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

Overview of Flow Studies for Recycling Metal Commodities in the United States

By Scott F. Sibley

U.S. GEOLOGICAL SURVEY CIRCULAR 1196–AA

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Sibley, S.F., 2011, Overview of flow studies for recycling metal commodities in the United States, chap. AA *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. AA1–AA25, available only at http://pubs.usgs.gov/circ/circ1196-AA/.

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 40 percent of the U.S. metal supply.

Marcia K. McNutt
Director

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Mass	
kilogram (kg)	2.205	pound (lb)
metric ton (t, 1,000 kg)	1.102	short ton (2,000 lb)
million metric tons (Mt)	1.102	million short tons

Overview of Flow Studies for Recycling Metal Commodities in the United States

By Scott F. Sibley

ABSTRACT

Metal supply consists of primary material from a mining operation and secondary material, which is composed of new and old scrap. Recycling, which is the use of secondary material, can contribute significantly to metal production, sometimes accounting for more than 50 percent of raw material supply.

From 2001 to 2011, U.S. Geological Survey (USGS) scientists studied 26 metals to ascertain the status and magnitude of their recycling industries. The results were published in chapters A–Z of USGS Circular 1196, entitled, "Flow Studies for Recycling Metal Commodities in the United States." These metals were aluminum (chapter W), antimony (Q), beryllium (P), cadmium (O), chromium (C), cobalt (M), columbium (niobium) (I), copper (X), germanium (V), gold (A), iron and steel (G), lead (F), magnesium (E), manganese (H), mercury (U), molybdenum (L), nickel (Z), platinum (B), selenium (T), silver (N), tantalum (J), tin (K), titanium (Y), tungsten (R), vanadium (S), and zinc (D). Each metal commodity was assigned to a single year: chapters A–M have recycling data for 1998; chapters N–R and U–W have data for 2000, and chapters S, T, and X–Z have data for 2004. This 27th chapter of Circular 1196 is called AA; it includes salient data from each study described in chapters A–Z, along with an analysis of overall trends of metals recycling in the United States during 1998 through 2004 and additional up-to-date reviews of selected metal recycling industries from 1991 through 2008.

In the United States for these metals in 1998, 2000, and 2004 (each metal commodity assigned to a single year), 84 million metric tons (Mt) of old scrap was generated. Unrecovered old scrap totaled 43 Mt (about 51 percent of old scrap generated, OSG), old scrap consumed was 38 Mt (about 45 percent of OSG), and net old scrap exports were 3.3 Mt (about 4 percent of OSG). Therefore, there was significant potential for increased recovery from scrap. The total old scrap supply was 88 Mt, and the overall new-to-old-scrap ratio was 36:64. On a weighted-average basis, the recycling rate overall for these metals was 40 percent, and the estimated efficiency of recovery was 63 percent. New scrap consumed was 21 Mt. The United States was a net exporter of most scrap metals, and the net exports of 3.3 Mt were valued at $2 billion in constant 1998 dollars. Metals show a wide range of recycling rates, recycling efficiency, and new-to-old-scrap ratios. Recycling rates cluster in the range from 15 to 45 percent, whereas efficiencies are fairly evenly distributed over a range from 7 to 97 percent.

INTRODUCTION

Metal supply is composed of primary material, which may be a principal product, a coproduct, or a byproduct of a mining operation, and secondary material, which may be either new or old scrap. New scrap is material that has been returned from a manufacturing plant and that has not yet been used. Old scrap is postconsumer material, also referred to as "obsolete scrap." The foregoing components were the focus of U.S. Geological Survey (USGS) studies of metal recycling. Industrial stocks—producer, trader, exchange, and consumer—are part of supply, but they were not considered except in calculating apparent supply. The supply chain includes mining, processing, and smelting or refining, and scrap is an important component of the supply chain for most metals.

From 2001 to 2011, USGS scientists studied 26 metals to ascertain the status and magnitude of their recycling industries. The results were published in chapters A–Z of USGS Circular 1196, entitled, "Flow Studies for Recycling Metal Commodities in the United States" (table 1). These metals were aluminum (chapter W), antimony (Q), beryllium (P), cadmium (O), chromium (C), cobalt (M), columbium (niobium) (I), copper (X), germanium (V), gold (A), iron and steel (G), lead (F), magnesium (E), manganese (H), mercury (U), molybdenum (L), nickel (Z), platinum (B), selenium (T), silver (N), tantalum (J), tin (K), titanium (Y), tungsten

(R), vanadium (S), and zinc (D). Each metal commodity was assigned to a single year: chapters A–M have recycling data for 1998; chapters N–R and U–W have data for 2000; and chapters S, T, and X–Z have data for 2004. Chapters were released separately online as they were completed; chapters A–M were combined into a printed and online volume in 2004, and the online volume was revised in 2006 (Sibley, 2006).

This 27th chapter of Circular 1196 is called AA; it includes salient data from each study described in chapters A–Z, along with an analysis of overall trends of metals recycling in the United States during 1998 through 2004 and additional up-to-date reviews of selected metals recycling industries during 1991 through 2008. Circular 1196 provides a framework, in terms of structure and definitions, on which future studies can be based. A recent study on recycling rates (Graedel and others, 2011) included data from this Circular. Definitions of selected terms are in the appendix of this chapter. All values are given in constant 1998 dollars based on the Consumer Price Index from the U.S. Department of Labor, Bureau of Labor Statistics (2010).

SUPPLY OF SECONDARY MATERIAL

Recycling can contribute significantly to the production of a metal, sometimes accounting for more than 50 percent of raw material supply. The importance of the supply of secondary material is not widely known because industry has integrated the recycling of many metals into process streams to such a degree that recycled material is considered essential feedstock and is sometimes taken for granted. Underreporting or lack of reporting is also common, making analysis difficult.

For the 26 metal commodities studied, for 1998, 2000, and 2004 (each commodity assigned to a single year), the total value of old scrap consumed was $9 billion, and 92 percent of this scrap by weight and 41 percent by value were in iron and steel. The years on which the studies were based were 1998, 2000, and 2004, depending on the year the metal commodity study was prepared. The results of the studies reported in chapters A–Z are summarized in table 2. As mentioned above, values in dollars were put in constant 1998 dollars in table 2.

In terms of conserving resources, an advantage that metals have is that they can be repeatedly recycled, in contrast to many other materials, which can be recycled only a few times, if at all. Therefore, the reusable nature of metals contributes to their sustainability of use in the general economy. Recycling of metals also reduces energy consumption and, therefore, air pollution and carbon release. It is estimated that making aluminum metal from scrap takes only about 5 percent of the energy needed to make aluminum from bauxite (Schlesinger, 2006; U.S. Department of Energy, 2007); making iron and steel from scrap takes only about 28 percent of the energy needed to make iron and steel from iron ore (W. Heenan, President, Steel Recycling Institute, written commun., February 16, 2005), and making lead from scrap takes less than 25 percent of the energy needed to make lead from primary sources (Sinclair, 2009, p. 267). Moreover, recycling reduces land disturbance and depletion of limited natural resources. Not only does recycling conserve natural resources and improve the environment, it lowers import reliance, which is particularly important for metals critical to the U.S. industrial base and national defense.

Calculations of the recycling rate or recycling efficiency are difficult because material is traded at different levels or stages, from ore through finished product. Generally, an attempt was made to maintain consistency in the chapters for the stage of the supply chain at which materials were counted—production, consumption, and trade. The materials counted were usually ore, semirefined or refined metal, chemical compounds, and scrap. Care must be taken to avoid double counting—for example, if an imported raw material is upgraded within the flow cycle. Information on the recycled content of imported metals is typically not available, but if imports of refined metal include some metal that originated as recycled metal in a foreign country, because that recycling was done in another country, it is not counted as recycled input. Thus, consistent country comparisons of recycling rate can be made. Downstream imports of semifabricated products may be considered as part of the flow if significant.

GENERAL RECYCLING FLOW CHART

The generalized flow chart for metals (fig. 1) shows how metals make their way into products and flow back into the production stream during fabrication and after use. Typically, the majority of primary feedstock would be ores and concentrates. After manufacture, all products become part of a reservoir or pool-in-use (circle on the right side of fig. 1), parts of which become obsolete or reach the end of their useful life in any given year (segments C and D). That point may be reached in less than a year for some products, such as aluminum cans made in the same year they became obsolete (A). The bulk of recycled material on average is material that has been used for many years (B). As shown in the chart, only a portion of expended products is actually recycled (D), while the rest (C) is unrecovered in place (so-called hibernating stock, such as abandoned buildings, rails left on old rights-of-way, or old wire left in place when new wiring is installed), dissipated (such as corrosion on bridges or wheel weights lost from automobile tires (Bleiwas, 2006)), or disposed of in landfills.

Each industry was studied in detail, and the core of each study is a flow chart that, in general, shows the domestic supply of primary and secondary metal, the reservoir of metal in use and changes in the level of that reservoir, and the distribution of domestic supply (fig. 2). Usually, the supply of potentially recyclable old scrap material is composed of old scrap generated, old scrap imports, and old scrap stock releases. This secondary supply may be distributed as old scrap consumed, unrecovered old scrap, old scrap exports, or old scrap stock increases. The total supply, composed of primary and secondary production plus primary and secondary imports, may be distributed, in turn, as apparent consumption or exports.

DERIVATION OF RECYCLING RATE AND RECYCLING EFFICIENCY

Quantities for such categories as consumption, imports, exports, stocks, and unrecovered scrap were recorded or estimated by the USGS scientists who wrote chapters A–Z of Circular 1196. These figures have varying levels of uncertainty, and knowing this can be important for anyone consulting these data. Reported data, such as imports and exports or old scrap consumption, have the least uncertainty. Derivative numbers, such as recycling efficiency, particularly those involving estimates, such as old scrap generated, are more uncertain. Old scrap generated is probably the most difficult component of secondary supply to estimate because it requires estimation of lifetimes of products so that the amounts becoming obsolete can be estimated.

Amounts dissipated may not be readily apparent. The determination of amounts dissipated could significantly affect recycling efficiency and, for titanium and vanadium, also the recycling rate. In a steel furnace, alloying elements are lost through stack emissions or report to slag, while only small fractions of these elements are reused in new alloys. One chapter author might consider these metal losses to be potentially recyclable given the right price and technology, whereas another might consider the metal not to be realistically recyclable. For example, large amounts of molybdenum and vanadium are used in steel, but the metals show a significant difference in recycling efficiencies (30 and 94 percent, respectively) because of different interpretations of dissipation by the authors of chapters L and S. Steel companies know or can calculate the quantity of alloying elements introduced to the furnace in scrap charges. The quantities of refined metal added to make alloys, as well as the alloy metal content of new alloys, are also known. Therefore, in theory, percentage loss can be determined. This is a subject that requires further research to determine exactly the percentages of alloying elements that are not reused, and it could be a separate study in itself. If these metals were toxic, a way would probably be found to prevent such losses, and so taking a position that reuse of these metals is technologically feasible seems reasonable.

Similarly, for electronic scrap (Bleiwas and Kelly, 2001; Sullivan, 2006; Bleiwas, 2010), the degree of dissipation varies significantly by country and metal commodity. In some markets, every effort is made to recover all valuable metals from electronic scrap. In others, only the most valuable precious metals are recovered, and in still others, no metals are recovered because the process is considered too costly, and most circuit boards end up in landfills. How electronic scrap is treated is partly a function of operating cost, including labor, and partly a function of availability of processing technology.

RECYCLING RATE

The USGS defines the recycling rate as the quantity of old and new scrap recycled as a percentage of apparent supply (see appendix). The difference between the recycling rate and 100 percent is the primary supply. Recycling rates are an important measure from an environmental perspective because they indicate the status of primary material consumption and of progress toward environmental goals, such as (1) to minimize the use of primary material in order to minimize energy use (thereby reducing pollution), (2) to minimize land used for mining (thereby preserving land for more environmentally friendly uses), and (3) to conserve natural resources. Recycling rates are shown in figure 3 as percentages of supply that are recycled material.

Each industry is unique, and for some, such as vanadium and titanium, uses that were considered dissipative, specifically steel and paints, respectively, were deducted from apparent supply, thereby raising their recycling rates above what they would have been. Each chapter author made judgments about the recyclability of different end uses; however, a similar general methodology was used throughout the study described in Circular 1196.

There was no definitive pattern of certain types of metals having higher or lower recycling rates. Ferrous and nonferrous metals were fairly evenly distributed across a range of 10 to 70 percent. A high recycling rate for lead (63 percent) is easily explained because its recycling is regulated and therefore mandated. Low rates for gold (29 percent) and chromium (20 percent) may be explained by a continuing growth in demand and an abundance of primary material, with a relatively low quantity of secondary material available to meet demand. For example, ferrochromium made from chromite ore supplied significantly more of the chromium units needed to make stainless steel than did recycled stainless steel, even though stainless steel recycling efficiency is relatively high because of its high value. Recycling rates for iron and steel (41 percent) and manganese (37 percent) are similar because a principal use of manganese is in making steel, and much of the contained manganese is reused when steel is recycled but is not separated before reuse.

Factors that influence recycling, and which therefore could increase the share of supply accounted for by recycling, include the type of product and how well it was designed for recycling, its composition and the value of its constituents, and the presence or absence of toxic metals. All of these factors will affect how and whether a metal is recycled.

Table 1. Citations for chapters of U.S. Geological Survey Circular 1196.

[To show the chapter letters, subject years, and metal commodities at a glance, citations for the chapters of Circular 1196 are listed in this table instead of the References Cited]

Chapter	Subject year	Citation
A–M	1998	Sibley, S.F., ed., 2006, Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196–A–M (ver. 2.0), chapters are separately paged, available at http://pubs.usgs.gov/circ/2004/1196am/ as http://pubs.usgs.gov/circ/2004/1196am/c1196a-m_v2.pdf. (Version 2.0 of the volume containing chapters A–M is available only online; it superseded version 1.0, which was printed and put online in 2004.)
A	1998	Amey, E.B., 2006, Gold recycling in the United States in 1998, chap. A *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. A1–A8, available at http://pubs.usgs.gov/circ/2004/1196am/.
B	1998	Hilliard, H.E., 2006, Platinum recycling in the United States in 1998, chap. B *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. B1–B9, available at http://pubs.usgs.gov/circ/2004/1196am/.
C	1998	Papp, J.F., 2006, Chromium recycling in the United States in 1998, chap. C *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. C1–C11, available at http://pubs.usgs.gov/circ/2004/1196am/.
D	1998	Plachy, Jozef, 2006, Zinc recycling in the United States in 1998, chap. D *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. D1–D7, available at http://pubs.usgs.gov/circ/2004/1196am/.
E	1998	Kramer, D.A., 2006, Magnesium recycling in the United States in 1998, chap. E *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. E1–E12, available at http://pubs.usgs.gov/circ/2004/1196am/.
F	1998	Smith, G.R., 2006, Lead recycling in the United States in 1998, chap. F *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. F1–F9, available at http://pubs.usgs.gov/circ/2004/1196am/.
G	1998	Fenton, M.D., 2006, Iron and steel recycling in the United States in 1998, chap. G *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. G1–G8, available at http://pubs.usgs.gov/circ/2004/1196am/.
H	1998	Jones, T.S., 2006, Manganese recycling in the United States in 1998, chap. H *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. H1–H9, available at http://pubs.usgs.gov/circ/2004/1196am/.
I	1998	Cunningham, L.D., 2006, Columbium (niobium) recycling in the United States in 1998, chap. I *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. I1–I9, available at http://pubs.usgs.gov/circ/2004/1196am/.
J	1998	Cunningham, L.D., 2006, Tantalum recycling in the United States in 1998, chap. J *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. J1–J10, available at http://pubs.usgs.gov/circ/2004/1196am/.
K	1998	Carlin, J.F., Jr., 2006, Tin recycling in the United States in 1998, chap. K *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. K1–K8, available at http://pubs.usgs.gov/circ/2004/1196am/.
L	1998	Blossom, J.W., 2006, Molybdenum recycling in the United States in 1998, chap. L *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. L1–L9, available at http://pubs.usgs.gov/circ/2004/1196am/.
M	1998	Shedd, K.B., 2006, Cobalt recycling in the United States in 1998, chap. M *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. M1–M16, available at http://pubs.usgs.gov/circ/2004/1196am/.

Table 1. Citations for chapters of U.S. Geological Survey Circular 1196.—Continued

[To show the chapter letters, subject years, and metal commodities at a glance, citations for the chapters of Circular 1196 are listed in this table instead of the References Cited]

Chapter	Subject year	Citation
N	2000	Hilliard, H.E., 2003, Silver recycling in the United States in 2000, chap. N *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. N1–N11, available at http://pubs.usgs.gov/circ/c1196n/. (Supersedes USGS Open-File Report 03–033.)
O	2000	Plachy, Jozef, 2003, Cadmium recycling in the United States in 2000, chap. O *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. O1–O9, available at http://pubs.usgs.gov/circ/c1196o/. (Supersedes USGS Open-File Report 03–049.)
P	2000	Cunningham, L.D., 2004, Beryllium recycling in the United States in 2000, chap. P *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. P1–P10, available at http://pubs.usgs.gov/circ/c1196p/. (Supersedes USGS Open-File Report 03–282.)
Q	2000	Carlin, J.F., Jr., 2006, Antimony recycling in the United States in 2000, chap. Q *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. Q1–Q8, available at http://pubs.usgs.gov/circ/c1196q/. (Supersedes USGS Open-File Report 2005–1079.)
R	2000	Shedd, K.B., 2011, Tungsten recycling in the United States in 2000, chap. R *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. R1–R19, available at http://pubs.usgs.gov/circ/circ1196-R/. (Supersedes USGS Open-File Report 2005–1028.)
S	2004	Goonan, T.G., 2011, Vanadium recycling in the United States in 2004 (ver. 1.1), chap. S *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. S1–S17, available at http://pubs.usgs.gov/circ/circ1196-S/.
T	2004	George, M.W., and Wagner, L.A., 2010, Selenium recycling in the United States in 2004, chap. T *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. T1–T7, available at http://pubs.usgs.gov/circ/circ1196t/.
U	2000	Brooks, W.E., and Matos, G.R., 2005, Mercury recycling in the United States in 2000, chap. U *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. U1–U21, available at http://pubs.usgs.gov/circ/c1196u/. (Supersedes USGS Open-File Report 2005–1236.)
V	2000	Jorgenson, J.D., 2006, Germanium recycling in the United States in 2000, chap. V *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. V1–V10, available at http://pubs.usgs.gov/circ/c1196v/. (Supersedes USGS Open-File Report 2005–1274.)
W	2000	Plunkert, P.A., 2006, Aluminum recycling in the United States in 2000, chap. W *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. W1–W11, available at http://pubs.usgs.gov/circ/c1196w/. (Supersedes USGS Open-File Report 2005–1051.)
X	2004	Goonan, T.G., 2010, Copper recycling in the United States in 2004, chap. X *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. X1–X30, available at http://pubs.usgs.gov/circ/circ1196x/.
Y	2004	Goonan, T.G., 2010, Titanium recycling in the United States in 2004, chap. Y *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. Y1–Y16, available at http://pubs.usgs.gov/circ/circ1196-Y/.
Z	2004	Goonan, T.G., 2009, Nickel recycling in the United States in 2004 (ver. 1.1), chap. Z *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. Z1–Z30, available at http://pubs.usgs.gov/circ/circ1196-Z/.
AA	1998, 2000, & 2004	Sibley, S.F., 2011, Overview of flow studies for recycling metal commodities in the United States, chap. AA *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196, p. AA1–AA25, available at http://pubs.usgs.gov/circ/circ1196-AA/.

Table 2. Salient statistics for recycling of selected U.S. metals in 1998, 2000, and 2004.

[Values are in thousands of metric tons and billions of constant 1998 dollars, unrounded, unless otherwise specified. Terms: --, zero; NA, not available. Data are from chapters A–Z of USGS Circular 1196; see list in table 1. See index Web page for file of table 2 printable on one oversize sheet]

Recycling category	Metal commodity (chapter) and base year						
	Gold (A) 1998	Platinum (B) 1998	Chromium (C) 1998	Zinc (D) 1998	Magnesium (E) 1998	Lead (F) 1998	Iron and steel (G) 1998
Old scrap:							
Generated[2]	0.166	0.043	132	672	108	1,220	75,000
Consumed[3]	0.130	0.008	75.3	82	31.8	1,060	35,000
Value of old scrap consumed	$1.234	$0.11700	$0.0664	$0.071	$0.0721	$0.263	$3.79
Recycling efficiency[4] (percent)	96	76	87	19	39	95	52
Supply[5]	0.178	0.048	144	702	112	1,230	78,000
Unrecovered[6]	0.008	0.009	18	505	68.2	63	38,000
New scrap consumed[7]	0.045	0.006	28.6	344	44.6	55	18,000
New-to-old-scrap ratio[8] (percent)	25:75	42:58	28:72	81:19	58:42	5:95	34:66
Recycling rate[9] (percent)	29	16	20	27	33	63	41
Apparent supply	0.60	0.08	519.50	1,577.78	231.52	1,769.84	129,268.29
U.S. net exports of scrap[10]	0.028	0.014	41	5	7.5	103	2,510
Value of U.S. net exports of scrap[11]	$0.272	$0.2	$0.154	$0.012	$0.022	$0.0268	$0.272

Table 2. Salient statistics for recycling of selected U.S. metals in 1998, 2000, and 2004.—Continued

[Values are in thousands of metric tons and billions of constant 1998 dollars, unrounded, unless otherwise specified. Terms: --, zero; NA, not available. Data are from chapters A–Z of USGS Circular 1196; see list in table 1. See index Web page for file of table 2 printable on one oversize sheet]

Recycling category	Metal commodity (chapter) and base year—Continued						
	Manganese (H) 1998	Columbium[1] (niobium) (I) 1998	Tantalum (J) 1998	Tin (K) 1998	Molybdenum (L) 1998	Cobalt (M) 1998	Silver (N) 2000
Old scrap:							
Generated[2]	463	2.90	0.30	13	26.7	3.50	1.760
Consumed[3]	218	1.00	0.09	8	8.0	1.70	1.680
Value of old scrap consumed	$0.12	$0.02	$0.008	$0.065	$0.07	$0.04	$0.256
Recycling efficiency[4] (percent)	53	50	35	75	30	68	97
Supply[5]	481	3.00	0.37	13	26.8	3.83	1.820
Unrecovered[6]	227	1.50	0.24	3	18.7	1.23	0.054
New scrap consumed[7]	108	0.80	0.12	8	4.0	1.70	0.530
New-to-old-scrap ratio[8] (percent)	33:67	44:56	57:43	50:50	33:67	50:50	24:76
Recycling rate[9] (percent)	37	22	21	22	33	32	32
Apparent supply	881.08	8.18	1.00	72.73	36.36	10.63	6.91
U.S. net exports of scrap[10]	18	0.40	-0.03	5	-0.19	1.20	0.026
Value of U.S. net exports of scrap[11]	$0.01	$0.006	($0.00270)	NA	($0.00180)	$0.04	$0.004

Table 2. Salient statistics for recycling of selected U.S. metals in 1998, 2000, and 2004.—Continued

[Values are in thousands of metric tons and billions of constant 1998 dollars, unrounded, unless otherwise specified. Terms: --, zero; NA, not available. Data are from chapters A–Z of USGS Circular 1196; see list in table 1. See index Web page for file of table 2 printable on one oversize sheet]

Recycling category	Metal commodity (chapter) and base year—Continued						
	Cadmium (O) 2000	Beryllium (P) 2000	Antimony (Q) 2000	Tungsten (R) 2000	Vanadium (S) 2004	Selenium (T) 2004	Mercury (U) 2000
Old scrap:							
Generated[2]	2.400	0.130	9	7.300	3.010	NA	0.250
Consumed[3]	0.285	0.005	8	6.200	2.780	NA	0.155
Value of old scrap consumed	$0.0001	$0.0017	$0.011	$0.033	$0.0208	NA	$0.000634
Recycling efficiency[4] (percent)	15	7	89	66	94	NA	62
Supply[5]	2.400	0.140	9	9.700	3.010	0.030	0.250
Unrecovered[6]	2.030	0.130	1	3.300	0.176	NA	0.095
New scrap consumed[7]	0.005	0.030	2	1.600	0.069	NA	0.005
New-to-old-scrap ratio[8] (percent)	2:98	86:14	20:80	20:80	02:98	NA	3:97
Recycling rate[9] (percent)	14	10	20	46	40	NA	NA
Apparent supply	2.015	0.350	50.00	16.96	6.899	NA	NA
U.S. net exports of scrap[10]	0.085	0.005	--	2.940	0.054	0.004	NA
Value of U.S. net exports of scrap[11]	$0.00003	$0.00063	--	$0.01421	$0.00119	$0.00021	NA

Table 2. Salient statistics for recycling of selected U.S. metals in 1998, 2000, and 2004.—Continued

[Values are in thousands of metric tons and billions of constant 1998 dollars, unrounded, unless otherwise specified. Terms: --, zero; NA, not available. Data are from chapters A–Z of USGS Circular 1196; see list in table 1. See index Web page for file of table 2 printable on one oversize sheet]

Recycling category	Metal commodity (chapter) and base year—Continued					Total or wtd. average[13]
	Germanium (V) 2000	Aluminum (W) 2000	Copper (X) 2004	Titanium[12] (Y) 2004	Nickel (Z) 2004	
Old scrap:						
Generated[2]	0.009	4,000	1,920.000	28	247.000	83,860
Consumed[3]	0.005	1,370	230.000	22	95.600	38,223
Value of old scrap consumed	$0.00538	$1.7993	$0.263	NA	$1.018	$9
Recycling efficiency[4] (percent)	76	42	43	91	56	63
Supply[5]	0.009	4,625	2,000.000	28	267.000	87,663
Unrecovered[6]	0.002	2,660	1,150.000	3	123.000	42,849
New scrap consumed[7]	0.007	2,080	735.000	NA	13.000	21,427
New-to-old-scrap ratio[8] (percent)	60:40	60:40	76:24	89:11	12:88	36:64
Recycling rate[9] (percent)	50	36	30	52	41	40
Apparent supply	0.023	9,583.33	3,227.42	42.31	264.878	147,579
U.S. net exports of scrap[10]	0.002	50	553.000	1	30.200	3,321
Value of U.S. net exports of scrap[11]	$0.00227	$0.0909	$0.59892	$0.00173	$0.310	$2

[1]Columbium and niobium are synonyms; in 2008, USGS minerals information reports changed from using "columbium (niobium)" as in Circular 1196–I to using "niobium (columbium)."

[2]Metal content of products theoretically becoming obsolete in the United States in the base year. Old scrap excludes dissipative uses.

[3]Metal content of products that were recycled in the base year.

[4](Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus old scrap stock decrease or minus old scrap stock increase). Weighted average, as shown in the last column, is 63 percent. Nonweighted average is 61 percent.

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

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

[7]Prompt industrial scrap. Home scrap is excluded.

[8]Ratio of quantities consumed, measured in weight and expressed in percent of new plus old scrap consumed. Weighted average, as shown in the last column, is 36:64. Nonweighted average is 40:60.

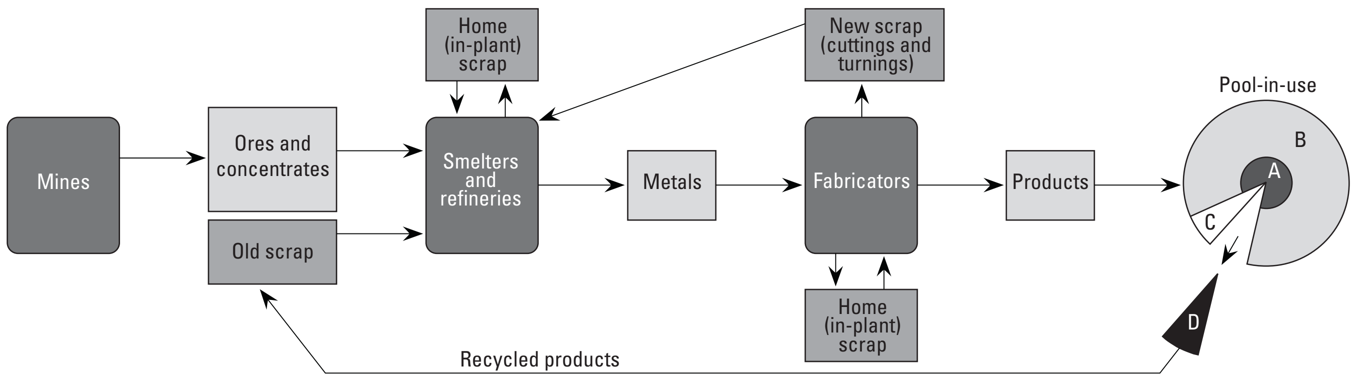
[9]Supply fraction that is scrap, on an annual basis. It is defined as (old plus new scrap consumed) divided by apparent supply [primary plus secondary production (old scrap plus new scrap) plus imports minus exports plus adjustment for Government and industry stock changes]. Weighted average, as shown in the last column, is 40 percent. Nonweighted average is 32 percent.

[10]For most metal commodities, trade is assumed to be principally old scrap.

[11]Parenthetical entries for tantalum and molybdenum show values for net imports and are subtracted from values for the total net exports to yield the values in the last column.

[12]Titanium figures are old plus new scrap, as applicable.

[13]Totals are weights in thousands of metric tons or values in billions of constant 1998 U.S. dollars. Weighted (wtd.) averages are percentages.



EXPLANATION

A Products made in current year
B Products made in prior years
C Unrecovered products
D Recycled products

Figure 1. Generalized metals recycling flow chart. Flow charts for all of the metals in the study follow this general outline.

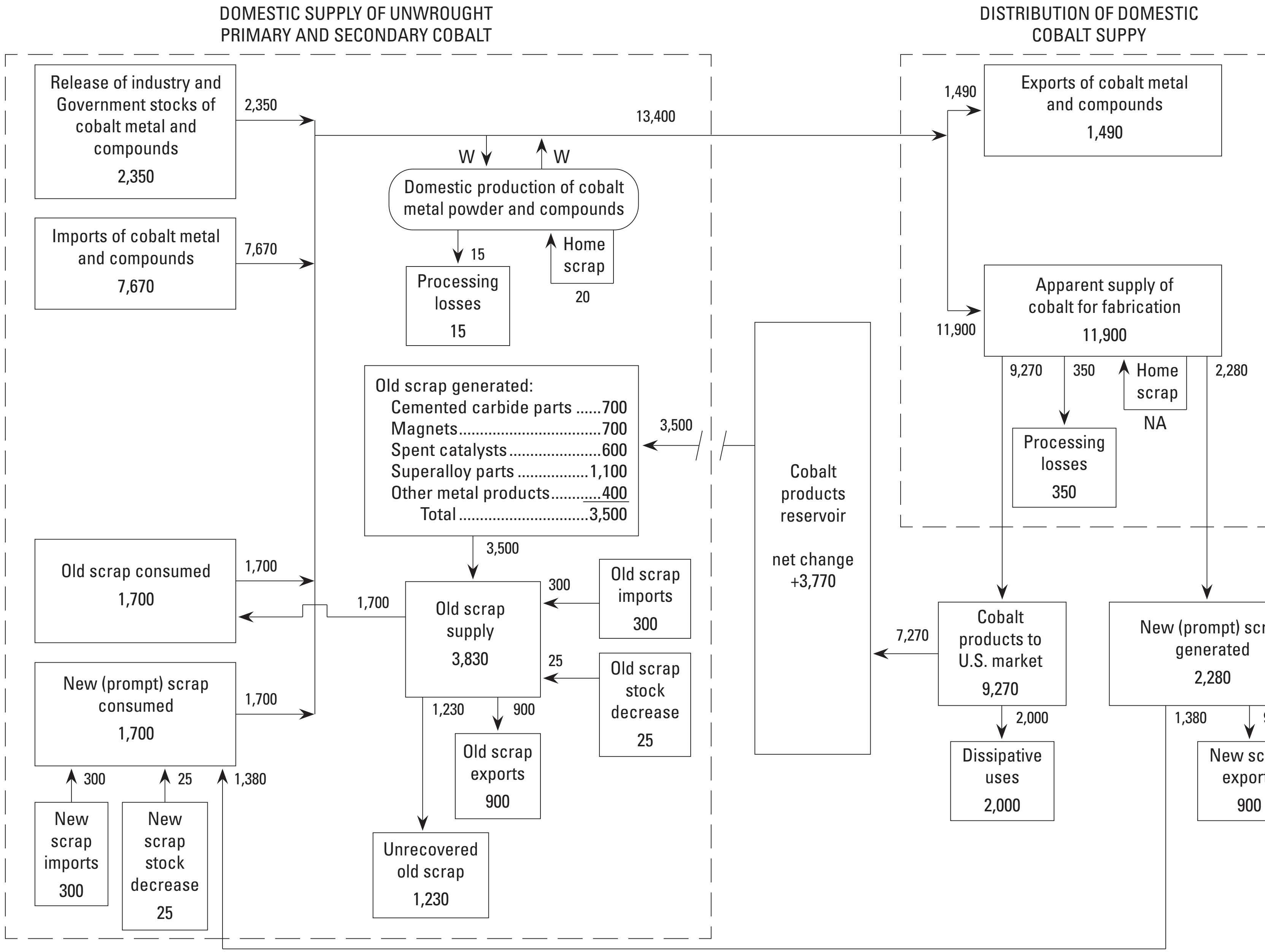


Figure 2. Example of a typical detailed flow chart showing the materials flow of cobalt in the United States in 1998. For some metals, detailed information like that shown for cobalt is not available. Values are in metric tons of contained cobalt, are rounded to no more than three significant digits, and may not add to totals shown. NA, not available; W, withheld to avoid disclosing company proprietary data. Source: Shedd (2006, fig. 1).

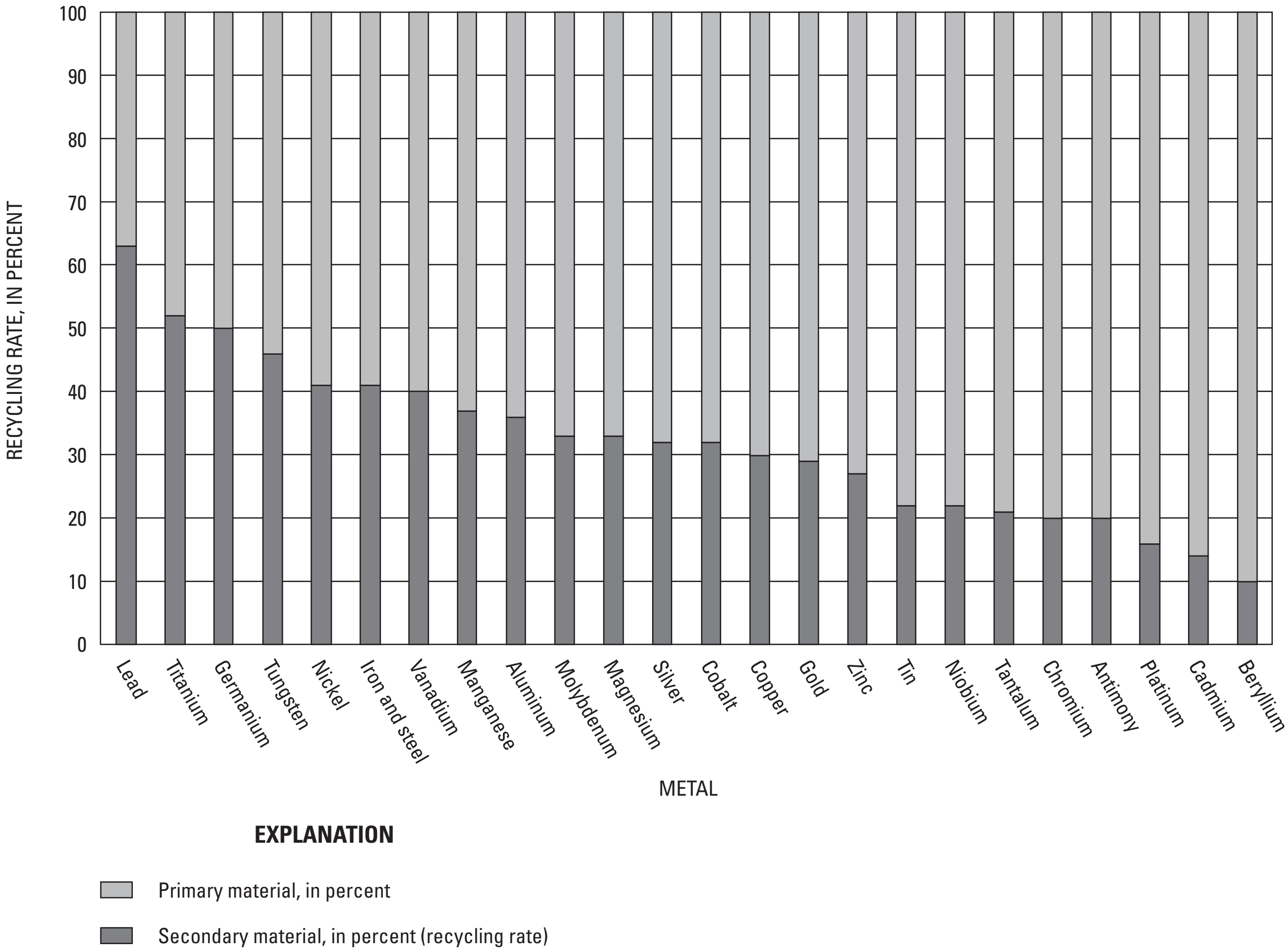


Figure 3. Bar graph showing recycling rates for metals studied for chapters A–Z of U.S. Geological Survey Circular 1196 (table 1). Each bar has data for a single base year, which is 1998, 2000, or 2004. The recycling rates and base years from the chapters are summarized in table 2 of this chapter AA; rates are not available for two metals (mercury and selenium). The total supply (100 percent) is shown as secondary material, in percent (recycling rate), plus primary material, in percent.

RECYCLING EFFICIENCY

Old scrap recycling efficiency is the amount of old scrap recycled as a percentage of old scrap available to be recycled, and the difference between that and 100 percent is unrecovered scrap, which goes into landfills or hibernates in place (see fig. 4). New scrap was not included in a calculation of general recycling efficiency because the efficiency of use of new scrap was considered to be very high already because companies generating it take advantage of its availability to maximize profit.

Old scrap recycling efficiency is important from an environmental perspective because it is an indication of the effectiveness of recycling programs in a particular metal industry. For cadmium and zinc, efficiencies were estimated to be relatively low (15 and 19 percent, respectively), indicating significant potential to recover more material from old scrap. Highly valued metals, such as gold and silver, not surprisingly, are at the high end of an efficiency spectrum that ranges from 7 to 97 percent. The challenge is for industries such as cadmium and zinc to recycle more of the material that has become obsolete. Titanium efficiency (91 percent) was high because of a high proportion of dissipative uses in pigments and paints, which were excluded from old scrap generated.

RECYCLING RATE AND RECYCLING EFFICIENCY COMPARISONS

The recycling rate is a function of apparent supply, and the old scrap recycling efficiency is a function of old scrap generated plus imports of old scrap. Scrap consumed is

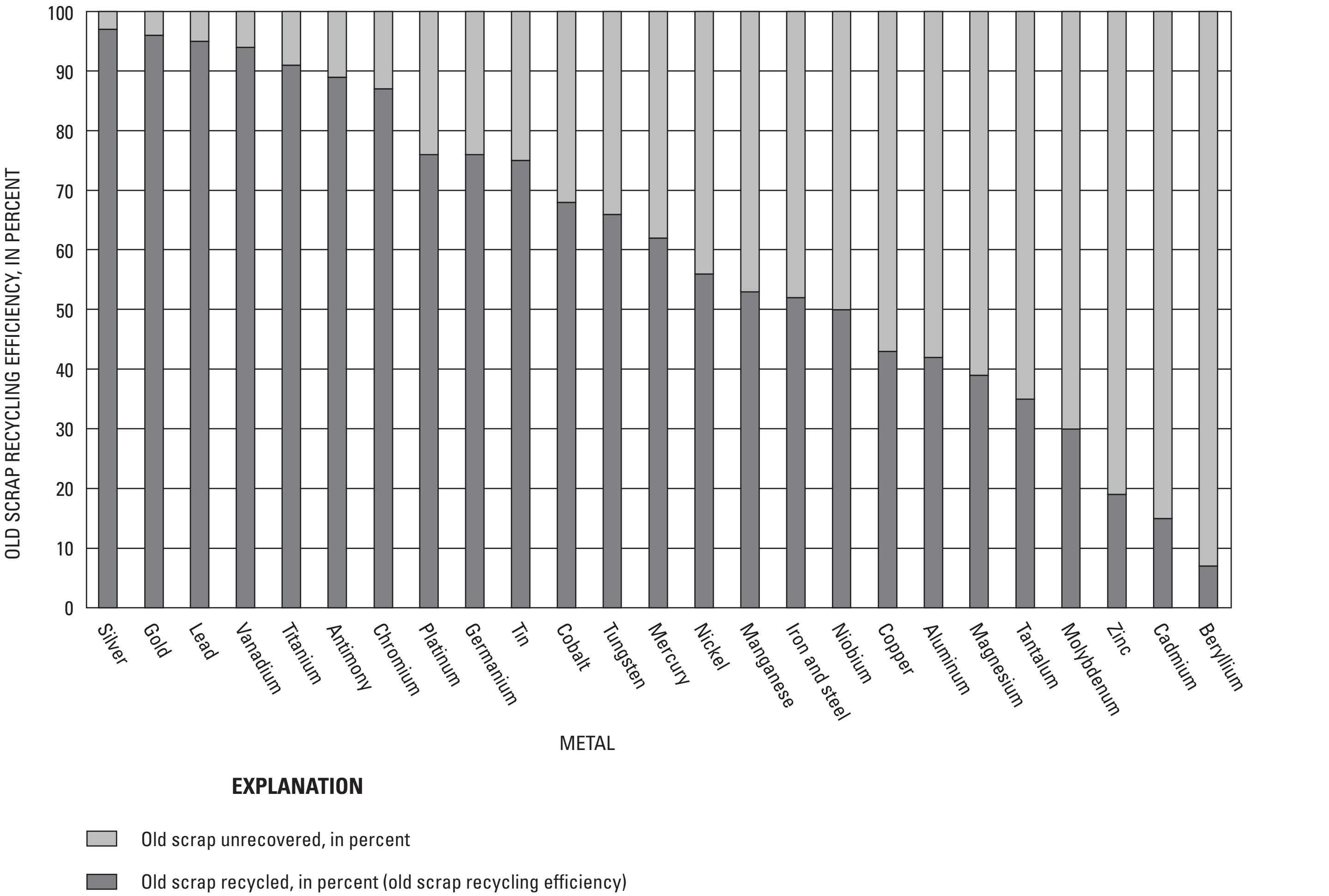
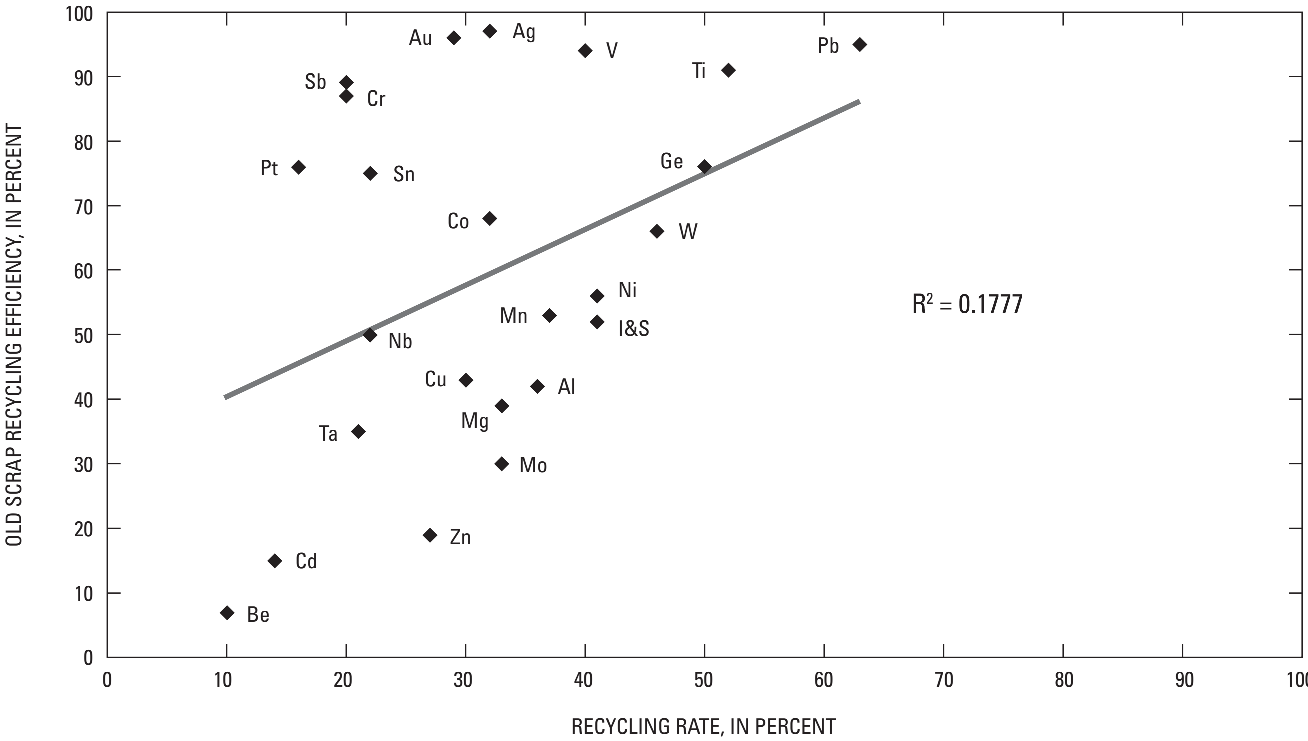


Figure 4. Bar graph showing old scrap recycling efficiency for metals studied for chapters A–Z of U.S. Geological Survey Circular 1196 (table 1). Each bar has data for a single base year, which is 1998, 2000, or 2004. The old scrap recycling efficiency values and base years from the chapters are summarized in table 2 of this chapter AA; a recycling efficiency value is not available for one metal (selenium). The old scrap available to be recycled (100 percent) is shown as old scrap recycled, in percent (old scrap recycling efficiency), plus old scrap unrecovered, in percent.

compared with (divided by) each, respectively, to determine recycling rate and recycling efficiency. Because of significant differences in these formulas (see appendix), a correlation would not necessarily be expected. However, as figure 5 shows, there is a suggestion of direct proportionality between efficiency and recycling rate (R^2 = 0.1777), and a direct proportionality would be logical because a higher usage of scrap would be expected with greater efficiency, possibly displacing use of some primary material. There is an obvious clustering of recycling rates in the range of 15 to 45 percent, whereas efficiencies are evenly distributed over a range from 7 to 97 percent (fig. 5).

Recycling rate and recycling efficiency usually do not make dramatic shifts over short periods of time (figs. 6 and 7), and so these measures often may continue to be useful after the year of a particular study, and they will be useful for comparison with future studies. Metals with comparatively well developed recycling infrastructures, such as antimony, tungsten, cobalt, tin, and titanium, had relatively high efficiencies but lower recycling rates because of low cost and readily available primary material. For other metals, such as beryllium, cadmium, tantalum, and zinc, efficiencies were low because of difficulty in collection, even though the metals were considered to be available for recycling; recycling rates for these metals were also low for the same reason, as well as the availability and low cost of primary metal.

If the individual metal recycling industries are considered to be independent, the overall metal recycling rate can be calculated by averaging percentages, rather than by using a total-weight basis; the nonweighted average overall recycling rate is 33 percent, which is comparatively low, reflecting the less developed recycling infrastructure of the lower



EXPLANATION

Ag	Silver	Cr	Chromium	Mo	Molybdenum	Sn	Tin
Al	Aluminum	Cu	Copper	Nb	Niobium (columbium)	Ta	Tantalum
Au	Gold	Ge	Germanium	Ni	Nickel	Ti	Titanium
Be	Beryllium	I&S	Iron and steel	Pb	Lead	V	Vanadium
Cd	Cadmium	Mg	Magnesium	Pt	Platinum	W	Tungsten
Co	Cobalt	Mn	Manganese	Sb	Antimony	Zn	Zinc

Figure 5. Scatter diagram of old scrap recycling efficiency versus recycling rate for 24 metals and base years of 1998, 2000, and 2004; see figures 3 and 4. The plot suggests a weak correlation. R^2, or the square of the correlation coefficient, is a measure of how well the data fit a pattern or trend, in this case, a straight-line regression analysis, where 1 is the highest value possible and would represent the best fit. The value of R^2 for these data is 0.1777.

volume metal commodities, such as cobalt, molybdenum, and tantalum, uses for which tend to be more dissipative. The weighted average recycling rate is higher at 40 percent, gravitating toward that of steel, the highest volume recycled metal. The recycling rate for iron and steel in 1998 was 41 percent. If a similar comparison is made for efficiency, overall efficiency calculated by averaging percentages is 61 percent (the nonweighted method), indicating that, in general, a high proportion of the material considered to be available for recycling is being collected and recycled. More highly valued metals, such as gold, platinum, silver, and stainless steel, tend to have higher efficiencies. Recycling rates are relatively low for these metals because of the abundance of primary material. Factors affecting recycling efficiency include cost of collection, cost of processing, volume of scrap material available, and price of processed scrap.

NEW-TO-OLD-SCRAP RATIO

The proportion of new scrap and old scrap to total scrap will change over time (figs. 8, 9, 10), reflecting the different practices in metal commodities' respective industries, including the different mix of products, manufacturing processes used to make the products, and the in-service times of the products (or lifetimes of products). This proportion is referred to as the new-to-old-scrap ratio, and ratios for the studied metals are plotted in figure 8.

For the metals studied, the new-to-old-scrap ratio was 36:64 on a weighted-average basis (table 2), dictated primarily by iron and steel, as that category had far more old scrap consumed than any other metal. Zinc and beryllium have high proportions of new scrap compared with old scrap (81:19 and

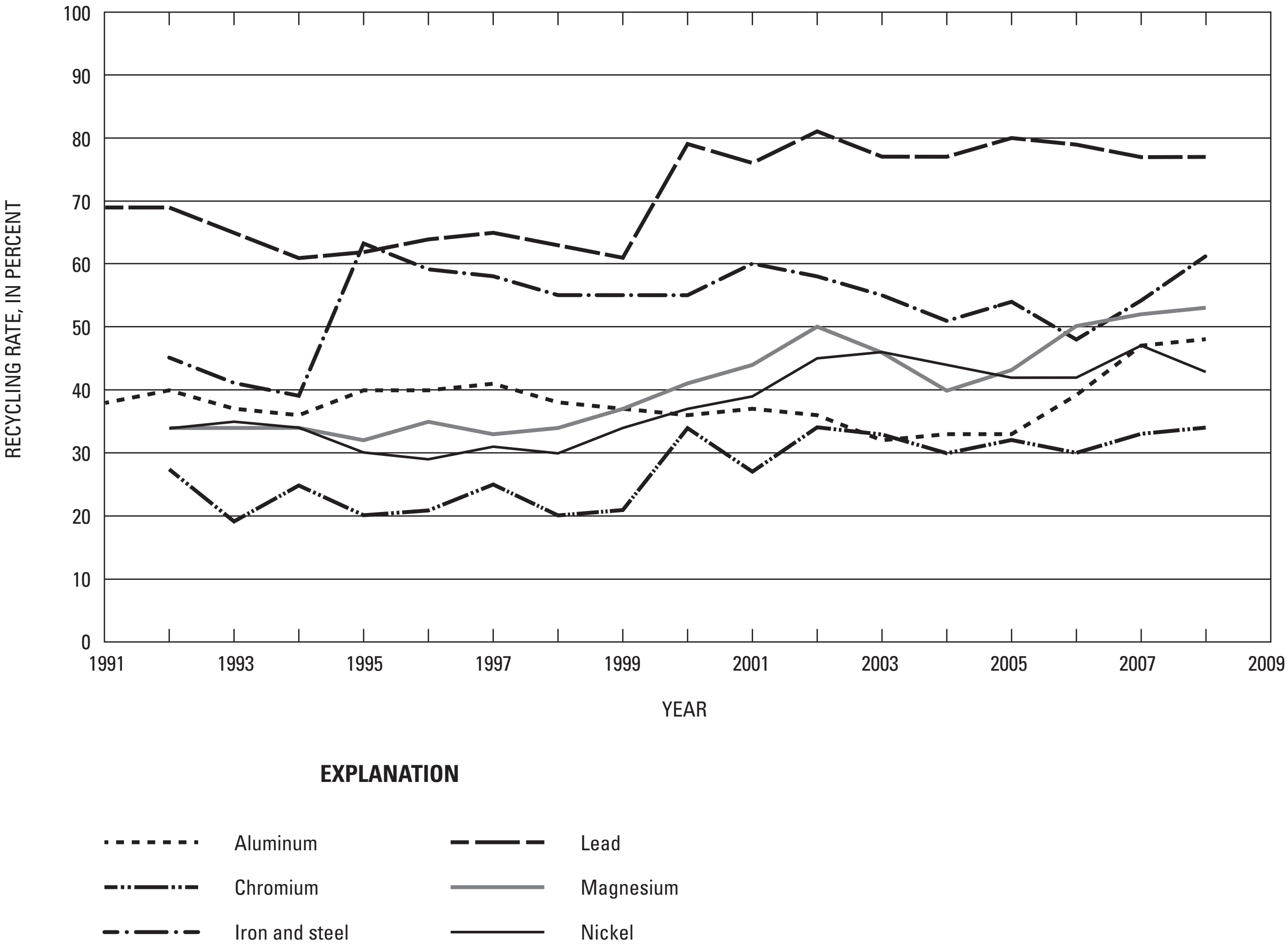


Figure 6. Graph showing increasing recycling rates for six metals in the United States in 1991 through 2008. Data sources: U.S. Geological Survey (1997–2006) and Papp (2007–2010).

86:14, respectively) because of the difficulty in obtaining and processing old scrap, such as galvanized steel and beryllium alloys, respectively. Cadmium has a low proportion of new scrap (2:98) because cadmium scrap is mostly from recycled nickel-cadmium batteries from which little new scrap is generated in production. In the aluminum industry, the ratio is high (60:40) because fabrication processes for aluminum cans, for example, generate comparatively large amounts of scrap. In-service time for aluminum cans is relatively low, but in other segments of that industry, such as castings for automobiles, in-service time may be 10 to 12 years on average. Sheet metal for aircraft is in use even longer.

Because old scrap consumed and old scrap exported are the only components of the numerator in the formula for old scrap recycling efficiency, efficiency rates might be expected to steadily increase with an increase in old scrap's share of total scrap in any metal industry (that is, with an increase in the second part of the new-to-old-scrap ratio). Unfortunately, such a correlation could not be made with these studies because efficiencies are difficult to calculate owing to the fact that they depend on estimating old scrap generated each year, and such estimates are not available in a time series.

RECYCLING RATE AND NEW-TO-OLD-SCRAP RATIO CHANGES OVER TIME

Although recycling rates usually do not make dramatic shifts over short periods of time, recycling rates for most metals changed during 1991 through 2008, whereas for some, there was nearly no net change (figs. 6 and 7). For metal commodities for which there is an historical record

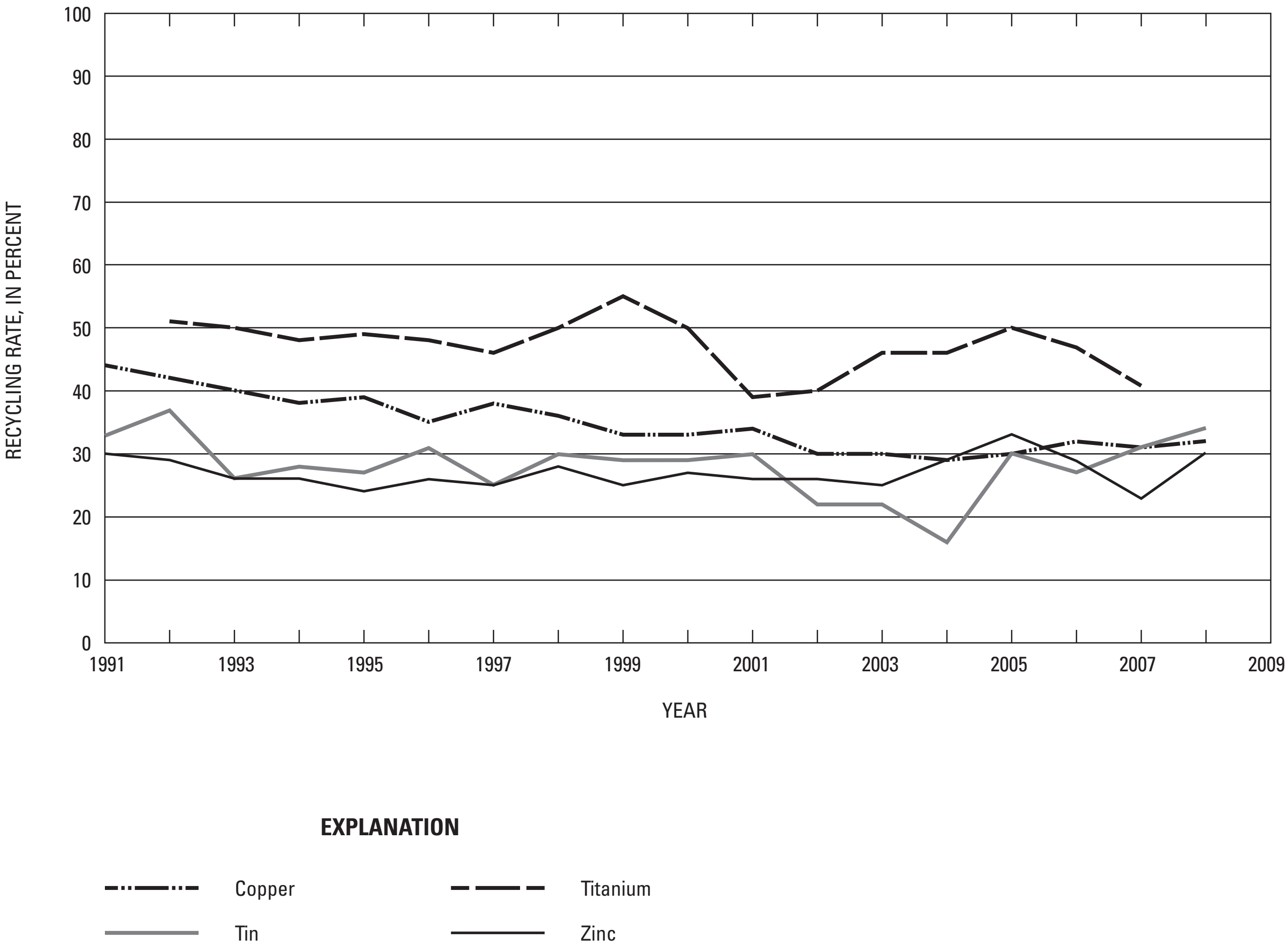


Figure 7. Graph showing declining or stagnant recycling rates for four metals in the United States in 1991 through 2008. Data sources: U.S. Geological Survey (1997–2006) and Papp (2007–2010).

(U.S. Geological Survey, 1997–2006; Papp, 2007–2010), those for which recycling rates have increased are aluminum, chromium, iron and steel, lead, magnesium, and nickel (fig. 6). Copper recycling rates have clearly trended downward, whereas rates for tin, titanium, and zinc fluctuated but did not trend significantly either upward or downward (fig. 7). Reasons for these changes vary by industry. These reasons are detailed below for some of the principal metal commodities that are recycled.

ALUMINUM

The increased recycling rate for aluminum during 2006 through 2008 (fig. 6) was attributed to higher prices for scrap aluminum, increasing scrap recovery, and better participation in surveys of scrap consumers. The declining old scrap share of total aluminum scrap during 1991 through 1997 (fig. 10) was attributed to an increased share of old scrap in exports. Starting in 2000, declining used beverage can (UBC) recycling resulted in less old scrap being consumed at the same time as exports of old scrap continued to increase, further decreasing the share of old scrap consumed in the United States. The increased share of old scrap during 2007 and 2008 was attributed to higher scrap prices, resulting in increased recovery of all types of old scrap (especially of UBC) and better participation in surveys of scrap consumers, including several which consume relatively large amounts of old scrap compared with new scrap.

CHROMIUM

The United States is a major world producer of chromium-bearing stainless steel and is a net exporter of stainless steel scrap. As an integral part of stainless steel,

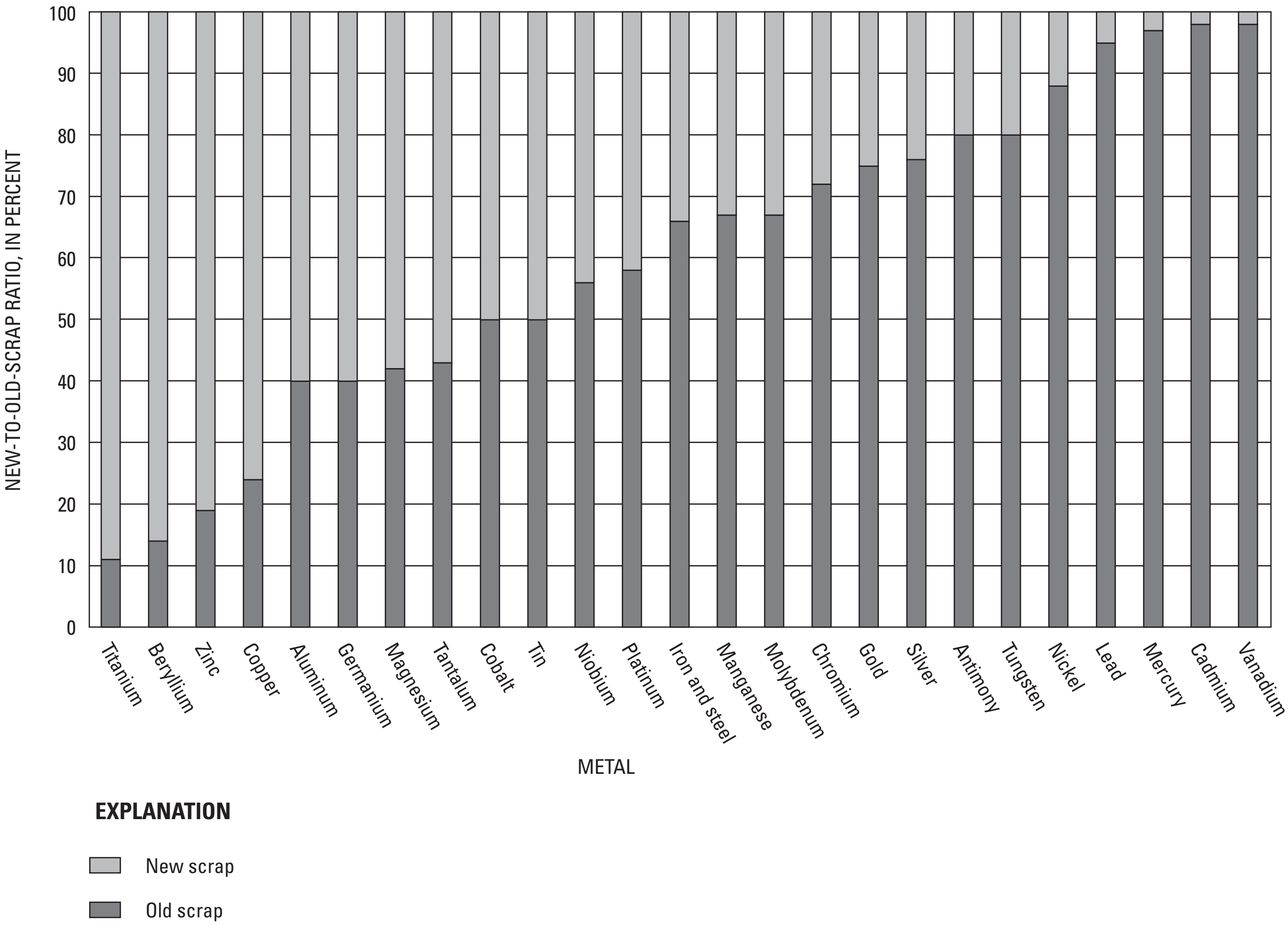


Figure 8. Bar graph showing new-to-old-scrap ratios for metals studied for chapters A–Z of U.S. Geological Survey Circular 1196 (table 1). Each bar has data for a single base year, which is 1998, 2000, or 2004. The ratios and base years from the chapters are summarized in table 2 of this chapter AA. The new-to-old-scrap ratio is defined as new scrap consumption compared with old scrap consumption in the United States, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60). Each bar shows the two parts of the ratio.

chromium is recycled when stainless steel is recovered and reused. New stainless steel scrap is generated in the production and processing of stainless steel into consumer products. The longer the economy has been using stainless steel, the more old scrap there is available for recycling. Because the United States was one of the early producers of stainless steel, the U.S. economy is a mature stainless steel user. As a result, old stainless steel scrap is more readily available in the United States than in many other places. As shown in figure 6, from 1992 through 1999, the average recycling rate was 22 percent, and during the period from 2000 through 2008, the average recycling rate was 32 percent. Part of this increase may be due to the increased use of stainless steel in automotive systems during the 1990s, which reached almost 30 kilograms per automotive vehicle in the United States by the year 2000 (Cobb, 2010, p. 324). Another factor was the increase in value of stainless steel scrap, as indicated by the export value, which increased by almost 50 percent in the period from 2000 through 2008 from the value in 1992 through 1999; the increased value of scrap provided a greater incentive to recycle.

COPPER

Because of its infinite recyclability and the economic advantage of processing secondary materials over mined ore, copper scrap has always been a significant component of copper supply. In recent years, however, domestic recovery of copper from scrap, especially old scrap, has fallen victim to industry consolidation, restructuring, and offshore processing. Beginning in 1986, and ending in 2001, after the last domestic secondary smelter closed, the United States lost more than 500,000 metric tons (t) of secondary copper

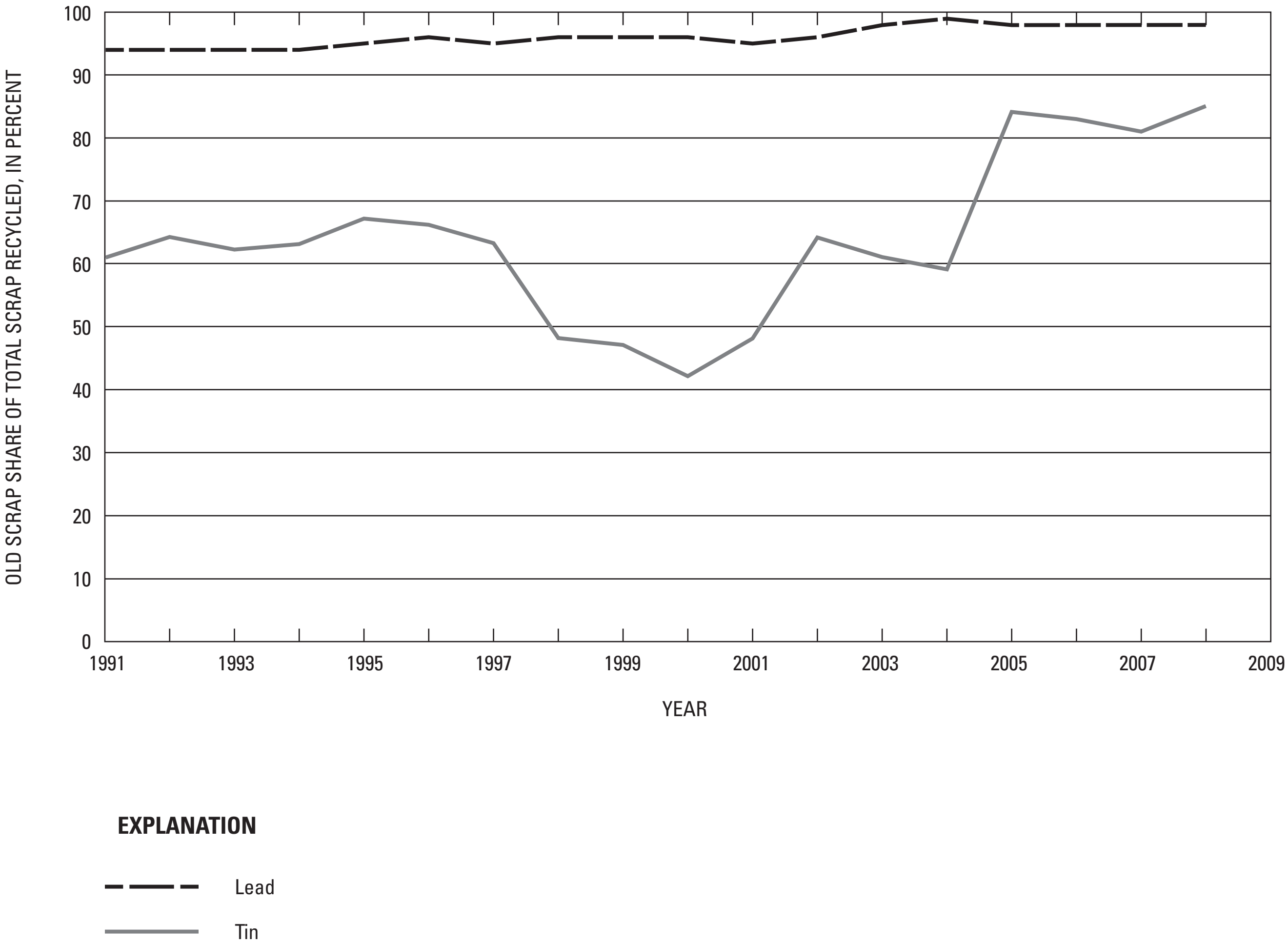


Figure 9. Graph showing increases in old scrap shares of total scrap for two metals in the United States in 1991 through 2008. Data sources: U.S. Geological Survey (1997–2006) and Papp (2007–2010).

smelting capacity. Most of this cutback took place during an 8-year period (1994 through 2001) owing to the combination of stricter environmental regulation and sustained low copper prices, particularly during the latter 4 years of the period (fig. 7). Similarly, consolidation and a shift away from reverberatory smelting at primary smelters reduced their ability to add scrap to their feed mix. Because of rising environmental compliance costs and reduced processing margins, the last remaining integrated secondary smelter opted to close its smelter and refinery in 2000 and purchase primary cathode to feed its rod mill.

Without a domestic outlet, significant quantities of low-grade and mixed-alloy scrap entered the export stream, thus decreasing the old scrap share of total scrap recycled in the United States (fig. 10). Net exports of copper scrap (gross weight) rose from about 60,000 t in 1993 to more than 400,000 t by 2002 and to about 800,000 metric tons per year in 2010. Since 2002, the rise in copper scrap exports has been fueled by the erosion of domestic manufacturing, the substitution of plastic in the scrap-intensive copper plumbing market, aggressive buying by foreign importers, especially China, and a sustained period of higher prices that brought more old scrap to the market. The rise in exports has generated a tight domestic supply of certain scrap types, encouraged substitution of refined copper for scrap by some semimanufacturers, and contributed to further industry rationalizations and reduced scrap consumption by manufacturers who could no longer compete with copper imports given higher raw material costs.

IRON AND STEEL

The recycling rate of scrap is an indicator of demand for scrap by the steelmaking industry, and, under normal conditions of supply and demand, the recycling rate is related to prices that the steelmaking industry is willing to pay for scrap. Changes in the recycling rate over time may be correlated with fluctuating demand for scrap and consequent

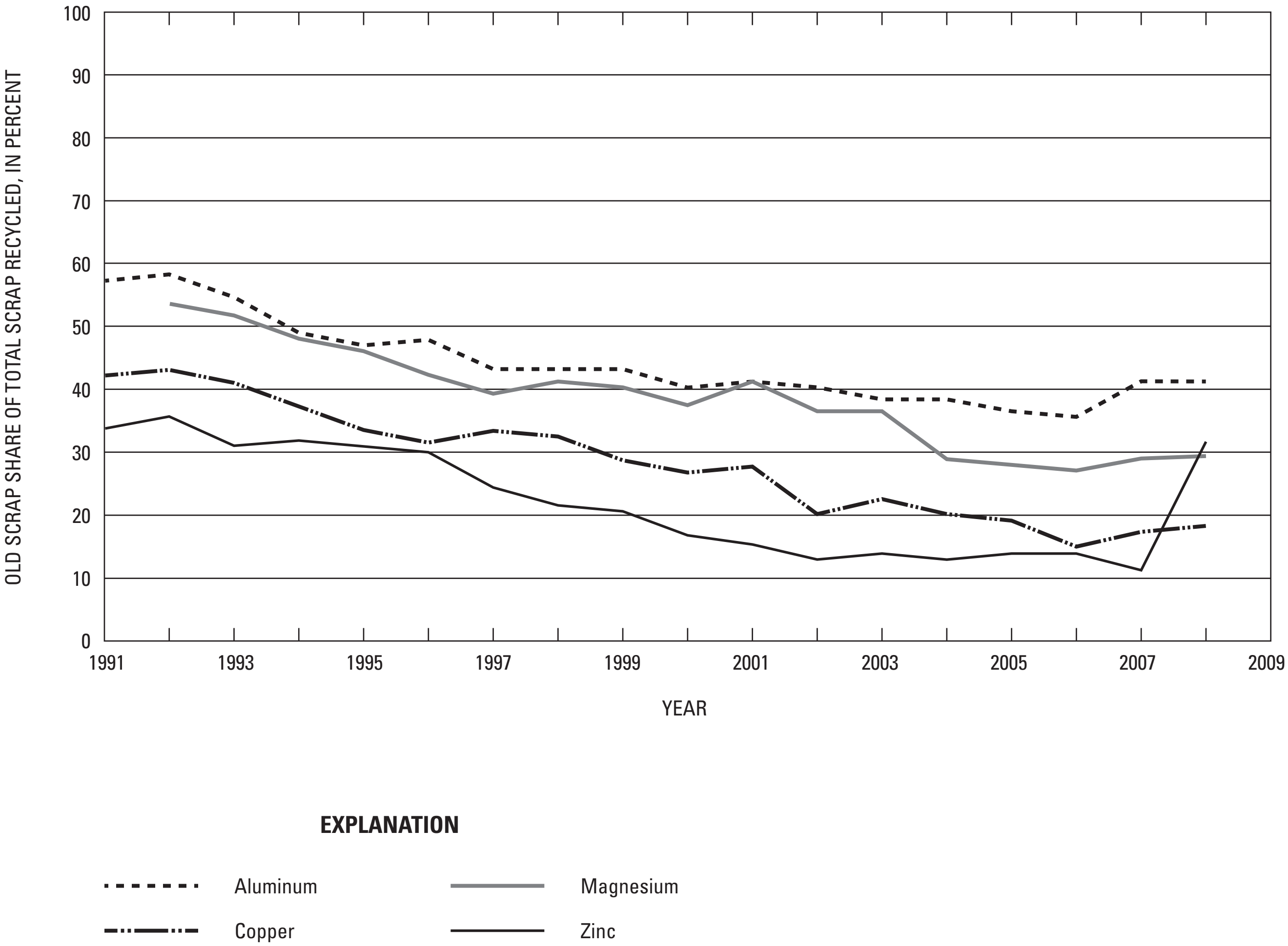


Figure 10. Graph showing decreases in old scrap shares of total scrap for four metals in the United States in 1991 through 2008. Data sources: U.S. Geological Survey (1997–2006) and Papp (2007–2010).

changes in scrap prices, but exact correlations are not always possible. Factors complicating correlations include the following: mills use other iron units (ore, pellets, direct reduced iron (DRI)) mixed in various proportions with scrap; scrap stockpiles may not be used during the year purchased; and companies may have unidentified business reasons for paying certain prices for scrap.

The recycling rate changes between 1991 and 1995 correlate with falling and then rising prices (fig. 6). However, a price reversal occurred 1 year before the 1994 recycling-rate reversal. Scrap prices and recycling rates decreased from 1995 to 2000. However, prices continued to decrease for another year to 2001, while the recycling rate increased after 2000 to 2001. Contrary to expectations, between 2001 and 2004, scrap prices increased as recycling rates decreased. The unusual number of bankruptcies in the steel industry at this time, while steel demand was increasing, may have caused recycling activity to diminish, resulting in a shortage of scrap and an increase in scrap prices. Prices decreased as the recycling rate increased from 51 percent in 2004 to 54 percent in 2005. Prices then increased through 2008, while the recycling rate decreased to a low point in 2006 (48 percent) before increasing to 61 percent in 2008. Major events in the steel industry or the national economy have not been identified as causing any inflection points on the steel-recycling curve.

LEAD

In 2008, the recycling rate for lead in the United States was greater than 75 percent for the ninth consecutive year (fig. 6), and the rate is expected to increase in the future owing to the highly concentrated use of lead in batteries. In 2008, lead-acid batteries accounted for about 88 percent of reported lead consumption in the United States. The recycling rate for lead-acid batteries in North America was estimated to be 96 percent in 2008 (Battery Council International, 2009), and essentially all of the lead contained in batteries was recovered and recycled. Battery recycling legislation has led to the establishment of a distribution infrastructure that ensures that nearly all used lead-acid batteries are returned to recycling facilities. Several leading lead-acid battery manufacturers have integrated their operations and have the capabilities to recycle used batteries, refine secondary lead, and manufacture new batteries.

Recent regulatory actions have decreased the amount of lead consumed for other uses such as ammunition, fishing sinkers, solder, and wheel weights (Bleiwas, 2006). A decline in the amount of lead used in these applications should increase the overall recycling rate because the metal contained in these applications is recycled at a lower rate than that in lead-acid batteries.

During the last two decades, there has been a significant reduction in domestic primary lead production owing to an increased reliance on secondary lead (fig. 6). Secondary lead accounted for nearly 80 percent of total domestic lead consumption in 2008.

MAGNESIUM

Magnesium recycling rates generally follow those of aluminum. The leading use of magnesium metal is as an alloying addition to aluminum to increase the hardness and corrosion resistance of the pure metal. On average, 75 to 80 percent of the magnesium recycled in the United States is as a component of aluminum-based scrap, much of which is new scrap generated from aluminum beverage can manufacturing.

Beginning in the mid-1990s, magnesium use as diecastings in automotive applications began to increase significantly. In 1990, the average weight of magnesium in a North American-produced automobile was 1.4 kilograms; by 2000, this had increased to 3.6 kilograms. In diecasting magnesium, about 50 percent of the material ends up as new scrap; as more diecastings are manufactured, more new scrap is generated and recycled. The increased generation of new scrap in the diecasting process was the principal driving force in the increase in the recycling rate at the end of the 1990s (fig. 6), and it also resulted in a declining percentage of old scrap in the total of new and old scrap (fig. 10).

NICKEL

The U.S. recycling rate for nickel has been gradually increasing since 1990 (fig. 6). The growth curve is marked intermittently by small inflections that represent increases in the recycling rate during years of surging nickel prices, such as in 1990, 2000, and 2007. Several forces are driving this growth in the recycling rate.

First, world production of marketable nickel gradually increased from 923,000 t in 1991 to 1,410,000 t in 2008 as new markets for the metal opened up, the population of the world grew, and income increased, particularly in China. At the same time, the world price of nickel in constant 1998 dollars has either kept pace with inflation or spiked owing to short-term supply deficits of the metal. Nickel-bearing scrap in 2010 was being recycled at all levels of usage because of the relatively high dollar value of nickel in comparison with values for chromium, iron, and manganese. Nickel-bearing grade 316 stainless steel (austenitic) bar, for example, is 20 to 30 times more expensive than conventional carbon steel bar, making 316 an attractive recycling target.

Second, recent technological advancements in metallurgical engineering have made consumption of recycled materials easier and more acceptable to the industrial consumer of scrap. In 2009, the United States produced 1.16 million metric tons (Mt) of nickel-bearing stainless steel, with about 78 percent of the nickel content coming from scrap (Eramet Group, 2010, p. 39). The equivalent production for 1994 (15 years earlier) was 1.21 Mt, with about 64 percent coming from scrap. In 2009, about 80,000 t of nickel was in all nickel-bearing scrap, which was mostly stainless steel.

Third, new waste management regulations, coupled with concerns about the carcinogenicity and toxicity of some nickel compounds, have encouraged more nickel recycling. In 1996, the Mercury-Containing and Rechargeable Battery Management Act became public law. The law made reclamation of spent nickel-cadmium and nickel-metal hydride batteries more economically feasible and removed a number of regulatory burdens from the battery recycling industry. In 2010, INMETCO processed a large part of the spent nickel-cadmium, nickel-metal hydride, and nickel-zinc batteries collected in the United States at its facility in Ellwood City, Pennsylvania.

Fourth, the recycling community has made a number of technological advances. In 2008, for example, Xstrata plc commissioned a state-of-the-art calciner and granulating plant adjacent to its nickel smelter at Falconbridge, Ontario, Canada (Tollinsky, 2008; Wilburn, 2009). Many spent lithium batteries containing cobalt with or without nickel and some nickel-metal hydride batteries were shipped in 2010 to Xstrata's calciner for processing into granules. The granules were then smelted together with sulfide concentrate and superalloy scrap to produce a nickel-cobalt matte suitable for downstream processing at Xstrata's Nikkelverk refinery in Norway.

Fifth, the continuous introduction of new nickel-bearing products into the marketplace created new opportunities for recyclers. The rapid obsolescence of modern electronic devices has led to the creation of a fast-growing global network of recycling companies that specialize in recovering nickel and other transition metals from electronic scrap (ISRI, 2010). The introduction of the first plug-in electric automobiles in late 2010 and the continuing worldwide growth in sales of hybrid electric vehicles are expected to increase the recovery of nickel and cobalt from spent automotive propulsion batteries after 2020.

TIN

The recycling rate for tin during the years 1991 through 2008 shows a generally declining trend for most of those years, with a marked increase from 2004 through 2008 (fig. 7). There are more than 20 end-use categories for tin, even though solder, tin chemicals, tinplate, and brass and bronze constitute the bulk of the end-use tonnages, so that any analysis of the trend pattern from 1991 through 2008 must take into account the important end-use items and their recycling characteristics.

Alloys make up the largest segment of the tin recycling industry, and this segment has generally been steady, although there has been an increase in demand and recycling activity for solders (especially solders used for electronic devices). The usage of other alloys, such as brass, bronze, and babbitt, generally decreased from 1991 through 2008. The marked increase in recycled tin from 2004 through 2008 is mostly because of the increased use of tin in solder (largely as a replacement for lead owing to lead's toxicity) and the recovery of tin from solder via the recycling process.

Tin chemicals are generally dissipative in their end uses and thus contribute little to tin recycling. Domestic consumption of tinplate generally declined somewhat from 1991 through 2008. The tin coating thickness on tinplate had been in a steady decline from the mid-1960s until the mid-1990s, when it leveled out. Because the tin coating weight on tinplate (and tin cans) is now so low, there has been less interest by the recycling industry in detinning, and the number of detinning facilities in the United States declined from 1993 through 2008.

TITANIUM

The recycling rate for titanium is influenced by several factors that include, but are not limited to, the price and availability of supply of primary metal (titanium sponge), the generation of scrap by mill product producers, competition for scrap by steel producers and nonferrous metals producers, and scrap processing capacity. The expansion of cold hearth melting in the 1990s improved the ability of titanium ingot producers to recycle both old and new scrap; however, excess global sponge capacity resulted in a decline in the domestic titanium recycling rate through much of the decade (fig. 7). In the later half of the 1990s, increased production of titanium mill products increased availability of scrap and resulted in an increase in the recycling rate. A slowing of the global economy and the terrorist actions in September 2001 depressed demand for titanium metal and decreased the availability of titanium scrap. Because of a lack of demand, domestic sponge capacity decreased significantly to 8,940 t in 2002 from 21,600 t in 2000. A sharp rise in demand, primarily from the commercial aerospace industry, began in 2003 and caused an increase in the recycling rate, and the commercial sector remained the dominant user of titanium alloys for aircraft from 1991 through 2008. Sponge producers responded to the increased demand and expanded capacity to 23,100 t in 2008 from 8,940 t in 2004. The increased availability of sponge resulted in a decline in the recycling rate in 2006 and 2007.

ZINC

Brass scrap is the leading source of secondary zinc material. However, brass scrap is exclusively recycled within the brass and copper circuits for its high monetary value and high copper content (over 60 percent). Thus, overall zinc recycling rates are not necessarily closely tied to demand for refined zinc. The leading source of old zinc scrap in the United States is flue dust from steelworking electric arc furnaces (EAF dust). For many of the years between 1991 and 2008, the two largest domestic consumers of old zinc scrap were not included in the data. In 2008, one of these consumers began reporting, and an estimate was made for the other consumer; this accounts for the large uptick in percentage of old scrap used in 2008 seen in figure 7. The 2008 data indicate that the ratio of new scrap to old scrap should probably have hovered around 65:35 for the entire time span from 1991 through 2008.

PRICE

Generally, the price of secondary material tracks that of metal, since it is subject to the same market forces. In making alloys, metal units sourced from scrap compete with metal units supplied by primary material. The price differences for the metal price, master-alloy price, and scrap price can be substantial, as in the case of steel scrap versus steel, or narrow, as in the case of aluminum scrap versus aluminum metal. Only for the major metal commodities, such as iron and steel, copper, aluminum, lead, and tin, are there publicly quoted scrap prices. Because scrap usage in smaller industry markets, such as cobalt, tungsten, mercury, or molybdenum, is a limited market in which producers pay spot or contract prices to specialized suppliers, or because recycling is incidental to alloy fabrication, as for manganese, a price of secondary material may not have been publicly established. Metal price was compared with recycling rate, recycling efficiency, and percent of scrap that is old scrap by plotting price against each in a scatter diagram. There was no clear correlation in any of these comparisons (see old scrap recycling efficiency versus price in fig. 11).

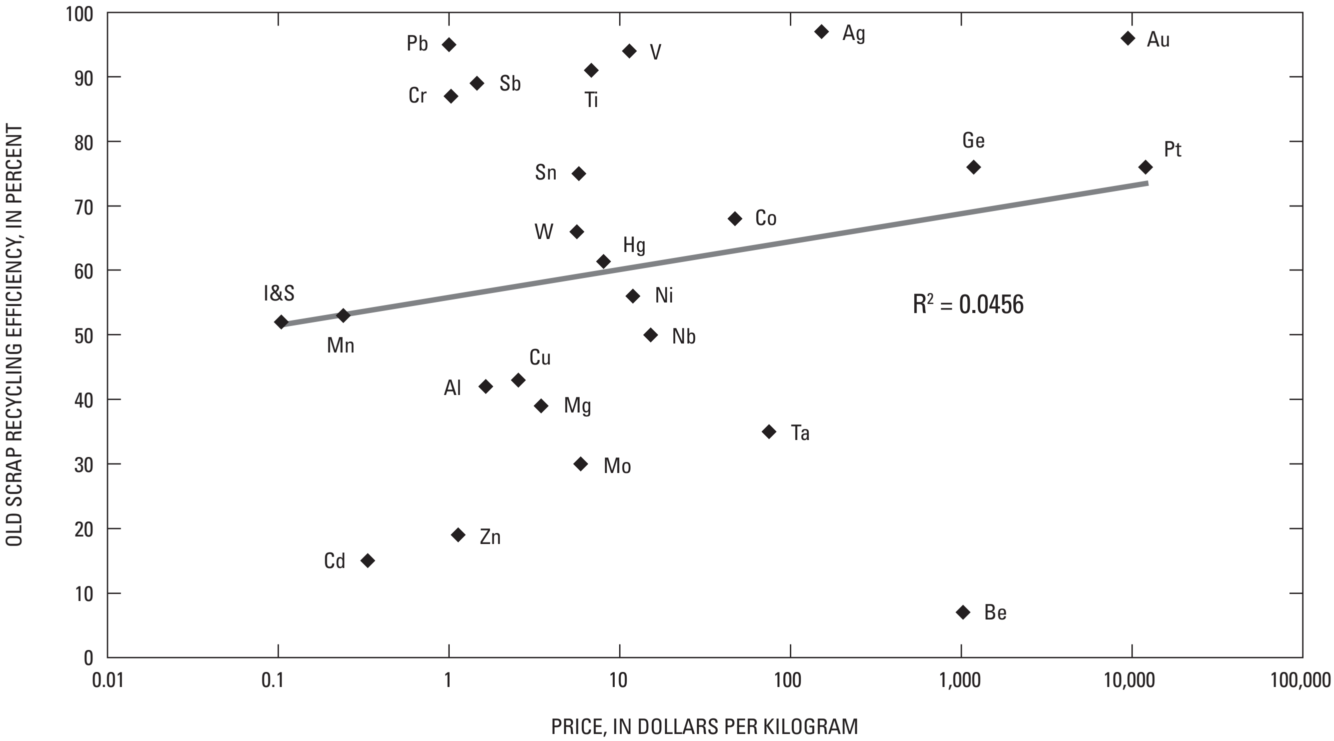


Figure 11. Scatter diagram of old scrap recycling efficiency versus price for 25 metals and base years of 1998, 2000, and 2004. No correlation is indicated; R^2 is 0.0456. Chemical symbols are defined in figure 5. For efficiency data, see figure 5 and table 2. Prices from U.S. Geological Survey Mineral Commodity Summaries (U.S. Geological Survey, 2003, 2005, 2009) were converted to constant 1998 dollars based on the Consumer Price Index from the U.S. Department of Labor, Bureau of Labor Statistics (2010).

SUMMARY

In general for metals, there is significant potential for increased recovery of hibernating and unrecovered scrap, but the significance of metal scrap recovery for total supply differs among metal commodities. The approaches used to take advantage of that potential will also be different for different industries. Despite the availability of scrap in any given year, scrap prices may not be high enough to cause businesses to recycle more than is already being recycled. It likely will take a concerted effort on the part of industry and Government to significantly raise overall recycling rates and efficiencies. Design for recycling will affect all industries and is one step that can be taken to increase recycling efficiency. Another is developing the infrastructure to facilitate recycling.

Trends for recycling rates differ by metal industry for recycling in the United States, with some rates showing declines over the period from 1991 through 2008. In general, principal reasons for any declines in recycling rates appear to be excess primary production capacity, increased exports of scrap, and scrap price declines. Where recycling rates have increased, important influences are new processing technology, new uses that generate more scrap, regulation, scrap price increases, and shortage of primary production. Because it is not known whether imported metal is produced from recycled material or primary material, use of metals *derived* from recycled material may be higher than recycling rates indicate. In any case, because the cost of making alloys from recycled material for industrial applications is significantly lower than the cost of making them from primary material, particularly with respect to energy consumption, recycling is expected to continue at a level equal to or greater than that of 2008. As more products are designed for recycling over time, it will be even less costly to recycle, and recycling rates and efficiencies would be expected to go up. However, recycling rates can only approach 100 percent in theory; as long as economies are growing and there is increased use of metals, recycling rates will remain well below 100 percent on average.

ACKNOWLEDGMENTS AND USGS SOURCES OF INFORMATION

U.S. Geological Survey (USGS) scientists who contributed to this report were E. Lee Bray (aluminum), James F. Carlin, Jr. (tin), Daniel L. Edelstein (copper), Michael D. Fenton (iron and steel), Joseph Gambogi (titanium), David

E. Guberman (lead), Deborah A. Kramer (magnesium), Peter H. Kuck (nickel), John F. Papp (chromium and metals recycling), and Amy C. Tolcin (zinc). Special recognition for his contribution is given to Thomas G. Goonan, who authored the last four chapters completed in Circular 1196—copper (X), nickel (Z), titanium (Y), and vanadium (S).

USGS minerals information is collected domestically from producers and consumers and internationally from a variety of sources in foreign countries. All USGS minerals information publications are available on the Internet and can be downloaded at http://minerals.usgs.gov/minerals. The types of information that are collected and disseminated include primary and secondary production and consumption, stocks, trade, prices, mineral commodity issues, and mineral industry developments. The information is used in determining apparent consumption, import reliance, and price trends, as well as in materials flow studies, among other applications.

REFERENCES CITED

Battery Council International, 2009, National recycling rate study: Chicago, Ill., Battery Council International, August, 11 p. (Also available at http://www.batterycouncil.org/LinkClick.aspx?fileticket=fnM%2F%2FCsWoQE%3D&tabid=145&mid=553.)

Bleiwas, Donald I., 2006, Stocks and flows of lead-based wheel weights in the United States: U.S. Geological Survey Open-File Report 2006–1111, 6 p., available only at http://pubs.usgs.gov/of/2006/1111/.

Bleiwas, Donald I., 2010, Byproduct mineral commodities used for the production of photovoltaic cells: U.S. Geological Survey Circular 1365, 10 p., available at http://pubs.usgs.gov/circ/1365/.

Bleiwas, Donald, and Kelly, Thomas, 2001, Obsolete computers, “gold mine,” or high-tech trash? Resource recovery from recycling: U.S. Geological Survey Fact Sheet 060–01, July, 4 p. (Also available at http://pubs.usgs.gov/fs/fs060-01/.)

Cobb, H.M., 2010, The history of stainless steel: Materials Park, Ohio, ASM International, 359 p.

Eramet Group, 2010, Nickel outlook: Paris, France, Eramet Group, June, 54 p.

Graedel, T.E., Allwood, Julian, Birat, J.-P., Reck, B.K., Sibley, S.F., Sonnemann, Guido, Buchert, Matthias, and Hagelüken, Christian, 2011, Recycling rates of metals—A status report—A report of the Working Group on the Global Metal Flows to the International Resource Panel: United Nations Environment Programme (UNEP), 44 p., accessed July 1, 2011, at http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf.

ISRI, 2010, Online membership directory: Institute of Scrap Recycling Industries, Inc., accessed December 2, 2010, at http://www.isri.org/iMIS15_PROD/ISRI/Directory/isri.org/Directory.aspx?hkey=fed054ed-907a-44a2-8634-4a2addc4dd6e.

Papp, J.F., 2007–2010, Recycling—Metals, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2005–2008, v. I, variously paged, available at http://minerals.usgs.gov/minerals/pubs/commodity/recycle/.

Schlesinger, M.E., 2006, Aluminum recycling: Boca Raton, Fla., CRC Press, 248 p.

Shedd, K.B., 2006, Cobalt recycling in the United States in 1998, chap. M *of* Sibley, S.F., ed., Flow studies for recycling metal commodities in the United States, chap. A–M (ver. 2.0): U.S. Geological Survey Circular 1196, p. M1–M16, available at http://pubs.usgs.gov/circ/2004/1196am/.

Sibley, S.F., ed., 2006, Flow studies for recycling metal commodities in the United States: U.S. Geological Survey Circular 1196–A–M (ver. 2.0), chapters are separately paged, available at http://pubs.usgs.gov/circ/2004/1196a-m_v2.pdf. (Version 2.0 of the volume containing chapters A–M is available only online; it superseded version 1.0, which was printed and put online in 2004.)

Sinclair, R.J., 2009, The extractive metallurgy of lead: Carlton South, Victoria, Australia, Australasian Institute of Mining and Metallurgy Spectrum Series, no. 15, on CD-ROM.

Sullivan, D.E., 2006, Recycled cell phones—A treasure trove of valuable metals: U.S. Geological Survey Fact Sheet 2006–3097, July, 4 p. (Also available at http://pubs.usgs.gov/fs/2006/3097/.)

Tollinsky, Norm, 2008, Xstrata boosts recycling capacity: Sudbury, Ontario, Canada, Sudbury Mining Solutions Journal, June quarterly, 2 p., available at http://www.sudburyminingsolutions.com/articles/SustainableDevelopment/06-08-xstrata.asp.

U.S. Department of Energy, 2007, U.S. energy requirements for aluminum production; Historical perspective, theoretical limits and current practices: Washington, D.C., U.S. Department of Energy, 135 p., accessed May 16, 2011, at http://www1.eere.energy.gov/industry/aluminum/pdfs/al_theoretical.pdf.

U.S. Department of Labor, Bureau of Labor Statistics, 2010, Consumer Price Index—All urban consumers (CPI–U), U.S. city average, all items: U.S. Department of Labor, Bureau of Labor Statistics, accessed June 20, 2011, at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt.

U.S. Geological Survey, 1997–2006, Recycling—Metals, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 1995–2004, v. I, variously paged, available at http://minerals.usgs.gov/minerals/pubs/commodity/recycle/.

U.S. Geological Survey, 2003, Mineral commodity summaries 2003: Reston, Va., U.S. Geological Survey, 199 p. (Also available at http://minerals.usgs.gov/minerals/pubs/mcs/.)

U.S. Geological Survey, 2005, Mineral commodity summaries 2005: Reston, Va., U.S. Geological Survey, 197 p. (Also available at http://minerals.usgs.gov/minerals/pubs/mcs/.)

U.S. Geological Survey, 2009, Mineral commodity summaries 2009: Reston, Va., U.S. Geological Survey, 195 p. (Also available at http://minerals.usgs.gov/minerals/pubs/mcs/.)

Wilburn, D.R., 2009, Flow of cadmium from rechargeable batteries in the United States, 1996–2007 (ver. 2.0): U.S. Geological Survey Scientific Investigations Report 2007–5198, 26 p., available at http://pubs.usgs.gov/sir/2007/5198/.

APPENDIX—DEFINITIONS

apparent consumption. Primary production plus secondary production (old scrap) plus imports minus exports plus adjustments for U.S. 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.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived. For example, a superalloy used in making alloy steel rather than new superalloy.

hibernating scrap. Material at the end of its service life that could be recovered and recycled if prices and other economic factors warranted.

home scrap. Scrap generated as process or runaround scrap and consumed in the same plant where generated. It does not enter into trade and is not considered in this study.

hydrometallurgy. A process of separating desired metals from aqueous solutions.

new scrap (prompt scrap). Scrap that is 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, and that is obtained from a facility separate from the recycling refiner, smelter, or processor. 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 in the United States, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

nominal price. The price at the time of sale.

obsolete material. Material removed from service at the end of its useful life or material that is no longer wanted; equivalent to old scrap.

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" or "obsolete scrap" and may originate from industry or the general public. Expended and obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap exports. The amount of old scrap exported from the United States in a subject year.

old scrap generated. The metal content of products theoretically becoming obsolete and available for recycling in the United States in a subject year. This definition excludes dissipative uses.

old scrap imports. The amount of old scrap imported into the United States in a subject year.

old scrap recovered and used. Equals old scrap reported or estimated as consumed.

old scrap recycling efficiency. The 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:

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

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

old scrap unrecovered. Scrap that might have been abandoned in place (hibernating) or sent to a landfill. It is calculated as old scrap supply minus old scrap consumed minus old scrap exported minus any old scrap stock increase.

primary metal (primary production). Metal produced from ore, whether as a byproduct, coproduct, or principal product.

product reservoir. The stock of metal-bearing materials serving consumer needs. It is otherwise known as "in-service" stock or pool-in-use.

pyrometallurgy. A process of separating metals from materials under conditions of high heat, as in roasting or smelting.

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; may also be referred to as scrap production.

secondary metal (secondary production). Metal derived from or contained in scrap.

superalloys. Alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is required.

supply of recoverable metal. The sum of new (prompt) scrap, old scrap recovered, old scrap imports, and any old scrap stock decrease.

swarf. Fine metallic particles and abrasive fragments removed by cutting or grinding tools.