

LITHIUM

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Introduction

In 2002, Chile was once again the world's leading producer of lithium carbonate. Production was from its two lithium brine operations on the Salar de Atacama in the Andes Mountains and two lithium carbonate plants in Antofagasta. In the United States, production continued at a single lithium brine operation and lithium carbonate plant in Nevada. There was one lithium carbonate plant and one lithium chloride plant in Argentina on the Salar del Hombre Muerto; the carbonate plant operated below capacity. China and Russia continued lithium carbonate production. Australia, Canada, and Zimbabwe were important sources of lithium concentrates. A large percentage of the lithium carbonate produced in South America was exported to the United States as feed material for the production of downstream lithium compounds, such as lithium hydroxide monohydrate, lithium metal, and organic lithium compounds, and for consumption in industrial applications.

Many commercial lithium products are available because of lithium's electrochemical reactivity and other unique properties. Lithium is sold as brines, compounds, metal, or mineral concentrates depending on the end use. Most lithium compounds and minerals are consumed in the production of ceramics, glass, and primary aluminum. The use of organic lithium compounds as industrial catalysts and the consumption of various lithium compounds in lithium batteries are the most rapidly expanding markets.

Production

The U.S. Geological Survey collects domestic production data for lithium from a voluntary canvass of U.S. operations. The single U.S. lithium carbonate producer, Chemetall Foote Corp., responded to the survey, representing 100% of total production. Production and stock data were withheld from publication to avoid disclosing company proprietary data (table 1).

Chemetall Foote (a subsidiary of the German company Chemetall GmbH) produced lithium carbonate from brines near Silver Peak, NV. The company's other lithium operations included a lithium hydroxide plant in Silver Peak; a butyllithium plant in New Johnsonville, TN; and facilities for producing downstream lithium compounds in Kings Mountain, NC.

FMC Corp., Lithium Division produced a full range of downstream compounds, lithium metal, and organic lithium compounds at its facilities in Bessemer City, NC, and Bayport, TX. FMC operated a lithium carbonate plant and spodumene mine in North Carolina until 1998. Since 1999, the company has met most of its lithium carbonate requirements through a long-term agreement with Chilean producer Sociedad Quimica y Minera de Chile S.A. (SQM) to supply FMC with lithium

carbonate produced at SQM's brine operation. FMC determined that the supply agreement with SQM would be more economical than continuing to produce lithium carbonate from its own operation in Argentina that began production in 1997 (FMC Corp., 2001, p. 25). FMC produced lithium chloride and a limited amount of lithium carbonate in Argentina in 2002.

LithChem International (a subsidiary of ToxCo, Inc.) of Anaheim, CA, produced lithium carbonate and lithium hydroxide at its plant in Baltimore, OH. LithChem produces these compounds from lithium compounds that are products of ToxCo's lithium battery recycling operation in Trail, British Columbia, Canada. Another ToxCo subsidiary, Ozark Fluorine Specialties Inc. in Tulsa, OK, produces hydrofluoric acid, some of which is converted to lithium hexafluorophosphate, high-purity lithium fluoride, and other electrolytes used in lithium batteries (McCoy, 2002).

Lithium carbonate is the most important lithium compound produced from brine and ore deposits. In most cases, other lithium compounds require lithium carbonate as a feedstock for further processing. The only domestic producer of lithium carbonate from brine is Chemetall Foote's operation in Nevada. Nevada brines enriched in lithium chloride, which averaged about 300 parts per million (ppm) when Foote Mineral Co. (the original owner of the deposit) began operations in 1966, are pumped from the ground and progress through a series of evaporation ponds (Engineering and Mining Journal, 1970). During the course of 12 to 18 months, the concentration of the brine increases through solar evaporation to 6,000 ppm lithium. When the lithium chloride reaches optimum concentration, the liquid is pumped to a recovery plant and treated with soda ash, precipitating lithium carbonate. The carbonate is then removed through filtration, dried, and shipped. A similar process is used to recover lithium from the Chilean brines, with slight adjustments to account for their different chemistries. The brine operation in Argentina uses a different, proprietary technology that allows for the lithium recovery as either carbonate or chloride (FMC Corp., 1998, p. 23, 25).

Until the last domestic mine closed in 1998, spodumene had been the major raw material used for the production of lithium carbonate in North Carolina, and small amounts of spodumene concentrate were produced for sale. Spodumene is the most common lithium mineral, but petalite and lepidolite are other minerals that are mined in different parts of the world for their lithium content. These three minerals are beneficiated to produce lithium concentrates that can be used directly in certain applications.

Extracting lithium from spodumene entails an energy-intensive chemical recovery process, which is more costly than that used for brines. Because of the high cost of producing lithium carbonate from spodumene, most lithium carbonate

production has shifted to brine deposits. Spodumene was believed to be the source of lithium carbonate production in China and Russia. After mining, spodumene is crushed and undergoes a flotation beneficiation process to produce concentrate. The concentrate is heated to 1,075° C to 1,100° C, changing the crystal structure of the mineral and making it more reactive to sulfuric acid. A mixture of finely ground converted spodumene and sulfuric acid is heated to 250° C, forming lithium sulfate. Water is added to the mixture to dissolve the lithium sulfate. Insoluble portions are then removed by filtration. The purified lithium sulfate solution is treated with soda ash, forming insoluble lithium carbonate that precipitates from solution. The carbonate is separated and dried for sale or use by the producer as feedstock in the production of other lithium compounds.

Consumption

The aluminum, ceramics and glass, lubricating grease, and synthetic rubber industries used most of the lithium minerals and compounds consumed in 2002. Estimated domestic consumption was stable from 1997 through 2000, but in 2001, consumption plummeted to only 50% of what it was in the 4 previous years. In 2002, consumption decreased an additional 21%, resulting in consumption of less than 40% of what it had been only 2 years earlier. In 2001, primary aluminum production, a major end use for lithium carbonate, decreased by 28% from the previous year. This production rose slightly in 2002, but not enough to have much impact on lithium consumption (Plunkert, 2002, 2003^{§1}). Further decreases in estimated consumption indicated decreased lithium consumption in other end uses, including ceramics and glass, lubricants, synthetic rubber, and pharmaceuticals, although data to support this assumption were not available.

The largest use of lithium in the United States was in ceramics and glass manufacturing processes. The addition of lithium to the glass melt as lithium carbonate or lithium concentrates lowers process melting points, reduces the coefficient of thermal expansion and the viscosity, and eliminates the use of more toxic compounds. The production of ceramics and glass was the only use for lithium concentrates. The domestic manufacture of thermal shock-resistant cookware (pyroceramics) consumed the majority of lithium used in the ceramics and glass industry. Low-iron spodumene and petalite were sources of the lithium used to improve the physical properties of container and bottle glass as well as sources of alumina, another important component of glass. Glass manufacturers used lithium in container and bottle glass to produce a lighter weight, thinner walled product. Lithium concentrates are the predominant lithium source for ceramics and glass uses, but lithium carbonate also is used.

The second largest lithium use was in primary aluminum production. Adding lithium carbonate to aluminum potlines lowers the melting point of the cryolite bath, allows a lower operating temperature for the cells, increases the electrical conductivity, and decreases bath viscosity. These factors contribute to increased production without changing any other operating conditions.

¹References that include a section mark (§) are found in the Internet References Cited section.

Perhaps more important are the environmental benefits of lithium consumption at aluminum smelters, reducing fluorine emissions by 20% to 30%. More modern aluminum smelters are more efficient and less polluting without the addition of lithium carbonate (Chemetall GmbH, 2001§).

Domestically, the third largest and the fastest growing end use for lithium compounds was as catalysts in the production of synthetic rubbers, plastics, and pharmaceuticals. *N*-butyllithium is used to initiate the reactions between styrene and butadiene that form abrasion-resistant synthetic rubbers that require no vulcanization. Other organic lithium compounds were used as catalysts for the production of plastics, such as polyethylene. Lithium metal and compounds also were used as catalysts in the production of an analgesic, anticholesterol agents, antihistamines, contraceptives, sleep inducers, steroids, tranquilizers, vitamin A, and other products. Lithium catalysts were used in the production of protease inhibitors, important drugs in the treatment of human immunodeficiency virus type 1/acquired immunodeficiency syndrome (HIV-AIDS) (Schmitt, 2001). Pharmaceutical-grade lithium carbonate was used in the treatment of manic-depressive psychosis. This was the only treatment approved by the U.S. Food and Drug Administration in which lithium was consumed by the patient.

The multipurpose grease industry was another important market for lithium in 2002. Lithium hydroxide monohydrate was the compound used for the production of lithium lubricants. Lithium-based greases were favored for their retention of lubricating properties over a wide temperature range; good resistance to water, oxidation, and hardening; and formation of a stable grease on cooling after melting. These greases continued to be used in aircraft, automotive, industrial, marine, and military applications.

Almost all major battery manufacturers marketed some type of lithium battery. Research and development continued, and innovative rechargeable battery configurations continued to be developed to meet the changing requirements of electronic equipment, such as portable telephones, portable computers, and video cameras. Lithium-ion batteries were of particular interest for these applications because they take advantage of the large power capacity available from lithium batteries with fewer safety problems than are encountered when batteries contain lithium metal, a very reactive and volatile material when exposed to air and moisture. Electric vehicles (EVs) have been considered a large potential market for lithium batteries, but general acceptance of these vehicles has been slow. Hybrid vehicles and vehicles powered by fuel cells may find greater popularity in the near future than pure EVs.

Nonrechargeable (primary) lithium batteries offer improved performance compared with alkaline batteries at a slightly higher cost and have been commercially available for more than 10 years. They are used in cameras, electronic games, microcomputers, small appliances, toys, and watches. The military purchased large and small lithium batteries for a variety of military applications. For example, in 2000, two lithium oxyhalide reserve batteries were qualified for use in two different missile programs, the High Altitude Area Defense Program and the Boeing Ground Based Program. These reserve batteries, which are stored in an inactive form until needed for short-term use, provide high current for short times from small packages (McHale, 2000).

Aircraft manufacturers in several countries have considered using aluminum-lithium alloys for wing and fuselage skin or for structural members in different types of aircraft. Use of these alloys could reduce the weight of the aircraft by more than 10%, allowing significant fuel savings during the life of the aircraft. The alloys, which are 2% to 3% lithium by weight, were attractive to the aircraft and aerospace industries because of their reduced density and improved corrosion resistance compared with conventional aluminum alloys. These alloys, however, have not been as widely used in aircraft manufacture as a result of direct competition from composite materials consisting of aramid, boron, or graphite fibers embedded in polymers. McCook Metals LLC produced an aluminum-lithium alloy that is being used for a fatigue-critical aft bulkhead replacement and other parts on the F-16 fighter plane built by Lockheed Martin Corp. The alloy was produced at the McCook, IL, plant formerly owned by Reynolds Metals Co. (Light Metal Age, 1998).

The superlightweight external fuel tank for the National Aeronautics and Space Administration's space shuttle was made with another aluminum alloy containing 4% copper, 1% lithium, 0.4% silver, 0.4% magnesium, and the remainder aluminum. This alloy was 30% stronger and 5% less dense than the more traditional aluminum alloy that it replaced. The redesigned fuel tank weighed about 3,400 kilograms less than the original design; the weight savings were used to increase the payload capacity for shuttle missions (Light Metal Age, 1998).

Small quantities of other lithium compounds were important to many industries. Lithium chloride and lithium bromide were used in industrial air-conditioning and commercial dehumidification systems and in the production of sophisticated textiles. Sanitizers for commercial glassware, public restrooms, and swimming pools contained lithium hypochlorite, as did dry bleaches for commercial laundries. Lithium metal was used as a scavenger to remove impurities from bronze and copper, and anhydrous lithium chloride was used as a component in fluxes for hard-to-weld metals, such as aluminum and steel alloys.

Prices

Since lithium pricing became very competitive when SQM entered the market in 1998, it has become difficult to obtain reliable price information from the companies or trade publications. The companies may announce price hikes, but they are reported relative only to previous prices. Producers negotiate with consumers on an individual basis; price information is not usually reported.

Customs values for lithium carbonate entering the United States from Chile are a good indication of the trends in lithium pricing, although they have never reflected exactly the producers' average prices for lithium carbonate. In 2002, the customs unit value for imported lithium carbonate was \$1.59 per kilogram, about 7% higher than in 2001.

Foreign Trade

In 2002, total exports of lithium compounds from the United States increased by 9% compared with the previous year. About 44% of all U.S. exports of lithium compounds were to Germany and Japan. The remainder was divided among many other countries (table 2).

Imports of lithium compounds decreased by 4% in 2002 following a 31% decrease in 2001, which resulted from significantly decreased demand. In 2002, 84% of lithium imports came from Chile, 9% came from Argentina, and 7%, from other countries (table 3). Lithium concentrates from Australia, Canada, and Zimbabwe were believed to have been consumed in the United States, but no import data were available.

World Review

A small number of countries throughout the world produced lithium concentrates and brine. Chile, China, and the United States were the leading producers of lithium carbonate. Significant quantities of lithium compounds and concentrates also were produced in Argentina, Australia, Brazil, Canada, Portugal, Russia, and Zimbabwe. Namibia, Rwanda, South Africa, and Congo (Kinshasa) are past producers of concentrates. Production figures for lithium concentrates and lithium carbonate are listed in table 4. Pegmatites containing lithium minerals have been identified in Austria, France, India, Ireland, Mozambique, Spain, and Sweden, but economic conditions have not favored development of the deposits. Lithium has been identified in subsurface brines in Bolivia, China, and Israel. Companies in France, Germany, Japan, Taiwan, and the United Kingdom produced downstream lithium compounds from imported lithium carbonate.

The total lithium-compound market was estimated to be about 45,000 metric tons (t) of elemental lithium contained in compounds in 2001 (Schmitt, 2001). Global consumption of lithium minerals was estimated to be around 158,000 t in 2000 (Glass International, 2001). Similar data were not available for 2001 and 2002, but level compound consumption was likely for those years with a slight increase for minerals.

Argentina.—Sources in Argentina reported lithium carbonate production of 906 t and lithium chloride production of 4,730 t in 2002, although FMC's Argentine facility was designed to produce about 12,000 metric tons per year (t/yr) of lithium carbonate and about 5,500 t/yr of lithium chloride (North American Minerals News, 1998). After operating for only 1 full year, technical problems and poor market conditions prompted FMC to severely curtail lithium carbonate production at the facility in 1999 and purchase most of its lithium carbonate requirements from other sources, SQM in particular (Industrial Minerals, 1999).

Brazil.—Two companies produce lithium minerals in Brazil. Companhia Brasileira de Lítio produces spodumene concentrates from the underground Cachoeira Mine in Araçuaí. This material is used as feedstock for lithium carbonate and lithium hydroxide production at a plant in Aguas Vermelhas in Minas Gerais. Arqueana de Minérios e Metais Ltda. produces a mixture of spodumene, petalite, and lepidolite from several mines in Araçuaí and Itinga. In Brazil, lithium compounds and minerals are used in greases and lubricants, primary aluminum production, ceramics, batteries, and nuclear reactors (Ramos, 2001).

Canada.—Tantalum Mining Corp. of Canada Ltd. (Tanco) (a subsidiary of Hudson Bay Mining Co.) operates a spodumene mine and concentrating plant at Bernic Lake, Manitoba. Development of Avalon Ventures Ltd.'s Big Whopper petalite portion of its Separation Rapids rare metals project in

northwestern Ontario and Emerald Fields Resource Corp.'s Big Mack petalite project, on the same pegmatite body between the Tanco and Avalon operations, was being considered, but neither deposit had been developed for commercial production. Because customers for established lithium minerals had strong relationships with long-term producers, new product sources were not in high demand. For this reason, Avalon reconsidered its plan to produce petalite concentrates from Big Whopper and proposed an operation to produce a high-lithium, low-iron feldspar product instead. The lithium feldspar product would offer a lower cost option for lithium additions to ceramics and glass manufacturers (Industrial Minerals, 2002).

Chile.—With two large brine operations at the Salar de Atacama and their associated lithium carbonate plants, Chile was the largest lithium carbonate producer in the world. Chemetall Foote's plant first produced lithium carbonate in 1984; it uses its lithium carbonate as feedstock for its downstream chemical production in the United States and supplies the operations of its parent company Chemetall in Germany and Taiwan. SQM completed its first full year of production in 1997 and has the capacity to produce about 23,000 t/yr (Schmitt, 2001). Both Chilean companies transport concentrated brines from the Salar de Atacama to lithium carbonate plants in Antofagasta. Chemetall Foote and SQM lithium carbonate production and markets are nearly equal; smaller quantities are available from China and Russia (McCoy, 1999).

Germany.—Chemetall has been a major producer of lithium compounds for many years at its lithium operations in its Langelsheim plant. The company has lithium operations in Chile, Germany, Taiwan, and the United States.

Outlook

The health of the domestic lithium industry remains closely tied to the performance of the primary aluminum and the ceramics and glass industries in the United States and the U.S. economy in general. Changes in consumption of lithium in these industries determine the performance of the entire lithium industry. With nearly one-third of U.S. aluminum capacity idle in 2001 and much of 2002, lithium consumption suffered. There were some indications at yearend 2002 that the aluminum industry was beginning to recover, increasing demand for lithium in this sector. Lower estimated consumption indicated decreases in other end uses.

Demand for lithium metal for batteries and to some extent for alloys is expected to increase, but total consumption of metal will remain low in comparison with the demand for lithium compounds. Lithium-ion and lithium-polymer batteries appear to possess the greatest potential for growth. First introduced in 1993 with minimal sales, the market for these rechargeable batteries grew to \$3 billion in 1998 and is expected to top \$6 billion by 2005 (Pacific Lithium Ltd., 2000§). No estimates of the amount of lithium required for these batteries have been made, but the value of lithium materials sold for battery production was estimated to be \$111 million in 1997. Forecasted average annual increases of 16% through 2008 could increase material demand at a comparable or faster rate (Saller and O'Driscoll, 2000, p. 41).

Too many unknowns remain, however, to allow for a reliable forecast of the quantity of lithium that will be required for the

future EV market. Not only is there the question of whether lithium will be part of the superior EV batteries, but also whether batteries or fuel cells will be the preferred sources of power. Developments in 2002 indicated that fuel cells might eventually become the preferred power sources for EVs. In addition, questions as to when and if EVs will make up a significant portion of new car sales in the United States and around the world have been raised. Sales and leases of EVs currently lag behind previous expectations.

Other markets should remain stable. Lithium demand could increase dramatically if the technology for nuclear fusion, where lithium would be used as a cooling fluid, is perfected. This is not expected to take place within the next 25 years and may never happen.

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TABLE 1
SALIENT LITHIUM STATISTICS¹

(Metric tons of contained lithium)

	1998	1999	2000	2001	2002
United States:					
Production	W	W	W	W	W
Producers' stock changes	W	W	W	W	W
Exports ²	1,340	1,330	1,310	1,480	1,620
Imports ²	2,590	2,640	2,880	1,990	1,920
Consumption:					
Apparent	W	W	W	W	W
Estimated	2,800	2,800	2,800	1,400	1,100
Rest of world, production ³	14,900 ^r	15,100 ^r	16,900 ^r	14,900 ^r	16,200

¹Revised. W Withheld to avoid disclosing company proprietary data.

²Data are rounded to no more than three significant digits.

³Compounds.

³Mineral concentrate and lithium carbonate.

TABLE 2
U.S. EXPORTS OF LITHIUM CHEMICALS, BY COMPOUND AND COUNTRY¹

Compound and country	2001		2002	
	Gross weight (metric tons)	Value (thousands)	Gross weight (metric tons)	Value (thousands)
Lithium carbonate:				
Australia	--	--	130	\$551
Canada	410	\$1,470	331	1,190
China	29	108	100	361
Germany	865	2,360	1,100	3,120
India	22	78	53	162
Japan	1,080	4,020	1,450	4,800
Korea, Republic of	26	92	25	90
Mexico	3	14	7	25
Netherlands	88	317	90	333
Taiwan	9	33	20	71
United Kingdom	247	763	175	582
Other	136	556	138	626
Total	2,920	9,810	3,620	11,900
Lithium carbonate U.S.P.:²				
Australia	50	226	45	182
China	20	35	39	71
Germany	64	117	138	276
Israel	2	67	1	26
Singapore	19	39	--	--
Sweden	13	57	--	--
Venezuela	100	170	--	--
Other	13 ^r	119 ^r	28	122
Total	281	830	251	677
Lithium hydroxide:				
Argentina	96	324	69	208
Australia	189	788	56	237
Canada	326	1,290	132	515
Chile	39	142	24	107
China	15	36	22	88
Germany	516	1,540	646	2,000
India	298	858	521	1,320
Japan	910	4,780	759	3,700
Korea, Republic of	237	909	241	846
Mexico	98	344	55	191
Netherlands	172	431	103	406
New Zealand	266	1,100	22	80
Philippines	32	100	17	49
Singapore	86	359	108	395
Thailand	109	286	87	233
Taiwan	36	163	23	92
United Kingdom	245	1,490	194	1,170
Other	1,630	7,510	2,320	9,000
Total	5,300	22,400	5,400	20,600

^rRevised. -- Zero.

¹Data are rounded to no more than three significant digits; may not add to totals shown.

²Pharmaceutical-grade lithium carbonate.

Source: U.S. Census Bureau.

TABLE 3
U.S. IMPORTS FOR CONSUMPTION OF LITHIUM CHEMICALS BY COMPOUND AND COUNTRY¹

Compound and country	2001		2002	
	Gross weight (metric tons)	Value ² (thousands)	Gross weight (metric tons)	Value ² (thousands)
Lithium carbonate:				
Argentina	808	\$1,290	882	\$2,010
Chile	9,160	13,200	8,660	12,800
France	--	--	11	32
Germany	10	28	15	49
Japan	1	6	138	268
Mexico	113	87	36	27
New Zealand	145	577	31	121
Other	22 ^r	78 ^r	59	210
Total	10,300	15,300	9,830	15,600
Lithium hydroxide:				
China	341	901	401	1,060
Japan	5	66	14	145
United Kingdom	15	246	6	38
Other	1	23	11	44
Total	362	1,240	432	1,290

^rRevised. -- Zero.

¹Data are rounded to no more than three significant digits; may not add to totals shown.

²Customs value.

Source: U.S. Census Bureau.

TABLE 4
LITHIUM MINERALS AND BRINE: ESTIMATED WORLD PRODUCTION, BY COUNTRY^{1,2}

(Metric tons)

Country ³	1998	1999	2000	2001	2002
Argentina: ⁴					
Lithium carbonate	6,000	1,592 ^{r,5}	2,161 ^{r,5}	-- ^{r,5}	906 ⁵
Lithium chloride	2,500	2,794 ⁵	5,182 ⁵	4,512 ⁵	4,729 ⁵
Spodumene and amblygonite	-- ^r	-- ^r	-- ^r	-- ^r	--
Australia, spodumene	63,190 ⁵	75,824 ⁵	81,891 ⁵	63,443 ⁵	100,000
Brazil, concentrates	9,485 ⁵	11,122 ⁵	10,875 ⁵	11,000	11,200
Canada, spodumene ⁶	22,500	22,500	22,500	22,500	22,500
Chile, carbonate from subsurface brine	28,377 ⁵	30,231 ⁵	35,869 ⁵	31,320 ^{r,5}	31,500
China, carbonate	13,000	12,500	13,000	13,000	13,000
Namibia, concentrates, chiefly petalite	500	--	--	--	--
Portugal, lepidolite	7,000	14,862 ⁵	9,352 ⁵	10,000	9,500
Russia (minerals not specified) ^{7,8,9}	2,000	2,000	2,000	2,000	2,000
United States, spodumene and subsurface brine	W	W	W	W	W
Zimbabwe, amblygonite, eucryptite, lepidolite, petalite, and spodumene	28,055 ⁵	36,671 ⁵	37,914 ^{r,5}	36,103 ^{r,5}	32,000

^rRevised. W Withheld to avoid disclosing company proprietary data. -- Zero.

¹Table includes data available through March 28, 2003.

²Estimated data are rounded to no more than three significant digits.

³In addition to the countries listed, other nations may produce small quantities of lithium minerals. Output is not reported; no valid basis is available for estimating production levels.

⁴New information was available from Argentine sources, prompting major revisions in how lithium production was reported.

⁵Reported figure.

⁶Based on all Canada's spodumene concentrates (Tantalum Mining Corp. of Canada Ltd.'s Tanco property).

⁷These estimates denote only an approximate order of magnitude; no basis for more exact estimates is available.

⁸Lithium contained in concentrates and brine.

⁹Other countries from the Commonwealth of Independent States, including Uzbekistan, could have produced or could be producing lithium, but information is not available for estimating production levels.