Energy and Environmental Profile of the U.S. Aluminum Industry

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Overview

1.1 Cornerstone of an Energy-Efficient U.S. Economy

Aluminum is widely used throughout the U.S. economy, particularly in the transportation, packaging, and construction industries. As a light-weight, high-strength, and recyclable structural metal, aluminum has and will continue to play an important role in a healthy economy as applications are extended in the infrastructure, aerospace, and defense industries.

The U.S. Department of Energy and the Aluminum Industry of the Future

The U.S. Department of Energy's (DOE's) Office of Industrial Technologies has formed a partnership with the U.S. aluminum industry to accelerate the development of technologies and processes that will improve the industry's energy efficiency and environmental performance. This report is intended to support the DOE/Aluminum Industry Partnership.

Aluminum's benefits have led to its growing use throughout world markets. World aluminum consumption doubled every decade between 1900 and 1980; over the last three decades alone, its consumption in Western countries has increased fourfold.

The aluminum industry enjoyed considerable stability in terms of demand and prices through the early 1970s. Since then, however, continuing economic fluctuations have become the norm. In particular, the transition of the industry to commodity pricing on the London Metals Exchange (LME) in the late 1970s (first for ingot and subsequently for semifabricated products based on ingot pricing) has contributed to price instability.

The Industry Is Recovering from Market Imbalances of the Early 1990s

The world aluminum industry is still coming out of a painful adjustment to dramatic changes in the world market and political climate following the collapse of the former Soviet Union in 1989 - 1990 (Born 1996). Throughout the early 1990s, industry supply and demand were severely out of balance, largely because of excess metal from the Commonwealth of Independent States (CIS) and reduced CIS demand for military and aerospace requirements.

In 1994 and 1995, the world aluminum market underwent adjustments to bring the Russian aluminum industry into the world market. During this period, fundamental demand for aluminum in Western markets increased, making 1994 an extraordinary year for total consumption (Born 1996). The industry appears to have made the necessary adjustments and inventories have returned to more reasonable levels.

Today, Western demand for primary aluminum continues to exceed Western production, but the market is in better balance because Russian metal has been integrated into the system. Growing market demand has absorbed the excess CIS metal, and China's huge increases in aluminum demand have been met primarily by that country's own production (Born 1996). In spite of these improved market conditions, inventories on the London Metal Exchange remain at relatively high levels, and producer prices are low.

The same forces that have influenced the primary sector (overcapacity in world markets and economic conditions) have also had an impact on producers of semifabricated products. Supply for semifabricated products has exceeded demand around the world in recent years. The resulting global competition has created substantial pressure on U.S. fabricating plants.

Throughout 1996, producers responded to competitive pressures by working to streamline their operations and cut operating costs. Some consider 1996 a "retooling" year, as flat-rolled aluminum producers made adjustments in their operations to garner larger market shares, particularly in the automotive market.

The U.S. aluminum market's sensitivity to the global marketplace can be traced to the commodity nature of aluminum, exchange price-setting, and extensive industry globalization. Despite fluctuations in specific markets, overall domestic consumption levels have remained relatively stable, helping to offset global trends. Growth in aluminum cans, other packaging, and transportation-based end uses have compensated for a slight decline in the construction market, which tends to be cyclical.

Major Sectors Include Raw Materials, Semifabricated, and Finished Products

The aluminum industry is comprised of three principal sectors:

- The **raw materials sector** produces alumina from bauxite (the ore of aluminum) and primary and secondary (scrap-based) molten metal and ingot.
- The **semifabricated sector** produces sheet, plate, foil, forgings, castings, wire, rod, bar, extrusions, elemental and alloyed powders, and alumina-based chemical products.
- The **finished products sector** uses products from the first two sectors to manufacture a wide variety of consumer/commercial products, including aircraft, automobiles, building components, and packaging for food products.

Primary Aluminum Production Is Concentrated in the Pacific Northwest and Ohio River Valley

Aluminum is produced by the electrolysis of alumina through a consumable carbon anode in the Hall-Heroult process. Alumina is itself extracted from bauxite, a natural ore, by the Bayer process. The aluminum industry produces ingots of pure (greater than 99%) aluminum that serve as feedstock for other materials and processes.

The domestic primary aluminum smelting industry (SIC 3334) consists of 23 facilities operated by 13 firms with a total workforce of approximately 20,000 (see Table 1-1). The secondary smelting industry operates an estimated 68 plants employing 3,600 people. These figures have remained fairly stable since

Table 1-1. Number of Aluminum Manufacturing Facilities in the United States (as of 1992)

Product	Number of Plants
Primary Ingot	23
Secondary Ingot	68
Sheet & Plate	48
Foil	21
Wire, Bare, Conductor, & Non-conductor	21
Steel-Reinforced Aluminum Stranded Conductor (ACSR) and Aluminum Cable, Bare	14
Wire & Cable, Insulated or Covered	37
Extruded Products	190
Powder & Paste	16
Forgings	47
Impacts	13

Source: *Aluminum Statistical Review for 1995*, The Aluminum Association, 1996.

1988, reflecting the industry's strength following restructuring in the early 1980s (EPA 1995).

Overall, the U.S. aluminum industry employs more than 130,000 people, directly contributing more than $30 billion to the U.S. Gross Domestic Product.

Total primary aluminum installed capacity in the United States was 4,190 thousand metric tons (4,610 thousand tons or 9,225 million pounds) in 1995. As shown in Table 1-2 and Figure 1-1, the United States accounted for 17.3% (3,375 thousand metric tons) of the world's primary aluminum production of 19,442 thousand metric tons (21,425 thousand tons) that year.

The majority of primary aluminum producers in the United States are located either in the Pacific Northwest (approximately 39% of capacity) or the Ohio River Valley (about 31% of capacity). Most secondary aluminum smelters (part of SIC 3341) tend to be located in the Great Lakes Region and Southern California (see Figure 1-2).

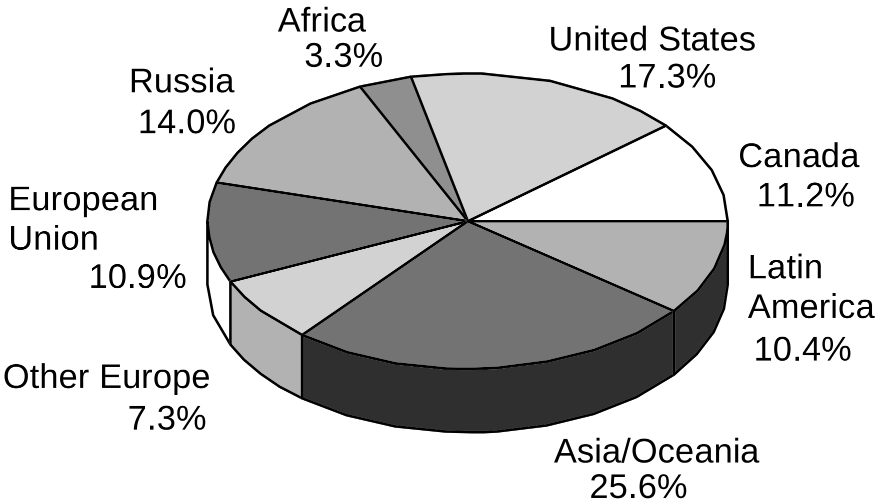
Primary and secondary aluminum production facilities are located in different regions because of the electricity-intensive nature of primary aluminum production. Primary smelters prefer to locate in regions where hydropower is abundant and electricity rates are lower. Secondary smelters typically locate near major industrial and consumer centers to take advantage of the availability of large amounts of scrap (EPA 1995).

Bauxite, the source of alumina in primary production, is imported from Australia, Jamaica, and other countries. It is refined in this country at five Bayer plants with an estimated combined capacity of 5.1 million metric tons (5.6 million tons). These plants are mostly situated in the Gulf region because of proximity to port facilities.

Table 1-2. World Primary Aluminum Production - 1995

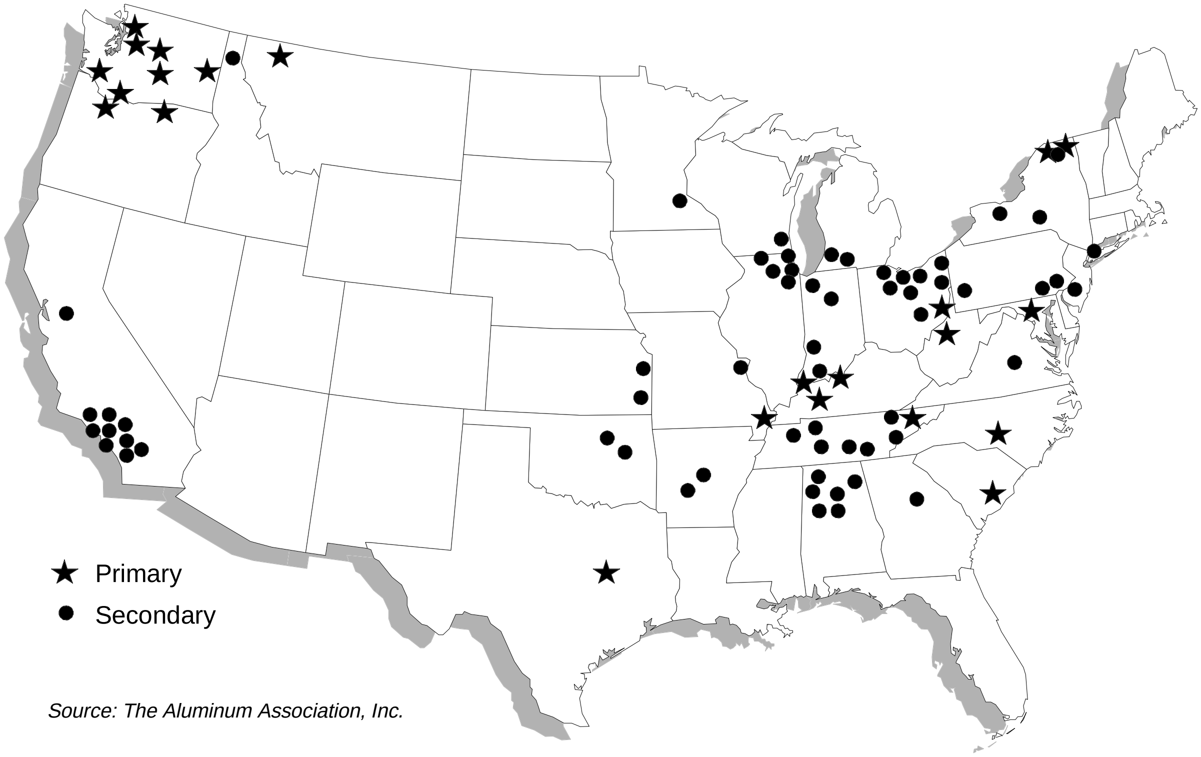
Country/Continent	Production (thousand metric tons)	Percentage (%) of World Production
Africa	639	3.3
North America Canada United States	5,547 2,172 3,375	28.5 11.2 17.3
Latin America	2,020	10.4
Asia	3,400	17.5
European Union	2,113	10.9
Russia	2,722	14.0
Other Europe	1,431	7.3
Oceania	1,570	8.1
TOTAL WORLD	**19,442**	**100.0**

Source: *Aluminum Statistical Review for 1995*, The Aluminum Association, 1996.



Source: The Aluminum Association, Inc.

Figure 1-1. World Primary Aluminum Production



Source: The Aluminum Association, Inc.

Figure 1-2. Distribution of Aluminum Plants in the United States

The U.S. aluminum mill products industry, which produces wrought or fabricated products and castings, is the largest in the world. As can be determined from Table 1-1, approximately 400 facilities in the United States produce aluminum mill products. In addition, an estimated 700 or so facilities produce aluminum die castings.

Integrated fabricators -- companies that encompass both production of the primary or secondary aluminum and fabrication of products -- accounted for approximately two-thirds of U.S. production of aluminum mill products in 1992 (ITC 1994). The remaining third was produced by independent fabricators who purchase primary forms of aluminum and then roll, extrude, cast, or forge them into finished products

Recycled Aluminum Comprises One-Third of Total Market

Recycling is a critical component of the aluminum industry based on its favorable economic impact on production as well as its contribution to the environment. Aluminum recycling has nearly doubled in the last ten years; recycled aluminum currently represents one-third of the total U.S. aluminum supply.

Secondary refiners recover aluminum from both purchased new and old aluminum scrap. New (industrial) scrap is generated by plants making end products, while old (consumer) scrap comes from metal products that have been discarded by consumers.

In 1995, 3,188 thousand metric tons (3,513 thousand tons) of metal valued at more than $3 billion were recovered from both new and old aluminum scrap. Of this total, approximately 47% (1,505 thousand metric tons) was recovered from old scrap, with the remaining 53% (1,683 thousand metric tons) from new scrap (AA 1996).

Reclamation of used aluminum beverage cans continues to be a major source of supply for the U.S. aluminum industry. As shown in Figure 1-3, the recycling rate for aluminum beverage containers was approximately 62% (63 billion cans) in 1995, yielding 915 thousand metric tons of aluminum (AA 1996).

Recycling of aluminum is highly beneficial, saving approximately 95% of the energy required for producing primary aluminum. Recovery and recycling also result in lower origination and transportation costs.

1.2 Market Trends and Statistics

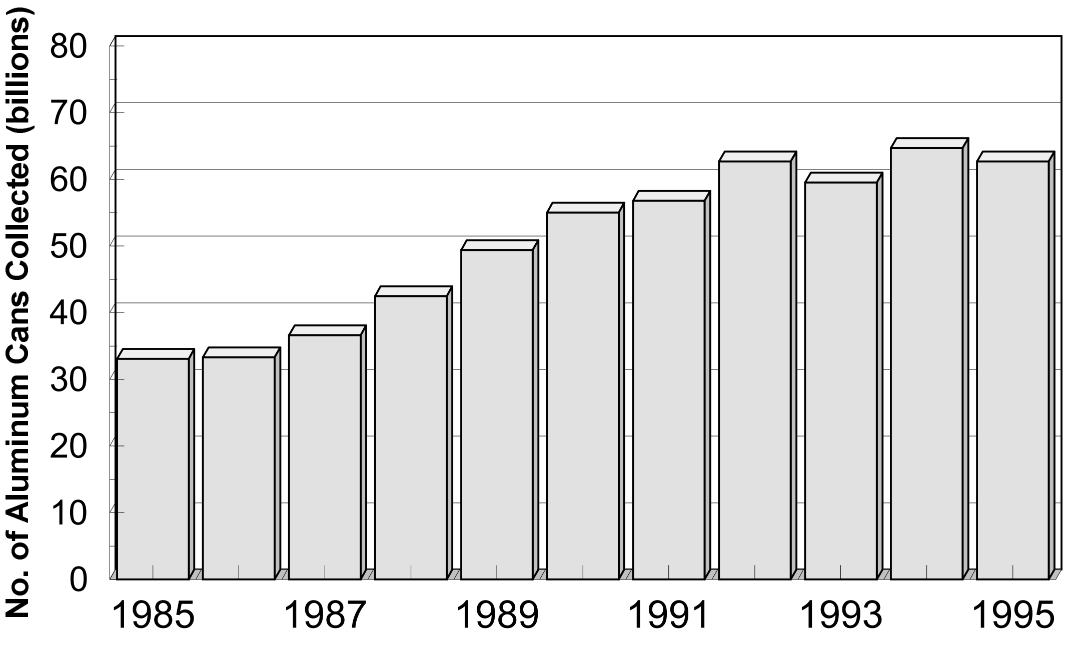
Primary and Secondary Production Are Supplemented by Imports

The United States' supply of aluminum is calculated as the sum of domestic primary production, imports of primary and mill products, and metal recovered from scrap. Since 1985, the total supply has expanded at the average rate of 3.7% per year. In 1995 primary production increased to 36.4% of total supply, imports declined to 29.2%, and secondary recovery accounted for 34.4%.

In 1995 the nation's total aluminum supply was 9,265 thousand metric tons (10,192 thousand tons, or about 20,380 million pounds) (AA 1996). Table 1-3 shows total U.S. aluminum supply for the period 1970 to 1995. The contributors to the 1995 total (in thousand metric tons) were as follows:

- primary production -- 3,375
- primary imports - 1,976
- imports of mill products -- 726
- secondary recovery -- 3,188

Figure 1-4 compares total aluminum supply by source for 1985 and 1995. Figure 1-5 summarizes primary aluminum production for the period 1985 to 1995. Total primary production



Source: Estimated by the Aluminum Association Statistical and Market Research Committee through 1988. From 1989 forward, figures are based on joint survey conducted by the Aluminum Association and the Institute of Scrap Recycling Industries (ISRI). Beginning in 1987, UBC data includes estimates of exported can scrap.

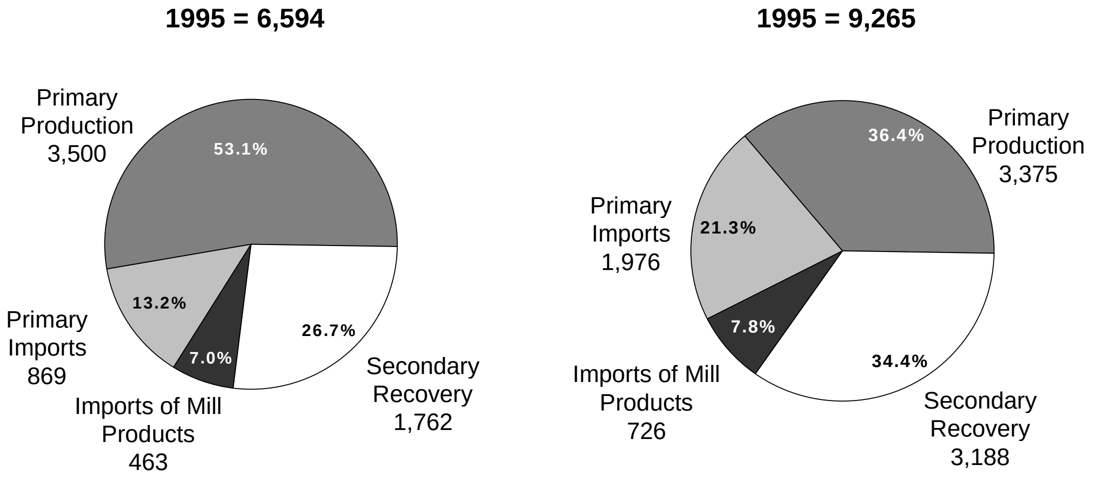
Figure 1-3. Aluminum Can Reclamation Data, 1985 - 1995

Table 1-3. Total U.S. Aluminum Supply, 1970 - 1996 (thousand metric tons)

Year	Domestic Primary Production	Total Secondary Recovery	Imports: Primary	Imports: Mill Products	Imports: Total Imports	TOTAL SUPPLY
1970	3,607	937	318	88	406	**4,950**
1975	3,519	1,121	394	59	453	**5,093**
1980	4,653	1,577	527	76	603	**6,833**
1985	3,500	1,762	869	463	1,332	**6,594**
1990	4,048	2,390	962	459	1,421	**7,863**
1991	4,121	2,286	1,029	369	1,398	**7,805**
1992	4,042	2,756	1,164	409	1,573	**8,371**
1993	3,695	2,944	1,850	477	2,327	**8,966**
1994	3,299	3,086	2,536	600	3,136	**9,520**
1995	3,375	3,188	1,976	726	2,701	**9,265**
1996	3,577	NA	NA	NA	NA	**NA**

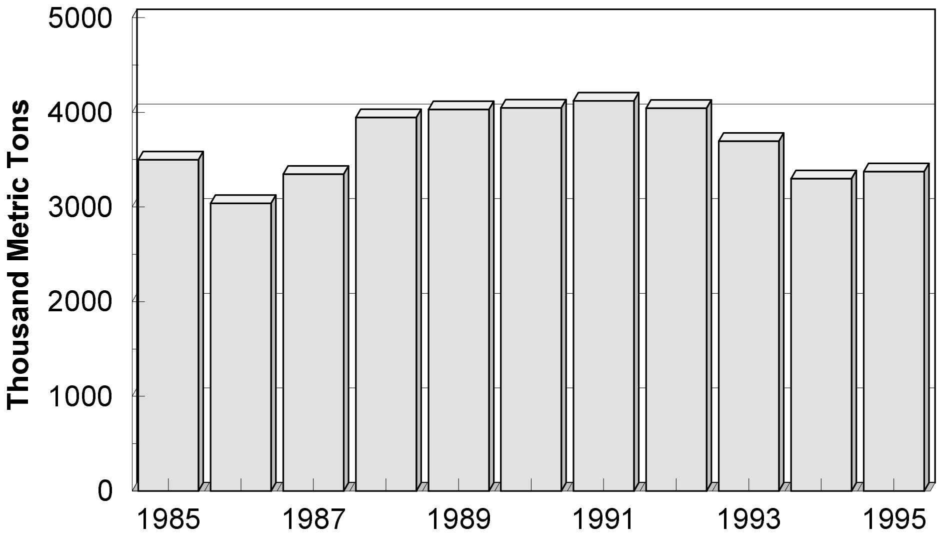
NA Data not yet available.

Sources: *Aluminum Statistical Review for 1995*, The Aluminum Association, 1996.
"Primary Aluminum Production," The Aluminum Association web site, March 1997.



Source: The Aluminum Association, Inc., *Aluminum Statistical review for 1995.*

Figure 1-4. Total U.S. Aluminum Supply, 1985 and 1995 (thousand metric tons)



Source: The Aluminum Association, Inc.

Figure 1-5. U.S. Primary Aluminum Production, 1985 - 1995

in 1996 was reported to be 3,577 thousand metric tons (AA 1997).

Total Net Shipments Are About 21 Billion Pounds

Table 1-4 summarizes key aluminum industry data for 1995 and 1996, including production, imports, exports, and shipments. Preliminary Aluminum Association figures for 1996 indicate that industry shipments, including exports, totaled an estimated 9,446 thousand metric tons (20,825 million pounds), down 1.2% from the 1995 total of 9,557 thousand metric tons (21,070 million pounds). The total value of shipments for 1993, the most recent year for which these figures are available, was $27.45 billion (AA 1996a). Figure 1-6 shows the distribution of aluminum net shipments by major market.

U.S. exports of aluminum ingot and mill products were reported at 1,310 thousand metric tons (2,889 million pounds) during 1996, rising less than 1% from the 1995 total of 1,307 thousand metric tons (2,881 million pounds). Imports fell almost 5% from 2,701 thousand metric tons (5,956 million pounds) to 2,572 thousand metric tons (5,671 million pounds).

For the full year 1996, domestic shipments totaled an estimated 8,136 thousand metric tons (17,936 million pounds), down 1.4% from 1995. Mill shipments were reported at 6,990 thousand metric tons (15,411 million pounds), down 2.4% from 7,160 thousand metric tons (15,784 million pounds) in 1995.

Shipments of aluminum in the United States in 1995 included the negative effects of inventory destocking that year. In spite of this, consumption of aluminum was up marginally from previous years, a respectable performance considering the industry's strong showing in 1994.

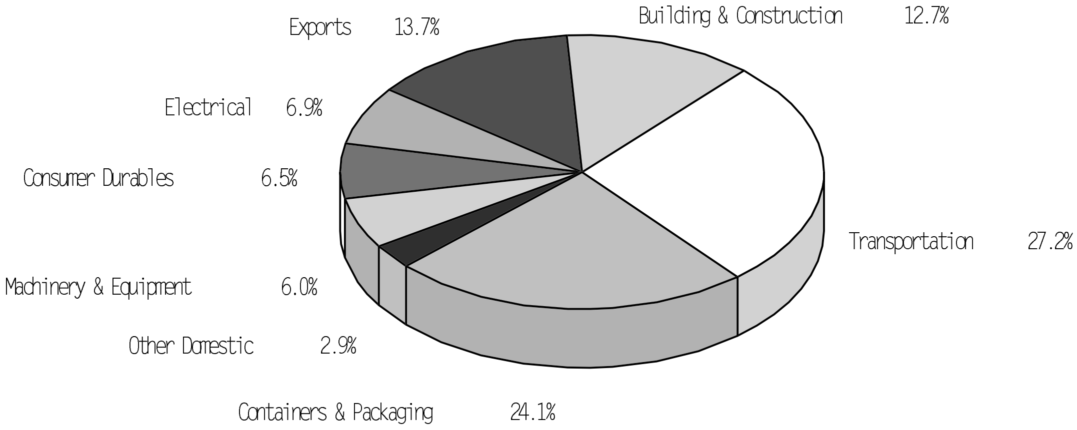
On the trade side, U.S. producers increased exports by close to 10% in both ingot and mill products in 1995. Although total imports were down about 11%, reflecting weaker U.S. economic growth, they are still responsible for more than one-quarter of the total U.S. aluminum supply. Imports of mill products were actually up, but represent only one-third of the volume of ingot imports. Ingot imports dropped off sharply from 1994 because of slower economic growth and the weaker U.S. dollar (Born 1996).

Table 1-4. Capsule Review of the U.S. Aluminum Industry - 1995

Measure	Thousand Metric Tons [million pounds]	
	1995	1996[a]
SUPPLY		
Primary Production	3,375 [7,441]	3,577 [7,884]
Imports	2,702 [5,956]	2,573 [5,671]
Secondary Recovery	3,188 [7,028]	NA
TOTAL	9,265 [20,425]	NA
PRIMARY CAPACITY (year end)	4,184 [9,222]	NA
NET DOMESTIC SHIPMENTS TO MAJOR MARKETS		
Building & Construction	1,216 [2,679]	NA
Transportation	2,602 [5,736]	NA
Consumer Durables	621 [1,368]	NA
Electrical	657 [1,448]	NA
Machinery & Equipment	569 [1,255]	NA
Containers & Packaging	2,309 [5,088]	NA
Other	279 [615]	NA
TOTAL	8,253 [18,189]	8,138 [17,936]
EXPORTS[b]	1,307 [2,881]	1,311 [2,889]
TOTAL NET SHIPMENTS	9,560 [21,070]	9,449 [20,825]

NA Data not yet available.
a Preliminary data.
b Estimated.

Sources: *Aluminum Statistical Review for 1995,* The Aluminum Association, 1996.
Data reported on The Aluminum Association web site.



Source: The Aluminum Association, Inc.

Figure 1-6. Distribution of Aluminum Net Shipments by Major Market - 1995

The majority of U.S. aluminum metal imports come from Canada (60% in 1995) because of its proximity and extensive ties to U.S. operations (e.g., Alcan and Reynolds). Another 18% of 1995 imports came from Russia. Venezuela is an ingot source, and Mexico and Venezuela are secondary scrap sources. Of the 124 countries receiving aluminum products from the United States in 1995, 33% of the total went to Canada and about 18% to Japan.

Transportation Sector Is Largest Market for Aluminum

The largest concentration of domestic aluminum shipments is to the transportation, container and packaging, and building and construction markets. Combined, these three markets account for almost two-thirds of industry consumption (see Figure 1-6). The next largest grouping includes electrical, consumer durables, and machinery and equipment. Exports account for the remaining 13.7%.

The transportation sector continues as the largest market for aluminum, representing 27.2% of total domestic shipments in 1995. Included in this market are passenger cars, trucks and buses, and trailers and semi-trailers. This market has grown more than 65% over the last decade, primarily due to increased use of aluminum in passenger cars.

Aluminum's use in vehicles is rapidly increasing, where its cost per pound can be justified on the basis of weight reduction and performance. From about 100 lb/car on average in 1960, current models average about 250 lb/car. Aluminum can provide a weight savings of up to 55% compared to an equivalent steel structure, while matching or exceeding crashworthiness standards of a similarly sized steel structure (AA 1997).

At 24.1% of total domestic shipments, the containers and packaging industry is the second largest market for aluminum. Representative products include metal cans, semi-rigid food containers, and household and institutional foils. To a large degree, the strength of this market can be attributed to the recyclability of aluminum cans; about two-thirds of the aluminum cans produced today are recycled at more than 10,000 recycling centers nationwide.

The buildings and construction market accounted for 12.7% of total shipments in 1995, a decrease of about 13% from 1994 shipments. This market includes residential, industrial, commercial, farm, and highway applications as well as mobile homes.

Other significant markets include:

- electrical (ACSR and insulated wire and cable products)
- consumer durables (large appliances and air conditioning equipment)
- non-electrical machinery and equipment (agricultural, construction and industrial machinery, irrigation pipe, ladders, fasteners, etc.)

Total demand for aluminum is driven by the strength of demand in these end-use sectors and by the ability of the metal to substitute for other materials, based on cost and design considerations. The integrated primary aluminum producers are also the principal suppliers of fabricated aluminum products. Other purchasers of aluminum raw materials include independent fabricators, distributors, and metal traders.

1.3 Energy and Materials Consumption

Primary Production Is Very Electricity-Intensive

The production of primary aluminum relies on an electrolytic process and is thus very electricity-intensive. In fact, the aluminum industry spends more than $2 billion annually on energy, the majority of which is for electricity. One-third of the average cost of aluminum is for the energy required to make it (Evans 1995).

Major energy savings are achieved through the recycling of scrap aluminum. Reusing aluminum by remelting and casting requires only 5 to 8% of the original energy input of aluminum produced from bauxite (Huglen and Kvande 1994). Increased use of aluminum in transportation and elsewhere have also helped reduce energy and fuel consumption (AA 1997).

The current U.S. average energy consumption for aluminum reduction in an electrolytic cell is estimated to be 15.18 kWh/kg (6.9 kWh/lb) of aluminum (Richards 1997). However, the most efficient smelters operate with an energy consumption of about 13 kWh/kg (5.9 kWh/lb). The average energy consumption of aluminum reduction will continue to decrease as old and obsolete smelters are shut down, existing smelters are retrofitted and modernized, and new cells lines with modern technology are built.

This technology renewal process is slow, particularly because of the high investment costs of new capacity. However, it will give a small but steady reduction in the "industrial average" energy consumption (Huglen and Kvande 1994). Large energy savings from the Hall-Heroult electrolytic process are not expected, however, unless some technological breakthroughs are achieved (e.g., the introduction of dimensionally stable anodes and "wettable" cathodes).

Primary Production Relies Heavily on Hydroelectric Power

The primary source of electric power and the power ownership are very influential on the price of the power used and therefore on the economics of aluminum production. In the United States, primary aluminum production facilities are concentrated in areas with significant hydropower resources because of the lower electricity costs associated with this type of power (Figure 1-1 showed the geographic distribution of both primary and secondary aluminum production plants in the United States).

In cases where an industry is distributed more or less evenly around the country, the fuel mix for the national grid can be used, making calculations easier without sacrificing accuracy. However, electroprocess industries such as aluminum smelting are not distributed uniformly around the country, so a national electricity grid is not a reasonable approximation of their energy use (Hunt et al. 1992). Aluminum smelters are concentrated heavily in the Pacific Northwest where electric power is relatively inexpensive; therefore, specific regional grids are used to calculate smelting energy use.

Table 1-5 shows the grid assumptions for the United States as a whole and for the U.S. aluminum smelting capacity. These assumptions were used to 1) calculate the energy efficiency of the electricity generating and delivery system, and 2) calculate combustion-related emissions associated with major aluminum processes.

Based on the data in Table 1-5, **the conversion factors used for electricity (including losses) were 7,596 kj/kWh (7,234 Btu/kWh) for primary aluminum smelting, and 11,530.6 kj/kWh (10,981 Btu/kWh) for all remaining industry processes** (Richards 1997). Hydropower is counted at its theoretical energy equivalence of 3,580 kj/kWh (3,410 Btu/kWh) with no precombustion impacts included. These impacts are not assumed for hydropower because water does not have an inherent energy value from which line transmission losses, etc. can be subtracted (Hunt et al. 1992).

Energy to Produce Al from Scrap Is 5 to 8% of that Required for Primary Production

Table 1-6 summarizes the unit energy requirements of the primary aluminum production processes of alumina refining, anode manufacture, aluminum smelting, and ingot casting. Table 1-7 summarizes the same information for scrap pretreatment, secondary melting/refining, and hot and cold rolling. Table 1-8 presents the percentage use of each fuel for all of the processes given in Tables 1-6 and 1-7.

As noted previously, reusing aluminum by remelting and casting requires only 5 to 8% of the original energy input of aluminum produced from bauxite (Huglen and Kvande 1994). The data in Tables 1-6 and 1-7 confirm this ratio. According

Table 1-5. Fuel Mix for Estimates of Emissions and Energy Loss Conversion Factors (Percent)

Area	Coal-Fired	Hydro	Natural Gas	Nuclear	Oil	Other
U.S. Aluminum Smelting	50.0	48.0	0.5	1.5	0.0	0.0
U.S. National Grid	56.0	9.8	9.2	20.9	3.6	0.4

Sources: Data reported by Nolan Richards, 1997.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

Table 1-6. Estimated Specific Energy Consumption (by Energy Source) of Primary Aluminum Production Processes (MJ/metric ton of primary aluminum, except as noted)

Energy Source	Specific Energy Consumption [10^6 Btu/ton]					
	Alumina Refining[a]	Coke Production[b,c]	Pitch Production[c,d]	Anode Production[c]	Aluminum Production (Smelting)	Primary Ingot Casting[e]
Electricity	462 [0.40]	35 [0.03]	0.00	826 [0.72]	115,330 [99.85]	1,910 [1.65]
Natural Gas	23,336 [20.20]	763 [0.66]	20 [0.02]	696 [0.60]	752 [0.65]	2,417 [2.09]
Distillate Oil	--	327 [0.28]	8 [0.01]	149 [0.13]	20 [0.02]	698 [0.61]
Residual Oil	243[f] [0.21]	--	--	--	5 [0.005]	698 [0.61]
Propane/LPG	--	--	--	149 [0.13]	8 [0.01]	465 [0.40]
Coal	729 [0.63]	--	--	--	--	--
Gasoline	--	--	--	--	5 [0.005]	372 [0.32]
Carbon Anodes	--	--	--	--	17,325 [15.00]	--
TOTAL	**24,770 [21.44]**	**1,125 [0.97]**	**28 [0.03]**	**1,820 [1.58]**	**133,445 [115.54]**	**6,560 [5.68]**

[a] Assumes 1,880 kg of alumina per metric ton of aluminum (3,760 lb/ton).

[b] Assumes average anode coke content of 60%.

[c] Assumes an average of 0.45 metric ton of anode per metric ton of primary aluminum produced (Welch 1993). Total shown is for prebaked anodes (used in 80% of production); Soderberg anodes are baked in-situ and use only electricity.

[d] Assumes average anode pitch content of 15%.

[e] Energy per ton of primary aluminum ingot cast.

[f] Includes some distillate oil.

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"A Model for Petroleum Coke Reactivity," Welch et al., *Light Metals 1993*.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

Table 1-7. Estimated Specific Energy Consumption (by Energy Source) of Secondary Aluminum Production Processes and Aluminum Semi-Fabrication Processes (MJ/metric ton of aluminum processed, except as noted)

Energy Source	Specific Energy Consumption [10^6 Btu/ton]				
	Scrap Pretreatment[a]	Secondary Melting/ Refining[b,c]	Hot Rolling - Softer Alloys[d]	Hot Rolling - Harder Alloys[e]	Cold Rolling
Electricity	300 [0.26]	1,521 [1.31]	3,530 [3.05]	3,800 [3.29]	5,390 [4.67]
Natural Gas	1,300 [1.13]	4,247 [3.68]	2,536 [2.20]	1,766 [1.53]	2,349 [2.03]
Distillate Oil/Diesel	--	44 [0.04]	29 [0.03]	20 [0.02]	27 [0.02]
Residual Oil	--	44 [0.04]	--	--	--
Lube Oil	--	--	146 [0.12]	102 [0.09]	135 [0.12]
Propane and LPG	--	66 [0.06]	29 [0.03]	20 [0.02]	27 [0.02]
Coal	--	--	146 [0.12]	102 [0.09]	135 [0.12]
Gasoline	--	--	29 [0.03]	20 [0.02]	27 [0.02]
TOTAL	**1,600 [1.39]**	**5,922 [5.13]**	**6,445 [5.58]**	**5,830 [5.05]**	**8,090 [7.00]**

a Energy per metric ton of scrap input.
b Energy per metric ton of scrap melted.
c Includes casting energy requirements.
d Softer alloys are represented by 3104.
e Harder alloys are represented by 5182.

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

to Table 1-6, the specific energy requirements to produce one metric ton of primary aluminum (including ingot casting) are approximately 167,750 MJ (corresponding to about 145.2 10^6 Btu/ton).

From Table 1-7, the specific energy requirements to produce one metric ton of secondary aluminum (including scrap pretreatment, melting, refining, and casting) are approximately 7,500 MJ (6.5 10^6 Btu/ton). According to these figures, the energy requirements of producing aluminum from scrap are therefore about 5% those of producing aluminum from bauxite.

U.S. Primary Production Consumed Close to Half a Quad of Energy in 1995

Table 1-9 presents an estimate of the total U.S. energy consumption associated with the production of molten primary aluminum in 1995. The energy used in reduction cells (smelting) represents approximately 86% of the total 522.2 10^9 MJ (497.3 10^{12} trillion Btu). Alumina refining accounts for another 13% of total energy requirements and anode manufacture the remaining 1%. Casting, rolling, and other semi-fabrication steps are not included in these figures.

The most recent Aluminum Association industry energy survey, which was conducted in 1989, reported a total of 648.0 10^9 MJ (617.1 10^{12} Btu) for the same primary aluminum production steps (AA 1991). When this total is adjusted to use the same electricity conversion factors used in the

Table 1-8. Estimated Percentage Use of Each Energy Source by Major Process

Process	Energy Source (%)								
	Electricity[a]	Natural Gas	Dist. Oil	Resid. Oil	Lube Oil	Propane & LPG	Coal	Gasoline	Carbon Anodes[b]
Alumina Refining	1.8	94.2	0.0	1.0	0.0	0.0	3.0	0.0	0.0
Anode Production[c,d]	45.3	38.2	8.25	0.0	0.0	8.25	0.0	0.0	0.0
Aluminum Production	85.9	0.2	0.2	0.0	0.0	0.1	0.0	0.1	13.5
Ingot Casting	29.1	36.9	10.6	10.6	0.0	7.1	0.0	5.7	0.0
Scrap Pretreat	18.8	81.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Scrap Melting/ Refining	25.7	71.7	0.75	0.75	0.0	1.1	0.0	0.0	0.0
Hot Rolling[e]	65.2	30.3	0.3	0.0	1.8	0.3	1.8	0.3	0.0
Cold Rolling	66.7	29.0	0.3	0.0	1.7	0.3	1.7	0.3	0.0

a Includes losses using conversion factor of 7,596 kj/kWh (7,234 Btu/kWh) for aluminum smelting and 11,530.6 kj/kWh (10,981 Btu/kWh) for all other processes.
b Approximately 81% of energy content of anode is from petroleum coke; other 19% is from pitch.
c Does not include embodied energy of anode; this is included under alumina reduction.
d Non-electric fuel percentages are estimated based on data supplied by Richards (Richards 1997).
e Harder alloys represented by 5182.

Sources: Data reported by Nolan Richards, 1997.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

current study, the total comes to 662.9 10^9 MJ (631.3 10^{12} Btu). The 1989 total was based on a total primary aluminum production of 4,030.2 thousand metric tons (4,433.2 thousand tons); the 1995 production of 3,375.2 thousand metric tons (3,712.3 thousand tons) represents a 16% decrease from the earlier level. However, the total energy use decreased 21% between 1989 and 1995, indicating some improvement in energy efficiency during that time period.

Specifically, the unit energy requirements of the reduction process decreased from 144.7 10^3 MJ/metric ton (125.3 10^6 Btu/ton) in the 1989 survey (using an adjusted electricity conversion factor) to 133.4 10^3 MJ/metric ton (115.5 10^6 Btu/ton) in 1995, an 8% drop. Similarly, the unit energy requirements of alumina production decreased from 26.1 10^3 MJ/metric ton (22.6 10^6 Btu/ton) of primary aluminum to 24.7 10^3 MJ/metric ton (21.4 10^6 Btu/ton) of primary aluminum, a 5% improvement.

The Aluminum Association's 1989 survey also reported a total of 206.4 10^9 MJ (196.6 10^{12} Btu) used for the processes of holding, melting, and casting; mill products (semi-fabrication); and other fabrication. Adjusting these totals with the electricity conversion factors used in this study yields 224.4 10^9 MJ (213.7 10^{12} Btu). Nearly two-thirds of this total was attributed to mill products, and nearly one-third to holding, melting, and casting.

Table 1-9. Estimated Total Industry Energy Use Associated with Primary Aluminum Production - 1995[a]

Process	Estimated Total Production - 1995 (thousand metric tons)	Estimated Industry Energy Use	
		10^9 MJ	10^{12} Btu
Alumina Refining	4,970.0	65.5	62.4
Anode Manufacture[b]	1,518.8	6.3	6.0
Primary Aluminum Production (Smelting)	3,375.2	450.4	428.9
TOTAL	**--**	**522.2**	**497.3**

a Covering process steps up to and including the production of molten metal in reduction cells.

b Prebaked anodes are assumed to be used for 80% of primary aluminum production, Soderberg for 20% (EPA 1996). An average anode requirement of 0.45 metric ton per metric ton of primary aluminum produced is assumed (Welch 1993). Includes energy use associated with coke and pitch production, assuming an average 60% coke and 15% pitch content.

Sources: Data reported by Nolan Richards, 1997.
Aluminum Statistical Review for 1995, The Aluminum Association, 1996.
"World Bauxite and Alumina Production Capacity in the Mid-1990s," E. Sehnke, *Light Metals 1996*.
Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards, U.S. Environmental Protection Agency, July 1996.
"A Model for Petroleum Coke Reactivity," Welch et al., *Light Metals 1993*.

Similar industry-wide energy estimates could not reliably be made for 1995 because of the lack of data on the amounts of aluminum (including scrap, ingot, etc.) undergoing each of the processes. The large differences in the amounts of secondary metal recovery and imports (of both primary aluminum ingot and mill products) meantthat extrapolation of the 1989 data to 1995 could not reliably be performed.

Table 1-10 presents estimates of total U.S. aluminum industry energy use (both primary and secondary production, where possible) from several sources for the years 1989, 1991, and 1995.

Total energy use for the entire industry (including primary and secondary processing) was reported by The Aluminum Association to be 854.4 10^9 MJ (813.7 10^{12} Btu) in 1989 (AA 1991). Applying the electricity conversion factors used in this study for purposes of comparison yields an adjusted total of 887.3 10^9 MJ (845.1 10^{12} Btu).

The most recent Energy Information Administration Manufacturing Consumption of Energy Survey (MECS), which was for the year 1991, gave totals of 312 10^9 MJ (297 10^{12} Btu) for total primary aluminum industry (SIC 3334) energy consumption and 64 10^9 MJ (61 10^{12} Btu) for aluminum sheet, plate, and foil (SIC 3353). Both of these totals excluded losses associated with electricity generation, transmission and distribution. When losses are factored into the MECS data (applying the conversion factors used in the current study), the respective totals are 583 10^9 MJ (555 10^{12} Btu) and 97 10^9 MJ (93 10^{12} Btu), for a combined total of 680 10^9 MJ (648 10^{12} Btu). The 1991 MECS industry total is significantly lower than the 1989 AA industry total in spite of the fact that 1991 aluminum production levels (both primary and secondary) were somewhat higher. In addition to the problems with comparing different years, discrepancies arise from differences in data collection and estimation methods, and in the processes and types of facilities that were covered.

Table 1-10. Total U.S. Aluminum Industry Energy Use - Recent Estimates (10^9 MJ)

Process/Energy Source	Estimated Annual Energy Use [10^{12} Btu]		
	Aluminum Association Survey (1989)	MECS Survey (1991)[a]	Current Study (1995)
Primary Production[b]			
Non-Electric	139.1 [132.5]	70.4 [67.0]	131.5 [125.2]
Electric[c]	245.0 [233.3]	241.5 [230.0]	184.1 [175.3]
Electric Losses[d]	278.8 [265.5]	270.8 [257.9]	206.6 [196.8]
SUBTOTAL	662.9 [631.3]	582.7[e,f] [554.9]	522.2 [497.3]
Semi-Fabrication			
Non-Electric	124.2 [118.3]	48.3 [46.0]	NA
Electric	31.1 [29.6]	15.2 [14.5]	NA
Electric Losses	69.1 [65.8]	33.9 [32.3]	NA
SUBTOTAL	224.4 [213.7]	97.4[g] [92.8]	NA
TOTAL	**887.3 [845.0]**	**680.1 [647.7]**	**NA**

NA Data not available.

a MECS data is not believed to cover as many processes and types of facilities as the 1989 AA survey.
b Including alumina refining, anode manufacturing, and smelting.
c At 3,580 kj/kWh (3,410 Btu/kWh).
d Using adjusted conversion factors from current study -- 7,596 kj/kWh (7,234 Btu/kWh) for reduction; 11,530.6 kj/kWh (10,981 Btu/kWh) for all other processes.
e Includes casting.
f Assumes the same ratio of alumina refining energy use to smelting energy use found in the 1989 AA survey.
g Represents SIC 3353, Aluminum Sheet, Plate, and Foil.

Sources: Data reported by Nolan Richards, 1997.
Manufacturing Consumption of Energy 1991, Energy Information Administration, DOE/EIA--0512(91), December 1994.
“Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

Table 1-11. Breakdown of Aluminum Production Costs for Several Major Producers - 1989 (cents/pound)

Country	Labor	Alumina/ Supplies	Energy	Overhead	Transport	Net Costs
Australia	8.4	23.4	12.4	4.2	0.8	49.2
Brazil	5.0	28.3	18.0	4.9	0.4	56.6
Canada	11.2	25.8	5.4	3.9	0.6	46.9
United States	12.8	21.5	20.7	6.5	0.7	62.2

Sources: “Aluminum Availability and Supply, A Minerals Availability Appraisal,” Wilburn and Wagner, Info. Circular 9371, U.S. Bureau of Mines, 1993.
“Electricity in the Production of Metals: From Aluminum to Zinc,” J. Evans, *Metallurgical and Materials Transactions*, Vol. 26B, April 1995.

Higher Electricity Costs Affect U.S. Competitiveness

The United States is at a considerable disadvantage compared with Canada, Venezuela, Australia, and other countries in terms of the costs of electricity for primary aluminum. Table 1-11, an examination of the costs of aluminum production in various countries, reveals wide variation in labor costs and even wider disparities in energy costs. This variation occurs in spite of the fact that there is little difference in the energy required to produce a ton of aluminum in the major Western producing countries (Evans 1995).

Some experts feel that low-cost hydroelectric power, coupled with low labor costs and the strategic importance of aluminum, will continue to lead countries outside the United States to subsidize aluminum smelting capacity, maintaining metal production even during periods of low demand (Evans 1995).

Variety of Materials Are Used to Produce Primary, Secondary Metal

The primary aluminum industry imports bauxite ore and refines the ore to extract aluminum oxide (known as alumina). Alumina is subsequently reduced in electrolytic cells to produce molten aluminum. In 1994, the last year for which the U.S. Bureau of Mines collected data, total U.S. alumina production was 4.86 million metric tons (5.35 million tons) (Sehnke 1996). Extrapolating this data to 1995 based on total primary aluminum production (and assuming the same proportions of imported alumina and alumina produced domestically) yields 4.97 million metric tons (5.47 million tons) of alumina produced domestically.

Assuming that approximately 2.3 metric tons of bauxite are required to produce one metric ton of alumina, the total 1995 bauxite requirement is estimated to be approximately 11 to 11.5 million metric tons.

As shown in Table 1-9, an estimated 1,518.8 thousand metric tons of carbon anodes were consumed in the electrolytic reduction of alumina to aluminum in 1995. At average anode contents of 60% and 15%, consumption of petroleum coke and petroleum pitch (or coal tar) is estimated at slightly over 900 thousand metric tons and 225 thousand metric tons, respectively.

In addition to recycling consumer scrap, the aluminum industry recycles scrap generated at its own production facilities, scrap that includes a material known as “dross.” Dross, a byproduct of aluminum melting operations, consists of a mixture of aluminum and oxides that float to the surface of the molten aluminum. White dross is produced at primary aluminum smelters and semi-fabricating facilities, while black dross is generated by secondary aluminum smelters and other recyclers. White dross typically has a higher aluminum content (from 15 to 80%) than black dross (usually <30% aluminum).

The total amount of dross produced at secondary smelters each year has been estimated to be 170,000 tons (154,550 metric tons) (DeSaro 1995). Dross is treated to recover the valuable aluminum metal content; metal recovery from black dross is typically 8 to 30% (AA 1996b). The recovered aluminum is recycled by secondary smelters.

1.4 Environmental Overview

Industry Spends Millions of Dollars Annually on Pollution Control and Abatement

The aluminum industry has managed its pollution control efforts to prevent, rather than passively respond to, environmental issues. The industry has promoted energy conservation and effective waste reduction within the industry; today, aluminum is one of the most commonly recycled metals in the world.

Many aluminum companies participated in the Environmental Protection Agency’s 33/50 program to reduce toxic air pollutants, and are actively involved with other EPA-sponsored pollution prevention programs such as Green Lights, Waste Wise, and the Voluntary Aluminum Industrial Partnership.

Capital and operating costs have increased for many U.S. industries, including the aluminum industry, to meet increasingly stringent environmental standards. In 1994, the primary aluminum industry spent nearly $20 million on capital expenditures for pollution control equipment, on top of more than $32 million the previous year. The aluminum sheet, plate, and foil industry also spent $32 million in 1993 and another $18 million in 1994, while the extruded products sector spent another $4 million in each year (DOC 1996 and 1995). More than half of these expenditures were for air pollution control equipment.

The 1990 Amendments to the Clean Air Act (CAA), the Resource Conservation and Recovery Act (RCRA), and the Clean Water Act have all impacted the aluminum industry. The Clean Air Act, which regulates emissions of various pollutants from aluminum operations, has perhaps had the most impact.

Table 1-12 summarizes the emissions, effluents, and byproducts and solid wastes associated with primary and secondary aluminum production and semi-fabrication processes.

Emissions Generated in Fuel Combustion and Manufacturing Processes

There are two basic types of emissions discussed in this profile:

- combustion emissions associated with the combustion of fuels, including fuels used in the generation of purchased electricity
- process emissions associated with manufacturing processes

Combustion emissions for aluminum can be calculated on a unit basis from the energy data reported in Tables 1-6 and 1-7. These emissions are shown in Table 1-13 for the processes of

Table 1-12. Summary of Emissions, Effluents, Byproducts and Solid Wastes from Primary and Secondary Aluminum Production

Process	Air Emissions[a]	Effluents	Byproducts and Solid Wastes
Alumina Refining	Particulate	Wastewater containing starch, sand, and caustic	Red mud, sodium oxalate
Anode Production	Particulate, fluorides, polycyclic organic matter, SO_2	Wastewater containing suspended solids, fluorides, and organics	Carbon dust, tar, refractory waste
Aluminum Production (Smelting)	CO_2, CO, SO_2, fluorides (gaseous and particulate), perfluorocarbons (CF_4, C_2F_6), polycyclic organic matter	Wet air pollution control (APC) effluents (if applicable)	Spent potlining (RCRA-listed K088), environmental abatement wastes (e.g., wet APC sludge)
Scrap Pretreatment	Particulate, organics, chlorides	Wet air pollution control effluents (if applicable)	Environmental abatement wastes
Scrap Smelting/Refining	Particulate (including trace metals), organics, chlorides, fluorides	Magnesium removal ("demagging") effluents	Dross, salt cake
Semi-Fabrication	Particulate, chlorides, organic droplets and vapors	Cast water blowdown, cooling water blowdown, roll coolant waste, coating line waste	Oils, greases

a Excluding combustion-related emissions.

Table 1-13. Combustion-Related Air Emissions for Major Aluminum Industry Processes[a,b]
(kg/metric ton of aluminum, except as noted)

Process	Emission Factor [lb/ton]						
	SOx	NOx	CO_2	CO[c]	Particulate	VOCs[d]	Organics[c]
Alumina Refining	1.09 [2.18]	1.80 [3.60]	1,251.1 [2,502.2]	1.0 [2.0]	0.34 [0.68]	0.063 [0.126]	3.60 [7.20]
Anode Production[e]	0.56 [1.12]	0.30 [0.60]	137.72 [275.44]	ND	0.15 [0.30]	0.005 [0.010]	ND
Aluminum Production (Smelting)[f]	62.41 [124.82]	24.11 [48.22]	5,514.0 [11,028]	1.30 [2.60]	17.98 [35.96]	0.127 [0.254]	0.70 [1.40]
Primary Ingot Casting	1.72 [3.44]	0.80 [1.60]	372.5 [745.0]	0.20 [0.40]	0.36 [0.72]	0.028 [0.056]	0.75 [1.50]
Scrap Pretreatment[g]	0.18 [0.36]	0.15 [0.30]	81.06 [162.12]	ND	0.05 [0.10]	<0.01 [<0.01]	ND
Secondary Melting/Casting	0.96 [1.92]	0.63 [1.26]	304.51 [609.02]	0.21 [0.42]	0.27 [0.54]	0.013 [0.026]	0.85 [1.70]
Hot Rolling[h]	2.43 [4.86]	1.06 [2.12]	318.05 [636.10]	ND	0.70 [1.40]	0.011 [0.022]	ND

ND Not determined.

[a] Electricity-based emissions based on the fuel mixes in Table 1-4 (U.S. National Grid used for all processes except smelting). Combustion emissions factors used (in lb/million Btu) were as follows: Natural Gas/Propane/LPG (SOx - 0.0, NOx - 0.14, CO_2 - 118.8, Particulate - 0.003, VOCs - 0.006); Distillate Oil (SOx - 0.16, NOx - 0.14, CO_2 - 161.4, Particulate - 0.01, VOCs - 0.002); Residual Oil (SOx - 1.70, NOx - 0.37, CO_2 - 173.7, Particulate - 0.08, VOCs - 0.009); Gasoline (SOx - 0.00, NOx - 0.14, CO_2 - 157.0, Particulate - 0.00, VOCs - 0.090); Coal (SOx - 2.50, NOx - 0.95, CO_2 - 207.1, Particulate - 0.72, VOCs - 0.005); Hydro and nuclear - no combustion emissions. For the U.S. smelting grid, the electricity conversion factors in lb/million Btu were calculated to be: SOx - 1.250; NOx - 0.4820; CO_2 - 109.5; Particulate - 0.360; VOCs - 0.0025. For the U.S. national grid, the electricity conversion factors in lb/million Btu were calculated to be: SOx - 1.406; NOx - 0.550; CO_2 - 133.4; Particulate - 0.4038; VOCs - 0.0034.

[b] Calculations of combustion emission factors based on energy use data by fuel type presented in Tables 1-5 and 1-6.

[c] Emission factors reported by Nolan Richards.

[d] Volatile Organic Compounds.

[e] Prebaked anodes are assumed to be used for 80% of primary aluminum production, and Soderberg for 20% (EPA 1996). An average anode requirement of 0.45 metric ton per metric ton of primary aluminum produced is assumed (Welch 1993). Includes emissions from coke and pitch production (assumes an average anode content of 60% coke and 15% pitch).

[f] Does not include emissions related to anode consumption.

[g] Emission factors per ton of scrap input.

[h] Harder alloys (e.g., 5182) scalped, soaked or preheated, and rolled to form coil.

Sources: Data reported by Nolan Richards, 1997.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.
Emissions of Greenhouse Gases in the United States, Energy Information Administration, DOE/EIA-0573, November 1994.

alumina refining, anode production (including coke and pitch production), primary aluminum smelting, primary ingot casting, scrap pretreatment, secondary melting/casting, and hot rolling. Using the data in Table 1-13, industry-

Table 1-14. Estimated Industry-Wide Combustion Emissions Associated with Primary Aluminum Production - 1995[a,b] (thousand metric tons)

Process	Pollutant [thousand tons]						
	SOx	NOx	CO_2	CO	Particulate	VOCs	Organics
Alumina Refining	3.68 [4.05]	6.08 [6.69]	4,222.71 [4,645.00]	3.37 [3.71]	1.15 [1.26]	0.21 [0.23]	12.15 [13.36]
Anode Production [c]	1.89 [2.08]	1.01 [1.11]	464.83 [511.32]	ND	0.40 [0.44]	0.02 [0.02]	ND
Aluminum Production (Smelting)[d]	210.65 [231.71]	81.38 [89.51]	18,610.85 [20,471.94]	4.39 [4.83]	60.69 [66.75]	0.43 [0.47]	2.36 [2.60]
TOTAL	**216.22** **[237.84]**	**88.47** **[97.32]**	**23,298.39** **[25,628.23]**	**7.76** **[8.54]**	**62.24** **[68.46]**	**0.66** **[0.72]**	**14.51** **[15.96]**

ND Not determined.

[a] Estimates based on the data in Table 1-13 and on a 1995 production level of 3,375.2 10^3 metric tons of primary aluminum.

[b] Industry-wide estimates cannot reliably be made for holding, melting, casting, semi-fabrication, and other fabrication processes because of the lack of data on the amounts of metal undergoing each process.

[c] Includes prebaked anodes only, which are assumed to be used for 80% of primary aluminum production (EPA 1996). An average anode requirement of 0.45 metric ton per metric ton of aluminum produced is assumed (Welch 1993).

[d] Does not include emissions related to anode consumption.

Sources: Data reported by Nolan Richards, 1997.
Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards, U.S. Environmental Protection Agency, July 1996.
"A Model for Petroleum Coke Reactivity," Welch et al., *Light Metals 1993*.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

wide combustion emissions associated with primary aluminum production (including alumina refining, anode manufacture, and smelting) in 1995 are estimated in Table 1-14. Emissions related to anode consumption during smelting are not included in these figures because they are considered process emissions.

Table 1-15 presents a summary of emissions from various aluminum manufacturing processes, including for alumina refining, anode manufacture, primary aluminum smelting, primary ingot casting, scrap pretreatment, secondary melting/refining, and hot and cold rolling. These emissions include CO_2, CO, SOx, particulate, organics, and fluorides from melting and anode manufacture, and particulate, organics, and chlorides from secondary operations. These emissions are discussed in greater detail in Sections 2 through 7. A discussion of major concerns related to air emissions and other environmental issues associated with the aluminum industry follows.

The Industry Complies with Numerous Environmental Regulations

The major Federal statutes and regulations that apply to the aluminum industry include

- the Clean Air Act,
- the Clean Water Act, and
- the Resource Conservation and Recovery Act (RCRA).

Table 1-15. Process-Related Air Emissions for Major Aluminum Industry Processes (kg/metric ton of aluminum, except as noted)

Process	Emission Factor [lb/ton]							
	SOx	NOx	CO$_2$	CO[c]	Particulate	Organics	Chlorides	Fluorides
Alumina Refining	--	--	--	--	0.5 [1.0]	--	--	--
Coke Production[a]	0.81 [1.62]	0.18 [0.36]	--	0.37 [0.74]	0.40 [0.80]	0.29 [0.58]	--	0.0004 [0.0008]
Anode Production[a]	0.70 [1.40]	0.16 [0.32]	--	0.25 [0.50]	0.63 [1.26]	0.20 [0.40]	--	0.25 [0.50]
Aluminum Production (Smelting)	18.0 [36.0]	2.9 [5.8]	1,400.0 [2,800.0]	125.0 [250.0]	4.2 [8.4]	0.13 [0.26]	--	1.3 [2.6]
Primary Ingot Casting	--	--	--	--	0.10 [0.20]	--	0.0078 [0.0156]	--
Scrap Pretreatment[b]	--	--	--	--	0.20 [0.40]	0.05 [0.10]	0.20 [0.40]	--
Secondary Melting/ Casting	--	--	--	--	0.19 [0.38]	0.05 [0.10]	0.17 [0.34]	--
Hot Rolling Softer alloy[c] Harder alloy[d]	--	--	--	--	 0.8 [1.6] 1.2 [2.4]	 1.0 [2.0] 0.3 [0.6]	--	--
Cold Rolling	--	--	--	--	0.42 [0.84]	1.80 [3.60]	--	--

a Emission factors per unit of anode produced.
b Emission factors per unit of scrap input.
c Softer alloys are represented by 3104.
d Harder alloys are represented by 5182.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991).

Other regulations that affect the industry to varying degrees are

- the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (commonly known as Superfund),
- the Toxic Substances Control Act (TSCA), and
- the Endangered Species Act.

The Clean Air Act Limits Emissions of a Wide Range of Pollutants

The Clean Air Act (CAA) and its amendments, including the Clean Air Act Amendments (CAAA) of 1990, direct the Environmental Protection Agency (EPA) to establish national standards for ambient air quality and for EPA and the states to implement, maintain, and enforce these standards through a variety of mechanisms.

In the first section, or "title" of the CAA, EPA has established national ambient air quality standards
(NAAQSs) to limit levels of "criteria pollutants," including carbon monoxide, nitrogen dioxide, lead, particulate matter, ozone, and sulfur dioxide. Title I also authorizes EPA to establish New Source Performance Standards (NSPSs), uniform national emission standards for new stationary sources falling within particular industrial categories. A total of five potlines at four plants are subject to the NSPS.

Title I of the CAA also directs EPA to establish and enforce National Emission Standards for Hazardous Air Pollutants (NESHAPs), uniform national standards oriented towards controlling particular hazardous air pollutants (HAPs). Title III of the CAAA further directed EPA to develop a list of sources that emit any of 189 HAPs, and to develop regulations for these categories of sources. The emission standards will be developed for both new and existing sources based on "maximum achievable control technology" (MACT). The MACT is defined as the control technology achieving the maximum degree of reduction in the emission of the HAPs, taking into account cost and other factors.

In addition to general CAA requirements, specific standards apply to primary aluminum reduction plants. The Standards of Performance for Primary Aluminum Reduction Plants (40 CFR Part 60, Subpart S) are applicable to potroom groups and anode bake plants that commence construction after October 23, 1974. These standards regulate emissions of total fluorides and the opacity of emissions from primary aluminum production.

The primary regulatory mechanism used to implement source emission requirements under the CAA is the State Implementation Plan (SIP), which provide the States with the authority and discretion to establish a strategy to attain primary NAAQS levels.

Carbon Dioxide Emissions Are a Major Industry Concern

Global climate change and its consequences have received widespread public attention since the 1980s. Carbon dioxide (CO_2) is one of the largest contributors to the so-called "greenhouse effect" that absorb and re-radiate energy back towards the Earth's surface.

Between 1968 and 1987, emissions of carbon dioxide from aluminum production in the United States decreased by approximately one-third because of factors such as the following (Forrest and Szekely 1991):

- reduced use of coal
- greater use of recycled aluminum scrap
- other efficiency improvements

The benefits of scrap recycling are especially dramatic in regards to reducing greenhouse gas emissions. It has been estimated that a savings of 2.75 metric tons (3.03 tons) of carbon equivalent is achieved for each metric ton of scrap aluminum substituted for raw ore product (Forrest and Szekely 1991).

In the past, the main concern for the environment was in the vicinity of smelters, with focus on the fluoride emissions from the reduction cells. The industry has made significant achievements in reducing these emissions. Since the 1970s, emissions of total and gaseous fluorides from both prebake and Soderberg cells have been reduced by more than 50% (see Table 1-16).

With the progress made in reducing fluoride emission, the focus of concern has shifted to CO_2 emissions. Carbon dioxide is the main component of the gas created during electrolysis of alumina to form aluminum. Further improvements in existing cell technology cannot be expected to reduce the CO_2 formation during smelting unless inert anodes become technically feasible (Huglen and Kvande 1994).

Carbon dioxide emissions are also strongly dependent on the source of electric power. A considerable reduction in CO_2 emissions may be

Table 1-16. Aluminum Industry Improvements in Fluoride and Particulate Emissions - 1970s to 1990s[a] (kg/metric ton)

Pollutant	Average Emission Factor		
	1970s	1990s	Improvement (%)
Total Fluoride			
Prebaked Cells[b]	3.4 ±2.4	1.65 ±.095	52
Soderberg Cells[c]	3.1	1.2 ±1.4	61
Gaseous Fluoride			
Prebaked Cells[b]	1.15 ±1.2	0.57 ±0.28	50
Soderberg Cells[c]	1.26 ±0.65	0.32 ±0.21	75
Particulate			
Prebaked Cells[b]	10.8 ±0.7	4.4 ±1.6	60
Soderberg Cells[c]	13.0 ±4.0	5.9 ±1.8	55

a Representing seven Washington state aluminum smelters.
b For prebaked cells in 1990s, controls were dry scrubbers and no controls on roof vents.
c For Soderberg cells in 1990s, one plant had wet scrubbers on ducted capture systems and no roof scrubbers, and two plants had dry scrubbers on ducted capture system (and one of these had wet scrubbers on roof vents).

Source: Data reported by Nolan Richards, 1997.

achieved by conversion from coal-fired to hydroelectric power generation.

Total process air emissions (excluding combustion emissions) for smelting and ancillary processes for representative technologies are about 1.56 kg/kg of aluminum, of which 90% (1.4 kg) is CO_2 (Richards 1994).

Total CO_2 releases (combustion-related and from manufacturing) for the unit processes of bauxite mining through the production of molten aluminum in a crucible, representing a blend of technologies in North America, have been estimated at 11.7 kg CO_2/kg of aluminum. Only 1.4 kg of this total is associated with the actual smelting process (excluding generation of electricity). Inclusive of CO_2 from fuel combustion and transportation, total CO_2 emissions are distributed as follows (Richards 1994):

- bauxite mining - 3.2%
- alumina production - 16.1%
- smelting - 81.7%

Power for smelting at the mix of the North American smelting grid (shown in Table 1-5) accounts for 69% of the total CO_2. Thus, reducing CO_2 emissions from the aluminum industry is predominantly affected by the source of power (Richards 1994).

Conversion to inert, non-consumable anodes would decrease CO_2 by 1.4 kg/metric ton of aluminum minus any CO_2 generated during the production of such new anodes. This substitution would also reduce fluorine releases from better hooding and elimination of anode baking, and drastically reduce organic emissions (Richards 1994).

Proposed Air Standards Would Be More Stringent, Cover More Processes

In addition to the CAA requirements already mentioned, EPA is currently working on several regulations that will directly affect the aluminum industry. Specifically, many of the proposed standards will limit the air emissions from various industries by proposing standards based on the Maximum Achievable Control Technology (MACT), standards that will set limits on emissions based upon concentrations in the waste stream.

Primary aluminum processors may be a major source of one or more hazardous air pollutants (HAPs). As a consequence, a MACT-based regulatory program is being developed by EPA. The MACT-based performance standards were proposed in September 1996 and are expected to become final in late 1997 or early 1998. The proposed standards would apply to emissions of HF, measured using total fluorides (TF) as a surrogate, and polycyclic organic matter (POM), as measured by methylene chloride extractables.

The aluminum industry, through The Aluminum Association, responded to the proposed rules in late 1996. The rules would go into effect approximately three years after promulgation.

EPA has determined that the secondary aluminum industry may reasonably be anticipated to emit several of the 189 HAPs listed in Section 112(b) of the Clean Air Act. As a result, EPA is working toward developing emissions factors based on actual operating data, and expects to propose MACT-based performance standards for secondary aluminum in the summer or fall of 1997. Industry will have 60 days to comment; the rules would be promulgated approximately one year later.

The new rules would cover the following areas:

- shredding
- drying/delacquering
- all furnace operations (melting and refining)
- dross cooling
- in-line fluxing

Alumina processing has also been listed by EPA as a source category. The industry, through The Aluminum Association, is in discussion with EPA over whether alumina processing, because of its heavy reliance on natural gas rather than oil, is actually a major candidate for MACT.

The Integrated Combustion Combined Rule (ICCR) MACT rule that is expected to go into effect in the year 2000 will affect emissions from boilers and process heaters. The Aluminum Association is following the development of this regulation, as well as proposed coil-coating MACT regulation.

Industry Working with EPA to Reduce Emissions of CO_2, Other Pollutants

In 1995 the primary aluminum industry entered into a voluntary partnership with EPA to reduce emissions of perfluorocarbons (PFCs) from aluminum smelting by 45% by the year 2000 from 1990 levels. The Voluntary Aluminum Industrial Partnership (VAIP) Program has nearly unanimous industry participation (12 of 13 U.S. companies, representing 94% of domestic production) and is already ahead of reduction schedules.

At EPA's request, the industry is currently considering adding CO_2 to the voluntary program. The industry is holding discussions with EPA to determine how the program could be expanded to cover these additional emissions.

The industry is also involved in discussions with EPA over the agency's November 1996 proposal for ozone and particulate matter. A potential implementation requirement for particulate matter 2.5 microns in diameter or less from baghouses is causing considerable concern in the industry. Current baghouses typically operate at about the 10-micron level; below this, the efficiency of the baghouses may decrease.

The Aluminum Association is also in the process of responding to an EPA proposal to test hydrogen fluoride and carbonyl sulfide under the Toxic Substances Control Act (TSCA). TSCA gives EPA the authority to create a regulatory framework to collect data on chemicals in order to evaluate, assess, mitigate, and control risks that may be posed by their manufacture, processing, and use. The Aluminum Association is reviewing test procedures and will make recommendations on tests to EPA.

In November of 1996, The Aluminum Association filed a petition for EPA to delist the normal alkanes used in rolling mills, exempting them from EPA's VOC requirements. The industry does not consider these substances to be reactive ozone-forming chemicals because of their low reactivity.

Effluents Are Regulated Under the Clean Water Act

The Clean Water Act regulates the amount of chemicals/toxins released by industries via direct and indirect wastewater/effluent discharges. If a facility is discharging directly into a body of water, it must obtain a National Pollution Discharge Elimination System (NPDES) permit. If it is discharging to a publicly owned treatment works (POTW), it must adhere to specified pretreatment standards.

The Aluminum Forming Point Source Category (40 CFR Part 467) is applicable to wastewater from these operations:

- rolling with neat oils
- rolling with emulsions
- extrusion
- forging
- drawing with neat oils
- drawing with emulsions

EPA has been developing effluent guidelines for metal products and machine processes that may include operations performed at aluminum industry plants. A proposal issued in 1995 was commented on by a coalition of industries, including The Aluminum Association.

Solid and Hazardous Wastes Are Managed Under RCRA

The Resource Conservation and Recovery Act (RCRA) was passed in 1976 as an amendment to the Solid Waste Disposal Act to ensure that solid wastes are managed in an environmentally sound manner. A material is classified under RCRA as a hazardous waste if the material meets the definition of solid waste and that solid waste material exhibits one of the characteristics of a hazardous waste or is specifically listed as a hazardous waste.

Spent potlining from primary aluminum reduction is a RCRA-listed hazardous waste designated "K088." EPA estimates that about 109,000 metric tons (120,000 tons) of K088 are generated annually (EPA 1996b).

As part of EPA's groundwater protection strategy, RCRA prohibits the land disposal of most hazardous wastes until they meet a waste-specific treatment standard. Of particular significance to the aluminum industry is a Phase III land disposal restrictions (LDR) rule that restricts the land disposal of spent aluminum potlining. Currently, about 80% of this waste is disposed in Subtitle C landfills, with the remainder recycled or incinerated (EPA 1996b).

EPA Currently Developing Several New Guidelines That Affect Aluminum Industry

The industry is currently working with the automotive and coil coating industry on the issue of aluminum conversion coating. A RCRA hazardous waste code, F019, lists the sludge generated from this process as hazardous waste, regardless of the chemical constituents present. Since the waste code was listed, chromium and cyanide have been replaced from chemical conversion coating formulations. The industry is petitioning EPA to redefine the waste code listing to reflect only those sludges generated from chromium- and/or cyanide-based formulations.

Potential Re-Engineering of RCRA of Concern to Industry

The industry is concerned over the potential for re-engineering of RCRA. Although this is under consideration by EPA, the timetable has been repeatedly pushed back. A specific area of concern is the potential for RCRA to be applied to recycled aluminum, defining this process as a waste treatment rather than a manufacturing process.

In April 1996 EPA promulgated treatment standards for hazardous wastes from primary aluminum production under Phase III of its Land Disposal Restrictions (LDR) program. As of July 1997, primary aluminum producers will have to ship and treat spent potliner. Hazardous constituents in these wastes will also be required to meet universal treatment standards (UTS) before disposal in a land-based unit.

Industry action with regard to Superfund Laws includes resolving retroactive as well as joint and several liability claims, and assuring that natural resource damage issues do not impose an overly heavy financial burden on the industry.

Industry Experts See Need for Involvement in Policy at the International Level

Recognizing that it is part of a worldwide market, the U.S. aluminum industry has consistently supported lowering tariffs and opening markets for primary metal as well as for semifabricated products.

According to Allen Born, Chairman and CEO of Alumax, Inc., the public policies that the aluminum industry is going to have to live with are being established at a supranational level. For example, instead of confronting a proposed BTU tax in the United States, a carbon tax designed to accomplish internationally agreed-upon objectives for a global-climate treaty could be imposed. The aluminum industry has concerns that universal environmental and energy policies could be abused by some countries to protect domestic industry from competition (Born 1996).

Under the Basel Convention, the recycling of aluminum scrap and dross (with an aluminum content less than 45%) has become classified as hazardous waste treatment in many other countries. In this country, the EPA has confirmed that scrap metal is not going to be regulated as a waste of any kind under the Resource Conservation and Recovery Act. However, this does not apply to dross at the international level (Born 1996).

Current industry practices may expose producers to the risk of significant liabilities associated with waste disposal and the potential for future remediation mandated by conditions that often lie outside their immediate control (Rooy 1995).

The International Standards Organization (ISO) is currently developing environmental standards based on life-cycle analysis. There is concern in the industry that, under certain circumstances, some countries could use ISO to dictate what production or process methods must be used in order to give their domestic industries a competitive advantage (Born 1996).

For many reasons, therefore, the industry must concern itself with public policy development at the international level, becoming engaged whenever possible.

2

Alumina Production

2.1 Process Overview

Alumina is Extracted from Bauxite by the Bayer Process

Alumina is extracted from bauxite ore using the Bayer process, which consists of the following five major steps:

- crushing/blending
- digesting
- clarification
- precipitation
- calcination

Most refineries use a mixture of blended bauxites to provide a feedstock with consistent properties. Crude bauxite ore is first dried, finely **crushed** in ball mills, and **blended** with recycled plant liquor to form a slurry. This liquor contains dissolved sodium carbonate and sodium hydroxide (caustic soda) recovered from previous extraction cycles, and supernatant liquor recycled from the red-mud holding ponds. Lime (CaO) is added to the slurry in mixers to control phosphorus content and to improve the solubility of alumina.

The slurried ore is then heated and pumped to **digesters** (heated pressure tanks), where it is reacted at a high temperature under steam pressure. The result is a mixture of dissolved aluminum oxides (sodium aluminate, $NaAlO_2$) and insoluble bauxite residues known as red mud. Sodium oxalate and other salts are also formed. Time, temperature, pressure, and concentration are all closely controlled to maximize the amount of alumina that will eventually be recovered.

During the digestion reaction a majority of the impurities such as silicon, iron, titanium, and calcium oxides drop to the bottom of the digester and form a sludge of red mud. To separate the red mud from the aluminate solution, the pressure is reduced and the mixture is sent to clarification. The remaining sodium aluminate slurry is then flash cooled by evaporation from nearly 260ºC (500ºF) to about 93ºC (200ºF) and sent for clarification. The steam produced during flashing is used to preheat the caustic liquor in heat exchangers running counter-current to the flash tanks.

During **clarification**, sand, iron oxide, and red mud are removed in a series of settling, thickening, and filtration units. The slurry is first sent through either a gravity separator (e.g., settling tank) or a wet cyclone to remove coarse sand particles. A flocculating agent (typically synthetic polymers and/or starch) is added to increase the settling rate of the red mud.

Typically, greater than 99% of the mud solids are removed during settling (Malito 1996). The overflow from the settling tank contains the alumina in solution, which is further purified by filtration (usually pressure filtration but occasionally sand filtration) to remove any fine impurities. These impurities and the red mud are sent to treatment and disposal units (see Section 2.6).

The filtered aluminate solution is then fed into a **precipitation** tank, where it is seeded with a small amount of fine aluminum hydroxide crystals. These "seeds" stimulate the alumina to initiate the precipitation of solid crystals of aluminum hydroxide. The solution is stirred continuously and slowly cooled for approximately 40 hours. Under these conditions, crystals of alumina trihydrate are formed, slowly increasing in size. Temperature and other variables are carefully controlled so that the crystals formed can be more easily filtered.

Up to two-thirds of the aluminum content forms into hydrate crystals during the precipitation process. The aluminum hydroxide crystals settle to the tank bottom and are removed. The crystals are separated into fine and coarse crystal fractions. The coarse crystals are washed to remove any caustic soda residues, vacuum dewatered, and sent on for calcination. The fines are used to seed future charges. The remaining aluminate solution is typically recycled to the start of the Bayer process to recover the caustic soda and alumina values.

In the **calciners** (a type of kiln), the aluminum hydroxide is roasted at about 980ºC (1800ºF). Two types of kilns are currently used in alumina refineries. The fluid-bed or stationary kiln is newer and more energy efficient; rotary kilns have higher energy requirements. Kilns are fired mainly by natural gas and less commonly by oil.

The heat in the calcination process drives off the remaining water (both chemically combined and absorbed water), leaving aluminum oxide (alumina or Al_2O_3) that is about 99.5% pure. The alumina is subsequently reduced to aluminum in electrolytic cells.

The production of one metric ton of alumina requires approximately 2.56 metric tons (5,642 pounds) of bauxite (or a dry weight of 2.23 metric tons or 4,913 pounds) (Oak Ridge National Laboratory 1980). In 1994, total U.S. alumina production was 4.86 million metric tons (5.35 tons) (Sehnke 1996).

2.2 Summary of Inputs/Outputs

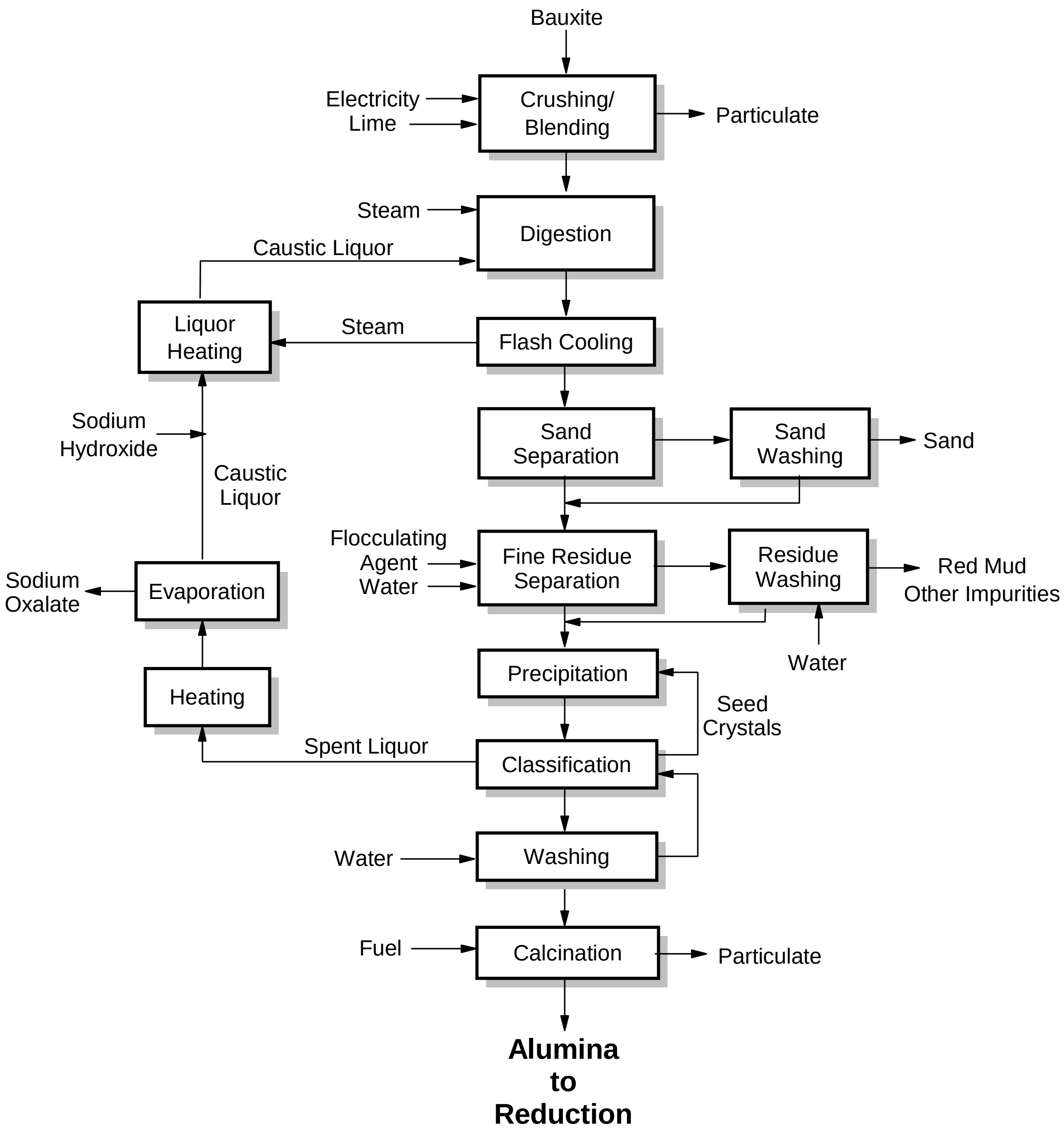
Inputs:	Bauxite Sodium hydroxide (NaOH) Lime (CaO) Starch or other flocculating agent Process water Fuel Steam
Outputs:	Aluminum oxide (alumina, Al_2O_3) Particulate Red mud Sodium oxalate Effluents from red mud washing

Figure 2-1 illustrates the Bayer alumina refining process with its major inputs and outputs.

2.3 Energy Requirements

Table 2-1 shows the energy requirements for alumina production. This table shows the specific energy requirements of alumina refining per unit of alumina produced and in per unit of primary aluminum. The energy requirements of bauxite mining are not included; the vast majority of bauxite used by the U.S. aluminum industry is imported from other countries. The latter calculations assume the need for 1.88 metric tons of alumina to produce one metric ton of aluminum (or 1.88 tons per ton) (Richards 1997).

The data in Table 2-1 are based on the results of a 1991 industry survey of North American plants (Richards 1997). In estimating the data in Table 2-1, a 5% improvement in energy efficiency was assumed to have occurred between 1991 and 1995. This assumption was based on recent



Key Energy and Environmental Facts - Alumina Production

Energy	***Emissions***	***Effluents***	***Byproducts***
Energy Use: *13,176 MJ/metric ton of Al_2O_3 (11.41 10^6 Btu/ton)* *24,770 MJ/metric ton of Al (21.44 10^6 Btu/ton)*	*Major Pollutant - Particulate* *Largest Source - Aluminum hydroxide calcining and bauxite grinding* *Typical Generation - 0.5 kg/metric ton (1.0 lb/ton)*	*Largest Source - Mud washing* *Typical Process Water Volume - 4,950 kg/metric ton (9,180 lb/ton) of alumina*	*Red mud - avg. of 1.0 to 1.6 metric tons of mud per metric ton of alumina extracted (or 1.0 to 1.6 tons per ton)*

Figure 2-1. Alumina Production Flow Diagram

Table 2-1. Process Energy Use in Alumina Refining

Energy Source	Specific Energy Use per Ton of Alumina[a]		Specific Energy Use per Ton of Primary Aluminum[a,b]		Estimated Total 1995 Industry Energy Use[c]	
	MJ/metric ton[d]	10^6 Btu/ton	MJ/metric ton[d]	10^6 Btu/ton	10^9 MJ[d]	10^{12} Btu
Electricity[e]	246	0.21	462	0.40	1.22	1.15
Natural Gas	12,413	10.75	23,336	20.20	61.69	58.77
Oil (Residual and Distillate)	129	0.11	243	0.21	0.64	0.60
Coal	388	0.34	729	0.63	1.93	1.86
TOTAL	**13,176**	**11.41**	**24,770**	**21.44**	**65.48**	**62.38**

a The percentage use of each non-electric fuel is assumed to be the same as the percentage use found in The Aluminum Association's 1989 industry energy survey: natural gas 95.7%; oil 0.3%; and coal 4.0%.

b Based on 1.88 metric tons of alumina per metric ton of aluminum.

c Based on an estimated 1995 U.S. alumina production of 4,970 10^3 metric tons (5,467 10^3 tons) (Estimation based on data from Sehnke 1996 and The Aluminum Association 1996).

d MJ is one megajoule, or 10^6 joules.

e Conversion factor of 11,530.6 kj/kWh (10,981 Btu/kWhr) (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"World Bauxite and Alumina Production Capacity in the Mid-1990s," E. Sehnke, *Light Metals 1996.*
Aluminum Statistical Review for 1995, The Aluminum Association, 1996.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

equipment and operating changes made in several of the plants participating in the survey, including the replacement of a rotary kiln by a stationary calciner at one plant.

Table 2-1 also shows an estimate of the total U.S. energy use associated with alumina refining in 1995. This estimate -- 65.48 10^9 MJ joules (62.38 10^{12} Btu) -- assumes a constant ratio between alumina and aluminum production from 1994 to 1995. Alumina production in 1995 is therefore estimated at 4.97 million metric tons (5.47 million tons), an increase of about 2.3% over 1994 production.

The values shown in Table 2-1 are consistent with other alumina refining energy estimates found in the literature. The specific energy use of 21.4 10^6 Btu/ton of aluminum from Table 2-1 compares with values of 26.4 and 21.2 10^6 Btu/ton of aluminum quoted in the literature from 1993 (Yoshiki-Gravelsins et al. 1993 and Yamada 1993).

The data are also consistent with data published in the most recent Aluminum Association industry energy survey in 1989. For that year, the AA survey estimated an alumina refining energy use of 13.8 MJ/kg (5,978 Btu/lb) of alumina. The corresponding value derived from the data presented in Table 2-1 is 13.2 MJ/kg, (5,705 Btu/lb), a 4.5% decrease from the 1989 data. It is about 30% less than the 18.8 MJ/kg (8,160 Btu/lb) of alumina reported in an earlier Aluminum Association survey conducted in 1985.

The significant reductions in energy per unit of alumina that have been achieved over the past 20 years have been the result of several factors, including greater use of higher pressures in digesters (which allows more effective extraction from previously marginal ores) and the use of fluidized-bed or flash calciners. These calciners use a much higher fraction of the hot gas, almost halving the energy needed for calcination.

2.4 Emissions

Most Particulate Generated During Grinding and Calcining Is Collected

Bauxite grinding, hydrated aluminum oxide calcining, and materials handling operations generate particulate. Various dry dust collection devices (centrifugal collectors, multiple cyclones, or electrostatic precipitators and/or wet scrubbers) have been used to control these emissions. Large amounts of particulate are generated during the calcining of hydrated aluminum oxide, but the economic value of this dust leads to the use of extensive controls that reduce emissions to relatively small quantities (EPA 1995a).

Table 2-2 lists EPA's emission factors for several major air pollutants for bauxite grinding and ore drying. Table 2-3 lists particulate emissions factors for aluminum hydroxide calcining. In addition, a life-cycle study that included a survey of operating refineries yielded an average particulate emission rate of 0.5 kg/metric ton (1.0 lb/ton) of alumina (Richards 1997).

2.5 Effluents

Red Mud Washing Has High Process Water Requirements

The Bayer process requires a considerable amount of process water for washing and filtering the red mud and the alumina. Mud washing water requirements have been estimated to be as high as 8,000 kg/metric ton (16,000 lb/ton) of alumina produced; alumina washing and filtering water requirements are about one ton per ton of alumina (Oak Ridge National Laboratories 1980). The results of the 1991 industry survey mentioned in Section 2.3 yielded an estimated total process water requirements of 4,590 kg of water per metric ton (9,180 lb/ton) of alumina produced (Richards 1997).

Table 2-2. Emission Factors for Bauxite Grinding/Drying (kg/metric ton of bauxite processed)

Source	Total Particulate [lb/ton]	PM10[a] [lb/ton]	CO [lb/ton]	SOx [lb/ton]
Uncontrolled	3.0 [6.0]	2.55 [5.1]	0.0	0.0
Spray tower	0.9 [1.8]	--	--	--
Floating bed scrubber	0.85 [1.7]	--	--	--
Quench tower and spray screen	0.5 [1.0]	--	--	--
Bauxite drying oven	0.6 [1.2]	0.35 [0.7]	--	0.7 [1.4]

[a] Particulate matter less than 10.0 microns in diameter.

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 2-3. Particulate Emission Factors for Aluminum Hydroxide Calcining (kg/metric ton of alumina produced)

Source	Total Particulate [lb/ton]
Uncontrolled	100.0 [200.0]
Spray tower	30.0 [60.0]
Floating bed scrubber	28.0 [56.0]
Quench tower	17.0 [34.0]
Electrostatic precipitator	2.0 [4.0]

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Effluent limitation guidelines for alumina refining are the same for both the best practicable technology currently available (BPT) case and the best available technology economically achievable (BAT) case. The first limitation is that there shall be no discharge of process wastewater pollutants to navigable waters. The second limitation restricts the volume of process wastewater that may be discharged from the overflow of a process wastewater impoundment.

Table 2-4 lists typical amounts of total suspended solids, oil/grease, and other pollutants contained in alumina production wastewater.

2.6 Byproducts

The major byproduct associated with converting bauxite to alumina is red mud; other byproducts include oxalates and miscellaneous wastes such as bricks and packaging.

Sodium Oxalates Are Removed from Bayer Liquor

The removal of sodium oxalate and other salts from Bayer liquor results in an oxalate/salt cake. Because sodium oxalate can crystallize in the precipitation circuit and cause problems, it is typically controlled by seeded precipitation in a separate unit or by deep evaporation of spent liquor. The latter process results in a mixture of crystallized salts. This waste is either land disposed, calcined with bauxite to form sodium aluminate, heated and causticized to form sodium hydroxide, or bio-oxidized to form sodium bicarbonate. Each of the methods except land disposal allows the recovery of either aluminum or sodium.

The sand and fine residues that are separated from the sodium aluminate slurry in the Bayer process are either disposed of with the red mud or in separate ponds, depending on disposal strategy.

Table 2-4. Estimated Average Pollutants Contained in Alumina Production Effluents (kg/metric ton of alumina)

Pollutant	Amount [lb/ton]
Total Suspended Solids	0.3 [0.6]
Oils/grease	0.0013 [0.0026]
Other Dissolved Metals	0.005 [0.010]

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Excluding red mud and its associated byproducts, the average amount of solid wastes generated during alumina production has been estimated from actual plant data to be 0.7 kg/metric ton (1.4 lb/ton) for packaging and 2.6 kg/metric ton (5.2 lb/ton) for all other wastes combined (Richards 1997).

Large Quantities of "Red Mud" Are Produced

Red mud is the iron-rich residue from the digestion of bauxite. In general, about 2.4 metric tons of bauxite are required for each metric ton of alumina, and from 0.5 to 2.0 metric tons (with an average of about 1.0 metric tons) of red mud are generated per metric ton of alumina extracted (or 1.0 ton of red mud per ton of alumina) (Piga et al. 1993). Another estimated average (based on the survey of 12 refineries) was 1.57 metric tons of red mud per metric ton of alumina extracted (or 1.57 tons of red mud per ton of alumina) (Richards 1997). It is estimated that nearly 40 million metric tons (44 million tons) of red mud are generated worldwide each year (Piga et al. 1993).

Red mud residues consist partly of minerals that do not dissolve during the caustic treatment of the bauxite (e.g., hematite, anatase, rutile, and quartz) and partly of desilication product (DSP). DSP contains silica (SiO_2) and considerable quantities of unrecoverable alumina and caustic soda (Piga et al. 1993). A typical DSP contains equal parts silica and alumina and 0.6 part Na_2O (Oeberg 1996).

On an elemental basis, red mud normally contains the following:

- iron (20 to 50%)
- aluminum (20 to 30%)
- silicon (10 to 20%)
- calcium (10 to 30%)
- sodium (10 to 20%)

Red mud may also contain trace amounts of elements such as barium, boron, cadmium, chromium, cobalt, gallium, vanadium, scandium, and lead, as well as radionuclides (EPA 1990). The types and concentrations of minerals present in the mud depends on the composition of the ore and the operating conditions in the digesters. Red mud has not been found to exhibit any of the characteristics of hazardous waste.

The red mud is removed from the settling tanks by filtering the sodium aluminate under pressure through heavy canvas filter presses. Washing does not ensure the complete recovery of the aluminate, which is the cause of the alkalinity of the red mud.

Red mud is managed on site in surface impoundments, the most common of which is a diked impervious area called a pond or lagoon. The mud slurry is pumped to the ponds situated close to the bauxite refinery. All ponds at U.S. bauxite refineries are underlain by clay.

The red mud accumulates and settles in the pond. The supernatant water containing caustic soda and sodium aluminate is recirculated into the plant. The remaining part of the soda and soda salts present in the mud as entrained liquor causes toxicity in the water.

In order to reduce alkali pollution through red mud, a number of dewatering methods using drainage, decantation, stacking, and special techniques such as dry disposal have been developed. Although dry disposal can conserve the land to a considerable extent, it does not conserve minerals. Settlement and natural evaporation can result in the mud being dewatered to 37% solids at a depth of 1.5 meters (4.9 feet) (Piga et al. 1993).

One U.S. bauxite refinery generates a residue that is different in color and is commonly called brown mud. The chemical characteristics of brown mud are not substantially different from red mud.

Attempts to Develop Uses for Red Mud Have Had Limited Success

Many attempts have been made in the past to utilize the red mud as raw materials for production of cement, bricks, aggregate to make concrete, and other building products. The use of red mud as a flocculant for the treatment and clarification of wastewaters and as a rubber filler has also been investigated (Piga et al. 1993).

Several processes have been developed to recover iron from the red mud residues, and the potential exists to use red mud as a raw material in the iron and steel industry (EPA 1990). Other substances for which recovery processes are technically feasible include alumina, titanium dioxide, and other rare metals such as gallium, vanadium, and scandium. Processing for recovery of metals other than iron, however, is not economically viable at present (EPA 1990).

2.7 Hazardous Wastes

There are no RCRA-listed hazardous wastes associated with the alumina refining process. However, significant quantities of acids and caustic materials (outside the Bayer process itself) and in some cases, solvents, are used at refineries. Therefore, most refineries have some amount of hazardous wastes that must be disposed.

3

Anode Production

3.1 Process Overview

The electrolysis of aluminum oxide (alumina) to form aluminum relies on the application of electric current to separate the oxygen from the aluminum. An electrolytic process requires an anode and a cathode; in the electrolysis of alumina, carbon anodes are used to pass the electric current into the "pot" where the process is taking place.

Petroleum Coke Is the Main Ingredient in Carbon Anodes

The major ingredient in carbon anodes is petroleum coke. Petroleum coke is typically calcined in a rotary kiln at temperatures between 1,250 and 1,450ºC (2,282 to 2,642ºF). To avoid airburning once it exits the kiln, the coke is usually sprayed with a minimal amount of water to reduce its temperature to approximately 100ºC (212ºF). Depending on the dissolved solids content of the quenching water, varying amounts of impurities can remain on the coke.

A number of different cokes with varying sulfur contents and other properties are used in anode production. The properties of the calcined coke have a significant effect on anode properties and on carbon consumption.

Carbon Anodes May Be Prebaked or Paste

Two types of carbon anodes may be used during the reduction process -- an anode paste or a prebaked anode. The anode paste plant, or "green mill," produces anode paste or briquettes for Soderberg cells and green pressed anodes (which are subsequently baked in an anode furnace) for prebake cells. Seventeen of the primary aluminum plants in the U.S. use prebaked anodes; the other six use anode paste.

In the prebake process, multiple anodes are formed and baked prior to their use in reduction cells. These prebaked blocks, each of which may weigh up to 1,000 kg (2,205 lb), must be replaced after two to three weeks of service (EPA 1995 and Emad 1996). A large smelter will consume several thousand anode blocks each week.

In the Soderberg process, a single mass of paste or briquettes forms the anode. Because the anode is baked in situ in the reduction cell, separate anode bake furnaces are not required.

Prebaked Anodes Predominate

The use of prebaked anodes requires that a prebaked anode fabricating plant be located on site or within a reasonable distance. Most aluminum reduction plants manufacture anode blocks on site. However, an increasing proportion “buys in” anodes and ships back cleaned “butts” for recycling (Richards 1997).

Not all the anode carbon is consumed in the cell in order to avoid contaminating the aluminum with iron from the electrical contacts (stubs) in the anode (Emad et al. 1996). The carbon that is not consumed is recycled to the anode manufacturing process as anode butts.

Typical prebaked anodes for aluminum production consist of the following (Richards 1997):

- 55 to 65% calcined petroleum coke
- 15 to 30% recycled anode butts
- 15% coal tar or petroleum pitch

The pitch is produced from the refining of coal tar and is recovered as a 40 to 60% bottoms fraction of heavy organics with very high boiling points.

Approximately 80% of anode production is prebaked anodes; the remaining 20% is anode paste for Soderberg cells (EPA 1996).

Prebaked Anodes Are Formed, Then Baked

The four main steps in prebake anode manufacturing are

- preparation and formulation of dry aggregate (e.g., crushing and classifying),
- mixing dry aggregate with pitch,
- forming green anode blocks by vibrocompacting or pressing in molds, and
- baking green anodes in an anode baking furnace.

To make prebake anode paste, the calcined coke and anode butts are **crushed and classified** into four fractions prior to being conveyed to oil-heated continuous mixers to be ball melted. The different fractions are **mixed** in certain proportions with hot liquid coal tar binder pitch at about 190ºC (374ºF) in order for the pitch to wet the filler coke. If the resulting green paste is to be used in prebake cells, it is compacted and shaped by **pressing or vibroforming** to yield an anode block.

Molded anode blocks for prebake cells are **baked** in a furnace at about 1,150ºC (2,100ºF) in order to carbonize the pitch and achieve optimum properties. However, like the shaping, sizing, and mixing operations, variability in baking temperatures also occurs. The net effect is to have the densities of finished anodes vary by almost 10%, the electrical resistivities vary by up to 20%, and the occurrence of local defects (Emad 1996).

Nearly all of the anodes produced for prebake plants are baked in a ring-fired, open- or closed-top furnace. These furnaces consist of a number of indirectly fired sunken ovens or open-topped brick pits. The pits are filled with green anodes; petroleum coke or other insulating material is then placed over the anodes. Natural gas or other fuel is injected into the furnace flue and ignited by the high air temperature. In the baking process, the anodes are heated to about 1,150ºC (2,100ºF), partly by the heat from the flues and partly by the calcining of volatiles released from the binder pitch in the anodes. The anodes are baked for 28 to 40 hours, after which they spend up to 18 days cooling.

After firing and cooling, the packing coke is removed from the pits by vacuuming or other means and reused (EPA 1996a and Richards 1997). The cured anodes are fixed to stubs and may be spray-coated with a layer of aluminum to protect the exposed carbon surfaces from air-burning in the pots.

Anode Paste Has No Baking Requirements

Anode paste for Soderberg cells is made from petroleum coke (four size fractions) and pitch; no recycled butts are used. Anodes for Vertical Stud Soderberg (VSS) cells typically contain 28% pitch, while anodes for Horizontal Stud Soderberg (HSS) cells contain 24% pitch.

The premixed dry coke aggregate is mixed in steam- or oil-heated blenders (continuous or batch). For VSS anodes, the paste is fed to a briquetter or extruder/chopper, and the briquettes are quenched in water. From there they are dried, stored, and ultimately transported to the cell. Paste for HSS anodes is dumped into a special hopper and directly transferred to the potrooms.

3.2 Summary of Inputs/Outputs

Inputs: Petroleum coke
Binder pitch
Recycled anode butts
Fuel (oil and natural gas)
Electricity
Outputs: Carbon anodes or anode paste
Emissions of organic compounds
Traces of fluorides
Sulfur dioxide (SO_2)
Combustion emissions
Carbon dust
Pitch fumes
Other particulate matter
Butt cleaning dust
Alumina from bake furnace dry adsorption units
Electrostatic precipitator tar
Burn-offs (contaminated anode material)
Refractory waste
Scrubbing water

Figure 3-1 illustrates a typical prebake anode production process with its major inputs and outputs.

3.3 Energy Requirements

Table 3-1 presents energy requirements for manufacturing the coke and pitch used in anodes. Table 3-2 shows the process energy requirements of anode production itself in terms of energy per ton of anode and energy per ton of primary aluminum. The specific process energy requirements for anode production are estimated to be 4,045 MJ/metric ton of anode (3.51 10^6 Btu/ton). The cost of this energy represents an estimated 8% of the total cost of anode production (Richards 1997).

In terms of aluminum produced, the specific energy requirements are estimated to be 1,820 MJ/metric ton of aluminum (1.58 10^6 Btu/ton). This assumes that 0.45 metric ton of anode is required in the production of 1.0 metric ton of primary aluminum (or 0.45 ton per ton) (Welch et al. 1993).

A substantial percentage of the total energy used in the anode baking process comes from the anode binder pitch (EPA 1996). The embodied energy of the anode is not shown in Table 3-2 but is accounted for in Table 4-3, which shows energy use in the reduction process.

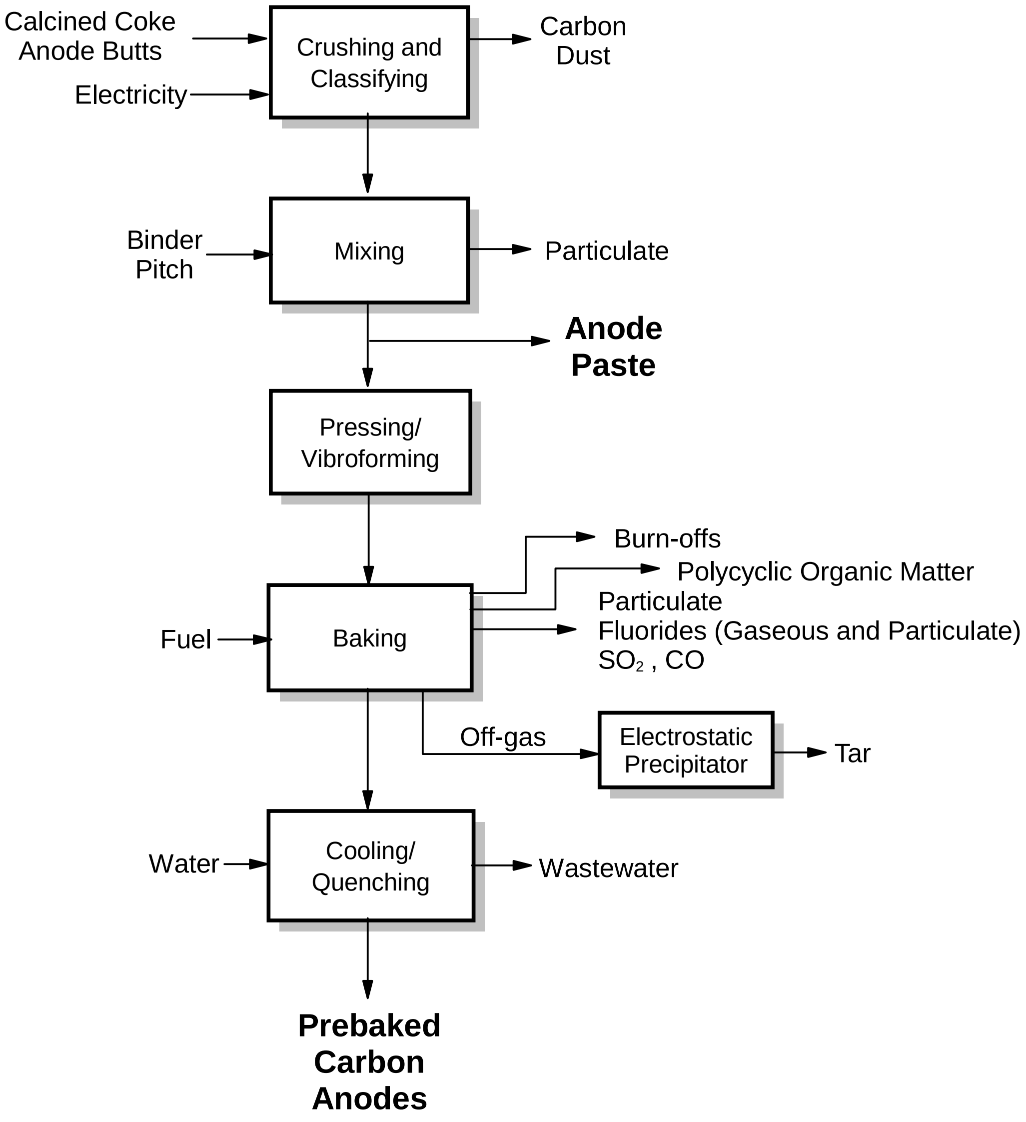
Very little energy is needed to produce anodes for Soderberg cells. VSS anode paste briquettes are primarily dried with their residual enthalpy (Richards 1997).

3.4 Emissions

Anode Manufacture Generates Several Types of Emissions, Including Hazardous Air Pollutants

Most emissions associated with anode manufacturing are generated during anode baking. Emissions from anode bake ovens include

- high boiling organics from the cracking, distillation, and oxidation of paste binder pitch;



Key Energy and Environmental Facts - Anode Production			
Energy	***Emissions***	***Effluents***	***Byproducts***
Energy Use *4,045 MJ/metric ton anode* *($3.51\ 10^6$ Btu/ton anode)* *1,820 MJ/metric ton Al* *($1.58\ 10^6$ Btu/ton Al)*	*Largest Source - Bake ovens* *Particulate, fluorides, polycyclic organic matter, and SO_2*	*Largest Source -Bake plant wet air pollution control* *Typical Process Water Volume - 3,215 kg/metric ton (6,430 lb/ton) of anode produced*	*ESP tar, carbon dust, burn-offs, refractory bricks* *Total generation of carbonaceous wastes - 14 kg/metric ton (28 lb/ton) of Al produced*

Figure 3-1. Anode Production Flow Diagram

Table 3-1. Process Energy Use in Coke and Pitch Production[a]

Energy Source	Coke Production[b]		Pitch Production[b]	
	MJ/metric ton of coke[c]	10^6 Btu/ton of coke	MJ/metric ton of pitch[c]	10^6 Btu/ton of pitch
Electricity[d]	130	0.11	0	0.0
Natural Gas	2,825	2.45	297	0.26
Distillate Oil	1,210	1.04	124	0.10
NET TOTAL	**4,165**	**3.60**	**421**	**0.36**

a Process energy only. Energy content of anodes is accounted for in Table 4-3.
b Non-electric fuel use is estimated to be 70% natural gas, 30% distillate oil. (Richards 1997).
c MJ is one megajoule, or 10^6 joules.
d Conversion factor of 11,530.6 kj/kWh, or 10,981 Btu/kWh (Richards 1997).

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Table 3-2. Process Energy Use in Anode Production[a]

Energy Source	MJ/metric ton of anode[b,c]	10^6 Btu/ton of anode[b]	Total Specific Energy Use per Ton of Aluminum[d]	
			MJ/metric ton[c]	10^6 Btu/ton
Electricity[e]	1,835	1.59	826	0.72
Natural Gas	1,548	1.34	696	0.60
Distillate Oil	331	0.29	149	0.13
Propane & LPG	331	0.29	149	0.13
NET TOTAL	**4,045**	**3.51**	**1,820**	**1.58**

a Process energy only. Energy content of anodes is accounted for in Table 4-3.
b Non-electric fuel use is estimated to be 70% natural gas, 15% distillate oil, and 15% propane (Richards 1997).
c MJ is one megajoule, or 10^6 joules.
d Assuming average of 0.45 metric ton of anode per metric ton of primary aluminum produced (Welch 1993).
e Conversion factor of 11,530.6 kj/kWh, or 10,981 Btu/kWhr (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"A Model for Petroleum Coke Reactivity," Welch et al., *Light Metals 1993.*

- sulfur dioxide from the sulfur in carbon paste, primarily from the petroleum coke;
- fluorides from recycled anode butts;
- other particulate matter; and
- the products of fuel combustion.

Concentrations of uncontrolled SO_2 emissions from anode baking furnaces range from 5 to 47 parts per million (based on 3% sulfur in coke) (EPA 1995a).

In addition to anode baking, air emissions are generated during anode paste mixing, transfer, and anode forming. These emissions include coke fines, particulate matter, and organic compounds.

The coke calcination process generates sulfur emissions, which are released with volatile matter during thermal devolatilization. Sulfur is also lost or burned in association with coke entrainment or combustion in the kiln coke bed and in the kiln exhaust. Additional sulfur is thermally dissociated from the coke during calcination (Garbarino and Tonti 1993).

The hydrogen fluoride (HF) and polycyclic organic matter (POM) emitted from the anode bake furnace stack are designated by the EPA as hazardous air pollutants (HAPs). Section 112 of the Clean Air Act as amended requires the development of National Emission Standards for Hazardous Air Pollutants (NESHAPs) for the control of emission of HAPs from both new and existing sources. The statute requires the standard to reflect the maximum degree of reduction in emissions that is achievable taking into consideration the cost of achieving the reduction, any non-air health and environmental reduction, and energy requirements. This level of control is referred to as the maximum achievable control technology (MACT).

Recycling Anode Butts Generates Hydrogen Fluoride Emissions

Hydrogen fluoride (HF) emissions originate from the recycling of anode butts when fluorides not removed during cleaning of the butts are volatilized in the furnace and removed with the flue gas stream. The amount of HF emitted depends on the quantity of anode butts recycled, the cleanliness of the butts, and the efficiency of the emission control device, if any, that was used (EPA 1996a).

The amount of particulate matter emitted can vary widely depending on the type of furnace, fuel used, and other factors. The particulate matter released consists mainly of condensed tar attached to dust released through openings in the oven brickwork, or from the placement and removal of packing coke (EPA 1996a).

Anode bake furnaces emit about 636 metric tons/year (700 tons/year) of total fluoride (TF), the vast majority of which is gaseous or hydrogen fluoride from uncontrolled bake furnaces (EPA 1996a). EPA's New Source Performance Standards (NSPS), which apply to facilities that commenced construction or modification after October 23, 1974, limit emissions of TF from anode bake furnaces to 0.05 kg/metric ton (0.1 lb per ton) of aluminum equivalent and opacity to 20%. No states have TF limits for the anode bake furnace for existing facilities not subject to the NSPS.

Fluorides also evolve from the furnace, originating from residual bath materials that adhere to the recycled anode butts. Because of residual moisture and the elevated temperatures in the furnace, most of the fluoride (about 95%) that is evolved is hydrogen fluoride (EPA 1996).

Polycyclic Organic Matter (POM) Is Released from Binder Pitch

Polycyclic organic matter (POM) refers to organic compounds with more than one benzene ring and that have a boiling point greater than or equal to 100ºC (212ºF). POM emissions originate from the coal tar pitch used as the binder, and evolve as the green anode is baked in the furnace. POMs are also generated during the production of Soderberg anode paste.

Anode bake furnaces emit about 500 metric tons (550 tons) of POM annually, measured as methylene chloride extractables (EPA 1996a). Tests at two bake furnaces showed that the 20 targeted POM compounds were generated at a rate of 0.15 to 0.45 kg/metric ton (0.3 to 0.9 lb/ton) of anode prior to control by dry alumina scrubbers. Total annual POM emissions from paste production plants in the U.S. have been estimated at 133 metric tons (147 tons) (EPA 1996a).

Dry Coke Scrubber Can Collect Up To 99.8% of POM Emissions

POM emissions generated during anode paste production are often collected with hoods or similar devices and routed to a baghouse, dry coke scrubber, dry alumina scrubber, or wet scrubber. The dry coke scrubber is the most effective method for controlling POM emissions from anode paste production. This type of scrubber, which is currently used at five plants, has been shown to achieve up to 99.8% capture of POM emissions. A baghouse is also used to control fine particulate matter and to remove coke fines. The coke can be returned directly to the paste production operation. Other plants use various types of controls for specific emission points in paste production (EPA 1996).

Emissions of gaseous and particulate fluorides and POM from anode bake furnaces are controlled most commonly (and effectively) with dry alumina scrubbers. In this type of scrubber, the alumina acts as an adsorbent for the HF gas and provides condensation surfaces for tars (a POM). A baghouse is used to control fine particulate matter containing fluorides and other POMs.

The dry alumina scrubber has been shown to achieve 99.0 to 99.6% control of TF emissions and 94 to 98% control of POM emissions (EPA 1996a). Of the 17 anode bake furnaces in the United States, 12 use dry alumina scrubbers. One U.S. anode bake plant uses a wet scrubber, and another uses an electrostatic precipitator to control HF and particulate. Three plants currently are not equipped with emissions control devices.

Because of its performance capability, the dry alumina scrubber has been identified as the MACT floor technology for anode bake furnaces located at a primary aluminum plant. For the bake furnace that is not located at such a plant, the MACT floor technology is an electrostatic precipitator.

The organic vapors that evolve from the anodes as they are baking are pulled into the hot flue gas system where they can be burned at a temperature of about 1,300ºC (2,372ºF). The degree of destruction of these organic compounds depends on an adequate supply of oxygen, sufficient residence time at temperature, and adequate mixing (EPA 1996).

Pitch fumes from storage tanks and pitch melters are controlled through the use of scrubbers or afterburners. The scrubber effluent can then be recycled or treated as a chemical waste.

Tables 3-3 and 3-4 list EPA's emission factors for several major air pollutants for anode bake furnaces. Table 3-5 lists two sets of process-related emission factors for coke and anode production. The first set was calculated as part of a 1991 survey of eleven smelters. These factors represent weighted average factors from actual plants with various emissions control technologies. The second set of data (anode production only) is the result of a 1994 survey of 27 European smelters.

3.5 Effluents

Process Water Recycled or Treated Before Leaving Plant

Prior to baking the warm, green anode blocks are conveyed in a tank of cold water that cools them and reduces deformation. This water has to be both recycled and treated if released. Lime-sand treatment is generally used to remove traces of organics (Richards 1997).

Table 3-3. Emission Factors for Anode Baking Furnace (kg/metric ton of molten Al)

Source	Total Particulate [lb/ton]	PM10[a] [lb/ton]	Gaseous Fluoride [lb/ton]	Particulate Fluoride [lb/ton]	CO [lb/ton]	SOx [lb/ton]
Uncontrolled	1.5 [3.0]	1.4 [2.8]	0.45 [0.90]	0.05 [0.10]	33.0 [66.0]	1.35 [2.7]
Fugitive	ND	--	ND	ND	--	--
Spray tower	0.375 [0.75]	--	0.02 [0.04]	0.015 [0.03]	--	--
Electrostatic precipitator	0.375 [0.75]	--	0.02 [0.04]	0.015 [0.03]	--	--
Dry alumina scrubber	0.03 [0.06]	--	0.0045 [0.009]	0.001 [0.002]	--	--

ND Not determined.
a Particulate matter less than 10.0 microns in diameter.

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 3-4. Emission Factors for Anode Baking Furnace (kg/metric ton of anode)

Source	Total Fluoride [lb/ton]	Gaseous Fluoride [lb/ton]	Polycyclic Organic Matter (POM) [lb/ton]
Uncontrolled	1.5 [3.0]	1.5 [3.0]	1.0 [2.0]
Electrostatic precipitator	0.075 [0.015]	0.075 [0.15]	0.2 [0.4]
Dry alumina scrubber	0.01 [0.02]	0.005 [0.01]	0.045 [0.09]

Source: *Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, July 1996.

The net process water consumption for anode production (excluding fuel-related water use) is estimated at 3,215 kg/metric ton (6,430 lb/ton) of anode (Richards 1997).

Table 3-6 presents EPA's effluent limitations for anode baking using best practicable control technology currently available (BPT). Table 3-7 presents effluent limitations using the best available technology economically achievable (BAT) for anode contact cooling and briquette quenching. Table 3-8 shows BAT limitations for anode paste plant and anode bake plant wet air pollution control.

Table 3-9 shows estimated average levels of TSS, fluorides, and organics contained in typical anode manufacturing process wastewater based on the 1991 survey.

Table 3-5. Typical Emission Factors for Coke and Anode Production (kg/metric ton of anode)

Pollutant	Amount [lb/ton]		
	Coke Production	Anode Production	
		N. American Survey[a]	European Survey[b]
Particulate	0.40 [0.80]	0.63 [1.26]	0.15[c] [0.30]
SOx	0.81 [1.62]	0.70 [1.40]	0.90 [1.80]
NOx	0.18 [0.36]	0.16 [0.32]	0.24 [0.48]
CO	0.37 [0.74]	0.25 [0.50]	NA
CO_2	0.00 [0.00]	0.00 [0.00]	NA
Organics	0.29 [0.58]	0.20 [0.40]	0.06[d] [0.12]
Fluorides	0.0004 [0.0008]	0.25 [0.50]	0.10 [0.20]

NA Data not available
a Weighted average composite values from 11 N. American smelters participating in a 1991 survey.
b Weighted average composite values from 27 European smelters participating in a 1994 survey.
c Reported as dust.
d Reported as polycyclic aromatic hydrocarbons (PAH).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
1994 Environmental Survey for Electrolysis Plants, presented at Pollution Prevention in the Aluminum Industry, sponsored by The Aluminum Association, November 1995.

Table 3-6. Anode Bake Plant Effluent BPT[a] Limitations - Average of Daily Values for 30 Consecutive Days (kg/metric ton, or lbs per 1,000 lbs of product)

Pollutant	BPT Limitation
Fluoride	1.0
Total Suspended Solids	1.5
pH	6-9

a Best Practicable Control Technology Currently Available.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.22, Bureau of National Affairs, 1992.

Table 3-7. Anode Contact Cooling and Briquette Quenching BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of anodes cast)	
Pollutant	**Anode Contact Cooling and Briquette Quenching**
Benzo(a)pyrene	0.003
Antimony	0.180
Nickel	0.077
Aluminum	0.566
Fluoride	5.518

a Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.23, Bureau of National Affairs, 1992.

Table 3-8. Anode Paste and Bake Plant Wet Air Pollution Control BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of anodes baked or paste produced)

Pollutant	Anode and Cathode Paste Plant	Closed Top Ring Furnace	Open Top Ring Furnace with Spray Tower Only	Open Top Ring Furnace with Wet ESP and Spray Tower	Tunnel Kiln
Benzo(a)pyrene	0.002	0.067	0.001	0.011	0.018
Antimony	0.117	3.719	0.043	0.628	0.979
Nickel	0.050	1.600	0.019	0.270	0.421
Aluminum	0.369	11.720	0.136	1.979	3.084
Fluoride	3.591	114.200	1.320	19.270	35.050

a Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.23, Bureau of Nat. Affairs, 1992.

3.6 Byproducts

Anode Manufacturing Generates Many Byproducts But Most Are Recycled

The production of carbon anodes generates several byproduct streams containing carbon contaminated with electrolyte materials. Most of these byproduct streams are recycled back into anode carbon or other uses, and only a few are disposed of as waste (see Table 3-10).

Table 3-9. Typical Anode Manufacturing Effluents

Pollutant	Quantity (mg/kg or lbs per 10^6 lbs)
Fluoride	4.8
Total Suspended Solids	3.9
Organics	5.0

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Table 3-10. Byproducts from Anode Manufacturing (kg/metric ton of anodes)

Byproduct	Pollution Abatement Method	Quantity [lbs/ton of anodes]	Method of Reuse/ Disposal
Carbon dust from dry aggregate preparation	Bag filters	--	Recycling in anodes
Butt cleaning dust	Bag filters	Avg: 17 [34] Range: 5 - 42 [10 - 84]	Partially recycled in anodes; partially chemical waste
Carbon dust from bake furnace dry adsorption units with lime as additive for F removal	Bag filters	Range: 40 - 50 [80 - 100]	Used as fuel in the cement industry
Alumina from bake furnace dry adsorption units	Bag filters	Range: 50 - 200 [100 - 400]	Recycled to aluminum reduction
Carbon dust from bake furnace cranes	Bag filters	Range: 2 - 3 [4 - 6]	Used as fuel in the cement industry or as carburizer
Bake furnace ESP tar	Electrostatic precipitator	Avg: 4 [8] Range: 1 - 16 [2 - 32]	Reused in aromatics refineries or as a fuel; sometimes incinerated
Burn-offs	--	Avg: 4 [8] Range: 0.2 - 30 [0.4 - 60]	Recycled in anodes or used as carburizer
Refractory bricks	--	Avg: 18 [36] Range: 4 - 40 [8 - 80]	Landfilled or recycled

Source: "Waste Materials in Anode Manufacturing; An Overview," Felix Keller, presented at Light Metals 1994.

Recycling carbon materials containing sodium has a deleterious effect on anode reactivity to carbon dioxide and on the life of anode baking furnace refractories (Sadler and Salisbury 1994).

During anode baking, approximately 35% of the pitch is volatilized. At plants with electrostatic precipitators (ESPs), the major part of uncombusted volatiles is collected as tar. The collected tar may amount to 2 to 4 kg/metric ton (4 to 8 lb/ton) of baked anodes, depending on the combustion efficiency. Traditionally the tar has been dealt with by deposition, recycling during carbon block production, or combustion (Foosnaes et al. 1994). Waste tar combustion systems have been developed that allow ESP tar to be used as a fuel, substituting for oil or gas in the anode baking furnace.

A worldwide survey sponsored by the Aluminum Committee of the Minerals, Metals, & Materials Society (TMS) found that carbonaceous waste materials from prebaked anode production are generated on the order of 14 kg/metric ton (28 lb/ton) of aluminum produced. Refractory wastes from anode baking furnaces are on the order of 11 kg per metric ton (22 lb per ton) of aluminum (Keller 1994).

The results of the TMS survey are shown in Table 3-10, which presents the major solid waste materials from anode production, together with the generally accepted pollution abatement method (if available), the quantity (average and range) of potentially critical waste materials, and the method of reuse or disposal.

A certain amount of the carbonaceous wastes from anode manufacturing is recycled in the process. However, there is evidence that petroleum coke and pitch quality will deteriorate in the future, making recycling less acceptable for disposing of carbon wastes (Keller 1994).

3.7 Hazardous Wastes

There are no RCRA-listed hazardous wastes associated with anode manufacturing.

4

Aluminum Production

4.1 Process Overview

Alumina Is Reduced to Aluminum in Electrolytic Cells

Aluminum is produced by the electrolysis of alumina dissolved in a molten cryolite-based electrolyte, the Hall-Heroult process. In this process, electric current is used to separate the alumina into aluminum and oxygen. The oxygen reacts with the carbon anode to form CO_2 that is liberated from the cell. A typical modern aluminum reduction cell, commonly called a pot, consists of a rectangular steel shell lined with refractory thermal insulation. Within this is an inner lining of carbon (the cathode) that contains the highly corrosive molten fluoride electrolyte.

From 150 to as many as 240 cells or pots are electrically connected in series to form a potline. The pots may be lined up side-by-side or end-to-end in one or more rows. From 360 to 2,350 kg (800 to 5,200 lb) of aluminum metal are produced per day in each pot.

Prebake and Soderberg Are Two Major Reduction Processes

Primary aluminum operations are differentiated by the type of anode used and the method by which the pot is worked or the anode is introduced into the cell. The two major technologies are prebake and Soderberg. The pots in prebake cells use multiple anodes that are formed and baked prior to consumption in the pots. Soderberg pots use a single, continuous anode that is shaped and baked in place directly in the pot (EPA 1996).

Seventeen of the 23 primary aluminum plants in the U.S. use prebake technology, with the number of potlines shown in Table 4-1. Although the main difficulty associated with Soderberg technology is its emissions of organics (discussed in Section 4.4), this problem is considered to be offset by the advantage of not needing an anode baking furnace (and its attendant controls).

Both prebake and Soderberg pots have two variations. The pots in prebake plants are classified as **center-worked prebake (CWPB)** or **side-worked prebake (SWPB)**, depending on where the pot working (crust breaking and alumina addition) takes place. Soderberg pots are differentiated by the positioning of the current-carrying studs in the anodes; the two types are **Vertical Stud Soderberg (VSS)** and **Horizontal Stud Soderberg (HSS)**.

In cells using prebaked anode technology, between 16 and 32 anodes fitted with steel stubs or rods are

Table 4-1. U.S. Primary Aluminum Potlines

Plant Type	Number of Potlines
Prebake	69
CWPB	64
SWPB	5
Soderberg	22
HSS	12
VSS	10
TOTAL	**91**

Source: *Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards*, U.S. EPA, July 1996.

suspended from axial busbars that function as the positive electrical connection. The anode blocks are consumed until they can no longer be used without attack on the stubs, at which point they are replaced.

Point feeders add frequent small doses of alumina into the cell to maintain a certain concentration in the bath. Practically all potlines are equipped with automatic computer control of the feeding frequency and of the cell voltage.

Soderberg cells use a single anode contained in a steel shell suspended above the pot. While descending through the shell, the paste bakes and forms carbon to replace the carbon being consumed at the bottom. Additional paste is added periodically as the anode is consumed. Current from the buses enters the anode through rows of pins inserted into the anode. The pins are periodically repositioned as the consumable anode progresses into the pot.

In VSS cells, the paste is spread on top of the monolithic anode casing about every day, keeping the casing consistently full. For HSS cells, paste is dumped about every seven to ten days on the existing semi-hard mass of unbaked carbon in the anode box. This mass of carbon, over which there is a thermal gradient of 950ºC to 30ºC (1,742 to 86ºF, ambient temperature), is consumed at the rate of 2.0 cm/day (0.8 inch/day). It takes approximately 55 to 60 days for the paste on the top to reach the bottom and be consumed (Richards 1997).

In both pre-baked and Soderberg cells, the distance between the anode and the molten aluminum (the anode-cathode distance) ranges from 3.0 to 6.0 centimeters (1.2 to 2.4 inches). Steel current-collector bars, joined into the carbon lining, carry the electric current from the cell. A layer of the cathode of alumina covers both the free surface of the bath and the anodes. Aluminum is electrochemically deposited from dissolved alumina into the molten aluminum pool at the bottom of the cell. It is removed using vacuum siphoning or gravity separation into cast-iron pots for transport to the casthouse.

The oxygen released from the alumina is attracted to and consumes the cell's carbon anodes, producing CO_2. The aluminum metal produced typically has a purity of about 99.85% by mass (Kvande et al. 1993). Approximately 1,880 kg of alumina are required per metric ton of aluminum (3,760 lb/ton) (Richards 1997).

Additives Improve Cell Efficiency and Performance

Molten cryolite (Na_3AlF_6) is the major component of the electrolyte, or bath; aluminum fluoride (AlF_3) is the most common additive. These two compounds maintain the desired ratio of sodium to aluminum fluoride and replace fluorides lost from the cell into pot linings or through volatilization. Cryolite has a high solubility of alumina but requires high operating temperature. Additives are therefore used to improve the current efficiency by reducing metal solubility and enabling a lower operating temperature.

Although AlF_3 is the most widely used bath additive, CaF_2, LiF, and MgF_2 may also be used to improve cell performance. Most modern plants use a low-ratio bath containing 6 to 13% AlF_3 and 3 to 8% Al_2O_3, and do not typically use LiF and MgF_2. Cryolite is not consumed, and can be recovered and recycled with small make-up.

Depending on the pot chemistry and other factors, the optimum operating temperature of the cell is between 940°C and 985°C (1,724 to 1,805°F). Using direct current, cells operate at 65,000 to over 250,000 amperes, although the majority of plants have 80,000 to 100,000 ampere cells. Anode current densities range from 600 to 800 amperes per square foot. The voltage drop across a single cell is 3.9 to 5.0 volts, and may reach 1,000 volts across an entire potline (EPA 1996). Pots produce an estimated 7.4 kg/day (16.2 lb/day) of aluminum for each kilampere of current. Cell efficiency is discussed in Section 4.3, Energy Requirements.

4.2 Summary of Inputs/Outputs

Inputs: Alumina
Carbon anodes or anode paste
Cryolite (Na_3AlF_6)
Aluminum fluoride (AlF_3), calcium fluoride (CaF_2), and other additives
Electricity
Fuel
Process water
Refractories, carbon cell lining
Outputs: Molten aluminum
Dust
Carbon dioxide (CO_2) and carbon monoxide (CO)
Gaseous fluorides (HF, SiF_4,CF_4 and C_2F_6)
Particulate fluorides (mainly $NaAlF_4$)
Polycyclic organic matter (POM), including polycyclic aromatic hydrocarbons (PAHs)
Sulfur oxides (SOx) and nitrogen oxides (NOx)
Effluents
Wet scrubber/ESP sludge
Spent potlining (RCRA-listed K088)

Figure 4-1 illustrates the two major types of aluminum production cells, the prebaked cell and the Soderberg cell.

4.3 Energy Requirements

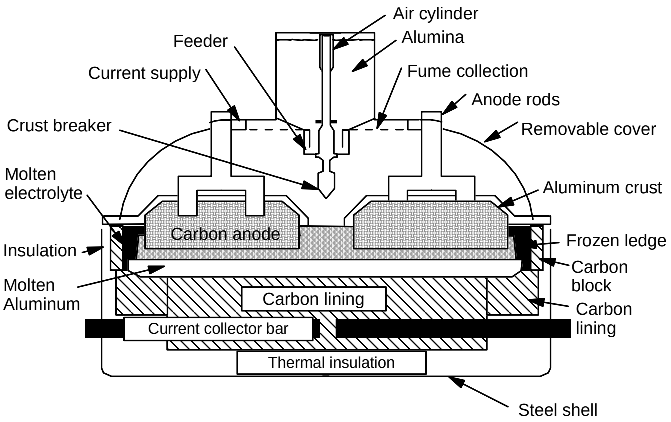
Aluminum Production Is Very Electricity-Intensive

The theoretical minimum energy consumption in aluminum electrolysis is 6.34 kWh/kg of Al (2.9 kWh/lb) (Grjotheim et al. 1995). The lowest energy consumption that can be achieved today is about 13.0 kWh/kg of Al (5.9 kWh/lb) for a whole line of modern, high-amperage alumina reduction cells, yielding a best possible energy efficiency of about 50%.

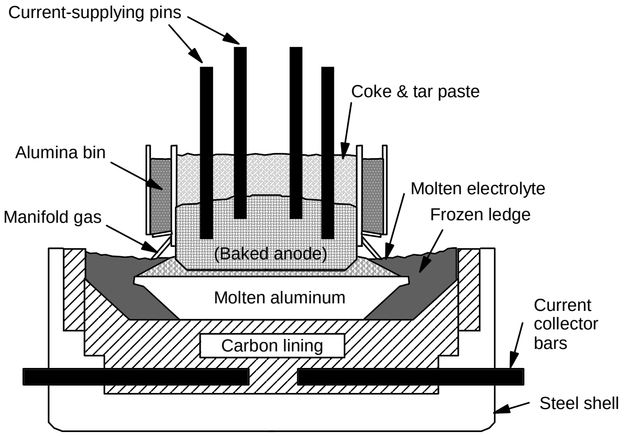
Production cells normally have current efficiencies ranging from 85 to 95%. Large, modern reduction cells operate with current efficiencies of 94 to 96% and a specific energy consumption of 13 to 14 kWh/kg (5.9 to 6.4 kWh/lb) of aluminum (Tabereaux et al. 1993). These modern cells operate efficiently because of the improvements made in the magnetic design of the electrical conductor bus components, application of state-of-the-art computer systems for control and management of cell operations with alumina point feeder systems, and operation with a low-ratio AlF_3 electrolyte chemistry (Tabereaux et al. 1993).

Older prebake cells have current efficiencies in the range of 92 to 94%, while the oldest cells of this type, as well as the best performing HSS and VSS Soderberg cells typically have efficiencies between 90 and 92%. Older Soderberg smelters are less efficient, typically 86 to 90% (Forberg 1996).

Depending on cell design and operation, specific energy consumption for the electrolysis process can be as high 19.0 kWh/kg of Al (8.6 kWh/lb) (Huglen and Kvande 1994). Using available data, it has been calculated that, on a tonnage-weighted basis, the most efficient third of the world's smelters operate with an average energy consumption of 13.9 kWh/kg of Al (6.3 kWh/lb), the medium-efficiency third at 15.0 kWh/kg of Al (6.8 kWh/lb), and the least efficient third at 17.2 kWh/kg of Al (7.8 kWh/lb) (Huglen and Kvande 1994).



Prebake Cell



Soderberg Cell (VSS)

Key Energy and Environmental Facts - Aluminum Production			
Energy	***Emissions***	***Effluents***	***Byproducts***
Electricity - 15.18 kWh/kg Al (115,330 MJ/metric ton, or 99.85 10^6 Btu/ton) *Non-Electric - 790 MJ/metric ton, or 0.69 10^6 Btu/ton* *Anode Energy Content - 17,325 MJ/metric ton of Al (15.0 10^6 Btu/ton)* *Total Industry Energy Use (1995) - 450.40 10^9 MJ (428.95 10^{12} Btu)*	*Normal cell operation: CO_2 and CO* *Anode effects: CF_4 and C_2F_6* *HAPS: HF, polycyclic organic matter (POM)* *Generation:* *CO_2 - 1.4 metric tons/metric ton of Al* *Total CF_4 and C_2F_6 - 2,700 metric ton/yr (2,970 ton/yr)* *Total Fluoride - 5,820 metric ton/yr (6,400 ton/yr)* *Total POM - 3,200 metric ton/yr (2,910 ton/yr)*	*Typical Process Water Use - 5.2 kg/metric ton of Al* *Typical Wastewater Volume - 0.0009 kg/metric ton (0.0018 lb/ton) of Al*	*Spent Potliner - RCRA-listed waste K088* *Generation - up to 50 kg/metric ton (100 lb/ton) of Al* *Total Generation - 109,100 metric tons (120,000 tons) per year*

Figure 4-1. Alumina Reduction Cells

Table 4-2. Current Average Specific Energy Consumption of U.S. Reduction Cells

Cell Type	Specific Energy Consumption[a]	
	kWh/kg of Al	kWh/lb of Al
Prebake	14.94	6.79
Soderberg	16.07[b]	7.30
All (composite)	15.18	6.90

a Weighted average values.
b Includes energy for baking anodes in the pot.

Source: Data reported by Nolan Richards, 1997.

Table 4-2 shows the current average specific energy consumption for both prebake and Soderberg reduction cells. The current average specific energy consumption for all U.S. reduction cells is estimated to be 15.18 kWh/kg (6.9 kWh/lb) (Richards 1997). Table 4-3 shows smelting energy use by energy source; by far the major energy source used is electricity.

Although the average unit energy requirements for Soderberg cells shown in Table 4-2 are higher than the corresponding requirements for prebake cells, it should not be concluded that Soderberg technology is less energy efficient than prebake technology. All of the energy for baking the anodes is included in the unit energy for Soderberg technology; for prebake technology, anode baking energy is separate (see Table 3-1).

In modern alumina reduction cells, approximately 45% of the energy input is lost as heat given off to the surroundings. About half of this heat loss is from the pot shell and half from the anodes and crust (Eika et al. 1993). Specific heat loss mechanisms include radiation, thermal conductance through electrode connections, exhaust gases and tapped metal, and electrodes removed from the cell (EPA 1996).

Anode changing in prebake cells is the routine operation that introduces the largest single thermal disturbance in the cell, causing a significant energy drain. For a modern anode weighing about one metric ton, this drain corresponds to an energy loss of about 0.18 kWh/kg of aluminum (0.08 kWh/lb) (Aune et al. 1996)

The application of new technology, improvements to existing equipment, and the adoption of good house keeping measures could reduce the "industrial average" energy consumption of 15.0 kWh/kg of Al (6.8 kWh/lb) by 10% (Huglen and Kvande 1994). Beyond that, it is believed that only a technological breakthrough (such as inert anode/cathode systems) could lead to significant reductions in electrolysis energy consumption.

4.4 Emissions

Emissions of PFCs, Fluorides and Other HAPs Are of Concern

The main gases emitted from alumina reduction cells are

- carbon dioxide (CO_2),
- carbon monoxide (CO), and
- gaseous and particulate fluorides.

Gaseous fluorides emitted include two perfluorocarbon gases -- carbon tetrafluoride (CF_4) and carbon hexafluoride (C_2F_6) -- as well as hydrogen fluoride (HF) and silicon tetrafluoride (SiF_4). Particulate fluoride consists mainly of

Table 4-3. Energy Use in Aluminum Production - 1995

Energy Source	Specific Energy Use[a]		Total Industry Use[b]	
	MJ/metric ton of Al[c]	10^6 Btu/ton of Al	10^9 MJ[c]	10^{12} Btu
Electricity[d,e]	115,330	99.85	389.26	370.72
Natural Gas	752	0.65	2.54	2.42
Distillate Oil	20	0.02	0.07	0.07
Residual Oil	5	0.005	0.01	0.01
Propane & LPG	8	0.01	0.03	0.03
Gasoline	5	0.005	0.01	0.01
SUBTOTAL (excluding energy content of anodes)	**116,120**	**100.54**	**391.92**	**373.26**
Carbon Anodes[f]	17,325	15.00	58.48	55.69
TOTAL	**133,445**	**115.54**	**450.40**	**428.95**

a The percentage use of each non-electric fuel is assumed to be the same as the percentage use found in The Aluminum Association's 1989 industry energy survey: natural gas 95.2%; propane & LPG 1.0%; distillate oil 2.6%; residual oil 0.6%; and gasoline 0.6%.

b Based on total 1995 U.S. production of 3,375.2 10^3 metric tons of primary aluminum (The Aluminum Association 1996).

c MJ is one megajoule, or 10^6 joules.

d Based on the U.S. average for all plants of 15.18 kWh/kg of aluminum (Richards 1997).

e Conversion factor is 7,596 kj/kWh (7,234 Btu/kWh) (Richards 1997).

f Energy content of carbon anodes based on 1,806.7 Btu/lb of aluminum (pitch) and 5,828.4 Btu/lb of aluminum (petroleum coke) (The Aluminum Association 1989). Nolan Richards reports an anode energy content of 15,577 MJ/metric ton of aluminum.

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
Aluminum Statistical Review for 1995, The Aluminum Association, 1996.
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year 1989," prepared by The Aluminum Association, August 1991.

entrained and volatilized bath ($NaAlF_4$). In addition, alumina and carbon dust will sorb HF and therefore contribute to particulate fluoride (Haupin and Kvande 1993).

Hydrogen fluoride, designated by the EPA as a hazardous air pollutant (HAP), is emitted from both prebake and Soderberg cells. In addition, Soderberg cells emit polycyclic organic matter (POM), also a HAP. Other HAP compounds associated with primary aluminum production include benzene, cyanide, metal compounds, phenol, toluene, and xylene.

Section 112 of the Clean Air Act as amended requires the development of National Emission Standards for Hazardous Air Pollutants (NESHAPS) for the control of emissions of HAPs from both new and existing sources. The statute requires the standard to reflect the maximum degree of reduction in emissions that is achievable taking into consideration the cost of achieving the reduction, any non-air health and environmental reduction, and energy requirements. This level of control is referred to as the maximum achievable control technology (MACT).

CO_2, CO, Perfluorocarbons (PFCs) Are Emitted During Electrolysis

During normal cell operation, the anode gas emitted during electrolysis contains 80 to 90% CO_2, 10 to 20% CO, and a small amount of SiF_4, depending on the silica content of the anodes. The exact ratio between the amounts of CO_2 and CO generated is believed to be a function of the current efficiency of the pots. However, the amount of CO_2 released during smelting using prebaked carbon anodes is estimated at 1.4 metric tons per metric ton of aluminum (1.4 tons per ton) (Richards 1994 and 1997). Huglen and Kvande estimate 1.5 metric tons of CO_2 per metric ton of aluminum from the best cells, and an average of 1.74 metric tons of CO_2 per ton of aluminum (Huglen and Kvande 1994).

Estimates of CO emissions range from 125 kg/metric ton of aluminum to 340 kg/metric ton (Richards 1997 and Huglen and Kvande 1994). The higher number comes with the explanation that most of the CO evolved from Soderberg cells will be oxidized to CO_2 in separate burners before leaving the stacks, and the CO emissions will then be small. Also, CO from prebaked anode cells is probably oxidized rapidly, and the actual CO emissions will be much smaller.

During an anode effect (AE), the anode gas composition changes to 2 to 10% CO_2, 70 to 95% CO, 3 to 20% CF_4, and minor amounts of C_2F_6 (Haupin 1995). Anode effects most often occur when the alumina concentration in the bath is nearly depleted (less than 2%, rather than the normal 2 to 6%), leading to anode overvoltage (30 volts or more). This causes large bubbles to form, eventually forming a single large bubble that covers most of the anode surface. The overvoltage increases even more, leading to the production of fluorine-carbon compounds (perfluorocarbons) on the anode. Anode effects occur at a rate of one per day per pot to one per week at better-controlled plants.

There is currently agreement among most researchers that perfluorocarbons (PFCs) are not emitted during normal electrolysis. EPA estimates that annual PFC emissions from U.S. aluminum smelting are about 2,700 metric tons (2,970 tons) (Gibbs and Jacobs 1996). The primary aluminum industry has teamed with EPA to reduce PFC emissions through the Voluntary Aluminum Industrial Partnership (VAIP) program. The participating companies have agreed to reduce the frequency of anode effects by up to 70% by the year 2000 from a 1990 baseline. It is hoped that this will reduce annual PFC emissions from U.S. aluminum smelters by 30 to 60% (or an average 45%) from 1990 levels.

Typical CF_4 emissions values have previously been estimated as high as 2.5 kg/metric ton (5.0 lb/ton) of aluminum produced. More recent data, however, indicate that much less CF_4 is being evolved. Recent measurements from one company's smelters show average emission values of 0.06 and 0.8 kg of CF_4 per metric ton (0.12 and 1.6 lb/ton) of aluminum produced from prebake and Soderberg cells, respectively (Huglen and Kvande 1994). Richards reports an average value of 1.3 kg/metric ton (2.6 lb/ton) of aluminum (Richards 1997).

Gaseous C_2F_6 is also formed during anode effects, but in smaller amounts. It has been estimated that C_2F_6 emissions are about 5 to 15% of the amount of CF_4 (Huglen and Kvande 1994).

Hydrogen Fluoride Emitted in Both Gaseous and Particulate Form

Gaseous hydrogen fluoride (HF) is produced by hydrolysis of bath and hydrolysis of pot vapor. Emissions of HF that are not collected by the primary system are released in the potroom where they mix with the ventilation air and escape through the roof monitor at most plants, although some plants have roof scrubbers. Secondary HF emissions are generated during charging alumina to the bath, removing (tapping) the molten aluminum, replacing anodes, and correcting anode effects.

Historically, the combination of gaseous and particulate fluorides emitted from aluminum plants have been measured and regulated as emissions of total fluoride, or “TF”. TF has therefore acted as a surrogate to represent this mixture, and most emissions data currently available result from sampling and analysis for TF.

Baseline emissions from potlines at the 23 primary aluminum plants in the U.S. are estimated at 5,820 metric tons (6,400 tons) of TF annually, which includes about 2,270 metric tons (2,500 tons) of gaseous fluoride (EPA 1996). Based on 1995 primary aluminum production levels, this works out to approximately 1.7 kg of TF/metric ton (3.4 lb/ton) of aluminum. Richards reports an average value of 1.3 kg of fluorides/metric ton (2.6 lb/ton) of aluminum (Richards 1997). Emissions from prebake cells are approximately 40% those from Soderberg cells on a unit basis (Huglen and Kvande 1994).

Most of the fluoride content of HF gas and of particulate released with cell gas is captured by the cell’s hooding and fume treatment system, which is typically 95 to 98% efficient (Haupin and Kvande 1993). Some plants have mechanized bar breakers and aluminum hoppers within hoods that have resulted in even more efficient fume capture (Richards 1994). Those fluorides that escape capture represent fluoride emissions.

Dry scrubbing systems used today are capable of recovering more than 99% of the fluorides in the collected cell gases. Dry scrubbing is based on chemisorption of gaseous HF on alumina, with subsequent formation of AlF_3 during its return to the cell. This significantly lowers the consumption of aluminum fluoride (Grjotheim et al. 1995). Wet scrubbing systems are also used to control emissions from reduction cells.

Most of the particulate fluoride evolved from Hall-Heroult cells results from vaporization of the cryolite bath. Other contributors to particulate emissions include alumina and carbon from anode dusting, as well as aluminum fluoride, calcium fluoride, chiolite ($Na_5Al_3F_{14}$) and ferric oxide (EPA 1995).

The Standards of Performance for Primary Aluminum Reduction Plants (40 CFR Part 60, Subpart S), or New Source Performance Standards (NSPS), are applicable to potroom groups that commence construction after October 23, 1974. These standards require that affected facilities control discharges to the limits shown in Table 4-4.

Table 4-4. New Source Performance Standards for Aluminum Production (kg/metric ton of Al)

Plant Type	Total Fluoride [lb/ton of Al]
Prebake	0.95 [1.9]
Soderberg	1.0 [2.0][a]

[a] With exceptions.

Source: *Basis and Purpose Document for the Development of Proposed Standards for the Primary Aluminum Industry*, U.S. EPA, July 1996.

In addition to the limits shown in Table 4-4, no emissions may be discharged if they exhibit greater than 10% opacity from any potline (EPA 1996). The NSPS applies to five U.S. potlines. Existing facilities are subject to varying state emissions regulations for TF.

Other HAPs Include Polycyclic Organic Matter (POM)

Polycyclic organic matter (POM) is defined as organic compounds with more than one benzene ring and that have a boiling point greater than or equal to 100ºC (212ºF). As such, POM includes coal tar pitch volatiles, which are high-molecular-weight, polycyclic (four, five, or six benzene rings) compounds whose normal state is particulate rather than gaseous. Emission test results reveal that POM compounds from aluminum production may include a combination of known HAPs such as anthracene, benzo(a)pyrene, and naphthalene, among others.

Many of the compounds found in POM are also known (and sometimes measured) as polycyclic aromatic hydrocarbons (PAHs). PAHs are a group of chemicals that are formed during the incomplete burning of coal, oil, gas, garbage, and other organic substances. PAHs, which are emitted mainly from Soderberg anodes, have been the focus of much attention in the aluminum industry during the last decade. The PAH problem is mainly related to the use of coal tar pitch as a binder phase in these carbon materials. Because the anode is baked in the reduction cell as part of the Soderberg process, larger quantities of organic compounds such as PAHs are emitted from Soderberg cells. The more toxic PAH compounds found include fluorene, anthracene, phenanthrene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, and others.

POM emissions (measured as methylene chloride extractables) are estimated at 3,200 tons/year (2,910 metric tons) for the U.S. primary aluminum industry (EPA 1996).

Sulfur Dioxide Also Emitted During the Reduction Process

The majority of sulfur emissions from electrolysis are mainly in the form of sulfur oxides, but some carbonyl sulfide (COS) is also typically generated. Sulfur oxide emissions originate from sulfur in the anode coke and pitch. Consequently, most plants limit SO_2 emissions by limiting the sulfur content they will accept in these raw materials. Emissions from Hall-Heroult plants usually have SO_2 concentrations ranging from 20 to 30 parts per million (EPA 1995). Some plants use SO_2 scrubbers following the dry alumina scrubbers of the primary control system to obtain additional SO_2 control. Several plants use wet roof scrubbers that provide some control of SO_2 in secondary (fugitive) emissions. The wet systems used by a few plants for primary control of fluorides, POM, and particulate also control SO_2.

The use of prebaked anodes virtually eliminates hydrocarbon emissions from electrolysis. The separate production of these anodes ensures that their gaseous products are combusted and that, during electrolysis, there will be no hydrocarbon evolution.

Emission Factors Have Been Determined Through Surveys

Table 4-5 lists EPA’s emission factors for several major air pollutants (total particulate and gaseous and particulate fluoride) for aluminum production using prebake cells; Table 4-6 shows these factors for Soderberg cells. Table 4-7 shows EPA’s emission factors for PM10 (particulate matter less than 10.0 microns in diameter), SOx, CO, and VOCs from both prebake and Soderberg cells.

Table 4-8 shows average process-related emission factors of particulate, organics, fluorides, and other pollutants from two surveys. The first set of factors represents data measured at eleven operating North American

Table 4-5. Emission Factors for Alumina Reduction (Prebake Cell) (kg/metric ton of hot metal)

Source	Total Particulate [lb/ton]	Gaseous Fluoride [lb/ton]	Particulate Fluoride [lb/ton]
Uncontrolled	47.0 [94.0]	12.0 [24.0]	10.0 [20.0]
Fugitive	2.5 [5.0]	0.6 [1.2]	0.5 [1.0]
Emissions to collector	44.5 [89.0]	11.4 [22.8]	9.5 [19.0]
Multiple cyclones	9.8 [19.6]	11.4 [22.8]	2.1 [4.2]
Dry alumina scrubber	0.9 [1.8]	0.1 [0.2]	0.2 [0.4]
Dry ESP plus spray tower	2.25 [4.5]	0.7 [1.4]	1.7 [3.4]
Spray tower	8.9 [17.8]	0.7 [1.4]	1.9 [3.8]
Floating bed scrubber	8.9 [17.8]	0.25 [0.5]	1.9 [3.8]
Coated bag filter dry scrubber	0.9 [1.8]	1.7 [3.4]	0.2 [0.4]
Crossflow packed bed	13.15 [26.3]	3.35 [6.7]	2.8 [5.6]
Dry plus secondary scrubber	0.35 [0.7]	0.2 [0.4]	0.15 [0.3]

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

melters taking part in a 1991 survey. The data reflect the use of a variety of emission control equipment. The second set of factors comes from a 1994 survey of European smelters.

Table 4-9 shows the average emission level after the MACT level of control, which includes using dry alumina scrubbers to adsorb gaseous pollutants and baghouses to remove particulate pollutants and the alumina. Table 4-10 summarizes the MACT emission limits proposed by EPA in September 1996.

Dry Scrubbers Are Most Common Control Method for Primary Emissions

To control pollution, fumes evolved from the cells during electrolysis are removed by a collection system followed in most cases by a dry scrubber, where the fluorides are adsorbed by alumina that is subsequently recycled to the potlines. Wet scrubbers or electrostatic precipitators are used at a few plants.

The hooding used to capture emissions from the reduction cell cannot totally enclose the cell at all times because of the need to add alumina and additives, replace anodes, correct anode effects,

and remove molten aluminum. Primary capture efficiencies of large CWPB cells (with amperages of 95,000 or more per potline) are typically 95 to 99%, compared to a 90 to 95% for small CWPB cells. SWPB potlines are capable of achieving a primary collection efficiency of no higher than 85%, although exceptions have been reported (EPA 1996).

Horizontal stud Soderberg (HSS) potlines are capable of achieving total fluoride primary capture efficiencies of 85 to 95%; efficiencies for VSS potlines are in the range of 75 to 92% (EPA 1996). In VSS cells, a gas collection skirt

Table 4-6. Emission Factors for Alumina Reduction (Soderberg Cell) (kg/metric ton of hot metal)

Source	Vertical (VSS)			Horizontal (HSS)		
	Total Particulate [lb/ton]	Gaseous Fluoride [lb/ton]	Particulate Fluoride [lb/ton]	Total Particulate [lb/ton]	Gaseous Fluoride [lb/ton]	Particulate Fluoride [lb/ton]
Uncontrolled	39.0 [78.0]	16.5 [33.0]	5.5 [11.0]	49.0 [98.0]	11.0 [22.0]	6.0 [12.0]
Fugitive	6.0 [12.0]	2.45 [4.9]	0.85 [1.7]	5.0 [10.0]	1.1 [2.2]	0.6 [1.2]
Emissions to collector	33.0 [66.0]	14.05 [28.1]	4.65 [9.3]	44.0 [88.0]	9.9 [19.8]	5.4 [10.8]
Spray tower	8.25 [16.5]	0.15 [0.3]	1.15 [2.3]	16.0 [32.0]	3.75 [7.5]	1.35 [2.7]
Venturi scrubber	1.3 [2.6]	0.15 [0.3]	0.2 [0.4]	--	--	--
Multiple cyclones	16.5 [33.0]	14.05 [28.1]	2.35 [4.7]	--	--	--
Dry alumina scrubber	0.65 [1.3]	0.15 [0.3]	0.1 [0.2]	0.9 [1.8]	0.2 [0.4]	0.1 [0.2]
Scrubber plus ESP, spray screen	3.85 [7.7]	0.75 [1.5]	0.65 [1.3]	--	--	--
Floating bed scrubber	--	--	--	9.7 [19.4]	0.2 [0.4]	1.2 [2.4]
Scrubber plus wet ESP	--	--	--	0.9 [1.8]	0.1 [0.2]	0.1 [0.2]
Wet ESP	--	--	--	0.9 [1.8]	0.5 [1.0]	0.1 [0.2]

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.

AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 4-7. Emission Factors (PM10, SOx, CO, VOCs) for Alumina Reduction (kg/metric ton of hot metal)

Cell Type	PM10[a] [lb/ton]	SOx [lb/ton]	CO [lb/ton]	VOCs [lb/ton]
Prebake	27.25 [54.5]	28.65 [57.3]	184.5 [369.0]	0.05 [0.1]
Horizontal Stud Soderberg	28.4 [56.8]	5.0 [10.0]	122.0 [244.0]	0.5 [1.0]
Vertical Stud Soderberg	35.9 [71.8]	8.5 [17.0]	174.5 [349.0]	0.5 [1.0]

[a] Particulate matter less than 10.0 microns in diameter.

Source: *AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants*, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 4-8. Typical Emission Factors for Aluminum Production (Smelting) (kg/metric ton of aluminum)

Pollutant	Amount	
	N. American Survey[a] [lb/ton]	European Survey[b] [lb/ton]
Particulate	4.2 [8.4]	3.0[c] [6.0]
SOx	18.0 [36.0]	10.0 [20.0]
NOx	2.9 [5.8]	1.0 [2.0]
CO	125.0 [250.0]	101.0 [202.0]
CO_2	1,400.0 [2,800.0]	1,873.0 [3,746.0]
Organics	0.13 [0.26]	0.05[d] [0.10]
Fluorides	1.3 [2.6]	1.1 [2.2]

a Weighted average composite representing data from 11 North American smelters, including 9 prebakes (3 modern) and 2 VSS plants.
b Weighted average composite representing data from 27 European smelters, including 81% prebakes (31% modern) and 18% VSS by capacity.
c Reported as dust.
d Reported as polycyclic aromatic hydrocarbons (PAHs).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
1994 Environmental Survey for Electrolysis Plants, presented at Pollution Prevention in the Aluminum Industry, sponsored by The Aluminum Association, November 1995.

is installed between the anode casing and the bath, collecting gases that are ducted to burners where carbon monoxide, tars, and other hydrocarbons are burned prior to the primary control device. Because the design of HSS cells restricts the installation of a gas collection device, the collected gases from these cells are too dilute to be combusted (EPA 1996a).

Dry alumina scrubbers are the most common primary emissions control device in the U.S., and are used on 73 out of 91 (80%) domestic potlines. These scrubbers use alumina feedstock to adsorb gaseous pollutants and a baghouse to capture fine particulate pollutants. The alumina is then cycled to the potlines and the cleaned gases are released through a stack.

Two basic types of dry scrubbers are used -- fluidized-bed (40 potlines) and injection (33 potlines). When operating properly, the alumina scrubber/baghouse combination has a control efficiency for total fluoride in excess of 99% and 90 to 99% for POM emissions (EPA 1996 and 1996a). Therefore, the dry alumina scrubber has been designated the MACT floor technology and the best control for primary emissions.

Four of 23 primary aluminum plants in the U.S. use wet scrubbers to control emissions from reduction cells; three of these plants also use an electrostatic precipitator in series with the scrubber. The removal efficiencies of these systems are much lower than those of dry alumina scrubbers, typically 88 to 90% for total fluoride. However, plants using wet scrubbers can produce a higher purity aluminum because contaminant impurities are not recycled to the cells.

Table 4-9. MACT Emission Factors for Aluminum Production[a] (kg/metric ton of hot metal)

Potline Type	Total Fluoride [lb/ton]	Gaseous Fluoride [lb/ton]	Polycyclic Organic Matter [lb/ton]
CWPB			
Large, modern potlines	0.55 [1.1]	0.2 [0.4]	0.15 [0.3]
Older potlines, smaller cells	1.05 [2.1]	0.45 [0.9]	0.55 [1.1]
Potlines using wet scrubbers for primary emissions control	1.0 [2.0]	0.4 [0.8]	0.5 [1.0]
SWPB	0.5 [1.0]	0.1 [0.2]	0.15 [0.3]
HSS	1.0 [2.0]	0.4 [0.8]	1.3 [2.6]
VSS			
No freezing problems	0.65 [1.3]	0.1 [0.2]	0.2 [0.4]
Freezing problems	1.05 [2.1]	0.45 [0.9]	0.3 [0.6]

[a] These emission factors are approximations of the average level of emissions on a nationwide basis for the MACT level of control (dry scrubbers followed by baghouses). Emissions may vary significantly from potline to potline based on site-specific differences.

Source: *Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, July 1996.

Table 4-10. Proposed MACT Emission Limits for Aluminum Production - Existing Sources (kg/metric ton of hot metal)

Potline Type	Total Fluoride [lb/ton]	Polycyclic Organic Matter [lb/ton]
CWPB		
Large, modern potlines	0.95 [1.9]	--
Older potlines, smaller cells	1.5 [3.0]	--
Potlines using wet scrubbers for primary emissions control	1.25 [2.5]	--
SWPB	0.8 [1.6]	--
HSS	1.35 [2.7]	2.35 [4.7]
VSS		
No freezing problems	1.1 [2.2]	1.2 [2.4]
Freezing problems	1.35 [2.7]	1.85 [3.7]

Source: Federal Register, Vol. 61, No. 188, 40 CFR Part 63, *National Emission Standards for Hazardous Air Pollutants: Primary Aluminum Reduction Plants; Proposed Rule,* U.S. Environmental Protection Agency, Thursday, September 26, 1996.

Secondary Emissions Are Mainly Controlled Through Operating Practices

Secondary emissions are those fugitive emissions that escape capture by the primary control system for the cell. For example, plants using prebake cells must periodically remove and replace spent anodes, leading to secondary emissions. Older and smaller cells have more frequent anode changes per ton of aluminum than newer and larger cells, leading to greater quantities of emissions.

At most primary aluminum plants, secondary emissions escape through the roof monitor and are controlled by operating, maintenance, and work practices. However, four U.S. plants control secondary emissions using wet roof scrubbers.

4.5 Effluents

Alumina Reduction Requires Little Process Water

Total process water usage in alumina reduction is small, averaging 5.2 kg/metric ton (10.4 lb/ton) of aluminum. Total effluents average 0.0009 kg/metric ton of aluminum (0.0018 lb/ton) (Richards 1994).

Plants with wet scrubbers have a wastewater stream from the wet scrubber blow down. A wet primary control system (wet scrubber or wet ESP) generates 0.05 kg of fluoride and 0.1 kg of total suspended solids per metric ton of aluminum (0.1 and 0.2 lb/ton, respectively) (EPA 1996a).

Table 4-11 presents EPA's effluent limitations for primary aluminum smelting using best practicable control technology currently available (BPT). Tables 4-12 and 4-13 present effluent limitations using the best available technology economically achievable (BAT). Table 4-12 contains guidelines for cathode (cryolite bath) reprocessing operated with dry potline scrubbing, and with or without commingling of wastewaters with other process or non-process wastewaters.

Table 4-11. Primary Aluminum Smelting BPT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (kg/metric ton, or lbs per 1,000 lbs of molten aluminum)

Pollutant	BPT Limitation
Fluoride	1.0
Total Suspended Solids	1.5
pH	6-9

a Best Practicable Control Technology Currently Available.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.22, Bureau of National Affairs, 1992.

Table 4-12. Cathode Reprocessing BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of cryolite recovered)

Pollutant	Dry Potline Scrubbing/No Commingling	Dry Potline Scrubbing/ Commingling	Wet Potline Scrubbing
Benzo(a)pyrene	0.547	0.547	--
Antimony	189.2000	30.120	0.000
Cyanide	70.060	70.060	0.000
Nickel	35.030	12.960	0.000
Aluminum	122.600	94.930	0.000
Fluoride	13,310	924.800	0.000

[a] Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.23, Bureau of National Affairs, 1992.

Table 4-13. Potline Wet Air Pollution Control BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 10^6 lbs, or mg/kg of molten aluminum)

Pollutant	No Cathode Reprocessing	Cathode Reprocess/ No Commingling	Cathode Reprocess/ Commingling	Potroom Wet Air Pollution Control	Potline SO_2 Emissions Control
Benzo(a)pyrene	0.013	0.013	0.013	0.026	0.021
Antimony	0.721	4.525	0.721	1.428	1.153
Cyanide	--	1.676	1.676	--	--
Nickel	0.310	0.838	0.310	0.614	0.496
Aluminum	2.271	2.933	2.271	4.499	3.634
Fluoride	22.130	318.500	22.130	43.830	35.400

[a] Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.23, Bureau of National Affairs, 1992.

Table 4-13 lists guidelines for potline wet air pollution control, operated with or without cathode reprocessing, and with or without commingling of wastewaters. Effluent guidelines for potroom wet air pollution control and potline SO_2 emissions wet air pollution control are also given. EPA's discharge rules require either lime treatment of a bleed stream off the scrubber loop or cryolite recovery with lime treatment of the cryolite bleed stream if wet control technology is used.

4.6 Solid Wastes and Byproducts

Wastes Generated Include Dust and Wet Air Pollution Control Sludge

Dust (mainly fine-grained alumina) arises during transportation of alumina to the cell and feeding it to the bath. Solid waste is generated by wet air emission control devices, such as wet scrubbers and wet ESPs, and the associated wastewater treatment. Dry alumina scrubbing does not generate these wastes because the captured solids are recycled to the process. Wet scrubbers and wet ESPs generate 60 to 77 kg/metric ton of aluminum (120 to 154 lb/ton) of solid waste, which results in 5,450 to 13,640 metric tons/year (6,000 to 15,000 tons/year) of solid waste per plant, depending on its size (EPA 1996a). Table 4-14 presents estimates of several types of solid wastes generated during aluminum reduction based on the 1991 survey previously mentioned.

White dross, a slag-like material containing oxides of aluminum, is also produced at primary smelters. White dross has a high metallic content, typically 15 to 80%.

4.7 Hazardous Wastes

About 120,000 Tons of Spent Potlining Are Generated Annually in the U.S.

Although the carbon potlining used to hold the alumina/cryolite solution during electrolytic reduction can have a useful life exceeding ten years, it eventually cracks and needs to be replaced. Spent potlining was listed by EPA on September 13, 1988 (53 Fed. Reg. 35412) as a hazardous waste under Title 40 Code of Federal Regulations (CFR), Part 261, Subpart D, because it contains significant amounts of leachable fluoride, iron cyanide complexes, and free cyanides, as well as lesser amounts of PAHs and other organics.

In April 1996 EPA promulgated a Phase III Land Disposal Restriction (LDR) rule that sets concentration-based treatment standards for K088. Hazardous constituents in this waste are also required to meet universal treatment standards (UTS) before disposal in a land-based unit.

Table 4-15 shows the typical composition of spent potlining. This waste is generated at a

Table 4-14. Estimated Average Solid Wastes - Aluminum Production[a] (kg/metric ton of aluminum)

Waste	Amount [lb/ton]
Liquid (e.g., waste oils, grease)	0.22 [0.44]
Packaging	0.40 [0.80]
Environmental Abatement (e.g., landfilled waste, spent baghouse bags)	0.30 [0.60]
Other	3.75 [7.50]

a Excluding spent potlining.

Source: Data reported by Nolan Richards, 1997.

Table 4-15. Typical Spent Potlining Composition

Constituent	Range of Composition (%)
Carbon	9.6 - 51.0
Sodium	7.0 - 20.0
Aluminum	4.7 - 22.1
Fluoride	6.0 - 18.9
Calcium	1.1 - 2.9
Lithium	0.3 - 1.1
Magnesium	0.3 - 0.9
Silicon	0.0 - 12.3
Iron	0.3 - 2.1
Sulfur	0.1 - 0.3
Cyanide	0.02 - 0.44

Source: "Spent Potlining Treatment Using the Reynolds Metals' Low Temperature Process," Greg Felling and Paul Webb, 1996.

rate of up to 50 kg/metric ton (100 lb/ton) of primary aluminum produced (Pawlek 1993). The 1991 survey yielded an average of 25 kg of spent potliner generated per metric ton of aluminum (50 lb/ton) (Richards 1997). EPA estimates a total U.S. generation of 107,270 to 109,100 metric tons (118,000 to 120,000 tons) of K088 annually (EPA 1996b). About 80% of this waste is disposed in Subtitle C landfills at present, with remainder recycled or incinerated (EPA 1996b).

EPA has identified several options for treatment, recycling, reclamation and reuse of K088. Although the Agency prefers those technologies that recycle or reclaim spent material, it recognizes that limited data are available on the effectiveness of these technologies. EPA therefore has set numerical treatment standards for this waste to be landfilled, and any technology that meets these standards is acceptable (EPA 1996b).

Methods of Reusing Spent Potlining Are Being Investigated

Although there are a number of methods for recovering useful materials from spent potlining, many of these methods are not economically feasible. Therefore, the most common method of disposing of this material has been in piles at the smelters, or in landfills. However, expensive, carefully constructed and maintained landfills are required to prevent leaching of environmentally unacceptable species from spent potlining. For these reasons, reuse of this waste is an attractive alternative (Belitskus 1992).

A number of techniques for treating spent potlining have been investigated, including its use as a substitute for fluorspar additions to steel furnace slags and as a flux additive in cupola production of gray iron. Other options include using spent potlining as a cement kiln fuel supplement or as a mineral wool cupola fuel supplement, both of which appear to be capable of resulting in a zero-residuals product. Recovery of cryolite and/or carbon, while technically (and potentially economically) feasible, could result in a disposal problem with the black mud residue.

The most recently developed methods to treat spent potlining can be separated into low-temperature leaching methods, gas-treatment processes (application of moderate temperatures), and thermal treatment processes that take place at high temperatures (Pawlek 1993). Some of these processes are in the pilot-plant stage, while others are in operation on an industrial scale.

The primary aluminum industry is interested in detoxifying or rendering inert spent potlining efficiently in order to be able to discharge the treated material in open landfills. A further advantage is accrued if aluminum fluoride and/or cryolite can be recovered. However, when treating spent potlining thermally only to detoxify or render inert, the volume of waste to be landfilled may be increased substantially because of the addition of additional compounds such as limestone (Pawlek 1993).

Reynolds Metals Thermal Treatment Process Is Already in Commercial Use

One of the thermal treatment processes receiving considerable industry attention is the Reynolds Metals inertization process. Reynolds Metals has developed a commercial process to treat spent potlining, yielding a byproduct that is a non-hazardous raw material (delisted in December 1991) with potential uses.

In the Reynolds process, a blend of pre-sized spent potlining, limestone, and brown sand is fed to a rotary kiln and thermally treated. The cyanides are destroyed by oxidation at the elevated temperatures and the soluble fluoride salts react with the limestone to form calcium fluoride, a stable and relatively insoluble form of fluoride. The brown sand is blended with the spent potlining and limestone in an amount sufficient to prevent the agglomeration of the solids as they pass through the kiln. The kiln discharge contains such low levels of cyanides and soluble fluorides that it qualifies as a non-hazardous byproduct (Felling and Webb 1995).

EPA has estimated the cost of treatment at the Reynolds Metals facility in Arkansas to be $200 to $500 per ton (including ash disposal), depending on the quantity of waste delivered and other factors. EPA also estimates an average transportation cost to this facility of $110 per ton. For comparison, EPA has estimated that disposal of K088 at a Subtitle C landfill would cost $257 per ton, including transportation (EPA 1996b).

Several of the technologies under development for recovering materials from spent potliner may be less expensive than the Reynolds thermal treatment process. Precise cost estimates of using these technologies are not yet available. However, it is anticipated that a large portion of their potential cost savings could come from reduced transportation costs since at least some of these technologies could be located closer to the aluminum production facilities that generated them (EPA 1996b).

5

Secondary Aluminum Production: Scrap Pretreatment

5.1 Process Overview

Aluminum Scrap Characterized by Many Grade Variations and Quality Levels

Secondary aluminum producers recycle aluminum from aluminum-containing scrap purchased from recyclers, brokers, or scrap yards. This scrap comes from a variety of sources. "New" scrap is generated by pre-consumer sources such as drilling and machining of aluminum castings, scrap from aluminum fabrication and manufacturing, and aluminum-bearing residual material (dross) skimmed off molten aluminum during smelting operations. "Old" scrap is material that has been used by the consumer and discarded such as appliances, aluminum foil, automobile and airplane parts, and beverage cans.

For marketing purposes, scrap is classified into several grades:

- remelt scrap ingot
- segregated briquettes or too heavy to briquette
- segregated, baled, or packaged
- segregated loose
- nonsegregated
- borings and turnings
- skimmings

Well-segregated scrap is most easily used; remelting and ingot casting facilities are thus generally located at a large fabricating plant (Brondyke and McCormick 1967). The heavier grades of scrap or tightly briquetted material, which can be submerged in molten aluminum without special effort, are preferred because of minimum oxidation occurring during the melting operations. Turnings and borings and various grades of finely divided scrap are relatively poor materials for recycling purposes because they have a large surface area per unit mass, which increases oxidation during melting.

Pretreatment operations include sorting, shredding, and cleaning scrap prior to smelting and refining. Preprocessing the scrap prior to melting reduces aluminum loss within the furnace while reducing furnace emissions of hazardous air pollutants and other toxic substances.

Sorting and Shredding Separate Aluminum from Other Scrap

Almost all scrap aluminum (with the exception of sows, ingots, and very small scraps) is sorted and shredded before being charged into a melting furnace. These processes, which physically separate aluminum from other scrap, are sometimes referred to as mechanical cleaning.

Shredding is the tearing, ripping, and crushing of aluminum scrap down to small, manageable sizes. It increases the surface area of the aluminum, promoting quicker melting in the furnace.

Aluminum shredding is performed by hammer mills or ring crushers. The scrap is fed into the system after being picked over to eliminate oversize materials and to remove non-aluminum components such as iron, zinc, magnesium, stainless steel, and other contaminants. Systems range from 2,270 to over 22,700 kg/hr (5,000 to over 50,000 lb/hr) (EPA 1994). There are approximately 51 crushing and shredding operations in the United States (EPA 1996c). Other beneficiating processes include vibratory screens and air classifiers.

Cleaning Processes Remove Oils, Organic Coatings, and Other Contaminants

If scrap is contaminated with more than the normal dirt, oxide, or miscellaneous materials not easily separated and not conducive to the production of high-quality ingot, some preliminary cleaning process must utilized. Oils and various organic covering materials such as insulating coatings on cable or heavy enamel paint on sheet stock can be removed by carefully controlled burning (pyrometallurgical) processes, or in some cases using hydrometallurgical techniques. If the scrap does not contain these types of contaminants, it is ready to be charged to the melting furnace.

Pyrometallurgical (or drying) techniques such as roasting and sweating use heat to separate aluminum from oils and organic and metal contaminants.

In **roasting**, aluminum scrap that contains organic contaminants is crushed to a uniform small size and heated in rotary dryers to temperatures high enough to vaporize or carbonize organic contaminants, but not high enough to melt aluminum (i.e., less than the melting temperature of some aluminum alloys, about 450ºC or 842ºF). After leaving the dryer, the chips cross a magnetic separation system to remove any ferrous materials.

For example, oily scrap such as machine chips, turnings, and borings may be dried to remove the lubricants and/or coolants that may comprise up to 20% of their total weight. Chip and turning dryers are used to remove the machining oils, grease, and moisture from borings, turnings, and chips returned from aluminum manufacturing operations. There are approximately 20 aluminum scrap dryers in the U.S. (EPA 1996c).

Delacquering of used beverage cans (UBCs) is a roasting process. Beverage containers, which comprise a major portion of recycled aluminum scrap, are covered with both lacquers and sealers. UBCs are routinely "delacquered" prior to melting in order to increase the energy efficiency of melting and to minimize metal loss due to premelt burning. The delacquering is done at temperatures below the softening point of UBCs (particularly the lid 5182 high-Mg alloy), typically around 500ºC (932ºF). There are approximately 20 UBC delacquering operations in the United States (EPA 1996c).

In **sweating**, aluminum scrap that contains other metals is heated in a sweat furnace to temperatures above the melting temperature of aluminum but below that of the other metal. This causes aluminum to melt and trickle down into collecting pots, leaving the higher-melting materials in the furnace. High-iron-content scrap is typically sweated to reclaim the aluminum content so that excess iron does not get into the molten aluminum bath. There are approximately nine sweating furnaces in the United States (EPA 1996c).

A **catalytic technique** may be used to clean aluminum dross, the layer of impurities and semi-solid flux that has been skimmed from the surface of the molten aluminum. In this process, the dross is batch-fluxed with a salt/cryolite mixture in a barrel furnace. The cryolite acts as a catalyst, accelerating the separation and agglomeration of aluminum from the other materials.

Hydrometallurgical techniques such as leaching and heavy media separation use water to clean and process aluminum scrap. **Leaching** is used to recovery aluminum from dross, furnace skimmings, and slag. Leaching involves wet milling, screening, drying, and magnetic separation to remove fluxing salts and other waste products from the aluminum.

Heavy media separation separates high density metal from low density metal using a viscous medium. This technique has been used to concentrate aluminum recovered from shredded cars.

5.2 Summary of Inputs/Outputs

Inputs: Bulk scrap
Electricity
Fuel (natural gas, fuel oil)
Process water for wet air pollution control
Salt/cryolite catalyst
Outputs: Pretreatment contaminants (e.g., other metals, dirt, oil, plastics, paint)
Undissolved salts
Dust and fines
Particulate emissions (including chlorides and fluorides)
Organic vapors
Combustion emissions (including CO_2, SOx, NOx, and VOCs)
Wet air pollution control sludge

Figure 5-1 illustrates aluminum scrap pretreatment operations with its major inputs and outputs.

Some of the steps shown in Figure 5 -1 may be combined or reordered, depending on scrap quality, source of scrap, and auxiliary equipment available. Plant configuration, scrap type usage, and product output varies throughout the secondary aluminum industry (EPA 1995).

5.3 Energy Requirements

Natural Gas Fires UBC Delacquering Systems

Table 5-1 shows the specific energy requirements associated with scrap pretreatment, including UBC delacquering. The vaporized lacquer/paint/oil provide most of the fuel value, but supplemental natural gas is also required.

The 1,300 MJ/metric ton (1.13 10^6 Btu/ton) of input shown in Table 5-1 is the energy required for the roasting (delacquering) process. Figures in the range of 0.5 to 0.7 MJ/kg (200 to 300 Btu/lb) of input have been reported in the literature for delacquering systems that incorporate combustion air preheating. In either case, the hot shreds are usually conveyed directly to the reclamation melter or furnace.

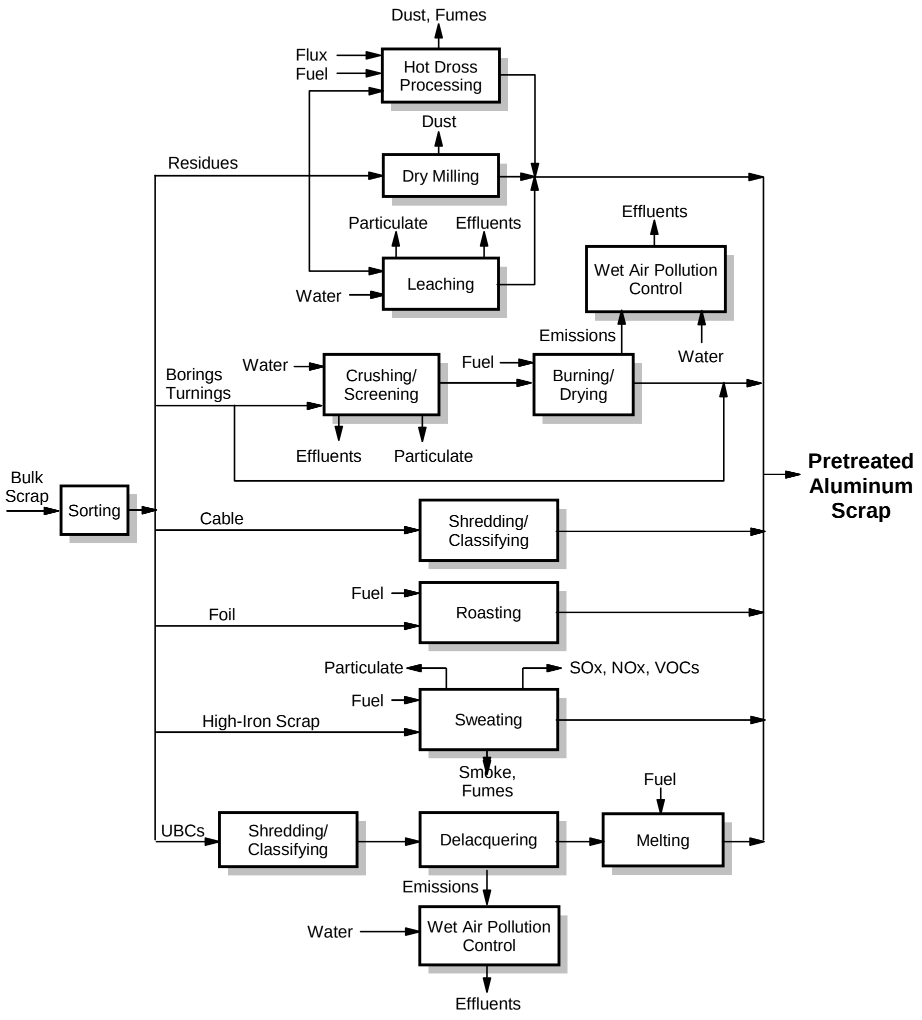
The overall energy requirements of the two types of systems are not significantly different, however, when downstream processes are considered. The shreds are hotter in systems without combustion air preheating, thereby conserving enthalpy and reducing downstream energy requirements compared with alternative systems where the shreds are not as hot (Richards 1997).

5.4 Emissions

Pyrometallurgical Cleaning Emits Chlorides, Organics

Emissions from secondary aluminum pretreatment operations consist mainly of particulate (including trace metals), gaseous organics or volatile HAPs, and acid gas emissions. The major sources of emissions from scrap pretreatment processes are

- scrap handling (including crushing and screening operations),



Key Energy and Environmental Facts - Scrap Pretreatment

Energy	***Emissions***	***Effluents***	***Byproducts***
Energy Use *1,600 MJ/metric ton of scrap input (1.39 10^6 Btu/ton)*	*Particulate, organics, chloride* *Largest Source - Roasting (inc. delacquering), sweating* *Generation:* *Particulate - 0.2 kg/metric ton (0.4 lb/ton)* *Chloride - 0.2 kg/metric ton (0.4 lb/ton)*	*Largest Source - Wet air pollution control*	*Baghouse fines from delacquering/decoating processes* *Amount generated - 112,422 - 181,820 metric tons/yr (102,016 - 200,000 tons/yr)*

Figure 5-1. Scrap Pretreatment Flow Diagram

Table 5-1. Process Energy Use in Scrap Pretreatment[a]

Energy Source	Specific Energy Use	
	MJ/metric ton of scrap input[b]	**10^6 Btu/ton of scrap input**
Electricity[c]	300	0.26
Natural Gas	1,300	1.13
NET TOTAL	**1,600**	**1.39**

a Includes sorting, shredding, and roasting (UBC delacquering).
b MJ is one megajoule, or 10^6 joules.
c Conversion factor is 11,530.6 kj/kWh (10,981 Btu/kWh) (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

- scrap dryers,
- sweating furnaces, and
- UBC delacquering systems.

Scrap handling, including receiving and storage of loose or baled scrap, generates minimal quantities of fugitive emissions, usually metallic aluminum that occur most frequently during bale-breaking operations.

In dry milling, large amounts of dust are generated from the crushing, milling, screening, air classification, and materials transfer steps. Mechanical cleaning techniques, including crushing, shredding, and screening, produce metallic and nonmetallic particulate. Leaching operations may produce particulate emissions during drying.

Scrap drying (including roasting and sweating) emits particulate and organic vapors. **UBC delacquering** furnaces emit volatile organic compounds as well as HCl, particulate chlorides and fluorides resulting from destruction of halogen-containing coatings, and metal and metal-oxide particulate. Any of the aluminum alloying and contaminant metals may be present, including antimony, arsenic, beryllium, cadmium, chromium, copper, lead, manganese, nickel, selenium, tin, and zinc. Organic compounds may include formaldehyde, other aldehydes, benzene and toluene from natural gas combustion, and furans and dioxins from the combustion of the chlorinated coatings (Jackson et al. 1992).

Other gases that may be emitted from **roasting and sweating**, depending on the composition of the contaminants, include chlorides, fluorides, and sulfur oxides. Specific emissions factors for these gases are not available from EPA.

Oxidized aluminum fines blown out of the dryer by the combustion gases contain particulate emissions. Particulate emissions from **roasting** result from the charring of carbonaceous materials (ash).

Emissions from **sweating** furnaces vary with the feed scrap composition. Smoke may result from incomplete combustion of organic contaminants (e.g., rubber, oil and grease, plastics, paint, cardboard, paper) that may be present. Fumes can result from the oxidation of magnesium and zinc contaminants and from fluxes in recovered dross and skims.

Table 5-2. Emission Factors for Scrap Pretreatment (kg/metric ton of hot metal)

Source	Total Particulate [lb/ton]	PM10[a] [lb/ton]	SOx [lb/ton]	NOx [lb/ton]	VOC [lb/ton]	CO [lb/ton]
Sweating furnace						
Uncontrolled	7.25 [14.5]	6.65 [13.3]	1.75 [3.5]	0.3 [0.6]	1.2 [2.4]	--
Baghouse	1.65 [3.3]					
Electrostatic precipitator	ND					
Crushing/screening	--	--	0.0	0.0	0.0	0.0
Burning/drying	--	--	1.5 [3.0]	0.25 [0.5]	16.0 [32.0]	--

[a] Particulate matter less than 10.0 microns in diameter.

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 5-2 lists EPA's emission factors for several major air pollutants for crushing/screening, burning/drying, and sweat furnaces. Although each step in scrap treatment is a potential source of emissions, EPA has not yet sufficiently characterized and documented emission factors for these processes (EPA 1995).

Table 5-3 presents estimated typical emissions of particulate, organics, and chloride from scrap pretreatment processes (including UBC delacquering) based on a 1991 survey of operating facilities. These data reflect the use of various emission control technologies.

Small Concentrations of Hazardous Air Pollutants Emitted

General secondary aluminum plant emissions have been found to include hazardous air pollutants (HAPs) such as antimony, cobalt, selenium, cadmium, and arsenic. Specific emission factors for these HAPs are not available from EPA. However, Table 5-4 presents a listing of measured concentrations of some of these toxics, as well as others, emitted by typical delacquering operations.

Control Methods Include Baghouses, Afterburners

Baghouses are typically used to control particulate emissions from shredding and crushing operations. Afterburners, or thermal incinerators, are frequently used to convert unburned VOCs from pyrometallurgical cleaning to carbon dioxide and water vapor. Afterburners are used specifically with dryers, delacquering kilns, and sweat furnaces to control the organic emissions generated by the thermal removal of oils, paints, lacquers, and other coatings or impurities from the feedstock.

Particulate control systems such as baghouses (or occasionally wet scrubbers) are sometimes used in conjunction with afterburners for fugitive loss control from dryers and UBC delacquering operations. Sweating furnaces typically use only a baghouse, although the proposed MACT for new sources includes both an afterburner and a baghouse (EPA 1996c). Emissions of acid gases (specifically from drying, delacquering, and sweating) are controlled using injection of a scrubbing agent, usually lime, prior to the baghouse.

Table 5-3. Typical Emission Factors for Scrap Pretreatment (kg/metric ton of input)

Pollutant	Amount [lb/ton]
Particulate	0.20 [0.40]
Organics	0.05 [0.10]
Chlorides	0.20 [0.40]

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Table 5-4. Emission Concentrations of Toxic Elements/Compounds from Delacquering Operations[a] (ug/dscm, except as noted)[b]

Element/Compound	Concentration	Element/Compound	Concentration
Antimony	3.0	Mercury	32
Arsenic	0.1	Nickel	7.4
Beryllium	Not detected	Phosphorus	23
Cadmium	0.5	Selenium	3.2
Chromium	30.0	Hydrogen chloride	50 - 400[c]
Lead	4.0	Dioxins/Furans	0.05 - 0.21[d]
Manganese	3.4		

[a] Data based on Secondary Aluminum MACT testing for systems with afterburners and lime-injected baghouses.
[b] Micrograms per daily standard cubic meter.
[c] Units are ppmv (parts per million volume).
[d] Units are ng TEQ/dscm, where ng is nanogram and TEQ is 2,3,7,8-Tetrachlorodibenzo-p-dioxin equivalents.

Sources: "Emission Testing for Air Toxics and Other Air Contaminants," M. Jackson and others, *The Proceedings of the 7th International Aluminum Sheet and Plate Conference*, 1992.
Data supplied by Bob Strieter, The Aluminum Association, 1997.

5.5 Effluents

There are no process water requirements for scrap pretreatment other than those associated with wet air pollution control methods (Richards 1997).

Table 5-5 presents effluent limitations using the best available technology economically achievable (BAT) for scrap drying wet air pollution control, scrap screening and milling, and delacquering wet air pollution control.

5.6 Byproducts

Solid wastes from the capture and treatment of delacquering fumes in baghouses are landfilled.

Table 5-6 shows estimated average process-related solid wastes associated with scrap

Table 5-5. Secondary Aluminum Processing BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of scrap/dross processed)

Pollutant	Scrap Drying Wet Air Pollution Control	Scrap Screening and Milling	Delacquering Wet Air Pollution Control
Lead	0.000	0.000	0.043
Zinc	0.000	0.000	0.140
Aluminum	0.000	0.000	0.903
Ammonia (as N)	0.000	0.000	19.514

a Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.33, Bureau of National Affairs, 1992.

Table 5-6. Estimated Average Solid Wastes - Scrap Pretreatment (kg/metric ton of input)

Waste	Amount [lb/ton]
Packaging	0.4 [0.8]
Environmental Abatement	7.0 [14.0]
Other	2.2 [4.4]

Source: Data reported by Nolan Richards, 1997.

pretreatment based on a 1991 survey of secondary aluminum facilities. The environmental abatement wastes include such items as spent bags for baghouses and other landfilled wastes. The total amount of baghouse fines generated by delacquering/decoating processes annually in the U.S. has been estimated to be approximately 181,820 metric tons (200,000 tons) annually DeSaro 1995). Another source estimates a alue of 32 kg/metric ton (64 lb/ton), yielding a total of 102,016 metric tons (112,422 tons) for 1995 (Taylor 1997).

5.7 Hazardous Wastes

There are no RCRA-listed hazardous wastes associated with the scrap pretreatment operations described above.

6

Secondary Aluminum Production: Smelting/Refining

6.1 Process Overview

Scrap is Melted, Cleaned of Impurities, Alloyed Prior to Casting

After aluminum scrap has been pretreated, it is sent for smelting and refining. Smelting and refining operations include

- charging and melting,
- fluxing,
- magnesium removal (demagging),
- degassing,
- alloying, and
- skimming and pouring.

Melting Technology Used Depends on the Charge

Pretreated scrap is charged into a melting furnace with flux materials that combine with contaminants and float to the surface, trapping impurities and providing a barrier that reduces oxidation of the melted aluminum. Scrap may be charged as high-density bales, loosely packed bales, or as dry shredded scrap.

The three basic objectives of melting aluminum alloys are

- to adjust the composition to that desired for the final product,
- to change to the form suitable for subsequent remelting and casting or fabricating into the desired product, and
- to improve the metal quality with respect to reduction of gas and nonmetallic inclusions.

A number of melting technologies are available; the characteristics of the scrap to be processed dictate the type chosen. Furnace operations can be placed in three subcategories:

- high-emitting furnaces
- low-emitting furnaces
- dross-only furnaces

A fourth subcategory -- sweat furnaces -- was discussed in Section 5. The total number of melting and holding furnaces (excluding sweat furnaces) in the U.S. secondary aluminum industry is approximately 417 (EPA 1996c).

High-emitting furnaces use either dirty scrap and/or chlorine (or other HAP-containing gas) for demagging/degassing. Dirty scrap is defined as scrap containing paint, oil, lubricants, coatings, and/or any HAP-containing substance (EPA 1994). Typical types of dirty scrap include insulated wire, oily borings and turnings, coated used beverage cans (UBCs), and coated/painted aluminum foil. Both reverberatory melters with a side-charge well and rotary barrel furnaces work well with smaller, dirtier types of scrap.

The standard reverberatory melting furnace is the most common method of smelting and refining in secondary aluminum production. With capacities ranging up to 75 metric tons (83 tons) and melting rates of 5,455 kg/hour (12,000 lb/hour) or more, reverberatory furnaces are generally employed to melt large volumes of metal. In this type of furnace, heat rising from ignited fuel is reflected back down from the curved furnace roof and into the melted charge. The molten metal is typically circulated using pumps or other methods to increase productivity, reduce fuel consumption, and enhance homogeneity.

Low-emitting, or "clean" furnaces are defined as any furnace design processing clean scrap only, employing no fluxing, and using non-HAP agents for demagging and degassing (EPA 1994). Typical types of clean scrap include delacquered UBCs, dried borings and turnings, uncoated aluminum siding, uncoated/unpainted aluminum foil, sows, sweated aluminum, and primary aluminum.

Direct charging to the hearth, such as reverberatory melting furnaces and round-top melters, works very well for larger (specifically, more surface area), cleaner scrap. Induction furnaces work well for scrap that has less surface area yet is still relatively clean. Low-frequency coreless induction furnaces are used for remelting fine scrap, including foil, scalper chips, and turnings. Such furnaces are in use with capacities ranging from 2,270 to 6,820 kg (5,000 to 15,000 lb) of aluminum.

Dross-only furnaces are those that recover aluminum from cooled, ground, and screened dross feedstock material (additional discussion in Section 6.6). This operation is carried out in rotary barrel furnaces (also known as salt furnaces) and rotary plasma furnaces.

Other melting methods include tower melters, vortex melters, and flotation melters. As the scrap gets smaller and dirtier, the cost of processing increases and the metal recovery decreases (Peterson 1995).

The crucible smelting/refining process is used to melt small batches of aluminum scrap. The induction smelting and refining process is designed to produce aluminum alloys with increased strength and hardness by blending aluminum and hardening agents in an electric induction furnace. The process steps include charging scrap, melting, adding and blending the hardening agent (e.g., manganese, silicon), skimming, pouring, and casting.

The recommended temperature range for melting and holding varies by alloy but rarely exceeds 800°C (1,475°F).

Fluxing Helps Removes Impurities

Some methods of melting aluminum scrap involve the addition of a molten salt flux. The salt is usually a mixture of NaCl and KCl, with a usual composition of 60% NaCl and 40% KCl. With sufficient agitation and a sufficiently fluid flux, the molten salt wets the impurities in the scrap and in doing so causes the aluminum to separate from both the flux and impurities. The flux also protects the melted aluminum, preventing it from becoming oxidized in the furnace itself. The separated aluminum forms droplets that coalesce to form a liquid aluminum pool beneath the molten salt (Sheth et al. 1995).

Fluxing is usually performed with standard reverberatory melting furnaces. Fluxing is not performed with induction furnaces.

Demagging Adjusts Magnesium Content of the Charge

Removal of magnesium, one of the most critical impurities in scrap, is important in the production of low-magnesium alloys for sand, permanent mold, and die casting applications. Secondary aluminum smelters almost always use a blend of scrap materials (e.g., beverage containers and wrought alloys used as building components), some of which can contain relatively high levels of magnesium. Therefore, some amount of magnesium must often be removed during secondary refining in order to reach the final specification level.

Demagging reduces the magnesium content of the molten charge from approximately 0.5% to about 0.1%. The most common materials used in demagging operations are chlorine and aluminum fluoride.

In chlorine demagging, chlorine gas is injected into the turbulent flow of the molten aluminum, where it reacts with the magnesium to form a solid that floats to the surface of the molten aluminum and is trapped in the flux layer. Other chlorinating agents or fluxes, such as anhydrous aluminum chloride or chlorinated organics, can also be used. In fluoride demagging, aluminum fluoride is reacted with the magnesium to produce a magnesium fluoride salt. Sulfur hexafluoride is another option to using chlorine gas or chlorine mixtures (EPA 1994).

The gas injection/circulation pump using chlorine has become the mainstay for demagging in aluminum remelt operations using reverberatory furnaces. This pump technology has a chemical reaction efficiency exceeding 95% and, when operated properly, virtually eliminates any emissions associated with chlorination during demagging (Neff and Cochran 1993).

Hydrogen Gas Removed by Degassing Operations

Degassing is performed to remove hydrogen gas bubbles, which cause inclusions and undesirable porosity in solid-phase aluminum. In degassing, the molten aluminum is agitated using high-pressure inert gases (chiefly nitrogen or argon), causing any entrained gases and solid particles to rise to the surface and be absorbed in the floating flux. Exposure to oxygen in the atmosphere causes the molten aluminum to oxidize, and the flotation of the impurities to the surface along with any salt flux creates a semi-solid known as black dross. The dross is then skimmed from the surface of the melt (see discussion of skimming below).

In-line degassing, which is often performed when the quality requirements of the aluminum are very high, is becoming increasingly widespread. In-line degassing operations include

- spinning nozzle inert flotation degassing,
- the Alcoa degassing process,
- the ALPUR process,
- the MINT system, and
- the DUFI system.

After the scrap has been melted and the impurities and entrained gases removed, the molten aluminum is typically pumped or gravity-fed from the reverberatory furnace into smaller holding furnaces, where it is alloyed and/or further refined based on the final product specifications.

Alloying Tailors the Metal's Properties to the User's Needs

Alloying combines the molten aluminum with zinc, copper, manganese, magnesium, silicon, or other agents in order to produce alloys of the desired composition and quality, changing the strength and ductility of the aluminum.

The alloying elements with melting temperatures near or below that of aluminum 660ºC (1,220ºF) are generally added as pure metals. These elements include bismuth, lead, magnesium, tin, and zinc. Two other major alloying elements, copper and silicon, may be added either as pure metals or as rich alloys. Alloying elements with high melting points, such as chromium, iron, manganese, and nickel, are added in the form of rich alloy ingot (alloying elements combined with aluminum) or master alloys; if added directly to the melt, these elements dissolve at exceedingly slow rates.

In addition, certain special materials are added as charge components for the purposes of grain refining. Titanium is the most effective grain refiner; others include vanadium, zirconium, and columbium. Titanium or titanium with boron generally is added as a rich alloy.

Skimming Removes Surface Oxide Film Prior to Pouring

Skim, an accumulation of oxide with entrapped metal, is formed on the metal surface after melting from oxide films introduced as surface oxides on all charge components. Skim is also formed from oxides generated on new metal surfaces exposed to the atmosphere during melting. Most of these metal oxides have an apparent density less than that of molten aluminum and float to the surface, where they are periodically removed by skimming. The recovery of metal from skim is discussed in Section 6.6.

After some combination of the above steps, the refined molten aluminum is either cast into a variety of forms (see Section 7) or is transferred to another facility in molten state for further processing.

6.2 Summary of Inputs/Outputs

Inputs:	Pretreated scrap
	Alloying and hardening agents
	Fluxing agent (e.g., salt)
	Fuel
	Electricity
	Process water
	Chlorine or fluorine gas
	Inert gases such as nitrogen and argon
Outputs:	Molten aluminum alloys
	Undissolved salts
	Dust and fines
	Black dross
	Reclaimed salt flux
	Particulate emissions
	Combustion emissions (e.g., CO_2, SOx, NOx, and VOCs)
	Chlorine emissions
	Effluents

Figure 6-1 illustrates aluminum scrap smelting/refining operations with its major inputs and outputs. Some of the steps shown in Figure 6-1 may be combined or reordered depending on scrap quality, source of scrap, auxiliary equipment available, furnace design, and product specifications. Plant configuration, scrap type usage, and product output varies throughout the secondary aluminum industry (EPA 1995).

6.3 Energy Requirements

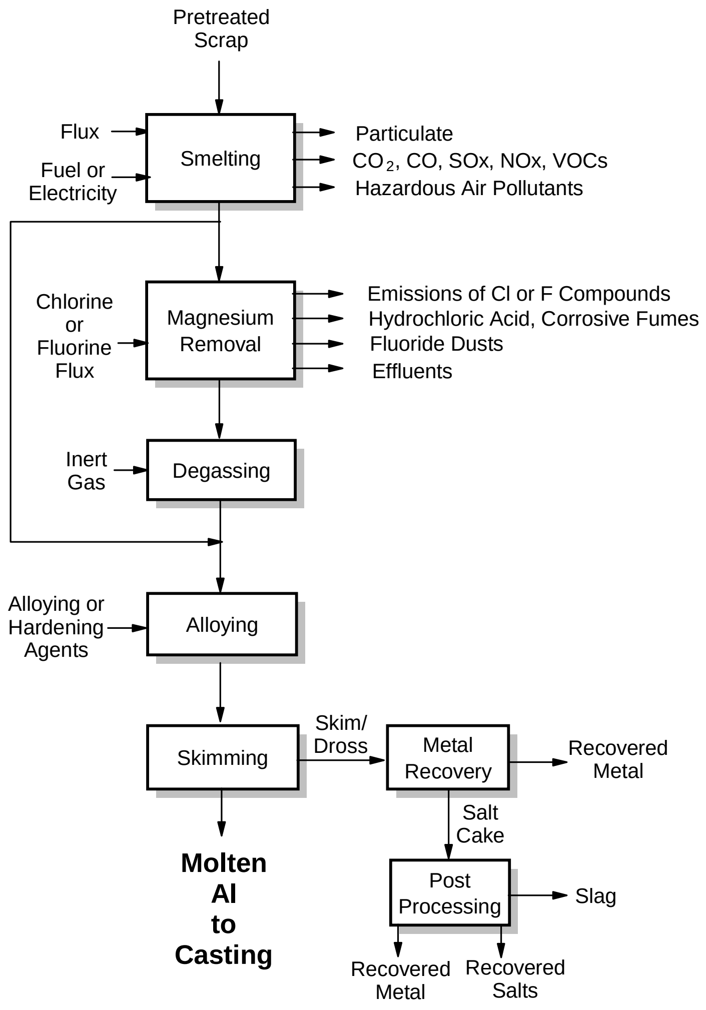
Newer or Modified Furnaces Consume Significantly Less Energy

Most melting furnaces are gas-fired (although a few are oil-fired); the rotary plasma furnace is a specially designed rotary furnace that is heated by a plasma arc gas heater instead of a regular gas burner.

Table 6-1 shows the average process energy requirements of secondary aluminum melting and refining (the data also include the energy requirements of casting, which is covered in Section 7). These data were derived from a 1991 survey of secondary aluminum facilities; a 10% improvement in energy performance was applied to the numbers to reflect increased efficiency between 1991 and the present (Richards 1997).

Table 6-2 presents some typical energy requirements of several types of melting furnaces used in the secondary aluminum industry. These requirements are expressed as ranges for some of the technologies. The higher energy requirements reflect older, less efficient furnaces, while the lower numbers reflect newer furnaces or those that have been modified with energy-saving features.

As shown in Table 6-2, rotary salt furnaces used to recover the metal content of dross generally consume about 7.4 MJ/kg (3,200 Btu/lb) of dross charged. These furnaces can recover about 90% of the dross' metal content. Assuming a 50% metal content in the dross, the specific energy



Key Energy and Environmental Facts - Scrap Smelting/Refining

Energy	***Emissions***	***Effluents***	***Byproducts***
Energy Use (includes casting): *5,922 MJ/metric ton of input (5.13 10^6 Btu/ton)*	*Major Emissions - Particulate, organics, chloride* *Largest Source - Demagging* *Generation:* *Particulate - 0.19 kg/metric ton (0.38 lb/ton)* *Chlorides - 0.17 kg/metric ton (0.34 lb/ton)*	*Largest Sources - Demagging; wet method residue processing* *Typical Process Water Volume - 320 kg/metric ton of Al*	*Dross - 154,500 metric tons/yr (170,000 tons/yr)* *Salt Cake - 657,900 to 727,270 metric tons/yr (725,000 to 800,000 tons/yr)*

Figure 6-1. Scrap Smelting/Refining Flow Diagram

Table 6-1. Process Energy Use in Secondary Melting/Refining[a]		
Energy Source	**MJ/metric ton[b,c]**	**10^6 Btu/ton[c]**
Electricity[d]	1,521	1.31
Natural Gas	4,247	3.68
Distillate Oil/Diesel	44	.04
Residual Oil	44	.04
Propane & LPG	66	.06
TOTAL	**5,922**	**5.13**

[a] Includes casting energy requirements. Casting is discussed in Section 7.

[b] MJ is one megajoule, or 10^6 joules.

[c] The percentage use of each non-electric fuel is assumed to be the same as percentage use in The Aluminum Association's 1989 industry energy survey: natural gas 96.5%; distillate oil 1.5%; residual oil 1.0%; propane & LPG 1.0%.

[d] Conversion factor is 11,530.6 kj/kWh, or 10,981 Btu/kWh (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," The Aluminum Association, August 1991.

Table 6-2. Energy Requirements of Scrap Melting Processes		
	Typical Range or Value	
Process/Equipment	**MJ/metric ton[a]**	**10^6 Btu/ton**
Standard reverberatory furnace	2,888 - 5,775	2.5 - 5.0
Coreless induction furnace	3,465 - 4,620	3.0 - 4.0
Tower melter	2,310	2.0
Flotation melter	2,310	2.0
Rotary salt furnace[b]	7,392	6.4

[a] MJ is one megajoule, or 10^6 joules.

[b] Value is per ton of dross charged.

Sources: "Effect of Low NOx Burner Modification on Melter Performance," D. Whipple, presented at Aluminum Industry Energy Conservation Workshop XI, sponsored by The Aluminum Association, November 1990.
"In-Plant Processing of Aluminum Melting Furnace Dross," R. Roberts, presented at Aluminum Industry Energy Conservation Workshop XI, sponsored by The Aluminum Association, Nov. 1990.
"Coreless Induction Melting of Aluminum," H. Heine and J. Gorss, presented at Aluminum Industry Energy Conservation Workshop XI, sponsored by The Aluminum Association, November 1990.

consumption of metal recovery from dross is approximately 16.4 MJ/kg (7,100 Btu/lb) of aluminum recovered (Roberts 1990).

At typical melting furnace temperatures of 1,093 to 1,204°C (2,000 to 2,200°F), only about one-third of the energy introduced is utilized in the furnace, with the remainder leaving in the form of flue gas losses (Wechsler and Gitman 1990).

Metal losses from oxidation during melting in low-frequency induction furnaces are very low, largely because heat is generated in the metal itself.

6.4 Emissions

Particulate, Organics, and Chlorides Are Emitted from Secondary Smelting/Refining Processes

Process emissions (excluding combustion emissions) from secondary aluminum smelting operations consist mainly of particulate (including trace metals), gaseous organics or volatile HAPs, and acid gas emissions (EPA 1994).

Although each step in scrap smelting/refining is a potential source of emissions, EPA has not yet sufficiently characterized and documented emission factors for these processes (EPA 1995). For example, chlorine emissions (in the form of chloride compounds) resulting from chlorine aluminum demagging processes have not yet been documented by EPA.

Table 6-3 lists EPA's emission factors for several major air pollutants for several types of furnaces, demagging processes, and other processes. Table 6-4 shows estimated process-related emissions of particulate, organics, and chlorides associated with secondary melting combined with secondary ingot casting (casting is described in Section 7). The data in Table 6-4 were calculated from the results of a 1991 survey of a number of secondary aluminum facilities using a variety of emissions control equipment.

Sources Include Charging, Fluxing, and Demagging

Specific sources of emissions include

- furnace charging and operation,
- fluxing, and
- demagging.

Emissions from reverberatory furnaces represent a significant fraction of the total particulate and gaseous effluent generated in the secondary aluminum industry. Emissions from the charging well consist of carbon dioxide and organic and inorganic particulate, as well as unburned organic vapors from partial combustion of oil and coatings on the charge.

Natural gas combustion generates nitrogen oxides, carbon monoxide, aldehydes, benzene, and toluene. Emissions from furnace burners contain carbon monoxide, carbon dioxide, sulfuric oxide, and nitrogen oxide. Furnace burner emissions are usually separated from process emissions (see Section 1.4).

Emissions from fluxing operations are dependent upon both the type of fluxing agents and the amount required, which are a function of scrap quality. Emissions may include common fluxing salts such as sodium chloride, potassium chloride, and cryolite. Aluminum and magnesium chloride may be generated from the fluxing materials being added to the melt.

Fluxing reactions also produce fume. Studies have suggested that fluxing particulate emissions are typically less than one micron in diameter. EPA does not have specific emissions factors for these compounds.

In the past, **demagging emissions** represented one of the most severe emissions problems in the secondary aluminum industry. Although newer chlorine demagging processes have reduced these emissions, chlorine emissions have not been eliminated. Total chlorine emissions are directly related to the amount of demagging effort and product specifications. Also, as the magnesium percentage decreases

Table 6-3. Emission Factors for Scrap Smelting/Refining (kg/metric ton of hot metal)

Source	Total Particulate [lb/ton]	PM10[a] [lb/ton]	SOx [lb/ton]	NOx [lb/ton]	VOC [lb/ton]	CO [lb/ton]
Smelting furnace - crucible						
Uncontrolled	0.95 [1.9]	0.85 [1.7]	1.25 [2.5]	0.85 [1.7]	1.25 [2.5]	--
Baghouse	ND	--	--	--	--	--
Electrostatic precipitator	ND	--	--	--	--	--
Smelting furnace - reverberatory						
Uncontrolled	2.15 [4.3]	1.3 [2.6]	0.45 [0.9]	0.4 [0.8]	0.1 [0.2]	--
Baghouse	0.65 [1.3]	--	--	--	--	--
Electrostatic precipitator	0.65 [1.3]	--	--	--	--	--
Chlorine demagging						
Uncontrolled	500 [1,000]	262.0 [532.0]	0.0	0.0	0.0	0.0
Baghouse	25 [50]	--	0.0	--	--	--
Electrostatic precipitator	ND	--	0.0	--	--	--
Aluminum fluoride demagging	--	--	0.0	0.0	0.0	--
Degassing	--	--	0.0	0.0	0.0	--
Hot dross processing	0.11 [0.22]	0.1 [0.2]	0.0	0.0	0.0	0.0

ND Not determined.
a Particulate matter less than 10.0 microns in diameter.

Sources: *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, U.S. Environmental Protection Agency, AP-42, Fifth Edition, January 1995.
AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants, U.S. Environmental Protection Agency, EPA 450/4-90-003, March 1990.

Table 6-4. Typical Emission Factors for Secondary Melting/Casting[a] (kg/metric ton)

Pollutant	Amount [lb/ton]
Particulate	0.19 [0.38]
Organics	0.05 [0.10]
Chlorides	0.17 [0.34]

a Data also reflect the unit process of delacquering at the appropriate weighted average of inputs.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991) during demagging, a disproportional increase in emissions results from the decreased efficiency of the scavenging process.

Both the chlorine and aluminum fluoride demagging processes create highly corrosive emissions. Chlorine demagging results in the formation of magnesium chloride that contributes to fumes leaving the dross. Excess chloride combines with aluminum to form aluminum chloride, a vapor at furnace temperatures, but one that condenses into submicrometer fumes as it cools. Aluminum chloride has an extremely high affinity for water and combines with water vapor to form hydrochloric acid. Free chlorine that does not form compounds may also escape from the furnace and become an emission.

Aluminum fluoride (AlF_3) demagging results in the formation of magnesium fluoride as a byproduct. Excess fluorine combines with hydrogen to form hydrogen fluoride. The principal emission resulting from aluminum fluoride demagging is a highly corrosive fume containing aluminum fluoride, magnesium fluoride, and hydrogen fluoride. The use of AlF_3 rather than chlorine in demagging reduces demagging emissions. Fluorides are emitted as gaseous fluorides (hydrogen fluoride, aluminum and magnesium fluoride vapors, and silicon tetrafluoride) or as dusts.

Some Furnace Emissions Are Hazardous Air Pollutants

According to the OVC/PM Speciate Data Base Management System, the following hazardous air pollutants (HAPs) have been found in emissions from reverberatory furnaces:

- chlorine
- compounds of manganese
- compounds of nickel
- compounds of lead
- compounds of chromium

In addition to the HAPs listed for reverberatory furnaces, general secondary aluminum plant emissions have been found to include HAPs such as antimony, cobalt, selenium, cadmium, and arsenic. Table 6-5 shows the components of typical scrap smelting/refining furnace off-gases.

Table 6-5. Components of Typical Furnace Off-Gases

Combustion products
Chlorine
Hydrogen chloride
Zinc chlorides
Magnesium chlorides
Aluminum chlorides
Aluminum oxide
Various metals and metal compounds

Specific emission factors for these HAPs are not available from EPA. However, Table 6-6 presents a listing of average measured concentrations of air toxic compounds emitted by melting operations, assuming the use of control systems normal for the industry. In addition to these data, emissions associated with fluxing operations have an average hydrogen chloride concentration of 150 mg/m^3 (Jackson et al. 1992).

Non-metal HAPs are generated from dross cooling and melting, fluxing, demagging, and degassing. These HAPs include Cl_2, HCl, HF, and others. For example, dross handling operations produce acidic chloride emissions of metal salts and hydrogen chloride (Jackson et al. 1992).

Dross Processing Generates Dust, Some Gases

Mechanically generated dust from rotating barrel dross furnaces constitutes the main air emission of hot dross processing. This dust, as well as fume, is generated when dross is thermitting, a reaction that occurs when hot dross is exposed to air.

The dross may also contain aluminum carbides and nitrides that can react with atmospheric moisture to produce aluminum oxide, liberating methane and ammonia gases (Roberts 1990).

Table 6-6. Emission Concentrations of Toxic Elements/Compounds for Melting[a]

Element/Compound	(mg/m^3)	Element/Compound	(mg/m^3)
Arsenic	0.02	Manganese	0.01
Cadmium	0.02	Mercury	0.0002
Chromium (total)	0.002	Nickel	0.02
Chromium (hexavalent)	0.001	Selenium	0.02
Copper	0.15	Zinc	0.8
Lead	0.03	Hydrogen chloride	55.0

[a] Data are average values for processes having control systems normal for the industry.

Source: *Emission Testing for Air Toxics and Other Air Contaminants*, M. Jackson and others, The Proceedings of the 7th International Aluminum Sheet and Plate Conference.

Hoods, Baghouses, Cyclone Used to Capture and Control Emissions

A number of methods are used to capture emissions from secondary aluminum smelting operations. These include canopy hoods, close capture hoods, and complete furnace enclosure.

Canopy hoods are typically used to capture emissions from furnace operations, including reverberatory furnaces, rotary furnaces, and front-charge melting and holding furnaces. These hoods are used to capture both fugitive and process emissions. Partition walls and curtains are used to reduce the effects of cross-drafts and to improve the flow of emissions to the canopy hoods (EPA 1994).

Partial enclosures, also referred to as close capture hoods, are similar to canopy hoods but with the addition of walls on the sides of the furnace charging well. Complete enclosure of the furnace is another technique to contain all the charging, melting, and refining emissions. Induction furnaces generate no combustion gases, and therefore no gas handling system is needed.

The most common emission control devices used in secondary aluminum smelting are **baghouses and cyclones**, which are used to control particulate emissions. For example, after fugitive emissions from dross furnaces are captured by hood systems, they are ducted to a baghouse.

Emissions of acid gases (specifically from high-emitting furnaces, dross cooling, and dross furnaces) are controlled using injection of a scrubbing agent, usually lime, prior to the baghouse.

Cyclones are used to remove larger particulate matter from hot vent streams and/or from streams that will be subsequently be sent to baghouses for particulate removal.

Furnace off-gas emissions, mainly fluxing salt fume, are often controlled by a **venturi scrubber**. Venturi scrubbers are also used for gaseous fluoride emission control from aluminum fluoride demagging.

6.5 Effluents

Process Water Requirements Are Relatively Small

The process water requirements associated with secondary melting (including casting) have been estimated at 320 kg/metric ton (640 lb/ton) of aluminum (Richards 1997). In addition, there may be water requirements associated with aluminum dross cooling.

Table 6-7. Scrap Smelting/Refining BPT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days

Pollutant	Chlorine-Based Magnesium Removal (kg/met ton, or lbs/1,000 lbs Mg removed)	Wet Method Residue Processing (kg/met ton, or lbs/1,000 lbs of product)
Total Suspended Solids	175	1.5
Fluoride	--	0.4
Ammonia (as N)	--	0.01
Aluminum	--	1.0
Copper	--	0.003
COD[b]	6.5	1.0

[a] Best Practicable Control Technology Currently Available.
[b] Chemical oxygen demand.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.32, Bureau of National Affairs, 1992.

Table 6-7 presents EPA's effluent limitations for chlorine-based magnesium removal ("demagging") and wet-method residue processing using best practicable control technology currently available (BPT). In addition to these limitations, the pH must be in the range of 7.5 to 9.0. The BPT limitation for processes that use water for metal cooling, and for aluminum-fluoride-based magnesium removal processes, is that there shall be no discharge of process wastewater pollutants to navigable waters.

Table 6-8 presents effluent limitations using the best available technology economically achievable (BAT) for dross washing and demagging wet air pollution control. Table 6-9 presents estimated amounts of total suspended solids, oils/grease, and biological oxygen demand (BOD) contained in effluents from secondary melting (including casting).

6.6 Byproducts

Metal and Salts Are Recovered from Dross and Salt Cake

Skim is the mixture of oxides, entrained metal, and entrained gases that forms when molten aluminum is exposed to the atmosphere. Aluminum reacts with the oxygen and nitrogen in the air (oxidizes), forming aluminum oxides and nitrides.

Dross is technically skim which has been treated or processed to reduce metallic content through the use of solid fluxes, active gas fluxes, or by post-furnace treatment. The terms skim and dross have become increasingly interchangeable and are now nearly synonymous (Rooy 1995). An estimated 657,900 to 727,270 metric tons (725,000 to 800,000 tons) of dross/salt cake are generated annually in the United States (Taylor 1997 and ANL 1997).

Methods that melt aluminum in the scrap while the scrap is in contact with a molten salt flux, such as some reverberatory melters, produce a dark-colored byproduct known as black dross. In addition to containing aluminum oxides, black dross contains a mixture of the removed impurities and the cleaning agents that were used to remove them. Also, salt flux will mix

Table 6-8. Scrap Smelting/Refining BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of scrap/dross processed)

Pollutant	Dross Washing	Demagging Wet Air Pollution Control
Lead	1.413	0.100
Zinc	4.565	0.324
Aluminum	29.450	2.090
Ammonia (as N)	636.900	45.180

[a] Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Iron and Steel Manufacturing*, 40 CFR Part 421.33, Bureau of National Affairs, 1992.

Table 6-9. Estimated Average Pollutants Contained in Secondary Scrap Melting/ Casting Effluents[a] (kg/metric ton)

Pollutant	Amount [lb/ton]
Total Suspended Solids	0.035 [0.07]
Oils/grease	0.01 [0.02]
BOD[b]	0.03 [0.06]

[a] Data also reflect the unit process of delacquering at the appropriate weighted average of inputs.

[b] Biological oxygen demand.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

with impurities (dirt or other foreign material) and become part of the dross (EPA 1994).

The dross production of melter installations varies greatly depending on factors such as furnace temperature, charge material, and contaminants in the charge. Casthouses melting only primary aluminum and clean in-house scrap may have dross generation of 0.5 to 1.0% of the metal melted. Those installations melting dirty, painted, or light-gauge scrap may produce dross in quantities of greater than 15% of the charge materials (Roberts 1990 and McMahon 1990). Table 6-10 shows some typical ranges of metal losses for different operations.

Because aluminum oxide (Al_2O_3) has a much higher melting point than pure aluminum -- 2,038°C (3,700°F) versus 660°C (1,220°F) -- the dross stays in the solid phase. Dross varies widely from plant to plant and even from furnace to furnace within a plant. It can vary from a sludgy material, high in metallic aluminum content and relatively low in

Table 6-10. Typical Furnace Melt Loss

Charge Material	Melt Loss (% of the metal melted)
Primary aluminum or clean scrap	0.5 - 1.0%
Heavy mill scrap, unalloyed ingot	1.5 - 3.0%
RSI[a], painted scrap, UBCs[b]	5.0 - 10.0%

a Remelt Secondary Ingot.
b Used Beverage Cans.
Source: Dross Cooling and Energy Savings, presented at the Aluminum Industry Energy Conservation Workshop, sponsored by The Aluminum Association, November 1990.

temperature, to a dry, friable material that is very hot (Roberts 1990). Dross must be skimmed away from the surface after melting is complete.

On a percentage basis, black dross typically consists of approximately 45% salt (a mixture of 50 to 60% sodium chloride and 40 to 50% potassium chloride), 45% aluminum oxide and other oxides, and about 10% aluminum metals fines (Sheth et al. 1996). The Aluminum Association reports a range of aluminum content of 8 to 30% (AA 1996b).

Salt Fluxes Used to Help Recover Metal from Skim and Dross

Some metal is always entrapped in the skim and should be recovered. The use of fluoride and chloride salt fluxes to dewet and absorb oxides, and promote coalescence and drainage of metal from the skim, is common practice. Gaseous fluxes, including reactive gases, are also used.

Another strategy for treating skim avoids the use of fluxes. In this case, a metal-rich skim (as much as 70% recoverable metal) is removed for secondary processing.

Mechanical processes used to treat (cool) skim after its withdrawal from the furnace also reduce metal content, leaving a metal-depleted dross for subsequent treatment in a rotary salt or rotary plasma furnace or for disposal (Rooy 1995). These processes include skim chilling in skim pans or buildings (an inefficient process that reduces the metal content of the dross), charging hot skim to a rotary cooler for quenching and separation into metallic and non-metallic fractions, and charging hot skim to a hydraulically pressurized container the separates metal from skim. There are approximately 86 dross cooling operations in the United States (EPA 1996c).

Both dross pans and dross buildings achieve cooling by exposing the metallic aluminum in the dross to oxygen in the surrounding air while still at high temperature. This can result in a reaction known as “thermitting,” which results in the reduction of the metal content of the dross by converting metallic aluminum to aluminum oxide.

Thermitting does not take place in rotary dross coolers. Instead, the dross is placed in an oxygen-starved environment within a water-cooled drum. The tumbling action of the drum promotes rapid cooling of the dross, which is subsequently prepared for use as a feedstock to an aluminum recovery furnace.

Most secondary smelters and some primary aluminum smelters employ facilities dedicated to the recovery of aluminum from dross. The most common method of treatment is the previously mentioned rotary salt furnace, ranging in capacity from several to about 40 metric tons (up to 90,000 pounds). The products of this furnace are RSI (Remelt Secondary Ingot) and salt cake, a mixture of spent salts, oxides, and residual metal.

In addition to the rotary salt furnace, there are other technologies available for secondary aluminum production and for separating the metal from the dross. These include rotary barrels, mechanical processes such as impact milling, and a plasma process that is similar to the rotary salt furnace except that it operates without salt.

The typical range of metal recovery from black dross is 8 to 30% (AA 1996b). The aluminum content of salt cake is typically lower than that of black dross, typically from 3 to 10% aluminum by weight (Roth 1996). A well managed process yields a typical salt cake of no more than 5 to 6% free metal, 15 to 30% metallic oxides, and the balance salts (Rooy 1995 and ANL 1997). The aluminum loss from dross at secondary smelters is estimated to be 154,550 metric tons (170,000 tons) per year (DeSaro 1995).

Residual Salt Cake May Undergo Additional Processing

After recovering the molten aluminum, the residual salt cake is typically disposed in specially constructed and monitored landfills that conform with environmental standards. The potential for environmental contamination remains, however, from the NaCl and/or KCl of the salt. Also, the salt slag in contact with water releases harmful gases such as hydrogen, ammonia, methane, and smaller amounts of hydrogen sulfide and phosphine (Sheth et al. 1996).

Because of such environmental concerns, salt cake and salt-rich drosses increasingly are sent for tertiary or post-processing to capture the metal units as well as the salt content. Recovered sodium and potassium salts can be reused or sold, enabling cheaper, unlined landfills to be used for the slag. An estimated 90,900 to 136,300 metric tons/year (100,000 to 150,000 tons/year) are currently recycled in the United States (ANL 1997). However, the majority of salt cake residues in this country are still landfilled without additional processing.

In salt recovery plants, the dross and salt cake are crushed and dissolved in water. Aluminum fractions are separated by screening, and non-metallic fractions (mainly aluminum oxide with other metallic oxides) are filtered from the brine. Salts may be recovered from the liquor by precipitation or by drying using crystallizers, kilns, or solar fields. The brine is evaporated and then recycled to the smelting process, and the insoluble, non-metallic product (NMP) is landfilled.

Industry efforts continue in the search for feasible applications of NMP; the inability to find uses for this material has hampered the economics of salt cake recycling. At least one company working in this area has reported finding applications for NMP in the production of abrasives, refractory, and fiber insulation (ANL 1997).

Other Solid Wastes Include Spent Baghouse Content

The total quantity of solid waste associated with secondary melting (including secondary ingot casting) has been estimated at 32 kg/metric ton (64 lb/ton) of aluminum based on a 1991 survey (Richards 1997). This figure also reflects the unit process of delacquering at the appropriate weighted average of inputs. The survey also estimated an average solid waste generation of 6.5 kg/metric ton (13.0 lb/ton) of aluminum related to environmental control (e.g., spent bags for baghouses) (Richards 1997).

6.7 Hazardous Wastes

There are no RCRA-listed hazardous wastes associated with the scrap melting/refining processes described above, unless dross/saltcake tests characteristic based on alloys such as lead or chromium.

7

Semi-Fabrication

7.1 Process Overview

Many Shaping and Treating Processes Required to Yield Wide Variety of Aluminum Products

After alloying and refining in a holding furnace, the molten primary or secondary aluminum undergoes some combination of the following steps:

- casting
- scalping
- preheating
- hot rolling
- cold rolling
- annealing
- sheet finishing
- drawing
- extruding

The molten aluminum is either cast into ingots, which are used as the basic charge components in subsequent remelting or mechanical operations, or is continuously cast and fed directly into a rolling mill. From there, the aluminum is rolled into plate, sheet, or foil using a variety of hot and cold rolling processes, or is drawn or extruded into tube, wire, or other similar products (see box).

Each flat-rolled product owes its final properties not just to the rolling process itself but to the preparatory steps of alloying, casting, scalping, and pre-heating; intermediate annealing; and such later finishing steps as solution heat treatment or final annealing, stretching, slitting, edge-trimming, and aging (AA 1990).

Product Definitions

Product	Cross-Section	Thickness[a]
Plate	Rectangular	>0.250"
Sheet	Rectangular	0.006 - 0.249"
Foil	Rectangular	<0.006"
Tube/Pipe	Circular	--
Wire Rod	Numerous	0.125 - 0.375"
Wire	Numerous	<0.125"

a - diameter for wire rod and wire

Both Ingot and Continuous Casting Are Used

Aluminum can be cast -- solidified from the molten state -- either into ingots or directly and continuously into plate or sheet. Ingot casting is much more common than continuous casting.

Ingot casting is used to produce sheet ingot suitable for rolling, T-ingot, pigs and sows for remelting, cylindrical billet for extrusion, and a form of rod for wire products.

There are several types of ingot casting. The most common method is the semi-continuous vertical direct chill (VDC) casting, in which molten metal is poured through a refractory spout into a short metal mold. The flow is controlled by a floating baffle or non-contact sensor. Mold cooling is provided by water running through channels in the mold. As the metal solidifies, the ingot is lowered from the bottom of the mold by a hydraulic platform, maintaining a constant molten metal head in the mold.

The resulting sheet ingot may be cast into a long length and then sawed to produce the size desired, or cast into the length required for rolling. If the alloy is to be used for various hot working and cold working operations it is cast into suitable size and shape for sheet, rod or bar rolling, extrusion, or forging. In this case, the product is called fabricating ingot.

Aluminum alloys destined for use in foundries can be direct chill (DC) cast as "T" ingots or can be cast in iron or steel molds as pigs or sows. Rich alloy ingot, or hardener ingot, is a combination of aluminum and relatively high percentages of the higher-melting elements used for alloying, such as chromium, iron, manganese, and/or nickel. Rich alloy ingots are used as part of the charge to a holding furnace to produce alloys containing these elements.

Ingots for Rolling Into Sheet and Plate Are Produced Using Vertical Direct Chill Casting

VDC casting is commonly used for the production of ingot/block to be used for rolling into sheet and plate. Blocks can range in size from 4,535 to 15,880 kg (10,000 to 35,000 lbs). A typical cross-section might be 137 to 152 cm (54 to 60 inches) wide by 51 to 71 cm (20 to 28 inches) thick, with a length of 508 to 737 cm (200 to 290 inches) and a weight of about 18 metric tons (20 tons). Generally two to as many as five blocks are cast at the same time. Billets for an extrusion operation are cast in the same way.

The VDC process runs the ingots/blocks down into a pit, which makes the process semi-continuous. Strip casting and horizontal direct chill (HDC) methods are continuous in that these processes can run many heats of metal before being shut down for maintenance. These processes may run for days, while the VDC operation runs for one to two hours per "cast."

Horizontal direct chill (HDC) casting is also used, although it is less common than VDC casting. Although HDC ingots do not have the length restrictions of VDC ingots, gravity can cause a problem with metal microstructure.

Airslip and Electromagnetic Casting Are Variations of VDC Casting

There are several variations of the standard VDC casting process that are used to provide smoother ingot/block surfaces than a conventional DC ingot. This reduces the need for machining or scalping of the as-cast ingot to ensure acceptable surface quality on the finished sheet and plate. The two major variations are "Airslip" or the Wagstaff process, and "EM" or electromagnetic casting.

In both Airslip and EM casting the molds used for the VDC process are modified to change the way the metal solidifies. A third variation of DC casting, known as the inert gas/water method, mixes inert gas or air with the cooling water to change the cooling rate at the surface of the solidifying ingot.

In the Airslip process, air is forced between the mold and the molten metal, thereby modifying the cooling at the surface. The gap between the mold and the metal is critical, especially in the early stages of solidification where the thin skin of solidified metal is weak.

In EM casting, an electromagnetic field is used to shape and contain the metal in a special mold. The molten metal is held away from the mold wall by the field, thereby controlling the mold/metal gap. However, EM casting is more sensitive to operate, requires more sophisticated controls, and is more capital intensive than a conventional direct chill caster. The advantages are smoother surfaces and reduction or elimination of the need for scalping before rolling.

Scalping is performed on an ingot to remove any irregularities or undesirable chemical compositions (such as excess oxides or concentrated alloying elements) left on the surface by ingot casting. In scalping, the broadest sides of the ingot are shaved by a machine with rotating blades called a scalper.

Continuous (Direct) Casters Produce Strip or Slab

For some applications, aluminum can be cast directly into sheet or plate in special machines such as roll casters, belt casters, or block casters. Continuous casters can also be described by the type of product they yield -- strip (continuous sheet) or slab (continuous plate) casters.

Strip casters can produce continuous aluminum sheet thin enough to be coiled immediately after casting without additional hot rolling. Slab casters produce continuous aluminum products in the plate thickness range, typically between 25 to 203 cm (10 and 80 inches) wide, at linear speeds around 6 m/min (20 ft/min) (AA 1990).

Because it is much thinner than ingot, direct-cast sheet or plate cools and solidifies much faster than DC ingot and therefore the as-cast structure differs metallurgically. Continuously cast slab is usually hot rolled directly after casting to a thickness compatible with the cold-rolling process. Strip casters provide strip that is ready for cold rolling directly.

Preheating Ingots Improves Their Metallurgical Properties

Prior to hot working, ingots and billets are usually homogenized at elevated temperatures to reduce alloy segregation and give a more uniform composition. Ingots that are to be hot rolled must be preheated for a number of reasons, including:

- preventing strain hardening during the rolling operation
- spheroidizing insoluble constituents
- softening the ingot
- relieving stresses in the ingot
- putting all soluble alloy constituents into solid solution

Ingots are preheated to 455 to 565°C (850 to 1,050°F) in temperature-controlled furnaces. Large ingots are carried through walking-beam furnaces, while smaller ingots are heated in brick-line soaking pits.

Hot Rolling Reduces Thickness, Changes Properties

Sheets and strip can either be hot rolled directly to the desired thickness or hot rolled to an intermediate thickness and then cold rolled to the final thickness. The latter process is used if improved surface finish or special temper and properties are desired. Aluminum plate and slab products are rolled and finished by procedures similar to those described below for sheet and strip.

Hot rolling deforms the metal in a temperature range that is usually above the recrystallization temperature of the metal. This process virtually eliminates strain hardening, thus making heavy reductions in section relatively easy. Cold rolling means rolling the metal at a temperature low enough for strain-hardening to occur. Hot mills currently roll sheet at rates of about 610 m/min (2,000 ft/min); cold mills can roll sheet at rates exceeding 2,135 m/min (7,000 ft/min) (AA 1990).

Aluminum is hot rolled to reduce thickness and refine the as-cast structure. The wrought microstructure is more workable and more adaptable to subsequent hot or cold working operations.

The most basic parts of a rolling mill are two motor-driven cylinders called work rolls. These rotating rolls draw the aluminum through and reduce its thickness to the width of the gap between them. A thick ingot can be reduced to thin sheet either by passing it repeatedly between the same work rolls and narrowing the gap each time, or by passing it through a series of rolls with progressively smaller gaps. A mill with one set of work rolls is a “single-stand” rolling mill;

several sets of work rolls in a coordinated series form a “multiple-stand” or “tandem” mill.

Most aluminum plate and sheet rolling requires so much force that it is difficult to avoid excessive flexing with only two work rolls. To deal with this force, each work roll is typically backed up by a larger roll pressing against it to keep it straight. A stand with two work rolls plus two back-up rolls is called a “four-high” stand or mill. Although some mills operate three-, five-, or six-high roll combinations, the four-high mill is the most widely used for rolling aluminum. Some mills are designed to roll in only one direction, while others (called reversing mills) can roll product back and forth.

The first rolling mill encountered by an aluminum ingot entering the rolling line is called the “breakdown mill.” The breakdown mill is usually a single-stand, four-high reversing hot rolling mill whose main function is to reduce the ingot’s thickness to that of plate product.

For some purposes the breakdown mill alone can produce final product thickness. For others, the product of the breakdown mill is fed through additional rolling mills for further thickness reduction and/or surface finishing.

If additional hot rolling is required (as for strip or sheet products), the plate-thickness slab is typically transferred to a tandem sheet-rolling mill. There, several thickness reductions take place simultaneously as the sheet passes between several sets of work rolls with smaller and smaller gaps. A typical product of the hot mill would have a thickness of about 0.32 cm (1/8 inch). Sheet destined for cold rolling to thicknesses under about 0.10 cm (0.04 inch) is usually hot rolled to about 0.30 to 0.61 cm (0.12 to 0.24 inch) before cold rolling.

A lubricant is used between the aluminum surface and the rolls to reduce frictional forces during rolling. For most hot rolling operations, large volumes of a water-soluble oil emulsion are used to provide lubrication as well as roll cooling. As sheet emerges from the hot mill, it is rolled up into a coil that may be as much as 2.4 m (8 ft) in diameter. The sheet can be edge-trimmed prior to coiling.

Cold Rolling Imparts Specific Properties to the Product

Aluminum is cold worked for one or more of the following reasons:

- increase strength and hardness (but at the expense of ductility)
- refine grain structure
- straighten or flatten the product
- increase the accuracy of dimensions (gauge tolerance)
- improve surface appearance
- control characteristics of metal flow during subsequent forming operations

Prior to the cold mill, the coils may be annealed to give the metal the workability for downstream processing. Some plants have moved towards self-annealing, which requires no additional energy investment but more careful control of the hot rolling process. The coils are then passed through cold rolling mills to reduce the gauge to the desired thickness.

Aluminum can be cold rolled down to thicknesses of around 0.05 mm (0.002 inch). Pure (low-alloy) aluminum can be cold rolled into foil as thin as 0.0025 mm (0.0001 inch). A typical thickness of small-gauge coil is in the range of 0.20 to 0.38 mm (0.008 to 0.015 inch). If the product is coil for beverage can manufacturing, the gauge is reduced to 0.30 mm (0.012 inch).

There are numerous types of equipment for performing the cold reduction. For narrow widths -- less than 50 cm (20 inches) -- the reductions can be performed on two-high mills, but for the greater widths, the four-high mill is typically used.

The amount of cold reduction performed depends largely on the application that is being considered. Increasing amounts of cold reduction will tend to make the resulting product finer grained and harder after annealing. Lubricants used for cold rolling are usually composed of an H-P additive in a light petroleum distillate oil.

Annealing Improves Metal Properties and Performance

Before, after, or between cold rolling passes the sheet may be fully or partially annealed by heating and then slow cooling. Annealing is used to improve the properties, performance, and durability of the product. This process softens the aluminum and counteracts the strain hardening and aging that has already taken place.

There are a number of annealing operations used in the production of sheet and strip. The most important are full annealing, partial annealing, and stabilization annealing.

Full annealing heats the alloy hot enough and long enough to soften the product completely, achieving full recrystallization. For full annealing of heat- treatable wrought aluminum alloys, the metal is typically "soaked" for about two hours at a temperature in the range of 335 to 370ºC (635 to 700ºF) to remove cold work, or 400 to 425ºC (750 to 800ºF) to counteract precipitation hardening. The metal is then cooled slowly to permit maximum coalescence of precipitating particles, minimizing hardness (AA 1990).

Partial annealing stops short of full annealing and instead applies patterns of temperature and time to strain-hardened, non-heat-treatable wrought alloys in order to develop properties in between fully soft and fully work-hardened product. It is typically performed after the completion of cold rolling.

Stabilization annealing is used to prevent further age-softening (gradual loss of some strength over time) of certain non-heat-treatable aluminum-magnesium alloys. It is accomplished by heating the products to about 180ºC (350ºF).

Finishing Operations Include Solution Heat-Treating, Slitting, Coating, Cutting

When rolling is completed, the sheet goes through selected finishing processes, including:

- solution heat-treating
- artificial or natural aging
- slitting
- tension-leveling
- coating and marking
- cutting to length
- stretching/leveling
- packaging and storage

Heat-treatable alloys may be **solution heat-treated** in batch or continuous furnaces to dissolve alloying elements more completely. These alloys are then quenched to freeze in that microstructure. The metal is strengthened when the solutionized product is aged.

Aging of solutionized sheet is used to precipitate intermetallic phases that strengthen the metal. Natural aging occurs at room temperature, while artificial aging is carried out at temperatures of 65 to 170ºC (150 to 350ºF). Peak aging is developed in a shortened time frame in artificial aging.

In **slitting**, circular knives are used to trim the edges of the coiled sheet straight. Before or after slitting, the sheet may also go through a **tension-leveler** to flex and stretch the metal to remove any buckling and to give it a uniform flatness. **Coatings** or decorations may be sprayed or rolled on at the mill, although this type of finishing is often done elsewhere.

When separate flat sheets are required, coiled sheet is sent to a **"cut-to-length"** line where it is uncoiled and cut to the specified lengths. If necessary, cut sheets are **stretched** to flatten them. Finally, the finished sheet is **packaged and stored** for shipping.

Rods Are Drawn to Form Wire

Drawing is used to produce wire, a term that is applied to any thread or filament, or to any slender rod or bar that has a uniform cross section. A great many products shaped by pulling metal through a die are called wire. The limits for drawn wire range from 0.0025 to approximately 2.5 cm (0.001 to approximately 1 inch) in diameter.

To produce wire, the rod is first hot rolled and coiled. The rod (or wire) is then drawn through a succession of dies to reduce its diameter. To improve drawing quality and to meet special requirements of mechanical properties, many sizes and grades of wire are heat treated as rod during process or in finished sizes.

Pipe, Tube, and Other Products Are Made Via Extrusion Processes

In extrusion, an ingot or billet is forced to flow under pressure through a die opening to form an elongated shape or tube. Extrusion processes use hydraulic presses, which include a container to hold the ingot, the die, and a ram that applies the extrusion pressure.

Extrusion processes can be direct or indirect. In direct extrusion, the ingot moves relative to the container wall; in the indirect process, the die moves. Extrusion is performed both hot and cold, although most commercial extrusion is done hot because of the reduced resistance of the metal to deformation at elevated temperatures. Cold extrusion, which requires very high pressures and stronger tooling, is limited to small ingots and simple shapes such as rod and bar. It is conducted at much higher speeds, with shorter cycle times per ingot, and develops closer dimensional tolerances than hot extrusion.

Hydraulic extrusion presses are either horizontal or vertical. Vertical presses, which seldom exceed 1,090 metric tons (1,200 tons) capacity (the amount of force that can be exerted on the ingot), are for specialized uses such as thin-wall tube. Horizontal presses can have capacities as high as 12,730 metric tons (14,000 tons), although the most common capacities are in the range of 1,450 to 2,270 metric tons (1,600 to 2,500 tons).

The usual stock for extrusion is an ingot cast by the direct-chill method, although ingots cast in water-cooled metal molds and rolled rod billets of small diameter are occasionally used. Based on cross-sectional configuration, extrusions are classified as rod, bar, solid shapes, semi-hollow shapes, hollow shapes, structural and stepped shapes, or tube.

Rod, bar, and solid and semi-hollow shapes are extruded from solid ingots through conventional dies. Stepped extruded shapes involving two or more consecutive cross sections in a single length are produced in split dies. Most hollow shapes and some tube are produced from solid ingot employing porthole or bridge dies. Pipe, redraw tube stock, tube, and some hollow shapes are produced as seamless products from hollow ingot by the die and mandrel process.

Prior to extrusion operations, ingots are reheated in gas- or oil-fired furnaces or electric induction furnaces. Additionally, furnaces are used to heat dies and tools before insertion into the press. For hot extrusion, the ingot and tooling are heated to temperatures between 288 and 565°C (550 and 1,050°F) to facilitate extrusion at available press capacity. For cold extrusion, the ingot, container, and tooling are heated no higher than about 300°F. Furnaces are also used for solution heat treatment of extrusions. No lubricants are needed for extrusion except on the surface of the mandrels for the extrusion of hollow blooms.

7.2 Summary of Inputs/Outputs

Inputs: Molten primary aluminum
Molten secondary aluminum
Alloying elements (e.g., magnesium, manganese, copper, silicon)
Chlorine or chlorine/nitrogen gas
Lubricants
Electricity
Fuel (e.g., natural gas, oil)
Process water
Outputs: Aluminum semi-fabricated products
Scrap (e.g., chips)
Dross
Particulate emissions
Chloride emissions
Organic mist and vapor
Combustion emissions (CO_2, SOx, NOx)
Effluents
Recovered oil and oil-laden solids
Residues from coating treatment

Figures 7-1, 7-2, and 7-3 illustrate the casting and semi-fabrication processes associated with the

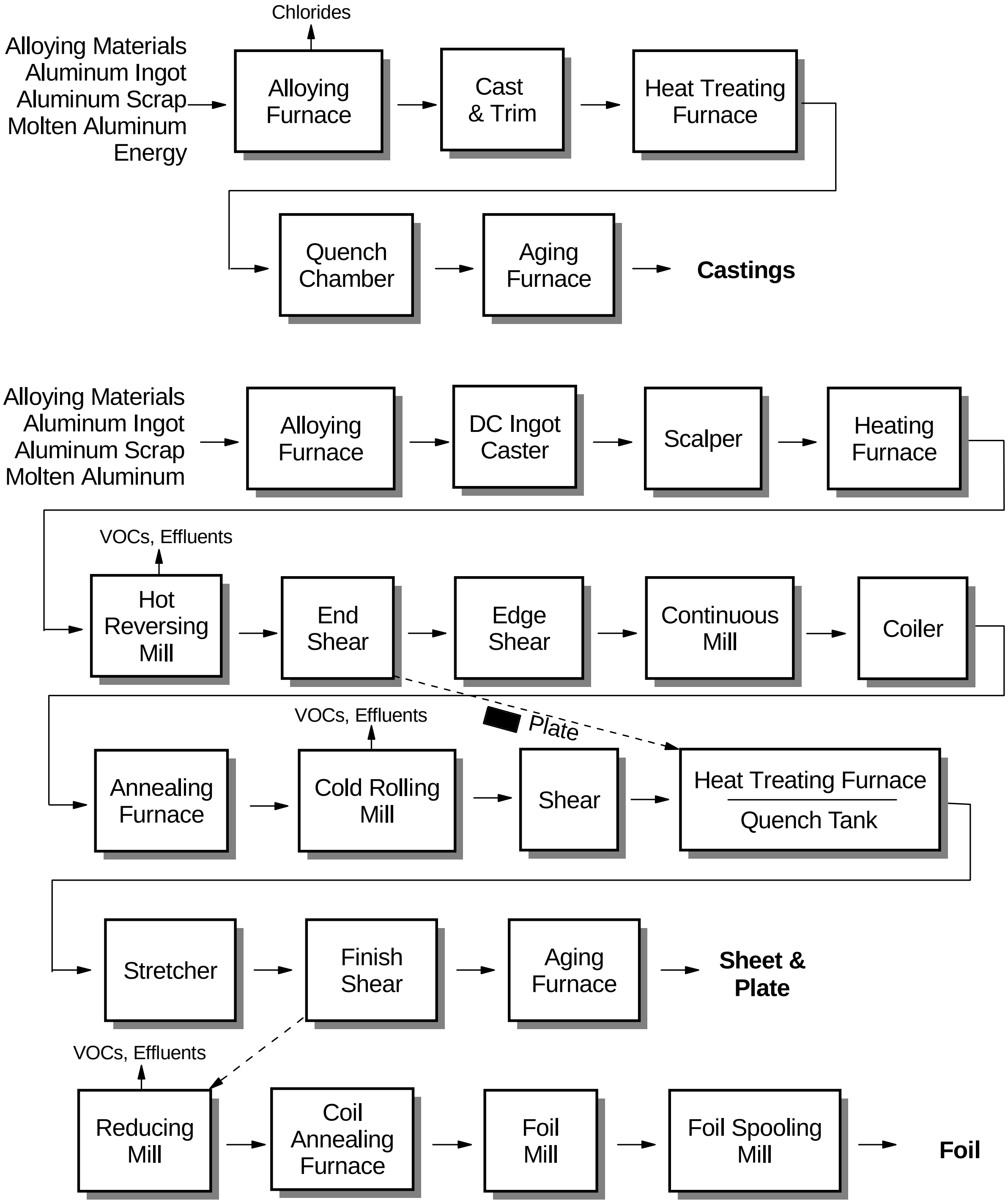


Figure 7-1. Semi-Fabrication Flow Diagram: Castings, Sheet & Plate, Foil

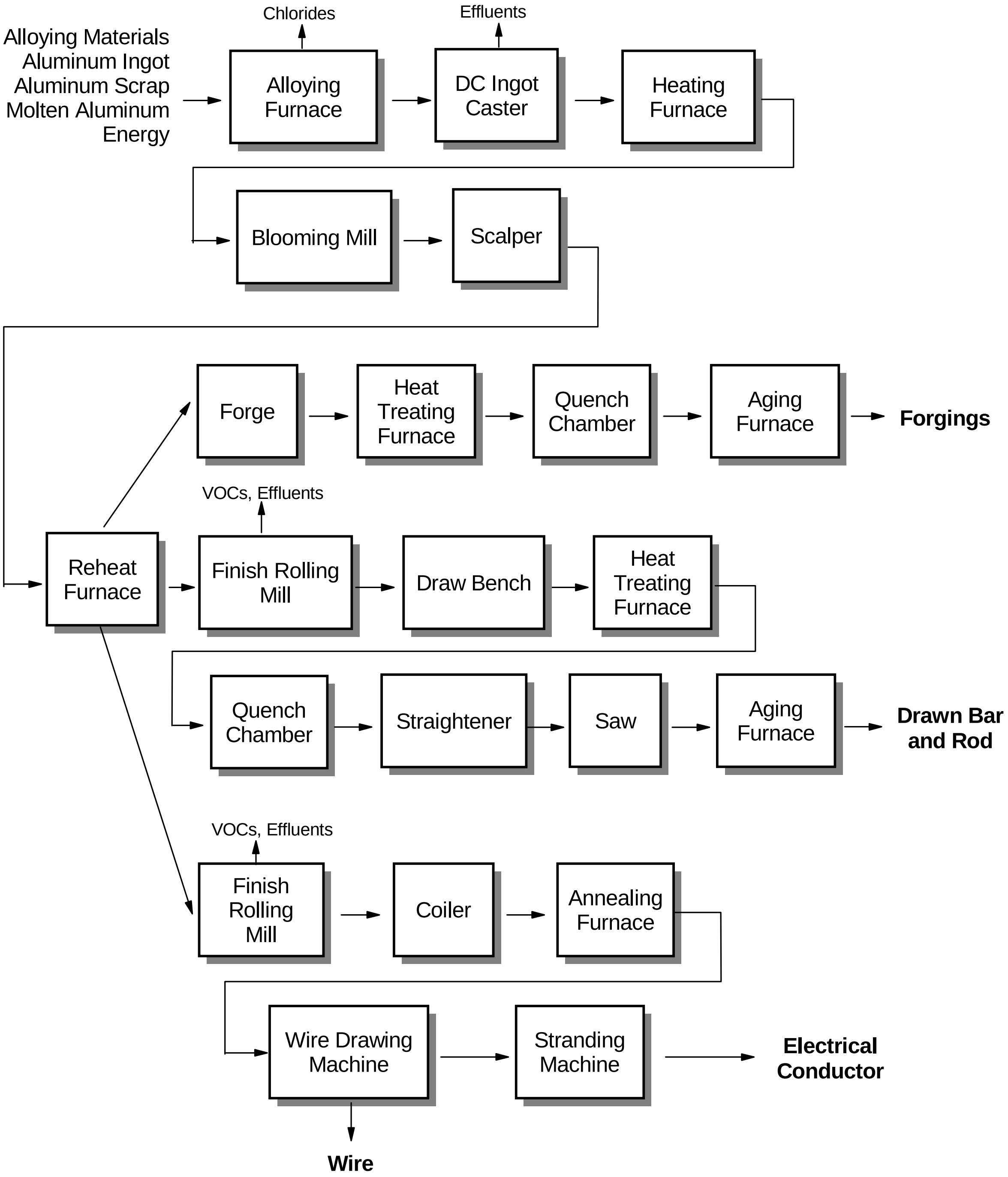
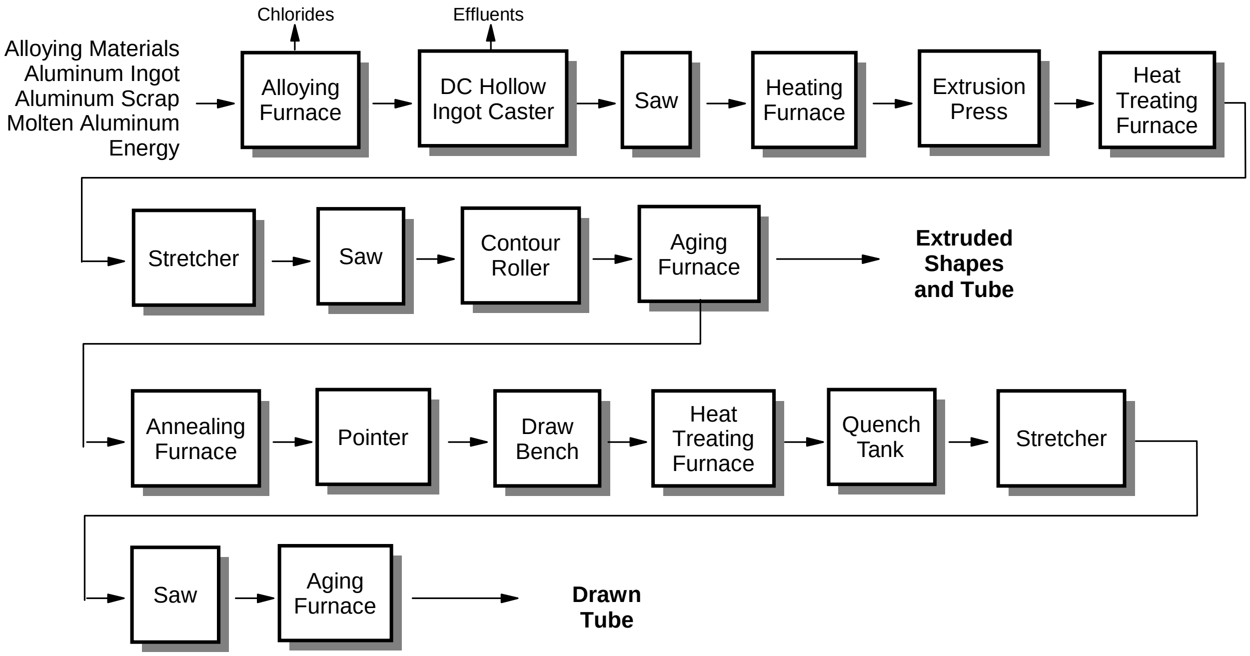


Figure 7-2. Semi-Fabrication Flow Diagram: Forgings, Drawn Bar and Rod, and Wire



Key Energy and Environmental Facts - Semi-Fabrication

Energy	***Emissions***	***Effluents***	***Byproducts***
Energy Use (MJ/metric ton) *Primary Ingot Casting - 6,560 (5.68 10^6 Btu/ton)* *Hot Rolling (softer alloys) - 6,445 (5.59 10^6 Btu/ton)* *Hot Rolling (harder alloys) - 5,830 (5.06 10^6 Btu/ton)* *Cold Rolling - 8,090 (7.00 10^6 Btu/ton)*	*Major Emissions - Particulate, chlorides, organic droplets and vapors* *Largest Source - Rolling mill oil mist and vapors*	*Largest Source - Primary ingot casting* *Other Sources - Secondary casting, roll cooling* *Typical Primary Casting Process Water Volume - 10,800 kg/metric ton (21,600 lb/ton) of Al cast*	*Oils, grease associated with casting and rolling* *Casting - 0.038 kg/metric ton (0.076 lb/ton)* *Rolling - 2.1 to 5.6 kg/metric ton (4.2 to 11.2 lb/ton)* *Packaging, effluent and air pollution control wastes*

Figure 7-3. Semi-Fabrication Flow Diagram: Extruded Shapes and Tube, Drawn Tube

production of aluminum sheet, plate, foil, and drawn and extruded products.

7.3 Energy Requirements

Electricity, Natural Gas Are Major Fuels Used in Casting and Rolling

The energy requirements of cold rolling are higher than hot rolling because it takes more energy to roll cold metal than metal that has been softened at high temperatures.

Table 7-1 shows the process energy requirements of primary ingot casting by fuel type. Table 7-2 shows these requirements for hot and cold rolling. Two sets of hot rolling data are presented; the first set is for softer alloys (such as 3104), and the second is for harder alloys (such as 5182).

In addition to ingot casting, the data in Table 7-1 include the process energy requirements of pretreatment (e.g., degassing), holding in a holding furnace, and fluxing. The rolling data in Table 7-2 include the process energy requirements of ingot scalping and ingot soaking or preheating in addition to rolling.

A higher proportion of ingot is currently produced by electromagnetic casting than in 1991 when the data in Table 7-2 were developed. Because electromagnetic casting requires somewhat less energy than direct chill casting, there could be minor decreases in the process energy requirements given in Table 7-2.

7.4 Emissions

Rolling Mill Is Typically Largest Source of Emissions in Semi-Fabrication

Continuous plate or ingot casting operations themselves generate insignificant quantities of air emissions (Jackson et al. 1992). The main air emissions from ingot casting processes are CO_2

Table 7-1. Process Energy Use in Primary Ingot Casting[a]

	Specific Energy Requirements[b]	
Energy Source	**MJ/metric ton**[c]	**10^6 Btu/ton**
Electricity[d]	1,910	1.65
Natural Gas	2,417	2.09
Distillate Oil	698	0.61
Residual Oil	698	0.61
Propane & LPG	465	0.40
Gasoline	372	0.32
TOTAL	**6,560**	**5.68**

[a] Includes pretreatment to remove alkali metals, holding, and fluxing.

[b] Non-electric fuel percentage use is assumed to be the following: natural gas - 52%; distillate oil 15%; residual oil 15%; propane & LPG 10%; gasoline 8% (Richards 1997).

[c] MJ is one megajoule, or 10^6 joules.

[d] Conversion factor is 11,530.6 joules/watt-hour (10,981 Btu/kWh) (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Table 7-2. Process Energy Use in Hot and Cold Rolling[a]

Energy Source	Hot Rolling - Softer Alloys[b,c]		Hot Rolling - Harder Alloys[b,d]		Cold Rolling[b]	
	MJ/met ton[e]	10^6 Btu/ ton	MJ/met ton[e]	10^6 Btu/ ton	MJ/met ton[e]	10^6 Btu/ ton
Electricity[f]	3,530	3.06	3,800	3.29	5,390	4.67
Natural Gas	2,536	2.20	1,766	1.53	2,349	2.03
Distillate Oil	29	0.03	20	0.02	27	0.02
Lube Oil	146	0.12	102	0.09	135	0.12
Propane & LPG	29	0.03	20	0.02	27	0.02
Gasoline	29	0.03	20	0.02	27	0.02
Coal and Misc.	146	0.12	102	0.09	135	0.12
TOTAL	**6,445**	**5.59**	**5,830**	**5.06**	**8,090**	**7.00**

[a] Includes scalping and soaking or preheating in addition to rolling.

[b] The percentage use of each non-electric fuel is assumed to be the same as the percentage use in The Aluminum Association's 1989 industry survey: natural gas 87%; distillate oil 1%; lube oil 5%; propane & LPG 1%; gasoline 1%; coal and miscellaneous 5%.

[c] Softer alloys are represented by 3104.

[d] Harder alloys are represented by 5182.

[e] MJ is one megajoule, or 10^6 joules.

[f] Electricity conversion factor is assumed to be 11,530.6 kj/kWh (10,981 Btu/kWh) (Richards 1997).

Sources: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)
"Patterns of Energy and Fuel Usage in the U.S. Aluminum Industry, Full Year - 1989," prepared by The Aluminum Association, August 1991.

from the combustion of fuel and chlorides from the fluxing operation. The chlorides, including chlorine and hydrogen chloride, are produced by the associated chlorine- or freon-based fluxing systems. Emissions from the combustion of natural gas occur where metal is held during the casting operation.

Table 7-3 presents estimated typical process air emissions of particulate and chloride associated with ingot casting. These data, which are weighted averages based on the results of a 1991 industry survey, reflect the use of a variety of emissions control equipment.

Annealing operations associated with rolling mills produce nitrogen oxide, carbon monoxide, benzene, formaldehyde, and toluene emissions. Rolling mills themselves produce fugitive and contained emissions of oil mist and vapors, metal and metal oxides, and rolling fluid additives (Jackson et al. 1992).

Aluminum cold rolling lubricants traditionally comprise a solution of an H-P additive in a base oil that is usually a light petroleum distillate. On contact with hot rolls the lower boiling fractions are evaporated and exhausted to the atmosphere. For example, cold rolling operations can emit non-metal HAPs such as 1,1,1-trichloroethane and others.

Table 7-3. Typical Emission Factors for Primary Ingot Casting (kg/metric ton)

Pollutant	Amount [lb/ton]
Particulate	0.1 [0.2]
Chlorides	0.0078 [0.0156]

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

In addition to VOCs in vapor form, the mills also emit anywhere from 5 to 25% liquid aerosols or droplets (Boddy 1992). The exact ratio between the droplet-phase and the gas-phase emissions varies according to mill parameters. For example, on a high-speed foil mill up to 95% of the total emissions can be gas-phase (Kohlrausch 1992).

Table 7-4 presents a listing of sample measured concentrations of organic droplets and vapors emitted by a typical rolling mill of a secondary aluminum plant. Table 7-5 shows average process-related emissions of particulate and organics associated with hot and cold rolling according to a 1991 industry survey.

Tight Control Measures Are Used to Handle VOC Emissions

Rolling mill emissions, including mist and vapor phases, require capture and containment by mill and hooding closure systems specifically designed for this application. Common containment technologies include a variety of hoods, including slotted perimeter hoods and air curtain hoods.

After collection, fumes from both hot and cold rolling operations are treated using one of several available particulate control technologies to reduce the chance of VOCs escaping to the atmosphere. Particulate collectors can be categorized as mechanical separators (such as cyclonic separators, impingement vane separators, deep-bed mist eliminators, purification systems using shallow bed elements, wet scrubbers, and stack skimmers) and electrostatic precipitators (Perryman et al. 1992). Some operations still only exhaust the collected fumes using big fans (Kohlrausch 1992).

Inertial or cyclonic separators are the most common type of liquid particulate collector in the aluminum industry. Although wet scrubbers are not a new design approach, their use in rolling mill applications represents a new approach. Stack skimmers, which collect condensed or agglomerated particulate from system exhaust points, are common in most new systems (Perryman et al. 1992).

The above devices remove oil droplets while discharging oil vapor unabated. Some new control systems are capable of achieving emission capture efficiencies as high as 98% (Perryman et al. 1992). However, these types of mechanical devices are not expected to be able to meet the anticipated vapor removal guidelines set out by the EPA (Boddy 1992). While they are suitable for the removal of droplets and aerosols from the exhaust streams, they are not effective at removing the coolant in vapor form because of the smaller particle size. However,
technology is available for control of oil vapor components (Jackson et al. 1992).

Table 7-4. Emission Concentrations of Toxics for Secondary Aluminum Rolling Mill[a] (mg/m^3)

Pollutant	Concentration
Organic droplets	8.0
Organic vapors	150

a Data reported are average values for processes having control systems normal for the industry.

Source: *Emission Testing for Air Toxics and Other Air Contaminants,* M. Jackson and others, The Proceedings of the 7th International Aluminum Sheet & Plate Conference, Volume 3, 1992.

Table 7-5. Typical Emission Factors for Hot and Cold Rolling (kg/metric ton of aluminum rolled)

Pollutant	Amount [lb/ton]		
	Hot Rolling (Softer Alloys)[a,b]	Hot Rolling (Harder Alloys)[a,c]	Cold Rolling[d]
Particulate	0.80 [1.60]	1.20 [2.40]	0.42 [0.84]
Organics	1.00 [2.00]	0.34 [0.68]	1.80 [3.60]

a Composite process to form coils that includes soaking or preheating and may include scalping.
b Softer alloys are represented by 3104.
c Harder alloys are represented by 5182.
d Cold mills to form small-gauge coil (e.g., 0.015 to 0.008 inch). Composite process that may include annealing, coating, slitting. Also includes both hard and soft alloys.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

7.5 Effluents

Process Water Used for Cooling During Casting and Rolling

The primary use of water in the casthouse is for the cooling of molten aluminum as it is formed into ingots in the casting process. In refining and casting, process water is required to make up evaporative losses from the cooling water system. Net process water consumption for primary ingot casting has been estimated at 10,800 kg/metric ton (21,600 lb/ton) of aluminum (Richards 1997).

For secondary casting (including melting), process water requirements were estimated to be 320 kg/metric ton (640 lb/ton) of aluminum (Richards 1997). One explanation of the large difference between the two is that most primary plants use “once through” water, whereas secondary plants can be coupled to mills where all process water is recycled several times (Richards 1997).

Process water requirements for hot rolling have been estimated at 58 kg/metric ton (116 lb/ton) of product for harder alloys, and 390 kg/metric ton (780 lb/ton) of product for softer alloys (Richards 1997). Average process water requirements for cold mills used to form small-gauge coil have been estimated at 760 kg/metric ton (1,520 lb/ton) of product, with a range of about 450 to 1,050 kg/metric ton (900 to 2,100 lb/ton) (Richards 1997). Wastewater streams include cast water blowdown, cooling water blowdown, roll coolant waste, and coating line waste.

The major environmental challenge for both the hot and cold rolling mills has historically been related to the requirement for lubrication in the milling operations. Mold lubricants such as castor oil are also used in primary ingot casting to prevent the metal from sticking to the sides of the molds. The industry has concentrated on reusing water and lubricants by improving the filtration and clean up of the lubricant systems. Recycling of cleaned process water is now standard operation. Water that must be discharged is treated to ensure that it meets state and federal standards.

Tables 7-6 and 7-7 respectively present EPA's effluent limitations for several refining and casting processes for primary and secondary aluminum production. These tables present effluent limitations using the best available technology economically achievable (BAT).

Table 7-8 presents estimated amounts of total suspended solids and the biological oxygen demand (BOD) contained in primary ingot casting effluents. Table 7-9 presents estimates of these same pollutants in hot and cold rolling mill effluents. The data in Tables 7-8 and 7-9 are both derived from the results of a 1991 survey of operating facilities.

7.6 Byproducts

Oils, Coatings Are Separated from Effluents

Oil contained in primary ingot casting wastewater is separated from the water (using an induced air flotation system, for example). The oil and oil-laden solids are collected for future recovery of the oil.

Rolling mill effluents are treated to separate the oils, suspended solids, and dissolved solids from
the process water. For example, heat and polymers can be applied to separate the oil,

Table 7-6. Primary Aluminum Production - Refining and Casting BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of aluminum product)

Pollutant	Degassing Wet Air Pollution Control	Direct Chill Casting Contact Cooling	Continuous Rod Casting Contact Cooling	Stationary Casting or Shot Casting Contact Cooling
Benzo(a)pyrene	0.000	0.000	0.000	0.000
Antimony	2.244	1.143	0.089	0.000
Nickel	0.965	0.492	0.038	0.000
Aluminum	7.071	3.602	0.282	0.000
Fluoride	68.880	35.090	2.746	0.000

[a] Best Available Technology Economically Achievable.

Source: *EPA Effluent Guidelines and Standards for Nonferrous Metals*, 40 CFR Part 421.23, Bureau of National Affairs, 1992.

Table 7-7. Secondary Aluminum Production - Refining and Casting BAT[a] Effluent Limitations - Average of Daily Values for 30 Consecutive Days (mg/kg, or lbs per 10^6 lbs of aluminum product)

Pollutant	Direct Chill Casting Contact Cooling	Ingot Conveyor Casting Contact Cooling[b]	Ingot Conveyor Casting Contact Cooling[c]	Stationary Casting Contact Cooling	Shot Casting Contact Cooling
Lead	0.173	0.009	0.000	0.000	0.000
Zinc	0.558	0.028	0.000	0.000	0.000
Aluminum	3.602	0.182	0.000	0.000	0.000
Ammonia (as N)	77.880	3.926	0.000	0.000	0.000

a Best Available Technology Economically Achievable.
b When chloride demagging wet air pollution control is not practiced on site
c When chloride demagging wet air pollution control is practiced on site

Source: *EPA Effluent Guidelines and Standards for Iron and Steel Manufacturing*, 40 CFR Part 421.33, Bureau of National Affairs, 1992.

Table 7-8. Estimated Amounts of Pollutants Contained in Primary Ingot Casting Effluents (mg/kg, or lbs per 10^6 lbs of aluminum cast)

Pollutant	Amount
Total Suspended Solids	0.002
BOD[a]	0.0016

a Biological oxygen demand.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some which was developed in 1991)

which is then stored for eventual shipment off-site for use as a fuel. If a coating line is used, the wastewater is first processed to remove fluorides and ammonia.

The wastewater is then typically sent to a settler for separation of solids. This generates a sludge that is additionally dewatered and landfilled. Each casting, extrusion, and finishing process also produces solid waste aluminum scrap, which is collected and remelted.

The generation of process-related solid wastes associated with primary ingot casting is shown in Table 7-10. Table 7-11 lists the wastes associated with hot and cold rolling. The data in both tables were derived from the results of the 1991 survey previously mentioned.

Table 7-9. Estimated Amounts of Pollutants Contained in Hot and Cold Rolling Effluents (kg/metric ton of aluminum rolled)

Pollutant	Amount [lb/ton]		
	Hot Rolling (Softer Alloys)[a,b]	Hot Rolling (Harder Alloys)[a,c]	Cold Rolling[d]
Total Suspended Solids	0.043 [0.086]	0.048 [0.096]	0.076 [0.152]
Oils/Grease	0.028 [0.056]	0.04 [0.08]	0.036 [0.072]
BOD[e]	--	0.14 [0.28]	0.24 [0.48]

[a] Composite process to form coils that includes soaking or preheating and may include scalping.
[b] Softer alloys are represented by 3104.
[c] Harder alloys are represented by 5182.
[d] Cold mills to form small-gauge coil (e.g., 0.015 to 0.008 inch). Composite process that may include annealing, coating, slitting. Also includes both hard and soft alloys.
[e] Biological oxygen demand.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

Table 7-10. Estimated Average Solid Waste Generation - Primary Ingot Casting (kg/metric ton of aluminum cast)

Waste	Amount [lb/ton]
Liquid (e.g., oils, grease)	0.038 [0.076]
Packaging	4.7 [9.4]
Other (e.g., bricks)	2.1 [4.2]
Environmental Control (e.g., spent bags)	1.0 [2.0]

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

7.7 Hazardous Wastes

There are no RCRA-listed hazardous wastes associated with semi-fabrication processes. However, the sludge generated from the conversion coating of aluminum in the automotive and coil coating industry is RCRA-listed waste F019.

Table 7-11. Estimated Average Solid Waste Generation - Hot and Cold Rolling (kg/metric ton of aluminum rolled)

Waste	Amount [lb/ton]		
	Hot Rolling (Softer Alloys)[a,b]	Hot Rolling (Harder Alloys)[a,c]	Cold Rolling[d]
Liquid (e.g., oils, grease)	2.1 [4.2]	5.6 [11.2]	5.0 [10.0]
Packaging	0.1 [0.2]	0.2 [0.4]	3.7 [7.4]
Effluent Treatment Wastes	8.0 [16.0]	10.0 [20.0]	0.8 [1.6]
Air Pollution Control Wastes	--	--	3.6 [7.2]
Other	--	--	1.1 [2.2]

a Composite process to form coils that includes soaking or preheating and may include scalping.
b Softer alloys are represented by 3104.
c Harder alloys are represented by 5182.
d Cold mills to form small-gauge coil (e.g., 0.015 to 0.008 inch). Composite process that may include annealing, coating, slitting. Also includes both hard and soft alloys.

Source: Data reported by Nolan Richards, 1997. (Note: the date refers to the release of the information, some of which was developed in 1991)

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