



Magnesium, its Alloys and Compounds

By Deborah A. Kramer

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INTRODUCTION AND HISTORY

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 averaging 0.13 percent. Although magnesium is found in over 60 minerals, only dolomite, magnesite, brucite, carnallite, and olivine are of commercial importance. Magnesium and magnesium compounds are produced from seawater, well and lake brines and bitterns, as well as from the minerals noted above.

In 1795, J.C. Delanethrie applied the term "magnesite" to a series of magnesium salts (carbonate, sulfate, nitrate, and chloride), and A. Brongmart applied the same term to a group of minerals including magnesium carbonates and silicates. Deposits of natural magnesium carbonate were discovered in Moravia, Czechoslovakia, and were described by C.F. Ludwig as talcum carbonatum in 1803. D.L.G. Karsten first restricted the term "magnesite" to the natural carbonate in 1808, and this term was gradually accepted.

Magnesite deposits were discovered in Austria and Greece during the latter half of the 19th century, and by 1890, magnesite was in general use in Europe for refractory linings in Bessemer and open-hearth furnaces. At the same time, magnesite mines were opened in Canada, and by 1909, substantial quantities of calcined magnesite were exported annually to the United States.

In 1886, deposits of magnesite were discovered in California, and by 1912, ground California magnesite was used in the Western United States to replace specified grades of imported material. In 1913, production of magnesia (magnesium oxide) by precipitation using dolomite began in Pennsylvania. Deposits in Stevens County, WA, were recognized as magnesite in 1916, and mining started the next year. Mining of brucite began in 1929 from a deposit in Nye County, NV, and in 1937, magnesite mining started in a nearby deposit. Mining and processing domestic magnesium ores was expanded in the early 1940's to provide material for the production of chemicals and magnesium metal as well as refractories. Also in the early 1940's, magnesium chloride, recovered from seawater, was used in large quantities to produce magnesium metal in plants in Freeport and Velasco, TX.

Magnesium metal was first reported to have been produced by Sir Humphry Davy in 1808 by reduction of magnesium oxide with potassium vapor. The first industrial production of magnesium was undertaken in France by Deville and Caron in 1863 and involved reduction of a mixture of anhydrous magnesium chloride and calcium fluoride by sodium. In 1833, Michael Faraday obtained magnesium by the electrolysis of fused anhydrous magnesium chloride, and in 1852, Robert Bunsen developed an electrolytic cell for this purpose. By the use of a modification of Bunsen's electrolytic cell, magnesium metal was produced on a pilot plant scale in Germany in 1886, and by 1909, had advanced to limited industrial production. The first magnesium plant in the United States was constructed by the General Electric Co. at Schenectady, NY, in 1914. Magnesium production in the United States increased steadily and experienced a sharp increase during World War II because of the use of magnesium in incendiary bombs. The U.S. Government constructed 13 magnesium metal plants between 1940 and 1943 to supply magnesium for the war. Shortly after the end of the war, these plants were either closed or sold to private industry (Comstock, 1963, p. 15-26).

OCCURRENCE

World magnesite reserves are shown in table 1. In addition to those estimates shown, magnesite deposits occur in Spain, Pakistan, and the Sudan. Deposits of less than 1 million metric tons (Mt) were reported in Mexico, Iran, the Philippines, Australia, Egypt, and the Republic of South Africa. Small deposits also have been noted in Cuba, Sweden, Norway, Poland, Scotland, France, Italy, Kenya, and Tanzania.

The reported estimate of 65 Mt of magnesite (15 Mt magnesium) reserve base in the United States is divided as follows: in Nevada, 88 percent, including 27 Mt of magnesite containing less than 5 percent CaO; in Washington, 11 percent; and in California, the remaining 1 percent. Magnesite also occurs in Texas, New Mexico, Idaho, Utah, Pennsylvania, Massachusetts, Maryland, New Jersey, and New York, but reserves have not been estimated in these States.

Brucite reserves are estimated to total 3 Mt in Nevada and 2 Mt in North Korea. The mineral is also found in Arizona and in the United Kingdom, Ireland, and Canada.

Reserves of olivine in North Carolina and Georgia are estimated at 230 Mt, averaging 48 percent MgO. Additionally, in Washington, the olivine reserve in the form of dunite is estimated at 50 Mt on Cypress Island and several million metric tons in the Twin Sisters region.

Reserves of magnesium salts obtained as brines from underground evaporate deposits are difficult to estimate. Available information on magnesium salts in surface evaporates is insufficient to estimate reserves. The Great Salt Lake contains an estimated 630 Mt of magnesium chloride.

Dolomite is a sedimentary rock commonly interbedded with limestone, which extends over large areas of the United States. Most dolomite occurrences are likely the result of replacement of calcium by magnesium in preexisting limestone beds. Magnesite is

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

primarily found in four types of deposits: sedimentary beds, alterations of serpentine, vein fillings, and replacements of limestone and dolomite. Brucite is found in crystalline limestone and as a decomposition product of magnesium silicates associated with serpentine, dolomite, magnesite, and chromite. Olivine generally occurs as granular masses or disseminated grains and crystals, and is a common constituent of basic igneous rocks such as basalt and gabbro. Dunite is an olivine-rich rock (Bodenlos and Thayer, 1973).

Evaporites are deposits formed by precipitation of salts from saline solutions found both on the surface and underground. The geological occurrence and chemical composition of inland brines cover a wide range, but little information has been published.

Table 1. World magnesite reserves and reserve base
[Million metric tons of contained Mg]

Country	Reserves	Reserve base ¹
Australia	NA	NA
Austria	15	20
Brazil	45	65
China ^e	750	1,000
Greece	30	30
India	30	45
Korea, North ^e	450	750
Russia ^e	650	730
Serbia and Montenegro	5	10
Slovakia ^e	20	30
Spain	10	30
Turkey	65	160
United States	10	15
Other countries	420	480
Total ²	2,500	3,400

^eEstimated. NA Not available.

¹The reserve base includes demonstrated resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).

²Data may not add to totals shown because of independent rounding.

PROPERTIES

Some of the physical properties of magnesium and its compounds are summarized in table 2.

Table 2. Properties of magnesium and its compounds
[Source: CRC Handbook of Chemistry and Physics]

	Atomic weight	Melting point °C	Density at 20 °C (g/cm ³)
Magnesium metal	24.31	650	1.738
Magnesium carbonate	84.31	990	3.05
Magnesium chloride hexahydrate (MgCl ₂ •6H ₂ O)	95.22	708	2.333
Magnesium chloride (MgCl ₂)	203.31	¹ 116-118	1.585
Magnesium hydroxide (MgOH ₂)	58.32	¹ 350	2.36
Magnesium oxide (dead-burned)	40.304	2,827 ± 30	3.581
Magnesium sulfate (MgSO ₄)	120.37	1,127	2.66
Magnesium sulfate (MgSO ₄ •H ₂ O) kieserite	138.38	¹ 150	2.571
Magnesium sulfate (MgSO ₄ •7H ₂ O) epsomite	246.48	¹ 150	1.678

¹Decomposes.

Magnesite, or magnesium carbonate (MgCO₃), has a theoretical magnesium content of 47.6 percent. Dolomite is a calcium carbonate-magnesium carbonate mineral (CaCO₃CMgCO₃) that has a theoretical magnesium content of 22 percent. Brucite, magnesium hydroxide [Mg(OH)₂], contains up to 69 percent magnesium, and olivine (Mg₂Fe₂SiO₄) contains up to 19 percent magnesium. Of these minerals, magnesite and dolomite are the largest sources of magnesium and magnesium compounds.

Seawater, brines, and bitterns represent vast sources of magnesium and magnesium compounds. In the United States, about 60 percent of the magnesium compounds produced annually is recovered from seawater and brines, and more than one-half of the magnesium metal production capacity uses seawater or brines as a raw material.

Various magnesia products are made by calcining magnesium carbonate or magnesium hydroxide at different temperatures. Caustic-calcined magnesia, which is readily reactive with water, is calcined at temperatures up to 890E C. Dead-burned magnesia, also called refractory or sintered magnesia, is calcined at temperatures up to 1,450E C and is unreactive with water. Fused magnesia is produced at temperatures greater than 3,000E C. Magnesia produced from magnesite is generally called natural magnesia, and magnesia produced from seawater or brines is called synthetic magnesia.

SOURCES AND SUPPLIES

MAGNESIUM OXIDE

A list of world producers of dead-burned and caustic-calcined magnesia is presented in table 3. Many of these, and other companies produce magnesium compounds, such as magnesium hydroxide, magnesium sulfate, and magnesium carbonate, but compilation of a detailed list of these producers is not possible.

Table 3. World magnesium compounds annual production capacity, yearend 2000
[Thousand metric tons, MgO equivalent]

Country and company	Raw material			
	Magnesite		Seawater or brines	
	Caustic-calcined	Dead-burned	Caustic-calcined	Dead-burned
Australia:				
Causmag Ore Co. Pty. Ltd.	18	—	—	—
Queensland Magnesia Pty. Ltd. (QMAG)	30	120	—	—
Austria:				
RHI AG	—	250	—	—
Styromagnesit Steirische Magnesitindustrie GmbH	35	—	—	—
Brazil:				
IBAR-Nordeste S.A.	13	6	—	—
Magnesita S.A.	45	270	—	—
Canada: Baymag Mines Co. Ltd.	100	—	—	—
China:				
China Metallurgical Import & Export Liaoning Magnesite Co.	—	200	—	—
Dashiqiao Guantun Magnesite Mine	—	130	—	—
Haicheng Dongxin Industrial Co.	—	50	—	—
Haicheng Houyin Magnesite Co.	—	600	—	—
Haicheng Huaya Group	—	550	—	—
Haicheng Pailou Magnesite (Group) Co.	—	150	—	—
Haicheng Xiyang Refractories Materials Corp.	—	340	—	—
Liaoning Magnesite and Refractories Corp. of China	200	20	—	—
Liaoning Yinglian Magnesite Materials Co. Ltd.	—	25	—	—
Manchurian Seawater Works	—	—	—	10
Shandong Magnesite Mine	—	60	—	—
Yingkou Qinhua Magnesite Corp.	—	350	—	—
France: Cie des Salins du Midi	—	—	30	—
Greece: Grecian Magnesite S.A.	120	80	—	—
India:				
Almora Magnesite Ltd.	—	24	—	—
Burn Standard Co. Ltd.	5	42	—	—
Dalmia Magnesite Corp.	—	60	—	—
Himilayan Magnesite Ltd.	—	11	—	—
Khaitan Hostombe Spinels	—	27	—	—
Magnesite & Minerals Ltd.	—	45	—	—
Pon Kumar Magnesite	—	8	—	—

Table 3. World magnesium compounds annual production capacity, yearend 2000
[Thousand metric tons, MgO equivalent]

Country and company	Raw material			
	Magnesite		Seawater or brines	
	Caustic- calcined	Dead- burned	Caustic- calcined	Dead- burned
India—Continued:				
Tamilnadu Magnesite Ltd.	20	30	—	—
Tata Iron & Steel Co. Ltd.	—	15	—	—
Iran: Iranian Refractories Procurement and Production Co.	—	30	—	—
Ireland: Premier Periclase Ltd.	—	—	—	90
Israel: Dead Sea Periclase Ltd.	—	—	10	60
Italy:				
Eraclit Venier SpA	25	—	—	—
Nuova Sardamag Srl	—	—	—	60
Sardamag SpA	—	—	5	70
Japan:				
Asahi Glass Co. Ltd.	—	—	15	15
Ube Chemical Industries Co. Ltd.	—	—	50	250
Korea, North: Korean Magnesite Works	—	500	—	—
Korea, Republic of: Sam Hwa Chemical Co.	—	—	—	50
Mexico: Quimica del Rey SA de CV	—	—	15	95
Netherlands: Nedmag Industries Mining and Manufacturing BV	—	—	—	150
Norway: Norsk Hydro A/S	—	—	25	—
Poland: Government plant	—	10	—	—
Russia:				
Bogdanovichsky Refractory Production Amalgamation	—	272	—	—
JSC Kombinat Magnezit	10	2,400	—	—
Serbia and Montenegro: Sour Magnohrom— Vatrostalni Materijali	40	200	—	—
Slovakia:				
Slovamag AS	—	90	—	—
SMZ AS Jelsava	—	350	—	—
South Africa:				
Chamotte Holdings (Pty) Ltd.	3	—	—	—
Venmag	4	—	—	—
Spain:				
Magnesitas de Rubian SA	80	—	—	—
Magnesitas Navarras SA	75	60	—	—
Turkey:				
Calmag	50	—	—	—
Konya Krom Magnezit Tugla Sanayii Muessessesi	—	45	—	—
Kumas-Kutahya Magnesite Works Corp.	—	144	—	—
Magnesit AS	—	120	—	—
Ukraine:				
Nikitovsky Dolomite Works	—	120	—	—
Sivash Magnesia Works	—	—	20	80
United Kingdom: Britmag Ltd. ¹	—	—	70	80
United States:				
Martin Marietta Magnesia Specialties Inc.	—	—	80	195
Premier Services Corp.	70	70	50	—
Rohm and Haas Inc.	—	—	10	—
Total ²	943	7,870	380	1,210

¹Raw material for MgO production is dolomite.

²Data are rounded to three significant digits; may not add to totals shown.

The largest magnesite production facilities in the world are in China, North Korea, and Russia. Together, these three countries account for 68 percent of the world magnesite production capacity. Japan and the United States account for 54 percent of the world's magnesia production capacity from seawater or brines. Fused magnesia is produced in Australia, Brazil, Canada, China, Israel, Japan, the Republic of Korea, Mexico, Russia, the United Kingdom, and the United States.

Norway, the world's principal producer of olivine, supplies its domestic needs and is a major world supplier of olivine. Countries with smaller output include Australia, Italy, Japan, Mexico, Pakistan, Spain, and the United States.

Table 4 summarizes the historical supply and demand statistics for magnesium compounds in the United States. Production data in this table include U.S. production of magnesite, dead-burned dolomite, olivine, and magnesium compounds from brines and seawater. Table 5 shows production and trade data for magnesium oxide only.

Table 4. U.S. historical salient magnesium compounds statistics
[Thousand metric tons MgO content]

Year	Production	Imports	Exports	Apparent consumption	Net import reliance ¹ as a percent of apparent consumption
1955	1,362	96	NA	NA	NA
1960	1,448	108	83	1,473	2
1965	1,837	126	70	1,894	3
1970	1,547	126	90	1,584	2
1975	1,313	148	83	1,378	5
1980	1,206	76	98	1,184	E
1985	697	222	41	877	21
1990	828	244	98	973	15
1995	597	544	90	1,051	43
1998	607	570	82	1,095	45
1999	655	532	87	1,100	40
2000	614	655	93	1,176	48

E Net exporter. NA Not available.

¹Defined as imports - exports + adjustments for Government and industry stock changes.

Table 5. U.S. magnesium oxide (magnesia) statistics
[Metric tons]

	1990	1995	1998	1999	2000	Principal sources or destinations, 2000, percent ¹
Caustic-calcined and specified magnesia:						
Production	135,000	141,000	177,000	179,000	172,000	XX
Imports (HTS 2519.90.2000 + 2519.90.5000)	88,900	152,000	127,000	141,000	155,000	China, 57; Canada, 29.
Exports (HTS 2519.90.2000 + 2519.90.5000)	40,100	14,700	18,700	19,000	33,000	Mexico, 26; Canada, 15; Brazil, 7.
Dead-burned magnesia:						
Production	335,000	234,000	215,000	216,000	196,000	XX
Imports (HTS 2519.90.1000)	155,000	393,000	427,000	392,000	501,000	China, 69; Australia, 13.
Exports (HTS 2519.90.1000)	58,600	74,800	63,200	66,700	59,800	Canada, 84.

XX Not applicable.

¹Source: U.S. Census Bureau.

Historically, overall U.S. consumption of magnesium compounds has declined, mainly because of a decrease in demand from the refractories industry, the largest consumer of magnesium compounds. U.S. production actually decreased faster than the drop in consumption because imports of low-cost dead-burned magnesia from China replaced part of the U.S. production. This can be seen in the significant increase in import reliance that occurred beginning in the 1980's. With the recovery in the U.S. economy in the late

1990's, overall consumption of magnesia increased as steel production increased, but this trend is expected to be short-lived. The quantity of refractory magnesia consumed per ton of steel produced continued to decline. For example, in the mid-1970's, the electric arc furnace used about 20 kilograms (kg) of refractories per metric ton of steel produced; this quantity has declined to about 4 kg per metric ton. The overall magnesia refractories market is expected to decline by about 4 percent by 2003 (Pearson, 2000, p. 52-55).

Some of the decline in consumption of magnesia for refractories has been offset by growth in caustic-calcined magnesia for two applications—water treatment and flame retardants. Although magnesium hydroxide is the principal product used in these applications, caustic-calcined magnesia is often the feedstock. The principal reasons for using magnesia or magnesium hydroxide for water treatment rather than caustic soda or lime include buffering ability, reduced quantities of sludge, heavy metal removal, and safety. The principal drawbacks are the higher cost and slower reaction time. Because of its enhanced properties, magnesia is expected to increase its share of the water treatment market, albeit at a slower pace than the industry originally forecast.

MAGNESIUM CARBONATE

The largest producer of magnesium carbonate in the United States is Rohm and Haas Co. Rohm and Haas operates a specialty magnesia facility in Manistee, MI, where it produces both light and heavy magnesium carbonate from magnesia recovered from underground brines. The company produces technical and United States Pharmacopeia (USP) grades of magnesium carbonate. From 1990 to 2000, U.S. magnesium carbonate production has ranged from 2,000 to 3,000 metric tons (t) annually. Trade data for magnesium carbonate are grouped with those of other carbonates in a “basket” category and cannot be separately identified.

MAGNESIUM CHLORIDE

In the United States, magnesium chloride is produced and used in two forms—magnesium chloride brines, which are about 30 percent magnesium chloride in concentration, and magnesium chloride hexahydrate (MgCl₂•6H₂O). IMC Kalium Ogden Corp., Ogden, UT, produces both the brines and hexahydrate. Reilly Industries Inc., Wendover, UT, and Western Salt Inc., Chula Vista, CA, produce magnesium chloride brines. IMC and Reilly Industries recover magnesium chloride from brines of the Great Salt Lake, and Western Salt produces magnesium chloride brines from seawater as a byproduct of salt production. Magnesium chloride is recovered from either brines or seawater by solar evaporation and sequential precipitation of the dissolved salts in the brine. Production data for magnesium chloride brines and hexahydrate are withheld to avoid disclosing individual company proprietary data; trade data for magnesium chloride are shown in table 6.

Table 6. U.S. magnesium chloride statistics
[Metric tons]

	1990	1995	1998	1999	2000	Principal source or destination, 2000, percent ¹
Production	W	W	W	W	W	XX
Imports, (magnesium chloride—hydrous and anhydrous HTS 2827.31.0000)	6,910	16,500	12,000	24,500	35,800	Israel, 91.
Exports, (magnesium chloride—hydrous and anhydrous HTS 2827.31.0000)	4,760	3,060	4,130	4,420	4,900	Canada, 79; India, 14.

W Withheld to avoid disclosing individual company proprietary data. XX Not applicable.

¹Source: U.S. Census Bureau.

MAGNESIUM HYDROXIDE

Magnesium hydroxide [Mg(OH)₂] is another material that can be found as a naturally occurring mineral or can be produced synthetically from seawater or brines. Magnesium hydroxide occurs as the mineral brucite. Small quantities of brucite are recovered in the United States by one firm, Premier Services Inc., as a byproduct of magnesite mining in Gabbs, NV. Applied Chemical Magnesias Corp. recovers brucite from a deposit in Bullhead City, AZ. The deposit is estimated to contain 450,000 t of ore grading 90 percent brucite (North American Minerals News, 1998). The company processes this ore and other materials at a 30,000-t/yr mill in Arizona into products for use as flame retardants, animal feed, and acid neutralization.

Several companies in the United States produce magnesium hydroxide synthetically. Barcroft Co., Lewes, DE; and American Premier Inc., Port St. Joe, FL, recover magnesium hydroxide from seawater. Dow Chemical Co., Martin Marietta Magnesia Specialties Inc., and Rohm and Haas recover magnesium hydroxide from underground brines in Michigan. In addition to its Michigan plant, Martin Marietta operates two plants—one near Pittsburgh, PA, and the other in Lenoir City, TN—that produce magnesium hydroxide from imported magnesite. The 30,000-t/yr Pittsburgh plant was commissioned early in 1994 and originally operated by Clearwater Inc.; Martin Marietta purchased the plant in late 1994. At this plant, magnesium hydroxide is produced by pressure

hydration of magnesium oxide. The 15,000-t/yr Tennessee plant was constructed by Martin Marietta in 1996 and uses the same production technology.

Production and trade data for magnesium hydroxide are shown in table 7. Of the production data in the table, a significant portion of the total is produced by Dow and pumped to the nearby RHI Refractories America plant where RHI Refractories produces dead-burned magnesia for refractory applications.

Table 7. U.S. magnesium hydroxide statistics
[Metric tons]

	1990	1995	1998	1999	2000	Principal sources or destinations, 2000, percent ¹
Production	366,000	297,000	241,000	233,000	212,000	XX
Imports (magnesium hydroxide and peroxide, HTS 2816.10.0000)	3,550	4,940	6,140	7,440	8,960	Japan, 35; Israel, 28, Netherlands, 12.
Exports (magnesium hydroxide and peroxide, HTS 2816.10.0000)	6,340	17,400	17,700	18,900	20,200	Canada, 70.

XX Not applicable.

¹Source: U.S. Census Bureau.

MAGNESIUM SULFATE

Magnesium sulfate can be found as a naturally occurring mineral or it can be produced synthetically. The two most commonly occurring magnesium sulfate minerals are epsomite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) and kieserite ($\text{MgSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$). Although these minerals occur in the Western United States, they are not mined.

The three U.S. producers of magnesium sulfate are PQ Corp., Giles Chemical Corp., and Southern Ionics Inc. PQ operates a facility in Utica, IL, where they produce a magnesium sulfate solution (25 percent solids) and $\text{MgSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ crystal. Giles has two plants that produce magnesium sulfate solutions and magnesium sulfate crystal—Greendale, IN, and Rouses Point, NY. Southern Ionics operates two plants producing 18 percent to 25 percent magnesium sulfate solutions in Chickasaw, AL and Baton Rouge, LA. U.S. production and trade in magnesium sulfate are shown in table 8.

Table 8. U.S. magnesium sulfate statistics
[Metric tons]

	1990	1995	1998	1999	2000	Principal sources or destinations, 2000, percent ¹
Production	55,400	46,100	57,500	47,100	44,000	XX
Imports:						
Epsom salts (HTS 2530.20.2000)	12,500	27,400	288	82	85	Germany, 90.
Kieserite (HTS 2530.20.1000)	44	26	26,000	23,800	27,000	Germany, 100.
Other magnesium sulfate (HTS 2833.21.0000)	9,990	16,000	21,900	26,700	31,800	Germany, 56; Canada, 33.
Exports:						
Epsom salts and kieserite (HTS 2530.20.0000)	241	1,830	69	393	453	Honduras, 44; Ireland, 27.
Other magnesium sulfate (HTS 2833.21.0000)	2,820	4,740	5,910	5,140	6,200	Canada, 87.

XX Not applicable.

¹Source: U.S. Census Bureau.

MAGNESIUM METAL

U.S. magnesium metal statistics are shown in table 9. Historically, the United States has been able to meet its demand with domestic production and has been a net exporter of magnesium metal. As consumption has grown, U.S. production also has increased. There was significant growth in magnesium consumption in the 1970's with the introduction of the aluminum beverage can. As aluminum replaced steel as the material of choice for beverage cans, magnesium consumption grew steadily. This market, although still the largest for magnesium, has leveled off as the beverage can market has become saturated; currently this market grows relative to population.

Table 9. U.S. historical salient magnesium metal statistics
[Thousand metric tons]

Year	Primary production	New scrap	Old scrap	Imports	Exports	Government stockpile releases	Stocks, yearend	Apparent consumption	Net import reliance ¹ as a percent of apparent consumption
1955	55	5	4	2	8	—	27	47	E
1960	36	5	4	(²)	5	—	24	48	17
1965	74	9	3	3	17	2	14	71	E
1970	102	8	3	3	32	13	12	88	E
1975	109 ³	16	9	7	30	—	36	60	E
1980	154 ³	21	16	3	51	—	45	117	E
1985	136	18	24	8	37	—	39	123	E
1990	139	23	31	27	52	—	26	145	E
1995	142	35	30	35	38	—	12	171	E
1998	106	45	32	83	35	—	22	185	25
1999	W	52	34	91	29	—	W	179	38
2000	W	52	30	91	24	—	W	160	43

E Net exporter. W Withheld to avoid disclosing company proprietary data.

¹Defined as imports - exports + adjustments for Government and industry stock changes.

²Less than ½unit.

³Derived from production reported by the International Magnesium Association and the Canadian Department of Energy, Mines and Resources.

In the 1990's, however, imports of magnesium have had an impact on the U.S. supply and demand of magnesium. When Norsk Hydro A/S opened its primary magnesium plant in Becancour, Canada, in 1990, production was targeted toward the U.S. market, and imports of primary magnesium from Canada increased significantly. With the dissolution of the former Soviet Union in 1991, imports of magnesium from Russia began entering the U.S. market. Antidumping and countervailing duties were assessed on imports of pure and alloy magnesium from Norsk Hydro in Canada in 1991, and imports from that country into the United States essentially ceased. By that time, the Russian material had begun entering the U.S. market, replacing some of the material from Canada. In 1994, the U.S. International Trade Commission began an investigation into antidumping of pure and alloy magnesium from Russia, China, and Ukraine. When the investigation began, imports from these countries also ceased.

At the same time that imports were dropping, demand in the United States began increasing, particularly for magnesium alloy diecastings for automotive applications. U.S. producers were operating near their rated capacity, and supplies became very tight, which, in 1995, caused a price escalation to a level that had not been experienced since magnesium was first produced commercially in the United States.

Resolution of the antidumping duties on magnesium from Russia whereby the large producing firms were allowed to import magnesium into the United States through specified importing companies without any penalty resulted in a resumption of imports of significant quantities of pure magnesium in 1996. Also in 1996, the antidumping duty on magnesium imports from Canada was eliminated, and the countervailing duties had been reduced to a level that would permit imports of magnesium alloy into the United States.

Although dumping duties had been established, imports of magnesium continued to increase. At the request of one of the U.S. producers, in 2000, the International Trade Administration (ITA) initiated a countervailing duty investigation of pure magnesium from Israel and antidumping duty investigations of pure magnesium from China, Israel, and Russia. The principal material under concern in these investigations was pure magnesium in granular or powder form, which was specifically excluded from earlier antidumping investigations on magnesium from China and Russia. This was the first investigation of magnesium from Israel; Dead Sea Magnesium Ltd. had opened its primary magnesium plant in 1998. In April 2001, the ITA had established preliminary antidumping duties on magnesium from China and Israel; Russia was determined not to have dumped magnesium into the U.S. market (U.S. Department of Commerce, 2001, a, b, c). In spite of the establishment of duties that could reduce the level of imports, U.S. producers of magnesium began to exit the market. In 1998, Dow Chemical closed its Freeport, TX, plant, Northwest Alloys Inc. planned to closed its Addy, WA, plant by October 1, 2001, and Renco Metals Inc., the parent of Magnesium Corp. of America, filed for chapter 11 bankruptcy in August 2001. Current levels of U.S. trade in magnesium are shown in table 10.

Table 10. U.S. imports for consumption and exports of magnesium
[Metric tons]

	1990	1995	1998	1999	2000	Principal sources or destinations, 2000, percent
Imports for consumption:						
Metal (HTS 8104.11.0000)	16,100	6,480	26,500	26,900	22,900	Russia, 47; Israel, 28; Canada, 14.
Waste and scrap (HTS 8104.20.0000)	4,080	11,500	5,720	6,780	9,890	Canada, 65.
Alloys (magnesium content) (HTS 8104.19.0000 + 8104.30.0000)	5,340	15,900	49,600	56,500	56,300	Canada, 46; China, 37.
Sheet, tubing, ribbons, wire, powder, and other (magnesium content) (HTS 8104.90.0000)	1,200	867	757	594	2,300	Canada, 76.
Total ¹	26,800	34,800	82,500	90,700	91,400	Canada, 40; China, 24; Russia, 15; Israel, 10.
Exports:						
Metal (HTS 8104.11.0000)	41,900	21,500	11,500	4,790	7,300	Canada, 37, Netherlands, 36.
Waste and scrap (HTS 8104.20.0000)	967	3,540	13,200	16,500	6,400	Canada, 98.
Alloys (gross weight) (HTS 8104.19.0000 + 8104.30.0000)	4,630	6,080	9,220	2,760	6,020	Canada, 82.
Sheet, tubing, ribbons, wire, powder, and other (gross weight) (HTS 8104.90.0000)	4,350	7,200	1,470	4,990	4,060	Mexico, 42; Canada, 24.
Total ¹	51,800	38,300	35,400	29,100	23,800	Canada, 51; Mexico, 10; Netherlands, 7.

¹Data are rounded to three significant digits; may not add to totals shown.

Source: U.S. Census Bureau.

In addition to imports, magnesium recovered from old scrap has become an important factor in the total U.S. metal supply. In 1980, secondary magnesium from old scrap represented 14 percent of the total U.S. demand and increased to a level of 19 percent in 2000. Much of this increase resulted from increased recycling of used beverage cans, fabricated from aluminum-magnesium alloys. With the increased use of magnesium in automotive components, secondary magnesium is expected to continue to supply an increasing portion of U.S. demand as cars are expected to be recycled for their metal content rather than junked.

Throughout the world, magnesium currently is manufactured by two methods— electrolytic reduction of magnesium chloride or thermic reduction of dolomite. Table 11 shows the world's producers of magnesium with their production capacity and raw material and production method used.

Table 11. Primary magnesium metal production capacities, yearend 2000

Country and company	Process and raw material ¹	Capacity (metric tons per year)
Brazil: Rima Industrial S/A (Brasmag)	Silicothermic (D)	12,000
Canada:		
Timminco Metals Ltd.	Silicothermic (D)	9,000
Magnola Metallurgy Inc.	Electrolytic (A)	63,000
Norsk Hydro A/S	Electrolytic (M)	55,000
China: ²		
Fushun Magnesium Co.	Electrolytic (M)	5,000
Gold River Magnesium Plant	Silicothermic (D)	9,000
Guangling Chemical Co.	Silicothermic (D)	8,000
Huaqi Magnesium Industry	Silicothermic (D)	6,000
Huayuan Shizuizhan Magnesium Plant	Silicothermic (D)	8,000
Jilin Linjiang Magnesium Industry Group	Silicothermic (D)	15,000
Minhe Magnesium Co.	Electrolytic (M)	7,000
Shanxi Yiwei Magnesium Co.	Silicothermic (D)	10,000
Shanxi Tongxiang Magnesium Co.	Silicothermic (D)	10,000

Table 11. Primary magnesium metal production capacities, yearend 2000

Country and company	Process and raw material ¹	Capacity (metric tons per year)
China—Continued:		
Taiyuan Luowei Oriental Magnesium Co.	Silicothermic (D)	5,000
Taiyuan Yiwei Magnesium Co.	Silicothermic (D)	15,000
Tongbao Magnesium	Silicothermic (D)	9,600
Taiyan Tongxiang Magnesium Co.	Silicothermic (D)	14,000
Wenxi Yinguang Magnesium Industry Co.	Silicothermic (D)	12,000
France: Sofrem (Pechiney)	Silicothermic (D)	17,000
India: Southern Magnesium and Chemicals Ltd.	Silicothermic (D)	900
Israel: Dead Sea Works Ltd.	Electrolytic (C)	27,500
Kazakhstan: Ust'-Kaminogorsk	Electrolytic (C)	50,000
Norway: Norsk Hydro A/S	Electrolytic (B)	35,000
Russia:		
Solikamsk Magnesium Works	Electrolytic (C)	20,000
Avisma	Electrolytic (C)	55,000
Serbia and Montenegro: Magnohrom	Silicothermic (D)	5,000
Ukraine:		
Kalush ³	Electrolytic (C)	15,000
Zaporzhye Titanium and Magnesium Co. ³	Electrolytic (C)	45,000
United States:		
Magnesium Corp. of America (Magcorp)	Electrolytic (B)	43,000
Northwest Alloys Inc. (Alcoa)	Silicothermic (D)	40,000
Total		626,000

¹Raw material source: (A)—Asbestos tailings, (B)—Brines, (C)—Carnallite ($MgCl_2 \cdot KCl \cdot 6H_2O$), (D)—Dolomite ($MgCO_3 \cdot CaCO_3$), and (M)—Magnesite ($MgCO_3$).

²Plant capacity 5,000 metric tons per year or greater. China is estimated to have more than 500 magnesium plants with a total annual capacity of 200,000 mt.

³Idle.

Because of the high projected growth rate in magnesium consumption for diecastings in automotive applications, many firms have announced plans to construct new magnesium plants. Table 12 lists the potential new facilities scheduled to come on-stream within the next few years.

Table 12. Primary magnesium metal production capacities, proposed facilities

Country and company	Process and raw material ¹	Capacity (metric tons per year)	Scheduled completion date
Australia:			
Australian Magnesium Corp. Ltd.	Electrolytic (M)	90,000	2004
Indor Ltd. (formerly Crest Resources NL, TasMag project)	Electrolytic (M)	95,000	NA
Pima Mining NL (SAMAG Ltd.)	Electrolytic (M)	65,000	2004
Pacific Magnesium Corp. Ltd. (formerly Golden Triangle Resources NL)	Electrolytic (A)	80,000	2006
Mt. Grace Resources NL	Silicothermic (M)	50,000	2004
Anaconda Nickel	NA (M)	100,000	NA
Congo (Brazzaville): Magnesium Alloy Corp.	Electrolytic (C)	60,000	2005
Canada:			
Cassiar Magnesium Inc.	Electrolytic (A)	90,000	2003
GeoTech Surveys Inc.	NA (A)	NA	NA
Gossan Resources	Silicothermic (D)	50,000	NA
Iceland: Icelandic Magnesium Corp.	Electrolytic	50,000	NA
Netherlands: Antheus Magnesium Development Programme Delfzijl	Electrolytic ? (B)	40,000-50,000	NA

Table 12. Primary magnesium metal production capacities, proposed facilities

Country and company	Process and raw material ¹	Capacity (metric tons per year)	Scheduled completion date
United Arab Emirates: Spectrum Technology Corp.	NA (S)	NA	NA

NA Not available.

¹Raw material source: (A)—Asbestos tailings, (B)—Brines, (C)—Carnallite (MgCl₂•KCl•6H₂O), (D)—Dolomite (MgCO₃•CaCO₃), (M)—Magnesite (MgCO₃), and (S)—Seawater.

Although world demand for magnesium is growing, it is not growing at a fast enough rate to support the additional production from all of the plants in the table above. Many of the companies that proposed the new magnesium plants are looking for a long-term purchase agreement or some type of financial commitment from a large end user of magnesium (primarily the automobile manufacturers) before the company will begin plant construction.

PRICES

MAGNESIUM COMPOUNDS

Published magnesium compound prices change infrequently. Price data for magnesium oxide and other compounds are shown in table 13.

Table 13. Yearend magnesium compound prices

Material	Units	1995	1996	1997	1998	1999	2000
Magnesia, natural, technical, heavy, 85%, f.o.b. Nevada	per short ton	\$232-\$265	\$232-\$265	\$232-\$265	\$232-\$265	\$232-\$265	\$232-\$265
Magnesia, natural, technical, heavy, 90%, f.o.b. Nevada	do.	265	265	265	265	265	265
Magnesia, dead-burned	do.	330	330	350	350	350	350
Magnesia, synthetic, technical	do.	366	366	385	385	385	385
Magnesium chloride, hydrous, 99%, flake	do.	290	290	290	290	290	290
Magnesium carbonate, light, technical (freight equalized)	per pound	0.73-.78	0.73-0.78	0.73-0.78	0.73-0.78	0.73-0.78	0.73-0.78
Magnesium hydroxide, powder, technical	do.	NA	NA	NA	NA	0.45	0.45
Magnesium sulfate, technical (epsom salts)	do.	0.16	0.16	0.175-0.185	0.18	0.18-0.195	0.18-0.195

NA Not available.

Source: Chemical Market Reporter.

MAGNESIUM METAL

Traditionally, magnesium metal and alloy prices had been set by the producer, and quantity discounts were given to large customers. Beginning in the 1990's, however, magnesium prices became more market driven.

In early 1990, North American production increased with the opening of a new 40,000_t/yr plant in Canada. Much of the Canadian production was imported into the United States, alleviating a supply shortage. As a result, producers' quoted prices dropped in 1990, and by the end of 1991, primary magnesium reportedly was selling at about \$1.10 to \$1.20 per pound. These low prices prompted one of the U.S. producers to request countervailing and antidumping duty investigations into imports of magnesium from Canada in September 1991; as a result of this action, magnesium imports from Canada essentially ceased.

With the dissolution of the former Soviet Union at the end of 1991, however, new suppliers entered the world market. Because of stockpiles that had been built up over many years, Russia and Ukraine had significant quantities of magnesium available to exchange for hard currency in the world market. In spite of the cessation of magnesium imports from Canada, magnesium imports were strong because of the increased supply of metal, particularly from Russia. As a result, U.S. prices dropped significantly in 1992, and a two-tier price system was established—a U.S. import price, and a U.S. transaction price, which reflected the prices charged by the U.S. producers.

By mid-1992, the ITC had established both antidumping and countervailing duties on magnesium imported from Canada, so this material essentially was eliminated from the U.S. market (U.S. Department of Commerce, 1992). Imports of magnesium from Canada were approximately replaced by imports from Russia, so there was no significant change in U.S. magnesium supplies, and as a result, the U.S. price moderated during 1992-93.

Low unit values for magnesium imported from Russia and Ukraine prompted one of the U.S. producers to request an antidumping duty investigation of magnesium imports from these two countries as well as from China in mid-1994. This resulted in a cessation of magnesium imports from these countries as well. As domestic demand continued to increase, mostly for magnesium components for automotive applications, the elimination of imported magnesium from Canada, China, Russia, and Ukraine led to tight U.S. supplies. As a result, the price began to increase.

Supplies remained tight through most of 1995, and by mid-year, the price escalated to its highest level since magnesium was first produced in 1915.

The ITC established final antidumping determinations in April 1995 for magnesium imports from China, Russia, and Ukraine (U.S. Department of Commerce, 1995a, b, c). 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), it was again possible to import magnesium from Russia, which had been the United States' largest magnesium supplier.

By 1996, the price began to drop as Russian magnesium returned to the U.S. market. At the same time, the countervailing duties on magnesium imports from Canada dropped enough so that Canada began exporting significant quantities of magnesium alloy into the United States. With these sources of imported material, the United States experienced an oversupply of magnesium, and prices dropped dramatically by yearend 1996. Also in 1996, the United States imported more magnesium than it exported for the first time in more than 20 years.

The United States continued to rely on imports of magnesium to meet its increasing demand, so U.S. prices continued to weaken slightly through 1998, although they were returning to more normal levels from the 1995 price spike. World supply also increased as a new 27,500-t/yr primary magnesium plant was commissioned at the end of 1996 in Israel. Although there was a small increase in the free market prices in 1999, magnesium prices generally have remained at low levels, reflecting an oversupply, or perceived oversupply, of material through 2000. Primary magnesium prices from 1992-2000 are shown in figure 1.

With the new production capacity that is projected to come on the market by 2004, either through plant expansion or greenfield projects, Metal Bulletin Research projects that magnesium prices will fall substantially below \$2,000 per metric ton, which could cause the closure of high-cost production capacity (Burstow, 2000).

Magnesium alloys, unlike other metals, have been traditionally priced lower than the primary metal price. The published prices are generally about 10 cents per pound less than those for primary metal and respond to the same market influences as primary metal prices, although the fluctuations have been less dramatic.

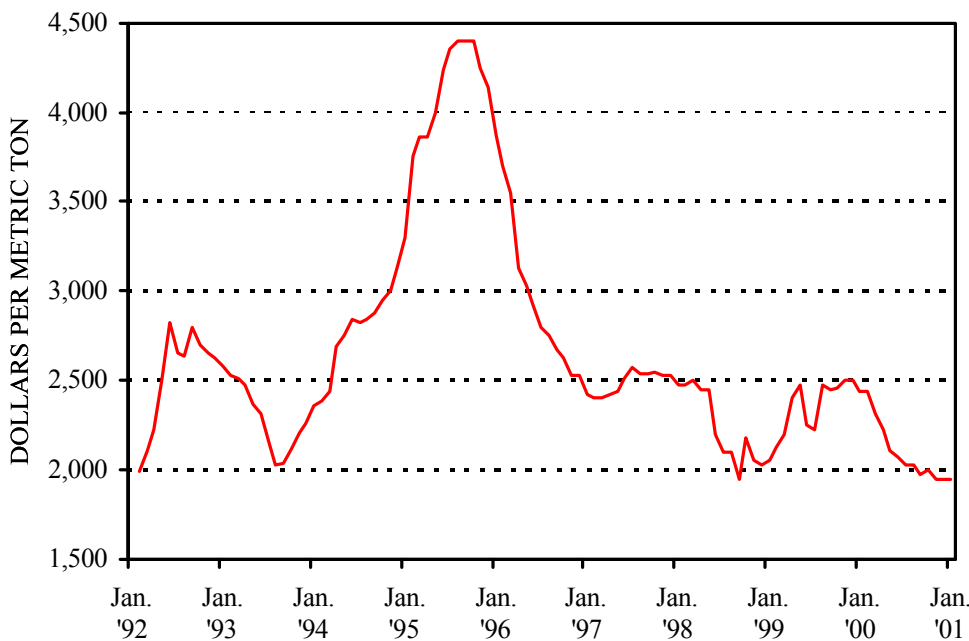


Figure 1. Average free market magnesium prices. [Source: Metal Bulletin.]

USES AND MARKET DEMAND

MAGNESIUM OXIDE

Refractory magnesia represents the largest tonnage use of magnesium in compounds. The iron and steel industry is the largest consumer of these products in the United States and most other magnesia-consuming countries. Dead-burned magnesia from magnesite, seawater, or well and lake brines is used as a major constituent in metallurgical furnace refractory products.

Caustic-calcined magnesia has uses in many market segments. In water treatment, magnesia is used to remove silica and heavy metals from industrial wastewater. It also is used as a neutralizing agent for some wastewater streams. Caustic-calcined magnesia is used for removal of SO₂ from industrial flue gases; the magnesium oxide reacts with the SO₂ to form magnesium sulfate. Magnesia competes with calcium compounds in this application. In 2000, environmental applications accounted for 41 percent of U.S. shipments of caustic-calcined magnesia.

Magnesia is also used in agricultural applications for animal feed and fertilizer. Magnesium serves as a structural part of the chlorophyll molecule, a compound necessary for plant photosynthesis. Without sufficient magnesium, either from the soil or from fertilizer application, plants can die. Corn, potatoes, cotton, citrus, tobacco, and sugar beets are among the crops that are highly responsive to magnesium fertilization (MicroJournal, undated).

Pasture fertilization with magnesium-containing fertilizers also is important in animal nutrition. Grazing ruminants, such as cattle and sheep, require magnesium in their diet to guard against hypomagnesia, also known as grass tetany, a potentially fatal disease. This disease most often occurs in cool weather when the animals are grazing on grass that has had a quick growth spurt. Two of the most popular methods of introducing magnesium in cattle diets are to incorporate the magnesium with molasses in a liquid lick, or adding caustic-calcined magnesia to purchased feed. In 2000, agricultural applications (fertilizers and animal feed) accounted for 18 percent of U.S. shipments of caustic-calcined magnesia.

An important use of caustic-calcined magnesia is in the production of magnesium oxychloride and oxysulfate cements, which are used primarily as flooring in industrial and institutional buildings. Magnesia also is used as a stabilizer or vulcanizing agent in rubber. Fused and boron-free magnesia or periclase are used for insulation of heating elements in electric furnaces and appliances.

In the manufacturing industry, caustic-calcined magnesia is used in the production of rayon, fuel additives, and rubber. Caustic-calcined magnesia is used to produce magnesium acetate, which is used for neutralization purposes in producing rayon fiber. Caustic-calcined magnesia is a starting material for the production of magnesium overbased sulfonates, which are used as acid acceptors and sludge dispersants in crankcase lubricating oils and as a fuel additive. Magnesium oxide also may be injected into oil-fired utility boilers where it reacts with vanadium salts to form a magnesium vanadate; this alleviates slagging and corrosion problems caused when using high-vanadium fuels. In water-base oil well drilling muds, magnesia is used as a buffer, for viscosity control, and as a corrosion inhibitor. In the rubber industry caustic-calcined magnesia is used as a vulcanizing agent in the curing of rubbers and elastomers.

Most of the end-use markets for caustic-calcined magnesia are mature, and there is little room for significant growth. The exception to this is the environmental market, where applications in water treatment are growing. Caustic-calcined magnesia competes with magnesium hydroxide in this market. Caustic-calcined magnesia has some advantages compared with magnesium hydroxide in this use. Magnesium oxide has more neutralizing capacity per unit volume, transportation costs are generally lower, and existing systems may be more easily converted from lime to magnesia.

MAGNESIUM CARBONATE

In pharmaceuticals, USP-grade magnesium carbonate is used as an inert vehicle and an adsorbent. Heavy magnesium carbonate is used in concentrations up to 45 percent in tablets as an inert material to aid in drug delivery. Light magnesium carbonate can be used in concentrations of 0.5 percent to 1.0 percent as a liquid absorbent, particularly for flavorings in tablets. One of its most visible uses is as an antacid. Magnesium carbonate is also used in cosmetic manufacturing. Because of its fine texture and high absorbency, light magnesium carbonate is an excellent carrier and retainer of perfumes. It also can be added to loose powders to provide fluffiness; in most cases it is blended with talc in quantities from 1 percent to 5 percent. The USP grade of magnesium carbonate is used as an additive to table salt to keep it free flowing. About 25 percent of magnesium carbonate is used annually in the United States for pharmaceuticals and cosmetics (Russell, 1998).

In the rubber industry, which accounts for about 30 percent of the total annual magnesium carbonate consumption, the material is used as a reinforcing agent. It also is used as a smoke suppressant in rubber and some plastics compounds to replace some of the alumina trihydrate that is traditionally used. The replacement of about 12.5 percent of the alumina trihydrate with magnesium carbonate increases the quantity of char that is formed in a fire. It also decreases the rate of flame spreading and the quantity of smoke generated. The remaining 45 percent of magnesium carbonate consumption is as an extender for titanium dioxide in paint, in lithographing inks, and as a precursor for other magnesium-based chemicals.

Because the uses for magnesium carbonate are essentially in mature markets, with the exception of flame retardants, significant growth in U.S. consumption is not expected. In flame retardants, magnesium carbonate competes with magnesium hydroxide; most of the growth in flame retardants is expected in magnesium hydroxide.

MAGNESIUM CHLORIDE

The largest use for magnesium chloride brine is as a suppressant for dust on dirt roads, construction sites, unpaved parking lots, mines, and quarries. A corrosion inhibitor may be added to the brine to reduce corrosion on structures, such as steel surfaces, that are associated with the sites where the brine is used. The inhibitor forms a protective coating so that the brine will not corrode metal surfaces. Magnesium chloride brine also may be used to melt ice on road surfaces, sometimes in conjunction with an abrasive such as sand. Brines may be used to make oxychloride flooring cements, known as Sorel cements. These are vermin-resistant flooring cements that are used in industrial buildings. Brines also have applications in oil-well completion fluids, as a component of some herbicides, and in regeneration of ion-exchange resins.

Magnesium chloride hexahydrate is almost exclusively used for melting ice. It is used in conjunction with, or in place of, salt for removal of ice and snow from sidewalks and roadways. Magnesium chloride has a lower freezing point than salt and is generally less corrosive to asphalt and cement, but it is significantly more expensive. In most cases, salt is used as the major melting agent for ice and snow, but if the surface that is being treated is expensive to maintain, the additional cost for magnesium chloride can be justified.

Weather plays an important role in the outlook for magnesium chloride. In the production process, weather in the Great Salt Lake area affects the salinity of the brines. Excessive snow or rainfall can dilute the lake. By decreasing the salinity of the lake by dilution, more water must be evaporated to produce the same quantity of salts. As a result, the length of the production cycle is increased. Snow and rainfall amounts also affect the demand for magnesium chloride. Obviously, the demand for magnesium chloride increases in winters with heavy snowfall and decreases in years with little snowfall. But, since municipalities often buy snow removal products before winter starts based on snow predictions, if there is a light snowfall in one year, the products bought for that year can be used for the next winter, reducing the municipalities' buying requirements. Rainfall amounts in the West affect the need for magnesium chloride as a dust suppressant. Lots of rain leads to decreased consumption, and dry weather results in increased consumption. Because of the unpredictability of the weather, it is difficult to predict the demand for magnesium chloride. With increasing environmental concerns, however, magnesium chloride hexahydrate demand is likely to increase for removal of ice and snow. Its lower level of corrosiveness is becoming more attractive to municipalities and homeowners despite its higher cost.

MAGNESIUM HYDROXIDE

After discounting the portion of magnesium hydroxide that is used to produce dead-burned magnesia, the largest use for magnesium hydroxide in the United States is for environmental applications. This portion of the market, which includes industrial water treatment, heavy metals removal, and flue-gas desulfurization, accounts for about 60 percent of the total U.S. consumption. For water treatment, magnesium hydroxide is supplied as a suspension containing about 58 percent solids, and it primarily is used to lower the pH of acidic solutions. In this market it competes with other acid neutralizing compounds, the most common being lime and caustic soda. Magnesium hydroxide has advantages and disadvantages when compared to the other materials in this use. One of the advantages is that it is a pH buffer, and wastewater treated with it will not exceed a pH of 9.5 even if excess magnesium hydroxide is added. In contrast, excess addition of lime can raise the pH to 12, and excess caustic soda addition can raise the pH to 14. In these cases, back additions of acid are necessary to lower the pH. Magnesium hydroxide also has a higher basicity per unit added than either lime or caustic soda; for equivalent neutralization, 0.72 t of magnesium hydroxide can replace 1 t of lime. Magnesium hydroxide is better than lime or caustic soda at removing some metals such as lead and trivalent chromium. Metal hydroxides that are precipitated with magnesium hydroxide rather than caustic soda or lime tend to form larger crystals, resulting in lower sludge volumes and hence, lower disposal costs. The solids formed through precipitation by magnesium hydroxide have a cakelike consistency, rather than that of a gel as do the solids formed by caustic soda precipitation; the cake is easier to handle (Wajer, 1994, p. 1-7).

One principal disadvantage of magnesium hydroxide is its cost compared to that of other materials. Another disadvantage is its slower reaction rate, particularly when precipitating high concentrations of metals (greater than 2,000 parts per million) or neutralizing weak organic acids. Most treatment systems in use today were originally designed to use lime or caustic soda, and as a result of magnesium hydroxide's slower reaction time, there may not be enough residence time in the system. In some cases, users must reconfigure their systems when switching to magnesium hydroxide.

Magnesium hydroxide slurry also competes with magnesium oxide where there are large neutralization requirements. Magnesium oxide has about 2.5 times as much neutralizing capability as magnesium hydroxide per unit volume, and transportation costs for the oxide are generally lower than those for the hydroxide slurry. In addition, existing lime neutralization systems may be more easily converted to use of the magnesium oxide powder rather than the hydroxide slurry.

In flue-gas desulfurization, magnesium hydroxide is used in place of lime in a few applications. Most of the processes designed for industrial gas scrubbing use lime or calcium in some form. Scrubbing with lime produces gypsum products, which need to be landfilled in most cases. The volume of these waste products may be greater than the original waste volume, so lime may not be appropriate for all scrubbing applications. In these instances, magnesium hydroxide may be used. Landfilling, however, may not be as much of a problem in the future for lime scrubber wastes because significant research and development is underway to find applications for the byproduct gypsum.

The second largest use for magnesium hydroxide is as a precursor for other magnesium chemicals, which accounts for about 20 percent of annual U.S. consumption. About 5 percent of magnesium hydroxide is used in pharmaceuticals. The pharmaceutical grades

of magnesium hydroxide include a 100 percent Mg(OH)₂ powder used in antacid tablets and a 30 percent Mg(OH)₂ paste used in liquid antacids such as milk of magnesia.

Flame retardants represent about 3 percent of the total magnesium hydroxide consumption in the United States. Like magnesium carbonate, magnesium hydroxide can replace alumina trihydrate in some flame retardants. Both alumina trihydrate and magnesium hydroxide function as flame retardants by releasing water vapor in an endothermic reaction that diverts the heat away from the flame, thereby reducing the formation of combustible gases. Alumina or magnesia remaining after the water is released is believed to have a high surface area available for absorbing smoke. Although the properties of alumina trihydrate and magnesium hydroxide are similar, magnesium hydroxide has a higher temperature stability. Magnesium hydroxide begins to decompose at about 330E C compared to about 200E C for alumina trihydrate. This higher temperature stability makes magnesium hydroxide more attractive for specific flame retardant applications. Some thermoplastics, such as polypropylene or nylon-vinyl, require temperatures in processing that are high enough to begin decomposing alumina trihydrate. In addition, the high processing speed of lines that produce plastic insulation for wire and cable generates enough friction to begin decomposing alumina trihydrate. In these cases, magnesium hydroxide is the flame retardant of choice (Hastabacka and Beekman, 1987).

Projected high growth rates for magnesium hydroxide in acid neutralization and flame retardant uses have prompted U.S. producers to increase capacity in the 1990's. In addition to the plants in Pennsylvania and Tennessee that were completed in 1994 and 1996, Martin Marietta increased magnesium hydroxide production capacity at its Michigan brine plant to 50,000-70,000 t/yr in early 1994. By September 1997, the company had started up a 35,000-t/yr magnesium hydroxide powder facility in Michigan. In 1993, Dow increased capacity at its Michigan facility to 125,000 t/yr, an addition of 30,000 t/yr. In all cases, the capacity expansions were attributed to increased demand for magnesium hydroxide for acid neutralization and flame retardants.

In addition, Rohm and Haas was increasing capacity at its Manistee, MI, facility. The first phase, which included the introduction of new production technologies, was completed in May 2000. The second phase will add to the facility's washing capacity and is expected to be completed by mid-2002. Rohm and Haas's principal markets for its magnesium hydroxide are over-the-counter pharmaceuticals and flame retardants.

Projected average annual growth rates for magnesium hydroxide in acid neutralization markets in the 1990's have ranged from 10 percent to 17 percent; however, this growth has not materialized as rapidly as producers would have liked. Based on data reported to the U.S. Geological Survey, even though there has been an increase in the quantity of magnesium hydroxide used for water treatment, it has not approached the projected high annual growth rates. The principal disincentive for switching from a traditional neutralizing agent to magnesium hydroxide is its price, which is significantly higher than caustic soda, lime or other alkalis. But once some users switch, the additional benefits outweigh the difference in pricing. In order to achieve significant growth in this market, producers need to make potential consumers aware of the benefits of using magnesium hydroxide. In addition, reducing transportation costs would help alleviate the pricing differential. One way to reduce transportation costs would be to increase the solids content of the slurry. Martin Marietta has made a step in this direction with its new powder facility; by shipping the material as a powder, the cost for transporting water is eliminated. Educating the consumer and additional research and development on magnesium hydroxide for the acid neutralization market will significantly improve the market potential for magnesium hydroxide. SRI International projects that demand for magnesium hydroxide for water treatment applications is expected to grow by 3 percent to 5 percent annually through 2005 (Van Savage, 2001).

Business Communications Co. estimates that the U.S. flame retardant market for magnesium hydroxide will grow at an average annual rate of 5 percent per year through 2003. Magnesium hydroxide accounts for an estimated 1 percent of total flame retardants and is forecast to grow at the same overall rate as the total flame retardant market (Chemical Market Reporter, 1998). For the past several years, analysts have cited potential U.S. regulation of halogenated flame retardants as affecting magnesium hydroxide replacement and increasing the projected growth rate. However, no specific legislation has been enacted, so this potential for growth continues to remain in the future.

MAGNESIUM SULFATE

Natural and synthetic magnesium sulfate have a wide array of end uses. The largest use for magnesium sulfate in all forms is for consumer goods. About 30 percent of magnesium sulfate is used in food additives and pharmaceuticals. Magnesium sulfate heptahydrate—epsom salts—is used for mineral baths and in medicine as a cathartic and analgesic soaking agent for bruises, sprains, localized inflammations, and insect bites. Magnesium sulfate is used as a micronutrient in some food products, and it is used in the production of high-fructose corn syrup (HFCS). In the early 1980's, replacement of most or all of the sugar by HFCS in soft drinks was expected to dramatically increase the market for HFCS, and as a consequence, boost magnesium sulfate consumption by as much as 5 percent per year. Although some sugar has been replaced, the high estimates of growth for magnesium sulfate in this application did not materialize.

Industrial uses account for about 25 percent of U.S. magnesium sulfate demand. The primary component of industrial applications is the use of magnesium sulfate as a precursor to other chemicals. It also is used in drying and flocculation applications and in catalyst preparation.

Animal feeds and fertilizers represent about 22 percent of the U.S. market for magnesium sulfate. Most end uses for magnesium sulfate use synthetically produced material because of its higher purity. Purity requirements for animal feeds and fertilizers are not as

stringent, so they use mainly the natural minerals, which are imported into the United States. The most effective way of preventing grass tetany is to provide magnesium to the pasture through fertilization. Magnesium also may be supplied in the form of epsom salts or kieserite that is added to the feed or drinking water.

In addition to pasture grasses, most crops require magnesium because magnesium is an essential constituent of the chlorophyll molecule. The average uptake of magnesium for field crops ranges from 10 to 30 pounds per acre annually, with root crops requiring about double that of grain crops. Most nitrogen-phosphorus-potassium fertilizers have very little magnesium in them, so magnesium is supplied through foliar application of epsom salts, kieserite, sulfate of potash magnesia, or magnesium oxide. Magnesium fertilizer applications range from 20 to 50 pounds per acre.

Pulp and paper processing accounts for about 14 percent of magnesium sulfate use in the United States. Magnesium sulfate is used by kraft pulp mills that use oxygen delignification on soft woods, but it is also used in conjunction with sodium silicate to increase the life of hydrogen peroxide in oxygen-based bleaching processes. Miscellaneous uses, which represent about 9 percent of magnesium sulfate demand, include textiles, matches, photographic solutions, rubber coagulation, refractory bonding agent in bricks, and oxysulfate cements (Chemical Products Synopsis, 1993).

Magnesium sulfate manufacturers cite the principal growth area for magnesium sulfate as pulp and paper processing. Increasing strictness of regulations on the release of chlorine-containing effluents has caused many paper mills to switch from chlorine-based processing to oxygen delignification. According to SRI Consulting, Menlo Park, CA, the pulp and paper industry's consumption of magnesium sulfate should grow at an average annual rate of 3 percent through 2001 because of this change in the manufacturing process. Other analysts feel that most of the mills that were going to convert to oxygen have already done so, and this market for magnesium sulfate has leveled off (Johnson, 1998).

MAGNESIUM METAL

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, UNS A95181 and A95182, respectively) and about 1.1 percent in the can body (alloy 3004, UNS A93004). Since the early 1980's, magnesium consumption in this market has grown at an average compound annual rate of 3.2 percent. Except for the significant increases in aluminum recycling, this rate might have been greater. More than 60 percent of aluminum beverage cans are recycled annually conserving 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 magnesium components such as clutch housings, headlamp assemblies, and grill covers to reduce vehicular weight. The power tool market includes magnesium castings in chain saws and lawnmower housings. Die-cast magnesium also is used in video camera, cellular phone, and computer 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 with permanent mold and plaster casting representing a small segment of the alloy market. Typical applications include helicopter gear housings, aircraft canopy frames, air intakes, engine frames, speed brakes, and auxiliary component housings.

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

In the iron and steel industry, magnesium is used as an external hot-metal desulfurization agent, and it is used 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 to 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 having improved toughness and ductility. Two principal applications for ductile iron are in the production of pipe and of automotive engine and drive train components.

Magnesium is used as a catalyst for producing certain organic chemicals and petrochemicals. Magnesium is used as a reducing agent for producing other nonferrous metals such as titanium, zirconium, hafnium, beryllium, and uranium. 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 graphic arts, pyrotechnics, and in alloys other than aluminum. Data on world shipments of primary magnesium, by application are shown in table 14.

Table 14. Primary magnesium shipments, by end use
[Metric tons]

Use	1990					1995					2000				
	Area 1— U.S. and Canada	Area 2— Latin America	Area 3— Western Europe	Area 4— Africa and Middle East	Area 5— Asia and Oceania	Area 1— U.S. and Canada	Area 2— Latin America	Area 3— Western Europe	Area 4— Africa and Middle East	Area 5— Asia and Oceania	Area 1— U.S. and Canada	Area 2— Latin America	Area 3— Western Europe	Area 4— Africa and Middle East	Area 5— Asia and Oceania
Aluminum alloying	60,000	1,000	37,800	3,800	28,000	77,600	3,200	36,400	4,100	35,800	73,800	3,900	52,200	5,100	30,100
Nodular iron	5,600	800	4,900	100	3,000	6,500	900	4,000	—	3,100	5,000	600	2,300	—	900
Desulfurization	19,900	400	7,600	—	100	22,200	—	12,900	600	600	26,700	600	21,800	—	2,500
Metal reduction	6,600	—	1,000	—	1,200	2,600	—	1,000	—	300	1,700	—	1,900	—	—
Electrochemical	7,400	700	600	100	800	6,800	700	1,700	—	1,400	3,000	500	2,200	—	1,800
Chemical	1,800	—	3,300	—	2,000	1,200	—	2,900	—	2,400	1,700	—	2,900	—	1,400
Diecasting	15,800	8,700	10,100	—	1,700	42,700	7,600	11,900	—	1,900	57,600	4,100	36,000	400	12,600
Gravity casting	800	—	2,400	—	100	800	—	1,000	—	—	1,000	—	1,200	—	—
Wrought products	6,000	—	500	—	200	2,800	—	1,100	—	300	3,400	—	—	—	—
Other ¹	3,400	—	500	—	3,300	2,200	500	1,100	200	1,000	2,800	1,600	2,400	—	1,200
Total	127,300	11,600	68,700	4,000	40,400	165,400	12,900	74,000	4,900	46,800	176,700	11,300	122,900	5,500	50,500

¹Includes shipments to secondary producers and shipments to China and the former Soviet Union
Source: International Magnesium Association.

The two end uses with the largest growth in the past 15 years have been diecasting and desulfurization. Growth in diecasting has been largely a result of increased use of magnesium components in automobiles. Table 15 shows the growth in magnesium diecastings content of the average North-American-produced family vehicle.

Table 15. Use of magnesium diecastings in North American-produced vehicles
[Source: American Metal Market.]

Model year	Total weight (pounds)	Percentage of total vehicle weight
1977	1	0.03
1978	1	0.03
1979	1	0.03
1980	3	0.10
1985	2.5	0.08
1987	2.5	0.08
1988	4	0.13
1990	3	0.10
1991	3	0.10
1992	3.5	0.11
1993	4.5	0.14
1994	5	0.16
1995	5	0.16
1996	5.5	0.17
1997	6	0.18
1998	6.5	0.20
1999	7	0.21
2000	8.0	0.24
2001	8.5	0.26

In the 1990's the use of magnesium in automobiles has increased dramatically; between 1990 and 2000 the total magnesium diecastings content more than doubled. Some of the components in which magnesium alloy has replaced steel or aluminum are brake and clutch pedal brackets, instrument panels, cylindrical head covers, transfer case housings, intake manifolds, and seat components.

Most of the original reason to use magnesium was because of its light weight. Auto manufacturers wanted to reduce overall vehicle fleet weight to meet Corporate Average Fuel Economy Standards mandated by the U.S. Government, and many of these components were considered after the original car model was well into the design process. This proved to be a costly way to incorporate magnesium. Once the companies started to use magnesium alloys, magnesium was shown to have advantages other than its light weight. In many cases, parts that were made of several steel pieces that had to be separately stamped then welded together, could be made as a one- or two-piece magnesium casting, reducing the cost of the finished part. As a result, magnesium components are now being designed into cars rather than being retrofitted after the design is completed. Including the material in the design process allows more opportunities to incorporate magnesium parts in a new or redesigned model.

These changes in the automotive industry have led to a significant increase in the demand for magnesium die castings. In addition, several research projects have been undertaken to increase the magnesium content of automobiles further. As one example, a consortium of the "Big Three" automakers—the Chrysler Group of DaimlerChrysler AG, Ford Motor Co., and General Motors Corp., their suppliers, and the U.S. Department of Energy planned to begin a 4-year project to develop magnesium-intensive auto engines. The project, conducted by the U.S. Automotive Materials Partnership, will use newly developed creep-resistant magnesium alloys to produce components such as cylinder blocks, engine covers, oil pans, and transmission cases and determine the alloys' suitability for these type of applications. The new project will complement a project started in 2000 that is investigating the potential for magnesium components in the structural undercarriage of automobiles (Wrigley, 2001).

The use of magnesium for desulfurization has grown significantly in North America and Europe in the past 15 years. However, it has increased to the point where it has almost 100 percent of the market in these geographic areas, therefore the growth rate is expected to slow. Because magnesium desulfurization reagents can be manufactured from either primary or recycled magnesium, there may be a switch from primary magnesium to lower cost alloy scrap and low-grade materials.

MANUFACTURING, PRODUCTION, AND SHIPMENT

MINING

Open pit methods are used to mine magnesite and olivine in Washington, North Carolina, and Nevada. Deposits of magnesite and associated brucite at Gabbs, NV, have been worked by selective open pit mining. The pit design was based on surface mapping and information from diamond drill cores. Determination of ore grades is based on assays for lime and silica from drill cuttings entered separately as isograms plotted on maps of the deposit. Superimposing one map on the other allows selection of any particular ore grade.

Typically, benches in the open pit mines are 3 meters high. From 400 to 1,000 blastholes at a time are shot with an ammonium nitrate-fuel oil mixture. Each such hole breaks approximately 60 t of rock. Secondary blasting is seldom necessary (Duncan and McCracken, 1994).

MAGNESIUM OXIDE

In the production of refractory magnesia and caustic-calcined magnesia, magnesite is delivered from the mine to a crushing plant where it is crushed in three stages. Depending on the grade of the ore, the crushed material is conveyed to one of three storage piles. Each storage pile feeds a separate production circuit—the flotation plant, the heavy-medium separation plant, and the rotary kiln plant. Concentrates from the flotation and heavy-medium separation circuits also feed the rotary kiln plant.

The kiln plant feed goes into two separate circuits for calcination. One, for the production of dead-burned magnesite, uses either rotary kilns or shaft furnaces, the other, for caustic-calcined magnesite, uses hearth furnaces or rotary kilns. Some of the raw feed is mixed with flue dust and briquetted prior to being dead burned in the rotary kiln. Two classes of refractory magnesia are made: brick grade and maintenance grade.

Dolomite and brucite are processed in similar manners. After primary crushing, appreciable quantities of raw, crushed dolomite are delivered to iron and steel plants, where they are calcined and used as dead-burned dolomite. Brucite is beneficiated in a heavy-medium plant for use as a refractory material.

When seawater or well brine is used as the feed for producing caustic-calcined or dead-burned magnesia, carbonate and sulfate levels are reduced so insoluble calcium compounds do not precipitate with the magnesium hydroxide. To accomplish this, either they are first combined with slaked lime to precipitate the bicarbonates as calcium carbonate, or they are combined with acid to liberate carbon dioxide. The treated solution is then mixed with either dry or slaked lime to precipitate magnesium hydroxide. The resulting magnesium hydroxide slurry is concentrated in thickeners and washed with fresh water in a countercurrent system, then filtered. The filter cake is either directly calcined to produce refractory or caustic-calcined magnesia, or it is calcined and pelletized prior to dead burning to give proper size and density characteristics. All refractory magnesia obtained from seawater, seawater bitterns, or well brines is of brick grade.

MAGNESIUM CARBONATE

Although magnesium carbonate (MgCO_3) occurs naturally as magnesite, magnesium carbonate used in the United States is synthetically manufactured. The chemical essentially is used in two forms—light and heavy, the difference being the number of water molecules that are included in the compound. Light magnesium carbonate has the empirical formula $(\text{MgCO}_3)_3 \cdot \text{Mg}(\text{OH})_2 \cdot \text{H}_2\text{O}$, and heavy magnesium carbonate has the formula $(\text{MgCO}_3)_3 \cdot \text{Mg}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$. In the United States, magnesium carbonate is recovered from a brine solution by the addition of a soluble carbonate, such as sodium carbonate, to precipitate the magnesium carbonate. Magnesium carbonate also can be manufactured by saturation of dolomite with aqueous carbon dioxide under pressure. Increasing the temperature precipitates calcium carbonate. After filtration, the solution is heated to near boiling, so that H_2O and any remaining CO_2 are vaporized, and magnesium carbonate precipitates, usually as light magnesium carbonate.

MAGNESIUM CHLORIDE

To recover magnesium chloride from brines, the water from the Great Salt Lake is pumped to a series of solar evaporation ponds where water evaporates to concentrate the brine. The first salt to precipitate as the water evaporates is sodium chloride. The next group of salts to precipitate is a mix of double salts containing potassium and magnesium. Depending on brine concentration, temperature, and other factors, kainite, schoenite, and carnallite may be precipitated. Sodium sulfate is then precipitated from the cooled brine in the winter (even though it is no longer harvested for sale). The final product remaining dissolved in the brine is magnesium chloride. In general, an equilibrium is reached at about 35 percent MgCl_2 concentration by weight in the brine. Although most of the sodium and potassium have been removed from the brine at this stage, it still contains some dissolved sulfate. The purity of this brine is sufficient for some applications, or it may be further purified if necessary. Purified brine then may be further processed to produce the hexahydrate solid. The overall production cycle takes about 2 years to complete (Industrial Minerals, 1984). A typical analysis of brine is shown in table 16.

Table 16. Magnesium chloride brine characteristics

[Source: Reilly Industries Inc.]

Chemical composition (weight percent):	
MgCl ₂	28.0 - 35.0
Cl	19.8 - 27.0
Mg	6.8 - 9.2
SO ₄	1.2 - 3.5
Na	0.2 - 1.0
K	0.1 - 0.8
Li	0.1 - 0.2
Br	0.1 - 0.2
Fe	5 - 10 ppm
Specific gravity	1.27-1.36 g/l
Bulk density	11 lbs/gallon

MAGNESIUM HYDROXIDE

Magnesium hydroxide is recovered from seawater or brines by precipitating the dissolved magnesium as magnesium hydroxide with the addition of dolime (CaO@MgO). Because the composition of seawater is slightly different from that of Michigan brine, removal of impurities or salable byproducts is slightly different. Representative brine and seawater compositions are shown in table 17.

Table 17. Typical composition of Michigan brine and seawater

[Grams per liter. Source: U.S. Bureau of Mines.]

	Michigan	
	brine	Seawater
MgCl ₂	8.2	4.176
MgSO ₄	—	1.668
MgBr ₂	—	0.076
CaCl ₂	13.64	—
CaSO ₄	—	1.268
NaCl	5.45	27.319
KCl	0.48	—
K ₂ SO ₄	—	0.869
Br ₂	0.2134	—
Specific gravity	1.264	1.024

Dow processes brine that is pumped from 2,800 feet below the Earth's surface from more than 20 production wells. Bromine is removed from the brine by being heated then chlorinated by chlorine gas, which replaces the dissolved bromine by chlorine, producing Br₂. The debrominated solution is mixed with preheated, slaked dolime to precipitate the magnesium hydroxide in settling tanks. The remaining calcium chloride solution is concentrated and then sold as a 32 percent to 45 percent liquor for a variety of applications.

Before the Moss Landing, CA, plant was closed in 1999, National Refractories & Minerals Co. screened seawater to remove any debris before being treated with dolime to remove any dissolved carbonate as calcium carbonate. After calcium carbonate was precipitated, the solution was treated further with sulfuric acid to remove any remaining calcium bicarbonate as calcium sulfate. The solution was then seeded with magnesium hydroxide and pumped to thickeners where the magnesium hydroxide slurry was concentrated. The slurry was filtered to produce a filter cake containing about 50 percent solids. This material was then sold or calcined at the plant to produce either dead-burned or caustic-calcined magnesia.

MAGNESIUM SULFATE

Magnesium sulfate produced in the United States is manufactured synthetically, normally by reacting magnesium oxide, hydroxide, or carbonate with sulfuric acid followed by crystallization. Anhydrous magnesium sulfate can be manufactured only by dehydration of a hydrate; crystallization from an aqueous solution is not possible.

MAGNESIUM METAL

Magnesium is manufactured by two methods—electrolytic reduction of magnesium chloride or thermic reduction of dolomite. Two thermal processes currently are in use to recover magnesium metal from dolomite—the Pidgeon process and the Magnetherm process. Both use the same basic chemistry, but 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 and condensed in a separate section of the retort. The Timminco plant in Canada uses this process to recover magnesium.

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. The Magnetherm process is used in plants in Brazil, France, Serbia and Montenegro, and the United States.

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, used by Dow Chemical Co. 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 and Norsk Hydro of Norway use an anhydrous magnesium chloride feed for their electrolytic cells. Magcorp uses solar evaporation initially to concentrate 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). Norsk Hydro starts with concentrated magnesium chloride brine. The brine is purified, concentrated, prilled, and dehydrated to produce anhydrous magnesium chloride.

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 differing in electrode positioning and utilization 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.

In 2000, Magcorp began installing new electrolytic cell technology at its Utah plant. Called the M cell, the new electrolytic cells are monopolar, diaphragmless, large-scale cells. The new cells can produce 2.8 t of magnesium per day, compared to the ones that they replace, which can produce only 1.0 to 1.4 t of magnesium per day. Magcorp also claims that the new cells have no requirement for control of cell electrolyte level, no requirement to replace graphite anodes, no desludging requirement, and greater than 99.9 percent collection of chlorine (Thayer and Neelameggham, 2001).

Magnesium production in Russia, Ukraine, and Kazakhstan uses carnallite, $MgCl_2 \cdot KCl \cdot 6H_2O$, either from natural deposits or synthetically manufactured, as its raw material. Magnesium chloride recycled from titanium sponge production also may be used as a feed material. Recrystallized carnallite has an average value of 32 percent $MgCl_2$. Carnallite is dehydrated in a two-step process. The first stage consists of a fluid bed/moving bed furnace with three distinct temperature zones. The temperature increases in each zone, going from 130 to 200EC, which results in a product containing 1 percent to 2 percent MgO and 3 percent to 6 percent H_2O . This product is then sent to a chlorinator, which operates at 700-750EC. The chlorinator is designed to remove most of the remaining impurities and settle out any solids. Considerable research effort is being done to improve the efficiency of the chlorination step. The molten $MgCl_2/KCl$ is tapped and either sent directly to the cells while still molten, or cooled to a solid and then fed to the cells. Magnesium electrolysis is conducted in diaphragmless electrolytic cells. After settling, crude magnesium is removed from the cells and refined in continuous furnaces, then cast into pigs (Roskill Information Services Ltd., 1996, p. 17-22).

Magnesium is also recovered by recycling magnesium chloride produced in the manufacture of titanium. Titanium is recovered from titanium tetrachloride by the Kroll process, where magnesium is used as a reducing agent. This reaction produces a pure anhydrous magnesium chloride that can then be used in an electrolytic cell to convert it back to magnesium metal. Electrolytic cells have been developed to take advantage of this type of feed.

In Canada, a new process to recover magnesium from asbestos tailings was commercialized in 2000 by Noranda Magnesium Inc. Typical analysis of the asbestos tailings is 40 percent MgO , 38 percent SiO_2 , 5 percent Fe compounds [Fe_2O_3 and $Fe(OH)_2$] and 13 percent H_2O . This material is slurried and fed to a magnetic separator to remove iron impurities; then the tailings are continuously

leached by a 33 percent hydrochloric acid solution. The leach overflow is partially neutralized to avoid silica gel formation, one of the major drawbacks to using silicate materials as feed for producing magnesium chloride brine. By carefully maintaining the pH of the slurry, base metal impurities are separated while avoiding magnesium precipitation. The slurry is filtered, and the impure brine produced is purified further by sparging with chlorine gas, and then fed through ion exchange columns to remove the remaining traces of the metal impurities. Purified brine is dehydrated in a fluid bed dryer. In the dryer, prills are formed that contain 1 percent to 2 percent MgO, which must be removed before being fed to electrolytic cells. This is done in a reactor where they are melted and contacted with hydrogen chloride gas. MgO-free magnesium chloride is electrolyzed in Alcan Multi-Polar Cells, and the magnesium produced is either cast into pure magnesium ingots or transferred to an alloying section where it is cast into alloy products (Brown, 1998).

Most magnesium extraction processing is followed by a refining operation to remove impurities and to manufacture clean alloy compositions. The metal is then converted to ingots, slabs, and billets. Magnesium is also converted directly into granules for subsequent use in steelmaking. Some magnesium process slags are beneficiated to recover magnesium granules without a remelting operation. Typical impurities are nonmetallic inclusions, metallic impurities, and hydrogen.

Normally magnesium is melted and alloyed in steel pots. In order to prevent oxidation of molten magnesium, it is necessary to cover the molten metal with a gas, the most common of which is a mixture of sulfur hexafluoride, carbon dioxide, and air. (Prior to the 1970's, the magnesium industry used salt-based fluxes to protect the metal; however, these created corrosive fumes in the foundry and were difficult to separate from the metal.)

Magnesium and its alloys can be cast by sand, die, and permanent mold processes. Sand casting follows conventional foundry techniques. Permanent molds are made of high-carbon gray cast iron and are more economical to use than sand casting when the number of castings reaches about 1,000 pieces. Die casting, in which the molten metal is forced into steel dies under pressure, has the advantages of speed of production and accuracy of dimensions.

Although magnesium forming is limited at room temperature, it can be readily extruded, rolled, drawn, and forged at temperatures ranging from 200 to 400E C. Magnesium alloys are extruded into many shapes by forcing round billets of the cast metal through steel dies. Magnesium alloys are prepared for rolling by casting the metal into slabs. If magnesium plate is desired, it is rolled hot to finished gauge; sheet is finished by rolling cold. Forging magnesium alloys is accomplished similarly to other metals.

Magnesium and its alloys are the easiest of structural metals to machine and they can be sawed and drilled at room temperature at greater speeds than most other metals. They can be joined by brazing, riveting, soldering, and adhesive bonding. Primary magnesium and most of its alloys are weldable under an inert atmosphere.

ECONOMIC ASPECTS

Costs to produce magnesium metal vary greatly, depending upon the feed material and the process used. Operating costs for magnesium production range from \$309 to \$2,283 per metric ton, with energy costs as the largest component of the total operating cost. A weighted average operating cost was estimated to be \$1,122 per metric ton. Total production costs from seawater sources were lower than from brines or dolomite sources. Magnesium compound operating costs also vary depending upon source material and processing techniques. Operating costs range from \$24 to \$425 per metric ton for magnesium compound production, with seawater as the most costly source. The weighted average operating cost for magnesium compounds production from all sources was \$288 per metric ton. Energy costs also represent the largest component of total operating costs (Wilburn, 1986).

Analysts at Commodities Research Unit (CRU) evaluated the direct operating costs of magnesium plants that operated during 1991. The operating cost curve showed that about one-half of the producers had direct operating costs less than \$1.00 per pound of magnesium, and about 20 percent of the production was at direct operating costs above \$1.25 per pound. In their cost estimates, CRU evaluated capital and operating costs for a 60,000-t/yr greenfield magnesium plant constructed in Australia. Capital costs were estimated at \$470 million, with a 20 percent rate of return on investment over a 10-year life of the loan. In addition, operating costs were estimated to be \$1.76 per pound in constant 1990 dollars, with most of the costs being capital charges resulting from the rate of return on investment and loan life. If the rate of return was lowered to 10 percent and the life of the loan was extended to 20 years, capital charge would drop by one-half (Foley and Gilbert, 1992). Metal Bulletin Research estimated that the majority of the Western World producers were producing magnesium at a cost of \$0.65 to \$1.15 per pound in 1999 (Burstow, 2000).

Several of the proposed plants for which feasibility studies have been completed operating costs that are lower than estimates for currently operating plants. For Australian Magnesium Corp.'s 90,000-t/yr electrolytic plant, the operating cost was estimated to be \$0.66 per pound, with a total capital cost of \$520 million. SAMAG Ltd.'s originally proposed 52,500-t/yr electrolytic plant was estimated to have an operating cost of \$0.60 per pound and a capital cost of \$375 million (Brown, R.E., 2000). In Congo (Brazzaville), Magnesium Alloy Corp.'s proposed 90,000-t/yr electrolytic plant was estimated to have an operating cost of \$0.55 per pound of magnesium (Magnesium Alloy Corp., June 1, 1999, Feasibility study confirms MAC's potential as low-operating-cost magnesium producer, accessed August 24, 2001, at URL <http://www.magnesiumalloy.ca/press/990601.htm>).

TARIFFS AND DEPLETION PROVISIONS

The tariffs on magnesia and magnesium items for countries with which the United States has normal trade relations are shown in table 18. In addition, because of trade agreements, some countries have special tariff rates; these are also shown in the table. Tariff rates have been established for countries with non-normal trade relations with the United States; these countries are Afghanistan,

Cuba, Laos, North Korea, and Vietnam. Because there is no appreciable trade between the United States and these countries, the non-NTR tariff rates are not shown.

Depletion allowances have been established for some domestic and foreign ores of magnesium and its compounds. Magnesium chloride from brines, wells, or saline perennial lakes within the United States has a depletion allowance of 5 percent. The depletion allowance for both domestic and foreign ores of dolomite and magnesium carbonate is 14 percent. Depletion allowances for other ores are as follows: brucite, 10 percent (domestic and foreign), and olivine, 22 percent (domestic) and 14 percent (foreign).

Table 18. U.S. 2001 tariff rates
[Source: U.S. Department of Commerce, International Trade Administration.]

HTS No.	Description	Normal Trade Relations	Special ¹
	Magnesium compounds:		
2519.10.00	Natural magnesium carbonate (magnesite)	Free	
2519.90.10	Fused magnesia and dead-burned (sintered) magnesia	Free	
2519.90.20	Caustic calcined magnesite	Free	
2519.90.50	Other magnesia	Free	
2530.20.10	Kieserite	Free	
2530.20.20	Epsom salts	Free	
2827.31.00	Magnesium chloride	1.5% ad valorem	Free (A*, CA, E, IL, J, MX)
2833.21.00	Magnesium sulfate	3.7% ad valorem	Free (A*, CA, E, IL, J, MX)
2816.10.00	Magnesium hydroxide and peroxide	3.1% ad valorem	Free (A*, CA, E, IL, J, MX)
2836.99.50	Magnesium carbonate	3.7% ad valorem	Free (A*, CA, E, IL, J, MX)
	Magnesium metal:		
8104.11.00	Unwrought magnesium, containing at least 99.8 percent by weight of magnesium	8% ad valorem	Free (A*, CA, E, IL, J, MX)
8104.19.00	Unwrought magnesium, other	6.5% ad valorem	Free (A+, CA, D, E, IL, J, MX)
8104.20.00	Waste and scrap	Free	
8104.30.00	Raspings, turnings and granules, and powders	4.4% ad valorem	Free (A, CA, E, IL, J, MX)
8104.90.00	Other magnesium metal	14.8¢/kg on magnesium content + 3.5% ad valorem	Free (A, B, CA, E, IL, J, MX)

¹A, A* or A+—Generalized System of Preferences; B—Automotive Products Trade Act; CA and MX—North American Free Trade Agreement; D—African Growth and Opportunity Act; E—Caribbean Basin Economic Recovery Act; IL—United States-Israel Free Trade Area; and J—Andean Trade Preference Act

GRADES, SPECIFICATIONS, AND QUALITY CONTROL

MAGNESIUM OXIDE

Standards for magnesia, including chemical composition, bulk density, particle size, and loss on ignition generally are set by the consumer for a specific application. Refractory magnesia composition depends on the area of the furnace in which the material is to be used. Magnesia produced from magnesite can contain between 88 percent and 98 percent magnesia, with varying quantities of alumina, calcium, iron, and silica impurities. Synthetic magnesia normally is purer than natural magnesia, containing between 92 percent and 99.5 percent magnesia, with smaller quantities of the same impurities found in natural magnesia. Synthetic magnesia also may contain boron impurities. Most fused magnesia contains greater than 94 percent magnesia.

MAGNESIUM METAL

Primary magnesium metal contains a minimum of 99.8 percent magnesium, which is of sufficient purity for most applications. Higher purity can be obtained by distillation. Magnesium alloys are most commonly designated by a system established by the American Society of Testing and Materials (ASTM) that covers both chemical compositions and tempers (American Society of Testing and Materials, 1998a, b). Tempers are treatments that usually improve toughness. The designations are based on the chemical composition, and consist of two letters representing the two alloying elements specified in the greatest amount, arranged in decreasing percentages, or alphabetically if of equal percentage. The letters are followed by the respective percentages rounded off to whole numbers, with a serial letter at the end. The serial letter indicates some variation in composition. The following letters designate various alloying elements: A, aluminum; C, copper; D, cadmium; E, rare earths; H, thorium; K, zirconium; L, lithium; M, manganese; Q, silver; S, silicon; T, tin; W, yttrium; and Z, zinc. For example, AZ91 contains about 9 percent aluminum (A) and 1 percent zinc (Z), and HK31 contains about 3 percent thorium (H) and 1 percent zirconium (K).

ANALYTICAL METHODS

Because the production of magnesium is a large-scale industrial process, fast and reliable methods for magnesium analysis have been developed for the quick turnaround times necessary in a production foundry. Referee methods that are more time consuming but have larger ranges and greater accuracy compared to the production methods have also been developed.

PRODUCTION METHODS

Analyses of magnesium or magnesium alloy batches are typically performed by atomic absorption (AA) spectroscopy, by emission spectroscopy employing an inductively coupled plasma (ICP) source, or direct spark emission spectroscopy. The atomic absorption method requires the dissolution of the sample in a standard solution followed by introduction into the flame of the AA unit. The absorption of light by the flame at specific wavelengths defines the concentration of the species. These methods require careful dilution of the sample and standard solutions since the response of the instruments are only linear over a small concentration range. The ICP emission instruments also require careful dilution but are linear over a wider range. Direct spark emission spectroscopy is a quick method of analysis, but is also subject to many sources of error. Sample preparation is important in this analytical method. The most severe limitation of this method is the absorption of light energy by atoms not completely excited. This is especially true in the case of aluminum where the response is linear over a small range and the response curve is not very steep.

REFEREE METHODS

ASTM has collected a series of standard referee methods for the analysis of magnesium and its alloys (American Society of Testing and Materials, 1998c). These methods are accurate over a larger range of concentration than the production methods, but are time consuming in their application. The methods are based on potentiometric titration, photometric methods, or gravimetric methods. The photometric methods are most common and are relatively straightforward.

ENVIRONMENTAL CONCERNS

MAGNESIUM COMPOUNDS

Magnesite and dolomite normally can be mined without interfering with other land use. Mine drainage from open pit or underground operations does not contribute significantly to stream pollution, since the drained areas usually contain no significant amounts of soluble materials. Dust collectors and wet scrubbers are used to control stack gas dust emissions from plants calcining and dead-burning dolomite, magnesite, and magnesium hydroxide.

In metal and magnesia plants, based on seawater, the water is returned to the ocean after the magnesia is removed. Recent innovations have decreased the turbidity of the effluent, resulting in minimal changes to the ocean environment. None of the discharges from either natural or synthetic magnesia plants has a noxious quality, and their appearance can be made acceptable with modern treatment methods.

Most magnesium compounds are treated as nuisance-causing dusts in the workplace. The American Conference of Government and Industrial Hygienists has established threshold limit values (TLV) for magnesium oxide fume and magnesium carbonate. The TLV for both substances has been established at 10 parts per million. TLV's for magnesium chloride and magnesium sulfate have not been established (International Chemical Safety Cards, undated, accessed August 21, 2001, via URL <http://www.cdc.gov/niosh/ipcs/icstart.html>). The Occupational Safety and Health Administration has set permissible exposure limits (PEL's) for magnesium carbonate and magnesium oxide fume. The PEL for magnesium oxide fume was established at 10 milligrams per cubic meter (total particulate), with a PEL of 5 milligrams per cubic meter for the respirable particulate (Magnesium oxide, undated, accessed August 21, 2001, at URL <http://www.cdc.gov/niosh/idlh/1309484.html>). The PEL for magnesium carbonate (magnesite) has been set at 15 milligrams per cubic meter for the total particulate and 5 milligrams per cubic meter for the respirable particulate (Magnesite, undated, accessed August 21, 2001, at URL http://www.cdc.gov/niosh/pel88/546_93.html).

Because of the chromium content in the material, magnesia-chrome bricks must be disposed of as a hazardous waste if an extract from a representative sample contains total chromium at a concentration greater than, or equal to, 5.0 milligrams per liter. The waste can be treated by chemical leaching or washing to dilute the concentration, but these options are costly, and if washing is used, the waste water must also be treated. Another alternative for treatment is high temperature reprocessing, but few firms have the treatment facilities necessary for this operation (Kendall, 1994).

MAGNESIUM METAL

Certain forms of magnesium metal, such as turnings, dusts, and scrap, react with water to generate hydrogen. This reaction may lead to spontaneous explosion; hence, these forms of magnesium must be stored and shipped in containers to insure a moisture-free environment.

The cover gas, sulfur hexafluoride, that is used to protect molten magnesium from oxidation has been implicated as a potential factor in global warming. Although studies on its effect continue to be done, its long atmospheric life (about 3,000 years) and high potential as a greenhouse gas (24,900 times the global warming potential of carbon dioxide) has resulted in a call for voluntary

reductions in its emissions (International Magnesium Association, 1998a). In May 2000, the IMA selected the Foundation of Scientific and Industrial Research at the Norwegian University of Science and Technology to conduct research on alternative materials for SF₆ in magnesium production and casting operations. The proposed activities of the research team include evaluating the performance characteristics of recently proposed alternatives and seeking out and testing new alternatives, evaluating the addition of minor elements on protective film formation, and optimizing delivery of the most promising alternatives. Research progress will be openly reported to benefit the entire magnesium industry and will be reported annually at the IMA meeting (International Magnesium Association, November 20, 2000, The International Magnesium Association & SF₆, paper presented at EPA Conference on SF₆ and the environment, accessed June 15, 2001, via URL <http://www.epa.gov/highgwpl/sf6/agenda.html>).

RECYCLING AND DISPOSAL

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. 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, 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.

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)

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 (Kramer, 2001).

Most uses of magnesium compounds are dissipative, so the material cannot be recovered. Some work is being done with refractories recycling; however, this is on a limited scale. As landfilling becomes more expensive and regulations regarding industrial waste become more stringent, recycling may become a more attractive option.

HEALTH AND SAFETY FACTORS

Magnesium articles or parts are difficult to ignite because of good thermal conductivity and high (>450EC) ignition temperatures. However, magnesium can be a fire hazard in the form of dust, flakes, or ribbon when exposed to flame or oxidizing agents. A magnesium powder or dust ignites readily, if suspended in air in concentrations above the lower explosive limit (0.04 grams per liter). Such ignition can result in a violent explosion (Jacobson, Cooper, and Nagy, 1964).

Magnesium fires are readily extinguished with the appropriate metal-extinguishing powder. Magnesium fires do not flare up violently unless there is moisture present, therefore water is not recommended for extinguishing magnesium fires and must be avoided

with molten magnesium or magnesium powders. Proper storage of magnesium products greatly reduces the risk of accidental ignition (International Magnesium Association, 1998b).

Because magnesium is essential to most plant and animal life, dietary deficiency, rather than toxicity, is the more significant problem.

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