FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

Magnesium Recycling in the United States in 1998

By Deborah A. Kramer

FIGURES

TABLES

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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, in the water, and in the air. As one of a series of reports on metals recycling, this report discusses the 1998 flow of magnesium from extraction through its uses with particular emphasis on recycling. In 1998, the recycling rate for magnesium was estimated to be 33 percent—almost 60 percent of the magnesium that was recycled came from new scrap, primarily waste from diecasting operations. The principal source of old scrap was recycled aluminum beverage cans.

INTRODUCTION

The materials flow study of magnesium, as shown in figure 1, is intended to provide a snapshot of the U.S. magnesium recycling industry in 1998. It 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 bitterns, 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, TX, Magnesium Corp. of America (MagCorp), Rowley, UT, and Northwest Alloys Inc., which is a subsidiary of Alcoa Inc., Addy, WA. Dow closed its magnesium operation in November 1998.

PRODUCTION TECHNOLOGY

Magnesium is manufactured by two methods—electrolytic reduction of magnesium chloride or thermic reduction of dolomite. Two thermal 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 dryer. The resulting powder is purified, concentrated, prilled, and dehydrated to produce anhydrous magnesium chloride (Kaplan, 1990).

[1]Magnesium Commodity Specialist, MS 983, U.S. Geological Survey, Reston, VA.

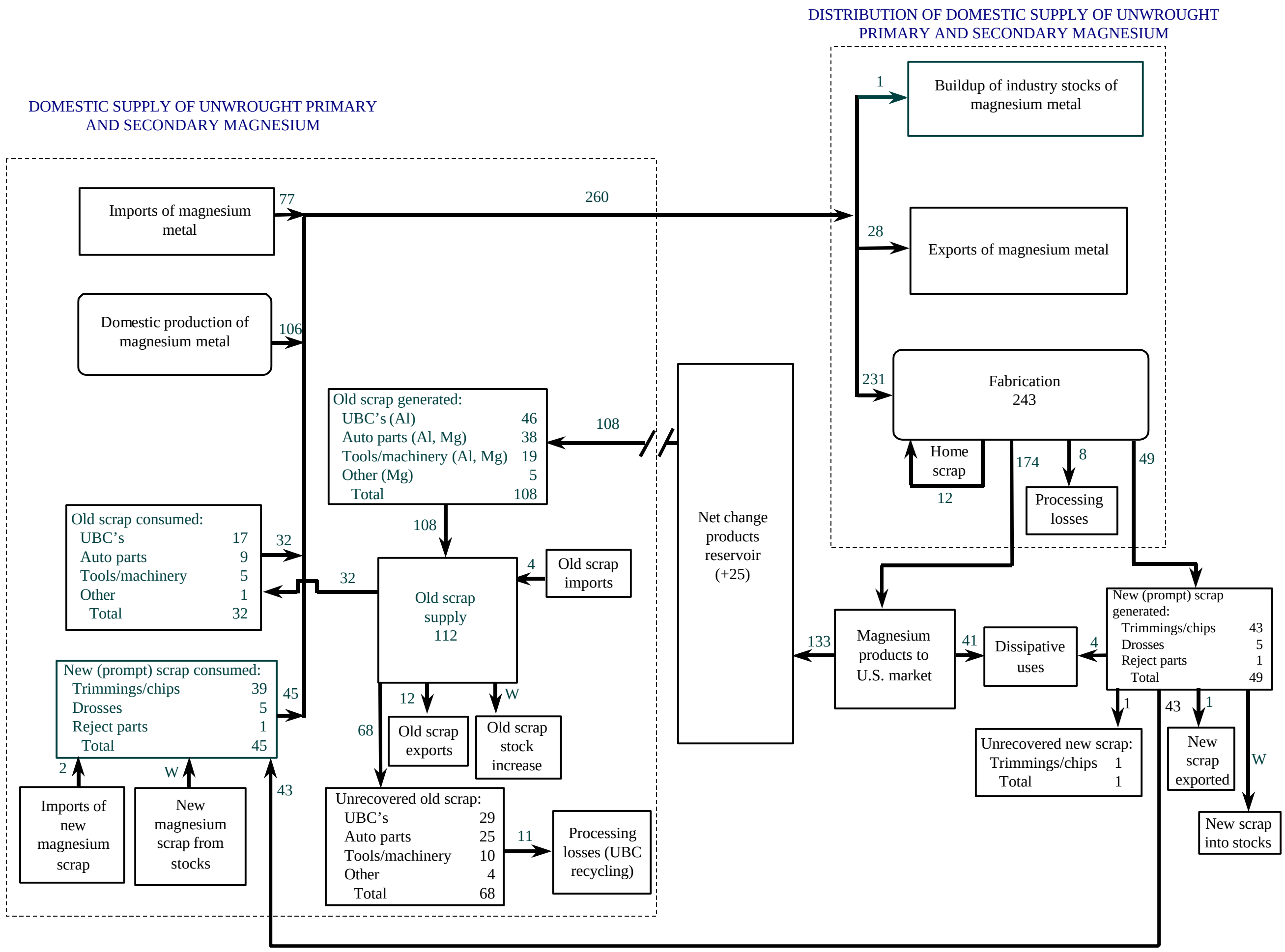

Figure 1. Magnesium recycling flow, 1998, in thousand metric tons contained magnesium. W, withheld to avoid disclosing company proprietary data; UBC's, used beverage cans.

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 700E 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, removal of the impurities in several steps, and recovery of 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 ($TiCl_4$) 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

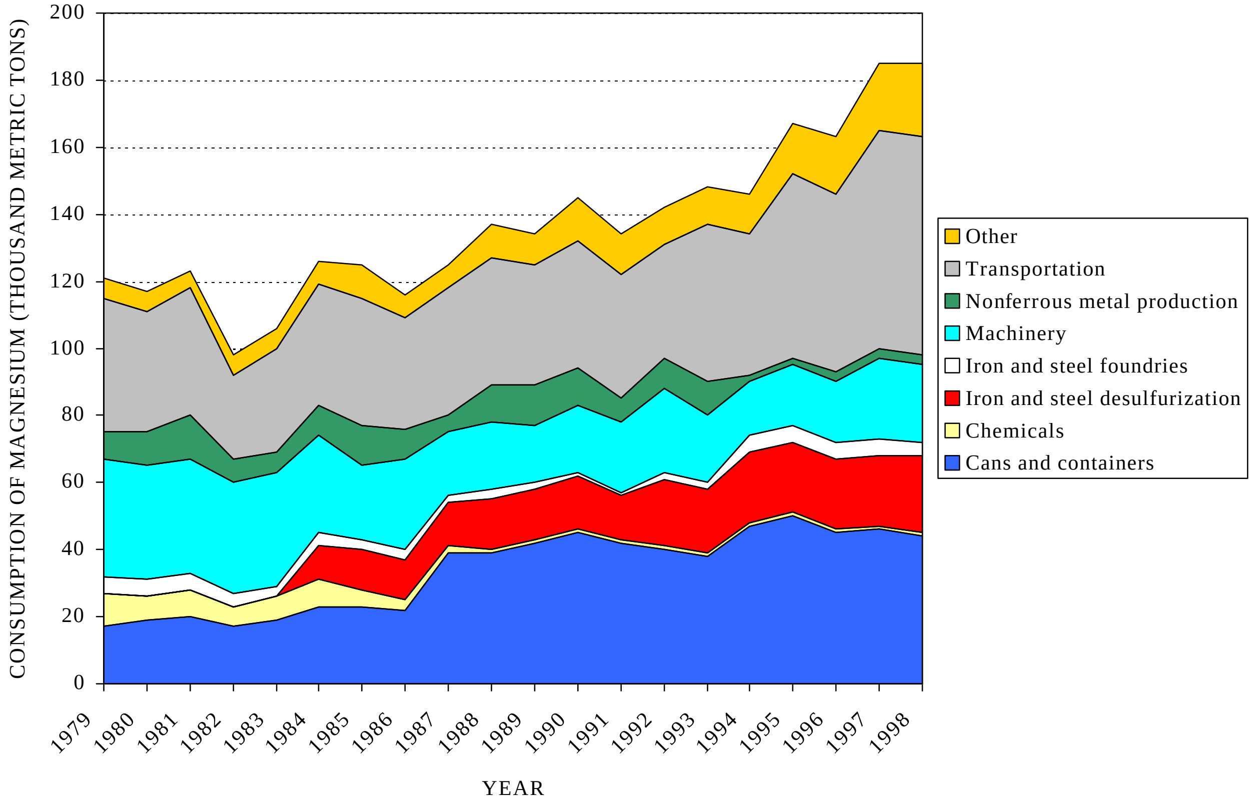

Figure 2. U.S. magnesium end-use patterns, 1979-98.

than 60 percent of aluminum beverage cans are recycled annually, which conserves both the aluminum and magnesium content 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 diecastings, gravity (sand and permanent mold) castings, and wrought products. Diecastings 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.

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 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 spheriodized (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 ductile 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; nodular iron, 2 percent; metal reduction, 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 published by the International Magnesium Association 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 diecasting, 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 that 70 percent). In South America, diecasting shipments are slightly larger that those for aluminum alloying, although this geographic area does not represent significant magnesium consumption (International Magnesium Association, 1999).

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 diecasting 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 diecasting magnesium alloys. This scrap is either reprocessed at the diecasting facility or sold to a scrap processor. The other types of scrap are either 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 scrap is 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 Minerals Yearbook series. Data on old and new aluminum-base scrap are reported to the USGS by means of a monthly survey of

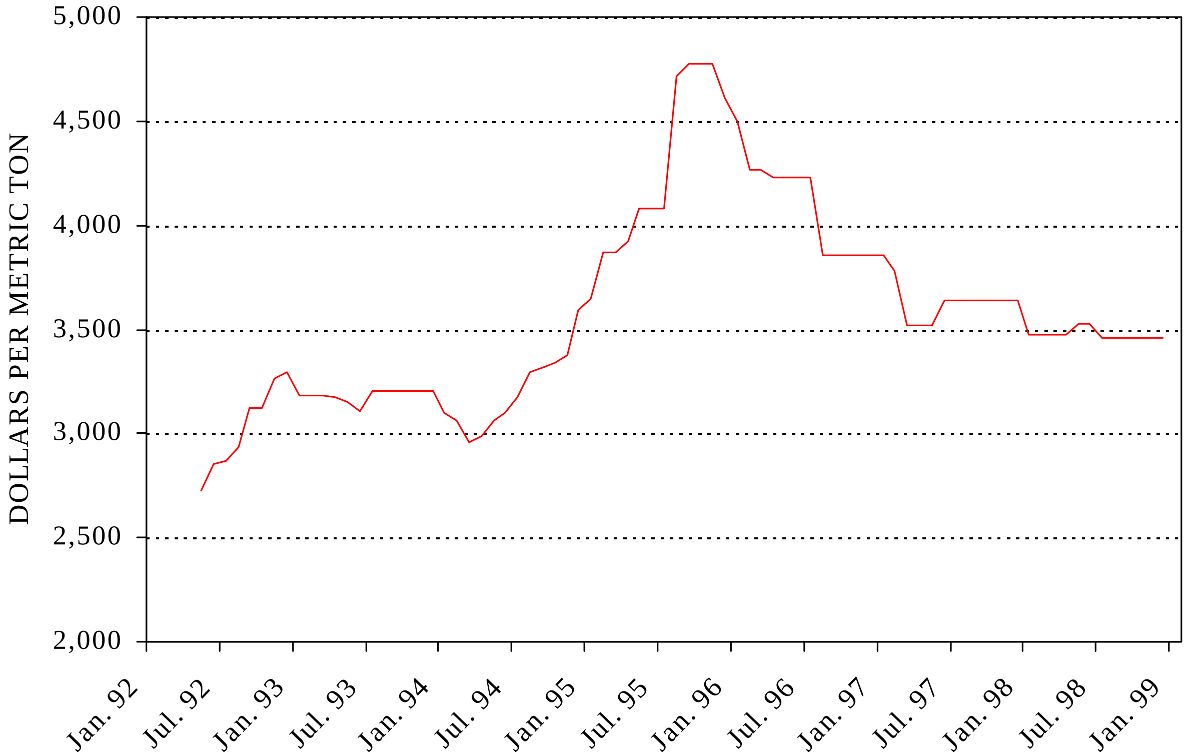

Figure 3. Average U.S. spot Western magnesium prices. (Source: Platt's Metals Week.)

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) is 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 would be estimated to be the quantity used in 1989, or 17,000 t. The "other" shown in figure 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 were also assumed to represent about one-half of the total "other" end uses. Therefore, the quantity of these materials that are estimated to be available for recycling is 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 component of old magnesium scrap is automobile components, which is 35 percent of the total. 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. Or 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 diecastings, 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.

Table 1. Salient magnesium scrap statistics, 1998
[Thousand metric tons, unless otherwise specified]

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

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

[2]Magnesium content of products that were recycled in 1998.

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

[4]Old scrap generated plus old scrap imports.

[5]Old scrap generated plus old scrap imports minus old scrap consumed minus old scrap exports.

[6]Prompt industrial scrap (excluding home scrap).

[7]Ratio of quantities consumed, in percent.

[8]This is the fraction of supply that is scrap on an annual basis. It is defined as old plus new scrap consumed divided apparent supply [primary plus secondary production (old plus new scrap) plus imports minus exports plus adjustments for Government and industry stock changes], in percent.

[9]Based on average value in 1998, trade in scrap is assumed to be principally old scrap.

INFRASTRUCTURE

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, TX; MagCorp recovered magnesium from brines from the Great Salt Lake at a 40,000-t/yr plant in Rowley, UT; and Northwest Alloys recovered magnesium from dolomite at a 40,000-t/yr plant in Addy, WA. Dow closed its plant in November 1998. Because each of these plants uses a different magnesium-recovery process, data on processing wastes is plant specific and can not 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 (Duff Wilson, July 13,1997, Alcoa building own plant to use waste in fertilizer, Seattle Times, accessed December 9, 1999, via URL http://www.seattletimes.com/). 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. Much 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 diecasting industry. Because some magnesium-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.

Although magnesium alloys have been used in such structural applications as diecastings and wrought products for tools and machinery for many years, the magnesium recycling industry was small. These uses were not considered to be important enough to warrant significant investment in recycling plants. A few facilities existed that could recycle old and new magnesium scrap, and many companies recycled their scrap in house. This has changed since the mid-1980’s when the use of magnesium alloys for automotive components began to grow. Many of the first secondary plants were established to produce sacrificial anodes for cathodic protection, primarily for cross-country pipelines (Brown, 2000).

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.

Table 2. Major U.S. magnesium-base scrap processors

Company	City	State	Product	Type of scrap processed	Capacity (metric tons per year)
Alabama Cathodic Metals Inc.	Foley	AL	Magnesium ingots (mostly for aluminum alloying) and anodes	New die-cast and old magnesium-base	[1]17,000
Garfield Alloys Inc.	Cleveland	OH	Magnesium ingots, anodes, powder, and granules	New (types II, III, IV)	13,600
Garfield Alloys Inc. (MagReTech Inc.)	Bellevue	OH	NA	New (type I)	15,000
IMCO Recycling Inc.	Sapulpa	OK	Magnesium ingot and anodes	Dross and old magnesium base	NA
Reactive Metals and Alloys Corp.	W. Pittsburg	PA	Desulfurization reagents	Dross	NA
Rossborough Manufacturing Co. L.P.	Walkerton	IN	do.	Chips	NA
Spectrulite Consortium Inc.	Madison	IL	Magnesium ingots	New die-cast	15,000

NA Not available.
[1]Closed in 2000.

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 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 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 SCRAP METALS

STRUCTURAL MAGNESIUM-BASE PRODUCTS

In making magnesium alloy diecastings, about 50 percent of the material ends up as a finished product, and the remainder as new scrap. Of the scrap generated in the diecasting 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, 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 separating 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 675E 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 delaquered. 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 was determined from the following content and recovery rates and using a 63-percent UBC recycling rate for 1998:

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

Type	Metal recovery	Magnesium content
Body stock skeleton (AA 3004, 1.05-percent Mg)	80	0.95
End and tab stock skeleton (AA 5182, 4.50-percent Mg)	90	3.4
Recycled beverage cans (1.9-percent Mg)	90	1.3

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 delaquering 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).

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). One hundred percent of this scrap is assumed to be returned to the sheet producer for reclaim. 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).

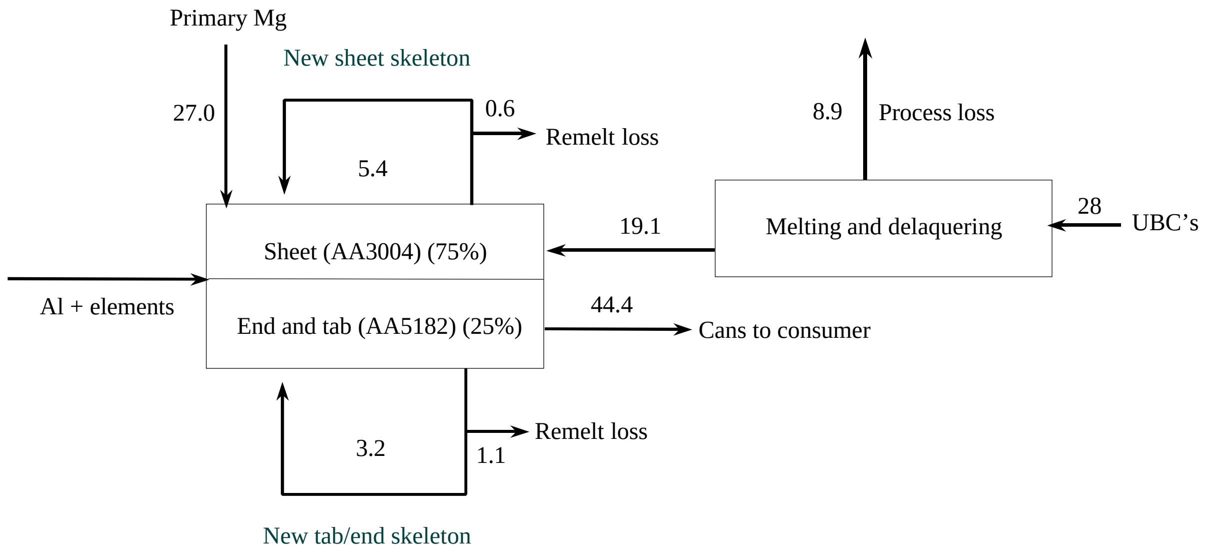

Figure 4. Simplified used beverage can processing, in thousand metric tons contained magnesium. UBC's, used beverage cans. (Adapted from Bowman, 1983.)

TITANIUM PRODUCTION

In addition to reprocessing alloys, 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, than 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 will vary from plant to plant (Poulsen and Sprayberry, 1992). This type of magnesium recycling would be 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 auto 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. 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 auto and recycled. With additional magnesium-containing parts, this would result in additional quantities of old scrap as a source of supply. Because automobiles are a global market, 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, 2000).

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 is 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) 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 (U.S. Environmental Protection Agency, April 1999, Inventory of U.S. greenhouse gas emissions and sinks—1990-1997, accessed September 13, 2000, at URL http://www.epa.gov/oppeoee1/globalwarming/publications/emissions/us1999/execsum.pdf.). 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 (U.S. Environmental Protection Agency, October 1998, New climate protection initiative with U.S. magnesium industry, accessed July 6, 1999, at URL http://www.epa.gov/appdstar/news.html). 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, 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; and HFC-134a has the ability to extinguish a magnesium fire once started, whereas SF_6 will not (Commonwealth Scientific and Industrial Research Organisation, [undated], Alternative magnesium cover gases—Reducing greenhouse gas emissions, accessed September 18, 2000, via URL http://www.cmst.csiro.au/).

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APPENDIX—DEFINITIONS

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

apparent supply (AS). AC plus consumption of new scrap (CNS).

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.

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 intermediate and ultimate consumption; it includes all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. This includes scrap generated at facilities consuming old scrap. Included as new scrap is prompt industrial 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 that includes, but is 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, metals from shredded cars and appliances, silver from photographic materials, spent catalysts, tool bits, and used aluminum beverage cans,. This is also referred to as “postconsumer scrap” and may originate from industry or the general public. Expended or obsolete material that is used dissipatively, such as paints and fertilizer, is not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration; this excludes 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, that is,

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

old scrap supply. Old scrap generated plus old scrap imports plus old scrap stock decrease; that is,

$$\text{OSG + OSI + OSS decrease.}$$

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exports minus old scrap stock increase; that is,

$$\text{OSS - COS - OSE - OSS increase.}$$

price. Unit value of primary magnesium metal used in calculating total value of contained metal in scrap.

recycling. Reclamation of a metal in useable 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 (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 plus consumption of new scrap divided by apparent supply measured in weight and expressed as a percentage; that is,

$$[(\text{COS + CNS})/\text{AS}] \times 100.$$

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