totaled about 20 t of contained columbium and were valued at more than \$200,000. Germany and Mexico were the major recipients of the materials.

PROCESSING OF COLUMBIUM-BEARING SCRAP

IRON AND STEEL SCRAP

Scrap is collected by scrap dealers and processed into a physical form and chemical composition that can be consumed by steel mills in their furnaces. The shredder, which is the largest and most expensive piece of equipment used in recycling, fragments vehicles and other discarded steel into fist-sized pieces. Baling presses are used to compact the scrap into manageable bundles. Scrap dealers sort scrap materials, and steelmakers carefully purchase scrap that does not contain undesirable elements that exceed acceptable levels. The scrap is mainly melted in basic oxygen and electric arc furnaces. In the fabrication of new steel products, new steel scrap with known chemical composition is produced. Preparation of the new scrap for recycling is usually limited to cutting, cleaning, and baling prior to shipment back to the steelmaker. The processing of iron and steel scrap is discussed in Fenton (in press). Stainless steel is recycled in a similar manner as iron and steel scrap, but the volume of material is less, and the value is greater. Increased demand raises the value of scrap, which enables more scrap to be recycled. Scrap dealers compete for stainless steel on national and international bases, and the scrap may be handled at several locations before it is sold for use (ASM International, 1998). Scrap separated by alloy type usually brings the highest price. Balers are used to compress the scrap; shredders are rarely used.

SUPERALLOYS

Superalloys are alloys developed for high-temperature conditions where stresses (shock, tensile, thermal, or vibratory) are high and where resistance to oxidation is required. The processing of superalloy scrap can be difficult and complicated. Hundreds of superalloys contain more than 20 alloying elements, and each element must be considered when designing and evaluating processes for separating and recovering the valuable metals. Each piece of superalloy scrap must be identified and its composition certified before it is sold. Turnings are degreased, fragmented, and

OUTLOOK

compressed for remelting. Balers are used to compress superalloy scrap; shredders are rarely used. Superalloys are usually air melted or vacuum melted. Recycled scrap is acceptable for most air-melted alloys. Product specifications, however, usually prohibit the use of recycled scrap in vacuum-melted alloys to reduce the chance that detrimental impurities may be included in the final product, such as in critical components for jet engines. Owing to the high cost and/or periodic scarcity of superalloys, scrap recycling is used extensively (Gupta and Suri, 1994, p. 139-140; ASM International, 1998).

Scrap is a preferred furnace charge for superalloy melters and can provide about 50 percent of a superalloy furnace charge. Scrap is prerefined, prealloyed, and easy to handle. New or home scrap turnings are the largest form of superalloy scrap. Vacuum-quality turnings are collected to produce a furnace-ready charge that can be easily melted. The first step is a qualitative verification of chemical purity to isolate severely contaminated material from chemically clean material. Turnings are crushed into chips, which are then cleaned of residual cutting fluids and dirt. Lot homogenization and certification follows; processed scrap is required to meet the same chemical requirements as the finished heat. In the case of alloy Inconel 718, which has a lower melting point than its constituents, using processed scrap in the melt saves on electrical costs and melting time (Lane, 1998). This scrap is then either remelted in the plant where it was originally produced (home scrap) or sold for remelting at another plant (new scrap).

A 20-year pattern of columbium consumption is shown in figure 2. The principal use for columbium is expected to continue as an additive in steelmaking, mostly in the manufacture of microalloyed steels used for automobiles, bridges, pipelines, and so forth. The production of high-strength low-alloy steel is the leading use for columbium, and the trend of columbium demand, domestically and globally, will continue to follow closely that of steel production. With about 80 percent of columbium being consumed in steelmaking, columbium recycling trends will be determined most by trends in the recycling of steel, which is discussed in Fenton (in press). U.S. scrap supply was reported to be a function of market price, which affects the collection of obsolete scrap; levels of activity in the metalworking industry, which influences the generation of prompt industrial scrap; and melting activity, which impacts the availability of home scrap (American Metal Market, 2001).

The outlook for columbium also will be dependent on the performance of the aerospace industry and its use of columbium-bearing alloys. Columbium consumption in the production of superalloys, which is the second largest end use for columbium, will be most dependent on the market for aircraft engines. Because nickel-base superalloys (such as alloy Inconel 718) can account for about 40 to 50 percent of engine weight, they are expected to be the materials of choice for the future owing to their high temperature operating capability (Tantalum-Niobium International Study Center, 1999b). Thus, the rate at which columbium is recycled will also depend upon the rate at which products that contain columbium-bearing superalloys are recycled.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinsplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinsplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Tantalum Recycling in the United States in 1998

By Larry D. Cunningham

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-J

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

Tantalum Recycling in the United States in 1998

By Larry D. Cunningham

ABSTRACT

This report describes the flow of tantalum in the United States in 1998 with emphasis on the extent to which tantalum was either recycled or reused. Tantalum was recycled mostly from new scrap that was generated during the manufacture of tantalum-related electronic components and new and old scrap products of tantalum-containing cemented carbides and superalloys. In 1998, about 210 metric tons of tantalum was either recycled or reused, about 43 percent of which was derived from old scrap. The tantalum recycling rate was calculated to be 21 percent, and tantalum scrap recycling efficiency, 35 percent.

INTRODUCTION

As shown in figure 1, this materials flow study of tantalum includes a description of tantalum supply and demand factors for the United States in 1998 to illustrate the extent of tantalum recycling¹ and to identify recycling trends. Figure 1 shows the tantalum recycling flow with domestic supply and distribution of domestic supply of primary and secondary tantalum in 1998.

Tantalum (Ta), which was discovered in 1802, is a refractory metal that is ductile, easily fabricated, highly resistant to corrosion by acids, a good conductor of heat and electricity, and has a high melting point (about 3,000°C). The major use for tantalum, as tantalum metal powder, is in the production of electronic components, mainly tantalum capacitors. Alloyed with other metals, tantalum is also used in making cemented carbide tools for metalworking equipment and in the production of superalloys for jet engine components.

Salient tantalum statistics are based mostly on the tantalum content of old cemented carbide and superalloy scrap (table 1). In 1998, about 300 metric tons (t) of tantalum contained in old scrap was generated, with about 90 t of tantalum valued at about \$8 million recycled or reused. The old scrap recycling efficiency was calculated to be about 35 percent, and the recycling rate, about 21 percent. Tantalum contained in new scrap consumed was about 120 t.

¹Definitions for select words are found in the Appendix.

GLOBAL GEOLOGIC OCCURRENCE OF TANTALUM

The principal source of tantalum is an isomorphous series of minerals that contain columbium (niobium), iron, manganese, and tantalum oxides. Columbium and tantalum have a strong geochemical affinity for each other and are found together in most rocks and minerals in which they occur. Tantalite-columbite, which is the major source for tantalum, occurs mainly as accessory minerals disseminated in granitic rocks or in pegmatites associated with granites. When tantalum predominates over columbium, the proper name for the mineral is "tantalite"; when the reverse is true, the proper name is "columbite." Economic mineral concentrations occur where weathering has led to residual or placer deposits, as in Nigeria or southeast Asia, or where the pegmatites contain a high concentration of these minerals, as in the Bernic Lake deposit in Manitoba, Canada. The microlite-pyrochlore mineral series is also a source of tantalum. These minerals consist essentially of complex oxides of calcium, columbium, sodium, and tantalum in combination with hydroxyl ions and fluoride(s). Microlite may contain as much as 70 percent tantalum oxide, and pyrochlore generally contains less than 10 percent. Microlite, which is often associated with tantalite or columbite, occurs mainly in the albitized zones of granite pegmatites. Struverite, which is a titanium-bearing oxide, is a low-grade source of tantalum that is recovered from tin-mining wastes in southeast Asia. Struverite typically contains about 12 percent each of columbium and tantalum oxides (Cunningham, 1985; Crockett and Sutphin, 1993, p. 6-7).

Tantalum resources and reserves occur mainly in pegmatite deposits in Australia, Brazil, Canada, and several African countries. The largest tantalum reserves and resources are located in Australia where reserves are estimated to be about 36,000 t of contained tantalum. Canadian tantalum reserves are estimated to contain more than 3,000 t of contained tantalum. Brazil's tantalum reserve base is estimated to contain about 53,000 t of contained tantalum (Cunningham, 2002). U.S. tantalum resources are of low grade, and none were considered to be economically minable in 1998.

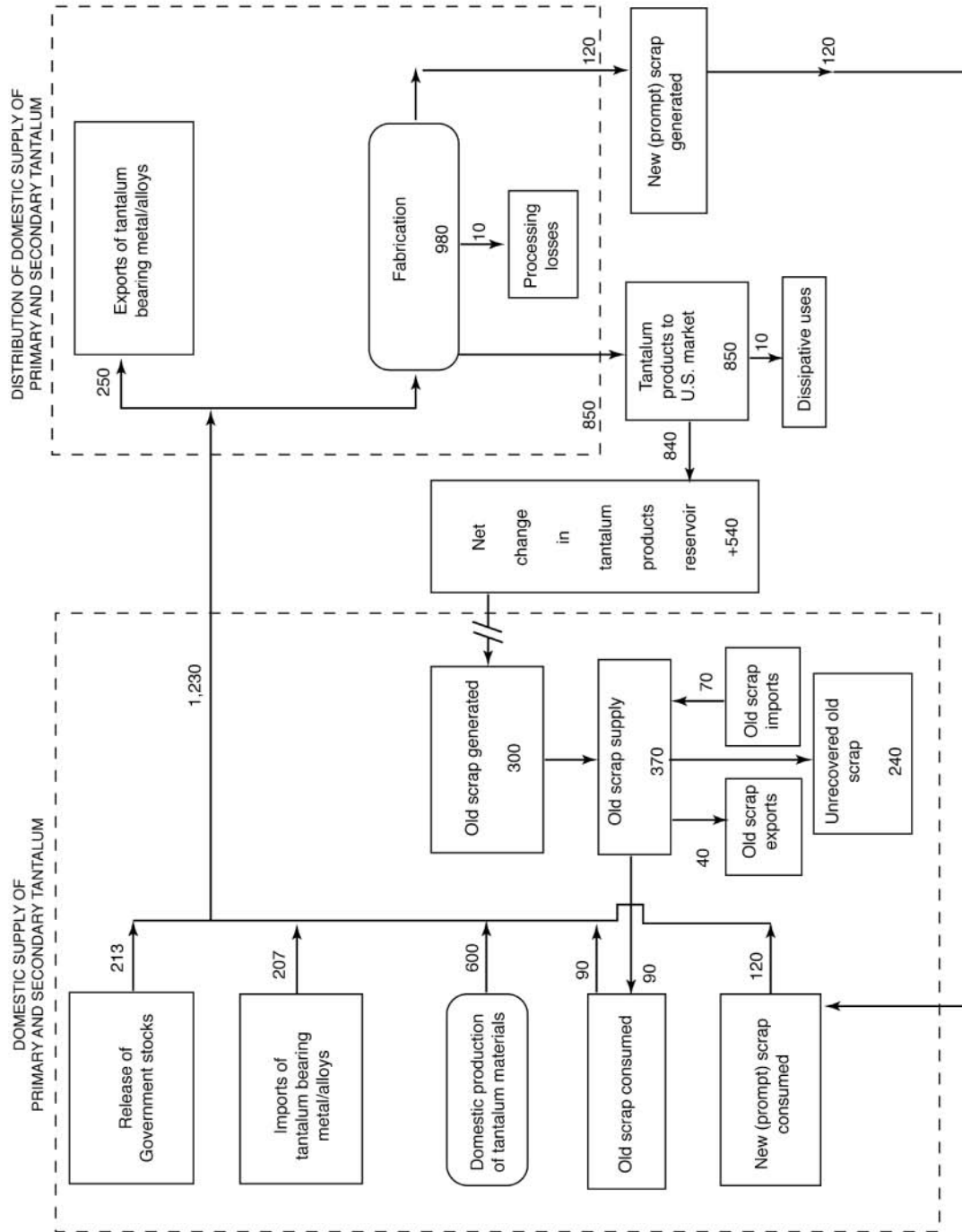


Figure 1. U.S. tantalum materials flow in 1998. Values are in metric tons contained tantalum.

Table 1. Salient statistics for U.S. tantalum scrap in 1998.
[Values in metric tons of contained tantalum, unless otherwise specified]

Old scrap:	
Generated ¹	300
Consumed ²	90
Consumption value ³	\$8 million
Recycling efficiency ⁴	35 percent
Supply ⁵	370
Unrecovered ⁶	240
New scrap consumed ⁷	120
New-to-old-scrap ratio ⁸	57:43
Recycling rate ⁹	21 percent
U.S. net imports of scrap ¹⁰	30
Value of U.S. net imports of scrap	\$2.7 million

¹Tantalum content of products theoretically becoming obsolete in the United States in 1998. It excludes dissipative uses.

²Tantalum content of products that were recycled in 1998.

³Unit value of contained tantalum in materials used in calculating total value of contained metal in scrap.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported).

⁵Old scrap generated plus old scrap imported.

⁶Old scrap generated plus old scrap imported minus old scrap consumed minus old scrap exported.

⁷Including prompt industrial scrap, but excluding home scrap.

⁸Ratio of quantities consumed, in percent.

⁹Fraction of the tantalum apparent supply that is scrap, on an annual basis.

¹⁰Trade in scrap is assumed to be principally in old scrap.

PRODUCTION AND PRODUCTION PROCESSES

The United States, which has no tantalum mining industry, must import all its tantalum source materials for processing. Tantalum mineral production comes mostly from columbite and tantalite mining operations in Australia, Brazil, and Canada and from smaller mining operations in several African countries. Australia, which is the largest producer, accounts for about 25 percent of the world's annual tantalum requirements. In 2002, Australia's Sons of Gwalia Ltd. total tantalum production capacity at its Greenbushes and Wodgina Mines was about 850 t of contained tantalum in mineral concentrate. Tantalum is also obtained from low- and high-grade tantalum-bearing tin slags, which are byproducts from tin smelting, principally from Asia, Australia, and Brazil. Low-grade tin slags, however, must first be treated by a pyrometallurgical technique to upgrade them to a synthetic concentrate before delivery to the tantalum extraction plant; this upgrading operation is performed in Germany. In past years, tantalum-containing tin slags were an important source of tantalum supply. Owing to structural

changes in the tin industry, however, their importance has decreased with the exception of accumulated inventory. Thus, future tantalum supply will have a greater dependence on natural sources, such as tantalite-columbite.

Most tantalum-related mining operations in the past generally were small, relatively high-cost, intermittent operations that depended on the recovery of byproduct or coproduct minerals for economic viability. Mine development, however, has shifted more to primary tantalum sources, notably in Australia. Alluvial and residual tantalum and tantalum-containing tin deposits are normally mined by dredges, hand, hydraulic monitors, or mechanized open pit mining. The mining of pegmatite deposits, which may be either open pit or underground, is carried out by blasting, transporting, and crushing the rock to free the tantalum and associated coproduct minerals. The materials are then concentrated by wet gravity methods (jigs, sluices, spirals, and tables) and finally separated from associated minerals by gravity and electromagnetic and electrostatic processes. The extraction of tantalum from tantalum source materials involves dissolution with hydrofluoric acid followed by liquid-liquid extraction with methyl isobutyl ketone (MIBK). This procedure efficiently recovers tantalum in a form that can then be further processed into potassium fluotantalate and tantalum oxide. Potassium fluotantalate is reduced with metallic sodium to produce tantalum metal powder. The tantalum metal powder produced by the sodium reduction process is treated to convert the metal to a form suitable for use as capacitor-grade powder and as feedstock for tantalum sheet and wire. A solid-state reaction between tantalum oxide and carbon under vacuum conditions produces tantalum carbide (Cunningham, 1985; Tripp, 1997, p. 660-669).

USES

The principal end use for tantalum is in the production of electronic components, mainly in tantalum capacitors. In 1998, estimated end-uses for tantalum in the United States were electronic components, 65 percent; machinery, 21 percent; transportation, 9 percent; and other, 5 percent. U.S. tantalum consumption during the past 20 years is shown in figure 2.

Faced with runaway tantalum source material prices during the late 1970s and early 1980s, processors were forced to pass along a large part of the price increases to end users, which had the effect of a decrease in the use of tantalum. Because of escalating tantalum prices, consumers began to substitute alternate products, to decrease tantalum content in products, and to increase recycling to substitute for virgin tantalum products. In the consumer electronics sector, tantalum was designed out of some circuits and replaced primarily with aluminum-bearing electronic components.

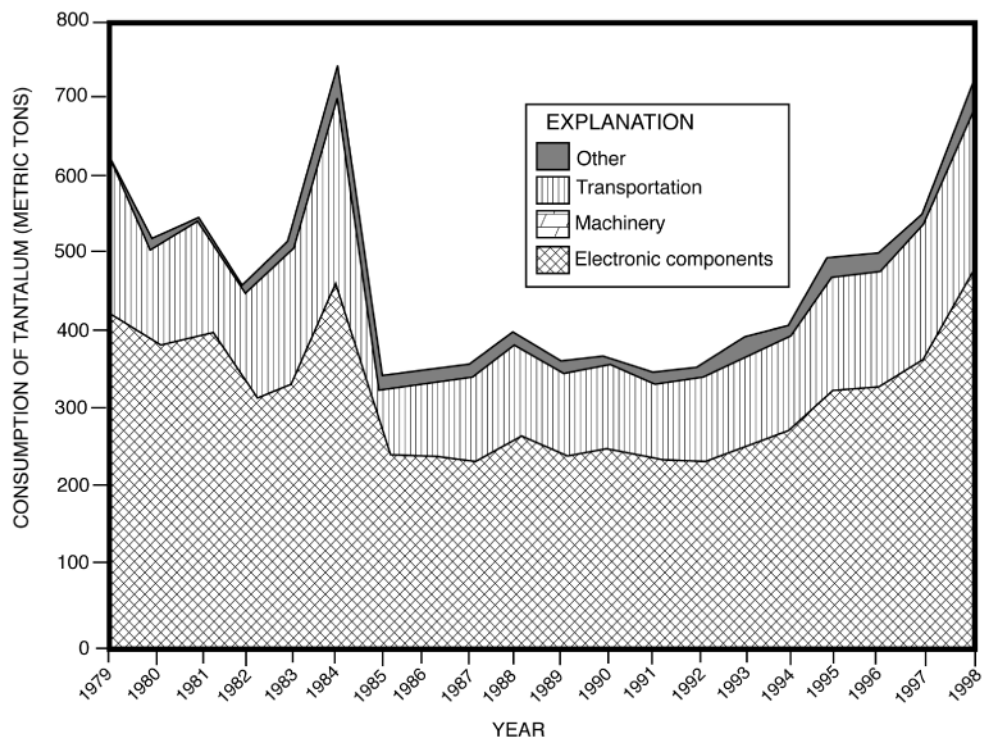


Figure 2. U.S. tantalum consumption, by end-use sector, from 1978 through 1998.

A significant spike in tantalum demand occurred in 1984. U.S. factory sales of tantalum capacitors were at an alltime high. The computer and automotive markets were experiencing steady growth that fostered a need for greater miniaturization without sacrificing tantalum capacitor performance. In 1985, demand for tantalum capacitors from computer manufacturers declined significantly. Tantalum for cemented carbides also decreased owing to the growing popularity of coated cutting tools and the automotive industry's emphasis on producing smaller vehicles that require less metal cutting.

During the 1990s, the demand for tantalum was strong; consumption increased in most years. Demand for tantalum capacitors was robust in such electronics sector products as automotive electronics, pagers, personal computers, portable telephones, and video cameras. Overall growth in this sector, however, was slowed owing to the industry's continued emphasis on the miniaturization of electronic components, which resulted in less tantalum used per unit. The tantalum capacitor exhibits reliable performance and combines compactness and high efficiency with good shelf life.

Because of its high melting point (about 3,000°C), good strength at elevated temperatures, and good corrosion resistance, tantalum is combined with cobalt, iron, and nickel to produce superalloys that are used in aerospace

structures and jet engine components. Tantalum carbide, which is used mostly in mixtures with carbides of such metals as columbium, titanium, and tungsten, is used in boring tools, cemented-carbide cutting tools, farm tools, and turning and wear-resistant parts. Owing to tantalum's excellent corrosion-resistant properties, tantalum mill and fabricated products are used for corrosion and heat-resistant chemical plant equipment, such as condensers, evaporators, heat exchangers, heating elements, and liners for pumps and reactors.

PRICES

Tantalum mineral concentrates (tantallite) are the main primary source of tantalum, and the price for tantalum products is affected most by events in the supply of and demand for tantallite. The price for tantalum metal products generally follows the pattern for that of tantalum concentrates. The price for tantalum metal products is also affected by the size of the order or contract and the material specification. Events that had some impact on the tantalum price during the 1990s include robust demand for tantalum capacitors in the electronics sector, long-term tantalum mineral supply contracts between major producers and processors, and initiation of sales of tantalum materials from the National Defense Stockpile (Cunningham, 1999).

Figure 3 shows trends in the yearend average tantalum concentrate price from 1979 to 1998. Between 1979 and 1980, the price for tantalum source materials exploded, and production could not meet market demand, which resulted in sustained inventory reduction. With optimistic forecasts of market growth, processors found themselves locked into a bidding contest for available tantalum source materials. By yearend 1982, large high-cost inventories of tantalum source materials were accumulated as a hedge against perceived future shortages. By 1988, price increases for tantalum source materials were again of major concern in the tantalum industry. The yearend 1988 price for tantalite ore nearly doubled the yearend 1987 price. The price escalation was attributed to increased demand for tantalum source materials following a drawdown of the tantalum inventories that had been built up. The price for tantalum ore continued its cyclic pattern through 1993; thereafter, the price was steady with some moderate increases.

In 1998, the Platt's Metals Week spot price for tantalite ore, which was based on contained Ta_2O_5 , f.o.b. U.S. ports, began the year at a range of \$32 to \$34 per pound, rose to a range of \$33 to \$35 per pound in March, and remained at that level through December. For the year, the Metal Bulletin published price for tantalite ranged from \$28.00 to \$31.50 per pound of contained Ta_2O_5 , and that for Greenbushes tantalite, Australia, which was based on 40% contained Ta_2O_5 , was \$40 per pound.

Industry sources indicated that the average selling prices per pound tantalum content for some tantalum products were as follows: capacitor wire, \$180 to \$270; capacitor-grade powder, \$135 to \$260; and vacuum-grade metal for superalloys, \$75 to \$100 (Mining Journal, 1999). In 1998, no public price for tantalum scrap was published. For this report, the price for tantalum contained in tantalum-bearing scrap was taken to be the average published price for tantalite ore (about \$33.80 per pound of contained Ta_2O_5).

SOURCES OF TANTALUM SCRAP

The value of tantalum is a driving force for its recycling. The major end use, which is more than 60 percent in the production of electronic components, is mainly in tantalum capacitors. The amount of tantalum recycled from finished electronic components (old scrap), however, is very small because this source has not yet been fully developed. New scrap materials reclaimed at manufacturing plants that produce tantalum-related electronic components are a major source of tantalum supply and are delivered back to tantalum processors for recycling (Tantalum-Niobium International Study Center, 1996).

Tantalum carbide is used mostly in the manufacture of cemented carbide inserts and tools for metal cutting and metalworking applications. Tools for metal cutting (an estimated 1-year or less lifetime) account for an estimated 30 percent of total demand for cemented carbides.

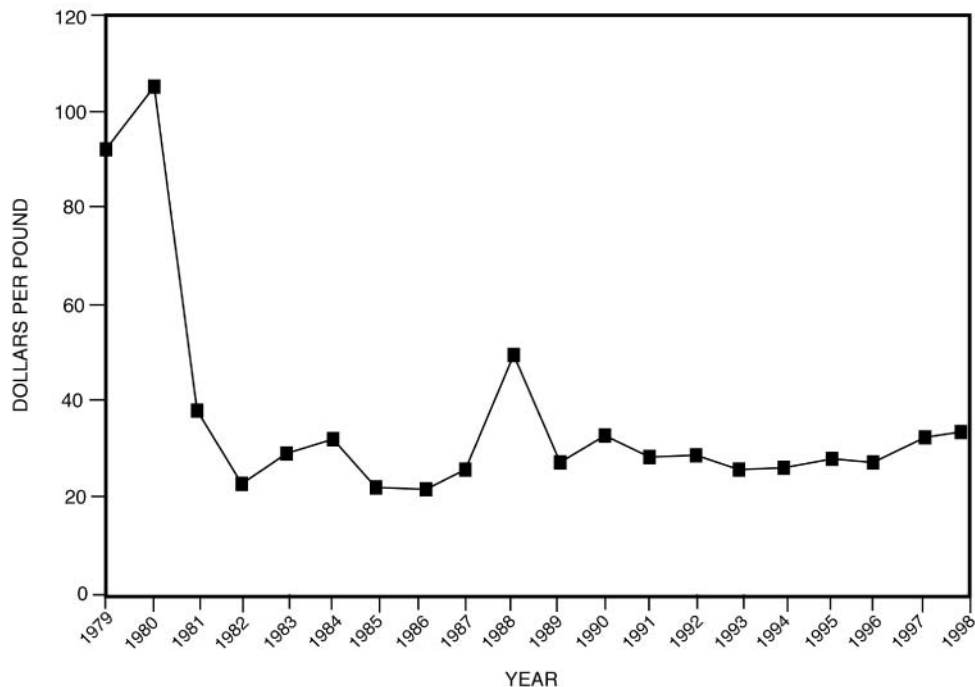


Figure 3. Yearend average tantalum concentrate price from 1978 through 1998. Values are in current dollars per pound contained pentoxide. (Source: Metals Week, 1979–92, and Platt's Metals Week, 1993–98).

Cutting tool insert demand is dependent on the demand for and sales of durable goods, such as automobiles, which accounts for an estimated 40 percent of total cutting tool consumption. The cemented carbide inserts typically contain about 3 percent tantalum. Events that affect the use of cutting tools include the use of coatings, such as titanium carbide, which increases cutting tool efficiency; increased use of ceramic tools; and net-shape-metal-forming processes that reduce the need for metal cutting (Santhanam, 1992; Roskill Information Services Ltd., 1999).

Superalloys are nickel- and cobalt-base materials used to make heat-resistant gas-turbine engine parts. These alloys are developed for high-temperature conditions where stresses (shock, tensile, thermal, and vibratory) are relatively high and where resistance to oxidation is required. Nickel-base superalloys are more widely used than cobalt-base superalloys. Tantalum is added to nickel-base superalloys to increase overall strength and to improve the oxidation resistance of the alloy. The first major use for tantalum in superalloys was in those alloys that contained up to 4 percent tantalum for use in jet engine turbine blades in the early 1970s. In the 1980s, single-crystal-casting techniques led to the commercialization of Pratt & Whitney's nickel-based single crystal alloy, PWA 1480, which contains about 12 percent tantalum. Although tantalum is not recovered from the superalloy scrap that contains it, recycling of superalloy scrap is significant, and tantalum content, where applicable, can be reused. New tantalum-bearing scrap is generated from fabricators of parts made from superalloys. This type of scrap is usually quickly returned to superalloy melters for remelting. Some major sources for old tantalum-bearing scrap are discarded or obsolete parts made from superalloys, mostly jet engine components (an estimated 20-year lifetime). Of the total superalloy scrap processed worldwide in 1996, about 70 percent was recycled into the same alloy; about 20 percent, downgraded; and the remaining 10 percent, sold to nickel refineries (Tantalum-Niobium International Study Center, 1982; ASM International, 1998).

DISPOSITION OF TANTALUM SCRAP

In 1998, the quantity of tantalum recycled or reused from old scrap represented about 7 percent of domestic tantalum supply. Because the United States has no tantalum mining industry, tantalum-bearing old scrap is a welcome addition to the tantalum supply chain. Of the estimated 370 t of tantalum contained in old scrap that was available for recycling in 1998, about 65 percent was unrecovered; about 24 percent, used for domestic tantalum supply; and the remainder, exported. Most of the unrecovered material was in the form of finished electronic equipment. Recycling of tantalum from old and/or discarded tantalum-containing electronic equipment has not been developed or used to any significant degree.

RECYCLING EFFICIENCY

Recycling efficiency shows the relation between what is theoretically available for recycling and what was recovered and not recovered. This relation is defined as the amount of old scrap consumed plus old scrap exports divided by the sum of old scrap generated and old scrap imports plus or minus old scrap stock changes, as applicable. Most tantalum is either recycled or reused in the form of superalloy and tantalum-bearing cemented carbide scrap. A tantalum recycling efficiency of about 35 percent was estimated to have been reached in 1998. The recycling efficiency would have been higher if not for the lack of a concerted program to reuse tantalum from its major end use, electronic components.

INFRASTRUCTURE

No tantalum was mined in the United States in 1998. Metal, alloys, and compounds, however, were produced mostly by three companies by using tantalum units obtained from imported tantalum-bearing concentrates and metal and from domestic and foreign scrap. Cabot Performance Materials, Boyertown, PA, had a production capability that ranged from raw material processing through to the production of tantalum end products; H.C. Starck Inc., Newton, MA, was a major supplier of tantalum products; and Kennametal Inc., Latrobe, PA, was a supplier of tantalum carbide. Tantalum consumption was mainly in the form of alloys, compounds, fabricated forms, ingot, metal, and powder in the cemented carbide, electronics, and superalloy sectors.

PM Recovery Inc. of Harrison, NY, which has been in operation since 1978, sorted, cleaned, and repackaged tungsten carbide and tantalum scrap at its Belfast, TN, facility. Hard-metal scrap, turnings, and sludges processed at the plant total about 900 metric tons per year (t/yr) (Cassidy, 2001). High-Temp Specialty Metals Inc., Willingboro, NJ, which was founded in 1983, was involved in the physical and chemical cleaning of molybdenum, tungsten, and tantalum scrap. Scrap was deoiled with water, soap, and orange oil. Leachates were evaporated, and salts were treated by E. I. du Pont de Nemours & Co. at its Deepwater, NJ, plant. Hi-Temp also leached tantalum capacitors to remove manganese and processed them to Ta₂O₅. Amlon Metals Inc. recycled about 200,000 t/yr of metal-bearing materials, which included tantalum; the company, which was founded about 1950, maintained offices in Australia, Brazil, China, India, Mexico, South Africa, Spain, Tanzania, the United States, and the United Kingdom (Cassidy, 2001). ECS Refining of Terrell, TX, was active in the recycling of electronic scrap, which included integrated circuits and circuit boards. Components were either reused or processed for their metal content (Mossholder, 2001).

The U.S. International Trade Commission's Harmonized Tariff Schedule System categorizes some selected tantalum materials. The United States imports a significant amount of its tantalum requirements. In 1998, imports of tantalum metal and alloys totaled about 207 t of contained tantalum valued at about \$56 million. Imports came mostly from China, Japan, and Thailand. Imports that were categorized as "waste and scrap" contained an estimated 70 t of tantalum scrap; China, Japan, and the United Kingdom were the major suppliers. Exports of tantalum metal and alloys totaled about 250 t of contained tantalum valued at about \$72 million. Germany, Israel, Japan, and the United Kingdom were the major recipients of the materials. Exports of tantalum waste and scrap contained an estimated 40 t of tantalum with most of the material going to Germany, Hong Kong, Taiwan, and the United Kingdom.

PROCESSING OF TANTALUM-BEARING SCRAP

CEMENTED CARBIDES

The emphasis for recycling most cemented carbide scrap is to recover the contained tungsten. There is value, however, in the recovery of other metals, such as tantalum. The choice of the process for recycling cemented carbide scrap depends on the concentration of tungsten, other metals, and the purity of the scrap. Recycling is accomplished by using mostly chemical or zinc processing methods. In the chemical process, carbide scrap with different contents of various metals, such as tantalum, are treated chemically to extract the tungsten and cobalt values first. The contained tantalum is collected in an oxide sludge, which is suitable as source material for the tantalum extraction plant (see section "Production and Production Processes"). The advantage to this process is that almost any type of cemented carbide scrap can be reused and that the resultant product is equivalent to virgin material (Tantalum-Niobium International Study Center, 1984; Stjernberg and Johnson, 1998).

The zinc process uses hard scrap, such as used tool inserts, as the source material. This process is not a purification process, and careful sorting and pretreatment to remove oil, solder, and refractory coatings is essential for satisfactory reclamation. Zinc treatment dissolves the binder phase of the cemented carbide without changing the base phase of the material. The composition of the carbide is conserved, and the treated carbide can be reused in a new batch of cemented carbides that requires the same or similar composition. At elevated temperatures, zinc metal is added to the scrap source material in a vacuum furnace, which results in a breakdown of the hard metal structure, thus allowing conversion into a powder form. Zinc is removed from the powder by distillation, and the powder can then be used directly in a blend with virgin carbides to manufacture cemented carbide parts (Tantalum-Niobium International

Study Center, 1984, 1996). The zinc process is less expensive than the chemical process, generates no waste products, and produces a powder that is essentially ready for use. The chemical and the zinc processes complement each other, and this results in the better use of tantalum source materials. Excluding some special applications, cemented carbide scrap is recycled either by the chemical process (about 35 percent) or the zinc process (about 25 percent); the remaining material is not recycled (Tantalum-Niobium International Study Center, 1984; Stjernberg and Johnson, 1998).

SUPERALLOYS

The processing of superalloy scrap can be difficult and complicated. Hundreds of superalloys contain more than 20 alloying elements, and each element must be considered when designing and evaluating processes for separating and recovering the valuable metals. Each piece of superalloy scrap must be identified and its composition certified before it is sold. Turnings are degreased, fragmented, and compressed for remelting. Balers are used to compress superalloy scrap; shredders are rarely used. Superalloys are usually air melted or vacuum melted. Recycled scrap is acceptable for most air-melted alloys. Product specifications, however, usually prohibit the use of recycled scrap in vacuum-melted alloys to reduce the chance that detrimental impurities may be included in the final product, such as critical components for jet engines. Owing to the high cost and/or periodic scarcity of superalloys, scrap recycling is used extensively (Gupta and Suri, 1994, p. 139-140; ASM International, 1998). Scrap is a preferred furnace charge for superalloy melters and can provide about 50 percent of a superalloy furnace charge. Scrap is prerefined, prealloyed, and easy to handle. New scrap turnings are the largest form of superalloy scrap. Vacuum-quality turnings are collected to produce a furnace-ready charge that can be easily melted. The first step is a qualitative verification of chemical purity to isolate severely contaminated material from chemically clean material. Turnings are crushed into chips, which are then cleaned of residual cutting fluids and dirt. Lot homogenization and certification follows; processed scrap is required to meet the same chemical requirements as the finished heat (Lane, 1998).

ELECTRONIC COMPONENTS

Although more than 60 percent of the tantalum that is consumed in the United States is in the electronics sector, the amount of tantalum recovered from obsolete electronic equipment is small. The trend toward higher capacitance tantalum powders and capacitor miniaturization promotes the use of less tantalum in products. Miniaturization, however, increases the amount of labor involved in recovery and results in less tantalum to be recovered when tantalum-bearing products are disassembled and recycled. One company processed capacitors by first leaching to remove manganese.

The capacitors were then disintegrated by hydriding in a retort and calcined to Ta_2O_5 (Cassidy, 2001). Computers, which are a major end use for tantalum, have a life span, which includes reuse, of up to 7 years at which time their materials must be recycled or disposed of. By 2005, about 64 million computers will have reached the end of their usefulness. Recycling of computers, however, can be difficult because they contain a number of recyclable materials, some of which present environmental problems on disposal. Such materials as lead solder and mercury are common in most electronics. Computer and electronic equipment account for only about 1 percent of the total waste generated in the United States, but an estimated 70 percent of heavy metals that go to landfills results from this 1 percent (Resource Recycling, 2000a, b, 2001).

A small amount of workable used computers will be sold and reused through the resale market, and some will be donated to schools and nonprofit organizations. Demanufacturing, which is the disassembly of obsolete products, is one method to recycle electronic equipment, such as computers. In North America, more than 300 facilities harvest such computer components as hard drives and circuit boards for resale value. Demanufacturing can be profitable, but barriers, such as the lack of an adequate collection infrastructure, limited and cyclical markets for recovered materials, and products that are not designed to be disassembled and recycled, exist. A major source of material for demanufacturing is institutions that frequently update equipment owing to software updates and technology requirements. Shredding is another option that can be used to recycle computer equipment. Components, which range from laptops to mainframes, can be shredded, and the materials, separated. This is an efficient way to recycle large volumes of computers, such as units formerly leased to businesses (Recycling Today, 2000; Resource Recycling, 2000a, b; Mossholder, 2001; U.S. Geological Survey, 2001).

OUTLOOK

A 20-year pattern of U.S. tantalum consumption is shown in figure 2. The principal use (more than 60 percent) for tantalum as tantalum metal powder and wire in the production of

electronic components, mainly tantalum capacitors, is expected to continue. This market sector is expected to be stimulated by the growth in the use of mobile telephones, which have a lifecycle of less than 2 years (Metal Bulletin Monthly, 2001). Each phone may contain from 10 to 20 capacitors. Development of tantalum recycling (old scrap) in the electronics sector, however, is very limited and represents a major potential for future tantalum recycling. Tantalum recycling in this area will have to be part of a total recycling concept for electronic equipment, which will require time and major effort and cooperation between the tantalum industry and the electronics equipment recyclers.

Concerns, factors, and issues that relate to disposal of obsolete and/or discarded electronic equipment include the need for a plan for the disposition of stored surplus equipment and the disposition of the increasing volume of equipment being sold; State government initiatives that affect electronic equipment disposition; loss of offshore processing and/or recycling capacity; and the logistics for the collection and transport of used equipment to scrap processors or recyclers (Resource Recycling, 2000a). Although the United States has no mandatory electronic take back or recycling program, certain U.S. computer manufacturers have voluntary internal recycling programs to handle some leased and purchased equipment. Legislation in the European Union (EU), however, set new standards for sale of electronic equipment in Europe; this includes equipment manufactured outside the region. The EU directives require companies to take back and recycle their electronic equipment and to phase out the use of various heavy metals, such as lead, in new equipment by 2008 (Metal Bulletin Monthly, 2001; Recycling Today, 2001).

Tantalum carbide in the metal-cutting industry will be dependent on the growth of the general economy and is expected to grow at an estimated 2 percent per year. Tantalum consumption in superalloys, mostly in the aircraft industry, is expected to grow by about 3 percent per year (Tantalum-Niobium International Study Center, 1996, 1998; Mining Journal, 2000). The rate at which tantalum is recycled in the carbide and superalloy sectors will depend on the rate at which tantalum-containing cemented carbides and superalloys are recycled.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Tin Recycling in the United States in 1998

By James F. Carlin, Jr.

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-K

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric ton (Mt)	1,102,001	short ton

Tin Recycling in the United States in 1998

By James F. Carlin, Jr.

ABSTRACT

This materials flow study includes a description of tin supply and demand factors for the United States to illustrate the extent of tin recycling and to identify recycling trends. Understanding the flow of materials from source to ultimate disposition can assist in improving the management of the use of natural resources in a manner that is compatible with sound environmental practices. The quantity of tin recycled in 1998 as a percentage of apparent tin supply was estimated to be about 22 percent, and recycling efficiency was estimated to be 75 percent. Of the total tin consumed in products for the U.S. market in 1998, an estimated 12 percent was consumed in products where the tin was not recyclable (dissipative uses).

INTRODUCTION

This materials flow study includes descriptions of trends in consumption, losses, and recycling of tin and tin-bearing materials in the United States in 1998. Of the approximately 76,000 metric tons (t) of tin consumed in fabrication in the United States in 1998, fabrication losses were estimated to be about 1,000 t, or about 1 percent.

Because tin has been one of the higher valued base metals and because the infrastructure to reclaim tin in the United States has been well-developed for many years, tin has had significant recycling rates, though lower than for some other metals. Recycling is especially important for tin because virtually all the domestic primary tin requirements have long been dependent on imports. Historically, the United States has had only a few small tin mines that have supplied a minuscule portion of domestic tin needs. Tin imports and sales of tin from the U.S. National Defense Stockpile have provided most of the Nation's primary tin needs for many years. The reclamation of scrap tin, however, has helped to reduce reliance on the Stockpile and foreign suppliers. The recycling rate for tin was estimated to be about 22 percent in 1998.

In 1998, tin imports in the form of metal or compounds amounted to 44,000 t, and exports of tin metal/compounds were approximately 5,000 t. No data are available on imports or exports of tin scrap. Imports were estimated to be nil, and exports were estimated to be 1 t.

Old scrap consumed was 7,710 t; old scrap recycling efficiency was determined to be about 75 percent; new (prompt) scrap consumption amounted to 8,390 t. The value of this total scrap use was about \$130 million.

Figure 1 shows the domestic flow of tin in 1998 with the flow of recycled tin shown in detail. Figure 2 shows domestic tin usage for the past 20 years.

GLOBAL GEOLOGIC OCCURRENCE OF TIN

Tin is a relatively scarce element with an average abundance in the Earth's crust of about 2 parts per million (ppm) compared with 94 ppm for zinc, 63 ppm for copper, and 12 ppm for lead (Lee and Yao, 1970). Tin is produced from lode (hard-rock) deposits and placer deposits derived from the lodes. The tin mineral cassiterite (SnO_2) is the source of most tin production; a notable exception is the complex tin sulfide minerals in the subvolcanic or tin-silver lode deposits in Bolivia. Cassiterite has a high specific gravity (6.8-7.1) and a Moh's scale hardness of 6 to 7 and is usually a dark-brown or black color with an adamantine luster.

Most lode tin deposits occur as greisen, replacement, skarn, or vein type deposits associated with granitic rocks or their extrusive equivalents where tin has been concentrated by magmatic differentiation processes (Sainsbury and Reed, 1973; Taylor, 1979, p. 1-12). Placer deposits of several types have been derived from lode tin deposits by weathering and erosion. Because cassiterite is heavy and chemically resistant, it is concentrated by weathering in place, which removes lighter minerals (residual placers), or by erosional processes on a slope (eluvial placers) or in streams (alluvial placers). Marine tin placers are formed when tin minerals are concentrated in stream channels or along beaches and then submerged as a result of sea-level changes (Sainsbury, 1969, p. 6-8).

Much of the world's past tin production has been from placer deposits, which generally can be mined more cheaply than lode deposits (Bleiwas and others, 1986, p. 33). From 1934 through 1987, Malaysia, Indonesia, and Thailand accounted for more than one-half of the world's 10 million metric tons of tin production by using major dredge production from marine placer deposits (Sutphin and others, 1990, p. 20).

¹Definitions for selected words are found in the Appendix.

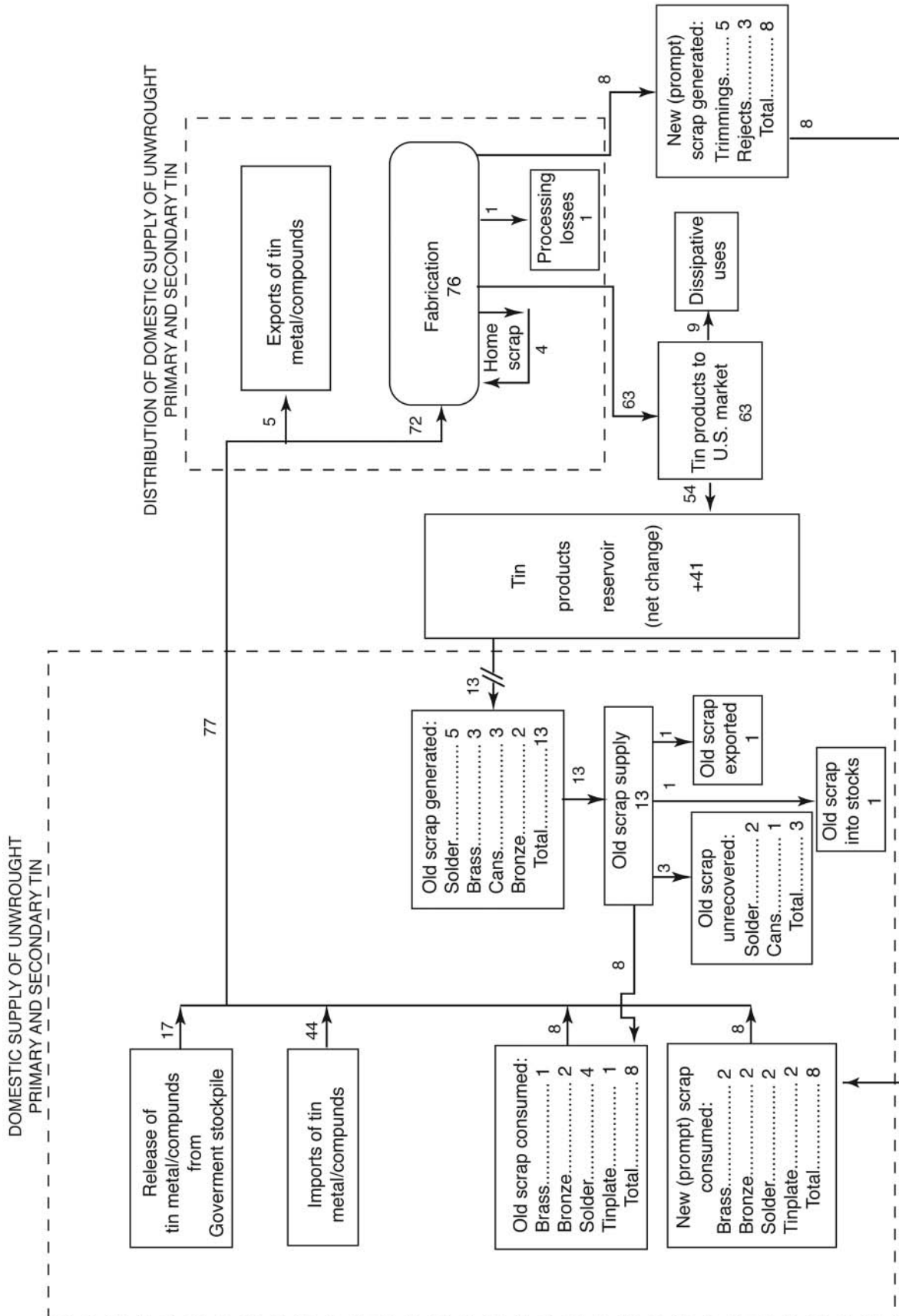


Figure 1. U.S. tin materials flow in 1998. Values are in metric tons contained tin.

Table 1. Salient statistics for U.S. tin scrap in 1998.

[Values in thousand metric tons of contained tin, unless otherwise specified; NA, not available]

Old scrap:	
Generated ¹	13
Consumed ²	8
Consumption value ³	\$65 million
Recycling efficiency ⁴	75 percent
Supply ⁵	13
Unrecovered ⁶	3
New scrap consumed ⁷	8
New-to-old-scrap ratio ⁸	50:50
Recycling rate ⁹	22 percent
U.S. net exports of scrap ¹⁰	5
Value of U.S. net exports of scrap	NA

¹Tin content of products theoretically becoming obsolete in the United States in 1998. It excludes dissipative uses.

²Tin content of products that were recycled in 1998.

³Based on tin scrap price, estimated from composite metal prices reported by Platts Metals Week. Values of tin scrap imports and exports are reported by the U.S. Census Bureau.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported minus old scrap stock increase).

⁵Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁷Prompt industrial scrap. Some scrap is excluded.

⁸Ratio of quantities consumed, in percent.

⁹Supply fraction that is scrap, on an annual basis. It is defined as (old plus new scrap consumed) divided by apparent supply [primary plus secondary production (old scrap plus new scrap) plus imports minus exports plus adjustment for Government and industry stock changes].

¹⁰Trade in scrap is assumed to be principally in old scrap.

In 2000, China, Peru, and Bolivia accounted for about 63 percent of the world tin production of 200,000 t in 2000 by producing tin from lode deposits. Placer production made up the remaining 37 percent, of which Indonesia accounted for two-thirds (Carlin, 2001b).

World reserve data indicate that China (lode deposits, 26 percent of world reserves), Brazil (placer, 23 percent), Malaysia (placer, 13 percent), and Indonesia (placer, 8 percent) may be expected to play major roles in future tin production. Identified resources of tin in lode and placer deposits in the United States are an insignificant part of world totals (Sainsbury and Reed, 1973). Undiscovered lode tin resources in Alaska's Seward Peninsula, if explored for and discovered, would probably add only modest increases to future domestic production (Reed and others, 1989). Small quantities of tin concentrate have been produced from placer deposits in Alaska and as a byproduct of molybdenum mining in Colorado and New Mexico (Carlin, 1985). The last reported production of tin in the United States was in 1994.

TIN PRODUCTION PROCESSES

Each type of tin deposit has its own characteristic processing technique. The crude tin concentrate from placer mining is upgraded by washing, tabling, and magnetic or electrostatic separation. The final product is virtually pure cassiterite.

Tin ore from lode deposits is reduced to the necessary size by conventional crushing and grinding. The ore is concentrated by gravity methods that involve screening, classification, jigging, and tabling. The concentrate is usually a lower grade than placer concentrate owing to associated sulfide minerals. The sulfide minerals are removed by flotation or magnetic separation, with or without roasting.

Cassiterite in placer deposits is fairly coarse-grained, and recoveries range from 90 percent for gravel-pump mines to 95 percent for dredging operations. The cassiterite in vein deposits, however, is typically very fine grained and is difficult to recover by gravity concentration. Cassiterite ore at lode mines in Australia and Bolivia are floated, but recoveries are seldom above 70 percent. Recovery of the tin content in Bolivia has been reported to be as little as 50 percent (Pearce, 1980, p. 755).

Cassiterite is reduced to tin by heating with carbon at 1,200 to 1,300 C. The almost pure cassiterite concentrate from placer deposits is smelted directly. Other concentrates, particularly from Bolivia, contain impurities that must be removed before smelting. This is usually done by roasting the tin concentrates with or without fluxes and followed by acid leaching. During roasting, most of the sulfur and arsenic are removed as oxides. Bismuth, copper, iron, and zinc oxides are removed by leaching the roasted concentrate with sodium carbonate or sulfate and leaching with water. Antimony, bismuth, lead, and silver are removed by a chloridizing roast followed by an acid leach.

In tin smelting plants, reverberatory furnaces are used to smelt primary tin concentrate and to resmelt slag for additional tin recovery. Blast and electric furnaces are often preferred because of better control, cleaner slags, and superior efficiency in smelting finely divided materials. Electric furnaces may be favored for energy-saving reasons at some operations, especially smaller smelters.

Tin smelting is a batch operation. A typical charge consists of cassiterite concentrate, a carbon reducing agent, and limestone and silica fluxes. Between 10 and 12 hours are required to smelt a charge. When smelting is complete, the molten batch is tapped into a settler from which the slag overflows into cast-iron pots. The molten tin from the bottom of the settler is cast into slabs or pigs for refining (Pearce, 1980, p. 766-768).

TIN MARKET PRICES AND USE PATTERNS

The price of tin is the most important factor that influences its recycling rate. In recent decades, tin generally has been the highest priced base metal. Although almost 20

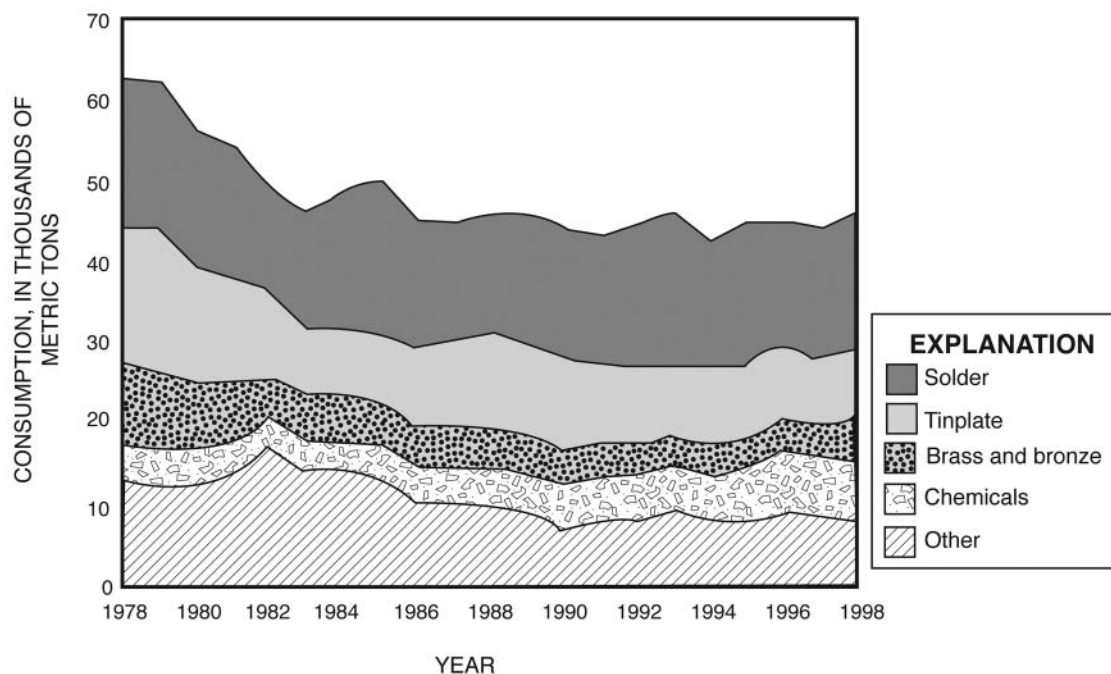


Figure 2. U.S. tin consumption, by end-use sector, from 1978 through 1998.

years have passed since tin reached its historical peak price of more than \$8 per pound, its recent pricing in the \$2.50 to \$4.00 range still provides an adequate incentive to recycle.

The price for tin metal did not vary much throughout 1998. The average composite price for the year, \$3.73 per pound, was 2 percent lower than that of 1997. The London Metal Exchange (LME) was the primary trading arena for tin. Tin was only one of six metals (along with aluminum, copper, lead, nickel, and zinc) to be traded on the LME. The Kuala Lumpur Commodities Exchange in Malaysia, continued as an active tin-trading forum (Platt's Metals Week, 1999).

In 1998, estimated uses of tin in the United States were cans and containers, 30 percent; electrical, 20 percent; construction, 10 percent; transportation, 10 percent; and other, 30 percent (Carlin, 2001b). These tin usage patterns are similar to those in the rest of the world (Carlin, 2000; Roskill Information Services Ltd., 1995, p. 156-170); Figure 2 shows total (primary and secondary) domestic tin consumption by end-use sector between 1978 and 1998.

TIN STATISTICS

Several sources of statistics on U.S. tin materials flow were used in this report to identify recycling parameters as well as the ultimate direction and disposition of domestic secondary supplies. Many of the tin data in this report have been extracted from U.S. Geological Survey (USGS) surveys of all known domestic firms that mine, smelt, use, import, and export tin or engage in scrap-tin recovery. A high percentage of those firms supply data; estimates are made for the

remainder. Most other information in this study that relates to production, supply, consumption, and scrap activity was obtained from USGS publications and industry contacts.

Table 1 and figure 1 present tin scrap data and recycling flow information used in this study.

SOURCES OF TIN SCRAP

Because tin was not produced in the United States in 1998, sources of old scrap and new scrap are key elements of U.S. tin material flow. All scrap tin in the United States is derived from domestic sources; no foreign sources have been reported. In 1998, sources of new scrap and old scrap consumed accounted for equal amounts of secondary tin (8,000 t) in U.S. markets.

OLD SCRAP GENERATED

Old scrap consists of tin-containing products, such as tin cans and electronic equipment, that have been discarded after use. Old scrap is sometimes also referred to as "post-consumer scrap." The old scrap generated in 1998 totaled 13,000 t. Approximately 60 percent of this amount was reused during the year; the remainder was not recovered or was exported or added to industry stocks.

NEW SCRAP GENERATED

New scrap is tin waste that is generated during manufacturing processes and, for the most part, remains the property of the manufacturers; it is continually being recirculated. Home scrap is new scrap that is immediately redirected back into the manufacturing process without leaving the

plant. Some new scrap is collected and later sold to scrap dealers who resell it to similar manufacturers. An example of new tin scrap would be the side trimmings made on a coil of tinplate (tinplate is essentially 99 percent flat-rolled steel with about a 0.5 percent-by-weight flash of tin coating on each side) in a steel mill to meet a customer's width specification; other examples include the tin cans rejected in a canmaking plant owing to poor quality, such as low tin coating weight or insufficient rigidity. In 1998, 8,000 t of new tin scrap was reused, which represented about one-half of the total scrap consumed.

DISPOSITION OF TIN SCRAP

Because of the relatively high value of tin compared with other base metals, such as copper, lead, and zinc, the domestic tin consuming and tin recycling industries have become more efficient in recapturing discarded tin products. Also, because of its value, tin often been the target of smuggling attempts in areas that range from tin smelter sites in developing countries to scrapyards sites in the United States. Smuggling has been especially prevalent at times when tin prices reached high levels. Tin has generally been considered to be a nontoxic material. Thus, environmental considerations are not major factors in recycling.

OLD SCRAP RECYCLING EFFICIENCY

The recycling efficiency of old tin scrap is substantial despite the fact that its recycling rate is relatively low. Old scrap recycling efficiency, which is the amount recovered and reused relative to the total amount of old scrap generated and theoretically available for recycling, was 75 percent in 1998, whereas the recycling rate was 22 percent. The lower recycling rate was partly due to the fact that the third leading use for tin (tin chemicals) has end uses that are nearly all dissipative.

INFRASTRUCTURE OF TIN SCRAP INDUSTRY

Tin has not been mined in the United States for several years. During the past decade, a few small tin mines, most of which are in Alaska, have satisfied only a small fraction of domestic demand. TexTin Corp., which was the only domestic tin smelter, operated for decades in Texas City, Tex.; it closed in 1989 because it was unable to economically compete for foreign tin concentrates. For most of its history, the United States has depended on tin imports, Government stockpile sales, and recycled tin scrap for its industrial requirements (Defense National Stockpile Center, 1998).

In 1998, scrap tin was generated domestically at 5 detinning plants and 46 secondary non ferrous-metal-processing plants. Old tin scrap was collected at hundreds of scrapyards, the five detinning plants, and most municipal

collection-recycling centers. New scrap was generated mainly in the tin mills at six steel plants and at scores of canmaking facilities. Most tin-scrap-processing plants are close to tin-using industries in major market areas, most of which are in the Midwest and the Northeastern United States.

Detinning facilities are unique to the tin scrap industry because no other major metal industry has numerous large-scale plants designed to remove metal plating. Detinning operations are performed on new tinplate scrap from tin mills and canmaking plants and from old scrap in the form of used (postconsumer) tin cans.

The domestic metals recycling industry, as a whole, has been undergoing substantial consolidation during the past 30 years. Before consolidation, the industry was characterized by a multitude of small, family-run firms, many of which dated back to the 19th century. Usually, the firms operated only locally or perhaps regionally. From 1970 onward, however, the industry has been characterized by fewer, larger units that serve national or international markets.

The Steel Recycling Institute (SRI), which is funded by the Nation's major steel producers, has promoted the recycling of used tin cans for more than a decade. These used tin cans have become an important raw material for the domestic steel industry during the past 20 years. According to the SRI, the steel can recycling rate had grown to 56 percent in 1998 from 15 percent in 1988. The increased recycling is significant to tin recovery because most steel cans are made from tinplate (Steel Recycling Institute, 1999).

Major domestic tin requirements have long been met by imports of primary refined tin. In recent years, Brazil has generally been the leading source followed by Indonesia, Bolivia, and China. Trade in tin scrap is relatively small, and trade figures are not available. No imports of tin scrap in 1998 were identified. The United States exported relatively small quantities of new and old tin scrap.

PROCESSING OF SCRAP METALS

Typically, the alloys of tin, such as brass and bronze, jeweler's metal, or babbitt, contain from 2 percent to 11 percent of tin as a minor component of the alloy. The major exception is solder. Solders for plumbing and construction-related uses have traditionally been 50 percent tin-50 percent lead, and those for electronics have usually been 70 percent tin-30 percent lead. The bulk of the secondary tin industry processes various alloy forms of tin (brass, bronze, and solder); the recovered tin is recycled within its own product-line industries and, thus, is used again in alloys. The scrap materials of all alloys of tin are collected via long-established commercial routes and transported back to the original makers of the alloys. Typically, these alloy producers then use a mix of primary tin along with the primary element(s) of the other component(s) of the alloy and com-

bine them in a batch heating process with the collected scrap materials to produce new units of the same alloys. Thus, the secondary tin industry is essentially involved in a process of successive regeneration with old and new scrap alloys being mixed with some primary material added for each new generation of alloys.

For most of this century, detinning has been the only process in the secondary tin industry through which tin alone, not in alloys, reached the marketplace. Consequently, detinning of tinplate is one of the most important sources of tin scrap in the United States. Tinplate scrap suitable for detinning is accumulated at various stages—off-specification tinplate generated in the tin mills at steel plants, reject tinplate and tin cans generated at canmaking facilities, reject cans at can-filling operations, and old scrap tin cans collected by municipalities via curbside collection programs. These collected forms of new and old tinplate scrap are transported to five domestic detinning plants. There, they are immersed in a heated sodium hydroxide solution, which is a batch process that is essentially the reverse of the original tin electroplating process. Tin ions leave the steel surface and migrate to an electrically charged cathode where they deposit and form a bar of tin. The detinned steel is then sold to scrap steel markets, most notably to be used as a scrap charge in the electric furnaces of steel minimills. The bars of scrap tin are then sold to appropriate users of secondary tin, such as producers of tin chemicals, firms that use tin to hot dip onto copper wire, makers of brass and bronze ingots, and the vast number of manufacturers of tin alloy. Traditionally, scrap tin is not used to make tinplate because of purity requirements. The tin coating thickness on steel in modern tinplate is only about, on average, one-half to one-third of what it was in the early 1960s. Today, the nominal tin coating thickness on each side of tinplate is only 0.000381 millimeters. Thus, the economics of detinning make it not nearly as profitable as it once was. Nevertheless,

for maximum steel cleanliness, some steel producers prefer to pay more to have tinplate scrap detinned before they use it; the presence of tin on the surface of scrap steel often is considered to be a major detriment to good quality steel (Groetsch and others, 1984).

OUTLOOK

The established stable consumption pattern of tin and the relatively high price of tin compared with that of other base metals indicates that plentiful amounts of tin will be available for recycling in future years. Moreover, the almost total U.S. reliance on tin imports, the planned elimination of Government tin stocks, and the expected technological advances will tend to encourage more recycling of tin in the next few decades. In addition, the United States will, most likely, continue to be the leading source of scrap for domestic tin markets. Except for dissipative uses, tin scrap for recycling will continue to come from all consumption sectors. Tin prices probably will remain as the most important influence on further recycling advances (Carlin, 1985; Roddy, 1995, p. 84-85).

Trends toward consolidation in the recycling industry are expected to continue, at least in the near future. The resulting larger enterprises presumably will be able to attract funds more easily for equipment modernization and technological improvement that often lead to lower unit processing costs. Thus, consolidation trends augur well for increased recycling of tin. The recycling of tin enhances the sustainability of tin production by reducing the need for primary production, thereby saving energy and extending the longevity of natural resources. The prospects for increasing the recycling rate for tin chemicals are not particularly good, however, because tin chemicals are mostly a dissipative end use. Additionally, some of the more promising new uses for tin, such as ammunition, are essentially dissipative (Carlin, 2001a).

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Molybdenum Recycling in the United States in 1998

By John W. Blossom

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-L

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

1. Salient statistics for U.S. molybdenum scrap in 1998	L3
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CONVERSION FACTORS

Multiply	By	To obtain
<i>Length</i>		
kilometer (km)	0.6214	mile
inch (in.)	25.4	millimeter
<i>Volume</i>		
cubic foot (ft ³)	0.02832	cubic meter
<i>Mass</i>		
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram
<i>Pressure</i>		
pound force per square inch	6.895	kilopascal
atmosphere (atm)	101.3	kilopascal

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Molybdenum Recycling in the United States in 1998

By John W. Blossom

ABSTRACT

This report describes the flow of molybdenum in the United States in 1998 with emphasis on the extent to which molybdenum was recycled. Molybdenum was mostly recycled from products of molybdenum-bearing steels and superalloys; some molybdenum products were recovered specifically for their high molybdenum content. In 1998, 8,000 metric tons of molybdenum were estimated to have been recycled, and the recycling rate was calculated to be 33 percent with a recycling efficiency of about 30 percent.

INTRODUCTION

The materials flow of molybdenum, as shown in figure 1, describes molybdenum supply and demand factors for the United States in 1998; the figure shows the extent of molybdenum recycling¹ and aids in identifying recycling trends. Knowledge of recycling trends is increasingly important because use of scrap promotes conservation of natural resources and enhances the sustainability of primary production for a cleaner environment. Definitions of specialized terms used in characterizing recycling of metals are given in the appendix. Most data used in this report are derived from U.S. Bureau of Mines and U.S. Geological Survey Minerals Yearbooks. Other estimates, such as that for old and new scrap generated, are based on these data. Some figures, such as unrecovered old scrap, are remainders.

Molybdenum is a refractory metallic element used principally as an alloying agent in cast irons, steels, and superalloys to enhance hardenability, strength, toughness, and wear and corrosion resistance. Primarily added in the form of ferromolybdenum or molybdic oxide, it is frequently used in combination with chromium, columbium (niobium), manganese, nickel, tungsten, or other alloy metals to achieve desired metallurgical properties. The versatility of molybdenum has assured it a significant role in contemporary technology and industry, which increasingly require materials that are serviceable under ever higher stresses, over greater temperature ranges, and in more-corrosive environments. Not only does molybdenum find significant

usage as a refractory metal, but also in numerous chemical applications, which include catalysts, lubricants, and pigments. The variety of uses for molybdenum materials, few of which afford acceptable substitutions, has resulted in a demand that is expected to grow at a greater rate than most other ferrous metals. Figure 1 shows the domestic flow of molybdenum in 1998 with the flow of recycled molybdenum shown in detail.

DISTRIBUTION OF MOLYBDENUM

Almost all molybdenum is recovered from low-grade deposits that contain the mineral molybdenite (MoS_2). Deposits mined primarily for molybdenum provide from 65 to 70 percent of U.S. output and about 45 percent of world output; the remainder is obtained mainly as a byproduct from mining large, low-grade porphyry copper deposits. Molybdenum ores generally grade from 0.2 to 0.5 weight percent molybdenite; copper ores from which byproduct molybdenum is recovered contain from 0.02 to 0.08 weight percent molybdenite.

Distribution of molybdenum reserves and productive capacity is concentrated in a few countries of the world. In 1998, world mine output was an estimated 135,000 metric tons (t) (molybdenum contained in concentrate), of which the United States, China, and Chile provided 80 percent; an estimated 10 percent of world output came from Canada and Mexico. These same five countries possess about 85 percent of the estimated 12 million metric tons (Mt) of molybdenum in the world reserve base. The reserve base for the top four countries, by contained molybdenum, is United States, 5,400,000 t; Chile, 2,500,000 t; China, 1,000,000 t; and Canada, 910,000 t. Mexico estimates its reserve base to be 230,000 t. These five countries are expected to continue to be the principal mine producers in the 21st century. Although exploration for new sources is likely to be successful in other areas, these five countries probably have the greatest potential for future additions to reserves and, ultimately, to mine output (Blossom, 2001).

As a result of the concentration of production capacity, international trade in molybdenum materials consists primarily of exports from the United States, China, and Chile to industrialized nations that lack mine production. The major importers are the countries of Western Europe and Japan.

¹Definitions for selected words are found in the Appendix.

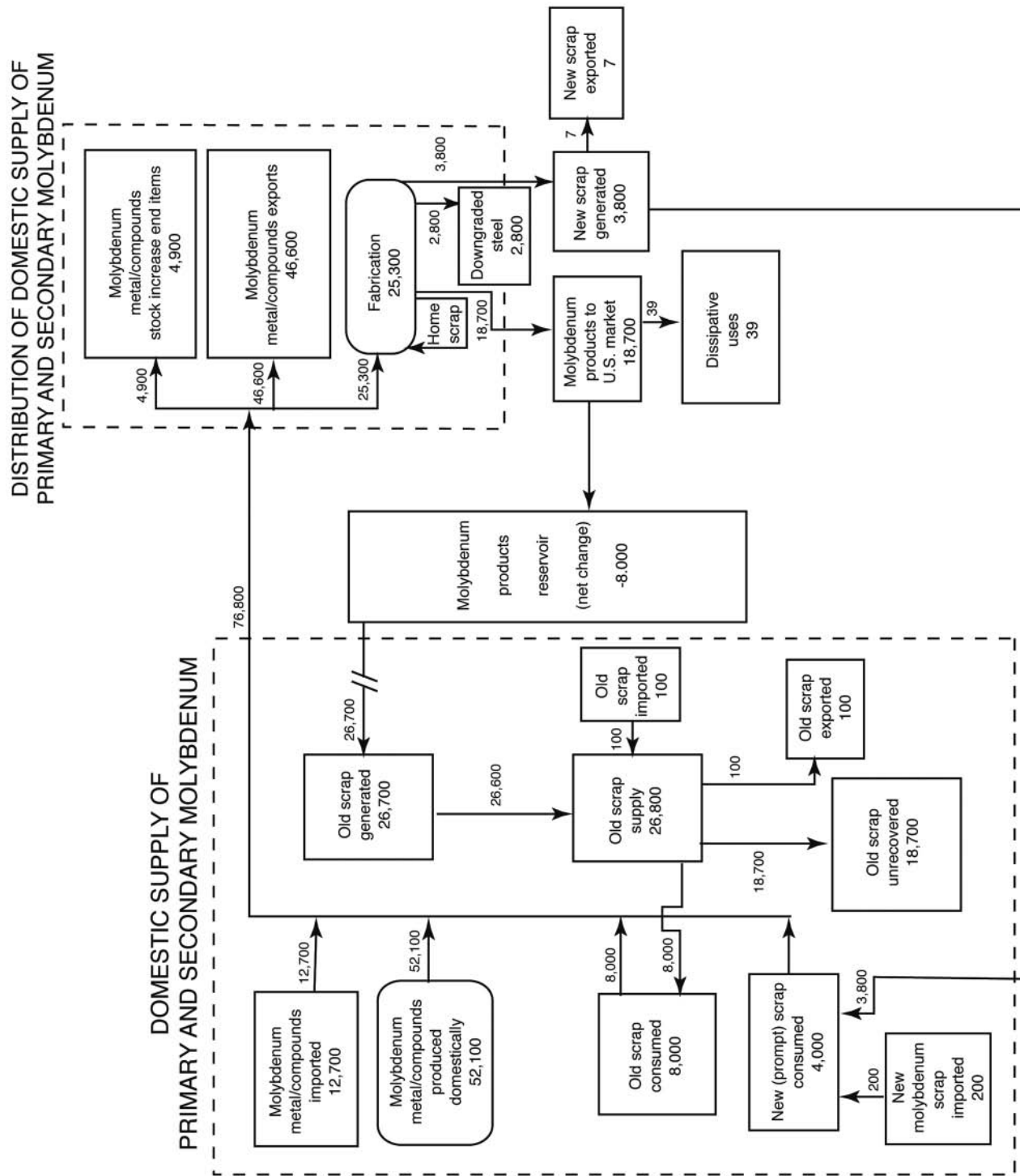


Figure 1. U.S. molybdenum materials flow in 1998. Values are in metric tons contained molybdenum.

Table 1. Salient statistics for U.S. molybdenum scrap in 1998. [Values in metric tons of contained molybdenum, unless otherwise specified]

Old scrap:	
Generated ¹	26,700
Consumed ²	8,000
Consumption value ³	\$70 million
Recycling efficiency ⁴	30 percent
Supply ⁵	26,800
Unrecovered ⁶	18,700
New scrap consumed ⁷	4000
New-to-old-scrap ratio ⁸	33:67
Recycling rate ⁹	33 percent
U.S. net imports of scrap ¹⁰	190
Value of U.S. net imports of scrap	\$1.8 million

¹Molybdenum content of products theoretically becoming obsolete in the United States in 1998. It excludes dissipative uses.

²Molybdenum content of products which were recycled in 1998.

³Unit value of contained molybdenum in molybdenum oxide was used in calculating total value of contained metal in scrap.

⁴(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁵Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁷Including prompt industrial scrap but excluding home scrap.

⁸Ratio of quantities consumed, expressed as a percentage ratio.

⁹Fraction of the molybdenum supply that is scrap on an annual basis. It is defined as consumption of old plus consumption of new scrap divided by apparent supply (see appendix); measured in weight and expressed as a percentage.

¹⁰Trade in scrap is judged to be about equally divided between old and new scrap. Net exports are exports of scrap minus imports of scrap.

The United States has exported about one-half of its mine output in recent years, mostly as concentrate or oxide, and currently (1998) supplies about 45 percent of the molybdenum consumed in other market-economy countries. Because U.S. producers have a viable molybdenum scheme made up of a strong reserve base and mining and marketing plans, the United States is expected to continue as a leading supplier of molybdenum to the world market (Blossom, 2002).

Salient molybdenum scrap statistics are based on the molybdenum content of catalyst, steel, and superalloy scrap. In 1998, about 26,700 t of molybdenum was contained in molybdenum-bearing old scrap available to be recycled. About 8,000 t of molybdenum, which was valued at about \$70 million, was recycled (table 1). The old scrap recycling efficiency was calculated to be about 30 percent, and the recycling rate was about 33 percent. Molybdenum contained in new scrap consumed was about 4,000 t.

GEOLOGIC OCCURRENCE OF MOLYBDENUM

The average crustal abundance of molybdenum is 1 to 2 parts per million (ppm). Molybdenum does not occur in nature in its free or native state, but is found only chemically combined with other elements. MoS₂, which is a lead-gray metallic mineral that characteristically occurs in thin, tabular, commonly hexagonal plates and is also disseminated as fine particles, is the only molybdenum mineral of commercial importance. It has a specific gravity of 4.6 to 4.7, a hardness of 1 to 1.5, and a greasy feel and soils the fingers. Superficially, it resembles graphite, for which it has commonly been mistaken (Blossom, 1985; King and others, 1973).

Wulfenite (PbMoO₃), which is a molybdate of lead, is a metallic mineral of variable color. The mineral has a resinous or adamantine luster, a hardness of 2.75 to 3, a specific gravity of 6.5 to 7, and a white streak. It generally occurs in well-formed crystals, chiefly square and tabular. Deposits are found almost entirely in veins, mostly in the oxidized parts of lead deposits. Occurrences of wulfenite are numerous, but none are of economic importance. Powellite-scheelite [Ca (Mo, W) O₄] is a calcium molybdate-tungsten solid solution series; tungsten may substitute for up to 10 percent molybdenum. Primarily hydrothermal, powellite and scheelite occur in veins and skarns and are not alteration products of molybdenite. Powellite-scheelite is nearly always impure; it has a hardness of 3.5 and a specific gravity of 4.3 and varies in color from dirty white to gray, straw yellow, greenish yellow, pale greenish blue, and brown. Powellite is found with scheelite, and this association helps identify the mineral because it fluoresces a golden yellow. Ferrimolybdite (Fe₂Mo₃O₁₂•8H₂O) is a very soft, hydrous mineral of distinctive canary-yellow color; it is an oxidation product of molybdenite and pyrite. It occurs as fine, needlelike crystals and has a hardness of 1.5 and a specific gravity of 2.99 to 4.5. Other molybdenum minerals include chillagite, eosite, ilsemannite, jordisite, koechlinite, and lindgrenite (King and others, 1973).

TYPES OF DEPOSITS

Molybdenum deposits are of five geologic types—porphyry or disseminated deposits, which include stockworks and breccia pipes in which metallic sulfides are dispersed through relatively large volumes of hydrothermally altered and fractured rock; contact-metamorphic zones and tactite bodies of silicated carbonate-bearing rocks, such as aplite dikes and pegmatites; bedded deposits in sedimentary rocks; carbonate-bearing shale, dolostone, and limestone, adjacent to intrusive granitic rocks; and quartz veins.

The first three genetic-type deposits are hydrothermal in origin and represent nearly all the identified molybdenum resources currently mined in the world. In hydrothermal deposits, metallic minerals are precipitated from high-

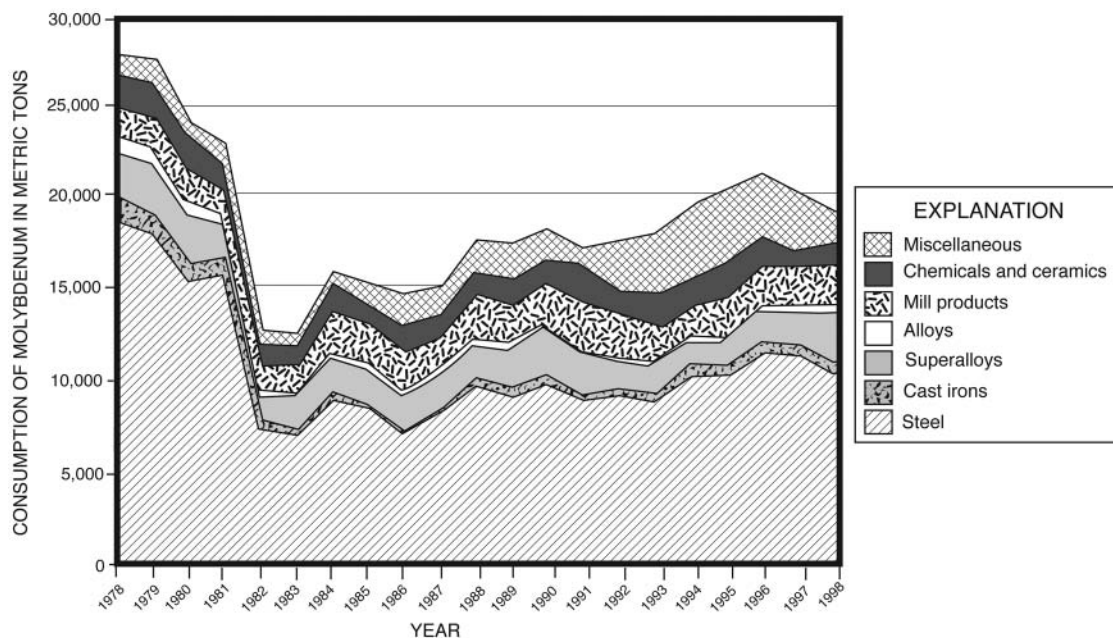


Figure 2. U.S. molybdenum consumption, by end-use sector, from 1978 through 1998.

temperature aqueous fluids either by changes in temperature and pressure or by evaporation of the liquid. Minerals are deposited in the cavities, cracks, or interstices of the host rock. Intrusive rocks, with which the metallic minerals are genetically related, range from intermediate to felsic in composition and include: porphyritic intrusions, dioritic, granitic, and quartz monzonitic composition (Bookstrom, 1999). Metallization commonly takes place in the host intrusive and in the surrounding or overlying country rock. The Climax and the Henderson deposits in Colorado and the Questa deposit in New Mexico are examples of such hydrothermal molybdenum stockwork deposits.

Most of the porphyry copper deposits in the Western United States contain small quantities of molybdenite disseminated with the copper minerals through large bodies of granite rock. The chief minerals are chalcopyrite and chalcocite; pyrite and small amounts of other sulfides, which include molybdenite, also are in the composition. In addition, minor amounts of other base-metal minerals, specular hematite, fluorite, and secondary silicate minerals are present. Chalcocite replaces chalcopyrite and pyrite in the zone of secondary enrichment. The copper-to-molybdenum ratio ranges from about 10 to 1 to perhaps 150 to 1, and generally increases inward and downward within the porphyry copper system.

Small quantities of molybdenite are widely distributed in lime-silicate deposits along the contacts between granitic intrusive rocks and lime-rich sedimentary rocks. Molybdenite is commonly associated with bismuthinite, copper sulfides, or scheelite in zones of silicated limestone near granitic intrusive rocks. The only domestic production from this type of mineralization has been as a byproduct from the

Pine Creek tungsten deposit in California. The mineral deposit originated by replacement of the carbonate rock.

Magmatic hydrothermal fluid also is involved in formation of aplites and pegmatites. Aplites form by “pressure quenching” of magma in response to rapid loss of aqueous fluid. In pegmatites, crystals and fluid coexist. Growth of large crystals is prompted by slow crystal nucleation and rapid ionic diffusion to crystal growth sites. In aplites and pegmatites, MoS_2 deposition involves interactions among crystals, magma, and magmatic-hydrothermal fluid. Pegmatites are coarsely crystalline and consist almost exclusively of quartz and feldspar. Molybdenite occurs as an accessory mineral, and the individual crystals are generally large and usually euhedral. Many pegmatites contain apatite, beryl, cassiterite, columbite, ilmenite, magnetite, rutile, wolfram, and zircon. The average grade of these types of deposits is low; hence, they are not important potential producers of molybdenum. Pegmatite-type deposits that contain disseminated molybdenum associated with bismuth were mined in Val d’Or and Preissac in Quebec, Canada (King and others, 1973).

Molybdenum minerals occur in coal, phosphorite, shale, lignitic sandstone, and some arkosic sandstone. A small quantity of molybdenum was recovered from uraniumiferous lignites in North Dakota and South Dakota until 1968 when output from these sources ceased.

Molybdenum is obtained from primary molybdenum mines and byproduct copper and tungsten mines. Countries that produced molybdenum in 1998 were Armenia, Canada, Chile, China, Iran, Kazakhstan, Mexico, Mongolia, Peru, the Republic of Korea, Russia, the United States, and Uzbekistan (Blossom, 2001).

SOURCES OF MOLYBDENUM FROM SCRAP

Molybdenum is recycled as a component of ferrous scrap, which comprises home, new, and old scrap. Home, or mill scrap is generated within the steel mill during production of iron and steel. Old scrap includes metal articles that have been discarded after serving a useful purpose. Because of the wide variety of chemical and physical characteristics, old scrap often requires significant preparation. The molybdenum component is identified, but in most cases, the scrap is selected for other elements that it contains. If additional molybdenum is required in the melt in making steel, then primary ferromolybdenum or molybdenum oxide, which are products derived from ore, are added.

When the valuable metals or compounds have been recovered, molybdenum catalysts are changed to an environmentally acceptable state so that catalysts do not become solid waste. These metals may be used again in other end uses or reused in catalysts.

Pure and alloyed molybdenum metal and compound scrap from chemical plants, furnaces, trimmings from fabrication processes, and unuseable fabricated items compose new scrap and reenter the flow and through the melt process.

Alloy and stainless steel are major sources of molybdenum-bearing scrap. Although molybdenum is not recovered separately from scrap steel and superalloys that contain it, recycling of these alloys is significant, and the molybdenum content is reused. Some of the molybdenum content that is recycled, however, may be effectively downgraded in alloys where it is tolerated, but not essential.

OLD SCRAP GENERATED

As shown in figure 1, the starting point for molybdenum scrap flow through processing is old scrap generated, which is the amount of molybdenum that became obsolete in 1998. The old scrap supply available to industry is estimated to be 26,700 t; the estimate was based on the lifetimes of products in which molybdenum is used, which ranged from 10 to 60 years, with an estimated average of 20 years. Some scrap is lost to the environment, and some is unrecoverable. In 1998, industry used an estimated 8,000 t of old scrap; 100 t was exported, and 18,700 t was unrecovered. Figure 2 shows changes in end-use patterns from 1978 to 1998; these changes will result in changes in the mix of end uses of old scrap generated in the future.

NEW SCRAP

New scrap consumed in 1998 was estimated to range from 3,800 to 4,000 t, of which 200 t was imported and the rest, domestically generated. The new-scrap-to-old-scrap-consumption ratio during 1998 was 33 to 67. New scrap consisted mainly of trimmings from fabrication processes, such as stamping and recycling of unuseable fabricated

items. New scrap may also be produced in the manufacture of another commodity product, such as the tungsten filament used in light bulbs. In its manufacture, the filament is twisted around a tiny molybdenum rod. The rod is then dissolved in acid and shipped for recycling as a sludge.

DISPOSITION OF MOLYBDENUM SCRAP

Old scrap consists mainly of molybdenum-bearing steel, which includes alloy, carbon, and stainless steel, that may have been used in many applications. The steel grades with the highest percentages of molybdenum are in the alloy and stainless steel categories. The highest volume of production, however, is in carbon steel. This scrap, which is derived from demolition of bridges, buildings, and other structures, junked cars, and manufacturing equipment, is sold to scrap dealers. Molybdenum catalysts, sometimes in relatively pure form and sometimes contained in sludges, usually are sold by chemical processors to small specialized catalyst-recycling plants.

RECYCLING EFFICIENCY FOR OLD SCRAP

The relation between the amount of scrap that is theoretically available for recycling and what is actually recovered and reused is called recycling efficiency. Old scrap recycling efficiency during 1998 was estimated to be 30 percent. Because data were not available, stock changes were not taken into account. Recycling efficiency is not expected to increase significantly because molybdenum scrap competes with new materials, which are readily available and tend to suppress some molybdenum-bearing scrap prices, thereby limiting scrap recycling and, consequently, recycling efficiency. Additionally, much molybdenum-bearing scrap, such as stainless steel scrap, is usually purchased for other metal content, so its collection usually is dependent on the prices of other commodities, such as chromium and nickel.

INFRASTRUCTURE OF THE MOLYBDENUM SCRAP INDUSTRY

Steel mills and foundries that require ferrous molybdenum-bearing scrap and superalloy melt shops that require pure molybdenum scrap are supplied by brokers and scrap collectors and processors (Fenton, 2001). Other types of scrap from spent catalyst and metal-laden solutions, such as those generated in the production of light bulb filaments, must be processed to comply with environmental requirements. Brokers bring scrap buyers and sellers together on a scrap transaction and receive a fee for this service. Consumers use brokers to procure scrap; processors use their services to market their scrap. Brokers purchase scrap for a particular client buyer without having storage or processing facilities or sometimes without any

certainty of finding a buyer who will offer a favorable price and profit. The scrap recycling infrastructure in the United States causes its recycling rate to be equal to and, in most cases, exceed that of other industrialized countries, and the rate is much higher than that of lesser developed countries.

Amlon Metals Inc., which was headquartered in New York, N.Y., and was founded about 1950, provided reclamation services worldwide. The company recycled about 200,000 t per year of metal-bearing materials and provided documents, sampling, transport, and certification of recycling materials. Their focus was on about 10 metals, which included molybdenum, and catalysts where a significant portion of their business. Hi-Temp Specialty Metals in Willingboro, N.J., processed chips, electrodes, molybdenum turnings, and wire. International Metals Reclamation Company, Inc. (INMETCO) in Ellwood City, Pa., converted about 63,000 t of molybdenum-bearing secondary material, which included electric-arc furnace (EAF) dust, spent catalyst, mill scale, and grinding swarf, into about 24,000 t of iron-chromium-nickel ingots with 1.1 percent molybdenum content. The molybdenum recycled from this source alone was about 264 t (Cassidy, 2001).

PM Recovery in New Castle, Pa., specialized in processing molybdenum-bearing nickel and cobalt-based grindings, turnings, and off-specification ingot. Kalumetals, Inc. in Latrobe, Pa., used a batch-process furnace to produce molybdenum oxide. Langeloth Metallurgical in Pittsburgh, Pa., used some secondary material in its molybdenum oxide roasters (Cassidy, 2001).

PROCESSING OF MOLYBDENUM SCRAP

By using a variety of equipment, scrap dealers collect and process scrap into a physical form and chemical composition that can be consumed. The type and size of equipment they use depends on the types and volume of scrap available in the area and the requirements of their customers. The largest and most expensive piece of equipment is the shredder. The shredder can fragment discarded objects into fist-sized pieces; shredded metals, glass, rubber, and plastic are segregated before shipment. Hydraulic shears, which have cutting blades of chromium-nickel-molybdenum alloy steel for hardness, slice heavy pieces of plate, chemical piping, and structural steel into chargeable pieces. Baling presses are used to compact scrap into manageable bundles, thereby reducing scrap volume and shipping costs. Scrap dealers must carefully sort the scrap they sell, and consumers must purchase scrap that does not contain unacceptable levels of undesirable elements.

Old and new molybdenum scrap consumed or recycled during 1998 was about 12,000 t (4,000 t new and 8,000 t old). Appliances, bicycles, and other molybdenum-bearing steel were shredded for recycling. More than 1,500 scrap yards processed steel from construction and demolition sites by shearing, shredding, and baling.

Fabrication of new products produces new scrap that is relatively chemically and physically clean and of known chemical composition. For this reason, most scrap consumers prefer new scrap to old scrap. Preparation of new scrap is usually limited to cutting, cleaning, and baling prior to rapid transport back to the consumer for recycling. Processes used may include calcining, drying, leaching, precipitation, and various means of separation. Some processing may be subcontracted for sludgelike material, catalysts, dusts, grindings, and solutions. Hi-Temp Specialty Metals processed chips, electrodes, molybdenum turnings, and wire by crushing and abrading the material in a ring mill to remove oxide films in preparation for vacuum melting by others. A roasting process was used by INMETCO and Langeloth Metallurgical at their Ellwood City and Pittsburgh, Pa., facilities (Cassidy, 2001).

SUMMARY AND OUTLOOK FOR MOLYBDENUM RECYCLING FLOW

Consumption of molybdenum, and the growth or decline of the scrap industry, depends directly on the health of the specialty and carbon steelmaking industries. Most regions of the world will see a marked increase in steel consumption during the next 5 years, according to the International Iron and Steel Institute (American Metal Market, 2000). In the United States, a steadily increasing population and a growing economy in the long term should assure that the demand for steel products, and the scrap used to make them, will also increase. Steel and scrap consumption will increase as Federal funding of highway and bridge projects increases and will require structural and reinforcement bar products. The use of steel framing is increasing in construction of multifamily developments, retirement homes, and single-family residences. A thriving industry is also dependent on plentiful inexpensive energy. As energy costs rise, the demand for some steel applications may be affected, but demand for pipe and tubular goods used in the oil and gas industry will increase for new drilling and refining projects (Fenton, 2001).

The EAF consumes mostly scrap to make steel. The EAF contribution to total steel production has risen dramatically during the past 30 years, and the amount of EAF-produced steel should continue to increase, perhaps at a rate of 4 percent per year during the next decade (Steel Times International, 2000). The EAF may be the primary steel production method in the world by 2010 (Forster, 1999). The use of the EAF has increased in minimills from small units limited in use for specialty steel production to the large-capacity furnace used to produce a wide range of steels, which includes flat product sheet and plate, long product bars, structural shapes, tubulars, and wire (Recycling Today, 1998). From 1998 through 2000, EAF steel comprised nearly 50 percent of all steel produced in the United States (Fenton, 2002).

The availability of scrap, and operating and capital cost advantages, have made EAF growth possible. Relocations and establishments of new minimills in areas of increasing population growth and manufacturing activity in the Southern States and the Western States and away from the traditional "Rust Belt" States have, to a large extent, satisfied demand for construction steel products and products used by the oil and gas industry. The EAF process is flexible in its material requirements, and plants can also operate with considerable flexibility in making various products depending on market requirements (Worden, 2000). EAF steel-making will continue to grow because of the capital and operating cost advantages relative to those of the basic-oxygen furnace (BOF), the increasingly wide range of steel products that it makes, and its environmental cleanliness. The use of the EAF is the most effective way of reducing carbon dioxide emissions, and less energy is needed to melt scrap than to smelt ore. Use of EAFs will increase as minimills are built, and EAFs may replace more operating BOFs (Katrak and others, 1999).

Ferrous alloy scrap will remain the most important raw material used. Increasing availability of direct-reduced and hot-briqueted iron from domestic producers because of the increasing need for low-residual element feedstocks for the production of high-quality flat steel and special-bar-quality steels required to compete in the higher end markets will be a factor in dampening this trend.

Recycling of molybdenum-bearing scrap will continue to be dependent on the markets for the principal alloy metals of iron, nickel, and chromium, in which molybdenum is often found. Although large quantities of molybdenum will continue to be consumed in downgraded form in steelmaking, molybdenum will continue to be recycled in this manner. As long as the value of molybdenum remains relatively low, scrap metal is not likely to be sought for its molybdenum content. Therefore, recycling rates and efficiency are not likely to change significantly in the near term.

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

primary metal commodity. Metal commodity produced or coproduced from metallic ore.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinsplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinsplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

secondary metal commodity. Metal commodity derived from or contained in scrap.

U.S. Department of the Interior
U.S. Geological Survey

Cobalt Recycling in the United States in 1998

By Kim B. Shedd

U.S. GEOLOGICAL SURVEY CIRCULAR 1196-M

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

1. Salient statistics for U.S. cobalt scrap in 1998	M3
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CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

Cobalt Recycling in the United States in 1998

By Kim B. Shedd

ABSTRACT

This report, which is one of a series of reports on metals recycling, defines and quantifies the 1998 flow of cobalt-bearing materials in the United States from imports and stock releases through consumption and disposition with particular emphasis on the recycling of industrial scrap (new scrap) and used products (old scrap). Because of cobalt's many diverse uses, numerous types of scrap were available for recycling by a wide variety of processes. In 1998, an estimated 32 percent of U.S. cobalt supply was derived from scrap. The ratio of cobalt consumed from new scrap to that from old scrap was estimated to be 50:50. Of all the cobalt in old scrap available for recycling, an estimated 68 percent was either consumed in the United States or exported to be recycled.

INTRODUCTION

The purpose of this report is to define and quantify the recycling¹ of cobalt-bearing scrap, which represents an important component of total cobalt supply. Figure 1 illustrates the flow of cobalt in 1998. It shows sources and distribution of U.S. cobalt supply with particular emphasis on the flow of cobalt-bearing scrap. Table 1 lists salient cobalt scrap statistics for 1998.

Cobalt is a silvery gray metal with many diverse uses that result from several of its unique properties—it has a high melting point, is ferromagnetic and retains its ferromagnetism at the highest temperature of any metal, is multivalent, and produces intense blue colors in conjunction with silica.

GLOBAL GEOLOGIC OCCURRENCE OF COBALT

The average concentration of cobalt in the Earth's crust is estimated to be approximately 0.002 percent. It is present in a large number of distinct mineral species, which include arsenides, hydrates, oxides, sulfarsenides, and sulfides. Most economically important terrestrial cobalt-bearing ore deposits can be classified as one of the following types: hydrothermal, lateritic nickel, magmatic nickel, or sediment-hosted (stratiform) copper. In addition to terrestrial deposits, large resources of cobalt are present in metal-rich nodules

and crusts on the ocean floor (Young, 1960, p. 12–15; Vhay and others, 1973, p. 145–150; Crockett and others, 1987, p. 6–7; and Alcock, 1988, p. 70–73, 78–81, 84–85).

Hydrothermal deposits form when cobalt minerals are precipitated from hot aqueous solutions into fractures or other openings or in place of preexisting minerals. Cobalt arsenides and sulfarsenides, such as cobaltite, skutterudite, and smaltite, are characteristic minerals of hydrothermal cobalt deposits (Young, 1960, p. 14, 16–17, 18, 22, 24; Vhay and others, 1973, p. 149–150; and Crockett and others, 1987, p. 7).

Laterites are soils formed over large areas of low relief by atmospheric weathering of sulfide and silicate ore minerals usually in hot and humid subtropical to tropical climates. Compared with the original unweathered rock, lateritic soils formed from ultramafic igneous rocks and their serpentinized derivatives are enriched in iron, nickel, cobalt, and other minor constituents. The nickel and cobalt minerals formed by this weathering include various complex carbonates, oxides, and hydroxides. Absolite, which is a mixture of cobalt and manganese oxides, is one example (Young, 1960, p. 14–16, 18, 25; Vhay and others, 1973, p. 148; Crockett and others, 1987, p. 7; Alcock, 1988, p. 78–81; and Burger, 1995, p. 1, 12, 14).

Magmatic ore deposits are formed when an immiscible sulfide liquid separates from and concentrates within a cooling and crystallizing mass of molten rock. This can occur above ground in lava flows or underground in intrusions of molten rock. In magmatic ore deposits, cobalt is concentrated along with nickel and iron in such sulfide minerals as pentlandite and pyrrhotite (Young, 1960, p. 12–16; Vhay and others, 1973, p. 146–147; Crockett and others, 1987, p. 6–7; and Alcock, 1988, p. 70–73).

Sediment-hosted copper deposits are also called stratabound or stratiform deposits. These deposits are copper-rich layers in sedimentary rocks. Some sediment-hosted copper deposits have been upgraded by supergene (weathering) processes. The cobalt-bearing minerals in unweathered rocks of these deposits include such sulfides as linnaeite and carrollite; oxides, such as heterogenite, are present in the weathered rocks (Young, 1960, p. 15–19, 21–22; Vhay and others, 1973, p. 150; and Crockett and others, 1987, p. 7).

¹Definitions for selected words are found in the Appendix.

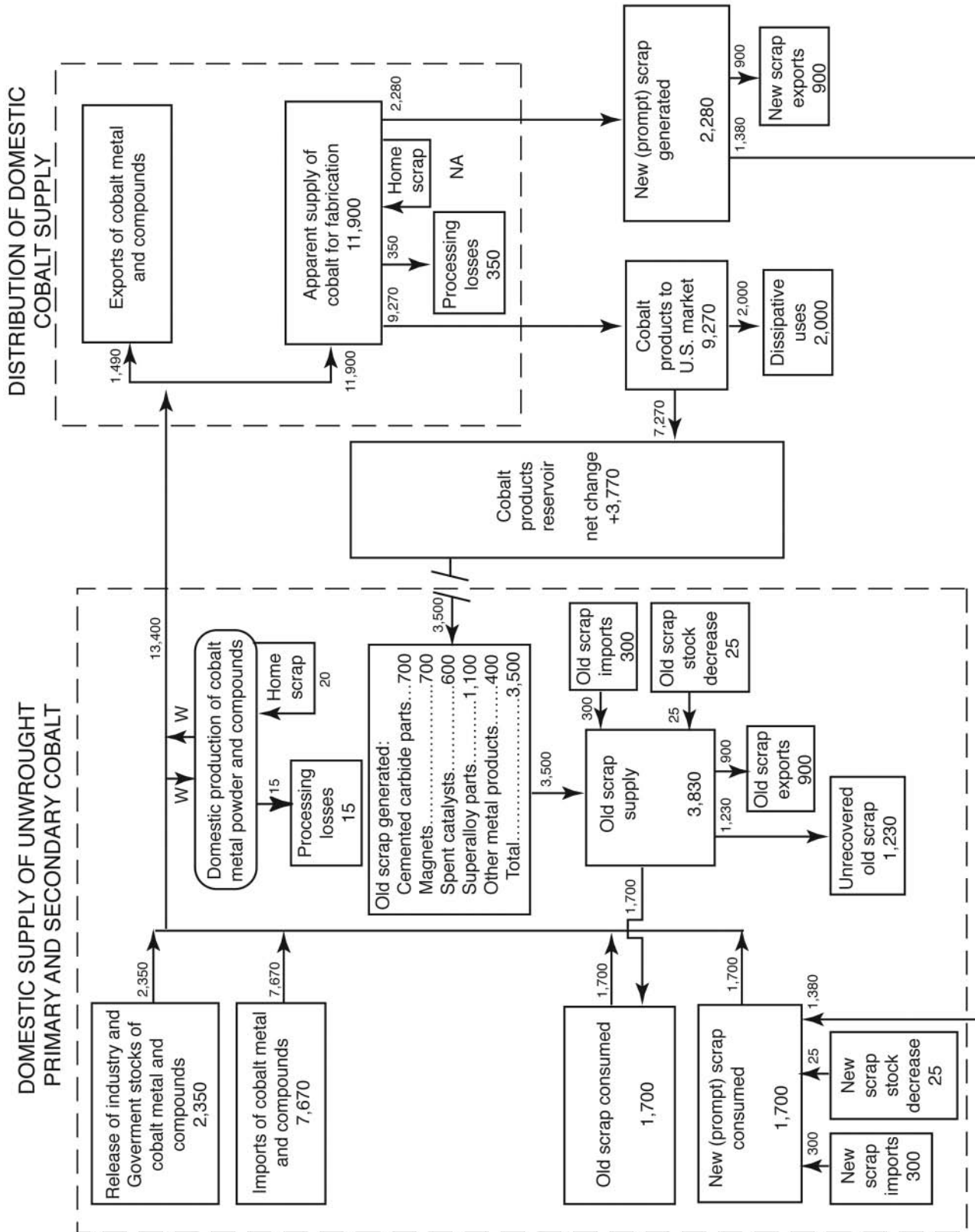


Figure 1. U.S. cobalt materials flow in 1998. Values are in metric tons of contained cobalt, are rounded to no more than three significant digits, and may not add to totals shown. NA, not available; W, withheld to avoid disclosing company proprietary data.

Table 1. Salient statistics for U.S. cobalt scrap in 1998.
[Values in metric tons of contained cobalt, unless otherwise specified]

Old scrap:	
Generated ¹	3,500
Consumed ²	1,700
Consumption value ³	\$40 million
Recycling efficiency ⁴	68 percent
Supply ⁵	3,830
Unrecovered ⁶	1,230
New scrap consumed ⁷	1,700
New-to-old-scrap ratio ⁸	50:50
Recycling rate ⁹	32 percent
U.S. net exports of scrap ¹⁰	1,200
Value of U.S. net exports of scrap ¹¹	\$40 million

¹Old scrap generated is estimated to have been the cobalt content of products theoretically becoming obsolete in the United States in 1998.

²Old scrap consumed is estimated to have been the cobalt content of used products that were recycled in 1998.

³Value of cobalt contained in old scrap, which was based on estimated quantities and values of the various types of cobalt scrap consumed.

⁴Recycling efficiency is (old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁵Old scrap supply is old scrap generated plus old scrap imported plus old scrap stock decrease.

⁶Old scrap unrecovered is old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁷New scrap consumption includes prompt industrial scrap but excludes home scrap.

⁸New-to-old-scrap ratio is the ratio of quantities consumed, expressed as a percentage.

⁹Recycling rate is the fraction of the apparent cobalt supply that is scrap, on an annual basis. It is defined as (consumption of old plus consumption of new scrap) divided by apparent supply (see Appendix); measured in weight and expressed as a percentage.

¹⁰Net exports of scrap are cobalt contained in exports minus cobalt contained in imports of scrap. Trade in cobalt-bearing scrap is assumed to be 50 percent new scrap and 50 percent old scrap.

¹¹Estimated unit value for net exports is greater than that for old scrap consumed because of the mix of scrap types assumed to be exported, imported, and consumed.

In 1998, the United States produced only negligible amounts of byproduct cobalt from its mining operations and had no production where cobalt was the primary commodity. The principal countries where cobalt was mined were Australia, Canada, Cuba, the Democratic Republic of the Congo [Congo (Kinshasa)], New Caledonia, Russia, and Zambia (Shedd, 2001, p. 20.17). Cobalt mined in Congo (Kinshasa) and Zambia was as a byproduct of copper from sediment-hosted deposits. Cobalt mine production from most other countries was as a byproduct of nickel. Cuban and New Caledonian production was from lateritic deposits. Canadian and most of the Russian production was from sulfide deposits. Production from Australia was from lateritic

and sulfide deposits. Only in Morocco was cobalt produced as the primary commodity from a mining operation; the deposits in Morocco are hydrothermal in origin.

COBALT PRODUCTION PROCESSES

Cobalt-bearing ores are mined by conventional underground or open pit methods. They are processed by a wide variety of extractive metallurgical techniques depending on the type of ore, the availability of energy, environmental concerns, market demand for primary products and byproducts, and overall project economics. Nickel laterite ores are usually processed directly. Most other cobalt-bearing ores are first beneficiated, either by mineral flotation or gravimetric methods, to produce a mineral concentrate (De Cuyper, 1988, p. 206). Some ores and concentrates are roasted or smelted to a material referred to as "matte" prior to refining. Most cobalt-producing refineries use hydrometallurgical methods to extract the desirable metals from the ores, concentrates, or mattes and to separate cobalt from the other metals present in the resulting solutions (Kerfoot and Weir, 1988, p. 256). Some refineries also process scrap and cobalt intermediates, such as alloys, impure cobalt compounds, mixed metal sulfides, residues, and slags. Depending on the final processing steps, refined cobalt can be in the form of cobalt metal (cathode, granules, or ingot), metal powder (loose or briquetted), or cobalt chemicals (acetates, carbonate, chlorides, hydroxides, nitrates, oxides, or sulfates).

USES

U.S. cobalt consumption in 1998 can be divided into the following end-use categories: superalloys (44 percent); chemical compounds for a variety of applications (31 percent); cemented carbides and diamond tools (9 percent); magnetic alloys (8 percent); and specialty steels, other alloys, and other metallic uses (8 percent) (Shedd, 2001, p. 20.12). Superalloys are alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is frequently required. Cobalt-bearing magnetic alloys include permanent magnetic alloys, such as alnico, samarium-cobalt, and iron-neodymium-boron, and soft magnetic alloys, such as permendur. Cobalt-bearing steels include high-speed steels from which cutting tools are made and maraging steels, which are characterized by their strength and workability. Other cobalt-bearing alloys are characterized by their resistance to corrosion and/or wear or by their controlled expansion.

Cemented carbides, which are also referred to as "hard-metals," are sintered powder metallurgical parts used as cutting tools and wear-resistant components by the metalworking, mining, oil drilling, and construction industries. In making these parts, cobalt metal powder is used as a binder to hold together the tungsten carbide grains. Diamond tools are similar to cemented carbides in that cobalt is used as a

binding agent to hold together wear-resistant particles, which, in this case, are diamonds. Saws for cutting non-metallic materials, such as stone and concrete, are essentially steel wheels with diamond-bonded segments attached to their circumference. The segments are made by blending, pressing, and sintering a mix of diamonds and cobalt metal powder. Diamond polishing wheels for grinding gem-quality diamonds are made by impregnating diamonds into a surface layer of cobalt on a steel wheel (Cobalt Development Institute, 1993; 2001, p. 83–84).

Applications for cobalt chemical compounds include animal feed additives, bonding agents in steel-belted radial tires, catalysts for the chemical and petroleum industries, drying agents for paint, electrodes for rechargeable batteries, glass decolorizers, ground coat frits for porcelain enamels, magnetic recording media, and pigments. Most of these applications are considered to be dissipative—the cobalt represents an important but very minor constituent of the final product, which is widely distributed during use. This makes cobalt reclamation or recycling impractical or impossible. Two exceptions are the use of cobalt in catalysts and rechargeable batteries, which are products that are recycled.

Cobalt catalysts are used to improve the reaction rates of various processes in the chemical and petroleum industries. In 1998, the top two applications that used cobalt catalysts were the hydroprocessing of petroleum and the production of terephthalic acid (TPA) and dimethyl terephthalate (DMT), which were intermediate compounds in the production of polyester (Field, 1999).

Rechargeable batteries are a relatively new and rapidly growing application for cobalt. In 1998, three types of rechargeable batteries contained cobalt—lithium-ion (Li-ion), nickel-cadmium (NiCd), and nickel-metal hydride (NiMH). The percentages by weight of cobalt in the electrodes in each of these battery types were as follows: Li-ion, 0 to 50 percent of the cathode; NiCd, 3 to 10 percent of the cathode; and NiMH, 3 to 10 percent of the cathode and 3 to 15 percent of the anode (Dominey, 1997). These batteries were either large wet industrial batteries or small sealed dry-cell consumer batteries.

In 1998, the United States was the world's largest consumer of cobalt (Burstow, 2000). Compared with total world cobalt consumption, the United States consumed proportionally more cobalt to make superalloys but less to make batteries (Clark, 1996; Dominey, 1997). Even though as much as 70 percent of cobalt-bearing batteries were made in Asia, a significant percentage of these batteries would have been sent to the United States to be used by U.S. consumers (Dominey, 1997).

Figures 2 and 3 show trends in U.S. consumption of cobalt by various industry sectors since 1978. In figure 2, the cyclic nature of commercial aircraft production is shown in the pattern of cobalt consumption to make superalloys (Schenk, 1998). Figure 3 shows a decrease in cobalt consumption by various industries in the late 1970s to early 1980s. This change in consumption was the result of efforts to conserve cobalt and to find substitutes following a rapid price increase in the late 1970s and recession in the early

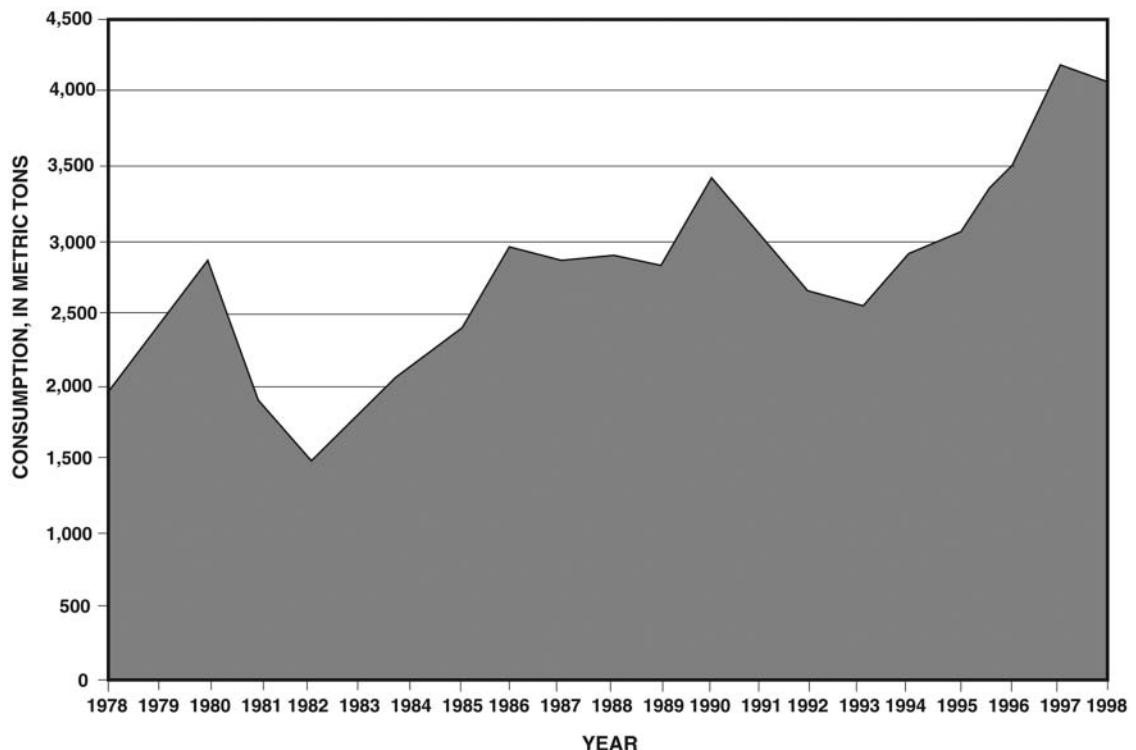


Figure 2. U.S. cobalt consumption in superalloys from 1978 through 1998. Values are in metric tons of contained cobalt.

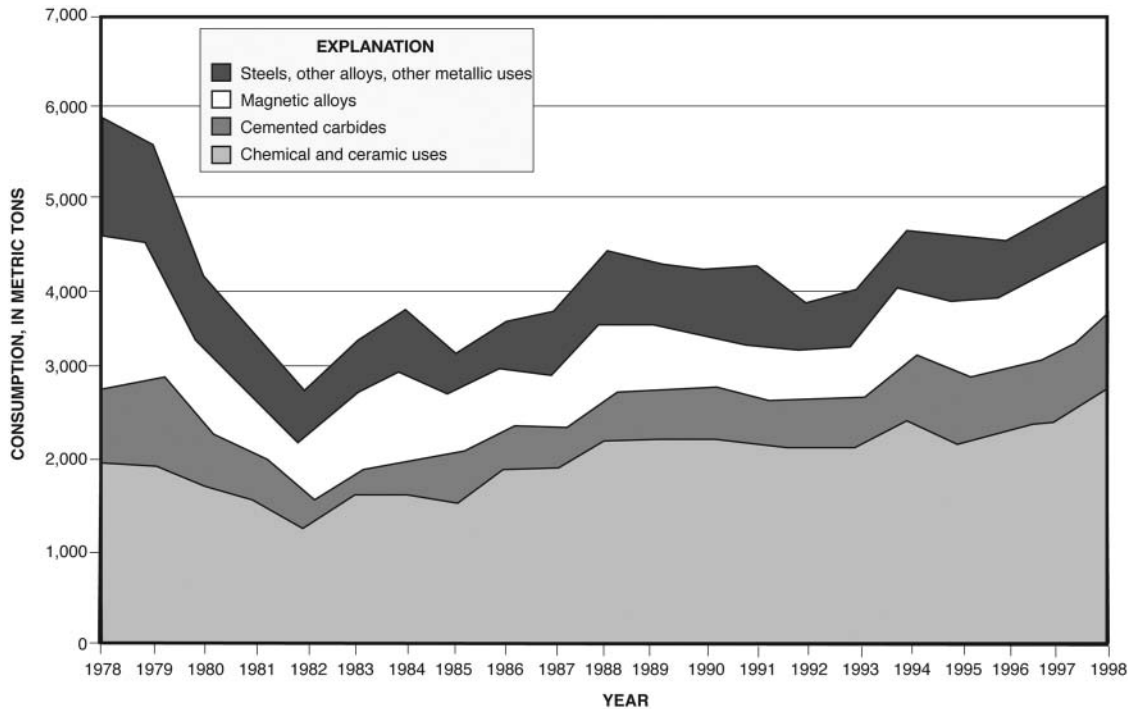


Figure 3. U.S. cobalt consumption, by end-use sector, excluding superalloys, from 1978 through 1998. Values are in metric tons of contained cobalt.

1980s (Shedd, 1999). Figure 3 also shows increasing cobalt consumption for cemented carbides and chemical applications beginning in 1983.

In the late 1970s, approximately one-quarter of U.S. cobalt consumption was for chemical uses, and three-quarters was for metallurgical uses. By the early 1990s, the proportion of U.S. cobalt consumption for chemical uses had grown to approximately one-third of total U.S. consumption. Although some chemical uses of cobalt are recycled, many are dissipative. As a result, an increase in cobalt consumption in chemical uses has the potential to decrease the proportion of cobalt consumption available for recycling.

PRICES

The price of cobalt metal has a significant influence on its recycling rate. Higher prices for cobalt encourage recycling and metal recovery; lower prices do not. Since the late 1970s, free market prices for cobalt have varied considerably (Shedd, 1999). During the 1990s, the U.S. spot price for cobalt cathode (minimum of 99.8 percent cobalt), as reported in Platt's Metals Week, fluctuated widely between a low of \$7.50 per pound (\$16.50 per kilogram) and a high of \$35 per pound (\$77 per kilogram) (figure 4). Although this price varied significantly during the course of each year, the annual average price has trended downward since 1995. During 1998, the U.S. spot cathode price decreased to a low of \$10 per pound (\$22 per kilogram) in mid-December from a high of \$26 per pound (\$57 per kilogram) in early January.

SOURCES OF COBALT SCRAP

Sources of cobalt scrap are key features of the U.S. cobalt materials flow shown in figure 1. Domestic scrap originates during manufacturing and following use of products in the United States. Scrap generated in foreign countries can enter the United States as imports.

OLD SCRAP GENERATED

Old scrap consists of cobalt-bearing products that are no longer being used. Some examples are used turbine blades and other parts removed from jet engines, spent rechargeable batteries, spent catalysts, used cemented carbide cutting tools, and magnets removed from consumer or industrial equipment. To estimate the amount of cobalt that becomes available from old scrap (termed "old scrap generated") in 1998, the following approach was used. For each cobalt-consuming industry in the United States, the average number of years the products would be in use was estimated. These product lifetimes were subtracted from 1998 to determine the year in which the product would have been manufactured. The amount of cobalt in the products was based on the amount of cobalt consumed by that industry sector during the year of manufacture minus the amount of cobalt that ended up as waste materials or new scrap. The amount of cobalt consumed by each industry sector in the year the products were manufactured was based on information collected by the U.S. Bureau of Mines or the U.S. Geological Survey. The percentage of cobalt consumed by each sector that ended up in final products was derived from the National Research Council (1983).



Figure 4. U.S. spot cobalt cathode prices from 1988 through 1998. (Source: Platt's Metals Week)

This method of estimating old scrap generated is based entirely on cobalt consumed to make products in the United States and does not take into account the amount of cobalt in products imported into the country or exported out of the country. Although the net trade of cobalt in products could significantly alter the estimation of old scrap generated, the amount of cobalt in imported and exported products would be very difficult to quantify. Such items as magnets and rechargeable batteries are present in a multitude of products, instrumentation, and equipment used by consumers, industry, and the military and come in a multitude of sizes and various chemical compositions, some of which contain cobalt and some of which do not. Because of the lack of adequate information from which to make reliable estimates, no attempt was made to estimate the net trade of cobalt in products for this study.

As shown in figure 1 and table 1, 3,500 metric tons (t) of cobalt was contained in products that theoretically became available for recycling in 1998.

NEW SCRAP

New scrap is generated during the manufacture of alloys and other cobalt-bearing materials and products. It is often divided into "hard" and "soft" scrap. Hard scrap is in the form of solid pieces, such as subspecification alloy or cemented carbide parts or excess alloy generated during casting operations or removed during pressing and forging operations. Soft scrap is finely divided material. Examples include grinding sludges, swarf, turnings generated during

machining of steel and alloy parts, baghouse dust from steel and alloy manufacturing, and loose powders generated from powder metallurgical processes.

The superalloy industry typically generates large quantities of new scrap. The buy-to-fly ratio, which is the weight of metal purchased versus the weight of the finished parts, provides a measure of the amount of scrap generated. Depending on the part being made, these ratios can range from less than 5 to 1 to greater than 20 to 1. In 1998, the average buy-to-fly ratio was about 7 to 1; this means that for every kilogram of aircraft engine parts produced, 7 kilograms (kg) of metal was purchased and 6 kg of scrap was generated (Lane, 1998; Schenk, 1998). New superalloy scrap can be in the form of solids, turnings, or grindings. By volume, turnings are the largest quantity generated (Lane, 1998).

New scrap is also generated during the casting of corrosion-resistant alloys. In this industry sector, for every kilogram of alloy poured, only 0.4 to 0.6 kg of usable casting is produced. In other words, 40 to 60 percent of the melt becomes new scrap, which would be either recycled in-house or sold to be recycled elsewhere. The number of buyers may be limited, however, by the composition of the scrap. Certain elements that may be present in cobalt-base corrosion-resistant alloys, such as copper and tungsten, are not tolerated in many other cobalt-bearing alloys (Spence and Stickle, 2002).

For the purpose of this study, new scrap does not include home scrap, which is generated and consumed

within a single plant. Quantities of new scrap and home scrap generated by U.S. producers of cobalt metal powder and chemicals were estimated from information in the U.S. Environmental Protection Agency's Toxics Release Inventory (TRI). Reports that provided data on releases, transfers, and recycling of cobalt compounds were generated by using the toxic releases query form at URL http://www.epa.gov/enviro/html/tris/tris_query.html. Reported data from individual plants were summed to estimate U.S. totals. In 1998, the cobalt metal powder and chemical producers recycled approximately 20 t of cobalt in new scrap inhouse (identified as home scrap in figure 1), transferred approximately 30 t of cobalt in new scrap to other plants to be recycled, and released approximately 15 t of cobalt as processing losses to the air, land, or water.

Cobalt in processing losses, new scrap generated, and products from U.S. industry sectors that produced alloys, parts, and other cobalt-bearing products are shown on the right-hand side of figure 1. The amount of cobalt lost during fabrication was derived from TRI releases. In 1998, approximately 350 t of cobalt was released as processing losses. This equaled 3 percent of the apparent supply of cobalt used for fabrication. The amount of cobalt in new scrap generated in 1998 was calculated by adding the estimates for cobalt in new scrap consumed and new scrap exports.

SCRAP IMPORTS

U.S. trade statistics are classified under the Harmonized Tariff Schedule of the United States Annotated (HTSA). The HTSA provides statistical categories and the applicable tariff rates for all merchandise imported into the United States. It is based on the international Harmonized System, which is the global classification system that is used to describe most world trade in goods.

The U.S. Census Bureau reported gross weight and customs value of imports of cobalt waste and scrap under HTSA category 8105.10.9000. The cobalt content of these imports was estimated as follows: for each month, for each country of origin and port of entry, the gross weight was multiplied by the unit value divided by Platt's Metals Week's monthly average spot price for cobalt metal.

In 1998, the United States imported an estimated 250 t of cobalt in cobalt-bearing scrap under HTSA category 8105.10.9000. On the basis of gross weight, most of this scrap originated from Belgium, Canada, Finland, France, Germany, Japan, the Netherlands, and the United Kingdom.

Additional cobalt was likely to have been imported in scrap listed under other HTSA categories. One example would be superalloy scrap imported under the HTSA category for nickel waste and scrap (7503.00.0000). The total estimated cobalt content of imported scrap was increased to 600 t to include an estimate for the cobalt content of these other types of scrap.

Specific information on the type of scrap imported was not available. Industry sources confirmed that much of the

imported superalloy scrap is in the form of turnings. The amounts of new and old scrap imported were estimated by using the new-scrap-to-old-scrap ratio of 50:50 that was calculated for U.S. consumption.

DISPOSITION OF COBALT SCRAP

Cobalt-bearing scrap can be consumed (by recycling, processing to recover the cobalt, or downgrading), stocked, exported, or disposed of.

SCRAP CONSUMPTION (RECYCLING AND RECOVERY)

Estimates of new and old scrap consumption were made by using information from various sources, which included data reported to the U.S. Geological Survey, personal communications with industry representatives, and published reports. In 1998, U.S. industry consumed an estimated 1,700 t of new scrap and 1,700 t of old scrap. This resulted in a new-to-old-scrap ratio of 50:50 (table 1).

Recycled cobalt includes cobalt in recycled scrap where the cobalt is not necessarily wanted, but is tolerated. This is referred to as "downgraded cobalt." Downgrading happens when cobalt-bearing scrap is recycled to a steel or to an alloy in which the cobalt is diluted to a residual or background level to a point where its unique properties are not fully utilized. Cobalt then effectively acts as a substitute for iron, nickel, or other alloying metals. For the purposes of this study, downgraded cobalt was counted as scrap consumption rather than as a loss (see definition for recycling in the Appendix).

SCRAP EXPORTS

The U.S. Census Bureau combined exports of cobalt waste and scrap with those of cobalt metal under HTSA category 8105.10.0000. The following procedure was used to distinguish cobalt scrap from cobalt metal. Data were available on a monthly basis for individual countries of destination and ports of departure. For each month, a minimum price for cobalt metal was determined from a comparison of prices published in Platt's Metals Week and Metal Bulletin and unit values of National Defense Stockpile (NDS) cobalt awarded by the Defense National Stockpile Center. Exports with unit values above this minimum were considered to be cobalt metal, and exports with unit values below this minimum were considered to be cobalt scrap. The cobalt content of the cobalt metal exports was assumed to be nearly 100 percent, or roughly equal to the gross weight. The cobalt content of the scrap exports was estimated as follows: for each month, for each country of destination and port of departure, the unit value in dollars per pound was calculated by dividing the free-alongside-ship value by the gross weight. The gross weight was then multiplied by the unit value divided by Platt's Metals Week's monthly average spot price for cobalt metal.

In 1998, the United States exported an estimated 200 t of cobalt in cobalt-bearing scrap under HTSA category 8105.10.0000. On the basis of gross weight, most of this scrap was sent to Belgium, Canada, China (which included Hong Kong), Finland, France, Japan, the Netherlands, and the United Kingdom. The remainder was sent to 14 other countries.

Additional cobalt was likely to have been exported in scrap listed under other HTSA categories. Following discussions with major foreign refiners of U.S. cobalt-bearing scrap and an analysis of exports of nickel waste and scrap under HTSA category 7503.00.0000, the total estimated cobalt content of exported scrap was increased to 1,800 t, and the new-to-old-scrap ratio was estimated to be 50:50.

UNRECOVERED OLD SCRAP

In figure 1 and table 1, unrecovered old scrap represents cobalt in scrap that has not been recycled either in the United States or elsewhere. The amount of cobalt recycled depends on the type of scrap and the price of cobalt (De Jonghe, 1996, p. 9-12). An estimate of the amount of cobalt in unrecovered old scrap was derived by subtracting old scrap consumption and old scrap exports from old scrap supply. The following factors could lead to overestimating the amount of unrecovered old scrap: an overestimate of the amount of old scrap generated that results from products that were still being used in 1998 or that had been exported prior to 1998, double counting between old scrap generated and old scrap imports that results from imported obsolete products that had been manufactured in the United States prior to 1998, and underestimates of old scrap consumed or exported.

OLD SCRAP RECYCLING EFFICIENCY

Recycling efficiency shows the relation between the amount of cobalt in used products theoretically available for recycling and the amount that is recovered or recycled. By definition, this relation is the amount of cobalt in old scrap consumed and exported divided by the amount of cobalt in old scrap generated, imported, and released from stocks. The recycling efficiency for old scrap calculated for 1998 was 68 percent (table 1). Factors that would lead to underestimating old scrap recycling efficiency are as follows: underestimates of the amounts of cobalt-bearing scrap consumed or exported and overestimates of old scrap supply.

INFRASTRUCTURE OF COBALT SCRAP INDUSTRY

Although the United States is a major cobalt consumer, it has not mined or refined a significant amount of cobalt for many years. In 1998, only negligible amounts of byproduct cobalt were produced as intermediate products from U.S. mining operations. U.S. cobalt supply comprised imports, releases from industry stocks, sales of excess cobalt metal from the NDS, and the recycling of cobalt-bearing scrap.

The collection and processing of cobalt-bearing scrap depended on several factors, such as the type, quality, and volume of the scrap. A wide variety of collecting, sorting, preliminary processing, and recycling or metal reclamation systems was used. Some scrap was handled by dealers, brokers, or waste management companies. Some scrap went through other collection, sorting, and processing routes. Examples of collecting, sorting, and preliminary processing routes for two types of scrap—alloy scrap and batteries—are described below. Following collection, sorting, and preliminary processing, most of the cobalt-bearing scrap was processed and/or consumed in the United States. Examples of scrap processing technologies used in the United States are described in the section "Processing of Cobalt Scrap." The remaining cobalt-bearing scrap was exported to foreign smelters, refiners, processors, or consumers either directly or following some initial processing.

ALLOY SCRAP

This category includes new and old scrap of the following types: corrosion- and wear-resistant alloys, magnetic alloys, specialty steels, superalloys, and other cobalt-bearing alloys. Scrap metal processors collect, sort, and process metal and alloy scrap and then return it to scrap consumers for melting (Institute of Scrap Recycling Industries, Inc., 1996, p. 15). Solid pieces of new and old metal and alloy scrap are first hand sorted by alloy type. Skilled sorters do a preliminary sort on the basis of shape (object recognition), color, and weight of the scrap items. If necessary, the items are then tested with one or more of the following methods: response to a magnet, analysis of the spark pattern generated when the alloy is ground on an abrasive wheel, or chemical or physical analysis by various methods (Newell and others, 1982, p. 1-2; Riley, 1990, p. 576-577). Once the solids have been sorted by alloy type, any attachments must be removed and all assemblies must be dismantled. Additional processing, such as washing, degreasing, chemical milling, shot blasting, pickling, and cutting to size, depends on the condition of the scrap and the customer's requirements (Meschter, 1990; Monico Alloys, Inc., undated).

Turnings represent the largest quantity, by volume, of superalloy scrap generated. Scrap processors collect these turnings; qualitatively verify their chemical purity to remove materials that would contaminate a superalloy melt; crush the turnings into chips; quantitatively assay the chips; clean residual cutting fluids and dirt from the chips by kiln processing, detergent cleaning, or solvent cleaning; sample and analyze the scrap to certify that it meets certain chemical specifications; prepare homogeneous lots if desired; densify the chips if desired; and then package the scrap for return to the superalloy melter (Lane, 1998).

Turbine engine parts from dismantled military aircraft are an example of cobalt-bearing old scrap. The Defense Reutilization and Marketing Service (DRMS) is the U.S.

Department of Defense (DOD) agency that disposes of excess property received from the military services. The DRMS first offers excess military property for reuse within the DOD, transfers it to other Federal agencies, or donates it to State and local governments and certain nonprofit organizations. Property that is not reused, transferred, or donated is offered for sale to private companies and individuals (Defense Reutilization and Marketing Service, undated). The DRMS periodically holds sealed bid sales with offers of high-temperature alloy scrap in the form of turbine engine parts. Scrap metal processors are potential buyers of this scrap.

BATTERIES

The use of rechargeable batteries and the subsequent recycling of spent batteries are motivated by the desire to conserve natural resources, to reclaim valuable metals, and to reduce the levels of hazardous metals released into the environment. Battery scrap can be classified into the following broad categories: manufacturing wastes, large wet industrial batteries, and small sealed dry-cell consumer batteries. Manufacturing scrap is generally limited in terms of the number of sources and battery chemistries at each source, a fact that facilitates collection for recycling. In contrast, industrial batteries and, to an even greater extent, consumer batteries become widely dispersed when put into products and distributed to end users. As a result, their collection and sorting by battery chemistry is one of the challenges to achieving a high recycling rate.

In 1998, U.S. collection programs for spent rechargeable batteries were coordinated by a wide variety of entities. "Charge Up to Recycle!" was a public education and battery recycling program. This program had been developed by the Portable Rechargeable Battery Association and was administered by Rechargeable Battery Recycling Corp. (RBRC), which was an international nonprofit public service organization funded by manufacturers and marketers of portable rechargeable batteries and products. In 1998, the RBRC program promoted and implemented the collection of spent NiCd batteries from households and businesses. These batteries were collected at an established network of more than 20,000 retail outlets, 300 community collection centers, and 1,000 businesses and public agencies. Batteries collected under the RBRC program were sent to The International Metals Reclamation Co. (INMETCO) for metal recovery. In early 2000, RBRC announced that it planned to expand its collection program to include Li-ion, NiMH, and small sealed lead rechargeable batteries (England, 1999; Rechargeable Battery Recycling Corp., 2000).

Most NiCd battery manufacturers maintained battery take-back programs and developed specific arrangements with metal recovery facilities to process the batteries (Morrow and Keating, 1999, p. 27, 34). Sony Electronics

Inc. had a take-back program for their Li-ion batteries. In 1998, approximately 1 to 2 t of spent Li-ion batteries was collected by Sony and sent to the company's Dothan, Ala., facility, where they were calcined to remove any residual charge. The calcined batteries were then sent to a refiner or processor to recover the cobalt (Smith, 1999).

By 1998, many manufacturers of NiCd battery-powered consumer products, such as Black & Decker Corp. and Motorola, Inc., had battery take-back programs and were participating in the RBRC program. End-users of industrial NiCd batteries generally had arrangements with their suppliers to return spent batteries for recycling. Some municipalities, armed services, and government agencies also ran battery collection programs (Biagoni, 1999; Morrow and Keating, 1999, p. 28, 34).

INMETCO collected consumer and industrial NiCd batteries under several programs that were developed to serve the needs of cellular phone companies, hospitals, police departments, libraries, municipalities, local communities, and lead smelters that received spent NiCd batteries instead of spent lead batteries. INMETCO collected consumer batteries via a mail-back program, a prepaid container program, the RBRC program, a small package program, and "milk runs" (see Appendix). INMETCO had its own industrial battery collection program and received industrial batteries collected by waste management companies. In addition to batteries from the United States, INMETCO received batteries from Canada, Europe, and South America and battery manufacturing scrap from the United States and elsewhere (Hanewald, McComas, and Liotta, 1999, p. 61-63).

Spent rechargeable batteries collected under various programs were either shipped directly to a metal recovery facility in the United States or elsewhere or sent to a battery processor, also referred to as a "battery breaker" or "secondary battery recycler." The responsibility of the battery processor was to sort the batteries by chemistry and then to send them to the appropriate recovery facilities. In some cases, the processor also dismantled the batteries, separated their components, treated the electrolytes, and/or stored batteries or electrodes prior to shipping them to recovery facilities (Morrow and Keating, 1999, p. 29-30). Kinsbursky Brothers, Inc., of Anaheim, Calif., is an example of a battery processor. In 1998, Kinsbursky Brothers was permitted to process the following cobalt-bearing battery types: Li-ion, NiCd, and NiMH (Coy, 1999).

PROCESSING OF COBALT SCRAP

A wide variety of technologies are used to process cobalt-bearing scrap in the United States. The following are brief descriptions of some of the technologies in use in 1998 for various types of this scrap.

ALLOY SCRAP

Sorting and processing activities performed by scrap metal processors were described previously in the section "Infrastructure of Cobalt Scrap Industry, Alloy Scrap." In some cases, alloy scrap required remelting before it could be reused. Greenville Metals, Inc., of Transfer, Pa., was a specialty alloy producer that offered scrap conversion services. These services entailed remelting customer alloy scrap in an electric arc furnace, adjusting its chemical composition, and then returning the scrap to the customer as an alloy in the form of shot, pigs, or ingots with a certified uniform chemistry. Greenville Metals was able to treat various forms of alloy scrap, such as grindings, turnings, and other low-grade scrap (Greenville Metals, Inc., undated a-d). Additional companies that treated alloy grindings and dusts by using hydrometallurgical or pyrometallurgical processes are described in the section "Mixed Scrap Feeds."

BATTERY SCRAP

When recycling cobalt-bearing batteries, certain metals, such as the cadmium in NiCd batteries and the aluminum in Li-ion batteries, were first recovered or separated from the scrap to facilitate processing the remaining scrap. The processes used by INMETCO and OMG Americas, Inc., to recycle battery scrap are described in the section "Mixed Scrap Feeds."

CEMENTED CARBIDE SCRAP

Many processes for recycling cemented carbide scrap were available for use during 1998. The processes could be generally classified as either direct or indirect recycling. In direct recycling, the cemented carbides were disaggregated, and the resulting powder of tungsten carbide and cobalt was more or less ready to be used to make new cemented carbide parts. Examples of direct recycling processes include bloating, the coldstream process, leach milling with partial cobalt removal, and the zinc process. In indirect recycling processes, the individual components were recovered and purified separately by using chemical methods. Examples of indirect recycling processes included chlorination, leach milling with total cobalt removal, nitrate and/or nitrate-carbonate fusion, and oxidation-sodium hydroxide leaching. In general, the chemical processes had advantages, such as the ability to remove impurities, but tended to have higher costs, higher energy consumption, lower yields, and more waste products than the direct recycling methods. A balance between using indirect chemical recycling and direct recycling processes allowed industry to recycle soft and hard, contaminated and clean cemented carbide scrap; to reduce the overall impurity levels in reclaimed materials; and to reduce recycling costs (Kieffer, 1982; Kieffer and Lassner, 1987; Stjernberg and Johnson, 1998; Gries, 1999; Oakes, 1999).

In the United States, an estimated 35 percent of cemented carbide scrap was recycled by using indirect chemical processes, 25 percent was recycled by using the zinc process, and 5 percent was recycled by using other processes. The remaining 35 percent was not recycled (Stjernberg and Johnson, 1998).

Osram Sylvania Inc. was an example of one U.S. company that used a chemical process to recycle cemented carbide scrap. Tungsten production at Osram's Towanda, Pa., plant was from ore concentrates and tungsten-bearing scrap. The concentrates and oxidized scrap were leached with sodium hydroxide to produce a sodium tungstate solution, which was filtered to remove byproduct sludge that contained cobalt and other metals recovered from the scrap. The sludge was treated chemically to separate the metals. Once separated, the cobalt was converted to cobaltic oxide, which was then reduced by hydrogen to cobalt metal powder. In addition to cemented carbide scrap, Osram's chemical process was able to treat other cobalt-bearing scrap, such as alloys and catalysts (GTE Products Corp., undated, p. 8-9, 16-17; Osram Sylvania Inc., undated).

In 1998, OMG Americas expanded its Apex hydrometallurgical plant in Saint George, Utah, to recycle hard and soft cemented carbide scrap. Cobalt compounds and ammonium paratungstate were the products of this recycling (Magdics, 1997, p. 17; 1998, p. 19, 22, 31; OM Group, Inc., 1999, p. 3). More information on the Apex plant is provided in the section "Mixed Scrap Feeds."

Some U.S. tungsten processors and cemented carbide producers used the zinc process to recycle hard cemented carbide scrap. The scrap was first sorted by grade and cleaned to remove any brazing or impurities and then immersed in molten zinc in the presence of argon gas. The molten zinc reacted with the cobalt binder, which caused the scrap to expand. The zinc was removed by vacuum distillation and left behind a tungsten carbide and cobalt material, which was crushed, milled, and blended. Following chemical analysis and carbon adjustment, the reclaimed powder was then ready to press into new cemented carbide parts (Kieffer, 1982; Stjernberg and Johnson, 1998).

DIAMOND TOOL SCRAP

Small amounts of scrap generated by diamond tool manufacturers were recycled, primarily to recover the diamonds. The recovered cobalt was sent to cobalt processors or refiners. Used tools were either discarded or downgraded to steel (De Jonghe, 1996, p. 9).

MIXED SCRAP FEEDS

In 1998, an undetermined number of plants in the United States recovered cobalt and other metals from a mix of waste and scrap types. The cobalt-bearing waste and scrap treated by these plants included alloys, battery scrap, cakes,

dusts, filters, grindings, overspray, powders, residues, slags, sludges, slurries, solids, solutions, and spent catalysts from the petroleum and chemical industries. Selected plants, the processes they used, and the types of scrap treated are described in the remainder of this section.

The OMG Americas Apex plant recovered cobalt from a variety of scrap materials, which included alloys, spent Li-ion and NiMH batteries, Li-ion and NiMH battery manufacturing scrap, spent catalysts from the petroleum and polyester fiber manufacturing industries, residues, and other cobalt-bearing materials. The general process for treating scrap at Apex was as follows: leaching, removal of impurities, solvent extraction, precipitating the cobalt as carbonate, and then drying the carbonate or calcining it to oxide. Torched spent battery scrap was shredded, screened, and then magnetically separated before processing. Li-ion battery electrode scrap was shredded, calcined, and then screened to separate aluminum from frit-grade oxide without hydrometallurgical treatment. Products from the Apex plant included cobalt carbonate, cobalt nitrate, cobalt oxide, cobalt sulfate solution, frit-grade oxide, lithium-cobalt dioxide, and custom-produced specialty chemicals. The plant had the capacity to recycle from approximately 450 to 900 metric tons per year (t/yr) of cobalt (Magdics, 1997, p. 17, 19–20, 25–29; 1998, p. 16, 19, 22, 24, 26–31).

The INMETCO plant in Ellwood City, Pa., used a high temperature metal recovery process to treat a wide range of nickel-, chromium-, and iron-bearing wastes, which included spent batteries, spent catalysts from oil refining and chemical manufacturing, and wastes from the plating, specialty steel, superalloy, and surface-finishing industries in the form of cakes, dusts, filters, grindings, mill scale, sludges, solutions, and swarf. Cobalt-bearing batteries accepted by INMETCO included Li-ion, NiCd, and NiMH. Some of the other materials processed by INMETCO also contained minor amounts of cobalt. In general, INMETCO accepted solid wastes with less than 2 percent cobalt on a dry-weight basis and liquid wastes with less than 1,800 milligrams per liter cobalt.

Spent NiCd batteries were first treated in INMETCO's cadmium recovery furnace to separate cadmium from the other metals present, which were primarily nickel and iron. At INMETCO's main metal recovery plant, solid wastes were blended with carbon and pelletized by using either liquid wastes or water. The pellets, spent catalysts, and shredded nickel and iron from the batteries were reduced in a rotary hearth furnace and then fed into a submerged electric arc furnace where they were smelted to extract the metals. The molten metal was cast into pigs, which were used as remelt alloy by the stainless steel industry. The remelt alloy was primarily iron with from 9 to 19 percent chromium, from 8 to 16 percent nickel, and a maximum of 0.8 percent cobalt.

The INMETCO process recovered 97 percent of the cobalt present in the waste and scrap. In 1991, the Ellwood

City plant had the capacity to treat 50,000 t/yr of raw material to produce 21,000 t of remelt alloy with an average cobalt content of 0.5 percent. This represented approximately 100 t/yr of cobalt. The INMETCO process also generated slag, which was sold as an aggregate, and flue dust and filter cake, which were treated offsite to reclaim lead and zinc (Hanewald, Munson, and Schweyer, 1991, p. 842–846; Hanewald, Onuska, and Schweers, 1995; International Metals Reclamation Co., Inc., The, 1998, p. 1–4, 8–10).

Agmet Metals, Inc., processed filter cakes, filters, grindings, solutions, and spent catalysts that contained primarily cobalt, copper, nickel, and/or zinc. The company produced metal oxide products by calcining these materials in a natural-gas-fired rotary furnace at its plant in Oakwood Village, Ohio. The metal oxides that contained nickel and cobalt were exported to Canadian smelters. Agmet also calcined TPA catalyst sludge, as necessary, to remove organics. The sludge was then toll-leached by Encycle, Inc., at its plant in Corpus Christi, Tex., to remove sodium bromide. The final product of this recycling was a cobalt-manganese powder that was used as a substitute for cobalt oxide by the frit industry (Cassidy, 2000; 2001, p. 2).

The International Metals & Chemicals Group produced a variety of cobalt and nickel compounds from metallic feeds, plating cake and solutions, and spent catalyst at its PPB Technologies plant in Shelby, N.C. The plant processed feed materials by leaching followed by precipitation and filtering (Cassidy, 2001, p. 11).

The Amax Metals Recovery, Inc., plant in Braithwaite, La., processed solutions and sludges that contained cobalt, copper, and nickel in soluble or hydroxide form by using the technology which is described in the section "Spent Catalysts" (Case, Garretson, and Wiewiorowski, 1995, p. 465).

The Osram Sylvania process, which is described in the section "Cemented Carbide Scrap," was able to treat various types of cobalt-bearing scrap, which included alloys and catalysts (Osram Sylvania Inc., undated).

SPENT CATALYSTS

In 1998, two companies operated metal recovery plants in the United States that used spent cobalt-molybdenum and nickel-molybdenum hydroprocessing catalysts as their main source of feed. At Gulf Chemical & Metallurgical Corp.'s Freeport, Tex., plant, spent catalysts and sodium carbonate were roasted in a multiple-hearth furnace to burn off the hydrocarbons and some of the sulfur and to convert the molybdenum, the vanadium, and the remaining sulfur to water-soluble salts. After roasting, the calcine was milled, leached with water to dissolve the molybdenum and vanadium compounds, and then filtered to separate the alumina, cobalt, and nickel solids from the molybdenum and vanadium in solution. The solution was treated to produce molybdenum and vanadium compounds. Depending on its metal content, the filtercake was sold to cement manufacturers or nickel refineries or smelted onsite in Gulf

Chemical's electric arc furnace. If smelted onsite, then the products were high-grade fused alumina for refractory and abrasive applications and an alloy that contained from 37 to 43 percent nickel and from 12 to 17 percent cobalt, which was sold to nickel-cobalt refineries (Gulf Chemical & Metallurgical Corp., 1999; Llanos and Deering, 2000, p. 764–768).

The Amax plant in Braithwaite, was operated under the name CRI-MET and was a partnership between subsidiaries of CRI International, Inc., and Cyprus Amax Minerals Co. This plant used a two-stage pressure-leaching process to recover metals from spent hydroprocessing catalysts. Spent catalysts were milled in a solution of sodium aluminate and sodium hydroxide. The resulting slurry was fed into an autoclave and leached under oxidizing conditions at elevated temperature and pressure to convert the sulfur to sulfate, to oxidize the organic compounds, and to dissolve the molybdenum and vanadium. The autoclaved material was thickened and filtered to separate the liquid from the solids. Molybdenum and vanadium were recovered from the liquid and converted to oxides. The solids, which contained alumina, cobalt, and nickel, were leached a second time at high temperature and pressure with a strong caustic to solubilize aluminum. The nickel-cobalt solids from the second leach were separated, washed, dried, and then shipped to another plant to be calcined. The calcined nickel-cobalt material was then exported to a nickel-cobalt refiner (Crnojevic and others, 1990, p. 463–467; Case and others, 1995, p. 450–453, 461).

Spent hydroprocessing catalysts were also processed by INMETCO and OMG Americas, as described in the section "Mixed Scrap Feeds."

Spent cobalt-manganese catalyst residues from the production of DMT and TPA were sent to cobalt chemical producers, such as OMG Americas and The Hall Chemical Co. These companies either reclaimed the metals by producing cobalt chemicals or upgraded the spent catalysts to new catalysts, which they then returned to the catalyst user (Chemical Marketing Reporter, 1995; Magdics, 1997, p. 19; Hall Chemical Co., The, undated). As described in the section "Mixed Scrap Feeds," Agmet Metals and Encycle converted spent cobalt-manganese catalyst residues into a cobalt-manganese powder that was used as a substitute for cobalt oxide by the frit industry (Cassidy, 2000).

OUTLOOK

The recycling of cobalt-bearing scrap and the recovery of cobalt from scrap materials are well-established practices for a number of reasons. The relatively high price of cobalt compared with that of many other metals and the relatively low price of cobalt-bearing scrap compared with that of primary cobalt make recycling and cobalt recovery economic and desirable. Concern over potential supply disruptions that could result from a high dependence on imports from uncertain supply sources has encouraged recycling and

metal recovery as a way to diversify the sources of raw materials for the production of cobalt and tungsten chemicals, metals, and end products. Additional factors that play a role in promoting cobalt recycling and recovery include environmental regulations; periodic increases in the price of cobalt; the desire to conserve resources and energy, to reduce mining and mineral processing wastes and the costs of disposing of these wastes and of used products, to reduce levels of such hazardous materials as cadmium in NiCd batteries from the environment, and to demonstrate an environmentally responsible image.

World cobalt consumption is expected to continue to increase in coming years. Because most cobalt products can be recycled, the availability of cobalt-bearing scrap is also expected to increase. Future increases in the supply of primary cobalt could negatively impact the amount of cobalt that will be recycled. Cobalt production has been increasing in recent years and is anticipated to continue to increase at a faster rate than that of cobalt demand. The likely response to a growing market surplus would be a generally downward trend in cobalt prices (Shedd, 2001, p. 20.8). The combined effect of a surplus of primary cobalt and low cobalt prices would impact the economics of some recycling and cobalt recovery processes. The prices at which cobalt recycling or recovery would become unprofitable for consumers, processors, and refiners are not available because companies do not want to reveal proprietary information related to their processing costs. One analyst has stated that chemical processors reportedly begin to hold back on using scrap when the price of cobalt is below approximately \$15 per pound (\$33 per kilogram) but that a major cobalt refiner reportedly has continued to process superalloy scrap when the price of cobalt was as low as \$10 per pound (\$22 per kilogram) (Hawkins, 1998). Another analyst has stated that there is some evidence that the economics of cobalt recycling and reclamation begin to be impacted when the price of cobalt decreases to \$12 per pound (\$26 per kilogram) but that the impact is much greater when prices drop to \$10 per pound (\$22 per kilogram) or lower (Kielty, 2001).

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

catalyst. A substance that changes the rate of a chemical reaction without being consumed in the reaction.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle or recover the metal.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

milk run. A routine trip involving stops at many places.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed as a percentage of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Cobalt content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as [consumption of old scrap (COS) plus exports of old scrap (OSE)] divided

by [old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks], measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Prices for cobalt scrap are not published. The average price of cobalt metal in 1998 was used to estimate the total value of old scrap consumed. For each type of scrap, a percentage was applied to adjust the relative value of cobalt contained in the scrap to the price of cobalt metal. The total value of net exports of cobalt scrap was derived from trade statistics reported by the U.S. Census Bureau as follows: total estimated value of cobalt scrap exports minus total estimated value of cobalt scrap imports. See “Scrap Exports” and “Scrap Imports” sections of this report for further information on how cobalt scrap trade statistics were estimated.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as [consumption of old scrap (COS) plus consumption of new scrap (CNS)] divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

superalloys. Alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is frequently required.

swarf. Fine metallic particles and abrasive fragments removed by cutting or grinding tools.