

4. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

4.1 PRODUCTION

Aluminum is the most abundant metallic element in the earth's crust, comprising approximately 8% of the crust (Brusewitz 1984). Aluminum does not occur naturally in the metallic, elemental state, but rather occurs in combination with oxygen, silicon, fluorine, and other elements (Browning 1969; Dinman 1983; IARC 1984; NRC 1982). The most important raw material for the production of aluminum is bauxite, which contains 40-60% alumina (aluminum oxide) (Dinman 1983; IARC 1984). Other raw materials sometimes used in the production of aluminum include cryolite, aluminum fluoride, fluorspar, corundum and kaolin minerals (Browning 1969; Dinman 1983; IARC 1984).

The principal method used in producing aluminum metal involves three major steps: refining of bauxite by the Bayer process to produce alumina, electrolytic reduction of alumina by the Hall-Heroult process to produce aluminum and casting of aluminum into ingots (Browning 1969; Dinman 1983; IARC 1984).

In the first step (Bayer process), bauxite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) is digested at high temperature and pressure in a strong solution of caustic soda. The resulting hydrate is then crystallized and calcined in a kiln to produce alumina (aluminum oxide). In the second step (Hall-Heroult process), alumina is reduced to aluminum metal by an electrolytic process involving carbon electrodes and cryolite flux ($3\text{NaF} \cdot \text{AlF}_3$). The electrolytic reduction process of transforming alumina into aluminum is carried out in electrolytic cells or pots. The areas where this occurs are called potrooms. Two types of electrolytic cells may be used, a prebake or a Soderberg cell. Their design differs, but the principle is the same. Alumina is dissolved in the cell in an electrolyte at a high temperature (950-970 °C) and a low voltage (4-6 volts). A high current is applied to the melted fraction. The alumina is reduced to aluminum at the cathode and the metal sinks to the bottom of the electrolytic cell. The aluminum is then removed by siphoning. The oxygen from the alumina migrates to the carbon anode of the cell, where it reacts to form carbon dioxide and carbon monoxide. The aluminum produced using the Hall-Heroult electrolytic reduction process may be refined to a maximum purity of 99.9% by the Badeau low-temperature electrolytic process (HSDB 1995). In the third step (casting), aluminum is taken from the cell to holding furnaces from which it is poured into molds and cast into aluminum ingots.

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The use of electrodes in aluminum reduction operations is associated with the generation of several types of wastes (Dinman 1983; IARC 1984). In aluminum reduction facilities using the prebake process, PAHs are generated. In aluminum reduction operations using the Soderberg cell process, considerable amounts of volatiles from coal tar pitch, petroleum coke, and pitch, including PAHs, are generated.

In 1997, domestic primary aluminum production totaled just over 3.6 million metric tons (7.9 billion pounds). Thirteen companies operated 22 primary aluminum reduction plants, and 1 plant remained closed. Montana, Oregon, and Washington accounted for 38% of the production; Kentucky, North Carolina, South Carolina, and Tennessee, 21%; and other States, 41%. Aluminum recovered in 1997 from purchased scrap was almost 3.5 million metric tons (7.7 billion pounds), of which 50% came from new (manufacturing) scrap and 50% from old scrap (discarded aluminum products) (USGS 1997a, 1998, 1999).

Aluminum is also an integral part of a variety of aluminum compounds used in industrial, domestic, consumer, and medicinal products. The methods of production for these compounds is described in the following section.

Aluminum chloride is produced by a reaction of bauxite with coke and chlorine at about 875 °C (HSDB 1995; Sax and Lewis 1987).

Aluminum fluoride is made by heating ammonium hexafluoroaluminate to red heat in a stream of nitrogen; by the action of fluorine or hydrogen fluoride gas on aluminum trihydrate at high temperatures, followed by calcining the hydrate formed; by fusing cryohte or sodium fluoride with aluminum sulfate; or by a reaction of fluosilicic acid on aluminum hydrate (HSDB 1995).

Aluminum hydroxide is produced from bauxite. The ore is dissolved in a solution of sodium hydroxide, and aluminum hydroxide is precipitated from the sodium aluminate solution by neutralization (as with carbon dioxide) or by autoprecipitation (Bayer process) (HSDB 1995; Sax and Lewis 1987).

Aluminum nitrate is formed by dissolving aluminum or aluminum hydroxide in dilute nitric acid and allowing the resulting solution to crystallize (HSDB 1995).

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Aluminum oxide is produced during the recovery of bauxite, which is crushed, ground, and kiln dried, followed by leaching with sodium hydroxide, forming sodium aluminate, from which alumina trihydrate is precipitated and calcined (Bayer process) (HSDB 1995).

Aluminum phosphide is made from red phosphorus and aluminum powder (Budavari et al. 1989).

Aluminum sulfate is manufactured by reacting freshly precipitated pure aluminum hydroxide, bauxite, or kaolin, with an appropriate quantity of sulfuric acid. The resulting solution is evaporated and allowed to crystallize (HSDB 1995).

Aluminum production in the United States in 1973 amounted to 4.5 million tons (9 billion pounds), representing an increase of 10% over that produced in 1972 (Stokinger 1981). In 1982, the United States produced 3.3 million tons (6.6 billion pounds). More recently, aluminum production has declined slightly from 1991 through 1996 (USGS 1996, 1997a). Annual primary production of aluminum in thousand metric tons was 4,121 (9.1 billion pounds), 4,042 (8.9 billion pounds), 3,695 (8.1 billion pounds), 3,299 (7.3 billion pounds), 3,375 (7.4 billion pounds), 3,577 (7.9 billion pounds), 3,603 (7.9 billion pounds), 3,700 (8.1 billion pounds) in 1991, 1992, 1993, 1994, 1995, 1996, 1997, and 1998, respectively (USGS 1996, 1997a, 1998, 1999). During this same period, secondary recovery of aluminum from new or old scrap aluminum increased slightly. The volume of secondary recovery of aluminum (from old and new scrap) in thousand metric tons was 2,290 (5 billion pounds), 2,760 (6.1 billion pounds), 2,940 (6.5 billion pounds), 3,090 (6.8 billion pounds), 3,190 (7 billion pounds), 3,310 (7.3 billion pounds), and 3,690 (8.1 billion pounds) in 1991, 1992, 1993, 1994, 1995, 1996, and 1997 respectively (USGS 1996, 1997b). Primary aluminum was produced in 43 countries worldwide in 1996 (USGS 1997b). The United States was the largest single producer with 17% of the total world production, followed by Russia with 14%, and Canada with 11% (USGS 1997b).

Table 4-1 lists the facilities in each state that manufacture or process aluminum the intended use, and the range of maximum amounts of aluminum that are stored on site. The data listed in Table 4-1 is derived from the Toxics Release Inventory (TRI 1998). Only certain types of facilities were required to report (EPA 1995e). Therefore, this is not an exhaustive list.

With respect to aluminum compounds, annual production capacity for aluminum chloride (anhydrous) in thousand metric tons was 34 (75 million pounds), 37 (82 million pounds), 46 (101 million pounds),

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Table 4-1. Facilities That Manufacture or Process Aluminum and Its Compounds

State ^a	Number of facilities	Range of maximum amounts on site ^b (in pounds)	Activities and uses ^c
AL	8	1,000–999,999	1, 5, 7, 8, 9, 11, 12
AR	10	0–999,999	1, 5, 6, 8, 9
AZ	1	1,000–9,999	1, 5, 7
CA	13	0–9,999,999	1, 3, 4, 5, 8, 9, 13
CT	2	0–99,999	1, 5, 8, 9, 12
GA	3	1,000–99,999	1, 5, 6
IA	7	1,000–9,999,999	1, 5, 7, 8, 9
IL	27	0–9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13
IN	25	0–9,999,999	1, 3, 4, 5, 7, 8, 9, 10, 12, 13
KS	2	1,000–99,999	8, 12
KY	10	0–9,999,999	1, 2, 3, 4, 5, 8, 9, 10, 11, 12, 13
LA	1	100,000–9,999,999	7
MA	3	1,000–99,999	2, 3, 4, 8
MD	3	1,000–999,999	1, 5, 9
ME	1	10,000–99,999	9
MI	12	1,000–999,999	1, 2, 3, 4, 5, 7, 8, 9, 10, 11
MN	5	1,000–999,999	1, 5, 7, 8, 9, 11, 12
MO	9	1,000–999,999	1, 3, 4, 5, 7, 8, 9, 10, 13
MS	1	100,000–999,999	11, 12
NC	7	0–99,999	1, 5, 7, 9, 10
NJ	5	1,000–9,999,999	1, 2, 3, 4, 5, 7, 8, 9, 11
NY	4	10,000–99,999	1, 2, 3, 4, 5, 8, 9, 10
OH	34	100–9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
OK	4	1,000–999,999	1, 5, 6, 8, 10
OR	4	1,000–9,999,999	10, 12, 13
PA	24	100–9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13
SC	4	0–99,999	1, 2, 3, 5, 7, 10, 13
TN	16	1,000–49,999,999	1, 2, 3, 4, 5, 6, 7, 9, 10
TX	7	1,000–999,999	1, 3, 4, 5, 7, 8, 9, 12
UT	3	10,000–9,999,999	8, 9, 12
VA	3	0–9,999	1, 5, 12
WA	2	10,000–99,999	1, 6, 8, 9
WI	13	100–999,999	1, 5, 8, 9
WV	2	1,000–9,999,999	7, 9

Source: TRI96 1998

^aPost office state abbreviations used^bRange represents maximum amounts on site reported by facilities in each state^cActivities/Uses:

- | | | |
|--------------------------|--------------------------|-----------------------------|
| 1. Produce | 6. Impurity | 10. Repackaging |
| 2. Import | 7. Reactant | 11. Chemical Processing Aid |
| 3. Onsite use/processing | 8. Formulation Component | 12. Manufacturing Aid |
| 4. Sale/Distribution | 9. Article Component | 13. Ancillary/Other Uses |
| 5. Byproduct | | |

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51 (112 million pounds), and 54 (119 million pounds) in 1988, 1990, 1992, 1994, and 1995, respectively (SRI 1988,1990, 1992,1994,1995).

Annual production capacity for aluminum oxide (alumina, calcined, reduction grade) in thousand metric tons was 4,896 (10.8 billion pounds), 5,245 (11.6 billion pounds), 4,980 (11 billion pounds), 4,980 (11 billion pounds), and 5,035 (11.1 billion pounds) in 1988, 1990, 1992, 1994, and 1995, respectively (SRI 1988, 1990, 1992, 1994, 1995). Table 4-2 lists the facilities in each state that manufacture or process aluminum oxide, the intended use, and the range of maximum amounts of aluminum oxide that are stored on site. The data listed in Table 4-2 is derived from the Toxics Release Inventory (TR196 1998). Only certain types of facilities were required to report (EPA 1995e). Therefore, this is not an exhaustive list. Small quantities of highly purified aluminum oxide are now produced for use in systems that measure doses of ionizing radiation (McKeever et al. 1995).

Aluminum sulfate was ranked 43rd among the top 50 chemicals produced in the United States in both 1993 and 1994 (Kirschner 1995). Annual U.S. production of aluminum sulfate has remained relatively constant from 1984 to (Kirschner 1995). Annual production (in thousand metric tons) was 1,129 (2.5 billion pounds), 1,268 (2.8 billion pounds), 1,222 (2.7 billion pounds), 1,227 (2.7 billion pounds), 1,237 (2.7 billion pounds), 1,243 (2.7 billion pounds), 1,227 (2.7 billion pounds), 1,185 (2.6 billion pounds), 1,047 (2.3 billion pounds), 1,050 (2.4 billion pounds), and 1,149 (2.5 billion pounds), in 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, and 1994, respectively (Kirschner 1995).

4.2 IMPORT/EXPORT

Limited data are available regarding the import and export of aluminum by the United States. A total of 1,484 million pounds and 1,000 million pounds of aluminum were imported by the United States in 1972 and 1975, respectively (HSDB 1995). More recently, import volumes (in thousand metric tons) were 1,490 (3.3 billion pounds), 1,730 (3.8 billion pounds) 2,540 (5.6 billion pounds), 3,380 (7.4 billion pounds), 2,970 (6.5 billion pounds), 2,810 (6.2 billion pounds), and 3,100 (6.8 billion pounds) from 1991, 1992, 1993, 1994, 1995, 1996, and 1997, respectively (USGS 1996, 1997a). U.S. imports for consumption decreased in 1995, reversing an upward trend that began in 1992. Although imports of semifabricated materials and scrap increased in 1995, crude metal and alloy imports decreased significantly compared to those in 1994 (USGS 1996, 1997a).

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Table 4-2. Facilities That Manufacture or Process Aluminum Oxide

State ^a	Number of facilities	Range of maximum amounts on site ^b (in pounds)	Activities and uses ^c
CA	3	10,000–999,999	2, 4, 7, 8, 12, 13
CT	1	10,000–99,999	12
GA	2	1,000–999,999	2, 3, 4, 9
IA	2	1,000–9,999	12
IL	1	1,000–9,999	12
IN	5	1,000–999,999	9, 12, 13
KY	2	1,000–99,999	8, 12
MI	2	1,000–99,999,999	9, 12
MN	1	1,000–9,999	2, 3, 12
MS	1	1,000–9,999	13
NC	1	1,000–9,999	12
NY	3	10,000–9,999,999	2, 4, 10, 12
OH	7	1,000–99,999	5, 9, 10, 12, 13
PA	2	0–999,999	9, 12
TN	2	10,000–999,999	8, 9
TX	2	10,000–99,999	8, 11
VA	1	10,000–99,999	12
WI	5	1,000–99,999	8, 9, 12

Source: TRI96 1998

^aPost office state abbreviations used^bRange represents maximum amounts on site reported by facilities in each state^cActivities/Uses:

- | | | |
|--------------------------|--------------------------|-----------------------------|
| 1. Produce | 6. Impurity | 10. Repackaging |
| 2. Import | 7. Reactant | 11. Chemical Processing Aid |
| 3. Onsite use/processing | 8. Formulation Component | 12. Manufacturing Aid |
| 4. Sale/Distribution | 9. Article Component | 13. Ancillary/Other Uses |
| 5. Byproduct | | |

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A total of 527 million pounds and 747 million pounds of aluminum were exported by the United States in 1972 and 1975, respectively. More recently, total exports of aluminum from the United States continued to increase in 1995, reaching their highest level since 1991 (USGS 1996, 1997a). Export volumes in thousand metric tons were 1,760 (3.9 billion pounds), 1,450 (3.2 billion pounds), 1,210 (2.7 billion pounds), 1,370 (3.0 billion pounds), 1,610 (3.5 billion pounds), 1,500 (3.3 billion pounds), and 1,600 (3.5 billion pounds) (January through November total) from 1991, 1992, 1993, 1994, 1995, 1996, and 1997, respectively (USGS 1996, 1997a).

4.3 USE

Aluminum metal and compounds have a wide variety of uses (Anusavice 1985; Browning 1969; Budavari et al. 1989; Frank and Haupin 1985; Hawley 1977; HSDB 1995; Locock 1971; Staley and Haupin 1992; Stokinger 1981; Venugopal and Lucky 1978). Most primary aluminum is used for metallurgical purposes; 85-90% of these uses are in the production of aluminum-based alloy castings and wrought aluminum products. Pure aluminum is soft and lacks strength. By forming alloys, one can increase the strength, hardness and add other useful properties to the metal while building on the inherent properties of aluminum of low density, high electrical and thermal conductivity, high reflectivity, and corrosion resistance. In speaking of the uses of metallic aluminum one is therefore referring to the uses of aluminum and its alloys.

The major uses of aluminum and its alloys are in packaging, building and construction, transportation, and electrical applications. Over 95% of beer and carbonated drinks are packaged in two-piece aluminum cans. Aluminum sheet and foil, are used in pie plates, frozen food trays and other packaging applications. In construction, aluminum is used for siding and roofing, doors, and windows. Aluminum is used in the bodies, trim and mechanical parts of cars, trucks, airplanes, ships, and boats, as well as other transportation-related structures and products such as bridges and highway signs. Electrical applications include overhead transmission lines, cable sheathing, and wiring. Other applications of aluminum include die-cast auto parts, corrosion-resistant chemical equipment, cooking utensils, decorations, fencing, sporting equipment, toys, lawn furniture, jewelry, paint, and in dental alloys for crowns and dentures. Other uses include absorbing occluded gases in the manufacture of steel; testing for gold, arsenic, and mercury; precipitating copper, as a reducer for determining nitrates and nitrites; in coagulating colloidal solutions of arsenic or antimony; in explosives; and in flashes for photography. Aluminum powder is used in paints, protective coatings, and fireworks.

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The transportation and container and packaging industries remained the dominant domestic markets for aluminum products in 1997. The transportation industry accounted for an estimated 34% of domestic consumption; containers and packaging, 25%; building and construction, 15%; electrical and consumer durables, 8% each; and other uses (including machinery and equipment), 10% (USGS 1997a).

Aluminum compounds and materials also have a wide range of uses summarized below (Anusavice 1985; Browning 1969; Budavari et al. 1989; Hawley 1977; Locock 1971; Sax and Lewis 1987; Stokinger 1981; Venugopal and Lucky 1978). Naturally occurring aluminum-containing minerals, such as bentonite and zeolite, are used in water purification, sugar refining, and in the brewing and paper industries.

Aluminum chloride is used as an acid catalyst (especially in Friedel-Crafts-type reactions), as a chemical intermediate for other aluminum compounds, in the cracking of petroleum in the manufacture of rubbers and lubricants, and as an antiperspirant (HSDB 1995). The hexahydrate form is used in preserving wood, disinfecting stables and slaughterhouses, in deodorants and antiperspirants, in cosmetics as a topical astringent, in refining crude oil, dyeing fabrics, and manufacturing parchment paper (Budavari et al. 1989).

Aluminum chlorohydrate is the active ingredient in many antiperspirants and deodorants (Budavari et al. 1989; Hawley 1977; Sax and Lewis 1987).

Aluminum hydroxide is used in stomach antacids (including Maaloxe, Mylanta, and Delcide), as a desiccant powder; in antiperspirants and dentifrices; in packaging materials; as a chemical intermediate; as a filler in plastics, rubber, cosmetics, and paper; as a soft abrasive for brass and plastics; as a glass additive to increase mechanical strength and resistance to thermal shock, weathering, and chemicals; and in ceramics (HSDB 1995). Aluminum hydroxide is also used pharmaceutically to lower the plasma phosphorus levels of patients with renal failure (Budavari et al. 1989; Sax and Lewis 1987).

Aluminum nitrate is used in antiperspirants, for tanning leather, as a corrosion inhibitor, in the preparation of insulating papers, on transformer core laminates, in incandescent filaments, and in cathode ray tube heating elements (HSDB 1995).

Aluminum oxide is used in the production of aluminum; manufacture of abrasives, refractories, ceramics, electrical insulators, catalyst and catalyst supports, paper, spark plugs, crucibles and laboratory works,

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adsorbent for gases and water vapors, chromatographic analysis, fluxes, light bulbs, artificial gems, heat resistant fibers, food additive (dispersing agent), and in hollow-fiber membrane units used in water desalination, industrial ultrafiltration, and hemodialysis (HSDB 1995). A recent application of aluminum oxide, which may have wide occupational use in the future, is as a dosimeter for measuring personnel radiation exposure (McKeever et al. 1995; Radiation Safety Guide 1999; Radiation Safety Newsletter 1998).

Aluminum phosphate is used in over-the-counter stomach antacids (Budavari et al. 1989; Sax and Lewis 1987).

Aluminum phosphide is used as an insecticidal grain fumigant (Budavari et al. 1989).

Aluminum sulfate is used primarily for water purification systems and sewage treatment systems as a flocculent, in the paper and pulp industry, in fireproofing and waterproofing cloth, clarifying oils and fats, waterproofing concrete, in antiperspirants, in tanning leather, as a mordant in dyeing, in agricultural pesticides, as an intermediate in the manufacture of other chemicals, as a soil conditioner to increase acidity for plants (e.g., rhododendrons, azaleas, camellias, and blueberries), and in cosmetics and soap. A saturated solution of aluminum sulfate is employed as a mild caustic. Solutions containing 5-10% aluminum sulfate have been used as local applications to ulcers and to arrest foul discharges from mucous surfaces. Aluminum sulfate is also used in the preparation of aluminum acetate ear drops (HSDB 1995). With respect to use application, about 65% of the aluminum sulfate produced is used for water and sewage treatment (HSDB 1995).

Little information was located regarding the amounts of aluminum or aluminum compounds used by various industries or in various products.

4.4 DISPOSAL

Production of finished aluminum products by industrial facilities typically results in the generation of very large amounts of solid aluminum hydroxide anodizing residues (Saunders 1988). These aluminum-anodizing residues are currently classified as nonhazardous under the Federal Resource Conservation and Recovery Act (RCRA) regulations. These residues are typically dewatered to reduce the volume of waste prior to being landfilled. However, the heavy metal content of these solid waste residues can be of

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concern, especially in production processes using two-step anodizing systems that employ solutions containing elevated heavy metal concentrations. For these types of plants, Saunders (1988) has proposed implementation of a caustic-etch recovery system that will limit both the volume of aluminum-anodizing residue and the heavy metal content of the residue. Additional information on regulations and standards for aluminum and aluminum compounds is summarized in Chapter 7.

According to the Toxic Chemical Release Inventory, in 1996, an estimated 12,754 pounds of aluminum (fume or dust) were released by manufacturing and processing facilities to publicly owned-treatment works (POTWs) and an estimated 30,931,000 pounds were transferred off-site (TR196 1998). In addition, an estimated 1,328 pounds of aluminum oxide also were released by manufacturing and processing facilities to POTWs and an estimated 9527,000 pounds of aluminum oxide were transferred off-site (TR196 1998). The TRI data should be used with caution because only certain types of facilities are required to report (EPA 1995e). This is not an exhaustive list.

Aluminum recovered from purchased scrap increased to approximately 3.2 million tons (6.4 billion pounds) in 1995. Fifty-three percent of this recovered metal came from new (manufacturing) scrap and 47% from old scrap (discarded aluminum products). The recycling rate for used aluminum beverage can scrap decreased slightly from 65.4% in 1994 to 62.2% in 1995. During 1995, 62.7 billion used aluminum beverage cans were recycled in the United States. Aluminum beverage cans produced domestically in 1995 had an average of 51.3% post-consumer recycled content, the highest percentage of recycled content of all recyclable packaging materials (USGS 1996).