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Energy Use in the Production of Primary Aluminum

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ABSTRACT

As a part of a study of the possibilities of using alternate energy systems in industry, a review of the processes used in the production of primary aluminum from bauxite was carried out. An overview of the aluminum industry and a detailed process analysis with particular emphasis on the energy requirements is followed by a brief look at future possibilities. Calcining of alumina at about 1150°C, electrolytic reduction of alumina to aluminum metal (∿950°C) requiring about 15,600 kWh/ton Al, and anode baking at 1100°C are identified as the most demanding processes. The alternative sources of aluminum, e.g., clays; the possibilities for energy conservation, such as recycling and the Alcoa chloride cell; and the dependence of the U.S. aluminum industry on imports are discussed. This analysis shows that present technology requires an average of over 16,000 kWh of electricity and 90×10^6 Btu of thermal energy, including fuel equivalents of anodes and cathodes consumed in the process, to produce one ton of aluminum ingot from bauxite.

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ENERGY USE IN THE PRODUCTION OF PRIMARY ALUMINUM

Overview

The aluminum industry is fast-growing, very competitive and extremely energy intensive. The domestic demand for aluminum is expected to grow at about 5.8 percent per year between 1976 and 1980[1] compared with a past growth rate of over 7 percent per year. Because more aluminum, alumina and bauxite will be imported and environmental concerns will probably cause a continued increase in recycling, the U.S. primary aluminum production is expected to grow less rapidly. Nevertheless, the capital costs of an aluminum-producing facility — whether it be a bauxite mine, a Bayer conversion plant, an aluminum smelter, or a fabrication mill — are high, and the energy requirements are large. These factors suggest the value of subjecting the aluminum industry to a detailed energy analysis.

Aluminum metal and aluminum alloys are used in large quantities by construction, transportation, electrical, packaging, appliances, equipment, machinery, and defense industries that manufacture everything from baseball bats to lunar rovers. The widespread usages are due to a remarkable variety of desirable characteristics: aluminum and its alloys are lightweight, strong, highly workable, corrosion-resistant, highly reflective, nonmagnetic, nontoxic, attractive and abundant, and have high electrical and thermal conductivities. Aluminum can be recycled indefinitely, although only a small fraction of it is recycled presently.

Domestic demand for aluminum metal increased at about 7.4 percent per year from 1964 to 1974,[2] a faster rate than for other major metals. Measured either in quantity or in value, use of aluminum now exceeds that of any other metal except iron and continues to grow in the United States in spite of the following facts: (a) a very large portion of the raw materials is imported, (b) prices of these imports have increased rapidly because of the producers' cartel, (c) production is highly energy intensive, (d) each of the major processes used remains essentially unchanged since the metal first became available in commercial quantities about 90 years ago and (e) high capital costs of facilities make it difficult for new companies to enter the industry. Projections by the Bureau of Mines express total U.S. aluminum demands by the year 2000 at about 23 million tons compared with about 6 million tons in 1976.[1]

The smelting of aluminum requires immense amounts of electric power at a low cost. Several aluminum companies generate some of the electricity needed, but since a failure to receive power for about two to four hours can mean financial catastrophe if the pots freeze, aluminum smelters are located in areas where a low-cost reliable source of electric power is assured. A downtime of even 30 minutes can mean serious problems and great expense; therefore, even those smelters that own generating facilities are connected to an electric grid. In fact, the aluminum industry is looked upon as a necessary adjunct to development of many major electric power facilities throughout the world. Of the power used by aluminum companies, over 36 percent is derived from hydroelectric power stations, some self-owned, although less than 14 percent of the electricity generated in the United States in 1976 was hydroelectric. Natural gas curtailments have necessitated conversion to alternate fuels for some processes in aluminum production. While it might have been desirable to convert to coal-fired process furnaces and steam boilers, the design of the systems "precludes such modification,"[3] so many systems are now dual-fuel systems — gas and oil.

The principal raw material, bauxite, is mined in only a few (about 27) countries and 11 of the major bauxite-exporting countries belong to the International Bauxite Association (IBA), a cartel which was formed in 1974 to increase revenues from and control over bauxite operations in member countries. Levies on bauxite production in countries supplying the United States have become the largest element in the cost of bauxite. Dependence on imported bauxite and alumina is likely to continue until the use of alternate domestic materials becomes competitive.[1]

The dependence of the United States on imports for the production of aluminum deserves further comment since the total U.S. bauxite reserves are small. For example, in 1975 when 3879 thousand tons* of primary aluminum was produced, domestic bauxite supplied only about 416 thousand tons of aluminum. In addition to importing bauxite, the United States imported about 35 percent of the alumina used for metal production in 1975, mostly from Australia (61 percent), Jamaica (22 percent), and Surinam (14 percent), as well as some aluminum metal. The dependence of the U.S. aluminum industry on imports is depicted in

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*In this paper tons refers to short tons unless otherwise specified.

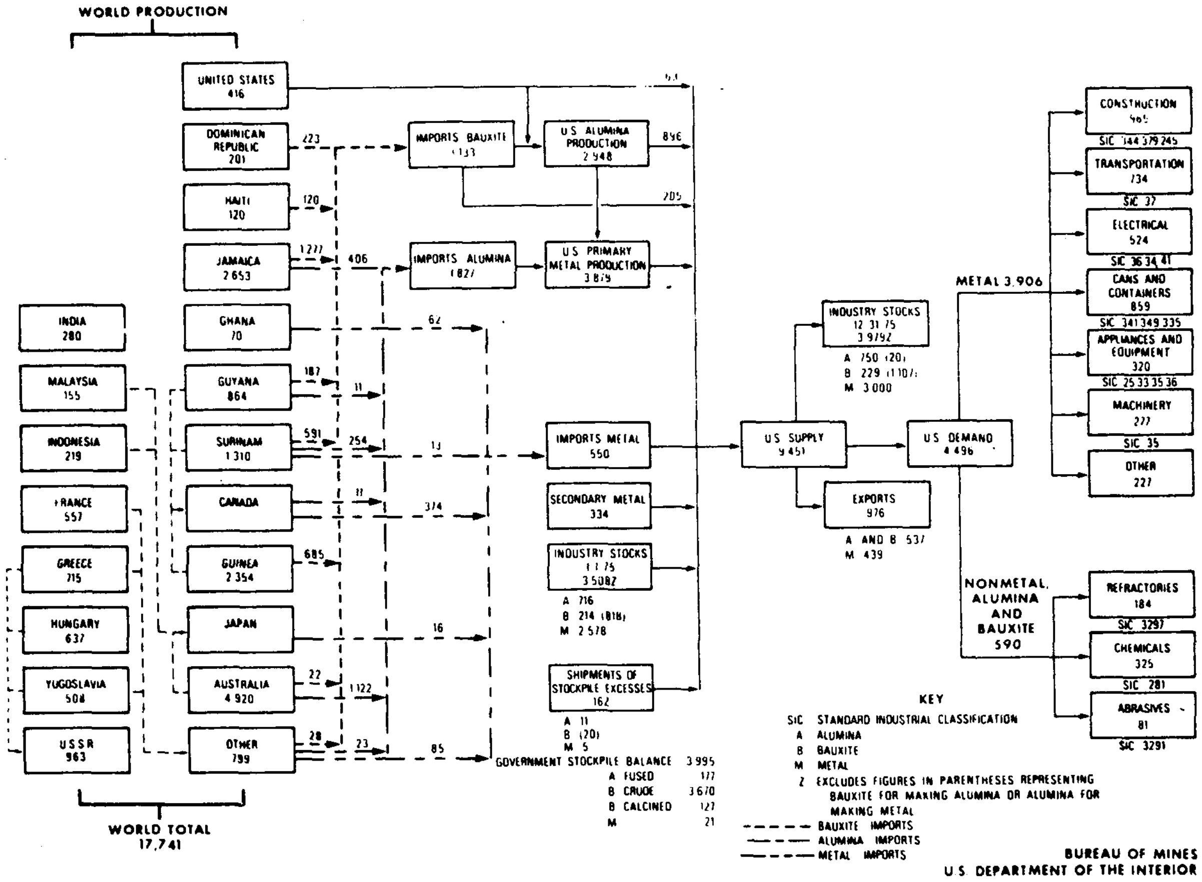
Figure 1. The source of raw materials[4] and the location and capacity[5] of aluminum plants is shown in Figure 2. Of the 12 firms producing aluminum in the United States in 1975, three accounted for 67 percent of production capacity.

In the United States an estimated 10 to 20 percent of the aluminum that is put into use as an industrial or consumer end product is eventually recycled as old scrap.[1] Some old scrap may have been in use 10 to 30 years prior to its return to the production stream; however, aluminum cans, about 25 percent of which are recycled, and certain foils may return to the production stream after a few months. Over 90 percent of the new aluminum scrap generated in the production of end products, called runaround or home scrap, is recycled almost immediately after it is generated. Recycling of pure aluminum requires only about 5 to 10 percent of the energy needed for primary production from bauxite; therefore most aluminum companies encourage recycling. Purity of secondary aluminum is frequently lower than primary; for this reason, some uses of the metal cannot be filled by secondary metal without some purification in secondary smelters.

Increased costs of foreign bauxite, higher taxes and levies paid to governments of bauxite-producing countries, and the formation of a bauxite cartel and its implications for the future (see References 1, 6, and 7), have generated an increased interest in developing commercially acceptable processes to produce alumina from the abundant low-grade domestic aluminum resources in spite of the higher energy use such production requires. The state of Georgia even has a "reward" available

FIGURE 1: ALUMINUM SUPPLY-DEMAND RELATIONSHIPS – 1975

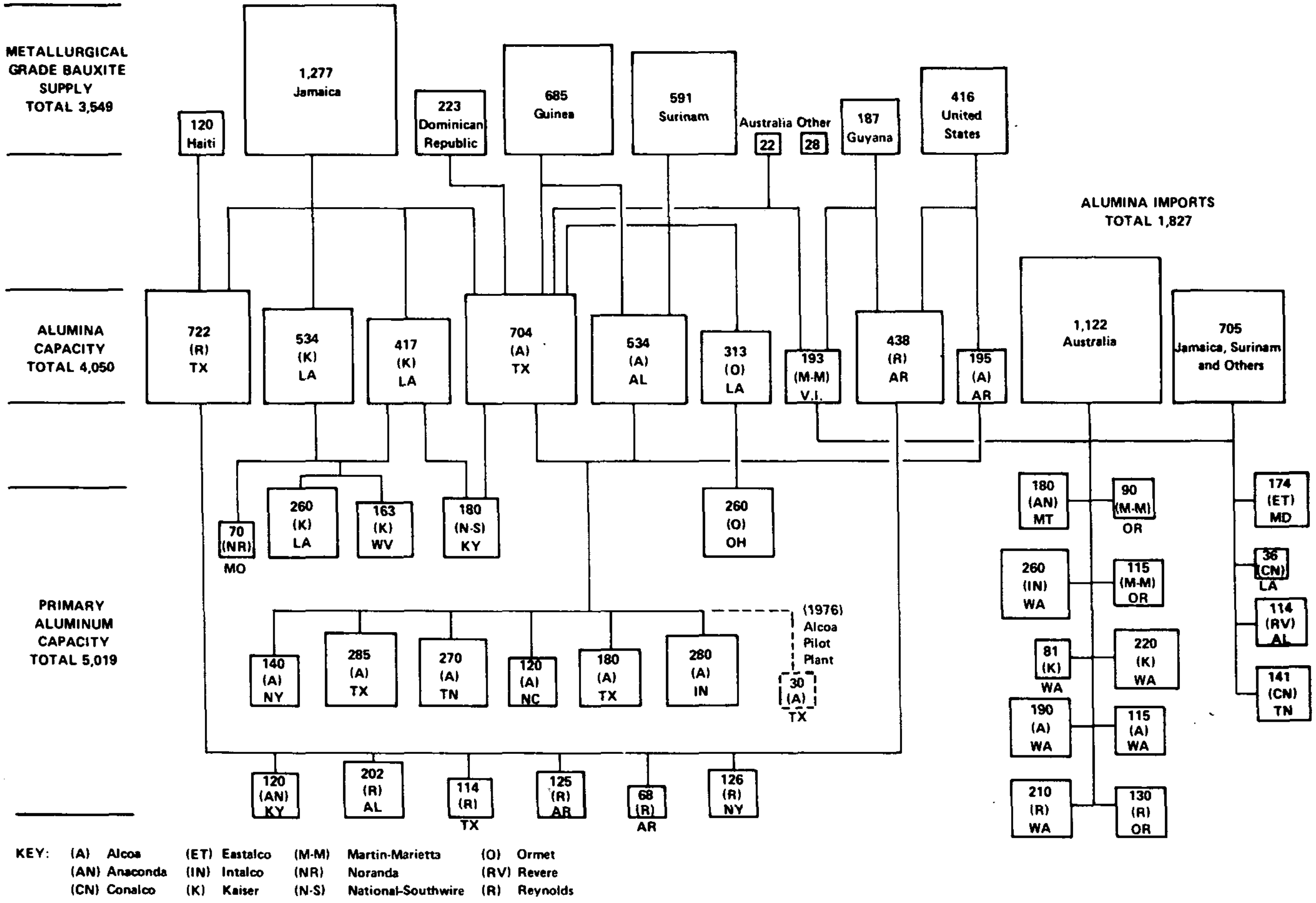
[Thousand Short Tons of Aluminum (Al)]



Source: U.S. Bureau of Mines (1977)[4]

FIGURE 2: SOURCES OF U.S. BAUXITE AND ALUMINA SUPPLY, AND OF ALUMINA AND ALUMINUM PLANT CAPACITIES, 1975

(Thousand Short Tons of Aluminum Content)



Note: Compiled from data in U.S. Bureau of Mines (1977)[4] and U.S. Environmental Protection Agency (1976)[5] to the person who discovers a commercially acceptable process of treating her clays.[8] Current research on aluminum is concentrated on developing such processes,[9] on improving the energy efficiency of the present process, on reducing the energy requirements in the electrolytic cell or finding new processes for each, and on increasing the life of the electrolytic cells and cell linings.

The remainder of this paper consists of analysis of the production of primary aluminum metal from bauxite followed by a summary of the energy requirements of each process including comments on expected future trends.

To produce primary aluminum metal, bauxite ores are dried, crushed, ground, digested and leached. Alumina (Al_2O_3) is then separated from impurities in the bauxite by a process patented in 1888 by Karl Bayer in Germany. The alumina is washed, calcined and sent to smelters where it is reduced to aluminum metal by an electrolytic process patented in 1886 by Charles Hall in the United States and by Paul Héroult in France. The production of 1 ton of primary aluminum requires about 2 tons of alumina obtained from over 4 tons of dried bauxite.

Bauxite

Bauxite is a heterogeneous material composed principally of the aluminum oxide minerals. Most of the bauxite used in the United States is primarily the trihydrate, gibbsite ($Al_2O_3 \cdot 3H_2O$), but some from

Jamaica contains as much as 20 percent monohydrate, boehmite ($Al_2O_3 \cdot H_2O$). Major impurities in bauxite include iron oxides, aluminum silicates, quartz (SiO_2), and titanium oxides (see Table 1).

Although world reserves of bauxite are large, about 16 billion long tons, U.S. reserves of metal-grade bauxite are estimated at about 40 million long tons, all located in Arkansas, and are expected to yield about 13 million tons of aluminum.[6] Bauxite for other purposes, such as chemicals, abrasives, ceramics and refractories, occurs in Alabama and Georgia. Other U.S. resources of aluminum-bearing deposits which have received attention are nonbauxitic and include kaolinitic clays, anorthosite, dawsonite, and alunite.[2] Other types of clays, shales, schists, nepheline, syenite, nahcolite, and saprolite are also potential, but less promising, aluminum raw materials. Several of these presently subeconomic resources of aluminum appear to be abundant in the United States, but detailed geologic information is incomplete[14] and further research is needed for reliable evaluation.

Although research on alumina extraction from various raw materials has continued for many years, virtually all commercially produced alumina is obtained by the Bayer processing of bauxite. Actual processing conditions such as leach temperature, holding time, and caustic concentration, as well as costs, are influenced by the type of bauxite to be processed. Because of the wide variations in the physical and chemical characteristics of bauxite, each Bayer alumina plant is designed to treat a specific composition of bauxite, usually from a

TABLE 1: BAUXITE SAMPLE ANALYSES

	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	Loss on Ignition[a]	Other Impurities
Jamaican (gibbsitic)[b]	49%	2%	20%	2.5%	26%	
Bauxite[c]	45-60%	2.5-18%	3-25%	2-5%	12-30%	1%
South America, Australia, etc.[b]	50-60%	1-6%	2-15%			
European[b]	45-65%	1-10%	15-30%			
Jamaican[d]	49%[e]	2.5%	20%	2.5%	25%	1%
Surinam[d]	55.5%	3.5%	9%	2.5%	29%	0.5%
Arkansas[d]	50%[f]	12%	8%	3%	26%	1%
Dried Metallurgical[b]	45-60%	1-15%	3-25%	1.5-3.5%		
Bauxite[g]	30-60%	1-15%	1-30%			
Typical Bauxite[h]	40-60%	1-15%	7-30%	3-4%	12-30%	0.05-0.20%

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[a] Largely water of hydration.

[b] Stamper and Kurtz (1975).[2]

[c] Aluminum Association (n.d.).[10]

[d] K. M. Reese and W. H. Cundiff (1955).[11]

[e] Includes 9 percent monohydrate.

[f] Includes 10 percent in clay.

[g] Bravard, Flora and Portal (1972).[12]

[h] Vachet (1963).[13]

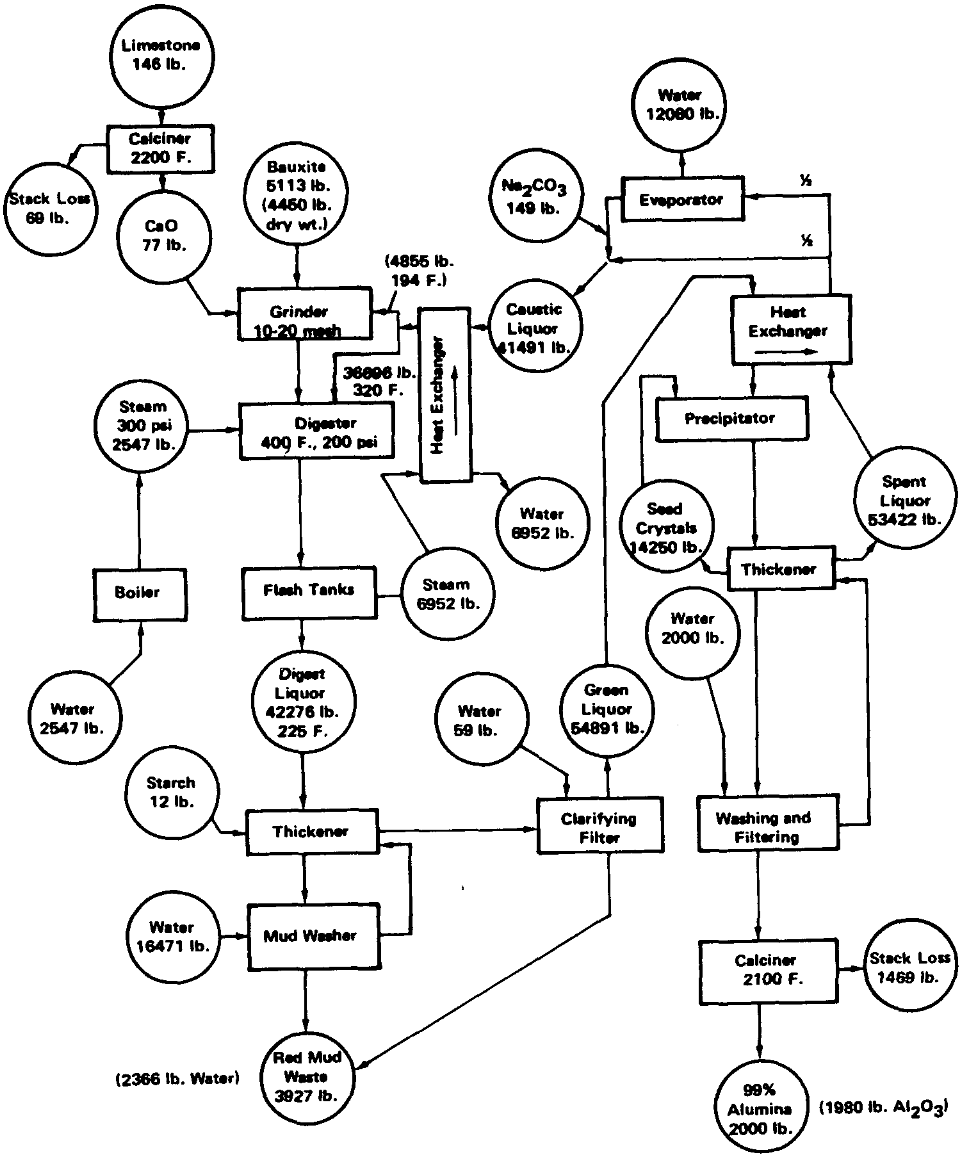
specific source, in order to operate at optimum efficiency. For this reason and because of the IBA pressures, new alumina plants frequently are located near the bauxite mine, whereas in the past, alumina plants have been located near the aluminum smelters. Although each plant uses slight variations, Figure 3 is representative of current practice and shows a flow sheet for the Bayer process.[15] Numbers shown are for a typical Jamaican ore because the United States imports a large portion, about 40 percent in 1975, of its bauxite from there and from other countries whose bauxite is similar (see Figure 2). For Jamaican ore, about 4.29 tons of bauxite yields about 1.93 tons of alumina from which about 1 ton of aluminum metal is produced.

The Bayer Process — Bauxite to Alumina

Most bauxite is obtained by open pit mining and is treated by crushing, washing and drying operations. The extent of the drying operation depends, in part, on the handling and dusting characteristics of the bauxite. For example, to prevent dusting, Surinam bauxite is shipped after drying to 3 percent and Jamaican bauxite is shipped after drying to about 15 percent moisture. Since crude bauxite may contain up to 30 percent free moisture, savings in freight may offset drying costs.

The Bayer process is initiated by mixing crushed (to about 2 inches) bauxite with preheated spent leach solution.[2] To speed reaction rates during digestion, bauxite may be ground to a fine particle size (about 35 mesh),[15] usually in the spent liquor solution using ball or

FIGURE 3: FLOW CHART FOR THE BAYER PROCESSING OF BAUXITE TO ALUMINA



Source: Battelle (1975)[15]

rod mills. Lime (CaO) is added to control phosphorus content and to increase the solubility of alumina. Lime and soda ash (Na_2CO_3) are used in nearly equal amounts ($Na_2CO_3 + CaO + H_2O \rightarrow 2NaOH + CaCO_3$) or, if caustic soda (NaOH) is added directly to reach the desired concentration, smaller amounts of lime must be added to causticize Na_2CO_3 formed in the process. The resulting slurry containing from 40 to 50 percent solids is pumped to pressurized digesters where high-pressure steam is used to raise the temperature.

1. Digestion

Digestion, in tanks 10 to 15 feet in diameter and up to 90 feet long, takes from less than one hour up to eight hours at temperatures ranging from about 104°C to 288°C with corresponding pressures ranging from about 4 atmospheres to 65 atmospheres. The lower temperatures and shorter times are used for bauxites with most of the available alumina present as gibbsite; higher temperatures and/or longer times are needed to dissolve boehmite. Caustic concentrations of the spent liquor, expressed as grams of soda ash (Na_2CO_3) per liter, average about 200 for gibbsite to about 300 for bauxites with high boehmite content.[2] The steam generated during cooling is used to preheat the bauxite-caustic mixture prior to entry into the digester. The digestion temperature is attained either by steam jacketing the reaction unit or, more commonly, by direct injection of steam.

2. Cooling and Settling

The resulting slurry of sodium aluminate solution and insoluble residues ("red mud") is cooled to atmospheric boiling temperature and a coarse sand fraction is removed by gravity separators. The red mud is then partially separated by decantation from settling tanks measuring about 15 feet in depth and 50 to 125 feet in diameter. In some plants, a flocculant such as starch (2 to 20 pounds per ton of Al_2O_3 product) is added to increase the settling rate of the red mud particles. The overflow from the settling tanks, still containing some solids, is further clarified by filtration.[2]

Red mud embodies iron oxides (Fe_2O_3), sodium aluminum silicate ($3Na_2O \cdot 3Al_2O_3 \cdot 5SiO_2 \cdot 5H_2O$), titanium oxides ($TiO_2$) and various other impurities of bauxite and thus represents a loss of both alumina and soda.[2] Therefore, a minimum reactive silica content in the bauxite is desirable, making bauxite of more than 8 percent silica content uneconomic for treatment by the Bayer process. A modification of the Bayer process (the combination process) permits treatment of high silica bauxites but is presently used only on domestic ores for refining alumina primarily for the production of refractories and uses other than aluminum metal (see Reference 16, p. 443). Higher silica bauxites may be blended to lower the silica content.

3. Clarification

The quantity of red mud to be removed from the caustic slurry following digestion varies with the bauxite ore and may range from 1/3 ton for Surinam bauxite to 2 tons for Arkansas bauxite per ton of alumina product.[5] Dilution with warm process water or spent liquor is used to aid separation, and thorough washing of the red mud is used to recover as much caustic solution as possible.

4. Precipitation

The clarified and diluted caustic liquor — clear "green liquor" which is largely sodium aluminate — is drained off and cooled in a heat exchanger to 50°C to 125°C and placed in large precipitation towers. The thousands of gallons of highly supersaturated green liquor are then seeded with crystals of alumina trihydrate and mildly agitated in tanks ranging from 25 to 35 feet in diameter and up to 80 feet high to precipitate dissolved alumina according to the reaction

$$2NaAlO_2 + 4H_2O \rightarrow Al_2O_3 \cdot 3H_2O + 2NaOH.$$

About 50 percent of the alumina is precipitated in 24 to 36 hours by sedimentation and filtration.[15] A portion of the precipitate (as sandy crystalline agglomerates) is used to seed subsequent liquor and the spent liquor is returned to the process. Caustic soda regenerated in the precipitation, together with the unprecipitated alumina, is recycled to the digesters. Washing is used to minimize caustic soda losses.

5. Spent Liquor Treatment

Spent caustic solution containing about half the $NaAlO_2$ originally present is returned to the process following precipitation and filtration

Since the free caustic content of the solution is low (due to dilution during settling, filtration, reactions with organics and gases, and losses of soda in complex silicates removed with the red mud), evaporation of excess water and addition of caustic is necessary. Portions of the spent liquor may also be highly concentrated by evaporation to precipitate sulfates which tend to build up with time.

6. Calcination

After being washed to remove any remaining traces of impurities, the concentrated alumina hydrate is calcined in long, slightly inclined rotary kilns at temperatures above 1100°C to remove moisture and water of hydration.[10] Gravity carries the dry alumina to storage and the water is driven off as steam and vapor. Fluidized-bed calcining, which requires significantly less energy input, is presently replacing the rotary kiln process.[3] The flash calciner, through improved waste heat recovery and reduced radiant heat losses, reduces energy consumption per pound of alumina from 2000 to 1400 Btu, thus reducing the waste heat to about 250 Btu per pound, and is now used by most Alcoa refineries.

Alumina in the form of a dry white powder, which is over 99 percent pure (see Table 2), is shipped to the smelting facility by barge or railroad. At the smelter it is stored in large tanks until needed.

Alumina to Aluminum

In 1886, in their backyard woodshed near Oberlin, Ohio, Charles M. Hall, 22 years old, and his sister, Julia, obtained a few tiny buttons

TABLE 2: ALUMINA IMPURITIES

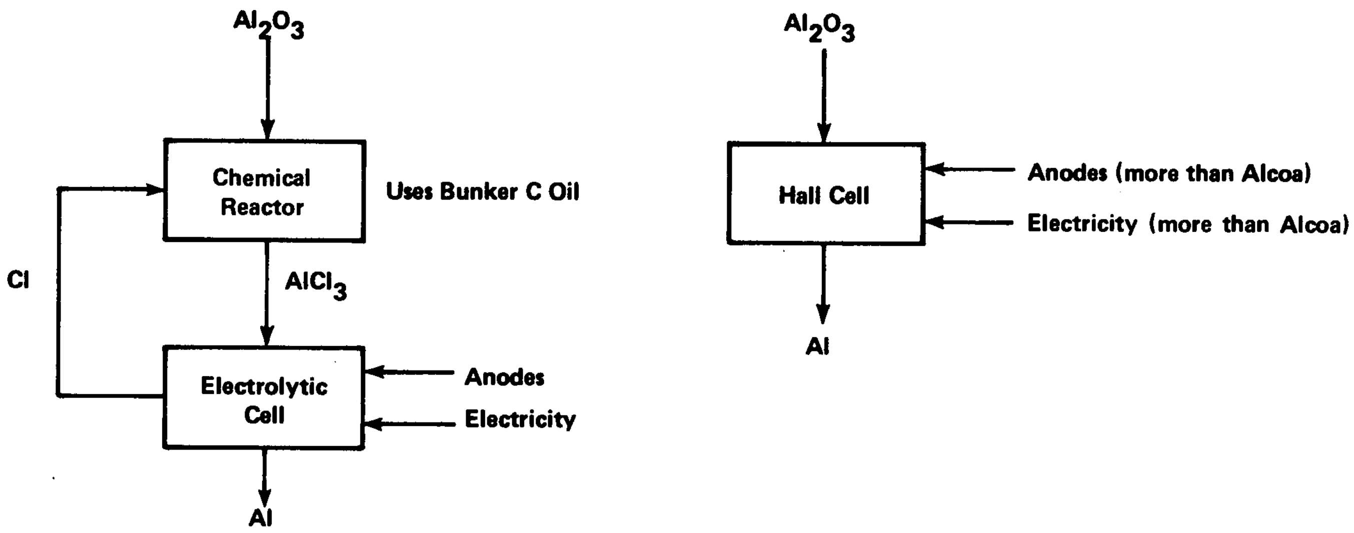
	Range (percent)		
Impurity	Stamper & Kurtz (1975)[2]	Vachet (1963)[13]	Alcoa Chloride
Silica (SiO_2)	0.01-0.025	0.005-0.015	0.025
Iron Oxide (Fe_2O_3)	0.015-0.04	0.005-0.020	0.03
Soda (Na_2O)	0.3-0.65	0.40-0.80	0.4
Calcium Oxide (CaO)	0.015-0.07		0.06
Zinc Oxide (ZnO)	0.007-0.02	<0.010	0.02
Titanium Dioxide (TiO_2)	0.002-0.007	0.004-0.005	0.005
Phosphorus Pentoxide (P_2O_5)	0.001-0.003	<0.002	0.005
Vanadium Pentoxide (V_2O_5)		<0.001	

Note: Typical alumina used in the production of aluminum contains impurities within the ranges shown in the first 2 columns. The last column shows the maximum limits on impurities that can be tolerated by an Alcoa chloride cell which requires a minimum of 99.426 percent Al_2O_3. Stamper (1971)[16].

of aluminum metal by electrolysis after adding some powdered alumina to cryolite in a small carbon-lined steel pot.[17] The battery used by Charles and Julia was homemade, as was most of the equipment. At almost the same time, Paul L. Héroult in France discovered the same process. Only relatively minor changes have been made in this Hall-Heroult process for commercial production of aluminum metal since the 1890s.

Today, primary aluminum is produced by the electrolysis of alumina in a molten bath of cryolite in large carbon-lined steel pots; about 100 to 150 of these pots or reduction cells are connected in series to form a potline. Despite the fact that over the past 30 years the electrical power requirements for smelting aluminum have been cut nearly in half,[3] about 60 percent of the energy used by the aluminum industry is in the form of electricity for the Hall-Heroult process. In a pilot plant in Palestine, Texas, Alcoa is testing a new chloride cell (Figures 4 and 5) which is expected to lead to a further reduction of about 30 percent (to about 4.5 kilowatt-hours per pound of aluminum). The chloride cell operates at a lower temperature, eliminates fluorine pollution control problems, and uses less anode carbon than do present Hall cells. Results so far show that the "new Alcoa smelting process is going well and looks optimistic. However, the chloride cells require a little more energy for production of the chemicals"[18] than do the current Hall cells. Thus the oil used together with the anodes consumed by the chloride cell may be equivalent to the anodes used by the Hall cell.[19]

FIGURE 4: COMPARISON OF ALCOA CHLORIDE CELL AND HALL-HEROULT CELL

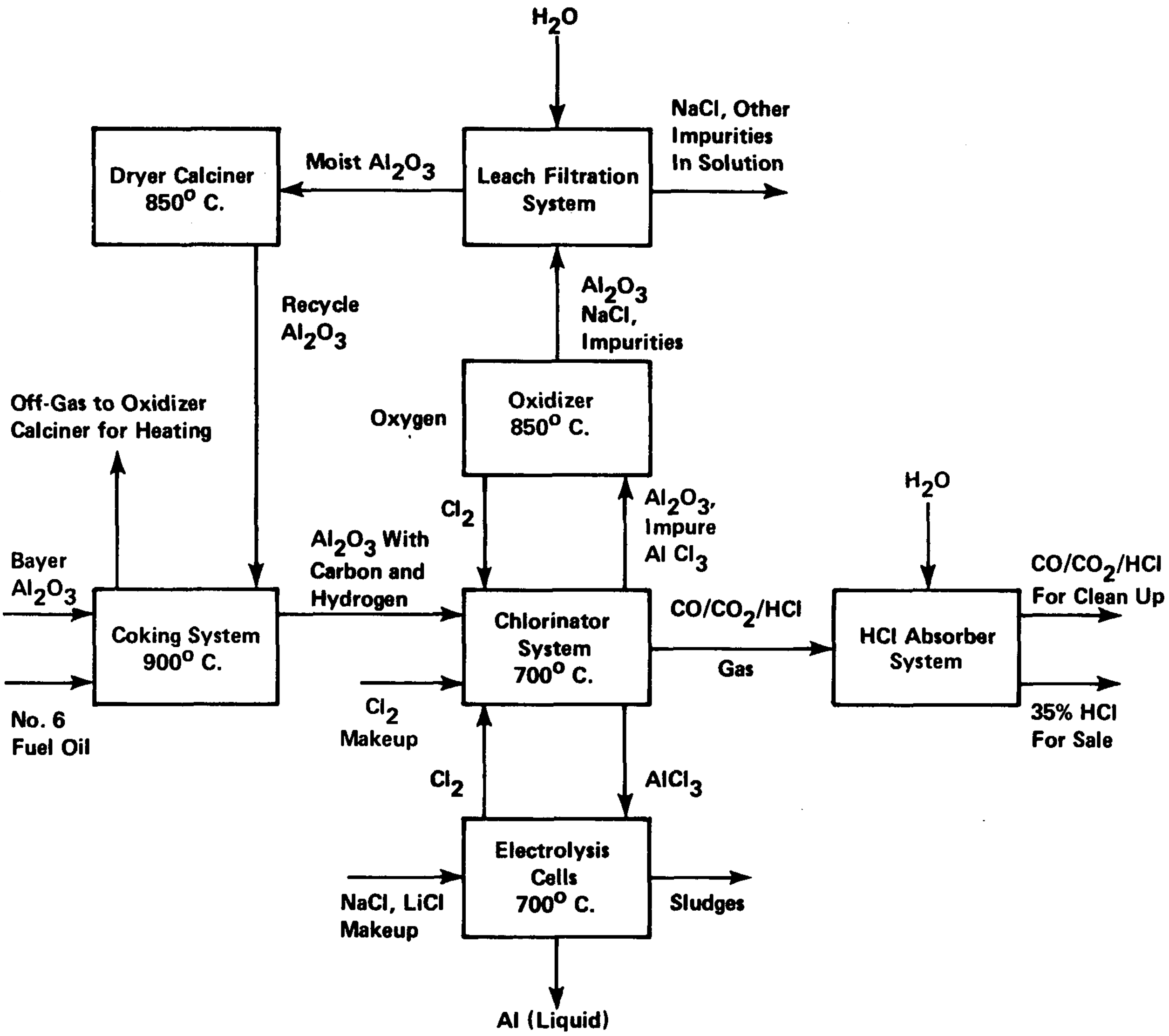


ALCOA SMELTING
~80% ENERGY EFFICIENT

HALL-HEROULT SMELTING
~45% ENERGY EFFICIENT

Source: Spreng (1977)[19].

FIGURE 5: ALCOA CHLORIDE PROCESS (ASSUMED SCHEME)



Source: U.S. Environmental Protection Agency (1976)[5].

Hall-Heroult Process

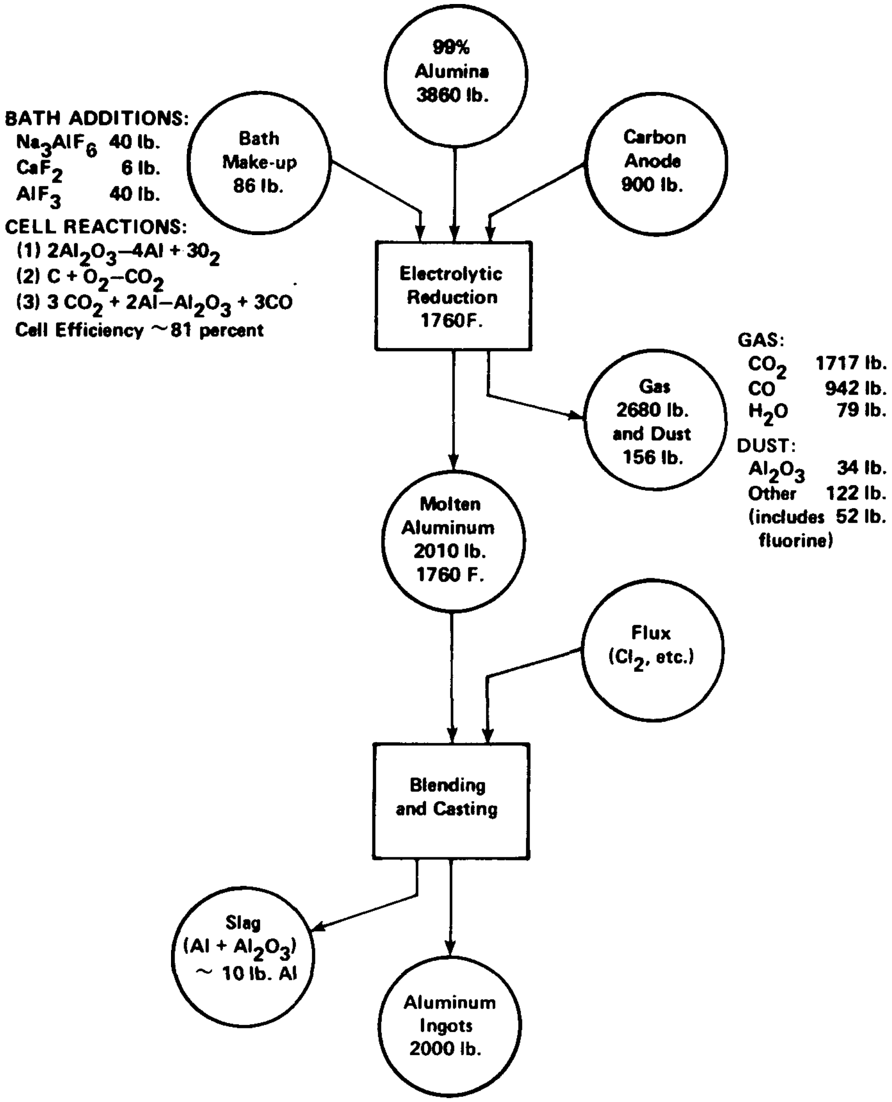
The Hall-Heroult process consists of two primary operations — electrolysis of alumina in a molten bath of cryolite (Na_3AlF_6) and manufacture of carbon anodes.

1. Electrolytic Reduction

The reduction cell is a large carbon-lined steel pot containing a pad of molten aluminum which serves as the cathode, the molten cryolite electrolyte, and the carbon anodes. Figure 6 shows a typical flow sheet for the Hall-Heroult process. In a modern plant, each step of the process is controlled by a computer which samples various characteristics of the system at 30-second intervals and makes adjustments to assure maximum operating conditions — e.g., (a) cryolite, aluminum fluoride, calcium fluoride or lithium is added to the electrolyte as needed to maintain the desirable ratio of sodium and AlF_3, to control soda impurities, and to adjust the melting point of the electrolyte; (b) alumina is added internally as needed to maximize production; and (c) anodes are lowered into the bath as they are oxidized or are raised as the level of molten aluminum rises to maintain optimum spacing between the electrodes, about 2 inches to minimize resistance.

A typical modern pot is about 40 ft x 10 ft x 5 ft, operates at about 980°C, and contains two rows of 16 anodes, each about 4 ft x 2 ft x 1 ft. Carbon monoxide burns whenever it forms in sufficient

FIGURE 6: TYPICAL FLOW CHART FOR THE HALL-HEROULT PROCESS



Source: Battelle (1975)[15]

quantity to cause a blowhole through the electrolyte surface. The entire pot is hooded to increase thermal efficiency by reducing heat losses and to prevent pollution by recycling usable gases. Fluorine, carbon dioxide and most other contaminants are pulled out continuously by a closed system. This system consists of hoods over the pots and a duct system leading to a fluidized bed of activated alumina which captures the fluorine for recycling and thus eliminates the need for scrubbers, etc. This Alcoa 398 process is said to be 98 percent efficient in cleaning captured gases, and Alcoa has offered it to other aluminum producers.[17]

Silicon rectifiers are used to convert three-phase alternating current to direct current to obtain the high current density needed for modern, large-capacity potlines. The pots are wired in series so that the current runs into each one through the carbon anode, into the electrolyte and out through the molten aluminum and carbon lining of the cell. Currents range from 50,000 amperes in older cells to over 200,000 amperes in new cells, and currents of 80,000 to 100,000 amperes and voltage drops of 4.5 to 5.0 volts per pot are common. Current efficiency is 80 to 90 percent depending on the skill of the operator; thus, a 100,000 ampere cell produces about 1600 pounds of aluminum per day.[18]

Typical electrolyte makeup is 80-85 percent cryolite (Na_3AlF_6), 5-7 percent calcium fluoride (CaF_2), 5-7 percent aluminum fluoride (AlF_3), and 2-8 percent alumina (Al_2O_3).[13] Lithium or lithium fluoride may be added to lower resistivity. The melting point of cryolite is 1006°C, and the addition of any of the above constituents lowers the melting point by 4-5°C per 1 percent by weight. Thus, modern pots operate in the range of 950°C, at which temperature the specific gravity of the bath is about 2.1 and that of aluminum is above 2.3; therefore, the aluminum settles to the bottom of the bath.

2. Anode Manufacture

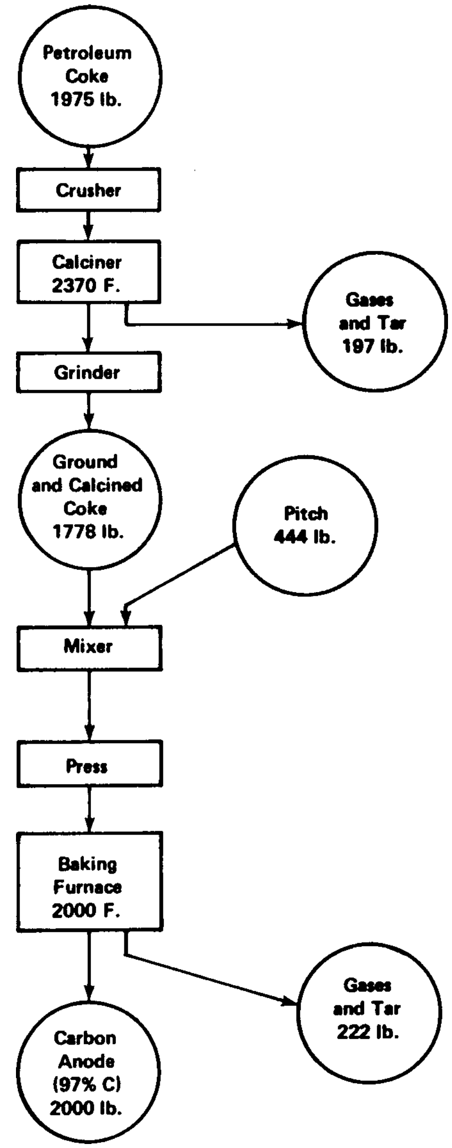
Anodes are consumed during electrolysis at about 0.5 pound of carbon per pound of aluminum, and thus must be replaced periodically ("prebaked" anodes) or continuously ("Soderberg" anodes). In either case, anode production represents a significant component of the energy used. In the United States most present-day aluminum smelters utilize the prebaked anode because of the lower cost (in spite of the higher labor requirements) "with a bonus reduction in energy consumption,"[3] and because of the environmental problems resulting from the release of hydrocarbons by Soderberg anodes.

Soderberg anodes are continuous and self-baking anodes formed by feeding a paste of pure carbon and pitch into the top of an anode casing, the lower end of which is in the electrolyte. The heat of the bath and that resulting from the electrical resistance heating bake the anode mass, so that about 20 inches above the bath the carbon becomes a hard mass. Less than 30 percent of U.S. pot capacity used these continuous anodes in 1976[5] compared with 64 percent in 1965.[20]

Prebaked anodes are used in all new plants and have been retrofitted to some older pots. Prebaked anodes are formed from high purity petroleum coke which is ground, calcined and blended with pitch to produce a paste which can be pressed into high-density shapes as required for each particular potline or plant. After formation, the anodes are processed in underground "ovens" or baking pits by a system of preheating, baking at about $1100^{o}C$ for at least two days, and cooling very slowly by remaining in place for about three or four weeks under considerable insulation (about 3 to 6 feet of earth) after the fuel supply is diverted to an adjacent set of burners to bake other anodes. This method allows about 80 percent recovery of the heat produced by the burning fuel. Anode baking has been performed almost exclusively with natural gas, but recent curtailments have necessitated conversion to a dual-fuel system. Since gas is cheaper, it is used whenever it can be obtained; when gas is not available, fuel oil is used. After the baking process is complete, the cooled carbon anodes are attached to support rods for use in the Hall cell.

A significant portion of the total energy and materials required for aluminum production is used in baking and producing anodes (see Figure 7). Typical anode materials required, per ton of aluminum produced, are 0.43 to 0.60 ton of petroleum coke and 0.1 to 0.2 ton of pitch.[5] Since the anodes are oxidized to CO and CO_2 in the cells, purity is of utmost importance; but, because of the higher sulfur content of presently used oil sources, pure petroleum coke is difficult to obtain and increasingly expensive. Nickel and titanium, if present in the anode carbon, pose serious problems because of their catalytic effects.

FIGURE 7: MANUFACTURE OF PREBAKED CARBON ANODES



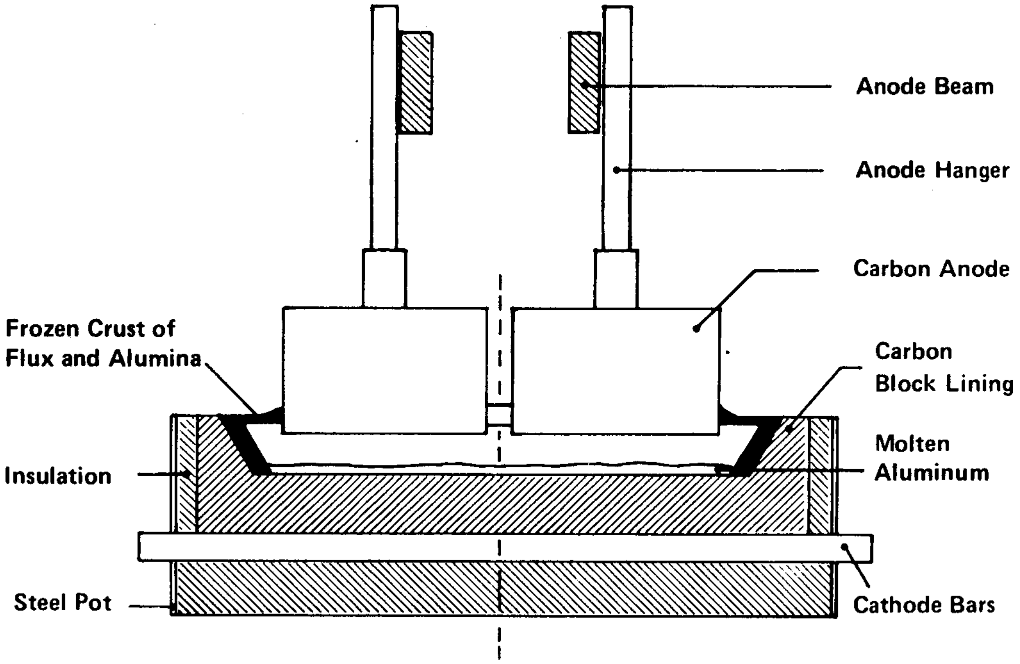
Source: Battelle (1975)[15]

Current enters the prebaked anodes, which are supported in the bath by steel or aluminum stubs or rods, through the supports. Figure 8 shows a diagram, not to scale, of a Hall cell with prebaked anodes.[21] Each anode is raised or lowered separately to maintain its optimum position relative to the molten aluminum and is replaced individually when it has been consumed sufficiently. Computer-controlled sampling indicates the condition of each anode periodically, and a team of four men replaces an anode in the pot upon receiving a vocal command from a tape controlled by the computer. Prebaked anodes must be replaced about every two or three weeks, and the cathode structures wear out and are replaced after approximately five years' use.[18] Although some of the carbon and aluminum compounds absorbed in the linings of the pots are recovered and recycled, the production of anodes causes the aluminum industry to be the single largest user of petroleum coke.[22]

3. Fabrication

Usually once a day, the molten aluminum is removed from each pot either (a) by siphoning using a curved cast iron tube, one end of which is placed in the molten metal and the other in a preheated crucible with an air hose to draw the vacuum; or (b) by tapping and allowing gravity to cause the metal to flow into a hot crucible. The filled crucibles, with capacities usually about 3500 to 8000 pounds of metal,[10] are carried either by overhead crane or by motorized vehicles to holding tanks prior to casting.

FIGURE 8: DIAGRAM OF A HALL-HEROULT CELL WITH PREBAKED ANODES



Note: Adapted from Smith (1974)[21]

If the metal is to be used as produced, i.e., about 99.5 percent pure aluminum, the crucibles are emptied into a holding furnace at about 800°C where the metal from several cells is mixed to equalize slight variations in purity. When the furnace is sufficiently filled with molten aluminum, the metal is drawn off to be continuously cast into ingots usually weighing from 30 pounds to 32,000 pounds and measuring up to 14 feet in length. For making sheets and plates, ingots may be 30 feet long and weigh up to 20 tons.[17]

The metallic aluminum can be further refined to produce "super-purity" aluminum which is 99.99 percent pure for special purposes such as catalyst carrier in high-octane gasoline, jewelry, and foil for electronics. However, most aluminum is used as an alloy in combination with a wide range of proportions of various other materials including copper, magnesium, manganese, silicon, zinc, bismuth, lead, beryllium, boron, chromium, zirconium, vanadium, nickel, and titanium. If the metal is to be used as an alloy, the furnace has two compartments; the second compartment is the holding tank and the first is the charging furnace where the metal is alloyed by adding other metals, usually at about 660°C.

In either case, in the furnace the metal is fluxed by bubbling nitrogen or various mixtures of chlorine or other gases through the molten metal. The aluminum oxides, which form on top of the metal while in the crucible and holding furnace, are heavier than the pure metal so they sink into the molten metal. By inserting long, perforated "lances" into the liquid and pumping gas through them, the oxides are forced back up to the surface since the bubbles attach themselves to the oxides. The oxides are then skimmed off with big, long-handled rakes.

Ingots which are to be used for rolling are usually cast by pouring the metal into long rectangular molds placed vertically. The bottom of the shell is a hydraulic ram which slowly lowers as the molten aluminum is poured into the mold.[10] The sides of the mold are cooled by water, freezing the molten metal very quickly and at the proper rate for the desired quality control.

Energy Analysis

As has been stated above, the aluminum industry is a major energy user, and the cost of energy is a substantial portion of the total cost of its production. Future energy needs of the industry depend, to a large extent, on the location of expansions in alumina capacity. Because of the extensive dependence on imports discussed earlier and the rising costs of transportation, it is likely that most of the increase in bauxite processing will be carried out in the ore-producing countries. However, Alumax has recently announced plans to build a $400 million plant in South Carolina to process bauxite from Australia; thus, the Bayer process has been included in the energy analysis which follows.

The precise values for the quantities of materials; temperatures, times and pressures of each process; and energy used in each process depend on the exact makeup of the ore being treated in the case of alumina production and on the particular potline used for aluminum smelting. Exact values are proprietary information. Reasonable values for materials and energy used in each step from crude ore to aluminum ingot were obtained from a review of the literature plus a series of discussions with industry personnel and visits to aluminum plants. Table 3 shows the ranges and the averages of quantities of necessary materials for the production of 1 ton of aluminum ingot, and Table 4 gives the cost or energy associated with each material.

Some of the reasons for such wide variation in the quantity of each material required are (a) variations in the amount and nature of impurities in bauxite ores (see Table 1), especially silica content; (b) degree of recovery and recycling of caustic solution, electrolyte, etc.; (c) extent of drying of bauxite ores; (d) proportion of monohydrate in the bauxite; (e) caustic makeup, e.g., adding caustic soda directly requires less lime than when soda ash is used; (f) choices of temperatures, pressures, concentrations, times, currents, voltages, size of tanks, size of pots, etc.; (g) quantity and identity of impurities in the alumina; (h) capacity of plant; (i) type of anode used; (j) degree of control exercised in maintaining optimum conditions; (k) age of plant; (l) purity of anode carbon; and (m) whether pots are hooded or not.

Table 5 shows typical values for the materials and costs for each step in the production of aluminum and, when possible, the energy needed for each step as it is presently performed. To develop energy requirements for the production of aluminum, average values shown in Table 3

TABLE 3: MATERIALS FOR PRODUCTION OF 1 TON OF ALUMINUM

Material	Minimum	Maximum	Average	Number of References with specified values
Bauxite	4.0 tons	5.0 tons	4.40 tons	9
Lime (CaO)	60 lbs	290 lbs	195 lbs	8
or Limestone	347 lbs	695 lbs	513 lbs	1
Soda Ash (Na_2CO_3)	100 lbs	340 lbs	290 lbs	7
or Caustic Soda (NaOH)	200 lbs	300 lbs	216 lbs	3
Starch	4.0 lbs	40 lbs	20 lbs	6
Alumina	1.9 tons	2.0 tons	1.93 tons	9
Cryolite (Na_3AlF_6)	10 lbs	100 lbs	55 lbs	11
Aluminum Fluoride (AlF_3)	20 lbs	100 lbs	60 lbs	12
Fluorspar (CaF_2)	4 lbs	8 lbs	6 lbs	6
Carbon Anode	800 lbs	2000 lbs	1000 lbs	7
or Petroleum Coke (calcined)	700 lbs	1200 lbs	1040 lbs	6
and Pitch	200 lbs	400 lbs	300 lbs	6

Note: Tables 3, 4 and 5 were compiled from data from 13 published reports included in references, numerous conversations with industrial and governmental personnel, and visits to an aluminum smelter and to a fabricating plant.

TABLE 4: ENERGY OR COST (1975) OF AUXILIARY MATERIALS

Material	Cost	Production Energy	Notes
Bauxite	\$23/ton[a]		U.S. \$5-15/ton f.o.b. mine[b]
Lime (CaO) or Limestone	\$30.75/ton[a] \$5/ton[a]	 1334 kWh_t/ton[c]	40 hp motor[d] used to grind
Soda Ash	\$68/ton[a]	18 x 10^6 Btu/ton[e]	0.5 ton coal/ton[d]
Caustic Soda (NaOH)		0.015 x 10^6 Btu/lb[e]	Or 19.7 kWh/kg[c]
Starch ($C_6H_{10}O_5$)		5 kWh_t/kg[c]	
Alumina	\$125/ton[a]		\$45-80/ton (1974)[f]
Cryolite (Na_3AlF_6)	\$336/ton[a]	46.3 kWh/kg[c]	All Imported[g]
Aluminum Fluoride (AlF_3)	\$350/ton[a]	4.05 kWh/kg[c]	
Calcined Coke	\$80/ton[a]	11.3 kWh + 1.33 x 10^6 Btu[g]	Purchased
Pitch	\$70.60/ton[a]		Purchased
Lithium (Li)	\$11.60/lb[b]		Purchased
Fluorspar (CaF_2)	\$87-106/ton[b]	5.1 x 10^6 Btu/ton[e]	80% Imported[g]

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[a] U.S. EPA (1976)[5]

[b] U.S. Bureau of Mines (1977)[1]

[c] Chapman (1974)[23]

[d] Bravard, Flora, and Portal (1972)[12]

[e] Battelle (1975)[24]

[f] Stamper and Kurtz (1975)[2]

[g] Gordian Associates (1975)[22]

TABLE 5: MATERIALS, COSTS, AND ENERGY USED PER TON ALUMINUM

Bauxite Mining and Preparation (crush, dry, etc.). Bauxite @ \$5-15/ton f.o.b. (4.40 tons).

Energy — Range: 3-13.6 x 10^6 Btu + 3-9 man-hours
Average: 25 kWh + 4 x 10^6 Btu + 6 man-hours + \$44*

Or Bauxite already crushed and dried @ \$20-36/ton (96% of bauxite is imported) at an average cost of \$123.20.

Bauxite Grinding
Range: 300-550 kWh
Average: 314 kWh*

Transport Bauxite
Range: 2-5 x 10^6 Btu
Average: 3 x 10^6 Btu*

Mixing Bauxite and Caustic 0.38 kWh + 0.03 x 10^6 Btu*

Lime 195 lbs @ \$28.75/ton f.o.b. = \$2.80 + freight

Or Limestone at negligible cost and prepare lime
Range: 0.5-7 x 10^6 Btu or 166.8-695 kWh
Average: 230 kWh*

And Soda Ash 290 lbs @ \$50.20/ton f.o.b. = \$7.30 + freight*

Or Purchase trona at negligible cost and use coal to prepare soda ash
Average: 2.61 x 10^6 Btu.

Or Lime and Caustic Soda 60 lbs lime @ \$28.75/ton f.o.b. and 216 lbs caustic soda @ \$68/ton.
Average: 117 kWh + 0.76 x 10^6 Btu + \$8.21 plus freight

Digestion and Steam Preparation (6000-27,000 lbs steam @ 200°C, 200 psi).
Range: 7384-12,306 kWh, or 10-30 x 10^6 Btu
Average: 24.3 x 10^6 Btu*

TABLE 5: MATERIALS, COSTS, AND ENERGY USED PER TON ALUMINUM (continued)

Starch 20 lbs @ $180/ton = $1.08*

Average: 45.5 kWh*

Cooling and Settling

Separation 6 kWh*

Clarification

Range: 50-83 kWh

Average: 70 kWh*

Red Mud Disposal (0.6-5 tons)

Precipitation @ 60°C

Wash

Filter

Spent Liquor Treatment

Calcine Alumina @ 1150°C

Range: 6.9-14.7 x 10^6 Btu

Average: 8 x 10^6 Btu*

Or Alcoa flash calciner at 315°C, 5.40 x 10^6 Btu

Miscellaneous Use in Bayer Process (evaporation, pumping, etc.)

Range: 2-5 x 10^6 Btu + 3-5 man-hours

Average: 3.5 x 10^6 Btu* + 4 man-hours

Transport Alumina to smelter

Average: 117.2 kWh or 1.23 x 10^6 Btu*

Hall-Heroult Electrolysis @ 980°C

Range: 13,000-17,600 kWh

Average: 15,600 kWh*

TABLE 5: MATERIALS, COSTS, AND ENERGY USED PER TON ALUMINUM (continued)

Or Alternate Alcoa chloride process @ 700°C and no fluorine emission

Expected: 9000 kWh

Ancillary Use 12.8 x 10^6 Btu*

Anode Baking

Range: 2.3-5.5 x 10^6 Btu

Average: 2.6 x 10^6 Btu (gas or oil)*

Or 25 kWh + 18.4 x 10^6 Btu including fuel equivalent

Cathode Manufacture 12.0 kWh + 1.04 x 10^6 Btu* (including fuel equivalent)

Cryolite 55 lbs @ $336/ton = $9.24 (80% imported)*

Or Cryolite Production

Range: 2-7 x 10^6 Btu

Average: 3.6 x 10^6 Btu

Recycle or Secondary Processing

Range: 4.7-12.2 x 10^6 Btu

Average: 8.5 x 10^6 Btu

Reheat and Holding Furnace

Range: 4-50 x 10^6 Btu

Average: 8 x 10^6 Btu*

Casting

Range: 1.5-11.0 x 10^6 Btu

Average: 5 x 10^6 Btu*

Labor and Supervision for Smelting and Casting

Range: 8-20 man-hours

Average: 10 man-hours*

TABLE 5: MATERIALS, COSTS, AND ENERGY USED PER TON ALUMINUM (continued)

Pollution Control

Range: 0.42-1.71 x 10^6 Btu

Average: 1.6 x 10^6 Btu*

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*Summed to derive totals:

TOTAL (not including fuel equivalent of anodes):
16,303 kWh + 75.1 x 10^6 Btu + 20 man-hours + $61.62.

TOTAL (including fuel equivalent of anodes and cathodes):
16,328 kWh + 90.9 x 10^6 Btu + 20 man-hours + $61.62.

were used, together with average cost or energy for each process shown in Table 4. Whenever data with sufficient detail was available, thermal energy needs are given in Btu's and electrical energy needs, in kWh. Alternate production schemes were considered; for example, most aluminum refineries buy carbon anodes in the form needed and bake them on site. Therefore, the cost of anode carbon constitutes one option, and costs of pitch and coke added to energy requirements for mixing and forming constitutes another. Similar options are given when data were available.

As seen in Table 5, present technology requires an average of over 16,000 kilowatt-hours of electricity and 90×10^6 Btu of thermal energy to produce 1 ton of aluminum ingot. This value includes fuel equivalents for anode and cathode materials consumed and thus appears higher than some other published data. However, it agrees fairly well with data that includes fuel equivalents of both anodes and cathodes.

Alternative Processing

Although only small pilot plants exist or have existed to treat any aluminum-bearing ores or clays other than bauxite, Table 6 shows some estimates of energy requirements for production of alumina from various clays, etc. Table 7 shows an overall comparison of energy requirements for several such processes. Note that Table 7 has values for the production of 1 ton of alumina while Table 6 shows values for the production of 1 ton of aluminum. In every case the energy required to produce

TABLE 6: ENERGY REQUIREMENTS FOR PRODUCTION OF ALUMINA BY ALTERNATE PROCESSES

(per ton aluminum)

	Clay[a]	Anorthosite[a]	Bayer (New)[b]	HCl Leach[b]	HNO_3 Leach[b]	Toth-Clay Chlorination[b]
Electricity	204 kWh	1,540 kWh	550 kWh	268 kWh	278 kWh	666 kWh
Steam (coal)	12,434 kWh	12,281 kWh			48 x 10^6 Btu	50.18 x 10^6 Btu
Gas or Oil	14,228 kWh	15,300 kWh	23.28 x 10^6 Btu	75.6 x 10^6 Btu	2.6 x 10^6 Btu	
Nitric Acid	300 kWh					
Soda Ash		697 kWh				
Limestone		695 kWh				
Environmental Control			0.12 x 10^6 Btu	0.04 x 10^6 Btu	1.40 x 10^6 Btu	0.59 x 10^6 Btu
TOTAL	92.7 x 10^6 [c] Btu	104 x 10^6 [c] Btu	29.18 x 10^6 Btu	78.45 x 10^6 Btu	54.92 x 10^6 Btu	57.76 x 10^6 Btu

[a] Bravard, Flora and Portal (1972)[12]

[b] U.S. EPA (1976)[5]

[c] Converted using 3413 Btu = 1 kWh.

TABLE 7: ENERGY CONSUMPTION FOR PRODUCING ALUMINA FROM DOMESTIC ORES

Process	10^6 Btu/ton Al_2O_3	Ratio to Bayer Process
Bayer/bauxite	15	1.00
HNO_3-ion exchange/clay	47	3.13
HCl-ion exchange/clay	35	2.33
Sulfurous acid/clay	38	2.53
Lime-soda sinter/anorthosite	46	3.07
HNO_3-pressure leach/clay	47	3.13
HCl-isoprophyl ether/clay	41	2.73

Source: Kirby (1974)[9]

alumina from clays is considerably higher than from bauxite; thus, use of domestic resources would necessitate higher energy demands. However, two alternate processes for refining of aluminum from alumina show promise as energy conservers. The Alcoa chloride process, which is being tested in a pilot plant in Texas, requires a lower temperature for the reduction cell and less electricity per ton of aluminum produced. One other change in aluminum refining is under study — use of titanium diboride cathodes.[5] By replacing the steel and carbon used to line the pots with titanium diboride, a power saving of about 5 to 10 percent should result and the rate of oxidation of the carbon anodes should be slowed by about 20 percent. If stable titanium diboride cathodes can be produced, a concomitant effect would be to reduce pollution problems and costs (see U.S. EPA[5], pp. 68-77 for details).

Summary: Energy Considerations of Primary Aluminum Production

Since converting crude bauxite to aluminum ingots requires many unit processes with many different temperatures, energy contents, reliability factors, etc., almost every available source of energy is used to some extent. Energy data were published for 1973,[25] when aluminum production was 4529 thousand tons (primary and secondary), and some of this data is reproduced in Table 8. About 57 percent of the total energy used by the aluminum industry was for generating electricity, either purchased or self-generated. About 21 percent of the

TABLE 8: ENERGY CONSUMPTION BY THE ALUMINUM METAL INDUSTRY IN THE UNITED STATES 1973*

(billion Btu)

	Bauxite	Alumina	Hot Metal Production	Holding, Casting, Melting
Natural Gas	80	101,785	21,835	50,089
Propane and LPG	6	-	471	1,142
Distillate Oils	45	114	722	1,990
Residual Oils	1	8,263	1,178	2,966
Lube and Rolling Oils	5	25	379	248
Gasoline and Kerosine	10	49	243	95
Coal and Other	-	-	1,764	466
Electricity —				
Hydro**		989	92,077	773
Thermal**	51	6,379	160,193	1,341
TOTAL	198	117,604	278,862	59,110

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*Excludes most secondary aluminum operations and aluminum foundries.

**Includes purchased and self-generated (1 kWh = 3413 Btu). The Aluminum Association furnished the numbers shown here.

Source: Stamper and Monroe (1975)[25]

electricity used was produced from petroleum products and natural gas, 41 percent from coal, 37 percent hydroelectric, and 1 percent nuclear energy.

In Bayer alumina plants, natural gas accounted for more than 86 percent of the total energy used. Because of uncertainties in supply and in future prices of gas, other sources are being studied and some plants have converted or plan to convert to dual fuel systems wherever feasible. Thus the possibility exists for changes to alternative energy sources in the not-too-distant future for certain processes in a Bayer plant as well as for future plants that use nonbauxite ores — e.g., clays or anorthosite.

Mining, crushing, washing, grinding, pumping, digestion, clarification, filtration, and evaporation of excess water require qualities and quantities of energy which can be derived from a variety of energy sources. For example, the most demanding of these, digestion, usually takes place at about 200°C and 200 psi. Each process listed can be interrupted and can be performed either with self-generated electricity, fluidized bed coal systems, or cogeneration systems; thus, there are several processes in the alumina production by the Bayer method which can be performed with alternative energy systems. To use solar energy for heating, focusing would be required and storage would be desirable, if not essential.

Drying of bauxite and calcining of alumina require temperatures of 600°C and 1100°C, respectively. A fluidized coal bed could be used for drying, but current systems cannot reach the temperature required for calcining alumina.

The most energy-intensive step of aluminum production, electrolytic reduction of alumina to aluminum by the Hall-Heroult method, is not amenable to a change in energy source because of the complete reliability of supply needed as well as the high temperature (980°C) necessary to prevent the freezing of the pots. If the values assumed by A. D. Little, Inc.,[5] and shown in Figure 5 are correct, the Alcoa chloride reduction cell will not alleviate these requirements, in spite of the slight reduction in temperatures; however, lesser quantities of electricity will be needed if the process proves to be commercially acceptable.

Holding furnaces usually operate at about 800°C and blending and casting at about 660°C; thus it is possible that reliable alternative systems, such as focused solar systems with back-up, could be developed for each of these. If cogeneration were used, waste heat could supply a large portion of the required heat, particularly reheating the metal which is allowed to cool before casting.

When natural gas is available, it is used for continuous baking of carbon anodes at about 1100°C for at least 48 hours. When gas usage is curtailed, fuel oil is used. This dual system for baking is likely to continue for as long as either fuel can be purchased.[18]

Additional consideration should be given to two facts that will influence the future of aluminum production in the United States.

First, because of the high capital costs, few significant changes in potlines are made except when new potlines are built or old pots are replaced (nine of the potlines presently operating are over 30 years old[5]). Second, most new alumina plants will probably be built in bauxite-producing nations because of the pressure exerted by the IBA, the reduction in freight charges for transporting alumina rather than bauxite, and the lower cost of labor and the availability of financing in the bauxite-producing countries.

If commercially acceptable methods of producing aluminum from domestic resources are developed, the aluminum industry is likely to change dramatically within a short time after such a development. However, each of the presently known processes for treatment of clay or anorthosite requires more energy than the Bayer process for the production of alumina.

An alumina plant or an anode baking pit could be supplied with gas from a coal gasification plant using technology available today. However, the cost of gas produced from coal may be prohibitive — about $3 per million Btu[27] for the short term. The small quantity of electricity needed (25 MW for a 700,000 tons/year alumina plant) is too small for economic performance alone;[28] but if coupled with an aluminum smelter of medium capacity (less than 200,000 tons/year), the need could be met with power produced on the site if a sufficient supply of coal, oil, gas, or nuclear fuel could be guaranteed. Such a system would necessitate extreme reliability or a standby grid connection; however, some of the process steam requirements could be met with the waste heat from the on-site power generator.

Increased recycling of aluminum is likely to cause a more noticeable change in the energy needs of the aluminum industry than are other changes. Recycling aluminum, including separation, requires less than 10 percent of the energy necessary for production of metal from bauxite; however, the difficulty of separating aluminum from other scrap, especially stainless steel, and the long lifetimes of aluminum products, many of which are relatively new, limit the total recycling anticipated for the near future by industry personnel.

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