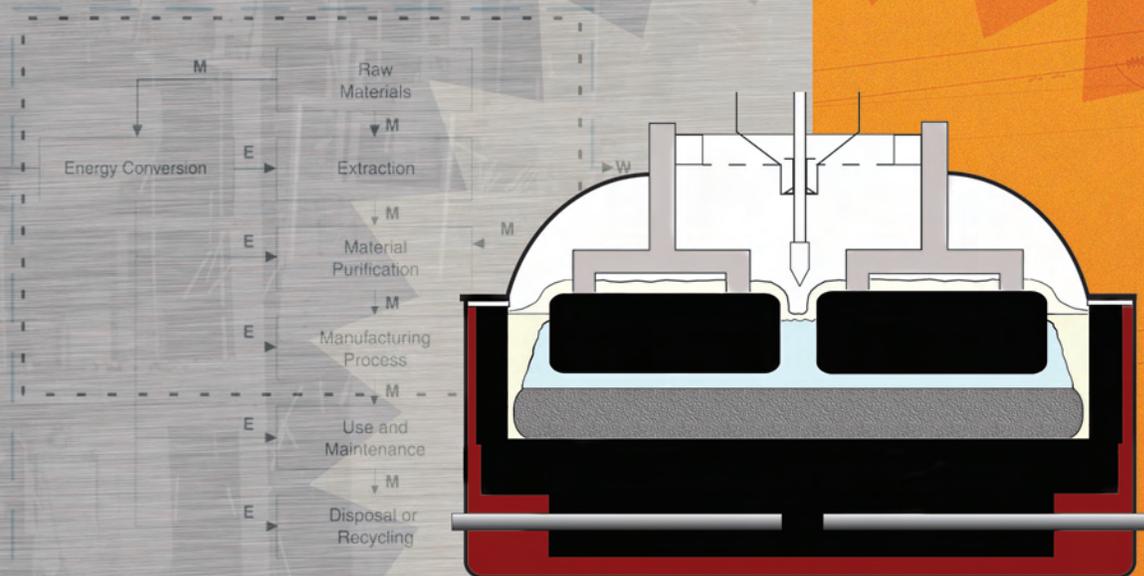


U.S. Energy Requirements for Aluminum Production

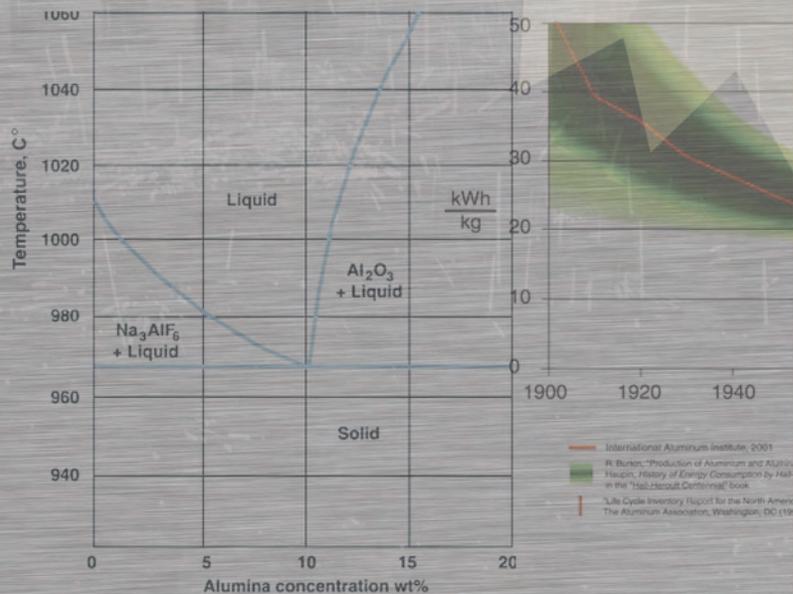
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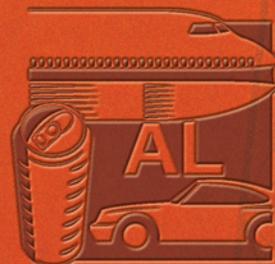
Life Cycle Boundaries

Value Chain Boundaries

M = mass
E = energy
W = waste and lost energy



February 2007





U.S. Department of Energy
**Energy Efficiency
and Renewable Energy**

Bringing you a prosperous future where energy
is clean, abundant, reliable, and affordable

U.S. Energy Requirements for Aluminum Production

Historical Perspective, Theoretical Limits
and Current Practices

Prepared for
Industrial Technologies Program
Energy Efficiency and Renewable Energy
U.S. Department of Energy

February 2007

Preface

This report provides reliable and comprehensive statistical data over the period 1960 to 2003 for the evaluation of energy trends and issues in the U.S. aluminum industry. It should be noted, however, that these trends need careful interpretation as they incorporate unusual circumstances of a single year, i.e., 2001. During the summer of 2001, the extensive heat wave in the western United States produced an increased demand for electricity. Simultaneously, the ability to generate hydroelectric power was reduced due to historically low snow packs in the Columbia River basin and new regulations mandating the spill of water to aid migrating salmon. The combination of high electricity demand and limited water supply contributed to a significant increase in the market price of electricity during this time. This price increase in the Pacific Northwest made it more economical for aluminum smelters to stop metal production and sell back power from their low-cost, fixed-price electric contracts to aid in minimizing the shortfall in energy supply. As a result, the majority of aluminum smelting capacity in the Pacific Northwest, representing approximately 43 percent of all U.S. primary aluminum capacity, shut down.

The dramatic and relatively quick shutdown of a substantial amount of the U.S. primary aluminum capacity can make certain trend numbers appear misleading. Throughout this report, percentages are given for 10-year trends in various sectors throughout the aluminum industry. For example, U.S. primary aluminum production has a 10-year annual growth rate of -2.5%, decreasing from 3,695 thousand metric tons in 1993 to 2,704 thousand metric tons in 2003. These numbers would seem to imply a steady decline throughout the specified time period, but this is not the case. In fact, the total drop in primary production over this time period (991 thousand metric tons) is less than the 1,031 thousand metric ton drop from 2000 (3,668 thousand metric tons) to 2001 (2,637 metric tons).¹ This one year drop coincides with the majority of the Pacific Northwest shutdown. Other primary production numbers in this report have similar trends, and this drastic shutdown should be taken into account when considering these numbers.

It is currently too early to accurately assess the long-term impact of these sudden shutdowns and changing conditions on the aluminum industry. It remains to be seen whether the shutdowns will lead to a permanent decline of primary metal production in the Pacific Northwest, or whether the industry will emerge robustly with additional self-generated power capacity and energy efficiency improvements. It was announced (October 8, 2004) that one of the shutdown smelters will be restarted at half capacity (+110,000 metric tons/yr), but it is difficult to judge whether or not this will be the common trend. Whatever the industry's future, it is clear that the local and global pressures to increase overall energy efficiency will determine its vitality. The energy efficiency opportunities discussed in this report are pertinent to the future of the aluminum industry.

Another recent trend to make note of is China's rapid growth in both primary and secondary aluminum production. While the United States has been slipping in its rank, China has taken worldwide lead in primary aluminum production, producing 5,450 thousand metric tons of primary

aluminum in 2003. Additionally, China has been buying up much of the excess aluminum scrap supply. In 2003, the United States exported 568,721 metric tons of scrap and dross, with 43 percent (244,374 metric tons) going to China.¹ These trends are manifested in the slight decline of secondary aluminum production within the United States.

Authors' Note

A complete accounting of the energy consumed in the production of any product should include the energy required to produce the fuels and electricity that are used plus the “feedstock energy” associated with any fuels that are used as materials (e.g., carbon used in anode production). This document, in many places, reports energy as a set of two numbers, e.g., 1.0 (2.0^{tf}) kWh. The first value represents the energy consumed within a facility (on-site energy consumption), while the value with "tf" superscript (tacit-feedstock energy) is a measure of energy that includes the energy used to produce and transmit the energy consumed within a facility and raw material feedstock energy. This adjustment is very significant in processes that consume electricity.

The U.S. average grid connection requires about 3.01 kWh (10,270 Btu) of fuel energy to deliver 1 kWh (3,412 Btu) of electrical energy (Table D.1, Appendix D). The average U.S. grid is supplied with approximately 7 percent hydroelectric generation. The aluminum industry is located near low-cost power sources and many of these are hydroelectric. Even today with the Pacific Northwest shut down, the average primary aluminum plant connection is 39.4 percent hydroelectric generation. The average primary aluminum plant grid connection requires 2.24 kWh (7,624 Btu) of fuel energy to deliver 1 kWh (3,412 Btu) of electrical energy. It should be noted that values reported in this document use the U.S. average grid connection values. The use of U.S. average grid values results in a higher reported tacit energy consumption value than the actual tacit value required for primary aluminum production. The advantage of reporting primary production energy consumption based on the U.S. average grid is that it allows easier and same basis comparisons to other U.S. manufacturing industries.

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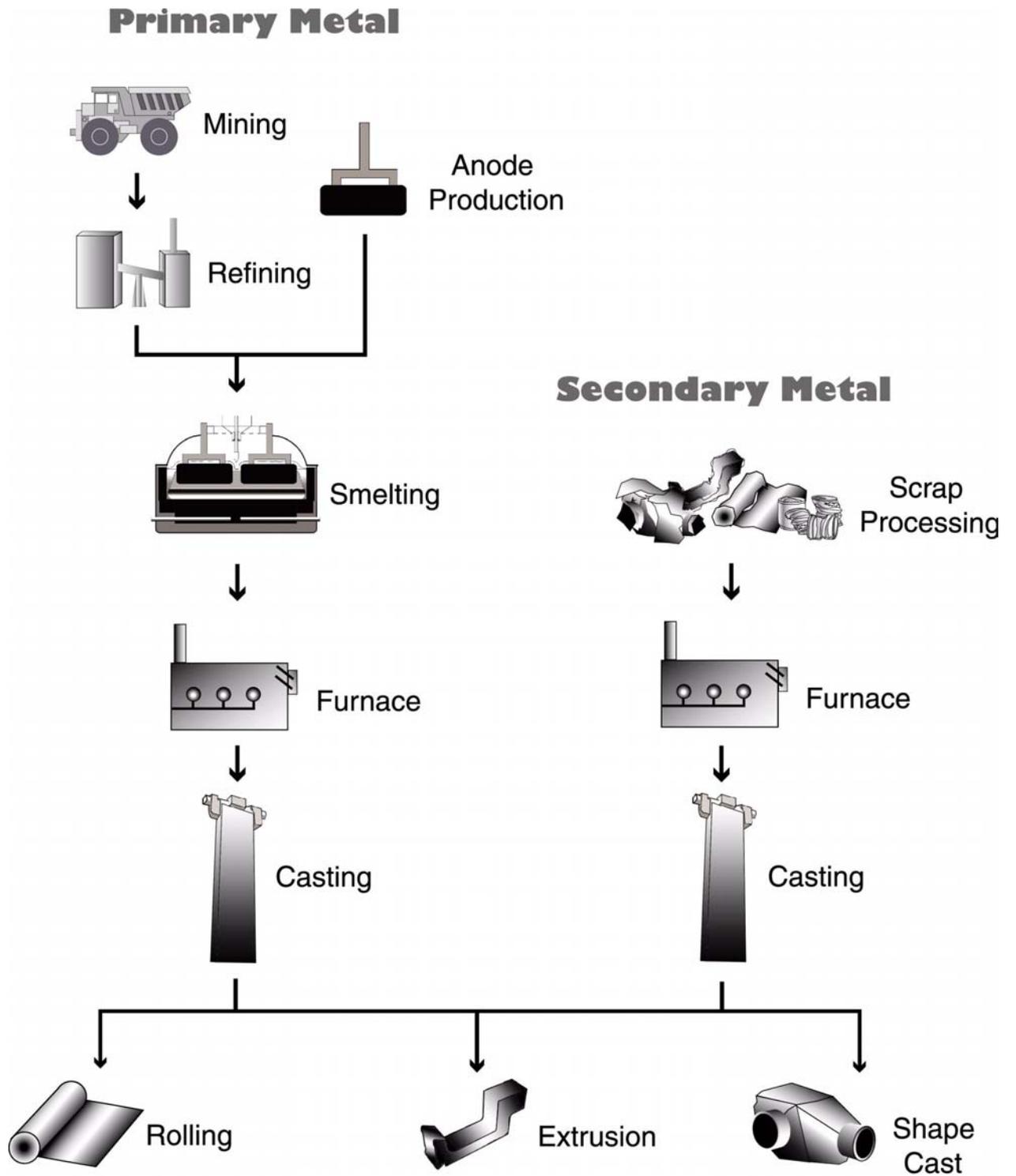


Figure A: Aluminum Industry Flow Diagram

Executive Summary

The United States aluminum industry is the world's largest, processing 9.6 million metric tons of metal and producing about \$40 billion in products and exports in 2003. It operates more than 400 plants in 41 states and employs more than 145,000 people. Aluminum impacts every community and person in the country, through either its use and recycling or the economic benefits of manufacturing facilities.

Energy reduction in the U.S. aluminum industry is the result of technical progress and the growth of recycling. These two factors have contributed 22 percent and 39 percent respectively to the total 61 percent energy reduction over the past forty years. By many measures, aluminum remains one of the most energy-intensive materials to produce. Only paper, gasoline, steel, and ethylene manufacturing consume more total energy in the United States than aluminum. Aluminum production is the largest consumer of energy on a per-weight basis and is the largest electric energy consumer of all manufactured products. The U.S. aluminum industry directly consumes 45.7×10^9 kilowatt hours (0.16 quad) of electricity annually or 1.2 percent of all the electricity consumed by the residential, commercial, and industrial sectors of the U.S. economy. This is equivalent to the electricity consumed by 5,222,000 U.S. households annually.

The aluminum industry has large opportunities to further reduce its energy intensity. The annual sum of all the energy required in the production of aluminum metal and products in the United States is equivalent to 183×10^9 kilowatt hours (0.62 quad). The difference between the gross annual energy required and the theoretical minimum requirement amounts to over 149×10^9 kilowatt hours (0.51 quad). This difference is a measure of the theoretical potential opportunity for reducing energy consumption in the industry, although achievable cost-effective savings are smaller.

U.S. Energy Requirements for Aluminum Production, Historical Perspective, Theoretical Limits and New Opportunities provides energy performance benchmarks for evaluating new process developments, tracking progress toward performance targets, and facilitating comparisons of energy use. The report provides a basic description of the processes and equipment involved, their interrelationship, and their effects on the energy consumed and environmental impact of manufacturing aluminum and aluminum products. This knowledge can help identify and understand process areas where significant energy reductions and environmental impact improvements can be made.

This report examines and carefully distinguishes between the actual "onsite" energy consumption values and gross or "tacit" energy values. The "tacit" or gross energy value accounts for the generation and transmission energy losses associated with electricity production, the "feedstock" energy of fuels used as materials, and the "process energy" used to produce fuels. Onsite energy improvements provide concomitant gross energy savings.

Primary aluminum is produced globally by mining bauxite ore, refining the ore to alumina, and combining the alumina and carbon in an electrolytic cell to produce aluminum metal. Secondary aluminum is produced globally from recycled aluminum scrap. Primary and secondary aluminum metal are cast into large ingots, billets, T-bar, slab or strip and then rolled, extruded, shape-cast, or otherwise formed into the components and useful products we use daily. Figure A (page i) shows the major processing operations required to produce aluminum and aluminum products. This report examines these processes and the energy they require.

Identifying Energy Reduction Opportunities

Energy performance benchmarks, current practice, and theoretical minimums provide the basis for evaluating energy reduction opportunities. These benchmarks and gross energy consumed during aluminum production in the United States are summarized in Table A.

Table A: U.S. Energy Requirements and Potential Savings

	U.S. Annual Production 2003	Theoretical Minimum Energy Requirement	U.S. Process Energy Required	Potential Process U.S. Energy Savings	Total U.S. Gross Energy^{tf} Required	Potential Gross U.S. Energy^{tf} Savings
	<i>metric tons</i>	<i>kWh (10⁹) / yr (quad)</i>	<i>kWh (10⁹) / yr (quad)</i>	<i>kWh (10⁹) / yr (quad)</i>	<i>kWh (10⁹) / yr (quad)</i>	<i>kWh (10⁹) / yr (quad)</i>
Bauxite Mining						
Alumina Refining	2,661,500	0.37 (0.001)	10.02 (0.034)	9.65 (0.033)	10.89 (0.037)	10.52 (0.036)
Anode Production	1,230,000	12.12 (0.041)	15.75 (0.054)	3.63 (0.012)	16.45 (0.056)	4.33 (0.015)
Al Smelting	2,758,000	16.52 (0.056)	42.97 (0.147)	26.46 (0.090)	128.36 (0.438)	111.84 (0.382)
Primary Casting	2,704,000	0.90 (0.003)	2.73 (0.009)	1.83 (0.006)	3.94 (0.013)	3.04 (0.010)
Secondary Casting	2,820,000	0.94 (0.003)	7.05 (0.024)	6.11 (0.021)	7.93 (0.027)	6.99 (0.024)
Rolling	4,842,600	1.55 (0.005)	3.04 (0.010)	1.49 (0.005)	6.08 (0.021)	4.53 (0.015)
Extrusion	1,826,000	0.80 (0.003)	2.37 (0.008)	1.57 (0.005)	2.77 (0.009)	1.97 (0.007)
Shape Casting	2,413,000	0.80 (0.003)	6.17 (0.021)	5.36 (0.018)	6.37 (0.022)	5.56 (0.019)
Total		34.00 (0.116)	90.10 (0.307)	56.10 (0.191)	182.77 (0.624)	148.78 (0.508)

Industrial processes that consume energy at significantly higher rates than their theoretical requirements are, on the surface, obvious targets for potential improvement. However, energy performance is only one factor in identifying the best opportunities for improving energy efficiency. Other factors, particularly market dynamics, process economics and forecasting of future demand are very significant in identifying real opportunities. This report examines the energy performance of the operations involved in manufacturing aluminum products.

The amounts of energy used onsite in the major processing operations of the U.S. aluminum industry are shown in Figure B (page v). The bottom band on each bar shows the theoretical energy requirement, while the top band of each bar shows the energy used above the theoretical minimum. The size of the top band is an indication of how large the opportunity is for energy reduction in that process step.

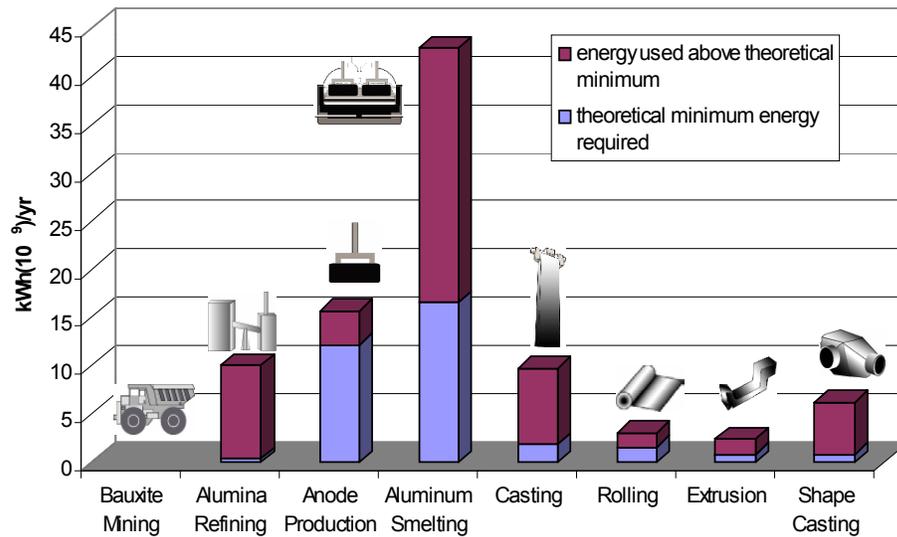
Smelting requires 46 percent of the total energy consumed in U.S. manufacturing of aluminum. This process is the largest consumer of energy and the most technically complex operation. Smelting requires more than twice its theoretical minimum energy and has the potential for the greatest energy reduction of all operations. Electricity is required for smelting and accounts for over 98 percent of the energy used in the process. Current research and development (R&D) efforts to advance existing technology and to develop alternatives to the existing smelting process have the potential to lower smelting energy consumption by more than 30 percent.

Process heating accounts for 27 percent of the total energy consumed in U.S. manufacturing of aluminum. Process heating is required for holding, melting, purifying, alloying, and heat treating. It is utilized in nearly all aluminum production operations. Heating is the second largest energy consuming operation.

Recycled aluminum now accounts for over half of all U.S. produced aluminum. It requires less than 6 percent of the energy to produce aluminum from mined bauxite and provides significant environmental benefits. R&D efforts that improve the ability to recycle aluminum offer some of the greatest opportunities for energy reduction in the industry, since recycling displaces aluminum produced by smelting.

The magnitude of the top bands of the energy bars in Figure B shows that large opportunities exist for lowering energy consumption in the industry. The *Aluminum Industry Vision, Sustainable Solutions for a Dynamic World* published by the Aluminum Association in 2001 recognizes these opportunities and sets industry goals for achieving further energy reduction. In Hall-Héroult smelting technology, the most energy-intensive process, the industry has set a target for reducing electrical energy usage from 15.4 kWh/kg to 11 kWh/kg of aluminum produced by the year 2020, a 27 percent reduction from 2000 practices. The 2003 U.S. average of 15.0 kWh/kg shows a slight improvement from 2000, likely due to the ongoing upgrades of larger, older primary production plants.

Figure B: Process Energy Used in U.S. Manufacturing of Aluminum Products



Evaluation of the many opportunities that exist for reducing energy consumption in the industry can only be made by comparing processes using consistent system boundaries and measures. This report provides data and information necessary for the reader to understand opportunities for energy savings in the aluminum industry.

1. Introduction

Aluminum is an essential material for modern manufacturing. It is a lightweight, high-strength, corrosion-resistant metal with high electrical and thermal conductivity, and it is easy to recycle. The U.S. aluminum industry is the largest in the world in terms of consumption. The U.S. aluminum industry utilized 9,592,000 metric tons of metal in 2003 to produce an enormous variety of products. U.S. per capita consumption was 29.5 kilograms. The industry operated more than 400 plants in 41 states and employed over 145,000 people to make aluminum products.¹ These products are shipped to thousands of businesses in the United States from which they are distributed or are incorporated into other products. Aluminum, per unit mass, is the most energy-intensive material produced in large quantities in the United States. Only paper, gasoline, steel and ethylene manufacturing consume more total energy for manufacturing in the United States than aluminum (Appendix B).

Research and development (R&D) efforts to reduce energy consumption are important, since energy consumption correlates to manufacturing economics, environmental impact and United States dependence on imported energy sources. Identifying process areas where opportunities for energy use reduction exist and applying resources to capture these opportunities will benefit the industry and the nation.

Aluminum manufacturing is energy intensive and roughly one-third of the cost to produce aluminum from ore is associated with the use of energy and environmental compliance. The aluminum industry, in the past forty years, reduced its overall energy intensity by nearly 61 percent (Appendix L). However, even with the large reduction in energy intensity, the industry consumes nearly three times the theoretical minimum energy required. Significant opportunities for further energy improvements still remain.

1.1 Purpose of Report

The energy consumption and environmental effects associated with product manufacturing and use are important measures of the product's impact on society. Energy consumption and environmental impact measures are becoming key decision tools for consumers and corporations when choosing a product. In the near future, manufactured products will compete not only on price and performance, but also on their impact on society.

The purpose of this report, *U.S. Energy Requirements for Aluminum Production, Historical Perspective, Theoretical Limits and New Opportunities*, is:

- to provide an understanding of the processes involved, the energy consumed and the environmental impact of manufacturing aluminum and aluminum products;
- to provide a common set of terms, benchmarks and values for comparing processes and issues related to the aluminum industry;

- to identify process areas in which significant energy reductions and environmental impact improvements could be made;
- to strengthen public and work force awareness, education and training (identified as an industry goal in *Aluminum Industry Vision*²).

This report focuses on the most energy-intensive manufacturing operations for aluminum, electrolysis (smelting) and process heating operations. These two operations account for over 69 percent of the energy used by the industry (Appendix F, Table F.8). There is a large difference between the theoretical minimum energy requirements and current practice energy values in electrolysis and melting. The magnitude of the energy consumed and the difference between current practice and theoretical energy levels means improvement in electrolysis and process heating will have the largest impact on the performance of the industry. This report documents existing operations and explores potential new technology opportunities.

The science and technologies associated with the production of aluminum and aluminum products are complex. This report attempts to provide the reader with a basic understanding of the science, technology and energy usage of the aluminum industry. More detailed books^{3, 4} are available for the reader who requires further in-depth study of the subject.

1.2 Energy and Environmental Overview

Technologies, practices and product use determine the energy consumption and environmental impact of aluminum. Many of the current technologies and practices used to produce aluminum metal and aluminum products are mature. New technologies and practices are being proposed and studied to improve aluminum manufacturing from an energy and environmental standpoint. The history and explanation of current state-of-the-art technologies and practices are presented so the reader can appreciate the values and benefits that new technologies or practices might bring to the aluminum industry. Current U.S. production levels, historical production levels and projected growth rates of aluminum are presented. These production values are needed to measure the magnitude of the impact of a change in technology or practice. The energy and environmental impacts from the use of aluminum products are generally low and in some applications may be significantly better than the impacts of alternative materials. As significant as these impacts on the use of aluminum products are, they are beyond the scope of this report.

The greatest impact on the future energy intensity of aluminum has been the structural change in the industry itself. More than 51 percent of the aluminum produced by U.S. industry in 2003 came from recycled material. In 1960, recycled material was used to generate less than 18 percent of U.S. produced aluminum (Appendix G). Recovering aluminum from wastes and scraps requires less than 6 percent of the energy of aluminum production from bauxite mining (Appendix F, Table F.6). This report examines how “urban mining” (recycling) will continue to change the structure of the

aluminum industry and continue to lower the overall energy associated with aluminum production. Recycling is the largest contributor to the reduction of the energy intensity of U.S. produced aluminum.

Aluminum is an “energy bank” in that nearly all of the original energy stored in the metal can be recovered again and again every time the product is recycled. Small fractions of the recycled metal are lost to oxidation (melt loss) and entrapment in purifying fluxes (dross) during the recycling process. Aluminum can be recycled indefinitely, allowing this saved energy to be collected again and again.

Greenhouse gas (GHG) emission reduction is a key environmental and sustainability issue for the twenty-first century. Energy-intensive manufactured materials (such as aluminum) could be significantly affected both in terms of price and use by GHG emission-reduction policies. However, contrary to common belief, aluminum production could be positively affected by GHG emission reduction policies. A combination of emission mitigation in production and significant GHG emission reduction further down the product chain enhance the attractiveness of aluminum for end-use applications.

Additional energy and environmental savings can be achieved in the aluminum product chain through the introduction of new alloys and improved (light weight) product design. These options will not be considered in this study, but their potential is at least of the same order of magnitude as changes to production practices and processes.

2. Methodology, Metrics and Benchmarks

There are a variety of metrics, measurements, benchmarks, boundaries, systems and units that are used differently by various analytical groups. These variations can cause confusion when comparing values stated in one report to those in another. Two commonly confused values are the relationship between onsite and tacit energy values, and between U.S. energy requirements and worldwide energy requirements. Onsite energy values are based on physical measurements. Tacit energy values have assumptions associated with them. These assumptions can create large differences in the reported values. The onsite and tacit values used in this report are explained in Section 2.2. The United States does not mine ore for aluminum production, but refines roughly half of the ore required domestically. This report focuses on energy consumption within the United States. The total energy associated with production of metal from ore is an important value and is reported as the “worldwide” energy requirement in this report.

2.1 Theoretical, Practical Minimum and Current Practice Benchmarks

When examining industrial processes, two metric values for energy requirement are obtainable with little debate: the process theoretical minimum value and the current practice value. The theoretical minimum energy requirement for chemically transforming a material is based on the net chemical reaction used to manufacture the product. In the case of aluminum made from alumina ($2\text{Al}_2\text{O}_3 \longrightarrow 4\text{Al} + 3\text{O}_2$), the theoretical minimum energy is 9.03 kWh/kg of aluminum produced (Appendix J). This minimum value is simplistic and represents the thermodynamically ideal energy consumption. It requires any reaction to proceed infinitely slowly. The theoretical minimum energy to transform a material from one shape to another shape is based on the mechanical properties of the material. It is also an idealized value. Neither chemical nor mechanical theoretical minimums can be realized in practice; however, these provide the benchmarks that no process can surpass (Analogy: The theoretical minimum score for a full round of golf is 18).

The current practice value is the average of the actual measurements of existing processes and practices (Analogy: The current practice value for golf is the average score of every player, which is well above par). The boundaries drawn around the process or practice, the number of samples, sampling techniques, etc., determine the precision and accuracy of this value. The difference between the theoretical minimum and current practice metric is a valuable measure of the opportunities for energy efficiency improvement in that process or practice.

Practical minimum energy is a term in common usage. However, its definition varies. In some instances, it is used to describe the process energy value that represents the combination of integrated unit operations using best available technology and best energy management practices. In other instances, practical minimum energy is defined as the optimal design value projected with the adoption of new, advanced technology. Practical minimum energy values are, in reality, a moving

target since it is not possible to predict the new technologies, practices and materials that will impact an industrial process. What is known about the practical minimum energy value is that it lies somewhere between the current best available value and the theoretical minimum value. (Analogy: The practical minimum score for golf is some value below par and over 18.)

The “Aluminum Industry Vision”⁵ has selected a goal of 11 kWh/kg of aluminum as its smelting current practice value for the year 2020. This represents a 27 percent reduction over 1995’s value of 15.4 kWh/kg of aluminum. The industry envisions this as an obtainable and practical minimum smelting energy goal for 2020.

2.2 Tacit, Process, Feedstock and “Secondary” Energies

Current practice process measurements are actual measurements taken within a facility on existing operations. These onsite process measurements are valuable because they are the benchmarks that industry uses to compare performance between facilities and companies. More importantly, these onsite process measurements are used to assess the value of new processes and practices. These are the critical values used in the decision-making process to adopt new technologies and practices. Onsite process measurements, however, do not account for the complete energy and environmental impact of manufacturing a product. A full accounting of the impact of manufacturing must also include the energy used to produce the electricity, the fuels and the raw materials used within a manufacturing facility. These “secondary energy” requirements for electric power generation and transmission, for the energy needed to produce fuels, and for the energy values of feedstock materials are very important from a regional, national, and global energy perspective, but they are seldom analyzed or accounted for within an individual plant site.

The process energy or “secondary energy” associated with the fuels used in aluminum processing is presented in Appendix C, Table C.1. The process energy adds approximately 3 percent to the energy values of the fuels used (Appendix C, Table C.2). Feedstock energy represents the energy inherent in fuels that are taken into a manufacturing process, but used as materials rather than fuels. Aluminum production uses coke as a raw material in the production of carbon anodes. Coke’s feedstock energy is significant and is equivalent to a 30 percent increase in the onsite energy consumption of the Hall-Hérault process (Appendix F, Table F.1). The energy contribution of feedstocks is expressed in terms of calorific or fuel value plus the “secondary energy” used to produce the feedstock. (Note: fuel and feedstock tacit energy values used in this report are the calorific fuel value plus the fuel processing energy, Appendix C, Table C.1).

Tacit energy is a term frequently used to describe the combined total of onsite energy and the “secondary energy” requirements. Tacit electrical energy and environmental impact measurements account for the fact that substantial electrical generation inefficiencies and transmission losses occur outside the facility. It can take as much as four units of hydrocarbon or coal calorific energy to

produce one unit of electric energy. Saving 1 kilowatt-hour of onsite electricity is equivalent to saving nearly 4 kilowatt-hour of the energy contained in the petroleum or coal-based fuels used to generate electrical power.

Tacit electric conversion factors are variable since they are dependent on the sources of the energy used to produce electricity. Each manufacturing facility has a different tacit conversion factor depending on its location. Typical U.S. grid electricity requires about 10,270 Btu of energy to deliver 1 kWh of onsite electricity (3,412 Btu) for use. Electricity production from coal requires 10,388 Btu to deliver 1 kWh of onsite electricity (3,412 Btu). Water has no fuel value and typically hydroelectric facilities are assumed to have a tacit energy requirement of 3,412 Btu to deliver 1 kWh of onsite electricity (3,412 Btu) and near zero greenhouse gas emissions (Appendix D). The onsite and tacit electric energy requirements for a facility operating on hydroelectric power are equal.

Comparing energy values for the various steps used in the production of aluminum products is simpler when a common unit is used for all processing steps. Since electricity is the single largest source of energy consumed in the manufacture of aluminum, the common units of a kilowatt-hour (kWh) are used in this report. Process energy values for production steps that consume fuels are converted to kWh using the conversion factor of 3,412 Btu/kWh.

The large variations in tacit electric energy conversion values, 10,388 Btu per onsite kWh for coal compared to 3,412 Btu per onsite kWh for hydroelectric, have a dramatic influence on the reported tacit energy profile of an industry. Aluminum smelting energy is 98 percent electric energy. A modern smelter operating from a hydroelectric utility requires onsite energy of 14.4 kWh/kg of aluminum produced and tacit energy of 14.4 kWh/kg of aluminum, whereas an identical smelter operating from a coal-fired utility requires onsite energy of 14.4 kWh/kg of aluminum and tacit energy of 36.0 kWh/kg of aluminum (Appendix C, Table C.3). The U.S. primary aluminum industry has approximately 40 percent of its capacity connected to hydroelectric facilities.

All values reported in this document use the U.S. average grid connection values (i.e., 10,270 Btu/kWh). The use of U.S. average grid values results in a higher energy consumption value than the actual tacit value required for primary aluminum production. The advantage of reporting primary production energy consumption based on the U.S. average grid is that it allows easier and same bases comparisons to other U.S. manufacturing industries. This report, for clarity, distinguishes between the onsite operating energy values and the secondary energy values that include tacit/feedstock contributions with the use of a superscript, *tf*. *Any value that includes tacit and/or feedstock components is denoted with the superscript “tf”, e.g., 1.0^{tf} kWh.*

2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is recognized as the most complete analysis model of a product's impact on energy, environmental, economic and social values. LCA of an industrial product extends from "cradle-to-grave", i.e., from material acquisition and production, through manufacturing, product use and maintenance, and finally, through the end of the product's life in disposal or recycling. LCA recognizes the importance of considering energy, economic and environmental factors not only during the production of a product, but also over the product's complete life cycle, including use and disposal. The LCA is particularly useful in ensuring that the benefits derived in one area do not shift the impact burden to other places within a product's life cycle.

The LCA "use and maintenance" factor for aluminum varies by end-product and in many applications is more significant in terms of energy and environmental impact than production. Aluminum, in some cases, provides LCA "use and maintenance" energy savings that are significantly greater than the energy used in its production. For example, production of an equal strength, but lighter aluminum product in the transportation sector saves significant amounts of transportation fuel and provides substantial reductions in greenhouse gases during the product's "use" phase when compared to traditional materials. In 2001, an estimated 2.2 billion gallons of gasoline use and 20 million metric tons of CO₂ emissions were reduced due to the use of lightweight aluminum castings in automobiles.⁶

Complete LCA for aluminum products must account for the significant portion of aluminum that, in the acquisition phase, comes from "urban mining" (recycling). Aluminum's ability to be easily recycled is reflected in the fact that over half of the U.S. produced aluminum now originates from recycled material. Recycling is the best option for disposal of nearly every product made from aluminum. This makes aluminum a "cradle-to-cradle" LCA product.

2.4 Energy Value Chain Analysis

The energy values studied and presented are based on an energy “value chain” analysis. The value chain analysis or “cradle-to-shipment dock” analysis provided is an integral part of an LCA. It provides valuable information and data values for organizations performing LCA on aluminum products. Value chain analyses are similar to LCA; however, they cover only a portion of a total LCA. Figure 2.1 shows the global boundaries of an LCA study and the boundaries for this study’s value chain.

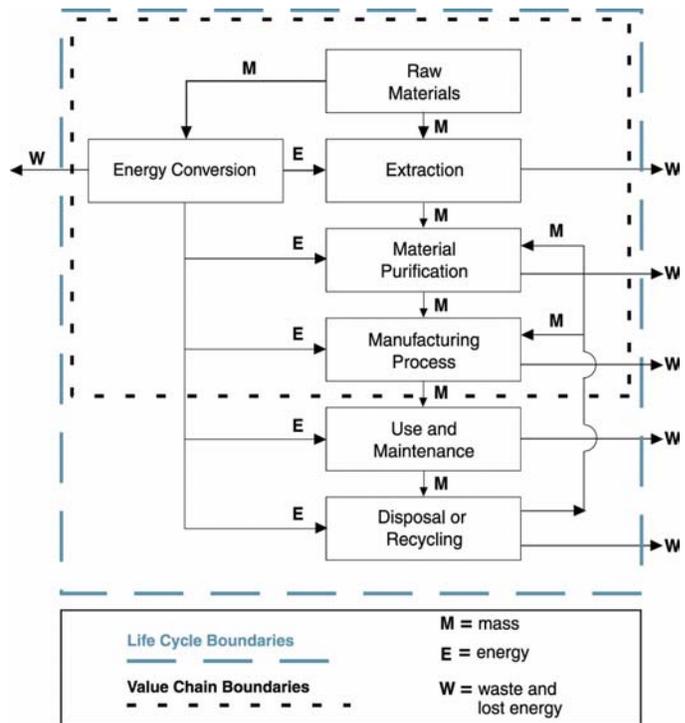


Figure 2.1: Boundaries for Life Cycle and Value Chain Assessments

Value chain analysis allows for the capture of the direct energy and feedstock inputs of each processing step (link) and builds a cumulative value of each product along the chain. This report looks at a portion of the LCA, the energy value chain from “cradle-to-shipment dock.” It does not account for the LCA “use and maintenance” phase energy or for “tertiary” energy inputs (i.e., the energy used to make the equipment or buildings that house the process steps). The “cradle-to-shipment dock” approach is valuable for providing decision-making analyses within the manufacturing sphere.

2.5 Transportation Energy

The transportation energy associated with acquiring raw materials and distribution of intermediate products is important for a full LCA. Transportation energy can account for a significant portion of the total energy associated with manufacturing a final product. The energy required to transport mined bauxite to refining operations, alumina to smelting operations, ingots to metal processors, and scrap from collection to melting is not accounted for in the process energy requirements that are developed in this report. This report focuses on the energy associated with the processing of raw materials and the processes employed in aluminum production. The transportation energy associated with these raw materials and processes is small in relation to the total energy consumed in production.

Transportation energy calculations for raw materials that are mined globally are highly variable. They are a function of the location and multiple modes of transportation, e.g., conveyors, trucks, trains, ocean freight. Transportation energy requirements were evaluated in the *Life Cycle Inventory Report for the North American Aluminum Industry*. Transportation of raw materials accounted for 2 percent of the total energy associated with primary aluminum production in the United States.⁷

Evaluation of the transportation energy requirements associated with secondary aluminum production is complicated. Consumer scrap can require considerable transportation energy resulting from individual consumer drop-off, curbside collection, transfer station collection and the actual transportation to a secondary processor. Transportation energy, associated with industrial manufacturing scrap and scrap originating at large automotive and white good scrap processing centers, is more easily estimated since its boundaries are easier to define. The *Life Cycle Inventory Report for the North American Aluminum Industry* estimates transportation energy from these sources to account for 6 to 8 percent of the total energy associated with the production of secondary aluminum products.

2.6 Emissions

Energy use and greenhouse gas emissions are closely related. This report provides overall carbon emission data associated with fuels used for aluminum operations. Other fuel-related emissions (e.g., nitrous oxides, sulfur dioxide, volatile organic compounds) are not considered because their quantities are typically small as compared to the carbon-based emissions. Emissions that are aluminum process-related (e.g., perfluorocarbons, from cryolite) are reported. *Energy and Environmental Profile of the U.S. Aluminum Industry*^{7,8} provides detailed emission data for aluminum operations.

Emission calculations for this report are shown in Appendix E. Greenhouse gases contribute to climate change by increasing the ability of the atmosphere to trap heat. Gases differ in their ability to trap heat. To express the greenhouse effect of different gases in a comparable way, atmospheric scientists use a weighting factor, global warming potential (GWP). The heat-trapping ability of one metric ton of CO₂ is the standard, and emissions are expressed in terms of a million metric tons of CO₂ equivalent or 10⁶ TCDE. This report uses carbon dioxide equivalents (CDE). Emissions are also commonly expressed in terms of a million metric tons of carbon equivalent (10⁶ TCE). Carbon comprises 12/44 of the mass of CO₂; to convert from CO₂ equivalent to C equivalent multiply the CO₂ equivalent by 0.273.

3. Aluminum Production

Aluminum metal is classified as primary aluminum if it is produced from ore and as secondary aluminum if it is produced predominantly from recycled scrap material. Primary aluminum metal production consists of bauxite mining, refining bauxite to produce alumina, and finally, smelting alumina to produce aluminum. Secondary aluminum is produced by sorting, melting and treating scrap aluminum. Primary and secondary aluminum metal are further processed using traditional metal working technologies-rolling, extrusion, forging, shaping and casting into thousands of products.

Aluminum is the most abundant metallic element in the Earth's crust. However, it is never found in natural deposits as a free metal, like copper and gold. Aluminum is typically found as one of several aluminum oxides or silicates mixed with other minerals and must be processed to be recovered in its pure form. All commercial primary aluminum is produced from one raw material, bauxite and by one process, electrolytic reduction. For economic and strategic reasons, the aluminum industry continues to perform research and development on alternative raw materials (e.g., kaolin clay) and processes (e.g., chemical reduction). Although these alternatives hold promise for reducing costs, energy consumption, and environmental impacts, none are near commercialization.

The markets for aluminum industry's raw materials and products are global. Global primary aluminum production has been growing at a rate of 3.6 percent annually over the last ten years.⁹ The U.S. aluminum total supply grew at an annual rate of 0.6 percent over the period of 1993 to 2003 (Appendix G). Aluminum is still in the growth phase of the product cycle. Demand for aluminum is increasing, mainly due to aluminum substitution for other materials in the transportation sector and other lightweight applications. Its light weight, corrosion resistance and processing possibilities coupled with its ease and value for recycling strengthen its position as the material of choice in many applications. Measured in either mass produced or economic value, aluminum's use exceeds that of any other metal except iron. It is important in virtually all segments of worldwide manufacturing.

The global estimate for economically recoverable bauxite reserves is 22,000,000,000 metric tons. This quantity can address the demands for the next century. Two countries have nearly half of the world's identified bauxite resources (Guinea has 25 percent and Australia has 20 percent). Bauxite is no longer mined in the United States as a commercial feedstock for aluminum production. Domestic ore, which accounts for less than 1 percent of the U.S. requirement for bauxite, is used in the production of non-metallurgical products such as abrasives, chemicals, flame retardants, and refractories.¹⁰

Alumina is produced by refining bauxite in a wet caustic chemical leaching process (Bayer Process). Imported bauxite is refined in the United States, the largest importer of bauxite and the second largest bauxite refiner after Australia. Alumina production is continuing to rise in Australia, Brazil, Jamaica,

Surinam, Venezuela and India, all countries with large indigenous bauxite reserves. The trend in alumina production is towards placing refining capacity near the mineral resources, thereby reducing transportation energy and costs, and adding more value to exports.

Primary aluminum (aluminum from ore) is globally produced by the Hall-Hèroult process, a method that involves electrolysis or smelting of alumina. Companies choose their smelting locations where production conditions are favorable, like the availability of skilled labor, proximity to a consumer market, and provision for a highly-developed infrastructure and, especially, for low cost and reliable energy. Hydroelectric power accounts for 50 percent of the energy used worldwide for electrolysis of aluminum (Appendix D, Table D.2). The bulk of energy use in aluminum production is related to the electricity required for primary electrolysis. Since energy costs are approximately one third of the total cost of smelting primary aluminum, smelter production has been moving from sites close to consumer markets to sites with low electricity costs. Most of the primary aluminum industry restructuring began in the late 1970s and continues to this day. China and Russia have emerged as major metal producers; other countries entering the world market include Canada, Australia, Brazil, Norway and countries in the Persian Gulf area, all areas with low energy costs.

Secondary aluminum is produced from scrap or recycled aluminum. The world’s average share of secondary aluminum production is roughly one quarter of total aluminum production. The United States produces over half of its aluminum from recycled aluminum scrap (Appendix G). Aluminum recycling is concentrated in the countries where the scrap is generated with the exception of Asia, which imports significant amounts of aluminum scrap (driven by the demand for cast aluminum in the Asian car industry).

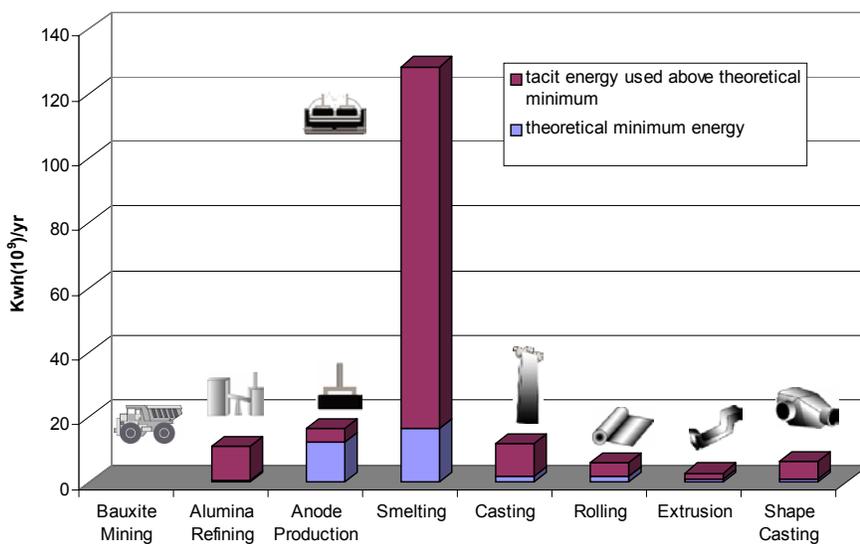


Figure 3.1: Energy^{tf} Consumption of U.S. Aluminum Operations

Primary and secondary aluminum are used to manufacture numerous products ranging from aircraft components to household and packaging foils. Each product requires processing like heating, melting, alloying and mechanical working. Figure 3.1 shows the tacit energy consumption of the major processes in the aluminum production chain. Production of primary aluminum accounts for 87.6^{tf} percent of the energy

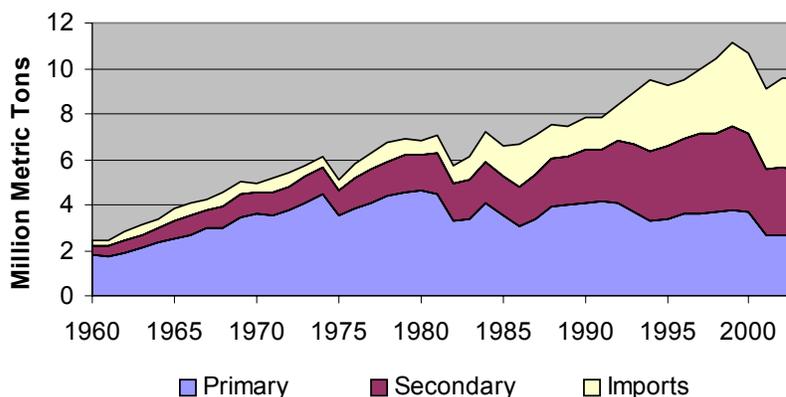
consumed by the U.S. industry; production of secondary aluminum for 4.3^{tf} percent ; rolling for 3.3^{tf} percent; extrusion for 1.5^{tf} percent; and shape casting for the remaining 3.4^{tf} percent (Appendix F, Table F.4).

Two operations, electrolysis and the heating/melting of aluminum, account for over 73(82^{tf}) percent of energy consumed in aluminum processing (Appendix F, Table F.8). Heating and melting technologies are used for holding, alloying, and treating metal as well as for recycling. Programs that improve thermal efficiency of heating and melting while minimizing the formation of aluminum oxide and/or dross, provide a much larger impact on decreasing industry energy usage than their energy consumption indicates.

3.1 U.S. Aluminum Supply

The U.S. aluminum supply of 9,592,000 metric tons in 2003 originated from three basic sources: primary aluminum (domestically produced), secondary aluminum (recycled domestic material), and aluminum imports. This consisted of 2,704,000 metric tons of primary aluminum, 2,820,000 metric tons of secondary aluminum and 4,068,000 metric tons of imported aluminum.¹¹ From 1993 to 2003, the annual U.S. growths of these supplies were –2.5 percent, –0.4 percent and 5.1 percent respectively. Since 1993, the total U.S. supply has risen at an annual rate of about 0.6 percent. Figure 3.2 shows the distribution of these supplies over the past 43 years (Appendix G).

Figure 3.2:U.S. Aluminum Supply from 1960 to 2003



Source: Appendix G

The United States is the fourth leading producer of primary aluminum metal in the world. However, its dominance in the global industry has declined. The U.S. share of world production in 1960 accounted for slightly more than 40 percent of the primary aluminum produced. By 2003, the U.S. share of world production had decreased to 9.8 percent. U.S. primary production peaked in 1980, and over the past twenty-three years has been gradually declining. Significant year-to-year variations occur as a result of U.S. electrical costs and global market changes.

Secondary (recycled) aluminum is of growing importance to the U.S. supply. In 1960, only 401,000 metric tons of aluminum were recovered. In 2003, 2,820,000 metric tons of aluminum were recovered. For the years 1993 through 2003, the secondary production of aluminum has dropped at an annual rate of -0.4 percent (Appendix G). Recently, the U.S. secondary aluminum growth rate has been slowing due to a combination of factors. Scrap collection programs are beginning to reach their maturation stage, and the market growth of scrap sources has slowed. Additionally, the U.S. has now become a net exporter of scrap and dross. In 1993, the U.S. had net imports of scrap and dross of 98,540 metric tons, while in 2003, the U.S. had net scrap and dross exports of 152,000 metric tons. The main cause for this change is again China's radical increase in demand for scrap. In 2003, 244,000 metric tons of the 567,700 metric tons of scrap and dross exported by the U.S. (43%) went to China.¹² These trends of decreasing U.S. secondary aluminum production are, however, expected to change. Use of aluminum in the automotive industry grew at over 5 percent annually between 1993 and 2003. This large and growing supply is now beginning to enter the scrap markets and will spur new growth in secondary aluminum.

Imported aluminum is the fastest growing source of U.S. supply with an annual rate of 5.1 percent over the 1993 to 2003 time frame (Appendix G). New primary aluminum facilities are being located outside the United States, near new sources of low-cost electricity.

4. Primary Aluminum Raw Materials

The total energy associated with producing the raw materials required for aluminum production from bauxite ore was approximately 8.25(14.23^{tf}) kWh/kg of aluminum in 2003. This accounts for 28 percent of the total energy required to produce primary aluminum metal and consists of:

- *0.32(0.34^{tf}) kWh per kg aluminum for bauxite mining*
- *7.27(7.87^{tf}) kWh per kg aluminum for bauxite refining to alumina, and*
- *0.66(6.02^{tf}) kWh per kg aluminum for carbon anode production.*

A complete account of the energy requirements and environmental impacts to produce any product must include the energy requirements and environmental impact associated with the production of the raw materials used. The raw material energy requirements and environmental impacts associated with primary aluminum production can be divided into the major operations required to produce it. These are bauxite mining, bauxite refining and carbon anode manufacturing. Roughly 5,900 kg of earth are mined to produce 5,100 kg of bauxite, which is refined into 1,930 kg of alumina. The 1,930 kg of alumina are electrolytically processed with 446 kg of carbon to produce one metric ton (1,000 kg) of aluminum (Appendix F, Table F.1).

Cryolite and other fluoride salts are used as the electrolytic bath for aluminum production. These materials are theoretically not consumed in the process or combined as part of the final product. However, approximately 19 kg of bath material is lost for every metric ton of aluminum produced (Appendix F, Table F.1). These losses are a result of process upsets and bath drag-out when molten aluminum is removed from the smelting operation. Since these salts represent only a small portion of the energy requirement for producing the raw materials required for aluminum production, they are not addressed in this report.

4.1 Bauxite

Aluminum, never found as a free metal, occurs naturally in the form of hydrated aluminum oxides or silicates. Since the silicates are mixed with other metals such as sodium, potassium, iron, calcium, and magnesium and it is chemically difficult and expensive to extract aluminum from them, the silicates are not a practical source of aluminum. The oxides are, therefore, used for producing aluminum. The aluminum oxides commonly found as naturally occurring minerals include

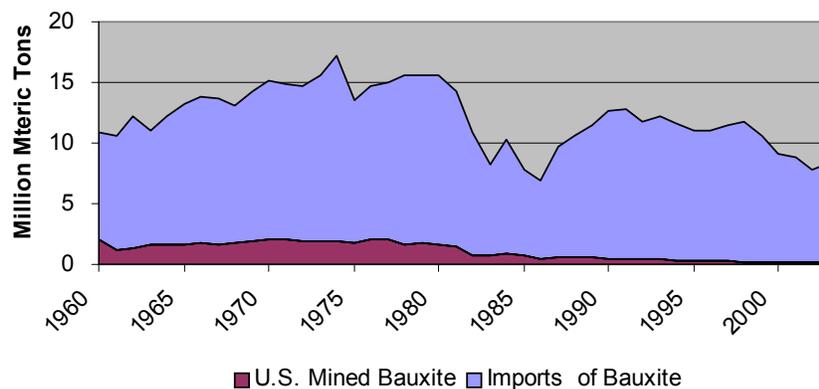
- corundum (alumina, Al_2O_3)
- böehmite ($\alpha\text{-Al}_2\text{O}_3\cdot\text{H}_2\text{O}$, a monohydrate containing 85 weight percent alumina)
- diaspor ($\beta\text{-Al}_2\text{O}_3\cdot\text{H}_2\text{O}$, chemically same as böehmite but with a different crystal structure)

- gibbsite ($\gamma\text{-Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, a trihydrate containing 65.4 weight percent alumina)

Alumina, used for the production of aluminum, is obtained from bauxite deposits. Bauxite is not a true mineral but a rock that contains mostly böehmite and gibbsite along with diaspore, corundum and numerous impurities (mostly compounds of iron, silicon and titanium). Bauxite commonly appears as a collection of small, reddish-brown nodules in a light-brown, earthy matrix. The alumina available in commercial bauxite ranges from 30 to 60 weight percent. Bauxite is typically classified according to its intended commercial application: abrasive, cement, chemical, metallurgical, refractory, and other end uses. The bulk of world bauxite production (approximately 85 percent) is metallurgical and used as feedstock for the manufacture of aluminum.

The United States mines less than 1 percent of the bauxite it uses annually, virtually all of which is used in the production of non-metallurgical products, such as abrasives, chemicals, and refractories.¹⁰ Nearly all bauxite consumed in the United States is imported. Figure 4.1 tracks the the domestic and imported components of U.S. bauxite supply from 1960 to 2003 (Appendix H).

Figure 4.1: U.S. Bauxite Supply 1960 to 2003



Source: Appendix H

In 2003, the United States imported a total of 8,300,000 metric tons of bauxite. About 95 percent of the imported bauxite is refined to produce alumina and approximately 90 percent of the refined alumina is used to produce primary aluminum. Approximately 7,097,000 metric tons of the imported bauxite were refined for the primary production of aluminum.

4.1.1 Bauxite Energy Requirements (Onsite and Theoretical)

Approximately 0.32(0.34^{tf}) kWh of process energy were required in 2003 to produce the 5.1 kilograms of bauxite needed to produce 1.0 kilogram of aluminum. Approximately 16.7 kilograms of carbon dioxide equivalent (CDE) were released for each metric ton of bauxite mined.

The energy demand associated with the extraction of bauxite is typical of most mining operations. Bauxite ore is generally strip-mined by removing the overburden (the soil on top of the deposit) and excavating it with mechanical equipment. The overburden is saved for reclamation operations which are extensively practiced to ecologically restore mined areas. The soft earthy nature of many bauxite deposits generally does not require drilling or blasting operations. After mining, the bauxite is crushed, sometimes washed and dried, and transported to refining plants via ship, barge, rail, truck or conveyor belt.

Approximately 5.1 kilograms of bauxite are required to produce a kilogram of aluminum. The energy requirement per kilogram of mined bauxite is 0.06 kWh for typical extraction.¹³ Since electricity accounts for less than 1 percent of the energy used in bauxite production, the tacit addition is negligible (Appendix F, Table F.1).

Calculation of a theoretical minimum energy requirement for mining bauxite is dependent on the system boundaries applied and the processes used. The laws of thermodynamics state that separating the constituents of a mixture, such as bauxite from bauxite-rich soil, requires a certain minimum expenditure of energy. Bauxite is the major constituent of bauxite-rich soils, and there is no change in the chemical nature of bauxite in the mining process. So the theoretical minimum energy for preparing bauxite is negligible. In addition, since it is theoretically possible to find bauxite on the surface, the theoretical minimum energy requirement to produce bauxite is very close to zero. *In the interest of simplicity, this report uses a zero theoretical minimum energy requirement for mining bauxite.*

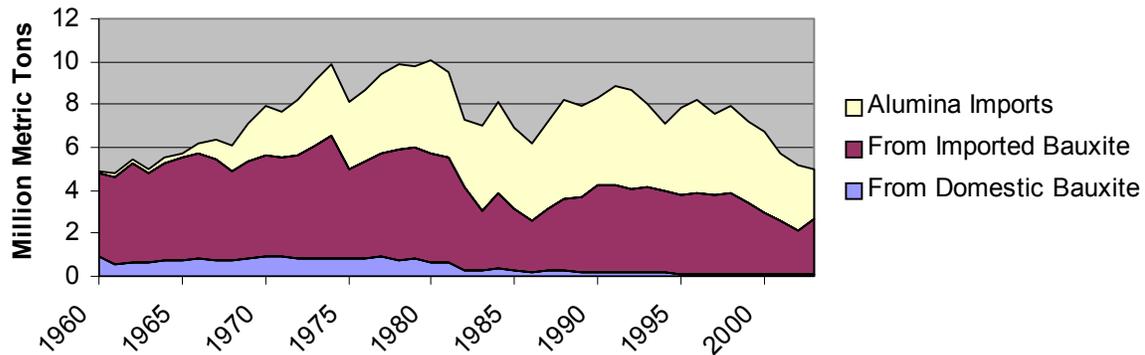
Emissions from fuels used in the extraction of bauxite are listed in Appendix E, Table E.2. These emissions are typically from surface mining operations and result from a variety of fuels used in the production of bauxite. Nearly 0.0167 kg CDE are emitted for each kilogram of bauxite mined.

4.2 Alumina (Al₂O₃)

Theoretically, from the stoichiometric equation ($2\text{Al}_2\text{O}_3 + 3\text{C} \longrightarrow 4\text{Al} + 3\text{CO}_2$), 1.89 kilograms of alumina is required to produce 1 kilogram of aluminum. In practice, a very small portion of the alumina supply is lost and the industry requires approximately 1.93 kilograms of alumina for

production of each kilogram of aluminum. In 2003, the United States produced 3,488,400 metric tons of alumina from bauxite and imported an additional 2,300,000 metric tons of alumina to make aluminum.

Figure 4.2: U.S. Alumina Supply 1960 to 2003

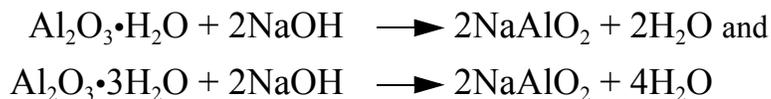


Source: Appendix H

Figure 4.2 shows the alumina supply sources from 1960 to 2003. The United States had three Bayer refineries in operation in 2003, and one temporarily idled at midyear. These refiners processed about 7,752,000 metric tons of bauxite into 3,488,400 metric tons of alumina. About 10 percent of the alumina produced is used to manufacture abrasive, refractory and other products. Approximately 3,139,560 metric tons of U.S. refined alumina were transferred to the primary aluminum industry. This quantity of alumina was not sufficient to supply the U.S. demand for alumina; therefore, an additional 1,300,000 (net) metric tons of alumina were imported (Appendix H)

All commercial alumina is refined from bauxite using the Bayer refining process. The process, developed by Karl Bayer in 1888, consists of four major steps. Bauxite composition varies and refining plant designs are slightly different to account for the site-specific quality of the bauxite.

1) Digestion – Crushed, ground, and sized bauxite is dissolved under pressure with a hot (180°C to 250°C) sodium hydroxide and sodium carbonate solution in a series of steam-heated digesters. The concentrations, temperatures, and pressures employed vary depending on the properties of the bauxite. Gibbsite is soluble in caustic soda above 100°C, while böehmite and diaspore are soluble in caustic soda above 200°C. Since the treatments of böehmite and diaspore require higher temperatures and longer digestion times, they are more expensive than treatment of gibbsite. The aluminum oxides in the bauxite react to form soluble sodium aluminate or “green liquor.”



Silicas in the bauxite are detrimental to the digestion efficiency. They react to form sodium aluminum silicate, which precipitates. This precipitate chemically binds the aluminum from the bauxite and the sodium from the sodium hydroxide into a solid from which the alumina cannot be economically recovered. This decreases the yield of alumina and increases the costs associated with sodium hydroxide. Chemical additions and the adjustment of refining practices can effectively provide desilication and decalcification of specific alumina streams.

2) Clarification – The green liquor produced by digestion is clarified to remove sand, undissolved iron oxides, titanium oxides, silica and other impurities. The insoluble materials, called “bauxite residue” or “red mud,” are thickened, washed, and dewatered to recover sodium hydroxide. Bauxite residue is a large-quantity waste product that is generally stored adjacent to refinery sites in landfills or lagoons. After weathering, the landfills can sustain vegetation.

3) Precipitation – The clarified liquid that results from clarification is cooled and “seeded” with crystals of gibbsite to aid precipitation of alumina trihydrate ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). This is the reverse of the digesting step ($2\text{NaAlO}_2 + 4\text{H}_2\text{O} \longrightarrow \text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} + 2\text{NaOH}$). However, by carefully controlling the seeding, temperature and cooling rate, specific physical properties can be given to the precipitating alumina trihydrate.

4) Calcination – Alumina trihydrate is typically calcined in a fluid bed or rotary kiln at about 980°C to $1,300^\circ\text{C}$ to remove the water of crystallization and produce the dry white powder, alumina ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} \longrightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O}$). Calcining rates and temperatures are carefully controlled and vary depending on the final physical properties specified for the alumina.

Alumina used for electrolysis not only has a chemical purity specification, but also a physical specification on particle size, surface area, bulk density and attrition behavior. These properties affect alumina’s free flowing properties (how it flows in feeders), the rate at which it dissolves in cryolite, dust levels, the strength of the alumina crust, its insulating properties and other properties important in the aluminum electrolysis cell operation. Alumina’s bulk density is 880 to $1,100 \text{ kg/m}^3$ while its specific gravity is 3.9 grams/cm³.

Bauxite residue (red mud) is a byproduct of the Bayer process and contains the insoluble impurities of bauxite. The amount of residue generated per kilogram of alumina produced varies greatly depending on the type of bauxite used, from 0.3 kilograms for high-grade bauxite to 2.5 kilograms for low-grade bauxite. Its chemical and physical properties depend primarily on the bauxite used and, to a lesser extent, the manner in which it is processed.

Although a great deal of effort has been expended over several decades to find and develop uses for bauxite residue, a cost-effective, large-scale bulk application has yet to be found.¹⁴ Numerous attempts have been made to recover additional metals from the residue, such as iron, titanium, and gallium. Other possible uses for the residue have included production of ceramic bricks or tiles, use as

roadbed material or as filler material for plastics, or production of cement. Accordingly, the current industry efforts focus on minimizing the amount of residue generated and improving its storage conditions.

Probably the most promising and recent application for the residue has occurred in Western Australia, where it is being evaluated as a soil amendment or conditioner. The soils in Western Australia are sandy and drain freely, allowing fertilizers to leach into waterways where they boost nutrient levels and can lead to problems such as algal blooms. The application of bauxite residue to these sandy soils aids the retention of phosphates and moisture, and reduces the need to apply lime for soil pH adjustments. As part of the Bauxite Roadmap project on bauxite residue, a model farm has been planned to run for 5-7 years with the application of red mud, and all its aspects and results will be studied in great detail.

4.2.1 Alumina Energy Requirements

Approximately 7.27(7.87^f) kWh of energy were required and 1.62 kg CDE were released to refine the 1.93 kg of alumina from bauxite needed to produce one kilogram of aluminum in 2003.

The energy required to produce alumina from bauxite in 1985 was estimated to range from 2 kWh/ kg to 9 kWh/ kg of alumina.¹⁵ This broad range of energy intensity reflects both bauxite quality (alumina content) and refinery design. It was estimated that in 1991, U.S. refiners averaged 3.66 kWh/kg of alumina produced.¹⁶ The most recent available refining data lists 3.76 kWh/kg of alumina for 1995.¹⁷ Calcination is the most energy-intensive operation of the Bayer process. On average, 1.93 kg of alumina are consumed to make one kilogram of aluminum.¹⁸ The alumina energy requirement for one kilogram of aluminum can be estimated as 3.76 kWh/kg of alumina times 1.93 kg alumina, or 7.27 kWh/kg of aluminum, a tacit value of 7.87^{tf} kWh/kg of aluminum.

The *Alumina Technology Roadmap* provides insight into the high-priority research and development needs of the global alumina industry.¹⁹ The Roadmap recognizes the need and the opportunity for a 25 percent energy reduction by 2020 and improved, more sustainable handling of bauxite residues. Better chemical process knowledge, waste heat utilization, and cogeneration are opportunities for energy reduction in the refining process.

Emissions from fuels used in the refining process are listed in Appendix E, Table E.2. These emissions are predominately related to natural gas and coal consumption for digestion and calcination. Nearly 1.62 kg CDE are emitted for each kilogram of refined alumina.

4.2.2 Alumina Theoretical Minimum Energy Requirements

The theoretical minimum energy required to produce alumina is 0.13 kWh/kg of aluminum produced.

The theoretical minimum energy requirements to produce metallurgical grade alumina from bauxite can be calculated from the reactions required in the process. The minimum energy requirements for the digestion, clarification, and precipitation steps are related to the two chemical reactions that take place during these processing steps.



However, since there is no net chemical or temperature change for the combined reactions the theoretical minimum energy requirement for these steps is near zero. The final reaction, calcination, requires energy to remove the hydrated water from alumina ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} \longrightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O}$). The theoretical minimum energy requirement to calcine (dehydrate) the alumina is 0.13 kWh/kg of aluminum produced (Appendix J, Table J.10). This value assumes that the precipitated alumina trihydrate is completely bone dry before entering the calcining process. At 8 percent moisture, this would add about 0.01 kWh/kg of aluminum to the minimum requirement.

4.3 Carbon Anode

The United States consumed 1,651,000 metric tons of carbon anode in 2000. Approximately 0.45 kilograms of carbon anode were needed to produce one kilogram of aluminum. (Appendix F, Table F.1) All commercial production of aluminum uses carbon as the anode material for the electrical reduction of alumina to aluminum. The carbon anode net reduction reaction ($2\text{Al}_2\text{O}_3 + 3\text{C} \longrightarrow 4\text{Al} + 3\text{CO}_2$) requires three carbon atoms for the reaction to free four aluminum atoms. The theoretical minimum anode consumption is 0.33 kg of carbon per kilogram aluminum [(3 x 12.01 carbon molecular weight) / (4 x 26.98 aluminum molecular weight)]. Anode material quality is important since all the impurities dissolve into the bath and ultimately contaminate the molten aluminum. The anode's physical quality also affects both the energy efficiency and productivity of smelting cells.

Anode consumption rates in practice, typically about 0.45 kg carbon per kg of aluminum, are 35 percent higher than the theoretical requirement. Excess carbon usage results from the need to protect the iron electrical connection within the carbon anode, and from air burning and dusting. The surface of the carbon is hot enough at cell operating temperatures to oxidize at a slow rate. This is minimized by coating the anode surface and covering the anode with alumina, which insulates it from air exposure.

Dusting, breaking off small particles of carbon into the air or bath, can account for half of the excess carbon used in the smelting process. Dusting is a direct function of the anode material uniformity. It is caused by selective electrolytic oxidation and air burning of the binder pitch, which releases aggregate carbon particles into the bath. Anode carbon dust is unavailable for aluminum production.

Two different anode technologies are utilized by the U.S. industry. “Prebaked” carbon anodes account for more than 86 percent of the U.S. capacity. Older, “in-situ-baked” Söderberg anodes account for the remainder of the capacity. New prebaked anode reduction cells have surpassed Söderberg anodes in terms of current efficiency and emissions control. Only three operational smelters in the United States are currently using Söderberg anodes. No new Söderberg cells are being built, and those that exist are progressively being replaced, converted, or shut down. *This report will focus mainly on “prebaked” anodes for smelting technology.*

Carbon “prebaked” anodes are made by mixing ground used carbon anodes, calcined petroleum coke and coal tar or petroleum pitch. Pitch acts as a binder to hold the anode mass in a “green” formed shape. Compacting the anode by using vacuum and vibrating the mixture when forming produces a denser, more conductive and lower dusting anode. Baking carbonizes the pitch and creates a solid bond between the particles of calcined coke and used anode material. Cast iron is poured into preformed sockets in the baked anode to form an electrical connection. “Prebaked” anodes can weigh as much as 1,250 kg and have a working face size of about 0.70 m x 1.25 m and a 0.5 m height. “Prebaked” anodes are removed before they are completely consumed. Used anodes are recycled into the anode production system to recover the carbon and the iron rods used for electrical connections. Used anodes can account for 15 to 30 percent of the mass used in green anode makeup.

Calcined petroleum coke is a byproduct of the crude oil refining industry. Green or raw coke contains 8 to 10 percent moisture and 5 to 15 percent volatile organic materials. Raw coke must be calcined at about 1,200°C to 1,350°C in gas-fired kilns or rotary hearths to remove the moisture, drive off volatile matter, and to increase the density, strength and conductivity of the product.²⁰ Calcined coke has a bulk density of about 800 kg/m³. Worldwide, about 25 percent of all raw coke is calcined and about 70 percent of all calcined coke goes to aluminum production. Modern calcining hearth and kiln designs capture and use the volatile organic matter in raw coke as their major fuel source.

4.3.1 Carbon Anode Energy Requirements

Approximately 0.66(6.02^f) kWh of energy were required and 0.12 kg CDE were released in the manufacturing of the 0.45 kg of carbon anode needed to produce one kilogram of aluminum in 2003.

Anode blocks are typically baked in a natural gas-fired furnace for several weeks. Quality anodes

depend upon careful baking controls to gradually raise the temperature to about 1,250°C. Volatile hydrocarbons from the pitch are gradually released during the baking process. Theoretically, these volatile compounds could provide sufficient heat for anode baking and no additional energy would be required. However, in practice, volatile organic compounds account for only 46 percent of the energy input to the prebake ovens. The remaining 54 percent of the energy needed comes from fuel. Only about 30 percent of the input energy goes into making the anode, 24 percent is lost from oven surfaces, 29 percent goes up the stack and 17 percent is lost in other ways. New prebake furnace ovens with computer controls are more efficient with both regenerative and recuperative elements.²¹

Emissions associated with prebaked anodes result mainly from the combustion of natural gas and the volatile organic compounds contained in the pitch. These amount to 0.27 kg CDE per kilogram of anode or 0.12 kg CDE per kilogram of aluminum (Appendix E, Table E.2).

The process energy used to produce a carbon anode is 1.36(1.66^{tf}) kWh/kg of anode from the most recent available U.S. data for 1995.²⁰ The total energy (see Appendix I) to produce a carbon anode is shown in Table 4.1. The energy per kg of aluminum produced is obtained by multiplying 0.45 times the total energy required to produce a kilogram of carbon anode.

Table 4.1: Energy Associated with Carbon Anode Manufacturing

	kWh per kg of Anode	kWh per kg of Aluminum
	a	0.45 X a
Pitch	0.003 (2.58 ^{tf})	0.001 (1.15 ^{tf})
Coke	0.13 (8.99 ^{tf})	0.06 (4.01 ^{tf})
anode	1.36 (1.93 ^{tf})	0.61 (0.86 ^{tf})
Total	1.49 (13.50^{tf})	0.66 (6.02^{tf})

Söderberg anodes use green coke and are baked in-situ. These anodes can be baked only to the maximum cell-operating temperature, which results in an anode with 30 percent higher electrical resistivity and a greater dusting propensity than a prebaked anode.²³ The cell emission control system is also more complex than for a prebake cell, since emission systems must be designed to handle the 5 percent to 15 percent volatile organic material content of the green coke.²⁴ Some plants employ both wet and dry gas scrubbing systems to meet the environmental regulations.

4.3.2 Carbon Anode Theoretical Energy Values

The minimum theoretical energy requirement to manufacture a carbon anode is the energy necessary to convert the coal tar pitch by destructive distillation to a coke-based binder. Approximately one-third of the pitch binder mass is lost in the baking process.²⁵ A portion of this loss consists of volatile components, while the remainder is the carbonization of the pitch. Pitch contains approximately 85 percent carbon. Approximately 79 percent of the pitch is actually carbonized, while 21 percent is volatilized. The fuel energy value of the pitch that is carbonized, 0.75 kWh/kg of anode, is a measure

of the theoretical energy required for anode manufacturing. In addition, the tacit or inherent energy of 11.55^{tf} kWh/kg of anode must be accounted for as part of the total theoretical requirement. Therefore, the total theoretical minimum energy associated with the production of pre-baked carbon anodes is 12.30^{tf} kWh/kg of carbon anode. Further, since 0.33 kg of carbon anode are required to produce a kilogram of aluminum in theory, the minimum energy requirement to produce anodes is 4.1 kWh/kg of aluminum.

5. Primary Aluminum Production

The total energy associated with primary aluminum production from bauxite ore was approximately 23.78(45.21st) kWh/kg of aluminum in 2003. This consisted of:

- *8.20(14.11th) kWh/kg aluminum for raw materials, and*
- *15.58(31.10th) kWh/kg aluminum for electrolytic reduction.*

Alumina is insoluble in all ordinary chemical reagents at room temperature and has a high melting point (above 2,000°C). These properties make conventional chemical processes used for reducing oxides difficult and impractical for conversion of alumina into aluminum.

Commercial primary aluminum is produced by the electrochemical reduction of alumina. Charles Martin Hall in the United States and Paul Lewis Toussaint Héroult in France independently developed and patented a commercially successful process for alumina reduction in 1886. This process, commonly referred to as the Hall-Héroult process, is still the primary method in use for aluminum production. Though the engineering has improved vastly, the process fundamentals are basically unchanged today. The Hall-Héroult process takes place in an electrolytic cell or pot. The cell consists of two electrodes (an anode and a cathode) and contains a molten bath of fluoride compounds (cryolite), which serves as an electrolyte and solvent for alumina. An electric current is passed through the bath, which reduces the alumina to form liquid aluminum and oxygen gas. The oxygen gas reacts with the carbon anode to form carbon dioxide. Molten aluminum collects at the cathode in the bottom of the cell and is removed by siphon.

5.1 Production, Capacity, and Growth

In 2003, 10 companies operated 15 primary aluminum production facilities in the United States. These facilities having a production capacity of approximately 4,149,000 metric tons, operated at approximately 65 percent capacity to produce 2,704,500 metric tons of aluminum in 2003.²⁶

Figure 5.1: U.S. Production of Primary Aluminum from 1960 to 2003 (Source: Appendix G)

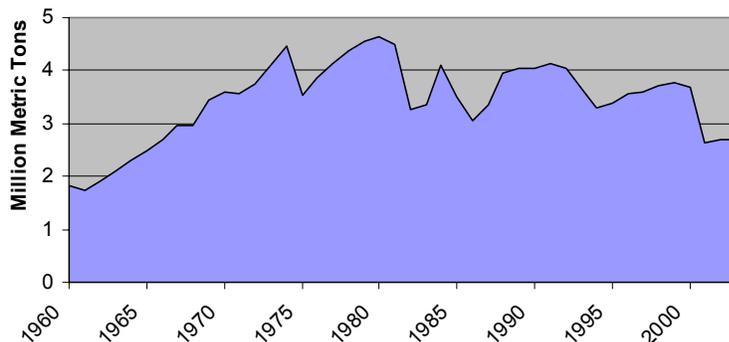


Figure 5.1 shows variations in the production of primary aluminum in the United States from 1960 to 2003. These production variations are more representative of the costs to produce aluminum than of the domestic demand. Primary aluminum is traded on a global market, and global supply has been growing steadily at a rate of 3.6 percent annually for the past ten years. The United States accounted for 9.8 percent of the world’s primary aluminum production in 2003.

5.2 Historical Hall-Héroult Energy Utilization

“The first commercial aluminum cells at Neuhausen, Switzerland (Héroult) and Pittsburgh, Pennsylvania (Hall) required more than 40 kWh/kg of aluminum produced and had current efficiencies ranging from 75 percent to 78 percent.”²⁷ The Hall-Héroult process is still electric energy intensive. Since electricity costs are an important component (about one third) of the total production costs, energy efficiency continues to be a major area of focus for the aluminum industry.

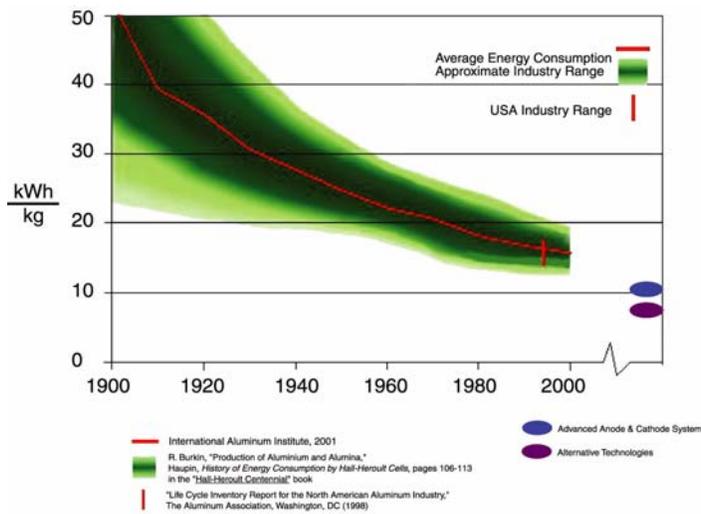


Figure 5.2: Primary Aluminum Electric Energy Consumption 1900 to 2000

The electrical energy consumed in a primary aluminum cell is measured by the number of watts consumed over a period of time. Wattage is determined by multiplying the cell voltage by cell amperage. Figure 5.2 shows the significant electrical energy improvements made between 1900 and 2000. Total electricity usage (excluding tacit generation and transmission losses) varies from less than 13 kWh/kg of aluminum for the state-of-the-art plants up to more than 20 kWh/kg for older Söderberg facilities (U.S. plants in 1995 averaged around 15.4 kWh/kg of aluminum). The theoretical minimum energy requirement for carbon anode aluminum electrolysis is approximately 5.99 kWh/kg of aluminum (see Section 5.3.1).

Compared to theoretical values, U.S. facilities are operating at roughly 38 percent energy efficiency.

Significant engineering changes in cell design and operation have occurred over the past fifty years. Table 5.2 shows the changes in operating parameters of a typical cell from 1948 to 1999.²⁸ Each new or updated primary facility tries to increase productivity and incorporate energy-reducing technologies to lower production costs. This results in gradual changes in the industry. The most significant change is the new equipment and techniques allowing for smaller and more frequent alumina additions (point feeders). This, combined with higher amperage, lower current density and larger cells, has dramatically improved current efficiencies and productivity.

Table 5.1: Typical Parameters of Aluminum Reduction Cells 1948 vs. 1999²⁸

Parameter	1948	1999
Current Rating (kA)	50 - 60	300 - 325
Aluminum Production (kg Al /pot day)	385	2,475
Energy Consumption (DC kWh/kg Al)	18.5 - 19	12.9 - 13.5
Anodic Current Density (A/cm ²)	1.2 - 1.3	0.8 - 0.85
Area of Cavity (m ³)	8	40 - 45
Nominal Anode Area (m ²)	4 - 5	38
Ratio of Area (Anode/Cavity)	~ 0.55	~ 0.9
Average Velocity of Flow in Cathode (cm/s)	10 - 15	4 - 6
Cathode Life (days)	600 - 800	2,500 - 3,000
Potroom Workers (hours/metric ton Al)	5 - 8	1.7
Interval for Alumina Additions (minutes)	80 - 240	0.7 - 1.5
Emissions (kg /metric ton Al)		
F	~ 30	< 0.5
CF ₄	~ 1.5	0.05
Anode Effects per Pot Day	3 - 4	0.05
Net Anode Carbon Consumption (kg C/kg Al)	0.55	0.43
Number of Pots per Potline	~ 40	~ 288
World Primary Production (10 ⁶) metric tons	~ 1	~ 20

There is a minimum cell amperage (electrical current) required to produce aluminum (see Section 5.3). Production in the the United States now operates at about 95 percent current efficiency, a significant improvement over the past several years, as shown in Figure 5.3. The high current efficiency of existing technologies leaves little opportunity for process or technology improvements to further reduce amperage and save additional energy. Since current efficiency is high, lowering the voltage requirements of cells presents the largest challenge and the best opportunity for improving Hall-Héroult efficiencies. The voltage requirements of a cell are described in section 5.4.2.

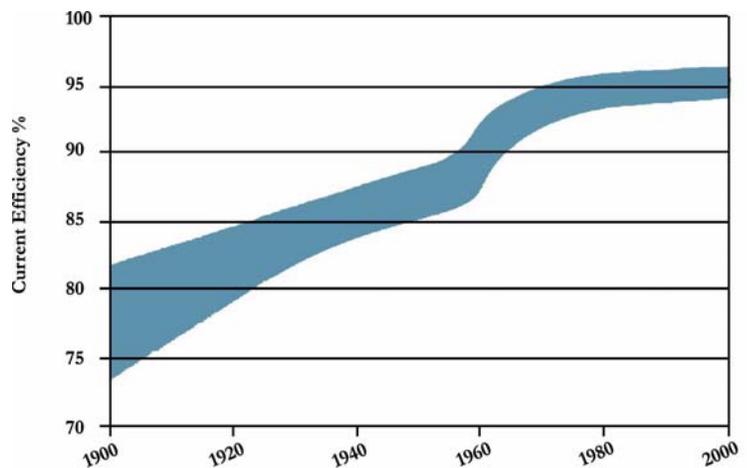


Figure 5.3: Primary Aluminum Current Efficiency 1900 to 2000

Source: Production of Aluminum and Alumina

5.3 Theoretical Minimum Energy Requirement for Reduction

All current primary production facilities and most alternative processes for aluminum production use alumina as their raw material. Any process that starts with alumina to produce aluminum has the same theoretical energy requirement. Different processes do not offer any theoretical energy advantage. However, they do offer significant tradeoffs between efficiencies, emissions, footprints, and sources of input energy (electricity, carbon, and fuels). The theoretical limits required to manufacture aluminum provide a valuable insight into Hall-Héroult cell operation and potential future reduction processes.

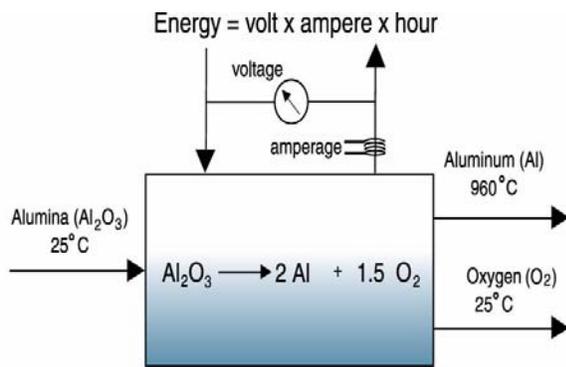


Figure 5.4: Alumina to Aluminum Theoretical Minimum Energy

The product of primary reduction process is molten aluminum. This report calculates the theoretical minimum energy by assuming the reactants enter and the byproducts leave the system at room temperature and that molten aluminum leaves the system at 960°C. The molten metal temperature, 960°C (1233°K), is an approximation of an average commercial operating cell. Figure 5.4 illustrates the theoretical boundaries for a system that reduces alumina to form aluminum and oxygen. Changes in the operating temperature of a cell have a minor effect on the theoretical energy requirements.

Operating changes of 100°C in a Hall-Héroult cell, operating in the range of 700°C to 1,100°C, result in less than a 1 percent change in the theoretical minimum energy requirements (Appendix J, Table J.7).

Some studies assume that the gases evolved during reduction leave the system at the molten metal temperature. In these studies, the theoretical minimum is 2.5 percent to 3 percent higher than the values presented in this report (Appendix J). Theoretically, it is possible to capture all the energy associated with these gaseous emissions. In practice, however, the gas stream is collected from hundreds of hooded pots and treated before release to the atmosphere. Only a very small portion of the heat is actually absorbed and returned to the system.

Three energy factors must be examined in the production of aluminum: the energy required to drive the reduction reaction forward, the energy required to maintain the system at constant pressure and temperature, and the energy required to change the temperature of the reactant and/or product. The thermodynamics and chemical equilibrium of the reactions are described by the following equation:

$$\Delta G = \Delta H - T\Delta S$$

The energy required to drive the reaction forward is the energy for the electrolytic reduction of alumina ($2\text{Al}_2\text{O}_3 \longrightarrow 4\text{Al} + 3\text{O}_2$) and is given by the change in the Gibbs free energy value (ΔG). The energy required to maintain system equilibrium is the difference between the heat of reaction

(ΔH) and the Gibbs free energy value (ΔG), which equals the entropy term ($T\Delta S$). Since the Gibbs free energy requirement is less than the heat of reaction for alumina reduction, additional energy must be added to the system to maintain the system temperature. Otherwise the system will cool as the reaction proceeds. Hence, for the alumina reduction reaction, the ΔH term provides the minimum theoretical energy requirement (reaction and equilibrium). Reduction cells operate at atmospheric conditions and no pressure change results from the reduction. Numeric values for these thermodynamic measures for the elements and compounds common to aluminum processing and the calculations used to determine the theoretical minimum energy requirement are given in Appendix J. The energy required to change the temperature of reactants and products is calculated from their heat capacities (C_p), which are provided in Appendix J.

Faraday's law provides the minimum amperage requirement for electrolytic reduction. This law states that 96,485 coulombs of electricity are passed through a cell to produce a one gram equivalent of an element or compound. Aluminum has an atomic weight of 26.98, a charge of 3^+ and therefore, has an 8.99 gram equivalent weight. Faraday's law is converted to more common measurements:

$$\left[\frac{96,485 \text{ coulombs}}{\text{gm equivalent}} \right] \left[\frac{\text{Ampere sec}}{\text{coulomb}} \right] \left[\frac{\text{hour}}{3,600 \text{ sec}} \right] \left[\frac{\text{gm equivalent}}{8.99 \text{ gm}} \right] \left[\frac{1,000 \text{ gm}}{\text{kg}} \right] = 2,980 \text{ Ah/kg}$$

The value 2,980 Ah/kg of aluminum is the theoretical minimum amperage (current) required for production. This value assumes perfect conditions, where there are no reverse or parasitic reactions that consume amperage and no limitation to the ionic species availability to react at the electrodes (no concentration gradients or gas bubbles). The Gibbs free energy (ΔG) divided by the Faraday amperage provides the minimum voltage required to drive the reaction forward. Cell voltage and current efficiency are variables that are controllable by design and they determine the electrical power required for reducing alumina. In practice, electrolytic cells have significant inefficiencies and operate above the minimum voltage requirement. This excess voltage provides the thermal energy required to maintain system equilibrium ($\Delta H - \Delta G$) and to produce molten material (C_p).

In the case of aluminum made directly from alumina ($2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al}+3\text{O}_2$), shown in Figure 5.4, the energy required to drive the reaction forward (ΔG) is 8.16 kWh/kg, the thermal energy ($\Delta H - \Delta G$) required to maintain thermal equilibrium is 0.48 kWh/kg, and the thermal energy (C_p) associated with producing the molten aluminum is 0.39 kWh/kg of aluminum. The theoretical minimum energy requirement is 9.03 kWh/kg of aluminum. (Note: if the gas emission at 960°C is included, the total theoretical minimum energy requirement is 9.30 kWh/kg of aluminum) (Appendix J, Table J.2).

5.3.1 Theoretical Energy for Hall-Héroult Carbon Anode Reduction

The theoretical minimum energy requirement for producing molten aluminum at 960°C in a Hall-Héroult cell with a carbon anode is 5.99 kWh/kg.

All commercial aluminum production uses a carbon anode in a Hall-Héroult cell. The carbon is consumed during the electrolytic process and supplies part of the energy necessary for the reduction of alumina. This gives the Hall-Héroult carbon anode process a lower energy requirement than the direct reduction of alumina to aluminum. The theoretical energy required for reduction is the same for prebaked or Söderberg carbon anodes.

The net reaction for the carbon anode Hall-Héroult process is $2\text{Al}_2\text{O}_3 + 3\text{C} \longrightarrow 4\text{Al} + 3\text{CO}_2$.

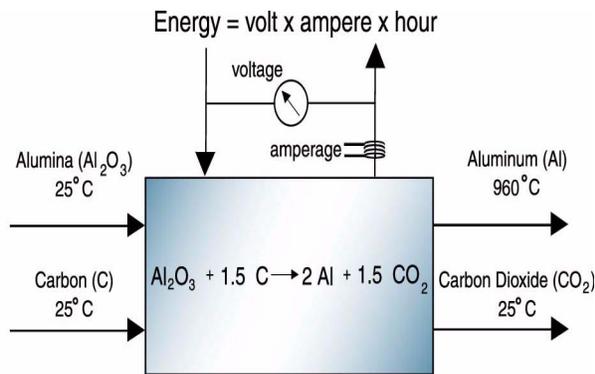


Figure 5.5: Alumina and Carbon to Aluminum Theoretical Minimum Energy

Figure 5.5 shows an idealized Hall-Héroult cell for the production of aluminum. In this cell, it is assumed that the reactants (alumina and carbon) enter the cell at 25°C, the carbon dioxide byproduct leaves the cell at 25°C, and the aluminum product leaves as molten metal at the cell operating temperature of 960°C. The reaction is assumed to occur under perfect conditions, where there are no reverse reactions, no parasitic reactions consuming additional anode carbon, no limitations to the ionic species reacting at the electrodes, and no heat or energy losses external to the system.

Appendix J, Table J.1 details the calculation of theoretical minimum energy for this reaction. The results show that the energy required to drive the reaction forward (ΔG) is 5.11 kWh/kg, the thermal energy required to maintain equilibrium is 0.49 kWh/kg and the thermal energy associated with the molten aluminum is 0.39 kWh/kg of aluminum. Therefore, the theoretical minimum energy requirement for the reduction of alumina in a carbon anode cell adds up to 5.99 kWh/kg of aluminum. (Note: if the CO_2 gas emission at 960°C is included, the total theoretical minimum energy requirement is 6.16 kWh/kg of aluminum).

In actual carbon anode cell operations, current efficiencies of less than 100 percent result from reverse oxidation reactions between part of the aluminum metal that is dissolved in the cryolite and carbon dioxide gas produced ($2\text{Al} + 3\text{CO}_2 \longrightarrow \text{Al}_2\text{O}_3 + 3\text{CO}$) and to a lesser extent between the carbon dioxide gas and the carbon anode ($\text{CO}_2 + \text{C} \longrightarrow 2\text{CO}$). Current efficiency losses can also result from direct shorting of the anode to the aluminum pad.

Today's state-of-the-art reduction cells are achieving current efficiency levels of more than 96 percent and energy consumption levels of less than 13.0 kWh/kg of aluminum.²⁹ The theoretical minimum energy requirement at 100 percent current efficiency is 5.99 kWh/kg of aluminum. The energy efficiency levels of present state-of-the-art carbon anode reduction cells are about 46 percent.

5.4 Hall-Héroult Reduction Process

The engineering, materials, and process knowledge of existing components and processes form the foundation for developing new components, processes, and techniques for producing aluminum. The Hall-Héroult cell works as a system where all the components perform together. Therefore, improving one component may not necessarily result in an improved cell or a more energy-efficient operation. To understand the impact of component and system changes on the cell performance, it is helpful to know about the Hall-Héroult process in terms of its components, operations and interrelationships. This section explains the process by describing a typical prebake anode operation.

5.4.1 Typical Hall-Héroult Cell Operation

A typical modern aluminum electrolysis Hall-Héroult reduction cell (pot) is a rectangular steel shell 9 m-12 m long, 3 m-4 m wide and 1 m-1.5 m deep (Figure 5.6). It has an inner lining of carbon, which is surrounded by refractory thermal insulation, that keeps it isolated thermally and electrically from the steel shell. Commercial cells range in capacity from 60,000 amperes to more than 500,000 amperes and can produce more than 450 to 4,000 kilograms of aluminum per day, respectively.

A cell typically operates at 950°C to 980°C and yields molten aluminum and carbon dioxide. The molten aluminum has a higher density than the electrolyte (cryolite bath) and settles to the bottom of the cell on top of the carbon lining. Molten aluminum at about 99.7 percent purity is periodically “tapped” by a vacuum siphon from the cell bottom. The tapped metal is transferred to holding furnaces where the metal is alloyed, and entrained gases and impurities are removed prior to casting. The carbon dioxide and other gases generated in the cell during the reduction process are collected and treated to meet environmental regulations.

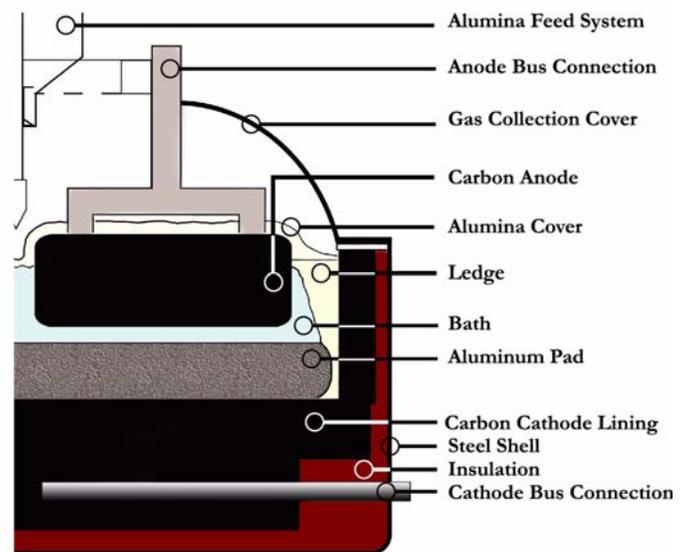


Figure 5.6: A Typical Hall-Héroult Cell

Electric current enters the cell through the carbon anode and flows through 3 cm–6 cm of electrolyte (bath) to the aluminum pad and carbon lining cathode. The aluminum pad is in intimate contact with the carbon lining and serves as the charged surface of the cathode. Steel collector bars are set near the bottom of the carbon lining to conduct the current to the anode of the next cell.

The 950°C to 980°C molten cryolite and aluminum used in a typical reduction cell are corrosive. Molten cryolite has low viscosity and interfacial tension that allows it to easily penetrate any porosity in the cell lining. To protect the carbon lining, the thermal insulation is adjusted to provide sufficient heat loss to freeze a protective coating of the electrolyte, known as “ledge,” on the inner walls. The molten aluminum pad protects the carbon bottom of the cell. The cell is never tapped completely dry of molten aluminum. It is essential that no alumina or frozen ledge form under the metal pad. The carbon cathode must remain bare for good electrical contact with the aluminum pad and to minimize wear of the carbon surface.

The reduction reaction is continuous and alumina must be supplied to the bath at a controlled rate to maintain constant conditions. This is accomplished with automatic feeders that break the surface crust and deposit alumina into the molten bath where it is dissolved for reaction. Alumina is also used to cover the carbon anodes and the frozen bath surface. The alumina covering serves as thermal insulation and as a protective cover to reduce air burning of the anode.

The electrolytic reaction in a Hall-Héroult cell consumes the carbon anode. Approximately 0.45 kilograms of the carbon anode is consumed for each kilogram of aluminum produced. The carbon anodes provide a necessary part of the energy required to operate a cell. The distance between the carbon anode and the metal pad is kept constant by adjusting the anode as it is consumed. The consumable carbon anodes must be replaced periodically, typically about every four weeks in a modern plant. The frequency of anode changing depends on the anode design and the cell operation. Anode changing represents the most frequent cell and productivity disruption. The removed portion of an anode (known as a “butt”) is recycled or sold as a fuel. The pot cover, which is part of the gas collection system, must be removed, the used anode must be pulled from the frozen surface crust, and the new anode must be inserted into the space of the consumed anode. This has to be accomplished without significant pot crust breakage or alumina falling into the bath. Anode changing is the single largest thermal, current, and magnetic disturbance in cell operation.

Cells are arranged in long rows called “potlines.” They are placed as close as possible to each other while maintaining sufficient room for anode changing, alumina feeding, and reasonably low electromagnetic interference. The cells are connected electrically in series. Rectifiers, which convert alternating current to direct current, are chosen to minimize capital investment and typically provide about 700 V(dc). Typically a reduction cell’s design requires about 4.6 V(dc) so that a potline of roughly 150 to 180 cells would be used.

5.4.2 Voltage Requirements

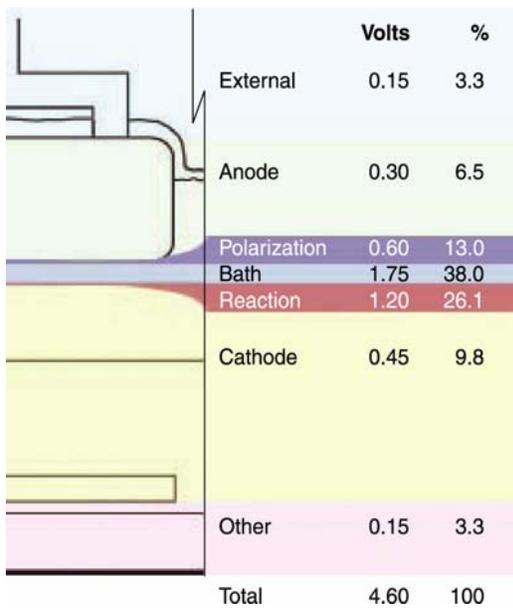


Figure 5.7: Voltage Distribution in a Hall-Héroult Cell

The energy consumed in an electrolytic reaction is a function of the voltage used and the current efficiency of the operating cell (the minimum current is fixed by Faraday’s Law, see Section 5.3 on page 27). Modern Hall-Héroult cells operate at high (96+ percent) current efficiencies. The approximate voltage components of a conventional cell are shown in Figure 5.7.

The electric current flows through the cell and the cell voltage components can be described as a set of resistors in series.

$$E = \text{cell reaction} + \text{overvoltage} + \text{bath} + \text{cathode} + \text{anode} + \text{connectors}$$

The cell reaction voltage is a function of temperature and at 960°C, is fixed at 1.2 V(dc).³⁰ This is the theoretical minimum voltage required for the reduction reaction to take place and no cell can operate at 960°C below this voltage.

The total cell operating voltage includes the addition of voltages required to overcome the ohmic resistance of the other cell components. These are described in the following section of the report.

5.4.3 Cell Subsystems and Variables

Busbars and Pot Connectors

Busbars electrically connect in series all the cells of a single potline, which typically contains more than 150 pots or cells. They are fabricated from highly conductive aluminum alloy and are sized for minimum overall system cost. Any voltage drop in the busbar and connector system results in energy loss.

Electrolyte

The electrolyte or bath used in Hall-Héroult is cryolite (Na₃AlF₆). This is modified with the addition of aluminum fluoride (AlF₃), calcium fluoride (CaF₂) and other additives to control the operating temperature, solubilities, activities of ionic species, conductivity, viscosity, interfacial tension, bath density, vapor pressure, hardness of the crust, and other factors. Bath chemistry, physical properties

and thermodynamics are very complex. The bulk electrical conductivity of the bath is influenced not only by its composition and temperature, but also by the presence of anode gas bubbles and carbon dust.

Aluminum fluoride (AlF_3) is the most common bath additive. It lowers the operating temperature, the solubility of the reduced aluminum, surface tension, viscosity and density. However, it has the undesirable effect of decreasing alumina solubility and electrical conductivity. The weight ratio of NaF to AlF_3 is referred to as the bath ratio. Controlling this ratio is important for efficient cell operation (Note: Outside the United States, many countries use the cryolite or molar ratio, which is twice the bath ratio).

The fluid bath circulates within the cell. As gas molecules are formed at the anode, they accumulate and coalesce into fine bubbles that aggregate into larger bubbles. These bubbles collect and move across the anode surface to escape around the edges of the anode. The buoyancy of the gas creates movement, which contributes to the motion of the bath and pad. The bath movement results from, in decreasing order of magnitude, gas bubble drag and electrolyte density difference caused by the bubbles generated at the anode, electromagnetic forces on the molten metal pad, and temperature gradients. This motion influences the concentration gradients of dissolved alumina and affects current efficiency. The motion also influences the heat transfer from the bath to the protective frozen ledge.

Anode-Cathode Distance

The anode-cathode distance (ACD) is the distance between electrode surfaces. In the Hall-Héroult cell, it is the distance from the lower face of the carbon anode to the top surface of the aluminum pad. This distance is typically about 4 cm–5 cm. The electrolytic bath occupies the space between the carbon anode and the aluminum pad. The voltage required for current to pass through the bath is related to the bath conductivity and the distance between the anode and the cathode. Decreasing the ACD lowers the voltage and energy requirements of the cell. The operating ACD is a compromise between keeping a low value of bath resistance, while at the same time enabling electrolyte rich in alumina ionic species to reach the charged surfaces and allowing reactant gas bubbles to escape. The ACD also must be large enough to ensure that the liquid metal does not contact the anode and short circuit the cell.

The heat required to keep the bath molten is in part supplied by the electrical resistance of the bath as current passes through it. The amount of heat developed depends on the current path or the ACD. Changing the ACD is one method of controlling the desired bath operating temperature.

Aluminum Pad

The molten aluminum pad that forms at the bottom of the cell is the cathodically-charged surface for the reduction reaction. The large amperage flowing through the cell creates electromagnetic forces and torques that cause the metallic pad to rotate. These magnetohydrodynamic (MHD) forces create this motion which deforms the molten aluminum/cryolite interface. The MHD forces cause local metal velocities of about 5 cm/sec to occur. Control of MHD effects is one of the key factors for successful cell operation with high current efficiency and low energy consumption. Cells are designed to minimize these forces and today, velocities are typically one third of what was common fifty years ago. Movement of the aluminum pad is mainly caused by electromagnetic forces in the cell and, to a smaller extent, by the interfacial drag of the bath fluid. Joint discontinuities in the carbon blocks create additional flow disturbances in the moving pad. The combination of all these forces causes the pad to undulate or roll which could result in waves forming on the surface of the pad. These waves can approach the anode and result in an electrical short circuit. The current that flows during this shorting produces no aluminum and results in a major loss of power and productivity. The motion of the aluminum pad also produces erosion of the carbon lining and shortens cell life. Since the distance between the anode and cathode is constantly changing as a result of the undulating pad, the ACD is kept large enough to avoid contact between the anode and the pad. This requires that the anode be backed away from its optimal position. Designing systems to minimize movements of the metal pad is a key factor in the efficient operation of a cell. A stable pad surface will allow the ACD to be decreased.

The newer concept of using a “drained cathode cell” is an approach to circumvent the difficulties associated with keeping the metal pad stable. Essentially the bulk of the metal is drained to a sump and the cathode is left wetted only by a thin metal sheet (Advanced Hall-Héroult Cells, Section 6.1 on page 43).

Cathode

The bottom lining of the cell also serves as a cathode and carries current from the molten metal pad. Since 10 percent of the total cell voltage drop is in the carbon cathode blocks, it is important that they have the highest density and electrical conductivity possible.

In an attempt to reduce the resistance of the cathode, some have experimented with cathode blocks containing a higher content of graphitic carbon. However, while less resistive, graphite is also less wear resistant and this compromises the life of the cathode. The cathode life generally determines cell life, since cathode replacement requires the complete dismantling of a cell. The advent of hard titanium diboride (TiB_2) coatings may offer an opportunity to increase the graphitic content of cathode blocks, and lower cell resistance, without reducing the cell life. Under optimal conditions, the life of a cathode or cell is in the range of 7 to 10 years.

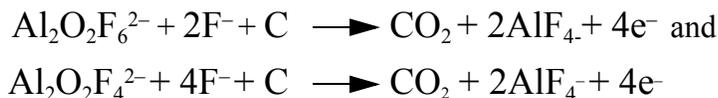
Current Density

Current density is a measure of the productivity of a cell. It is calculated by dividing the amperage supplied to an anode by the geometric face area of the anode. It is generally expressed in amperes per square centimeter (A/cm²). Most potlines operate in the range of 0.8 A/cm² to 1.0 A/cm². The quantity of aluminum produced per cell increases with increasing current density. The tradeoff is that as current density and productivity increase, current efficiency decreases, which results in a higher energy consumption per unit of metal produced. Lower current densities are more energy efficient, but increase capital and labor costs per unit of output.

Cell Polarization/Overvoltage

The reactions occurring at the anode and the cathode create localized conditions that are different from the bulk of the bath. The reactions deplete the supply of reactants and increase the quantity of products. This creates concentration gradients, which in turn cause concentration polarization. Additionally, the gas generated at the anode forms bubbles, which lower the effective bath conductivity. Localized conditions at the anode and cathode are unavoidable and require a voltage higher than the minimum reaction voltage to be applied to the cell.

No free aluminum (Al³⁺) or oxygen (O²⁻) ions are present in the bath. Alumina dissolves and dissociates into salt complexes in the bath. The dynamics at the anode are complicated by the release of gas bubbles. Oxygen-containing ionic species are transported through the bath and discharged on the carbon anode. These anode reactions are:



At least three phenomena have been identified as contributing to the anode overvoltage:

1. an increase in the local current density due to the presence of gas bubbles adjacent to the anode surface, which displace the electrolyte bath,
2. an ohmic component from an increase in the resistance of the electrolyte due to the presence of the bubbles, and
3. the concentration polarization overvoltage.³¹

Polarization effects at the cathode contribute much less to overvoltage than at the anode. The cathode reactions are (AlF₆³⁻ + 3e⁻ → Al + 6F⁻) and (AlF₄⁻ + 3e⁻ → Al + 4F⁻). The aluminum ion complexes, AlF₆³⁻ and AlF₄⁻ have higher ionic mobility than their anodic counterparts, which lowers the concentration polarization effect. In addition, no gas bubbles, which influence both resistance and concentration polarization, are produced at the cathode.

Anode Effects

Control of the quantity of alumina dissolved in the bath is important for proper operation of a cell. Alumina saturation is reached at about 7 percent alumina dissolved in a typical bath. The normal operating level is about 3 percent alumina. If the level goes above 4 percent, some of the added alumina may not dissolve rapidly and can settle to form a sludge on the cell bottom, thereby reducing the cell conductivity. If it falls below 1 percent alumina the cell is starved of the reactant and an “anode effect” ensues. When this occurs, the production of metal is interrupted and fluorine (F_2), hydrogen fluoride (HF), and two perfluorocarbon gases – tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) – are discharged instead of carbon dioxide. These perfluorocarbon gases have 6,000 to 9,000 times the global warming potential of carbon dioxide and require gas scrubbing to meet environmental regulations.

Significantly, alumina is a good absorbent of fluorine and hydrogen fluoride, but not perfluorocarbon gases. This allows primary production facilities to use their alumina raw material as an absorbent in dry gas scrubbing systems. The fluorides absorbed on the alumina in the scrubbers are recycled into the pot feeding systems, so that both the alumina and fluorides can be reused in the process.

Alumina Feed

Alumina is ideally added to the cell at a rate that exactly replaces the alumina that has been reduced. If alumina is fed too fast or in large increments, it may not dissolve and can form sludge. Sludge affects fluid flows within the cell and contributes to erosion of the cathode block surface. Under-feeding the cell results in an anode effect. There is no current technology for in-situ, real-time bath analysis to provide precise control of alumina concentration in the bath and alumina feed rate.

Alumina is fed by automatic handling and conveyor systems. The specifications for alumina are complex with numerous tradeoffs. It must dissolve rapidly; it should contain few impurities, and have a high surface area, yet be a relatively large particle (this apparent inconsistency is overcome by the particle having significant porosity). The particle must also be robust, create little dust, and resist breakage during handling. The introduction of dry scrubbing systems for the cell offgases, wherein the alumina is used as an adsorbent for fluoride emissions, further complicates the alumina specifications.

Alumina is “side-worked” in older prebake cell designs and Söderberg cells. Side-worked cells introduce alumina into the bath using automated crust-breaking and feeding machines that move along the length of the cell. Side-working is time-consuming and can take one to four hours before the machine feeds the same section of the cell again. Newer prebaked cell designs utilize the spaces between the anodes to feed alumina into the cells. “Point feeders” pierce the crust and dispense small quantities of alumina at numerous points, typically in the center of the cell. One-minute intervals between point feeding is common. This frequent addition of small quantities of alumina takes

advantage of the motion of the bath and provides significantly better control of local alumina concentration. This provides for better current efficiency, fewer anode effects and less erosion caused by solid alumina. Point feeders have proven to be significantly better and have replaced most feeding systems in both prebaked and Söderberg cells.

Cell Operating Temperature

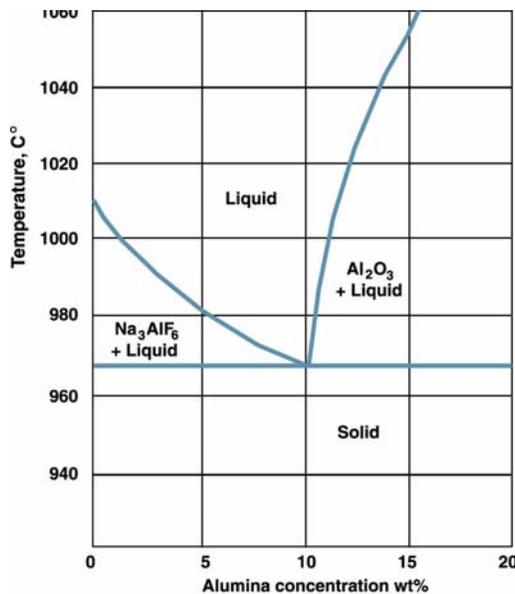


Figure 5.8: Cryolite-Alumina Phase Diagram

operating range with respect to alumina solubility. In practice, bath chemistry is modified with the addition of aluminum fluoride, calcium fluoride and other salts. These modifications lower the liquid phase temperature. However, the basic V-shape of the diagram is retained.

Heat Balance

Controlling the thermal balance of the cell is of prime importance for efficient operation and long cell life. There is no commercially available material that can retain its insulating value and resist penetration and chemical attack by cryolite at cell-operating temperatures. Accordingly, the method used to protect the side walls is to allow some heat loss so that the temperature of the exposed surface of the cell lining is below the freezing point of the bath. This creates a frozen layer or ledge of bath that protects the linings. Sidewall heat losses can account for 35 percent to 45 percent of the total heat loss in a cell.³² The frozen ledge, due to phase relationships, differs in composition from the bath. If the temperature rises above steady state, the ledge begins to dissolve and the bath ratio (sodium fluoride to aluminum fluoride) changes. If the temperature is allowed to fall too much, ledge formation is excessive, anodes are changed with great difficulty, alumina does not dissolve as readily,

and the bath ratio is affected. The frozen electrolyte ledge also provides the electrical insulation of the side walls. The thermal conductivity of frozen cryolite is an order of magnitude lower than that of the molten cryolite.

Large cell designs require less energy to maintain operating temperatures because of the lower ratio of cell surface area to volume. This is one factor in the trend to use larger cells in newer smelting plants.

5.5 Environmental Considerations

The *Energy and Environmental Profile of the U.S. Aluminum Industry*,⁸ compiled by the U.S. Department of Energy, Office of Industrial Technologies Program, and *Life Cycle Inventory Report for the North American Aluminum Industry*,⁷ published by The Aluminum Association, provide detailed environmental information on the overall aluminum production process. The byproducts generated in the Hall-Héroult process that are of environmental concern can be grouped into three areas: electrolysis, anode production, and cell waste products.

Electrolysis

Electrolysis green house gas (GHG) emissions in the Hall-Héroult process can be split into three groups: reduction reaction emissions, carbon dioxide (CO₂) and carbon monoxide (CO); process upset perfluorocarbons emissions; and hydrogen fluoride (HF) formed from the inclusion of moisture (H₂O) in the raw materials. Hydrogen fluoride gas is almost completely captured and returned to the cells by the alumina dry scrubbing system used in modern facilities.

The carbon-based emissions associated with the reduction reaction come from three sources:

1. **Reaction Products** – The reaction produces oxygen that reacts with the carbon anode to produce CO₂ and small quantities of CO; this reaction produces 1.22 kg of carbon dioxide equivalents for each kilogram of aluminum produced (Appendix E, Table E.4).
2. **Air Burning** – The carbon anode loses mass to oxidation with the atmosphere. This produces 0.30 kg of CO₂ for each kilogram of aluminum produced (Appendix E, Table E.4).
3. **Electricity Generation and Transmission** – The emissions related to the fuels used in electricity generation for U.S. primary facilities are 5.38 kg of carbon dioxide for each kilogram of aluminum produced (Appendix E, Table E.2).

A total of 6.90 kilograms of CO₂ gas is generated from the reduction process for each kilogram of aluminum produced in an average U.S. primary facility. It should be noted, that electricity-related emissions for specific potlines vary widely. Potlines operating on electricity obtained from coal-fired power plants produce 16.0 kg of CO₂ gas for each kilogram of aluminum produced, while potlines using electricity from hydro-power plants produce close to zero CO₂ gas emissions.

The perfluorocarbon emissions are related to the “anode effect.” If the concentration of alumina in the bath becomes too low, other reactions between the carbon anode and the bath occur and tetrafluoromethane (CF₄) and hexafluoroethane (C₂F₆) are generated. These gases have a high global warming potential (GWP). The GWP of a GHG is a ratio developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to CO₂ gas. The GWP of CF₄ and C₂F₆ is 6,500 and 9,200 respectively. In other words, 1 kg of CF₄ released to the atmosphere is equivalent in its warming potential to 6,500 kg of CO₂.

Aluminum smelting is the principal quantifiable source of perfluorocarbon in the United States. The U.S. Environmental Protection Agency (EPA) estimates U.S. emissions from aluminum production at 500 metric tons of CF₄ gas and 50 metric tons of C₂F₆ gas in 2003.³³ In 1995, the aluminum industry entered into a “Voluntary Aluminum Industry Partnership” (VAIP) with the EPA to reduce perfluorocarbon emissions by 46 percent during the next decade. Reductions in primary aluminum production and efficiency improvements to reduce anode effects have reduced emissions of CF₄ and C₂F₆ gases since 1990 by 71 percent each. The U.S. aluminum industry and EPA are continuing the VAIP to seek further GHG reductions beyond the original achievements. The total 2002 U.S. aluminum perfluorocarbon emissions are 2.0 CO₂ equivalent metric tons per ton of aluminum.

The emissions of perfluorocarbon for older side-fed cells are one order of magnitude higher than the emissions for cells with point feeders. The industry continues to improve point feed systems. Ultimately, with the entire industry on point feeders and advanced cell control systems, it should be possible to virtually eliminate anode effects and, hence, perfluorocarbon generation.

Anode Production

The CO₂ emissions for the carbon anode manufacturing amount to approximately 0.13 kg of CO₂ equivalents per kg of aluminum. In this report, the feedstock portion of the CO₂ emissions for carbon anode manufacturing are included in the electrolysis. More specific information on this topic can be found in the comprehensive life cycle information published by The Aluminum Association.⁷

Cell Waste Products

Aluminum electrolysis carbon slime (AECS) and spent potlining (SPL) are unavoidable byproducts of the aluminum smelting process and are listed in the United States as hazardous wastes. Development work is underway to mitigate problems associated with spent pot linings. Most development efforts attempt to combust the carbon linings to destroy any remaining toxic chemicals, to recover the valuable fluoride as AlF_3 , and to render the remaining material inert through vitrification. In some areas of the world, SPL is destroyed by combustion in the production of cement.

5.6 Technological Change in the Next Decade

The Hall-Héroult electrolysis process, utilizing a carbon anode and cryolite bath, is a mature technology. However, gradual improvements in both productivity and environmental performance are still possible. The typical Hall-Héroult cell life ranges from seven to ten years. Adoption rates of new technology and systems are governed to some degree by the cell life. There is a slow autonomous efficiency improvement in the Hall-Héroult process because of the continued adoption of advanced cell designs, feeding systems, bath composition, control systems, and other practices. This trend has resulted in a gradual decline in energy consumption in the range of 0.2 percent to 0.5 percent per year. Energy savings are actively pursued by aluminum producers since electricity costs constitute a high percentage of total production costs. Since current efficiencies are already over 95 percent, the goal is generally to reduce the overvoltage in the aluminum cells to increase the overall electric efficiency.

A number of technological and engineering improvement options exist and are being adopted by the aluminum industry. These include:

- **Point Feeders** – Point feeders enable more precise, incremental alumina feeding for better cell operation. Point feeders are generally located in the center of the cell and thereby cut down on the diffusion required to move dissolved alumina to the anodic reaction sites. The controlled addition of discrete amounts of alumina enhances the dissolution process, which aids in improving cell stability and control, minimizing anode effects, and decreasing the formation of undissolved sludge on the cathode. In the jargon of modern commerce, point feeders enable “just-in-time alumina supply” to permit optimum cell operation. Point feeder improvements continue to be made as more accurate cell controllers become available.
- **Improved Process Controls** – Advanced process controllers reduce the frequency of anode effects and control operational variables, particularly bath chemistry and alumina saturation, so that cells remain at their optimal conditions.
- **Slotted Anodes** – The use of transversally slotted anodes helps to facilitate the removal of anode gases from underneath the anode. This consequently lowers the overall anode polarization, allowing for incremental improvements in productivity and cell amperage.

5.6.1 Changes to the Hall-Héroult Cell and Alternative Technologies

Two innovative technological changes to the Hall-Héroult process, the wetted drained cathode and the inert anode, are on the near-term horizon for improving energy efficiency. These technologies can, with cell modifications, be retrofit into existing potlines and supporting infrastructure. Wetted cathodes are anticipated to lower energy consumption of a Hall-Héroult cell by 18th percent when compared to a modern Hall-Héroult cell. This report defines a modern cell as one that operates at 4.6 V(dc) and 95 percent current efficiency with the voltage distribution shown in Figure 5.7 (page 32). The combination of an inert anode with a wetted cathode could provide a 22th percent reduction in energy consumption and the elimination of cell CO₂ emissions. These technologies are described in Section 6.0, Advanced Hall-Héroult Cell (page 43), and the energy impacts are calculated in Appendix M. Multipolar cells using Hall-Héroult chemistry require the use of inert anode and wetted cathode technologies. The multipolar design allows for a more compact, more productive cell with significant thermal energy savings. Section 6.0 also describes multipolar electrolytic cells.

Two alternative technologies to the Hall-Héroult process, Carbothermic Reduction and Kaolinite Reduction, have been studied by several groups for many years. These alternative technologies could displace existing Hall-Héroult cells in the future. They are described in Section 7, Alternative Primary Aluminum Processes (page 54). Both these processes could potentially change where and how the aluminum industry operates, while lowering energy consumption. These alternatives consume more carbon and have higher onsite carbon emissions than the Hall-Héroult process. However, their electrical demands are lower which results in lower overall (utility-to-metal) CO₂ emissions. The carbothermic process is anticipated to save 20th percent in energy and be economical at a much smaller scale than the Hall-Héroult facilities. The kaolinite reduction process is anticipated to save about 12th percent of the energy required for a modern Hall-Héroult system. This value is impacted by the need to prepare additional ore mass and carbon for the process. However, the kaolinite reduction process is commercially interesting because of its lower onsite energy demands, domestically available ore, and lower-cost raw materials.

Table 5.2 summarizes the estimated energy performance of these near and midterm technologies (Appendix M, Table M.4). The onsite and tacit energy values in the table allow the processes to be compared on a reaction, raw material or a complete ore-to-metal basis. The table provides the energy associated with anode production and feedstock energies. The energy performance of the near-term technologies, wetted cathode and inert anode, are based on voltage changes in the electrolysis cell (Appendix M, Tables M.1 and M.2). These voltage changes are supported by theory and reported experiments and provide a good estimate of energy use. The energy values reported for midterm technologies, carbothermic reduction and kaolinite reduction, are approximations based on the theoretical energy requirements and assumed reactor inefficiencies. Both midterm technologies involve multiple reaction and separation zones. To date, no fully integrated reactor systems have been built. These midterm energy approximations assume that there is significant heat integration (recovery) within a facility.

Table 5.2: Ore-to-Metal Comparison of Near and Mid-Term Technology Improvements

Energy Input kWh/kg Al			Modern Prebaked Hall-Héroult	Wetted Cathode ACD = 2.0	Inert Anode Wetted Cathode ACD = 2.0	Carbothermic Reduction	Kaolinite (AlCl ₃) Reduction
ONSITE ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	7.59	7.59	7.59	7.59	
		Kaolinite					8.14
		Anode Materials	0.61	0.61	0.77		0.77
		Reaction Carbon				0	0
		Total	8.20	8.20	8.36	7.59	8.91
	Reaction Energy	Reaction Thermal				7.71	-1.90
		Furnace Losses				1.93	0.40
		Reaction	3.76	3.76	6.90		6.48
		Cell Ohmic	10.67	7.62	6.20		2.93
		Total Reaction	14.43	11.38	13.11	9.63	7.91
TOTAL Onsite		22.63	19.58	21.46	17.22	16.82	
Percent Energy Savings:							
		Reactions	21%	9%	33%	45%	
		Reactions & anode	20%	8%	36%	42%	
		Reactions, anodes & ore	13%	5%	24%	26%	
TACIT ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	8.24	8.24	8.24	8.24	
		Kaolinite					8.84
		Anode Materials	6.02	6.02	0.77		0.77
		Reaction Carbon				8.43	11.37
		Total	14.26	14.26	9.00	16.67	20.97
	Reaction Energy	Reaction Thermal				17.21	-1.90
		Furnace Losses				4.30	0.60
		Reaction	8.41	8.41	15.41		14.48
		Cell Ohmic	23.82	17.01	13.86		6.54
		Total	32.23	25.41	29.27	21.52	19.72
TOTAL Tacit		46.48	39.67	38.27	38.19	40.69	
Percent Energy Savings:							
		Reactions	21%	9%	33%	39%	
		Reactions & anode	18%	21%	44%	46%	
		Reactions, anodes & ore	15%	18%	18%	12%	

Many technical hurdles remain to be solved in these new processes before they become commercially viable. Wetted cathodes and inert anodes will be adopted as their performances are proven and existing cells need rebuilding. Industry will require significant demonstration time before adopting any alternative to Hall-Héroult technology.

6. Advanced Hall-Héroult Cells

The Hall-Héroult cell system efficiency can be improved with the adoption of new cell technologies described below. Wetted drained cathode technology offers the most significant improvement in energy efficiency, but its adoption will be gradual. Typical cell life is seven to ten years. The industry will optimize the capital invested in existing cells before retrofitting with new technology. Inert anodes offer significant environmental benefits, lower maintenance costs, and can be retrofit into the existing cells. Inert anodes could be adopted more quickly by industry since the carbon anodes are replaced approximately every four weeks. However, their superior performance must still be proven in industrial trials.

6.1 Wetted Drained Cathode

Wetted drained cathodes allow the anode-cathode distance to be reduced and are expected to result in a 20(18th) percent reduction in the electrolysis energy required to produce aluminum.

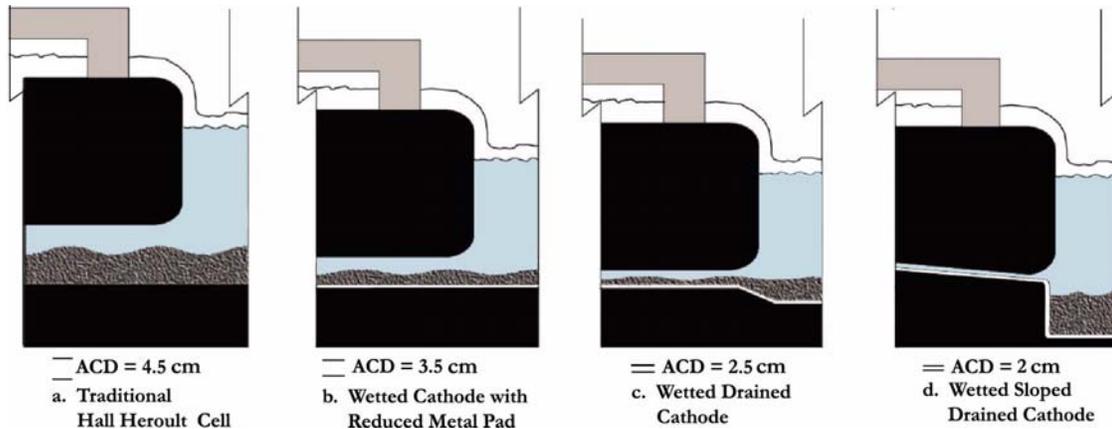
Molten aluminum does not wet the carbon lining of a Hall-Héroult cell. The aluminum pad rests on an extremely thin sheet of cryolite bath. This creates an electrical junction similar to the air gap between two metal bars and causes a small voltage drop. If the bars are clamped tighter, providing better contact, the junction voltage drop decreases. The thicker (heavier) the aluminum pad is, the thinner the cryolite sheet becomes and the lower the junction voltage drop. Modifying the cathode surface to make it more wettable would allow the same electrical contact with a decreased thickness in the pad. A thinner pad would be more hydrodynamically stable, have lower wave height, and allow a decrease in the anode-cathode distance (ACD). A decrease in the ACD results in energy savings. A cell lining that is completely wetted and inert to cryolite would be even more efficient. This combination of properties would allow the aluminum pad to be drained out of the anode-cathode spacing. Removing the unstable aluminum pad would allow the ACD to be considerably reduced and provide significant energy savings.

Titanium diboride (TiB₂) has been found to be a wettable cathodic material, and several approaches to incorporate TiB₂ into a Hall-Héroult cell are being studied.³⁴ Cathodes made wettable with TiB₂ appear to increase cell life by making the cathode less susceptible to penetration by bath material. This is a considerable benefit, as cell rebuilding costs are a major contribution to primary aluminum operational costs. Longer life cells also generate less cell lining waste material (spent pot liner) per ton of aluminum produced. These benefits have to be balanced with the higher costs associated with the TiB₂ material. Recent evidence also suggests that the wetted cathodes reduce the formation of sludge (undissolved alumina) on the cell bottom and improve cell operations.³⁵

Several concepts for wetted cathode and draining cells have been proposed. Figure 6.1 shows:

- a conventional cell,
- a low metal pad with a wetted cathode in a conventional cell,
- a hybrid cell with a metal sump, and
- a fully drained slanted cell.

Figure 6.1: Conceptual Wetted Cathode Cells



The decrease in ACD is shown for each configuration. These configurations offer attractive alternatives since they can be incorporated as a retrofit to the existing facilities. Some of these configurations are currently being evaluated in commercial cells and could soon be available.³⁶ However, as ACD is decreased, less bath is available for circulation and mixing. This requires retrofit cell designs to account for the change in bath dynamics. Designs must ensure that dissolved alumina is available across the anode surface to maintain high current efficiency and productivity and to avoid anode effects. Designs also need to compensate for the heat energy lost due to the lower cell voltage operation.

Conceptually, the fully-drained inclined cathode design offers the greatest potential for energy savings. By inclining the anode and cathode a few degrees, the molten metal pad (with all its complexities) is removed completely to a sump. Without the pad, the anode-cathode-distance is dimensionally stable and can be narrowed, which significantly reduces the total electrical resistance of the bath. The alumina feeding of the bath is not compromised because the buoyancy of the gas bubbles generated during reduction causes bath circulation and fresh alumina is drawn into the ACD gap and across the electrode face.

6.1.1 Energy Savings for Wetted Cathode Technologies

Decreasing the anode-cathode distance (ACD) results in a proportional decrease in the voltage drop associated with the electrolytic bath. Energy is saved when the ACD reduction is matched with the ability to maintain current efficiency and heat balance. The energy savings for the different wetted designs shown in Figure 6.1 are estimated in Appendix M, Table M.1.

The modern Hall-Héroult cell, shown in Figure 6.1 (a) has an ACD of 4.5 cm and a voltage distribution similar to that shown in Figure 5.7 (page 32). The traditional cell voltage distribution has 1.75 V(dc) associated with the ACD which accounts for approximately 38 percent of the total 4.60 V(dc) drop across the cell. As discussed in Section 6.1, a wetted cathode provides better electrical contact between the metal pad and the cathode allowing the ACD to be decreased. If the ACD were lowered from 4.5 cm to 3.5 cm, as shown in Figure 6.1 (b), the voltage associated with the bath would be proportionally lowered to 1.36 V(dc). The total voltage would decrease to 4.21 V(dc), which would provide an 8 percent reduction in the electrical energy usage.

Draining the metal pad into a sump would eliminate the unevenness of the pad and permit an even smaller ACD with greater energy savings. If the ACD were lowered from 4.5 cm to 2.5 cm, as shown in Figure 6.1 (c), the voltage associated with the bath would be proportionally lowered to 0.97 V(dc). The total voltage would decrease to 3.82 V(dc), providing a 16 percent reduction in the electrical energy usage.

Reducing the ACD is limited by the ability to transport the reactant (dissolved alumina) to the electrode interface and to remove products (aluminum and carbon dioxide) from the electrode interface. Sloping the electrode interface slightly as shown in Figure 6.1 (d), removes products and supplies reactants more effectively by using the buoyancy of the gas to induce bath circulation. It is estimated that under the best conditions, the ACD for a sloped configuration could be reduced to as little as 2.0 cm,^{37, 38} in which case, the voltage associated with the resistance of the bath would be 0.78 V(dc). The total voltage required would then decrease to 3.63 V(dc), providing nearly a 20 percent reduction in the electrical energy usage.

Table 6.1: Energy Consumption Associated with Various Wetted Cathode Arrangements (kWh/kgAl)

Energy Input kWh/kg Al			Modern Prebaked Hall-Héroult ACD = 4.5	Wetted Cathode ACD = 3.5	Wetted Cathode ACD = 2.5	Wetted Cathode ACD = 2.0
ONSITE ENERGY DEMANDS	Raw Materials	bauxite-alumina	7.59	7.59	7.59	7.59
		anode materials	0.61	0.61	0.61	0.61
		TOTAL	8.20	8.20	8.20	8.20
	Reaction Energy	Reaction Electrolysis	3.76	3.76	3.76	3.76
		Cell Ohmic	10.67	9.45	8.23	7.62
		TOTAL Reaction	14.43	13.21	11.99	11.38
	TOTAL Onsite		22.63	21.41	20.19	19.58
	Percent Energy Savings:					
	Reactions			8%	17%	21%
	Reactions & anode			8%	16%	20%
Reactions, anodes & ore			5%	11%	13%	
TACIT ENERGY DEMANDS	Raw Materials	bauxite-alumina	8.24	8.24	8.24	8.24
		anode materials	6.02	6.02	6.02	6.02
		TOTAL	14.26	14.26	14.26	14.26
	Reaction Energy	Reaction Electrolysis	8.41	8.41	8.41	8.41
		Cell Ohmic	23.82	21.09	18.37	17.01
		TOTAL Reaction	32.23	29.50	26.78	25.41
	TOTAL Tacit		46.48	43.76	41.03	39.67
	Percent Energy Savings:					
	Reactions			8%	17%	21%
	Reactions & anode			7%	14%	18%
Reactions, anodes & ore			6%	12%	15%	

Table 6.1 lists the data and measures the impact of the various wetted cathode arrangements. Depending upon the cell design, the reduction energy impact is expected to be as high as 18th percent.

6.1.2 Environmental Impacts for Wetted Cathode Technologies

The byproducts generated in the Hall-Héroult process that are of environmental concern are grouped into three areas: electrolysis, anode production, and cell waste products. Of these, the wetted cathode technology impacts electrolysis and cell waste products.

Electrolysis

Electrolysis green house gas (GHG) emissions can be split into three groupings: reduction reaction emissions, process upset perfluorocarbons emissions and hydrogen fluoride emissions from the bath. Wetted cathode technology does not change the emissions related to process upsets or bath emissions. The reduction reaction emissions come from three sources: the reaction products, anode air burning

and electricity generation and transmission. Wetted cathodes do not change the reaction products or anode air burning. Both wetted and traditional cathodes will produce 1.22 kg of carbon dioxide from the reduction reaction ($2\text{Al}_2\text{O}_3 + 3\text{C} \longrightarrow 4\text{Al} + 3\text{CO}_2$), 0.30 kg of carbon dioxide for each kilogram of aluminum produced from air burning of the carbon anode, and 0.12 kg of carbon dioxide for each kilogram of aluminum for the fuels associated with manufacturing the anodes.

The environmental benefit of wetted cathode technology is related to the emissions associated with the electricity production. A wetted cathode lowers the electrical energy requirement, which in turn reduces the emissions related to the fuels used in electricity generation and transmission. The electricity production (14.4 kWh/kg of aluminum) for a modern Hall-Héroult cell emits 5.04 kg of carbon dioxide equivalents (CDE) for each kilogram of aluminum produced. A wetted-sloped cathode cell with a 2.0 cm ACD will lower the CDE emission associated with electricity generation and transmission by nearly 21 percent to 3.98 kg CDE/kg of aluminum produced. This lowers the total CDE emissions associated with a wetted-sloped cathode cell from 10.62 kg CDE/kg to 7.90 kg CDE/kg of aluminum produced (Appendix E, Table E.4).

Cell Waste Products

One of the benefits of using wetted cathodes is longer cell life. Rebuilding cells less frequently will lower the quantity of spent pot liner waste per unit of aluminum produced.

6.2 Hall-Héroult Inert Anode

Carbon anodes are consumed in the Hall-Héroult process, making the continuous manufacture of new anodes and constant changing of the consumed anodes necessary. Anode changing upsets the stability, production, and energy efficiency of the cell. For more than 100 years, Charles Hall and other primary metal producers have attempted to find an inert anode that would eliminate the manufacturing and handling of consumable anodes.³⁹ The material demands of an inert anode require that it be highly conductive, and be thermally and mechanically stable at 800°C to 1,000°C. Further, it should not react or dissolve to any significant extent in the cryolite, or react or corrode in the 800°C to 1000°C oxygen containing atmosphere. Any undesirable reaction with the bath must occur at a very slow rate since this will result in the anode material contaminating the aluminum product.

Few materials are truly inert under the extreme conditions of a cell. Research has focused on three classes of inert anode materials: ceramics, cermets, and metals. The challenges to finding the most efficient material are substantial. Ceramics typically have poor thermal-shock resistance, are not mechanically robust, display poor electrical conductivity, and are difficult to connect electrically. Metals have good thermal, mechanical, and electric properties, but are attacked by the hot oxidizing atmosphere. Metal oxides are somewhat soluble in cryolite and can resist the hot oxygen atmosphere, but they exhibit lower electrical conductivity than metals. Once in solution, they electrochemically

reduce and contaminate the aluminum metal. Metal oxide solubility can be reduced dramatically in cryolite by operating with a bath saturated in aluminum oxide, alumina. However, this presents significant bath feeding challenges. Cermets combine the advantages and disadvantages of ceramics and metals. In addition to overcoming technical hurdles, the likely higher-cost of manufacturing inert anodes of commercial size must be compensated with longer life, lower energy consumption, and higher productivity.

An inert anode would enable greater control of the critical anode-cathode distance (ACD), which represents the largest voltage drop in the cell (Figure 5.7 on page 32). When used in conjunction with a drained cathode, it is estimated that an inert anode may save up to 21st percent of the energy required for reducing aluminum. Inert anodes offer a major environmental advantage and the potential of producing a valuable coproduct. Replacing the carbon anode with an inert material results in oxygen being discharged rather than carbon dioxide. If a significant market for oxygen is near the reduction facility, the oxygen produced could be collected and sold as a coproduct. Carbon credits are an unknown but potentially large economic force that could hasten the development of inert anodes.

Inert anode technology could potentially be retrofit into the existing cells with limited changes and use the existing alumina and aluminum handling infrastructures. Some electrical infrastructure changes would be required since the inert anode will operate at a higher voltage than the carbon anodes. Since frequent access to the cells is not required for changing anodes, cells can be sealed more effectively to provide better gas collection and treatments.

Notable progress in the production and testing of potential inert anode materials has been made in recent years.⁴⁰ Some companies are now conducting trials with relatively stable materials that offer the promise of inert anode performance. Using an inert anode and wetted cathode could also lead to the design of multipolar, vertical electrode cells, which would increase productivity and further reduce energy usage.

6.2.1 Theoretical Energy for Hall-Héroult Inert Anode

The theoretical minimum energy requirement for an ideal Hall-Héroult cell using an inert anode can be calculated from the thermodynamics of the reaction, $2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al} + 3\text{O}_2$ (Appendix J, Table J.2). The production of aluminum shown in Figure 6.2 assumes that the reactant (alumina) enters the cell at 25°C, the oxygen byproduct leaves the cell at 25°C, and the aluminum product leaves the cell as molten metal at 960°C. The theoretical minimum energy requirement is calculated under perfect conditions, an environment with no reverse reactions, parasitic

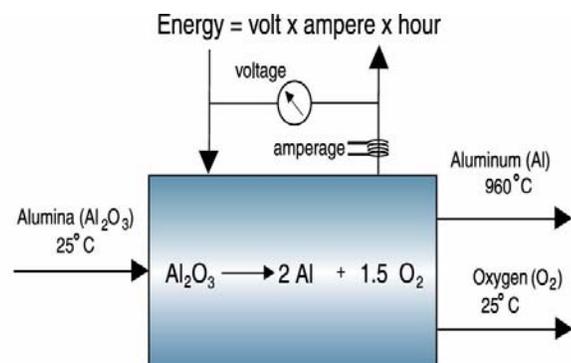


Figure 6.2: Theoretical Energy Schematic for Inert Anode

reactions, heat/energy losses external to the system, or limitations to the ionic species reacting at the electrodes. The results show that the energy required to drive the reaction forward (ΔG) is 8.16 kWh/kg, the thermal energy ($\Delta H - \Delta G$) required to maintain equilibrium is 0.48 kWh/kg and the thermal energy (C_p) associated with the molten aluminum is 0.39 kWh/kg of aluminum. The total theoretical minimum energy requirement for an inert anode adds up to 9.03 kWh/kg of aluminum. (Note: If the O_2 gas emission at 960°C is included, the total theoretical minimum energy requirement is 9.30 kWh/kg of aluminum).

In actual cell operations, current efficiencies of less than 100 percent can result from reverse oxidation reactions between part of the metallic aluminum and the oxygen gas produced by the reaction. Inert anode cell designs must ensure that oxygen bubbles are discharged from the system without contacting the molten aluminum being produced.

6.2.2 Comparative Energy Requirements for Carbon and Inert Anode Hall-Héroult Cells

The theoretical minimum energy requirement for an inert anode reaction is 51 percent higher than the carbon anode requirement. Both, the Hall-Héroult carbon and inert anode processes, use the same starting raw material, alumina, and require the same total theoretical energy, 9.03 kWh/kg of aluminum. The Hall-Héroult carbon anode is consumed as part of the reduction reaction and provides part of the energy to the system. The energy provided by oxidizing the carbon (3.04 kWh/kg of aluminum) lowers the carbon anode system's theoretical energy requirement to 5.99 kWh/kg of aluminum. The inert anode must supply the full minimum energy requirement for alumina reduction. The inert anode system requires 2.2 V(dc) compared to the Hall-Héroult reaction's 1.2 V(dc).⁴¹ This increase in reaction voltage supplies the additional 3.04 kWh/kg of aluminum minimum energy required by the inert anode system to reduce alumina.

Although the inert anode reaction voltage is 1 V(dc) higher than a carbon anode Hall-Héroult cell, three factors are expected to provide the inert anode with an overall improved operational energy performance than the carbon anodes:

- a. elimination of carbon anode manufacturing,
- b. reduction of anode polarization overvoltage, and
- c. reduction in ACD that results from a stable anode surface.

The impacts of these three factors are shown in Table 6.2 and calculations are presented in Appendix M, Table M.2.

Elimination of Carbon Anode

The energy inherent in the carbon and required for carbon anode manufacturing exceeds the additional theoretical energy need for the inert anode system. A complete account of the energy associated with the carbon-anode production shows that 6.02^{tf} kWh/kg of aluminum produced is

associated with the anode's manufacture and fuel value. This value is higher than the 3.04 kWh/kg of aluminum that the carbon anode supplies in the reaction for theoretical reduction. Since the actual values for manufacturing inert anodes are unknown at this time, a conservative estimate is made in Appendix M, Table M.3. This estimate, approximately 0.77 kWh/kg of aluminum, provides a basis for comparing the two processes. The total energy associated with an inert anode operating cell is 0.77^{tf} kWh/kg for anode manufacturing, 3.14 kWh/kg for the onsite additional voltage requirement, and 3.86^{tf} kWh/kg for the generation and transmission losses associated with the additional anode voltage. The inert anode requires 7.77^{tf} kWh/kg of aluminum produced, 29^{tf} percent more than the tacit energy associated with the Hall-Héroult carbon-anode requirement.

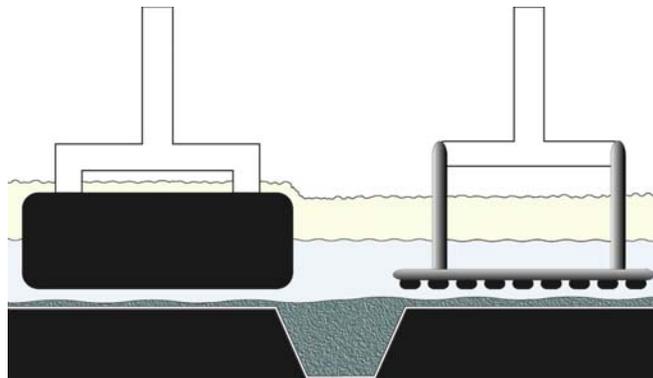
Table 6.2: Energy Impact of Inert Anode Technology

Energy Input kWh/kg Al		Modern Prebaked Hall- Héroult ACD = 4.5	Inert Anode a) Elimination of Carbon Anode ACD = 4.5	Inert Anode a) Elimination of Carbon Anode b) Low Polariza- tion ACD = 4.5	Inert Anode a) Elimination of Carbon Anode b) Low Polarization c) Wetted Cathode ACD = 2.0	
ONSITE ENERGY DEMANDS	Raw Materials	bauxite-alumina	7.59	7.59	7.59	7.59
		anode materials	0.61	0.77	0.77	0.77
		TOTAL	8.20	8.20	8.20	8.20
	Reaction Energy	Reaction Electrolysis	3.76	6.90	6.90	6.90
		Cell Ohmic	10.67	10.67	9.25	6.20
		TOTAL Reaction	14.43	17.57	16.15	13.11
	TOTAL Onsite Percent Energy Savings:		22.63 Reactions	25.76 -22%	24.35 -12%	21.30 9%
			Reactions & anode	-22%	-13%	8%
			Reactions, anodes & ore	-14%	-8%	6%
	TACIT ENERGY DEMANDS	Raw Materials	bauxite-alumina	8.24	8.24	8.24
anode materials			6.02	0.77	0.77	0.77
TOTAL			14.26	9.00	9.00	9.00
Reaction Energy		Reaction Electrolysis	8.41	15.41	15.41	15.41
		Cell Ohmic	23.82	23.82	20.67	13.86
		TOTAL Reaction	32.23	39.23	36.08	29.27
TOTAL Tacit Percent Energy Savings:		46.48 Reactions	48.23 -22%	45.08 -12%	38.27 9%	
		Reactions & anode	-5%	4%	21%	
		Reactions, anodes & ore	-4%	3%	18%	

As gas molecules evolve on the anode surface, they coalesce and form bubbles, which creates a layer of bubbles adjacent to the horizontal electrode. These bubbles jostle and move along as a result of their density difference with the bath and by the motion imparted from the aluminum pad.

Experimental evidence shows that the oxygen gas evolved in the bath has a different froth/foam dynamic than carbon dioxide. The molar volumes of gases that result from the reduction reaction are equal. However, because oxygen is 27 percent lighter than carbon dioxide, less mass moves through the electrode area. The physical properties, in practice, contribute to a lower anode overvoltage.⁴² The inert anode can also be shaped to allow for better release of the oxygen generated (Figure 6.3). The lower overvoltage of the inert anode, compared to a carbon anode, reduces the energy consumed. The overvoltage reduction combined with the elimination of carbon anode manufacturing, is estimated to provide a 5 percent energy improvement.

Figure 6.3: Inert Anode



Inert Anode-Wetted Cathode Combination

A more stable inert anode surface will allow the anode-cathode distance (ACD) to be reduced and will be simpler to control. Carbon anodes must be lowered as they are consumed to maintain an optimal ACD. Combined with a wetted cathode, the inert anode probably offers the greatest potential for bath voltage reduction. Inert anodes will also eliminate cell disruptions that occur with carbon anode changing.

Overall, inert anodes, when combined with a wetted cathode and compared to the traditional Hall-Héroult cells, are expected to provide

- a 10 percent reduction in operating costs (elimination of carbon anode plant and labor costs associated with replacing anodes),⁴³
- a 5 percent increase in cell productivity,⁴³ and
- a 41 percent reduction in greenhouse gas emissions (Appendix E, Table E.4)

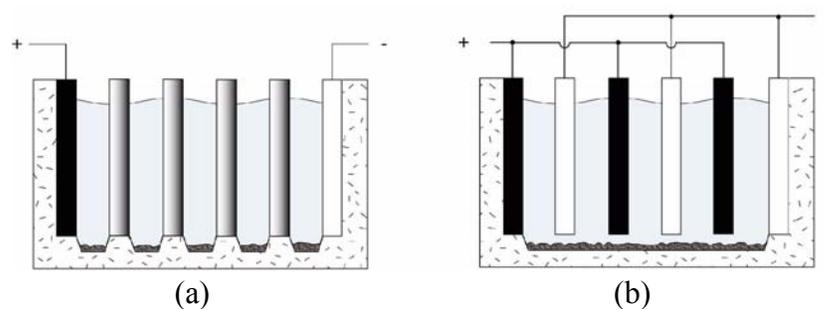
These practical scenarios provide the inert-anode cell with an overall lower-energy requirement than the state-of-the-art Hall-Héroult cell. However, the challenging engineering designs for the inert-anode cell systems must incorporate effective approaches for minimizing thermal losses from the reduction cells, the current-carrying bus systems, and the connectors external to the cell.

6.3 Multipolar Cells

Present Hall-Héroult industrial cells consist of a single cathode surface and essentially a single anode surface immersed horizontally one over the other in a bath. This single-pole arrangement makes aluminum reduction a capital-intensive process. Use of multipolar electrolytic cells would greatly increase productivity-per-unit-reactor volume by placing multiple electrodes in a single reactor. This arrangement would also provide better control of heat losses. For practical engineering reasons, a multipolar cell requires that the ACD be stable, which in turn requires an inert/stable anode. To date, the lack of suitable materials of construction have ruled out multipolar cells using molten fluoride electrolytes.

Two variations of electrochemical multipolar cells are possible, as shown conceptually in Figure 6.4. One system uses a cell with an anodic surface on one side, multiple bipolar electrodes in the center portion, and a cathodic surface on the opposite side, as in Figure 6.4 (a). One surface of a bipolar-electrode plate acts anodically, while the opposite surface acts cathodically. Bipolar electrodes must be electrically isolated and sealed to the cell walls to avoid bypass current efficiency losses. The second system uses independent pairs of electrodes immersed in the same cell, as shown in Figure 6.4 (b). Multipolar cell designs are complicated by the need to remove liquid metal and collect the gaseous reaction products.

Figure 6.4: Multipolar Cells



The bipolar-multipolar concept was successfully demonstrated for electrolytic aluminum chloride reduction.⁴⁴ In 1976, Alcoa Inc. began operating a multipolar, prototype plant with a capacity of over 18,000 kg of aluminum per day. Alcoa obtained 90 percent current efficiency at 9.26 kWh/kg of aluminum. The Alcoa multipolar cell was electrically 40 percent more efficient than a present day Hall-Héroult cell. However, the prototype plant was eventually shut down because of the combination

of the costs to produce anhydrous aluminum chloride feed, the failure to reach full design capacity, the need to remove and destroy trace amounts of chlorinated biphenal byproducts, the reactor capital costs, and general maintenance costs.⁴⁵

The Alcoa cell had distinct technical advantages over the classic Hall-Héroult cell: it worked at substantially lower temperatures, it had relatively high current densities, its carbon anodes were not consumed, it had no fluoride emissions, and the plant had a smaller footprint. The improvement in electrical energy efficiency was a result of the higher electrical conductivity of the electrolyte and the small interpolar distance. The cell feed consisted of 3 percent to 10 percent of purified aluminum chloride (AlCl_3), obtained by carbochlorination. The electrolyte consisted mainly of sodium chloride and potassium chloride, or lithium chloride. Electrolysis was performed in a sealed cell consisting of 12 to 30 bipolar carbon electrodes stacked vertically at an interpolar distance of 1 cm. The electrodes remained immersed in the electrolyte at an operating temperature of $700^\circ\text{C} \pm 30^\circ\text{C}$. A current density of 0.8 A/cm^2 to 2.3 A/cm^2 and a single-cell voltage of 2.7 V(dc) were typical operating conditions. An operating life of nearly three years was claimed for the electrodes.

A useful feature of the Alcoa cell was that the buoyant chlorine created a flow in the narrow gap between the bipolar electrodes. This aided in sweeping the aluminum from the cathodes and enhancing the formation of aluminum droplets. The gas also helped maintain a continuous flow of electrolyte across the cell. Chlorine was collected at the top of the cell and molten aluminum was collected in the bottom. The chlorine gas generated by the reduction reaction was completely recycled to produce new aluminum chloride feed for the cell.

A Hall-Héroult multipolar design, involving multiple inert anodes and wettable cathodes arrayed vertically in a fluoride electrolyte cell, has been explored by Northwest Aluminum.⁴⁶ In this concept, the operating temperature was 750°C , much lower than Hall-Héroult technology. Alumina saturation at the lower temperature of the electrolyte bath was maintained by controlling a suspension of fine alumina particles in the bath. This technology offered all the benefits of reduced energy consumption (low ACD), elimination of carbon anodes and associated emissions, as well as a significant increase in productivity per cell, as a result of the multipolar design. This work came to an unfortunate halt with the closure of Northwest Aluminum. However, recent multipolar cell work done at Argonne National Laboratory shows much promise, although it is still in the early stages.

7. Alternative Primary Aluminum Processes

Carbothermic reduction of alumina and chloride reduction of kaolinite clay have been under study for more than 40 years. These technologies have the potential to be alternative processes to the Hall-Héroult process. The non-electrolytic, carbothermic reduction of alumina is estimated to produce aluminum with significantly less energy consumption, reduced emissions, and lower investment costs. Multipolar-reduction technology to produce aluminum using aluminum chloride obtained from low-grade domestically available clays is also estimated to reduce energy consumption, capital costs, and emissions. The aluminum industry has yet to adopt these processes for producing aluminum, mainly because of the uncertain capital and operating economics associated with large-scale plants.

7.1 Carbothermic Technology

Carbothermic reduction of alumina is the only non-electrochemical process that has shown potential for aluminum production. This technology has been an industry objective and the subject of extensive research for more than forty years.⁴⁷ Carbothermic technology is projected to produce aluminum from ore at 38.2^{tf} kWh/kg or 18 percent below a modern Hall-Héroult carbon-anode technology (Table 7.1 on page 57).

Carbothermic reduction produces aluminum using a chemical reaction that takes place within the volume of a reactor. This volumetric reaction requires much less physical space than the area reaction of Hall-Héroult. These properties give carbothermic technology a smaller footprint and make it much less dependent on the economies of scale (large and long potlines) required for an economically efficient Hall-Héroult facility. If successful, this technology could significantly change the structure of the aluminum industry, allowing industry the freedom to relocate from regions of inexpensive power to centers of manufacturing. Aluminum production “mini-mills” could be placed adjacent to or within aluminum casting facilities. These “mini-mill” installations could provide molten aluminum and/or specifically alloyed metal directly to the casting operations. This would provide additional energy, economic, and environmental benefits to the industry.

Volumetric Vs. Area Processing

The Hall-Héroult reduction electrolytic reaction occurs on the surface of an electrode in a reactor (cell). Capacity is doubled simply by doubling the electrode surface area. Non-electrolytic reduction chemistry occurs within a volume of fluid. A spherical volumetric reactor can be doubled by increasing its radius 1.4 times. This difference between volume and surface area reactions provides significant savings in capital cost for a reactor.

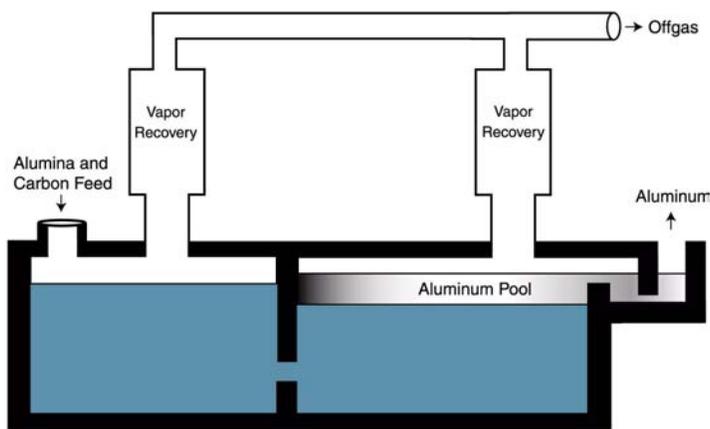


Figure 7.1: Carbothermic Reactor

Carbothermic reduction of alumina to aluminum is a multi-step chemical reaction process. The thermodynamic optimization for the reactions requires a multi-zone furnace operating at very high temperatures (Figure 7.1). In the first stage net reaction, alumina and carbon form an alumina-aluminum carbide slag at $\sim 1,900^{\circ}\text{C}$ ($2\text{Al}_2\text{O}_3 + 9\text{C} \rightarrow \text{Al}_4\text{C}_3 + 6\text{CO}$). In the next stage net reaction, aluminum carbide is reduced by alumina to form aluminum metal at $\sim 2,000^{\circ}\text{C}$, ($\text{Al}_4\text{C}_3 + \text{Al}_2\text{O}_3 \rightarrow 6\text{Al} + 3\text{CO}$). The

thermodynamics (temperatures and chemical equilibria) of these reactions are very complex. A significant portion of aluminum evolves as gas phase components (Al and Al_2O) at these operating temperatures. Careful process control is necessary to minimize the generation of volatiles. Recovery of these components in the form of Al_4C_3 in a vapor recovery system is required for the process to be economically viable. If the Al and Al_2O back react with CO to form Al_2O_3 , then the productivity of the process is decreased and the Al_4C_3 required to satisfy the process stoichiometry is deficient.

The complex thermodynamic controls, sophisticated equipment, and construction materials required to successfully develop an economical commercial system have eluded the industry so far. Current R&D efforts are reevaluating carbothermic technology in hopes of capitalizing on new, advanced, high-intensity, electric-arc furnace technology, advanced thermodynamic and system modeling techniques, and an improved understanding of the process dynamics.⁴⁸

7.1.1 Theoretical Energy for Carbothermic Reduction of Alumina

The theoretical minimum energy requirement for producing aluminum by the carbothermic reduction of alumina is 7.32 kWh/kg.

Carbon is a reactant in the carbothermic reduction reaction process and supplies part of the energy necessary to drive the reaction forward. This gives the carbothermic reduction process a lower theoretical energy requirement than the direct electrolytic reduction of alumina to aluminum.

The net reaction for the carbothermic reduction is $\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Al} + 3\text{CO}$. It is assumed that the reactants (alumina and carbon) enter the reactor system boundaries at 25°C, the carbon monoxide byproduct leaves at 25°C, and the aluminum product leaves the reactor system as molten metal at 960°C. The assumed molten metal temperature is lower than the actual reactor metal discharge temperature. Theoretically and practically, the energy in the higher temperature reactor discharge can be recovered efficiently (e.g., by mixing high temperature reactor aluminum with solid metal scrap to recover the heat energy and lower the temperature). To compare the theoretical limits of the various aluminum production processes, the same molten product temperature of 960°C is used throughout this report. The theoretical reaction occurs under perfect conditions when there are no reverse reactions, parasitic reactions, or heat/energy losses external to the system.

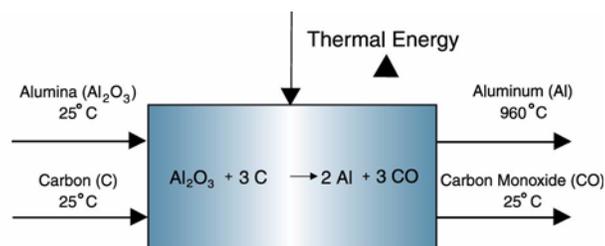


Figure 7.2: Carbothermic Theoretical Minimum Energy

The calculation of theoretical minimum energy requirement for the carbothermic reaction is detailed in Table J.3, Appendix J. The results show that the energy required to drive the reaction forward (ΔG) is 6.03 kWh/kg and this energy is supplied as thermal energy vs. the electrical energy used in a Hall-Héroult cell. The thermal energy ($\Delta H - \Delta G$) required to maintain equilibrium is 0.90 kWh/kg and the thermal energy (C_p) associated with the molten aluminum is 0.39 kWh/kg of aluminum. The theoretical minimum energy requirement under these conditions adds up to 7.32 kWh/kg of aluminum. (Note: If the CO gas emission at 960°C is included, the total theoretical minimum energy requirement is 7.51 kWh/kg of aluminum).

The carbon monoxide byproduct has a fuel value and would likely be captured and used to supply thermal energy to the carbothermic facility.

7.1.2 Comparative Benefits for Carbothermic Reactors and Hall-Héroult Cells

Electric furnace technology provides 90 percent thermal efficiency in many applications. Heat losses are limited to conduction and radiation losses from the furnace shell. Flue gas heat losses are eliminated, as are any undesired reactions between flue gases and molten aluminum metal. It is reasonable to assume that the carbothermic furnace/reactor can be designed with more than 85 percent thermal efficiency. If the thermodynamics of the reaction and offgas recovery can be controlled within 95 percent of the theoretical requirements, the electrical energy required for an operating carbothermic reactor would be $(7.32 \text{ kWh/kg} \div (0.85 \times 0.95))$ or 9.07 kWh/kg of aluminum produced. This represents a 37 percent reduction in energy use when compared to the 14.4 kWh/kg of aluminum from a modern Hall-Héroult Cell. Table 7.1 (page 57) shows the onsite and tacit energy savings potential of carbothermic technology.

In addition to electrical energy savings, carbothermic technology is expected to provide other benefits, like

- a reduction in capital costs by 50 percent or more as a result of volumetric processing through high-intensity smelting;
- a reduction in production costs by 25 percent through lower electrical demand and elimination of carbon anode manufacturing and handling,
- the production of a high purity CO/CO₂ stream for coproduct sale or energy integration,
- the potential to use small blocks of electrical power due to high turn-down ratio, and
- the potential of widely locating “mini-mills” with integral, captive smelters delivering molten metal.

Table 7.1: Comparison of Hall-Héroult and Carbothermic Reduction

Energy Input kWh/kg Al			Modern Prebaked Hall-Héroult	Carbothermic Reduction	
ONSITE ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	7.59	7.59	
		Kaolinite			
		Anode Materials	0.61		
		Reaction Carbon		0	
		Total	8.20	7.59	
	Reaction Energy	Reaction Thermal			7.71
		Furnace Losses			1.93
		Reaction	3.76		
		Cell Ohmic	10.67		
	Total Reaction		14.43		9.63
TOTAL Onsite		22.63		17.22	
Percent Energy Savings:					
		Reactions		33%	
		Reactions & anode		36%	
		Reactions, anodes & ore		24%	
TACIT ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	8.24	8.24	
		Kaolinite			
		Anode Materials	6.02		
		Reaction Carbon		8.43	
		Total	14.26	16.67	
	Reaction Energy	Reaction Thermal			17.21
		Furnace Losses			4.30
		Reaction	8.41		
		Cell Ohmic	23.82		
	Total		32.23		21.52
TOTAL Tacit		46.48		38.19	
Percent Energy Savings:					
		Reactions		33%	
		Reactions & anode		44%	
		Reactions, anodes & ore		18%	

7.1.3 Environmental Impacts of Carbothermic Technology

The carbothermic process, when compared to Hall-Héroult technology, results in significantly reduced electrical consumption, and the elimination of perfluorocarbon emissions that result from carbon anode effects, hazardous spent pot liners, and hydrocarbon emissions associated with the baking of consumable carbon anodes.

The total carbon dioxide emissions from carbothermic reduction, as with Hall-Héroult, depend on the source of electricity. Hydroelectric power generation emits almost no carbon dioxide, whereas the carbon dioxide emissions associated with the average U.S. grid electricity are 0.51 kg CDE/kWh (Appendix E, Table E.1). Since 40 percent of the U.S. primary industry operates on hydroelectric power, the aluminum industry's average electrical generation emission rate is 0.35 kg CDE/kWh. The carbothermic reaction results in the generation of carbon-based greenhouse gases (GHG), mainly carbon monoxide (CO), at twice the rate of the Hall-Héroult reaction. However, the carbothermic process only requires electricity for heating and not for the reduction reaction. Assuming carbothermic technology is used in "mini-mills" operating off the average U.S. electric grid, the total GHG emissions from "utility-to-metal" for the carbothermic process are reduced relative to the average U.S. Hall-Héroult system, because of carbothermic's lower electrical intensity. Table 7.2 (Appendix E, Table E.4) shows the lower electrical demand of carbothermic technology resulting in lower total carbon dioxide equivalent (CDE) emissions than for a Hall-Héroult system.

Table 7.2: Carbon Dioxide Equivalent Comparison of Hall-Héroult and Carbothermic Reduction

Emission Sources	Modern Hall-Héroult	Carbothermic	
	kg CDE/kg Al		kg CDE/kg Al
Carbon Anode	1.66		2.45
Reaction Energy Requirements:			
kWh/kg Al	14.43		9.63
kg CDE/kWh	0.349		.511
	5.04		4.92
Process	2.20		0.0
Total	8.91		7.37

7.2 Kaolinite Reduction Technology

Production of pure aluminum by reduction of aluminum chloride was discovered before the Hall-Héroult process, in 1825. Alumina conversion to aluminum chloride and reduction to aluminum using bipolar technology was demonstrated in the late 1970s, but it was not commercialized because of problems with the product purity and projected high capital and operating costs (Section 6.3 on

page 52). New construction materials, improved thermodynamic understanding, and the potential to use low-cost alumina containing clays have maintained the interest in chloride reduction technology for producing aluminum.

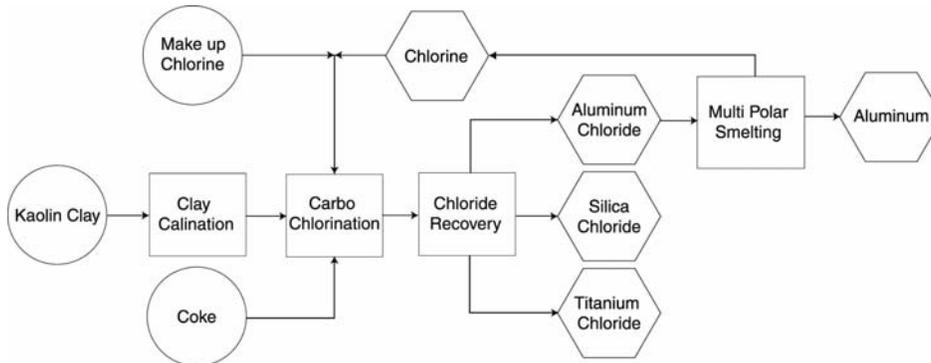
Compared to the current Bayer refining and Hall-Héroult fluoride-based smelting of alumina, the chlorination of alumina-containing clays promises many potential advantages:

- Raw materials are widely available, inexpensive, and indigenous to the United States.
- Thermodynamics provide high-speed, high-conversion reactions with lower electrical demand.
- No “bauxite residue” is produced, though there is waste from the clay chlorination.
- Conventional materials-of-construction (i.e., mild steel) can be used.

Industry has spent more than 30 years developing process technologies for the chlorination of widely available, low-grade kaolin clays. These clays contain kaolinite (hydrated alumina silicate, i.e., $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$), significant amounts of titanium dioxide (1 percent to 5 percent), and other materials. Titanium tetrachloride and other metal chloride byproducts are also produced when processing kaolin clays.

The basic steps of the clay to aluminum process are shown in Figure 7.3.⁴⁹

Figure 7.3: Clay to Aluminum Process Schematic



First, the kaolin clay and process coke are dried. All feed materials to the clay chlorination units must be dried to minimize chlorine absorption in any water and to reduce the corrosive effects of moisture in the chlorination offgas stream. The drying process involves controlled, catalyzed heating of the finely ground clay at $\sim 800^\circ\text{C}$ in a fluidized reactor, using coke and air to provide the heating energy. The hot reactor produces a dehydrated calcined clay, which is sent to carbo-chlorination.

The carbo-chlorination step is a high-speed, catalyzed exothermic reaction of calcined clay with chlorine and coke:



Chlorine is injected into the bottom of the fluidized reactor with the clay oxides and coke. The metallic oxides, principally those of aluminum and silicon, are converted to their chlorides. The chlorides exist as vapors at the reaction temperatures. The next process step is designed to suppress the formation of silicon tetrachloride. The offgases of the chlorination reactor are treated with a small amount of catalyst vapor and reacted in a second fluid bed reactor with additional calcined clay. The alumina portion of the clay is converted to aluminum chloride, and silicon tetrachloride is converted to solid silica and discharged ($3\text{SiCl}_4 + 2\text{Al}_2\text{O}_3 \longrightarrow 4\text{AlCl}_3 + 3\text{SiO}_2$). The net effect of this step is the preferential chlorination of alumina relative to silica. The hot vapors from the second reactor are cooled and crude aluminum chloride is recovered. Several byproducts are produced as an extension of the chlorination step. Titanium tetrachloride, silicon tetrachloride, and boron trichloride are not condensed in the cooler and can be recovered in subsequent processing. Silicon tetrachloride can be reacted with oxygen to recover chlorine, which is recycled back to the chlorination step as below:



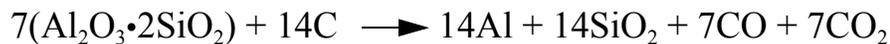
The crude aluminum chloride must be purified for ease of operation of the electrolytic reduction cells and for the final aluminum quality. The main impurity is iron, which is present as ferric chloride at levels as high as ~50,000 ppm. Impurities are removed by chemical treatment.

The electrolysis of aluminum chloride to aluminum takes place in an aluminum chloride smelting cell, which comprises a stack of horizontal bipolar graphite electrodes, between which the aluminum chloride is converted into high-grade aluminum and chlorine gas ($2\text{AlCl}_3 \longrightarrow 2\text{Al} + 3\text{Cl}_2$). The electrodes are immersed in a chloride bath, which is contained in fully enclosed, thermally lined vessels. The bipolar electrodes are supported and separated by inert spacers resting on the electrode below it, and the entire stack, consisting of bottom cathode, bipolar electrodes, and top anode, is supported by the walls of the cell.

7.2.1 Theoretical Energy for Kaolinite Reduction of Alumina

The theoretical minimum energy requirement for producing aluminum from kaolinite is 5.76 kWh/kg of aluminum produced. The theoretical minimum for the chloride reduction step of aluminum chloride is 7.66 kWh/kg of aluminum.

The theoretical minimum energy requirement can be calculated from the net chemical reaction in the kaolinite to aluminum process:



It is assumed that the reactants (kaolinite and carbon) enter the system boundaries at 25°C, the carbon monoxide and carbon dioxide byproducts leave at 25°C, and the aluminum product leaves the system as molten metal at 960°C. The theoretical net reaction occurs under perfect conditions when there are no reverse reactions, parasitic reactions, or heat/energy losses external to the system. These assumptions yield a theoretical minimum energy requirement of aluminum production from kaolinite as 5.76 kWh/kg of aluminum (Appendix J, Table J.5). This assumes a pure kaolinite feedstock.

The kaolinite process is accomplished in two steps, carbo-chlorination and aluminum chloride reduction. The electrolytic aluminum chloride reduction process used in the kaolinite process requires the exact same minimum amperage (2,980 Ah/kg of aluminum) as any electrolytic process for reducing aluminum. The theoretical chloride reduction reaction occurs under perfect conditions (where there are no reverse reactions, parasitic reactions, or heat/energy losses external to the system) and requires 7.66 kWh/kg of aluminum produced. The theoretical minimum energy requirement used in this report is calculated at 960°C to provide comparison with the other processes. The proposed multipolar system operates at about 700°C, which would lower the theoretical energy demand by about 0.09 kWh/kg of aluminum. The exothermic nature of the carbo-chlorination reaction (–1.90 kWh/kg of aluminum) results in the overall kaolinite to aluminum theoretical energy requirement to be lesser than the minimum energy requirement for the aluminum chloride reduction.

7.2.2 Comparative Benefits for Kaolinite Reduction and Hall-Hérout Cells

The kaolinite reduction process offers potential advantages when compared to the Hall-Hérout process. Table 7.3 shows the onsite and tacit energy comparison for Hall-Hérout and Kaolinite processes.

Table 7.3: Comparison of Hall-Hérout and Kaolinite Reduction

Energy Input kWh/kg Al		Modern Prebaked Hall-Hérout	Kaolinite (AlCl ₃) Reduction	
ONSITE ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	7.59	8.14
		Kaolinite		8.14
		Anode Materials	0.61	0.77
		Reaction Carbon		0
		Total	8.20	8.91
	Reaction Energy	Reaction Thermal		-1.90
		Furnace Losses		0.40
		Reaction	3.76	6.48
		Cell Ohmic	10.67	2.93
		Total Reaction	14.43	7.91
TOTAL Onsite		22.63	16.82	
Percent Energy Savings:		Reactions	45%	
		Reactions & anode	42%	
		Reactions, anodes & ore	26%	
TACIT ENERGY DEMANDS	Raw Materials	Bauxite-Alumina	8.24	8.84
		Kaolinite		8.84
		Anode Materials	6.02	0.77
		Reaction Carbon		11.37
		Total	14.26	20.97
	Reaction Energy	Reaction Thermal		-1.90
		Furnace Losses		0.60
		Reaction	8.41	14.48
		Cell Ohmic	23.82	6.54
		Total	32.23	19.72
TOTAL Tacit		46.48	40.69	
Percent Energy Savings:		Reactions	39%	
		Reactions & anode	46%	
		Reactions, anodes & ore	12%	

The combined clay carbo-chlorination and bipolar aluminum chloride smelting process is estimated to be 35th percent more tacit energy efficient than the Hall-Hérout, has a smaller plant footprint, can be more flexible in regard to use of off-peak power and power fluctuations, and produces fewer emissions and process wastes. Onsite energy use is about 19 percent lower than a modern Hall-

Héroult cell. The large tacit energy improvement results from a decrease in electrical use. Compared to the current Hall-Héroult smelting technology, the bipolar aluminum chloride smelting process consumes less electricity, yielding 60 percent more metal for the same electrical input. Bipolar cell designs provide significantly lower reactor volume per unit of product output. This lower volume allows the cell to idle and hold temperature much more efficiently than a single electrode cell. These properties allow multipolar cells to take better advantage of off-peak electrical costs. Chloride cells also operate at lower temperatures, providing additional savings.

Raw materials used in the kaolinite process require approximately 47 percent more energy compared to those in a modern Hall-Héroult process (Table 7.3). Kaolinite requires more energy for extraction on an aluminum basis and the carbo-chlorination step requires 2.5 times the carbon of a Hall-Héroult carbon anode system. The raw material energy expenses may be compensated for by the lower-cost domestic supply of kaolinite and the ability to use lower-cost carbon than Hall-Héroult systems.

It is important to emphasize that while significant elements of the kaolinite process have been studied and developed, no integrated production of aluminum from kaolinite clays has yet been attempted. Significant work in developing an integrated production process has been reported.

7.2.3 Environmental Impacts of Kaolinite Technology

Table E.4 in Appendix E tabulates the CDE emissions for the kaolinite to aluminum process. Operating off the average U.S. electrical grid, this process would produce 14 percent fewer CDE emissions than a typical Hall-Héroult facility. However, the same plant operating on the average U.S. smelter grid (50.2 percent hydroelectric) would actually result in 8 percent lower CDE emissions than Hall-Héroult facilities.

8. Secondary Aluminum (Recycling)

The production of primary aluminum ingots from bauxite ore requires approximately 23.8(62.2^{tf}) kWh/kg of aluminum. Recovering aluminum from scrap to produce secondary aluminum ingot consumes about 6 percent of the energy required to produce primary aluminum.⁵⁰ This significant energy difference drives the emphasis placed on aluminum recycling in today's society and in the aluminum industry.

Recycling in the United States saved more than 167×10^9 kilowatt hours (0.57 quad) of energy in 2003, the equivalent of 19,100 Megawatts. Each kilogram of aluminum that is recovered by recycling saves 59.4^{tf} kWh of the 62.2^{tf} kWh of energy consumed in producing a primary aluminum ingot from bauxite ore (Appendix F, Table F.6). Any process that improves the recovery of scrap aluminum is effectively making an order of magnitude change in the energy associated with aluminum production.

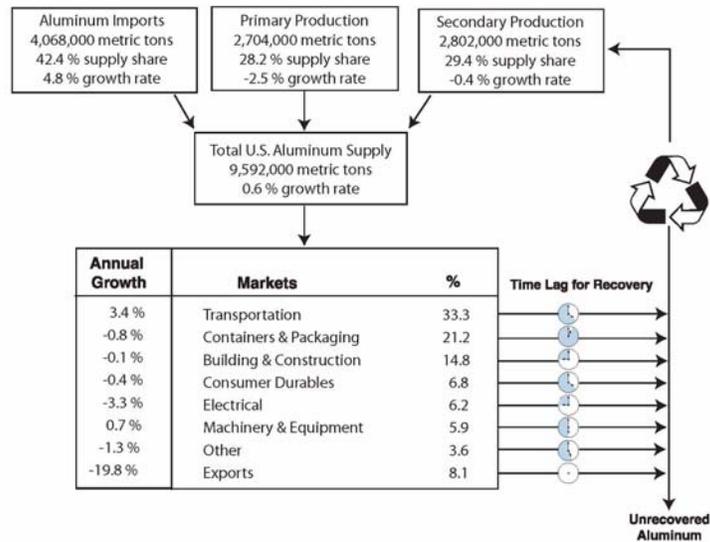
The growth of aluminum recycling represents the greatest change in the structure of the industry and in the energy associated with aluminum manufacturing. A common practice since the early 1900s, recycling was a low-profile activity until 1968 when aluminum beverage can recycling vaulted the industry into public consciousness. In 1960, recycled aluminum accounted for 18 percent of the nation's total aluminum supply (401,000 metric tons). Over the next 43 years, production of recycled aluminum rose by 703 percent to 2,820,000 metric tons. During those same 43 years, the total U.S. aluminum metal supply increased 300 percent (Appendix G). In 2003, 75 plants in the United States produced secondary ingots. Over half – 51 percent – of the aluminum metal produced in the United States in 2003 was from recycled material.⁵¹

The growth of the market for recycled aluminum is due in large measure to economics. It is cheaper, faster, and more energy-efficient to recycle aluminum than to manufacture it from ore. Recovered aluminum is easily melted at relatively low temperatures (aluminum alloys typically melt at temperatures below 660 °C). Producing a recycled aluminum ingot consumes only about 6 percent of the energy required to produce a primary aluminum ingot from bauxite ore. In addition, to achieve a given output of ingot, recycled aluminum requires only about 10 percent of the capital equipment costs compared with those required for the production of primary aluminum.

Aluminum products are corrosion resistant which allows them to be easily and repeatedly recycled into new products. The corrosion resistance is due to the metal's properties. When the surface of aluminum is exposed to air, it rapidly forms a tenacious, self-limiting, protective oxide layer. Other surface treatments can be applied to further enhance aluminum's corrosion resistance.

Figure 8.1 shows the annual growth rates of the three sources of metal supply between 1993 and 2003 period, together with the growth in the major aluminum product markets. Aluminum imports are growing at a rate of 5.1 percent per year while both U.S. primary and secondary productions are in decline (Appendix G).

Figure 8.1:U.S. Aluminum Market and Growth



Aluminum scrap is categorized as “new” or “old.” “New” scrap is generated when aluminum products are manufactured. It includes defective products; scalping chips; edge and end trim from rolling processes; skeleton scrap from stamping and blanking operations; flash, gates, and risers; extrusion butts and ends; and turnings and borings. “Old” scrap (post consumer or obsolete products) comes from discarded, used, worn-out, or out-of-date products that include automotive parts, white good parts, containers such as used beverage cans and closures, wires, cables, and building materials. “Runaround scrap” is “new” scrap that is recycled by the same company that generated it. Since runaround is usually not sold or marketed, it is not reported in the U.S. recycling statistics.

8.1 Secondary Aluminum Production

Secondary aluminum producers represent a separate and vital segment of the aluminum industry whose principal activities are converting purchased scrap, and metal recovered from skim and dross generated in molten metal operations into usable aluminum alloy products. Recycling in primary aluminum operations is typically confined to in-house or runaround scrap and manufacturing scrap returned directly from their customers. Secondary aluminum producers specialize in melting and processing a wide range of new and old, segregated and mixed, high and low-quality scrap.

The most desirable form of recycling is closed-loop in which scrap from specific product applications are returned for remanufacturing of the same products. Rigid container stock used in beverage cans is an example of closed-loop recycling since used beverage cans are processed exclusively to remanufacture can sheet. Secondary aluminum producers are involved in closed-loop recycling as contractors to primary producers for this and other products.

Scrap segregated by alloy has greater value than mixed scrap because it can be used predictably and most efficiently in the production of the highest value-added compatible compositions. Mixed scrap presents the greatest challenge, generally requiring added steps in melting, composition identification, and often casting into ingot form before consumption.

Casting alloys are the largest and the most important, but not the only market for secondary aluminum. Scrap is used, with primary metal, in the production of extrusion billet and fabricating ingot. Reclaimed smelter ingot (RSI) is produced from scrap and dross, often on a toll conversion basis.

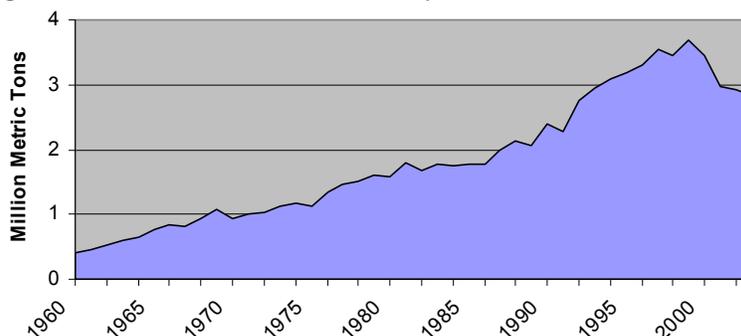
Alloys used by aluminum foundries in the production of shape or engineered castings include compositions designed to facilitate production from scrap. These alloys, which have been historically prominent, typically specify broader element ranges and higher impurity limits than the alloys developed for more specialized purposes and whose compositions require production from primary metal sources. The increased use of aluminum in structural applications in the ground transportation sector typically requires primary compositions, but the expanded use of aluminum in engine blocks, cylinder heads, and other power train parts relies on castings in secondary alloys. The emphasis on light weighting for improved fuel efficiency and reduced environmental degradation is encouraging the adoption of various wrought aluminum products such as auto body sheet, fuel tanks, seat backs, extruded drive shafts and stringers, and forged connecting rods. As the proportion of aluminum increases in ground transportation designs, segregating and blending scrap into saleable alloy compositions will become common practice.

New scrap sorting technology is developing, including those related to the recovery of aluminum from the large transportation and white goods markets.⁵² New technologies with computer screening are using color segregation and laser-induced-breakdown spectroscopy (LIBS) to sort wrought from cast and, in some instances, one alloy from another. Aluminum alloy separations will allow scrap to be segregated into more specific alloy groupings with higher economic value.

8.2 Production, Capacity and Growth

Aluminum scrap is widely recycled and supports a large secondary aluminum industry. In 2003, the United States produced 2,820,000 metric tons of secondary aluminum, amounting to nearly one-third of its total supply of aluminum. This market had an annual growth rate of -0.4 percent over the last ten years (Figure 8.2).

Figure 8.2: U.S. Production of Secondary Aluminum 1960 to 2003



Source: Appendix G

Market demand for recycled aluminum will remain strong due to its inherent low-energy cost relative to primary metal. Aluminum use in consumer products has become widespread in a trend described as the “urban mine.” Challenges in scrap recovery, alloy sorting and impurity removal can be addressed with the current technologies. The limitation to secondary metal market growth is the economic supply of scrap.

The urban mine has been accumulating scrap products for the past hundred years. There is a lag time from when aluminum leaves the shipping dock to when it becomes available for recycling. This lag time, or “use” phase life, varies significantly among aluminum products. For packaging products such as beverage cans, this lag is only about 65 days. Long-life products, such as building frames, can have a lag time of 40 to 50 years. Automobile lag time is 12 to 15 years. Aluminum in automobiles accounted for 5 to 10 percent of scrapped automobiles’ weight in 2000, but represents 35 to 50 percent of its scrap value. This source will grow rapidly as new automobile designs continue to utilize a greater proportion of aluminum.

Considering the large amounts of aluminum that are stored in long-life products (accumulated within the “urban mine”) and the continued growth in aluminum demand, recycling will continue to increase and be a significant contributor to the U.S. metal supply. In fact, recycling has overtaken primary production as the main source of domestically produced aluminum in the United States.

8.3 Recycling Processes

The objectives of the recycling process are maximum metal recovery, minimum contamination, and lowest conversion cost. Safety is of prime importance since components mixed with scrap can present the risk of explosive reactions and other concerns. Since moisture is a safety concern, remelt ingot and reclaimed smelter ingot (RSI) are routinely preheated before charging to the furnace hearth. Preheating methods vary from heating on the charging doorsill to using dedicated preheating ovens. Preheating standards from times of exposure and temperature also vary. In either case, energy is consumed for the promotion of operational safety.

Scrap for recycling is available in many forms. Light scrap is typically baled or briquetted to reduce transportation costs. Bales and briquettes are typically split for inspection of integrity and contamination and/or are crushed, shredded, or shrippped (sheared and ripped) to controlled flowable particle sizes. Conveyor systems segregate particle fines for separate processing, provide magnetic separation, and allow for visual or automated inspection.

Large volumes of aluminum scrap contain paint, enamel, lacquer, or porcelain coatings. These coatings, which contain oxidizing compounds, would significantly reduce metal recovery if not removed before melting. Conveyor furnaces or rotary kilns operating at temperatures near the melting point are required for their removal. Turnings, borings, and other fine scrap may contain oil from cutting fluids which must be removed for satisfactory metal recovery by swarf (metal fines and chips) drying in which the oil contributes to the energy required, or by elevated temperature treatment in rotating kilns. Fine scrap is conveyed to external charging wells for submergence by mechanical methods including the use of recirculating molten metal pumps. Light scrap is charged directly to the furnace hearth and is covered by additional heavier charge components.

Melting is typically accomplished in gas-fired furnaces ranging in size from 75,000 to more than 250,000 pounds. Coreless induction furnaces are in common use for rapidly melting fine scrap. Molten metal from these furnaces is transported to the main furnaces for further processing. After iterative alloying steps, molten metal is held and processed before casting. Furnaces have thermal efficiencies ranging from approximately 20 to 45 percent. Rotary kilns and conveyor furnaces operate in essentially the same efficiency range. Induction melting is more efficient at approximately 90 percent but furnace capacities are limited and additional steps are required to address oxide concentrations created by electromagnetic stirring. In-furnace and in-line molten metal treatments are employed to remove dissolved hydrogen and entrained oxides and other nonmetallics before casting. In-line systems are usually internally heated using gas-air or electric resistance immersion elements. Troughing and filter basins are preheated using air-gas torches or resistance elements. Open molds for casting remelt ingot and sow are routinely preheated before use.

The aluminum, recoverable from skim and dross obtained from foundries, and primary and secondary molten metal processing units, is typically extracted in secondary producers. While other dross treatment processes have been developed, rotary furnaces in which dross and salts are mixed and heated remain the most commonly used. The products of dross recovery treatment by this process are aluminum and black dross, a mixture of unrecovered aluminum, metallic oxides, and salt. Tertiary processes have been developed for separating the components of black dross into saleable salt fluxes, metal, and value-added nonmetallic derivatives such as calcium aluminate and additives for low-density cement. The economics of tertiary processing are strongly and adversely influenced by the current low-cost alternative of landfill disposal.

In summary, the energy intense operations common in recycling are:

- swarf drying for removal of combustible contaminants,

- kiln or conveyor delacquering of coatings,
- preheating charge components,
- melting,
- holding and melt processing, and
- rotary furnace operation

8.3.1 Theoretical Energy for Secondary Aluminum

The theoretical minimum energy required to produce secondary aluminum at 960°C is 0.39 kWh/kg of aluminum. On a theoretical and a practical basis, the energy required to produce secondary aluminum is less than 6.5 percent of the energy required to produce primary metal.

If the system boundaries are drawn around a secondary aluminum facility, the material entering and leaving is aluminum metal. Since no chemical change has occurred, the theoretical minimum energy requirement for scrap conversion is only the energy required to melt and raise the metal temperature to that required for casting. Molten metal furnace temperatures vary depending on the furnace, alloys, and other proprietary factors. A molten metal temperature of 960°C, the same production temperature as for primary aluminum, is used in this report for secondary aluminum to compare aluminum process technologies easily. In reality, normal pouring temperatures are much lower, in the range of 650°C to 750°C.

The theoretical minimum energy requirement to bring room-temperature (25°C) aluminum to its molten form at 960°C is 0.39 kWh/kg, which is less than 6.5 percent of the theoretical energy requirement for the primary production of aluminum. The theoretical energy required to heat aluminum from room temperature to its melting point, melt it, and raise the molten aluminum to a higher temperature is calculated and explained in Appendix K. Pure aluminum melts at 660°C and requires 0.30 kWh/kg to melt, 23 percent lower than the value used in this report.

8.3.2 Technological Change in the Next Decade

The energy efficiency of the entire aluminum industry can be further increased by capturing a greater percentage of material for recycling and by improving technology for scrap handling and melting. Non-technological and nonmarket factors are also important for the continued growth of recycling. Two of these factors, consumer awareness and incentives, can contribute significantly to the recycling volume. Consumer awareness requires continuing educating the public about the energy and environmental benefits of recycling. Offering incentives will aid in the return of aluminum scrap to the manufacturing base.

Recycling energy efficiency will be enhanced by developing technologies that minimize oxidation and improve thermal inefficiencies in scrap processing and melting. Improved collection systems and separation devices (e.g., eddy current, color sorting, laser sorting) can increase aluminum scrap

recovery by 20 to 30 percent. Improved technology can be applied to increase scrap recovery rates, especially with regard to aluminum in municipal solid waste. Incremental improvements in existing furnaces can further reduce the recycling energy requirements. They can be achieved by recuperating stock gas energy for preheating combustion air and metal feedstock, by modifying burner and furnace designs, and controlling furnace practice and operating conditions.^{53, 54} New technologies must also be developed to ensure more significant progress.

9. Aluminum Processing

The aluminum industry can be divided into metal- and product-producing sectors. In 2003, the metal-producing sector manufactured approximately 2,704,000 metric tons of primary metal and 2,820,000 metric tons of secondary metal. The product-producing sector processes these domestically produced and imported metals into approximately 5,497,000 metric tons of rolled products, 1,719,000 metric tons of extrusions, and 2,513,000 metric tons of shape castings.⁵³ Wire rod and bar, forgings, impacts, and powder products total more than 700,000 metric tons, comprising about 7 percent of the aluminum product market; these have not been studied as a part of this report.

Recoveries (yields) in each product processing sector are less than 100 percent. Handled, melted, and worked tonnage exceeds that implied by the product statistics. The manufacturing of circles and blanks from aluminum sheet, for example, may recover as little as 35 percent of the original ingot weight as shipped product. The gross to net weight ratio in gravity castings is often 2:1, in other words, fifty percent of the original cast weight is automatically designated for remelting.

Furthermore, many products have a genealogy of repeated melting and casting steps. Ingot cast at a primary smelter is remelted at a secondary producer for casting remelt ingot, which is again remelted at an aluminum foundry for casting production. On a yield basis, it may be conservatively estimated that more than 18,000,000 metric tons of aluminum alloys are melted each year to support aluminum industry shipments. Some casting operations are located sufficiently close to primary smelters and secondary aluminum producers to allow the molten metal to be shipped in insulated and protected crucibles, saving the energy of remelting.

Minimizing planned and unplanned scrap represents a large opportunity for energy and cost savings. Each kilogram of metal that does not go into a final product must be remelted, recast, and reworked. Remelting also leads to the loss of a percentage of metal to oxidation, which must be replaced with energy-intensive primary metal. Melting and melt processing operations are the most energy intense of all post-smelting processes.

9.1 Melting, Alloying, and Melt Treatment

In an aluminum primary smelting facility, molten metal is transferred from the smelting cells to furnaces for alloying and melt treatment prior to casting. In secondary and other casting plants, ingot, metallurgical metals, and master alloys must be melted and alloyed. The melting arrangement in most larger plants provides high heat-input, high melt-rate furnaces for melting, and separate holding furnaces to which molten metal is transferred for final alloying and preparation for casting. Some operations have combination melting/holding furnaces.

There are a wide variety of furnace types and designs for melting aluminum. Furnace choice depends on the required melt volume, melt rate, availability, cost of fuel and electrical energy, and emission standards. The most common in primary and secondary operations are natural gas-fired reverberatory furnaces reaching capacities of more than 120,000 kg. Crucible furnaces with capacities ranging from 160 to 4,500 kg are more common in small- and medium-sized foundries. Other furnace types include coreless and channel induction, electrical resistance and radiant tube furnaces.

Reverberatory furnaces are box-shaped and consist of an insulated steel shell with a refractory lining. Fuel-fired reverberatory furnaces are used when the melt rate and/or capacity are large. The fuel-fired reverberatory furnace fires natural gas, propane, or oil directly into the furnace from either the roof or more typically, the sidewall. The heat is transferred to the surface of the molten aluminum predominantly by refractory radiation and some convection. There are a large number of reverberatory furnace design variations: charging and access doors, refractory specifications, side-wells for charging and/or recirculation, hearth or sidewall induction stirring, split hearths, dry hearths, divided zones for melting and holding, and various burner capacities and types. Recuperation concepts include charge preheating, preheating combustion air, and cogeneration.

The growth in recycling has resulted in a number of specialized processes, furnaces, and systems to improve metal recovery from scrap. Molten metal pumps have been incorporated into these designs to provide rapid ingestion of fine scrap and more rapid melting of larger scrap forms. Salt flux additions maintain system cleanliness and aid in the separation of oxides. Pump-induced flow external to the furnace may include provisions for melt treatment and the separation of oxides as well as for melting.

Natural gas or oil-fired reverberatory furnaces use about 0.87 to 1.96 kWh/kg of aluminum.⁵⁴ In addition, a gas furnace increases metal losses due to oxidation. Gas furnaces have 5 to 8 percent metal loss compared to 0.5 to 3 percent loss in electric furnaces. Recent design innovations in fossil-fuel reverberatory furnaces help capture the waste heat in the stack gas to preheat incoming materials. This increases energy efficiency and reduces the time required to melt the metal. Recuperated waste heat can also be used to preheat combustion air. These technologies can reduce fuel usage to less than 0.57 kWh/kg of aluminum.

Crucible furnaces are more versatile with regard to alloy changes and melt quantities. Combustion occurs between an insulated steel shell and a crucible of silicon carbide, graphite, clay graphite or other refractory material resistant to molten aluminum attack. Electrical resistance elements can be substituted for gas burners in crucible furnace designs.

In recent years, much research has been done on using immersion heaters as a way to remelt aluminum. Immersion heaters have very low rates of heat loss (~97 percent thermal efficiency), and have energy usage levels of less than 0.50 kWh/kg of aluminum.

Skimming

Oxide naturally forms on the surface of molten aluminum, resulting initially in a thin protective film. With increase in time and temperature, the thickness of the oxide layer increases. Turbulence and agitation accelerate oxide formation and result in the intermixing of metal and oxides. Oxidation rates are influenced by alloy content and increase with temperature, especially when magnesium is present in the alloy. The oxide layer also effectively insulates the bath from radiation heat transfer and must be periodically removed to maintain thermal-efficiency in reverberatory furnaces.

If fluxes are employed to treat the skim before it is removed from the furnace, the oxides are typically dewet and a large portion of the molten aluminum entrained in the skim layer separates to the melt. In either case, untreated (skim) or flux-treated (dross) contains entrained free metal as a result of the skimming action. Efforts are usually made to recover entrained free aluminum after skimming. While still hot, metal can be drained from the skim gravimetrically and with vibration. Alternatively, skim may be rapidly cooled by inert gas quenching or in rotating water-cooled steel drums after which free aluminum may be physically separated. The residue comprising unrecovered aluminum and oxides is normally further processed for its metal content.

Gross melt losses typically range from 1 to 8 percent. The magnitude of the loss is dependant on the type of furnace and burners, the surface-to-volume ratio, the practices that are used, and the material being melted.⁵⁵ Melt loss has significant economic impact since oxidized metal must be replaced in the supply chain with new primary aluminum metal.

Alloying

Specific elements or combinations of elements are added to molten aluminum to produce aluminum alloys. Alloying provides the basis for a remarkable range of physical and mechanical property capabilities not displayed by unalloyed aluminum or by any other metal system. Among the elements and combinations of elements added to molten aluminum are modifiers and refiners, which provide finer grain structures, and controlled microstructural features, including metallurgical phases that influence recrystallization behavior.

Molten Metal Treatment

Molten aluminum contains dissolved hydrogen, entrained oxides, and other nonmetallic inclusions which, if not removed, would adversely affect metal acceptability and performance. Treatment with salt fluxes or active fluxing gases changes the interfacial relationship of included particles with the melt so that gravitational separation is facilitated. Fluxing with argon, nitrogen, and/or other gases results in flotation of entrained matter while dissolved hydrogen is reduced by partial pressure

diffusion. Metal treatment takes place in the melting furnace, holding furnace, or in-line between the furnace and the casting unit. Rotary degassers have been developed to provide the finest dispersion and intermixing of metal and fluxes for these purposes.

Molten metal filtration for the removal of particulate contamination was introduced in the 1950s and has grown in importance and application since that time. The first and still among the most effective filtration processes are deep bed filters using tabular alumina as the filtration medium. Crushed carbon beds are capable of fine inclusion removal and a reduction in sodium content that is important for many products. Porous foamed ceramics are widely used for commercial grade and higher quality requirements. Fused ceramic and refractory filtration elements are also available.

9.1.1 Energy Requirements for Melting Aluminum

Melting is an energy-intensive process; it requires nearly the same amount of energy to raise one kilogram of aluminum to a molten 700°C state as it does to raise one kilogram of iron to 1,500°C. However, nearly three times the volume of aluminum is produced compared to iron because of density differences.

The energy requirements for melting aluminum are presented in Section 8.3.1, Theoretical Energy for Secondary Aluminum. When the system boundaries are drawn around an aluminum melting facility, the material entering and leaving is aluminum metal. Since no chemical change has occurred, the theoretical minimum energy requirement is only the energy required to melt the metal. Molten metal furnace temperatures vary depending on the furnace, alloys, and other proprietary factors. The theoretical minimum energy requirement to bring room-temperature (25°C) aluminum to a molten 960°C metal is 0.39 kWh/kg. The theoretical energy requirement for melting pure aluminum to molten metal at various temperatures is presented in Appendix K.

Basic natural gas or oil-fired reverberatory furnaces range in efficiencies from approximately 20 to 45 percent. The more efficient furnaces employ recuperation of stack gas heat for reduced melting energy requirements through charge preheating or for more efficient burner operation through preheating combustion air. Furnace condition and operating practices have large effects on energy performance. Because heat transfer in reverberatory furnaces takes place principally through radiation, melt surface temperatures are considerably hotter, leading to more rapid oxidation and higher melt losses.

Electric furnaces, typically used in small processing operations, do not require a flue and their heating chambers can be made nearly airtight. A side-well is provided for charging metal and alloying materials. The side-well removes the need to open the furnace door and prevents a major convective heat loss. Energy losses (excluding electrical generation and transmission) in electrical furnace heating are principally due to conduction and radiation losses from the exposed furnace shell. Losses

are typically 0.49 to 0.81 kWh/kg of aluminum. Induction furnaces are typically more than 90 percent energy efficient, while gas-fired crucibles are 15 to 28 percent, and electrically heated crucibles 83 percent energy efficient.

9.1.2 Technological Change in the Next Decade

The industry is constantly evaluating, adopting, and improving furnace technologies and practices. This provides not only energy and environmental benefits, but also cost savings. New burner technologies and oxygen-enhanced combustion systems are being developed and evaluated to further improve efficiency and reduce the costs of melting without increasing emissions. All industry segments have transitioned to greater reliance on scrap and recycling for their metal needs. Technologies for sorting, handling, and remelting scrap in all forms with optimum metal recoveries and lowest costs are continuously being developed and refined. New technologies for melting thin gauge material to minimize oxidation losses are being developed and implemented. Also, industry is continually seeking better methods to recover the aluminum that is trapped in dross. Additional efforts are directed at the closed-loop recycling of dross-related wastes including saltcake.

New laser technologies will speed the in-situ chemical analysis of molten metal and minimize the processing time required for alloy compliance. The development of better, longer-lasting, ceramic materials for furnace linings is ongoing and will reduce the time required for furnace maintenance. The aluminum industry has recently published a technology roadmap in conjunction with the advanced ceramics industry, to encourage the development of superior furnace construction materials.⁵⁶

Finally, new melting technologies now under development offer the prospects for revolutionary improvements in melting efficiencies that may be applicable to the scale and operational demands of much of the industry. One exciting development is that of immersion heating with high watt-density elements for melting as well as temperature maintenance. The development of commercial immersion heaters for aluminum remelting is very likely to occur within the next few years.

9.2 Ingot Casting

Ingot casting is the solidification of molten alloys into shapes that are suitable for subsequent thermomechanical processing or for remelting. Ingots are made by controlled solidification in molds designed to produce the desired geometrical configuration and metallurgical characteristics.

Ingot casting is by itself not energy intensive; however, casting is typically a batch process, and large quantities of molten metal are held in furnaces in which alloying, fluxing, and degassing are performed. Accordingly, conductive and radiant heat losses occur from these furnaces operations.

Ingots for wrought product applications is almost universally cast by the semi-continuous direct-chill (DC) casting process. The process includes different means of introducing and controlling the flow of molten metal into the mold, lubrication methods, the use of insulation in mold construction, and the injection of air or imposition of an electromagnetic field for reducing or eliminating contact between molten metal and the mold. The process produces rectangular cross-section ingots for rolling, round log-like billets for extrusion, squares for wire, rod, and bar products, and various shapes as fabricating ingot in forging.

The DC casting process begins when aluminum flows from the furnace through troughs to the casting station. At the casting station, the aluminum flows into one or multiple water-cooled stationary molds that rest on the casting station table. The DC ingot molds are only a few inches deep and form the cross-section of the ingot or the billet. The ingot is initially formed in the water-cooled mold. Once perimeter solidification has begun, the casting table is gradually lowered into the casting pit, while additional molten aluminum is supplied to the top of the mold. The water-cooled mold remains at the top of the pit and continues to shape the casting. Water sprays impinging on the solid shell continue the solidification process of the molten ingot core. The casting table is lowered into a casting pit until the desired length is achieved. After casting, ingot intended for wrought fabrication may be stress-relieved, scalped, cut to length, and homogenized. Cutting, shearing, forming, and other mechanical operations, as well as melting, heating, casting, heat treating and other thermal operations are utilized by the product-producing sector.

Casting operations attempt to control the crystal/grain structure and composition gradient of cast products. Grain size and boundaries are important factors affecting the material's physical and mechanical properties in cast and wrought form. However, because there is a significant temperature profile across the ingot cross-section during solidification, grain structure and composition can vary from surface to center. For subsequent fabricating operations, it is usually necessary to remove the skin layer by scalping so that the final product has consistent physical properties. The amount of surface to be removed is dependent on shape, surface quality, and the depth of undesirable grain structure and segregation. Scalpings are remelted and reprocessed, which results in additional energy usage and metal losses due to oxidation.

A percentage of DC ingots are rejected for quality reasons. Cracking may occur during or after solidification. Surface defects may form, which affect the acceptability of the ingot for wrought processing. Other specialized standards concern grain structure, segregation, and microstructure. At times, ingots are found to exceed alloy specification limits. The processing energy used to produce the ingot is then lost and additional energy is required for remelting and reprocessing.

9.2.1 Energy Requirements

More than 2,704,000 metric tons of primary aluminum were cast into ingots in 2003 (Appendix G). The tacit energy consumed in aluminum processing operations can be divided into three categories:

1. fossil-thermal energy use, which includes furnaces, heating and heat treatment operations;
2. electrical energy required for heating, sawing and scalping, and for motor, pump and compressor operation; and
3. other fuel-consuming operations, including transportation.

Primary ingot casting has typical metal yields from 88 to 98 percent and requires about 1.01(1.46^{tf}) kWh/kg of cast ingot product (Appendix F, Table F.2).

Table 9.1: Primary Ingot Casting Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	79 (63 ^{tf}) %	21 (36 ^{tf}) %	0 (0 ^{tf}) %

The theoretical minimum energy requirements for primary and secondary castings are the same at 0.33 kWh/kg of aluminum (Appendix F, Table F.3). The difference in their actual energy usage results from their respective initial materials. In primary casting, the initial material is molten aluminum in a holding furnace, while the initial material in secondary casting is metal scrap. The scrap must first be melted before it enters a holding furnace, giving secondary casting a higher actual energy use than primary casting. Secondary aluminum was cast into 2,820,000 metric tons of ingots in 2003.

Secondary casting has typical yields of 96 percent and requires about 2.50 (2.81^{tf}) kWh/kg of product.

Table 9.2: Secondary Ingot Casting Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	77 (73 ^{tf}) %	5 (9 ^{tf}) %	18 (17 ^{tf}) %

9.2.2 Technological Change in the Next Decade

Ingot casters have strived to improve process yields and to refine practices to provide more consistent internal and surface quality in wrought ingot manufacture. These efforts have resulted in significant progress in surface, sub-surface, and metallurgical improvements. Grain refining by heterogeneous nucleation agents has benefited from decades of constant research and development by primary producers in cooperation with master alloy suppliers.

Molten metal fluxing and filtration processes continue to undergo changes leading to greater efficiencies, higher product quality, reduced environmental impact, and reduced costs.

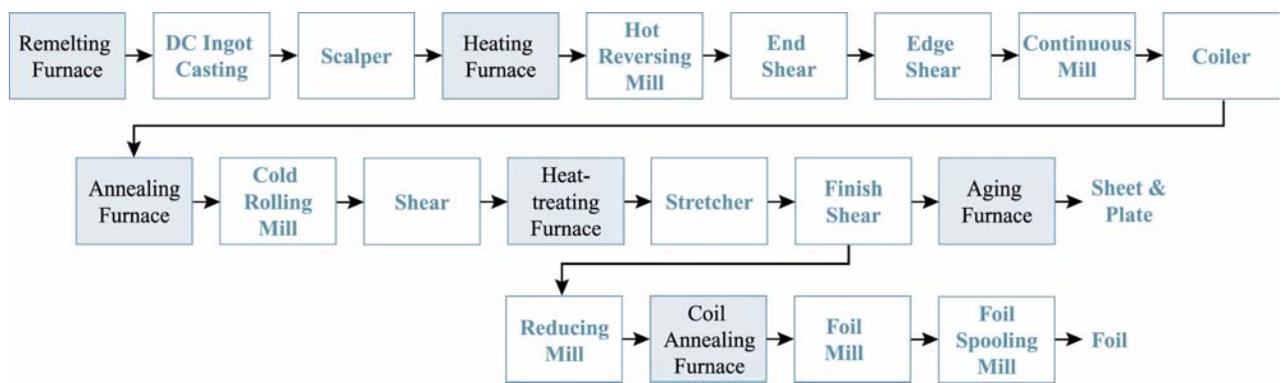
Numerous research programs are directed at the modeling and prediction of the solidification process for reduced cracking incidence and improved structural uniformity. The evolution of mold designs capable of improved surfaces, reduced scalping, and higher production rates continues in all wrought ingot production.

All of these developments reflect advances in sensors and instrumentation that permit more accurate monitoring and comprehensive control of the casting process.

9.3 Rolling

Rolling is the process of reducing ingot thickness by passing it between counter-rotating steel rolls. Aluminum-rolled products include plate (typically > 0.6 cm thick), sheet (typically 0.02 cm to 0.6 cm thick), and foil (typically < 0.02 cm thick). Figure 9.1 shows the unit operations of a typical rolling mill.

Figure 9.1: Typical Rolling Mill Processing Operations



Hot and cold rolling operations are used industrially to shape material into the broad category of flat rolled products. Hot rolling is generally performed at various temperatures exceeding the recrystallization temperature for differing rolling alloys. Cold rolling takes place at room temperature, but the heat generated can result in metal temperatures as high as 150°C.

Large high strength alloy ingot may require thermal stress relief after casting. Most ingots are homogenized to reduce intergranular segregation and to modify intermetallic particle form. Homogenization may be integral to preheating for hot rolling, or the preheating may take place separately. Although some ingot may be rolled with the cast surface intact, rolling surface faces are normally removed by scalping, and the head and butt of the ingot are “cropped” to assure finished product uniformity.

Hot rolling begins with repetitive reversing mill reductions on stock preheated to temperatures in the range of 400°C to 500°C. The slab is passed repeatedly back and forth through the rolls until the desired reduction in thickness is achieved. While heat is generated during deformation, the number of passes required at the reversing mills may – because of reducing section thicknesses, time, and coolant application – cause losses in temperature that require reheating before continuing the hot

rolling process. Slabs are lifted from the hot line and charged in reheating furnaces until working temperatures are restored. End crops are taken during breakdown rolling as required to maintain squareness.

Edge trimming knives remove stock from the edges of the sheet before coiling. The amount of edge trim required is determined by the depth of edge cracks and the ragged conditions associated with the unrestrained deformation that occurs during hot rolling. The amount of edge trim required with cropping losses represents a significant percentage of planned scrap that must be returned to the cast shop for remelting. Edge trim losses can be minimized by improved ingot quality and by edge rolling.

The hot rolling process completely changes the microstructure formed during casting and elongates the grain structure in the direction of rolling. Even though deformation temperatures are typically greater than the recrystallization temperature, there is inevitably some degree of equivalent cold work so that annealing at reroll gauge will result in recovery or recrystallization before cold rolling.

9.3.1 Energy Requirements for Rolling Aluminum

About half of U.S. rolled aluminum products are cold rolled. 2,421,300 metric tons of cold rolled products were produced in 2003 (Appendix F, Table F.4). Cold rolling has typical yields of about 84 percent and requires about 0.64(1.35^{tf}) kWh/kg of rolled product.

Table 9.3: Cold Rolling Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	42 (25 ^{tf}) %	55 (72 ^{tf}) %	3 (3 ^{tf}) %

In 2003, nearly 2,421,300 metric tons of hot-rolled products were produced (Appendix F, Table F.4). Hot rolling has typical yields of about 82 percent and requires about 0.62(1.16^{tf}) kWh/kg of rolled product.

Table 9.4: Hot Rolling Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	57 (38 ^{tf}) %	43 (62 ^{tf}) %	0 (0 ^{tf}) %

Theoretically, it is possible to roll products without the need for heat treatments and with no loss of material due to trimming or slitting. In this case, the minimum theoretical energy to roll a product is composed of only two components:

- the energy required to heat starting stock to the rolling temperature, and
- the energy required to deform the shape.

The hotter the material, the lower the deformation energy required. The heat capacity equations required to calculate the energy requirement for heating pure aluminum are listed in Appendix I. The energy required for deforming is given by the equation $E = \epsilon \sigma c$, where ϵ is the strain or deformation defined as $\epsilon = \ln(t_i/t_f)$, where t_i represents the initial and t_f the final dimension, σ denotes the yield stress, and c denotes a constant describing the shape of the stress strain curve. The yield stress value for aluminum can vary by as much as a factor of ten over the hundreds of alloys that are used by the industry.

The very large variations in alloy properties, particularly the shape and the magnitude of the stress strain curves, make it possible to calculate theoretical minimum energy requirements for rolling aluminum only for a specific rolling process with a specific alloy. There are a large number of heavy equipment requirements in rolling mill operations that are not confined to rolling. Roller and tension levelers, slitters, stretchers, roll formers, and paint or coating lines are examples of energy consuming operations that rely on pumps, motors, and compressors as well as on mechanical design for efficiency. A rough approximation of the rolling sector's minimum energy can be made by assuming overall process heating efficiencies and electric/hydraulic system efficiencies and by looking at the entire rolling sector yield and energy consumption. If the overall sector heating efficiency is 50 percent and the electric/hydraulic system efficiency is 75 percent, the estimate of the minimum energy requirement is 0.31 kWh/kg of product for hot rolling and 0.33 kWh/kg of product for cold rolling. These assumptions imply that cold rolling is operating at about 52 percent overall energy efficiency and hot rolling at about 50 percent overall efficiency (Appendix F, Table F.3).

9.3.2 Advanced Rolling Technology

Hot rolling typically requires numerous passes through the rolling mills and is energy intensive. One approach to improving productivity and reducing heating energy is to continuously cast molten metal into slab or strip.⁵⁷ Going directly to thin strip, continuous strip and slabcasting saves the energy required for homogenization, scalping, preheating, end and side trim, and multiple passes through rolling mills.

Continuous strip casting is in wide current use for some sheet and foil specifications and has demonstrated energy savings of more than 25 percent relative to conventional ingot rolling. These casters convert molten metal directly into reroll gauge sheet at 1 mm to 12 mm thickness. Continuous strip casters employ twin counter-rotating water-cooled rolls or belts to accomplish solidification. Strip casting is now restricted to certain low alloy content compositions. Technology is being developed for more complex or more highly alloyed compositions. Very high solidification rates and the extrusion component of casting between cylindrical rolls result in high degrees of segregation of solute to the centerline and in cracking tendencies.

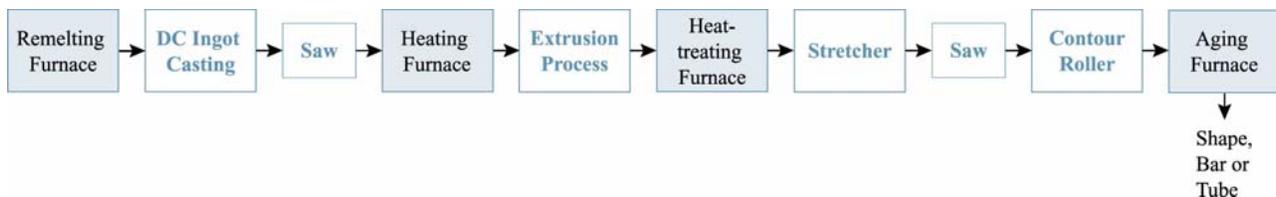
While continuous strip casting is recognized as alloy-constrained, an alternative continuous process for coiled reroll, slab casting is highly alloy tolerant and results in metallurgical structures that closely correspond to those of the ingot and wrought products produced by the Direct Chill process. In slab casting, solidification takes place between water-cooled belts or blocks. Slab thickness varies but typically corresponds to continuous hot mill entry gauges of 75 mm to 150 mm. An individual slab casting line has a production capacity ten times that of the largest strip caster. The cast slab is directly fed into one or more in-line, low-speed, high-torque, hot reduction mills that reduces thickness to coilable gauge. Slab casting processes have successfully produced high strength aluminum alloy sheet as well as challenging products such as beverage can sheet, but subtle differences in product performance—especially in formability and anisotropy—continue to favor the use of conventionally hot-rolled sheet in these applications.

A further advancement in rolling technology is spray rolling. In this process, molten metal droplets are sprayed directly into the nip of twin rolls and the material is solidified and consolidated directly into sheet material in one step. In concept, this offers the most energy-efficient process, and recent projects have sought to advance this technology.

9.4 Extrusion

Extrusion is the process of forcing an aluminum ingot or billet through a steel die to form an elongated shape of consistent cross-section. Extruded products include rods, bars, tubes, and specialized products interchangeably called shapes, sections, or profiles. Figure 9.2 shows the unit operations of a typical extrusion plant. After rolling, extrusion is the second most common processing technique for aluminum. Aluminum extrusion is remarkable because the process combines high productivity with an essentially infinite variety of extremely complex shapes, cross-sections, or profiles that cannot be economically duplicated in any other process. Furthermore, aluminum can be readily extruded; this process is either extremely difficult or impractical for many other metals.

Figure 9.2: Typical Aluminum Extrusion Processing Operations



It is possible to produce almost any cross-sectional shape, within wide limits. Through the use of hollow stock and floating or fixed mandrels, hollow shapes or cross-sections with complex enclosed configurations can be produced. The extrusion process is capable of producing a cross-section with a weight of a few grams to more than 300 kg/m, a thickness of less than 1 mm to over 250 mm, circumscribing diameters of 5 mm to 1,000 mm and lengths in excess of 30 m. The appropriate choice

of alloy and extrusion conditions can result in an optimum combination of properties for a particular application. Such properties may include tensile strength, toughness, formability, corrosion resistance, and machinability. Countless extrusion products are made in the United States. These include frame and supporting shapes for windows and doors, carpet strips, household bath enclosures, screens, bridge structures, automotive parts, aerospace components, and many other consumer products.

Operations at individual plants vary widely depending on the cross sections and alloys produced. Extrusion presses range in capacity up to 15,000 tons but the most common are perhaps 2,500 tons. Presses may extrude vertically or horizontally but virtually all modern extrusion presses are horizontal. Typically, billets in diameters up to 275 mm are preheated to temperatures ranging from 450°C to 550°C depending on the alloy, product design, and the desired mechanical characteristics. The preheated billet is charged to the extrusion press container and forced by hydraulic pressure through the extrusion die.

There are essentially two processes for extrusion production. In the direct extrusion process, the billet is hydraulically pressed through the die, while in the indirect extrusion process, the die is forced over the billet. In direct extrusion, the billet surface is retained in the extrusion container and contributes to butt loss, which may total 8 percent of the starting billet weight. Because the billet surface is not extruded to become part of the product, scalping is not required. For indirect extrusion, the billet surface becomes an integral part of the product and so, scalping before extrusion is essential.

The single largest area for energy improvement in extrusion technology is the reduction of process scrap, including butt losses. Extrusion product specifications include significant surface-quality and chemical finishing criteria. Defects include torn surface, die pick-up which is often related to the billet’s microstructure, and non-fill. Variable response to chemical finishing results in appearance and color mismatches which affects product acceptability.

9.4.1 Energy Requirements for Extruding Aluminum

The United States produced over 1,826,000 metric tons of extruded aluminum products in 2003 (Appendix F, Table F.4). Extrusion processes have typical yields of 69 percent and require about 1.30(1.52^{tf}) kWh/kg of extruded product.

Table 9.5: Extrusion Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	87 (25 ^{tf}) %	7 (72 ^{tf}) %	6 (3 ^{tf}) %

Theoretically, it is possible to extrude products without the need of additional heat treatments and without loss of material. The minimum theoretical energy to extrude a product, in such a case, is composed of only two components:

- the energy required to preheat the billet to extrusion temperature, and
- the energy required to deform the material through a die.

The hotter the material is, the lower the deformation energy required. The simpler the die, the lower is the extrusion-energy requirement. The heat capacity equations needed to calculate the energy requirements for heating pure aluminum are listed in Appendix K. The energy required to deform the material through the die is highly dependent on the size and shape of the product and the die design. Calculation of the minimum extrusion force is very complex and can only be estimated with theoretical and empirical models. Typical formulae have the following simplified form:

$$F = A_o(\sigma_m/\eta) \epsilon, \text{ where}$$

ϵ , the strain, corresponds to the reduction area, $\epsilon = \ln(A_o/A_f)$,

σ_m is the mean stress for the strain,

A_o is the original cross-sectional area, and

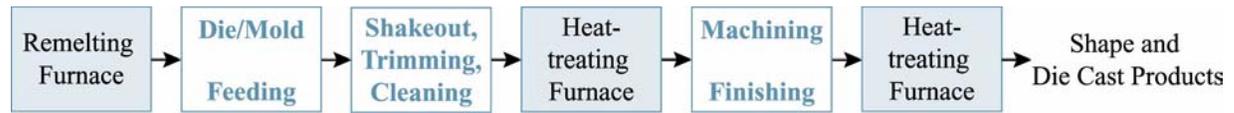
η is an efficiency factor.

The very large variations in alloy properties, particularly the infinite numbers of possible shapes, make it impossible to calculate a theoretical minimum energy requirement. This value can only be determined by analyzing a specific process, a specific extruded profile, and a specific alloy. The perimeter of the profile and the radius of intersecting edges have a large influence on the force required for extrusion. A rough approximation of a minimum energy value can be made by examining the entire aluminum extrusion industry yield and energy values, and assuming an overall process-heating efficiency and electric/hydraulic-system efficiency. This approach provides an estimate of the minimum energy, 0.44 kWh/kg of aluminum, when efficiencies are assumed to be 50 percent for heating and 75 percent for the electric/hydraulic system. These assumptions imply that overall extrusion facilities operate at about 34 percent energy efficiency.

9.5 Shape Casting

Shape casting or the casting of engineered designs enables the production of simple and complex parts that meet a wide variety of needs. The process produces parts weighing ounces to parts weighing several tons. Figure 9.3 shows the unit operations of a typical aluminum shape casting foundry. These operations vary significantly depending on the size of the operation, the processes employed, the complexity of the parts, alloy compositions, and the type of castings being produced.

Figure 9.3: Typical Aluminum Product Shape Casting Operations



The basic casting process consists of melting and alloying aluminum and pouring or injecting molten metal into molds containing single or multiple cavities of the desired shape. The important casting processes for engineered aluminum castings are pressure die, permanent mold, green and dry sand, plaster, and investment casting.

In pressure die or die casting, metal is injected at pressures up to 10,000 psi into water-cooled steel dies. Productivity rates are high and the process can be highly automated. While surface quality and dimensional accuracy are excellent, the typical die casting contains a degree of internal unsoundness associated with non-directional solidification, entrapped gasses and inclusions resulting from turbulent metal flow, and the presence of air and lubricants in the die cavity.

Permanent mold or gravity die-castings are produced by introducing molten metal by gravity or counter-gravity means into iron or steel molds. Productivity, surface quality and dimensional accuracy is lower than in pressure die-casting. Internal soundness, depending on the extent to which sound molten metal treatment for hydrogen elimination and oxide removal are practiced and the principles of directional solidification are employed, can meet the most challenging quality standards. Low-pressure casting is usually considered a variation of the permanent mold process even though dry sand and plaster cast parts have been produced. In this process, molten metal is forced by the application of pressure to rise through a tube into a mold mounted over the furnace. It has the advantages of a significantly reduced gross to net weight ratio and correspondingly lower trimming costs.

Green and dry sand casting can also yield high integrity parts. In green sand casting, sand, binders such as clays, and moisture are blended to provide the molding medium. Patterns may include loose pieces, wood models, cast match-plates, and molded styrofoam. For dry sand molding, air or thermal setting chemicals coat sand particles so that the finished mold after curing offers superior surfaces, dimensional accuracy, and shelf life.

Investment molds are produced by repetitive immersion of plastic, wax, or other low temperature melting and volatile pattern material into ceramic slurries. After drying, the hardened casing containing the pattern is heated to a temperature at which the pattern material is eliminated. Typically, the mold is preheated before pouring and may be filled under vacuum. Investment castings offer extremely fine finishes, thin walls, and excellent dimensional accuracy. Plaster molding offers the same advantages and may be used for the production of thicker sections, large parts for which investment is less suited.

Molten aluminum is required as the basis for all foundry production. High volume casting operations may acquire part or all of their metal requirements as molten metal delivered over-the-road in insulated crucibles. Other foundries melt and process prealloyed ingot, RSI, and internal scrap including gates and risers. All melting and melt processing technologies and considerations described in Section 9.1 are applicable to foundry operations.

9.5.1 Energy Requirements for Shape Casting Aluminum

Nearly 2,413,000 metric tons of shape-cast products were produced in 2003. Shape casting has typical yields of only 45 percent and requires about 2.56(2.64^{tf}) kWh/kg of cast product. The energy consumed is almost exclusively related to furnace and heating operations (Appendix F, Table F.4).

Table 9.6: Shape Casting Distribution of Energy Consumption (Appendix F, Table F.10)

Energy Category	Fossil-Thermal	Electrical	Other Fuels
Percent	100 (80 ^{tf}) %	0 (14 ^{tf}) %	0 (6 ^{tf}) %

The theoretical minimum energy requirement for shape casting can be calculated from the energy required to go from room temperature to liquid metal plus some superheat value (Section 8.2). Pure aluminum melts at 660°C. The minimum energy required to produce liquid aluminum at 660°C is approximately 0.3 kWh/kg.

Alloy composition, superheat requirements, mold sprue, gates, runners, and riser systems, and post-casting heat treatments vary by mold design and casting practices. A rough approximation of the aluminum shape cast sector’s minimum energy requirement can be made by looking at the entire sector yield and energy values (Appendix F, Table F.2), and assuming an overall process heating efficiency and electric/hydraulic-system efficiency. The estimate of the minimum energy requirement using this approach is 0.60 kWh/kg, when a 50 percent overall heating efficiency and a 75 percent electric/hydraulic system efficiency are assumed. These assumptions imply that shape-casting facilities operate at about 23 percent overall energy efficiency.

9.5.2 Technological Change in the Next Decade

Castings are among the most cost-effective and versatile solutions to part design and performance challenges. The range of available alloys and properties provides combinations of manufacturability and product characteristics for one-of-a-kind, prototype, limited, or high volume applications. Castings are near-net-shape with the potential for precise integral internal passages and complex shapes. Aluminum is cast in more alloys with a wider range of physical and mechanical properties by more processes than any competing metal system.

The most important trend affecting aluminum casting production is its continuous growth in automotive applications. The advantages of aluminum for many powertrain components including transmission cases, oil pans, pistons, intake manifolds, cylinder heads, and engine blocks have been reflected in its wide adoption.

Squeeze casting and semisolid forming have emerged as candidates for a new generation of process capabilities producing heat-treatable, high integrity pressure die castings that utilize lower impurity compositions, vacuum, and dry lubrication.

9.6 Thermal Treatments

A significant component of energy use in the aluminum industry is the heat treatment of metal and products. The physical and mechanical properties of aluminum alloys in any product form can be controllably altered by thermal treatment. Thermal treatments are used to soften the material and to recrystallize the grain structure. Other aluminum alloys, principally those containing copper, magnesium, silicon, and zinc can be thermally treated to significantly improve strength through the dissolution and reprecipitation of soluble phases. Aluminum alloys are categorized as heat-treatable if thermal treatments have significant hardening benefits or nonheat-treatable if the alloy is unresponsive to thermal treatments for hardening purposes. Among the latter are alloys dependent on work-hardening for strengthening and those whose properties are essentially fixed after solidification.

All product types including sheet, plate, foil, wire, rod, bar, extrusions, forgings, and castings are produced in heat-treatable alloys. The majority of extrusions, forgings, and a large percentage of plate and castings are heat-treated. Heat-treatment facilities are integral to larger operations. Commercial firms also provide contracted heat-treatment services.

Annealing is performed at temperatures from 300°C to 500°C to reduce strength, improve formability and ductility, lower residual stress levels, and improve dimensional stability in cast and wrought products. Since electrical conductivity is adversely affected by elements retained in solution, annealing is also used in electrical and electronic applications. Deep drawn sheet is normally annealed. Intermediate annealing is usual practice in rolled product manufacture to permit subsequent cold reductions. The final temper of nonheat-treatable rolled products may include annealing, partial annealing, or stabilization treatments. Most annealing is a batch operation.

Heat-treatable aluminum alloys contain intermetallic metallurgical phases which can be dissolved at elevated temperature (up to 550°C) and retained in solid solution by rapid quenching. Solution heat-treatment is batch or continuous. Sheet and foil can be heat-treated continuously through accumulator towers and plate, castings, and forgings by conveyer furnaces. Coiled sheet, plate, and extrusions are more typically batch treated. In either case, the product must be held at solution temperature long enough for complete solution to occur and for desirable changes in the shape or form of the insoluble intermetallics that are present in the microstructure. The quench medium is water at room

temperature. The retained metastable solid solution permits precipitation hardening at intermediate temperatures (170°C to 300°C) for fully hardened, partially hardened, or over-aged conditions. Each offers combinations of strengths, ductilities, toughness, stability, resistance to stress corrosion and hardness not achievable through solidification or work hardening. Precipitation hardening furnaces are also batch or continuous.

The high rate of solidification in many casting processes results in a degree of solution retention in heat-treatable compositions permitting age or precipitation hardening to be employed without solution heat-treatment. This method is extensively used in extrusions which can be press-quenched by forced-air or water-mist to improve solution retention.

Recommended solution heat-treatment practices have been standardized to reflect worst-case conditions. The cycle defines the minimum time at the required temperature for successfully treating the part requiring the longest exposure. A safety factor is usually also applied to assure that reheat-treatment will not be necessary. Practices are typically generic, applying to specific alloys and tempers without regard for section thickness or degree of metallurgical refinement. Thinner wall castings, forgings and extrusions generally respond to heat treatment more rapidly. Finer grain and dendrite cell sizes are reflected in smaller, more dispersed, solute particles which can be more rapidly dissolved. Solution heat treatment time can therefore be patterned to specific products and manufacturing processes and the combination of finer metallurgical structures. Decreased variability can result in substantially reduced cycle times and energy costs.

New heating technologies are being studied to reduce energy requirements through more rapid heating to treatment temperature. Fluidized beds and infra-red heating can be used to shorten heat-up times but do little to accelerate either the rate of solution or microstructural change once solution temperatures are reached.

Another approach being investigated is the use of sensible heat to reduce energy requirements. While there are metallurgical concerns, extrusions, castings, and forgings can be placed in heat-treatment furnaces directly from the mold or die, thereby preserving the latent heat of the casting or final forming operation.

9.6.1 Energy Requirements for Thermal Treatment

The theoretical energy required for all thermal treatments can be calculated from the specific heat or heat capacity of the various aluminum alloys. For example; it requires 0.06 kWh/kg (95Btu/lb) to heat A356 to its solution heat treatment temperature, 0.05 kWh/kg (80 Btu/lb) to reach annealing temperature for 1100 alloy, and 0.02 kWh/kg (32Btu/lb) to reach precipitation hardening temperature for alloy 2024.

Time at temperature for each procedure varies depending on alloy and product form but can exceed twelve hours. While most energy is consumed in raising the product and oven to temperature, additional energy is required to maintain the temperature for the duration of the cycle. Sustaining energy requirements are exclusively a function of furnace design and condition. Standard quench temperatures include room temperature: 65°C (150°F), 80°C (180°F), and 100°C (212°F). Large volumes of water must be heated and maintained at temperature by steam or other means for the latter practices.

Endnotes

- ¹ *Aluminum Statistical Review for 2003* (Washington, D.C.: The Aluminum Association, Inc., 2004), 7. The Aluminum Association's statistical reviews are issued annually and assemble, in one document, important detailed data from primary production, to markets for finished goods, to the recovery of scrap. Both U.S. and world information is included.
- ² *Aluminum Industry: Vision Sustainable Solutions for a Dynamic World*, (Washington, D.C.: Aluminum Association, Inc., November 2001), 3. The *Vision* document identifies key needs of the industry and outlines a comprehensive aluminum R&D agenda.
- ³ *Production of Aluminium and Alumina*, ed. A.R. Burkin (Chichester: John Wiley & Sons, 1987) (p. 38). This book, published on behalf of the Society of Chemical Industry, is one of the only texts to provide a comprehensive overview of the state-of-the-art of all science and technologies associated with primary aluminum production in a single volume. It is a detailed, academic volume that covers chemistry, thermochemistry, fluid dynamics, process dynamics, etc., from both a theoretical and practical perspective.
- ⁴ Dietrich G. Altenpohl, *Aluminum: Technology, Applications, and Environment; A Profile of a Modern Metal*, Sixth Edition (Washington, D.C.: The Aluminum Association, Inc. and the Minerals, Metals and Materials Society, 1998). This book is described in its foreword as having "global recognition as the definitive educational text and reference book for aluminum industry participants, a broad range of aluminum fabricators and users, students, and the scientific, engineering, and academic community."
- ⁵ *Aluminum Industry Vision, Sustainable Solutions for a Dynamic World*, 22.
- ⁶ Robert D. Naranjo, Ehr-Ping Huang Fu, and Mike Gwyn, "Castings Drive Fuel Efficiency," *Modern Casting* Vol. 94 No. 9 (September 2004), pg. 20.
- ⁷ *Life Cycle Inventory Report for the North American Aluminum Industry* (Washington, D.C.: Aluminum Association, Inc., 1998). This report is summarized in Appendix F. This report provides information on a life cycle inventory study of the North American aluminum industry in 1995. The report is the result of extensive surveying and contains the best and most complete industry performance information of any recent study. The report was produced in accordance with International Organization for Standardization (ISO) procedures and was favorably peer-reviewed by groups outside the industry.
- ⁸ *Energy and Environmental Profile of the U.S. Aluminum Industry* (Washington, D.C.: U.S. Department of Energy Office of Industrial Technologies Program, July 1998). This report reviews the energy and environmental characteristics of the key technologies used in the major processes of the aluminum industry.

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- ¹⁰ “Bauxite and Alumina Statistics and Information,” U.S. Geological Survey, Minerals Information, Available: [<http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/>].
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- ¹² *Aluminum Statistical Review for 2003*, 38, 42.
- ¹³ *Life Cycle Inventory Report for the North American Aluminum Industry*, E-3.
- ¹⁴ *Technology Roadmap for Bauxite Residue Treatment and Utilization* (Washington, D.C.: The Aluminum Association, February 2000). This booklet contains a comprehensive discussion of bauxite residue.
- ¹⁵ *Production of Aluminium and Alumina*, 38.
- ¹⁶ *Energy and Environmental Profile of the U.S. Aluminum Industry*, 29.
- ¹⁷ *Life Cycle Inventory Report for the North American Aluminum Industry*, E-8.
- ¹⁸ *Life Cycle Inventory Report for the North American Aluminum Industry*, E-8.
- ¹⁹ *Alumina Technology Roadmap* (Washington, D.C.: the Aluminum Association, Inc., November 2001). This document identifies performance goals and describes 25 research and development areas that are a priority for the global alumina industry.
- ²⁰ Paul J. Ellis, “Tutorial: Petroleum Coke Calcining and Uses of Calcined Petroleum Coke,” 13. Speech given at AIChE 2000 Spring National Meeting, 3rd International Conference on Refining Processes, March, 2000.
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- ²² *Life Cycle Inventory Report for the North American Aluminum Industry*, E-6.
- ²³ *Production of Aluminium and Alumina*, 49.
- ²⁴ Ellis, 13.
- ²⁵ “The Manufacture of Carbon and Graphite,” Chapter in *Industrial Graphite Engineering Handbook*, (Parma, OH: UCAR Carbon Company, Inc, 2001) 1-6.
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- ³⁰ *Report of the American Society of Mechanical Engineers' : Technical Working Group on Inert Anode Technologies* (Washington, D.C.: U.S. Department of Energy Office of Industrial Technologies, July 1999) Appendix A-9: Thermodynamics of Electrochemical Reduction of Aluminum, 3. This report reviews the literature and patents concerning inert anode technologies. It presents a theoretical discussion of aluminum reduction and has input from over eleven experts in the field. Carbon anode voltage equation $E = 1.898 - 0.0005728 \times T$, where E is in V(dc) and T is in degrees Kelvin.
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- ³² *Production of Aluminium and Alumina*, 63.
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- ⁴³ *Inert Anode Roadmap: A Framework for Technology Development* (Washington, D.C.: The Aluminum Association, Inc. and the U.S Department of Energy Office of Industrial Technologies Program, Feb. 1998), 1. This document describes the potential benefits, performance targets, technical barriers and technology development steps associated with the R&D and production of inert anodes.
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- ⁵⁰ *Life Cycle Inventory Report for the North American Aluminum*, E-12.
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- ⁵² “New Technology is a Breakthrough for Automotive Aluminum Recycling,” *Aluminum Now* November/December 2000: 28.
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- ⁵⁴ “*Aluminum Dross - Liability into Opportunity*,” E.L. Rooy, *Light Metal Age*, June, 1995.
- ⁵⁵ *Aluminum Statistical Review for 2003*, 19-23.
- ⁵⁶ *Metal Melting Practices and Procedure for Efficiency and Effectiveness*, 20
- ⁵⁷ *Metal Melting Practices and Procedure for Efficiency and Effectiveness* (California Cast Metals Association: Summer 2001), sponsored by The California Energy Commission. This and its companion booklet *Foundry Energy Use Study and Conservation Manual* provide detailed, furnace design information and operational survey data on melting and furnace practices for non-ferrous metals in the State of California.
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Glossary

Alumina	An oxide of aluminum (Al_2O_3) and the compound from which aluminum metal is commercially obtained.
Aluminum	<p>A versatile, silvery-white metal. When exposed to the atmosphere, aluminum rapidly forms an oxide film that prevents it from reacting with air and water. This gives it exceptional corrosion-resistant properties. Aluminum is not found in nature as a free metal like gold, but is chemically bound to other elements. Aluminum is the most abundant metal in the earth's crust (8.1 percent).</p> <p><i>Atomic Number ... 13</i> <i>Atomic Mass..... 26.982</i> <i>Melting Point 993.52 °K</i> <i>Boiling Point 2698 °K</i></p>
Anode	A positively charged mass or surface that attracts negatively charged ions (anions). The anode used in the Hall-Héroult Process is composed of carbon. The oxygen containing anions react on the anode surface, releasing oxygen that consumes the carbon to form carbon dioxide.
Anode-Cathode Distance (ACD)	The geometric linear distance between the anode and the cathode is a critical measurement in an electrolytic cell. This distance affects the voltage and energy requirement of a cell.
Anode Effect	An aluminum-industry idiom used to describe a process upset where the anode reaction shifts from producing oxygen to fluorine, and the cell voltage increases. Anode effects are primarily the result of having insufficient alumina dissolved in the bath and available at the anode for reduction.
Bath	An aluminum-industry idiom referring to the cryolite-based electrolyte pool in the reduction cell.
Bauxite	A prime source of alumina, found as a collection of small, reddish-brown nodules in a light brown, earthy matrix. Commercial bauxite ore contains 30 to 60 weight percent of alumina.
Bayer Process	A process developed by Karl Bayer in 1888 that refines bauxite ore into alumina grains. It is the process currently in use worldwide.
Calcining	The process of heating a material to a sufficiently high temperature to drive off volatile components or to oxidize the material without fusing it. The aluminum industry uses calcining in the Bayer Process to produce alumina and to prepare coke for anodes.
Carbon Dioxide Equivalents (CDE)	The preferred unit of measure used to compare the impact of different Greenhouse Gases. It is calculated by multiplying the quantity of a Greenhouse Gas emission by the Global Warming Potential (GWP) of the gas. The results are commonly expressed in terms of a million metric tons of carbon dioxide equivalent (10^6 TCDE).
Carbon Equivalents (CE)	A unit of measure used to compare the impact of different Greenhouse Gases (GHG). It is calculated by multiplying the Carbon Dioxide Equivalent (CDE) by 12/44, the mass ratio of carbon to carbon dioxide.
Carbothermic Reduction	An alternative process to electrolytic reduction. The carbothermic process reduces alumina in a high-temperature furnace with carbon.

Castings	Metal objects which are cast into a shape by pouring or injecting molten/liquid metal into a mold. This report divides castings into ingot and shape categories. Ingot castings are produced in molds of very simple cross-section and shape castings are complex structures.
Cathode	A negatively charged surface that attracts positively charged ions (cations). The cathode surface in the Hall-Héroult Process is the molten aluminum pad, which rests directly on the cell's carbon lining. The aluminum containing cations reacts on the cathode surface, releasing the aluminum as free metal.
Chloride Reduction	An alternative process to alumina electrolytic reduction in which aluminum chloride is used as the feed to the reduction cell.
Coke	A carbon product of the crude oil refining industry. Green or raw coke contains 8 to 10 percent moisture and 5 to 15 percent volatile organic materials. Coke is calcined in thermal kilns to remove moisture and volatile organic materials.
Cryolite	Na_3AlF_6 , a mineral that when molten dissolves alumina to form aluminum and oxide ions. It is the main component used in the electrolyte bath for aluminum production.
Dross	The material that forms on the surface of molten aluminum as it is held in a furnace. It is composed of impurities that have surfaced as a result of gas fluxing, oxidized aluminum that is the result of molten aluminum exposure to the furnaces atmosphere and aluminum that becomes entrapped in the surface material. Dross is periodically skimmed off the surface of molten aluminum and processed to recover its aluminum content.
Dusting	An aluminum industry idiom used to describe fine carbon anode particles that are lost in the electrolyte bath or atmosphere during electrolytic reduction. Dusting results in a loss of productivity.
Electrolysis	An electrochemical process in which the charged species in an electrolyte are attracted to electrodes where they react with the electrons of the electrical current. Positively charged ions migrate to the cathode and negatively charged ions migrate to the anode.
Electrolyte	A nonmetallic electrical conductor in which current is carried by the movement of ions.
Extrusion	The process of forcing the metal ingot (or billet) to flow through a die to create a new cross-section.
Feedstock Energy	These values represent the energy inherent in a fuel that is used as material. For example, aluminum production uses coke as the raw material in carbon anodes. The energy contribution of a feedstock is expressed in terms of calorific or fuel value plus the tacit/process energy used to produce the feedstock.
Global Warming Potential (GWP)	Greenhouse gases differ in their abilities to trap heat. Global Warming Potential is used to express the greenhouse effect of different gases in a comparable way. The heat-trapping ability of one metric ton of CO_2 is the common standard, and emissions are expressed in terms of a million metric tons of CO_2 equivalent or 10^6 TCDE.
Greenhouse Gases (GHG)	Atmospheric gases that contribute to climate change by increasing the ability of the atmosphere to trap heat.

Hall-Hérout Process	An electrolytic process for reduction of alumina, developed independently by Charles Martin Hall and Paul Lewis Toussaint Hérout in 1886. This process is commonly referred to using both names, the Hall-Hérout process. It is the process used worldwide for commercial aluminum production.
Ingot	Ingot as used in this report describes an aluminum casting of simple shape. It includes billets, pigs, sows, T-bar and other simple cast semifinished shapes.
Kilowatt-hour (kWh)	A unit of energy.
Life Cycle Assessment (LCA)	An internationally recognized analysis model of a product's impact on energy, environment, economic, and social values. LCA extends from "cradle-to-grave": from material acquisition and production, through manufacturing, product use and maintenance, and finally, through the end of the product's life in disposal or recycling. The LCA is particularly useful in ensuring that benefits derived in one area do not shift the impact burden to other places within a product's life cycle.
Onsite Energy	The energy used within a facility. This is sometimes called "primary energy." Electrical onsite energy is the kilowatt hours used and does not include the "secondary energy" required for generation and transmission of electricity. Fuel onsite energy use is based on the calorific heating value of the fuel and does not include the "secondary energy" required to produce and transport the fuel.
Pad	An aluminum industry idiom used to describe the body of molten aluminum that accumulates within the Hall-Hérout electrolytic cell.
Polarization	The nonuniform concentration gradients that form near electrodes during the reduction process. The reactions occurring at the anode and the cathode create localized conditions that are different from the bulk of the bath. The reactions deplete the supply of reactants and increase the quantity of products. Additionally, in aluminum electrolysis, gas is generated at the anode which lowers the effective bath conductivity. An electric overpotential is required to overcome the effects of polarization.
Pot	An aluminum industry idiom used to describe an electrolytic cell. The term was derived from the shape of the first cells.
Potline	An aluminum industry idiom that describes the arrangement of a long row of interconnected electrolytic cells (pots).
Potlining	An aluminum industry idiom that describes the refractory and carbon materials used to line the interior of the cell (pot).
Primary Aluminum	Refers to aluminum metal produced directly from alumina feedstock by chemical reduction.
Quad	A common abbreviation for a quadrillion Btu. (1 quad = 10 ¹⁵ Btu.)
Red Mud	The residue of insoluble materials that results from extracting alumina from bauxite ore. It is also referred to as "bauxite residue."
Reduction Cell	A container holding single or multiple anodes, cathodes and an electrolytic bath used for reducing a material.

Reverberatory Furnace	The most commonly used furnace type in the aluminum industry. The furnace is box-shaped and consists of a steel shell with refractory lining. Fuel is fired directly into the box either from the roof, or more typically, from the sidewall. Heat is transferred to the molten metal with convection and radiation.
Rolling	A process that results in the reduction of the cross-sectional area of a metal shape as it is passed through rotating rolls.
Secondary Aluminum	Aluminum metal that is produced from recycled aluminum products and wastes.
Tacit Energy	A term used to describe an energy value that equals the combination of onsite energy (“primary energy”) consumption, the process energy required to produce and transmit/transport the energy source (“secondary energy”), and feedstock energy (energy inherent in fuels used as materials). This report uses the superscript “tf” to denote any value that includes the tacit and feedstock energy contributions. The report does not include the energy used to make the equipment or buildings that house the process steps (“tertiary energy”).
Urban Mining	A term that describes the large source of aluminum available through urban recycling programs as compared to bauxite mining.
Value Chain Analysis	A method that captures the energy and material inputs and outputs of each processing step (link) and builds the cumulative value for each product along the chain. A value chain analysis or “cradle to shipping dock” analysis is an integral part of a Life Cycle Analysis.

Appendix A: Summary of Production and Energy Data for the U.S. Aluminum Industry

The following tables summarize the U.S. aluminum industry production and energy data developed in this report. Energy data are based on requirements to produce a kilogram of aluminum. Process energy is a direct measure of the energy used within a processing facility, the onsite energy. Gross Energy^{tf} is a tacit measure of the total energy consumed and consists of the process energy plus the energy associated with the generation and transmission of electricity, the energy content of fuel products that are used as materials (e.g., carbon used as anodes) and the energy required to produce fuels.

Table A.1: Theoretical, Process, and Gross Energy Requirements

	Ratio of Material to Primary Aluminum Produced	Theoretical Minimum Energy Requirement	Process Energy Required	Overall Process Energy Efficiency	Gross Energy^{tf} Required	Overall Gross Energy^{tf} Efficiency
	<i>kg/kg of Aluminum</i>	<i>kWh/kg of Aluminum</i>	<i>kWh/kg of Aluminum</i>	<i>percent</i>	<i>kWh/kg of Aluminum</i>	<i>percent</i>
Bauxite Mining	5.10	0.00	0.32	0%	0.34	0%
Alumina Refining	1.93	0.27	7.27	4%	7.90	3%
Anode Production	0.45	4.40	5.71	77%	5.96	74%
Aluminum Smelting	1.00	5.99	15.58	38%	46.54	13%
Primary Casting		0.33	1.01	33%	1.46	23%
Secondary Casting		0.33	2.50	13%	2.81	12%
Rolling		0.32	0.63	51%	1.26	25%
Extrusion		0.44	1.30	34%	1.52	29%
Shape Casting		0.33	2.56	13%	2.64	13%

Table A.2: United States Total Energy Requirements and Potential Savings

	U.S. Annual Production 2003	Theoretical Minimum Energy Requirement	U.S. Process Energy Required	Potential Process U.S. Energy Savings	Total U.S. Gross Energy^{tf} Required	Potential Gross U.S. Energy^{tf} Savings
	<i>metric tons</i>	<i>kWh(10⁹) /yr</i>	<i>kWh(10⁹) /yr</i>	<i>kWh(10⁹) /yr</i>	<i>kWh(10⁹) /yr</i>	<i>kWh(10⁹) /yr</i>
Bauxite Mining*						
Alumina Refining*	2,661,500	0.37	10.02	9.65	10.89	10.52
Anode Production	1,230,000	12.12	15.75	3.63	16.45	4.33
Aluminum Smelting	2,758,000	16.52	42.97	26.46	128.36	111.84
Primary Casting	2,704,000	0.90	2.73	1.83	3.94	3.04
Secondary Casting	2,820,000	0.94	7.05	6.11	7.93	6.99
Rolling	4,842,600	1.55	3.04	1.49	6.08	4.53
Extrusion	1,826,000	0.80	2.37	1.57	2.77	1.97
Shape Casting	2,413,000	0.80	6.17	5.36	6.37	5.56
Total		34.00	90.10	56.10	182.77	148.78

* Bauxite is no longer mined in the United States in quantities large enough for commercial aluminum production. Bauxite is imported and refined to alumina in the United States. However, the United States imported 53% of the alumina needed to produce aluminum in 2003 (see Appendix H).

Appendix B: Energy Intensity of Materials Produced in the United States

Aluminum metal is the most energy-intensive major product manufactured in the United States.

Aluminum, by several measures, is one of the most energy-intensive (Btu/lb) materials produced, ranking at the top among the major products of the United States. Table B.1 shows a comparison of the onsite energy requirements for several major products manufactured in the United States. These values do not include the energy content of fuels used as materials or the generation and transmission losses associated with electricity production.

Table B.1: Energy Requirements to Produce Materials in the United States (2002)

	a	b	c	a	b	c
	Btu/yr	Btu/lb	lb/yr	Data Sources [†]		
Paper & Paper Board	2.75E+15	15,590	1.76E+11	MECS	a/c	MECS
Gasoline	2.41E+15	2,659	9.07E+11	b*c	Drexel	EIA(2)
Iron & Steel	1.79E+15	8,700	2.06E+11	b*c	Steel, pg 23	Steel(A), pg 1
Ethylene	4.22E+14	8,107	5.21E+10	b*c	E&E, pg 28	ACC, pg 31
Aluminum (primary ingot)	7.22E+14	44,711	1.62E+10	b*c	Appendix F, Table F.1	Appendix G
Distillate	3.63E+14	990	3.67E+11	b*c	Drexel	EIA(2)
Ammonia	3.53E+14	12,150	2.90E+10	b*c	E&E, pg 32	ACC, pg 31
Propylene	4.30E+13	1,351	3.18E+10	b*c	E&E, pg 28	ACC, pg 31
Jet Fuel	1.46E+14	990	1.47E+11	b*c	Drexel	EIA(2)
Coal	1.29E+14	60	2.14E+12	b*c	EIA(1)	EIA(1)
Benzene	2.03E+13	1,255	1.62E+10	b*c	E&E, pg 30	ACC, pg 31

[†] The data sources in a,b and c columns indicate the source of values in the corresponding data columns. For key to the abbreviations, see Sources for Tables B.1 and B.2 on page 101.

The data in Table B.2 are the onsite process energy requirements to produce the corresponding products plus, the energy content of fuels used as materials, and the generation and transmission losses associated with electricity production. Examples of the energy content of fuels used as materials (feedstock energy) are: 22,681 Btu/lb is the feedstock energy for ethylene; wood products are commonly assumed to have no feedstock value since they are renewable resources; and petroleum calcined coke used as a raw material in aluminum production has a feedstock energy of 15,250 Btu/lb.

Table B.2: Gross Energy Requirements to Produce Materials in the United States (2002)

	a	b	c	a	b	c
	Btu/yr	Btu/lb	lb/yr	Data Sources [†]		
Paper & Paper Board	2.75E+15	15,590	1.76E+11	MECS	a/c	MECS
Gasoline	2.41E+15	2,659	9.07E+11	b*c	Drexel	EIA(2)
Iron & Steel	1.79E+15	8,700	2.06E+11	b*c	Steel, pg 23	Steel(A), pg 1
Ethylene	1.74E+15	33,470	5.21E+10	E&E, pg 28	a/c	ACC, pg 31
Propylene	8.90E+14	27,978	3.18E+10	E&E, pg 28	a/c	ACC, pg 31
Ammonia	6.95E+14	23,917	2.90E+10	E&E, pg 32	a/c	ACC, pg 31
Benzene	5.38E+14	33,305	1.62E+10	E&E, pg 30	a/c	ACC, pg 31
Aluminum (primary ingot)	5.59E+14	94,030	5.95E+09	a*b	Appendix F Table F.1	Appendix G
Distillate	3.63E+14	990	3.67E+11	a*b	Drexel	EIA(2)
Coal	1.29E+14	60	2.14E+12	b*c	EIA(1)	EIA(1)
Jet Fuel	1.46E+14	990	1.47E+11	b*c	Drexel	EIA(2)

[†] The data sources in a,b and c columns indicate the source of values in the corresponding data columns.
For key to the abbreviations, see Sources for Tables B.1 and B.2 below.

Sources for Tables B.1 and B.2

- ACC: Guide to The Business of Chemistry, American Chemical Council, 2003
- Drexel: Energy Analysis of 108 Processes, Harry Brown, Drexel University, 1996
- E&E: Energy and Environmental Profile of the U.S. Chemical Industry, May 2000, DOE-OIT
- EIA(1): Coal Industry Annual 2003, Energy Information Agency, DOE
- EIA(2): Petroleum Annual 2003, Energy Information Agency, DOE
- MECS: Manufacturing Energy Consumption Survey, Energy Information Agency, DOE
- Steel : Energy Use in U.S. Steel Industry: A Historical Perspective and Future Opportunities, Dr. J. Stubbles, Sept 2000
- Steel(A): Steel Industry of the Future, FY 2004 Annual Report, DOE

Appendix C: Energy Values for Energy Sources and Materials

Calorific energy values are the energy content inherent to the material. Except for pure materials, e.g., propane, these values vary depending on the raw materials used and the final products formulations.

Process energy is a measure of the energy required to manufacture the material. Process Energy values are also variable and depend on equipment efficiency estimates and system boundaries. These values for crude oil-derived products are variable and depend on the specific crude processed, refinery configuration, local product specifications and refinery efficiency. Process energy values from the California Energy Commission (CEC) include the energy for processing, as well as factors for raw material, e.g. delivery of crude to refiners and transporting fuels to their point of use.

Tacit or gross energy is the sum of the calorific and process energy values.

Table C.1: Energy Values for Energy Sources and Materials

	Input Unit	Calorific Energy Values "Primary Energy"		Process Energy Values "Secondary Energy"		Tacit Energy		
		Btu per Common Unit	Btu per Input Unit	Btu per Common Unit Required to Produce	Btu per Input Unit	Data Source	Btu per Input Unit	Input Unit
FUELS[†]								
Fuel Oil, medium	kg	139,000 Btu/gal	43,380	5,000 Btu/gal	1,321	Drexel	44,700	kg
Fuel Oil, light	kg	150,000 Btu/gal	46,813	5,000 Btu/gal	1,321	Drexel	48,130	kg
Diesel	L	5,670,000 Btu/bbl	35,667	5,200 Btu/gal	1,374	CEC	37,040	L
Kerosene	L	5,670,000 Btu/bbl	35,667	5,200 Btu/gal	1,374	CEC	37,040	L
Gasoline	L	5,198,000 Btu/bbl	32,698	12,000 Btu/gal	3,170	CEC	35,870	L
Natural Gas	m ³	1,027 Btu/ft ³	36,268	30 Btu/ft ³	1,059	E&E, Mining	37,330	m ³
Bituminous/Sub	kg	11,110 Btu/lb	24,493	60 Btu/lb	132	E&E, pg 52	24,630	kg
Calcined Coke	kg	15,250 Btu/lb	33,620	179 Btu/lb	395	E&E, pg 52	34,010	kg
Pitch	kg	6,065,000 Btu/bbl	38,152	18 Btu/lb	40	E&E, pg 52	38,190	kg
Green Coke	kg	14,200 Btu/lb	31,305	Btu/lb	500	Drexel	31,810	kg
Propane	L	3,824,000 Btu/bbl	24,055	Btu/lb			24,050	L
Coal	kg	10,240 Btu/lb	22,574	60 Btu/lb	132		22,710	kg
ELECTRICITY								
Electric	kWh	1 kWh	3412	Hydroelectric Utility	0	ISO	3,412	kWh
Avg U.S. Electric*	kWh	1 kWh	3412	Average U.S. Grid	6,856	tacit Btu	10,270	kWh
Primary AI Electric**	kWh	1 kWh	3412	Primary AI Electric**	4,208	tacit Btu	7,620	kWh
Coal-Fired Electric	kWh	1 kWh	3412	Coal-Fired Utility	6,976	tacit Btu	10,390	kWh

[†] Fuels and fuels used as materials

* Tacit Btu accounts for generation and transmission energy losses for average U.S. generation (see Appendix D, Table D.4)

** Tacit Btu for electrolysis and anode manufacture is lower than general electricity because of the large 39.4% hydro component

Sources for Table C.1

AEO2004 - Annual Energy Outlook 2004, Energy Information Agency, Jan 2004, pg 262

CEC - California Energy Commission

CIA2000 - Coal Industry Annual 2000, Energy Information Administration, Jan 2002, pg 284. This report uses an average value for bituminous and sub-bituminous coals.

Drexel - data derived from Drexel University study

E&E - the "Energy and Environmental Profile" for Aluminum and Mining (documents from DOE, ITP)

EIA - Emissions of Greenhouse Gases in the United States 1987-1992, Energy Information Agency, Oct 1994 (Appendix A)

ISO - Independent System Operators

EGGUS - Emissions of Greenhouse Gases in the United States 1987-1992, Energy Information Agency, Oct 1994 (Appendix A)

MidCon - data from Mid-Continent Coal & Coke Co.

The process ("secondary energy") energy values contribute about 3% additional energy to the total carbon-based fuel energy of the U.S. aluminum industry. This includes the energy expended worldwide for the production of aluminum in the United States. The United States does not mine bauxite, but refines it to supply 47% of the alumina needed in 2003 and imported the remaining 53% of alumina required for aluminum production.

Table C.2: kWh/yr of Fuels Consumed Worldwide for U.S. Aluminum Processing Excluding Electricity and Coke Feedstock Energy

	Mining	Refining	Anode w/ Feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL
No Process ("secondary energy") inputs for fuels (kWh/yr)	8.86E+08	1.95E+10	1.35E+09	5.00E+08	2.16E+09	6.73E+09	8.62E+08	6.93E+08	2.20E+09	6.16E+09	4.10E+10
With Process ("secondary energy") inputs for fuels (kWh/yr)	9.21E+08	2.00E+10	1.39E+09	5.14E+08	2.22E+09	6.95E+09	8.87E+08	7.17E+08	2.26E+09	6.34E+09	4.22E+10
Percent Process ("secondary energy") fuel contributor	4%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

Tacit electric energy conversion factors vary significantly depending on the fuel source used to generate electricity. The large variation in electric tacit conversion factors creates the need for careful analysis when comparing different studies. A completely coal-fired electric-based smelting operation requires 2.5 times greater tacit energy than a completely hydroelectric smelting operation (Appendix D, Table D.1).

Table C.3: Impact of Electric Tacit Conversion Factors on kWh/yr Consumed Worldwide for U.S. Aluminum Production

	Mining	Refining	Anode w/ Feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL
Average U.S. Aluminum Processing Facilities											
10,270 Btu of energy required to produce 1 kWh of onsite electrical power for all U.S. aluminum facility operations.											
kWh/yr	9.38E+08	2.18E+10	1.64E+10	1.28E+11	3.94E+09	7.93E+09	2.82E+09	3.26E+09	2.77E+09	6.37E+09	1.95E+11
Percent increase relative to a facilities with 100% hydroelectric energy resource	4%	9%	4%	199%	44%	12%	87%	112%	17%	3%	93%
U.S. Aluminum Processing Facilities with 100% electrical power generated by hydroelectric utilities											
3,412 Btu of energy required to produce 1 kWh of onsite electrical power from hydroelectric resources for all U.S. aluminum facilities:											
kWh/yr	8.99E+08	2.00E+10	1.57E+10	4.30E+10	2.73E+09	7.05E+09	1.50E+09	1.54E+09	2.37E+09	6.17E+09	1.01E+11
U.S. Aluminum Processing Facilities with 100% electrical power generated by coal-fired utilities											
10,390 Btu of energy required to produce 1 kWh of onsite electrical power from coal resources for all U.S. aluminum facilities											
kWh/yr	9.38E+08	2.18E+10	1.65E+10	1.33E+11	4.00E+09	7.97E+09	2.90E+09	3.36E+09	2.79E+09	6.37E+09	2.00E+11
Percent increase relative to a facilities with 100% hydroelectric energy resource	4%	9%	5%	211%	47%	13%	93%	119%	18%	3%	98%

Appendix D: Hydroelectric Distribution and Electrical Energy Values

Significant energy is consumed in the generation and transmission of electricity. Tacit electric energy conversion factors include the energy associated with production, processing and distribution of the "primary-energy" sources used in the production of electricity. Tacit values vary significantly depending on the source of energy.

In the United States, 39.4% of aluminum smelting capacity utilizes hydroelectric power.¹

Table D.1: Electric Tacit Energy and Emission Data for Fuels Used for Aluminum Production

Electrical Energy Source	U. S. Primary Aluminum Capacity ¹		Heat Rate ² (2003) <i>Btu/kWh</i>	Carbon Emission Coefficient ³ <i>Mt/Qbtu</i>
	<i>metric tons</i>	<i>%</i>		
Hydro	1,633,696	39.4%	3,412	0
Coal	2,415,826	58.2%	10,388	21.25
Oil	8,245	0.2%	10,203	19.08
Natural Gas	31,120	0.8%	8,021	12.50
Nuclear	60,112	1.4%	10,440	0
Total	4,149,000	100.0%		
Weighted Averages based on Aluminum Capacity			7,624	12.51
<i>Average US Grid ⁴</i>			10,268	13.56

¹ The distribution of electrical sources for U.S. Primary Aluminum capacity is obtained by subtracting the Canadian capacity of 2.827 million metric tons (2002), which is 100% hydroelectric, from the North American Totals presented in Table D.2.

² Heat Rate values are derived using the Primary energy values in Appendix C, Table C.1 and the Net Generation and Consumption values listed in the "Annual Energy Review 2003," Energy Information Administration, pg 224.

³ Carbon Emission Coefficient values are derived using the Heat Rate Values in this table and the Electric Power Industrial Sector Carbon Dioxide Emissions by Fuel Input for Year 2000 listed in the "Emissions of Greenhouse Gases in the United States 2000," Energy Information Agency, November 2001, page 23.

⁴ Appendix D, Table D.4

This Report Uses

10,270 Tacit Btu per kWh for all electricity consumed in U.S. aluminum processing operations. This value overstates the actual aluminum related tacit values (which is 7,620 Btu/kWh); but it is more useful for comparing the aluminum industry to other U.S. manufacturing operations.

Electrical Power Used In Primary Aluminium Production Worldwide

Table D.2: Energy Sources of Electrical Power in 2002 (electrical power used in gigawatt hours)

Electric Energy Source	Africa	North America		Latin America	Asia	Europe	Oceania	Total	Grand Total
	<i>GWh</i>	<i>GWh</i>	%	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	%
Hydro	6,444	50,312	64%	32,207	3,030	29,969	7,380	129,342	50%
Coal	13,443	27,248	35%	0	10,080	15,773	24,120	90,664	35%
Oil	0	93	0%	0	109	1,279	0	1,481	1%
Natural Gas	38	351	0%	1,343	16,336	6,199	0	24,267	9%
Nuclear	189	678	1%	0	0	12,672	0	13,539	5%
Total	20,114	78,682	100%	33,550	29,555	65,892	31,500	259,293	100%

Table D.3: Sources of Supply of Electrical Power in 2002 (electrical power used in gigawatt hours)

Electric Source of Supply	Africa	North America		Latin America	Asia	Europe	Oceania	Total	Grand Total
	<i>GWh</i>	<i>GWh</i>	%	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	<i>GWh</i>	%
Self-Generated	0	27,702	35%	4,386	28,228	9,193	1,244	70,753	27%
Purchased - Grid	20,114	39,015	50%	28,863	1,327	56,698	23,237	169,254	65%
Purchased - Other	0	11,965	15%	301	0	1	7,019	19,286	7%
Total	20,114	78,682	100%	33,550	29,555	65,892	31,500	259,293	100%
Self-Generated Other Purposes	0	351		253	2,662	1	0	3,267	

Tables D.2 and D.3 Source:
 International Aluminum Institute,
 New Zealand House, Haymarket,
 London SW1Y 4TE,
 United Kingdom
<http://www.world-aluminium.org/iai/stats>

Significant energy is consumed in the generation and transmission of electricity. Tacit electric energy conversion factors (Btu/kWh) include the energy associated with production, processing and distribution of the "primary-energy" sources used in the production of electricity. Tacit values vary significantly depending on the source of energy to produce electric power.

Table D.4: Average U.S. Grid Connection Tacit Energy

	U.S. Electricity Net Generation in 2003 ¹		Units Consumed ²	Heat Content	Energy Consumed 10 ⁹ Btu (d)	Btu/kWh (d) ÷ (a)
	billion kWh (a)	%				
Coal	1,970.3	51%	1,014.3 X 10 ⁶ short tons	20,620,000 Btu/ton ³	20,468,000 ⁸	10,388
Petroleum			30.3 X 10 ⁶ bbl Distillate	5,825,000 Btu/gal ³	176,498 ⁹	
			142.6 X 10 ⁶ bbl Residual	6,287,000 Btu/bbl ³	896,526 ⁹	
			3.4 X 10 ⁶ bbl Other Liquids	5,670,000 Btu/bbl ^{5,3}	19,278 ⁹	
			6.4 X 10 ⁶ short tons Coke	14,200 Btu/lb ⁶	181,760 ⁹	
Sub-Total	118.3	3%			1,207,000 ⁸	10,203
Natural Gas	629.2	16%	5,380 X 10 ⁹ ft ³	1,019 Btu/ft ³ ³	5,047,000 ⁸	8,021
Nuclear	763.7	20%	10,000 Btu/kWh ⁷		7,973,000 ⁸	10,440
Hydroelectric	275.0	7%	9,578 Btu/kWh ⁴		2,634,000 ⁸	9,578
Renewable	84.2	2%	957 X 10 ¹² Btu		896,000 ⁸	10,641
Other	5.1	0%	27 X 10 ¹² Btu		22,000 ⁸	4,314
Sub-Totals	3,845.8	100%			38,247,000	9,945
Transmission Losses					1,243,030	
TOTALS	3,845.8	100%			39,490,030	10,268

¹ AER2003 - Annual Energy Review 2003. Table 8.2a Electricity Net Generation, page 224

² AER2003 - Annual Energy Review 2003. Table 8.5a Consumption of Combustable Fuels for Electricity Generation, page 238

³ AEO2004- Annual Energy Outlook 2004, Energy Information Agency, Jan 2004 pg 262

⁴ Assumes that a substitute for hydropower is equivalent to the average of the other sources of electricity

⁵ Assumes diesel fuel is the majority of other fuels

⁶ Data from Mid-Continent Coal & Coke Co. for green petroleum coke

⁷ Data from Nuclear Energy Institute

⁸ AER2003 - Annual Energy Review 2003. Table 2.1f Electric Power Sector Energy Consumption, page 43

⁹ (c) x (b)

Appendix E: Emission Data and Calculations

Table E.1 presents the carbon dioxide equivalent emission values for the fuels and materials associated with the production of aluminum metal and aluminum products.

Table E.1: Carbon Dioxide Equivalent Emission Coefficients for Fuels Associated with Aluminum Production

FUEL	Input Unit (Appendix F)	Btu per input unit	Carbon Emission Coefficient	Carbon Emission Coefficient Source	Percent Carbon (EGGUS)	API Gravity (EGGUS)	Density (EGGUS) Pounds/gal	Million Btu/bbl (EGGUS)	Emissions per input unit Kilogram CDE †	FUEL
Fuel Oil, Heavy (#6)	kg	44,700	21.49	EGGUS	85.7	17.0	6.287	3,40E+00	Fuel Oil, Heavy (#6)	
Fuel Oil, medium	kg	48,130	20.72	a	86.3	33.9	7.064	3,52E+00	Fuel Oil, medium	
Fuel Oil, light (#2)	kg	37,040	19.95	b	86.3	35.5	7.064	2,71E+00	Fuel Oil, light	
Diesel	L	37,040	19.95	EGGUS	86.1	41.4	5.670	2,68E+00	Diesel	
Kerosene	L	35,870	19.34	EGG2000	86.6	58.6	5.253	2,54E+00	Kerosene	
Gasoline	L	37,330	14.47	EGG2000	n/a	n/a	2.33E+00	1,98E+00	Gasoline	
Natural Gas	m ³	24,630	25.81	EGGUS	85.8	25.6	3,47E+00	2,89E+00	Natural Gas	
Bituminous/Sub	kg	34,010	27.85	c	92.3	n/a	6.024	3,25E+00	Bituminous/Sub	
Calcined Coke	kg	38,190	20.62	d	n/a	n/a	1.52E+00	2,15E+00	Calcined Coke	
Pitch	kg	31,810	27.85	EGG2000	n/a	n/a	n/a	n/a	Pitch	
Green Coke	kg	24,050	17.20	EGGUS	n/a	n/a	n/a	n/a	Green Coke	
Propane	L	22,710	25.76	EGG2000	n/a	n/a	n/a	n/a	Propane	
Coal	kg	3,412	0.0	EGG2000	n/a	n/a	n/a	n/a	Coal	
Electricity										
Hydro Electric	kWh	10,270	13.56	EGG2000	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Hydro Electric	
Average U.S. Electric	kWh	7,620	12.51	e	5.11E-01	5.11E-01	5.11E-01	5.11E-01	Average U.S. Electric	
Primary Al Electric	kWh	10,390	21.25	EGG2000	3.49E-01	3.49E-01	3.49E-01	3.49E-01	Primary Al Electric	
Coal-Fired Electric	kWh	10,390	21.25	EGG2000	8.10E-01	8.10E-01	8.10E-01	8.10E-01	Coal-Fired Electric	

* M/Qbtu - million metric tons per Quadrillion Btu (10⁶ metric tons / 10¹⁵ Btu)

† CDE - Carbon Dioxide Equivalent

SOURCES

- EGG2000 Emission of Greenhouse Gases in the United States 2000, Energy Information Agency, Nov 2001, page 140
- EGGUS Emissions of Greenhouse Gases in the United States 1987-1992, Energy Information Agency, Oct 1994, Appendix A
- a Medium Fuel Oil values are the average of the light and heavy fuel oil values
- b Diesel and light fuel oil is assumed to have the same carbon coefficient in EGGUS
- c Green coke and Calcined coke are assumed to have the same carbon coefficient
- d Pitch is assumed to have the same carbon coefficient as asphalt reported in EGGUS
- e Primary Aluminum Carbon Dioxide Equivalent are based on the industry's mix of fuels (Appendix D, Table D.1)

Table E.2 uses the units of Energy Input from Table F.1 and calculates the CDE emissions for each Energy Input based on the CDE values for fuels presented in Table E.1.

Table E.2: Carbon Dioxide Equivalent (CDE) Emissions Associated with Primary Aluminum Production

Input/Output	Mining	Refining	Anode	Electrolysis	Primary Aluminum Production	Total CDE emissions from manufacturing the raw materials and electrolytic reduction required to produce aluminum
Rich Soil	1,150					
Bauxite	1,000	2,640	820	1,930		
Alumina		1,000	231			
Calcined Coke			85			
Pitch			1,000			
Green Coke				446		
Anode				18.6		
Fluorides				1,000		
Aluminum				Aluminum		
Ratio to Aluminum	Bauxite	Alumina	Anode	Aluminum		
Energy Inputs per 1,000 kg	units	kg CDE	units	kg CDE	units/kg Al	kg CDE/kg Al
Fuel Oil, medium	1.160	3.94E+00	3,790	1.29E+01	187.48	6.37E+02
Fuel Oil, light (#2)	4.370	1.18E+01	0.814	2.87E+00	0.36	1.28E+00
Diesel	0.274	6.97E-01	0.110	2.98E-01	25.54	6.92E+01
Kerosene			0.046	1.17E-01	-	0.00E+00
Gasoline			97.1	1.92E+02	1.46	3.72E+00
Natural Gas			225	4.46E+02	477.56	9.46E+02
Bituminous/Sub			8.59	2.00E+01	16.58	3.86E+01
Calcined Coke			0.00134	4.65E-03	365.72	1.27E+03
Pitch			231	6.67E+02	103.03	2.97E+02
Green Coke			85	2.76E+02	37.91	1.23E+02
Propane			0.136	2.06E-01	0.06	9.20E-02
Coal	0.4	2.04E-01	266	9.30E+01	1.57E+04	1.50E+02
Electric			VOC	4.99E-01		
TOTAL per 1000 kg						
Total kg CDE	1.67E+01	8.42E+02	4.09E+03	5.42E+03		8.96E+03
Manufacturing portion kg CDE	1.67E+01	8.42E+02	3.02E+02	5.42E+03		7.18E+03
Feedstock portion CDE			3.79E+03			1.69E+03
kg CDE / kg Al	0.085	1.626	1.83	5.42		8.96
Total Material Production in the U.S. for Aluminum Manufacturing	0	3,488,400	1,230,000	2,758,000		
metric tons						
Total U.S. Production Carbon Dioxide Emissions	0	2,938,677	5,034,490	14,953,252		22,870,282
metric tons CDE						
Total Material Production Worldwide for Use in the U.S. for Aluminum Manufacturing		5,323,000	1,230,000	2,758,000		
metric tons						
Total Worldwide Emissions Based on U.S. Production	234,418	4,484,170	5,034,490	14,953,252		27,047,491
metric tons CDE						
kg CDE / kg Al						9.81

Table E.3 uses the units of Energy Input from Table F.2 and calculates the CDE emissions for each Energy Input based on the CDE values for fuels presented in Table E.1

Table E.3: Carbon Dioxide Equivalent (CDE) Emissions Associated with Aluminum Production

Input/Output	Primary Ingot Casting		Secondary Ingot Casting		Hot Rolling		Cold Rolling		Extrusion		Shape Casting	
	units	kg CDE	units	kg CDE	units	kg CDE	units	kg CDE	units	kg CDE	units	kg CDE
Electrolysis Metal	1,020		21		498		474		559			
Alloy Additives			676		723		722		885			
Scrap			346		1,000		1,000		1,000			
Primary Ingot		Yield: 98%		Yield: 96%		Yield: 82%		Yield: 84%		Yield: 69%		Yield: 45%
Secondary Ingot	1,000		1,000		1,000		1,000		1,000		2,200	1,000
Product											2,200	1,000
												45%
Energy Inputs per 1,000 kg	<i>units</i>	<i>kg CDE</i>	<i>units</i>	<i>kg CDE</i>	<i>units</i>	<i>kg CDE</i>	<i>units</i>	<i>kg CDE</i>	<i>units</i>	<i>kg CDE</i>	<i>units</i>	<i>kg CDE</i>
Fuel Oil, medium	17.4	61	42.3	149	0.040	0.109	0.038	0	0.002	0	0	0
Fuel Oil, light (#2)	0.184		31,464	85	0.007	0			0.417	1		
Diesel					0.007				0.028	0		
Kerosene	0.075	0	12,757	32	0.007	0	2,150	5	0.044	0		
Gasoline	51.8	103	126.0	250	33.4	66	24.8	49	103.0	204		475
Natural Gas												
Bituminous/Sub												
Calcedined Coke												
Pitch												
Green Coke	0.798	1	1.941	3	0.034	0	0.238	0	4.460	7		
Propane									11.200	24		
Coal									93	47.49		
Electric	211	73.74	115,000	58.73	265	135.32	349	178.22			4	2.06
TOTAL per 1000 kg												
Total kg CDE		2.39E+02		5.78E+02		2.02E+02		2.33E+02		2.84E+02		4.77E+02
Total Material Production in the U.S. for Aluminum Manufacturing												
metric tons	2,704,000		2,820,000		2,421,300		2,421,300		1,826,000		2,413,000	
Total U.S. Production Carbon Dioxide Emissions												
metric tons CDE		646,233		1,629,782		488,308		564,819		517,866		1,151,974
kg of Carbon Dioxide Equivalent per kilogram of Product												
kg CDE/kg Al	10.05		0.58		0.20		0.23		0.28		0.48	

Table E.4 provides comparison of the ore-to-metal Carbon Dioxide Equivalent (CDE) emissions for a modern Hall-Héroult cell with the CDE emissions for improved Hall-Héroult and alternative technologies.

Table E.4: Carbon Dioxide Equivalent Emissions Associated with New Aluminum Production Technologies

	Typical modern Hall-Héroult cell operating at 95% current efficiency and with an ACD = 4.5 cm	Typical modern Hall-Héroult cell operating at 95% current efficiency, retrofitted with a sloped and wetted cathode surface, aluminum sump, and a reduced ACD, ACD = 2.0 cm	Inert anode operating at 95% current efficiency with oxygen polarization differences and using wetted cathode technology, ACD = 2.0 cm	Carbothermic Reduction with a reaction efficiency of 95% and a furnace efficiency of 85% with electric furnace operating on the Average U.S. grid	Chloride Reduction of kaolinite clays, electrolysis current efficiency 95%, and heating efficiency 85%, onsite electric furnace and electrolysis cell operating on the Average U.S. grid	
Mineral Material	kWh/kg Al	kgCO ₂ /kg Al	kWh/kg Al	kgCO ₂ /kg Al	kWh/kg Al	kgCO ₂ /kg Al
Tacit Energy Required	8.24	1.71	8.24	1.71	8.84	1.84
Onsite Reaction Energy Requirements						
Reaction Thermal Furnace Losses						
Reaction Electrolysis	3.76	1.32	6.90	2.41	7.71	3.94
Cell Ohmic	10.67	3.73	6.20	2.17	1.93	0.98
TOTAL Reaction Energy	14.43	5.04	13.11	4.58	9.63	4.92
Anode Related Emissions						
Anode Manufacturing	0.61	0.13	0.77	0.27		
Anode Use						
Anode Reaction	0.33 kg	1.22				
Anode Excess (Air Burning)	0.11 kg	0.30				
Total Anode	1.66	1.66				
Process Related Emissions						
Carbon Reactant					0.66 kg	2.45
Perfluorocarbon		2.20		0.00		0.00
TOTAL CO₂ Emissions						
Mineral Material	1.71	1.71	1.71	1.71	1.71	1.84
Reactions	5.04	3.98	4.58	4.58	4.92	4.04
Carbon	1.66	1.66	0.00	0.00	2.45	3.27
Process	2.20	0.55	0.00	0.00	0.00	0.00
TOTAL	10.62	7.90	6.29	6.29	9.08	9.15

Table F.2: Materials and Energy Associated with Aluminum Manufacturing Operations

Input/Output	Primary Ingot Casting	Secondary Ingot Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting
Electrolysis Metal	1,020					
Alloy Additives		21				
Scrap		676				
Primary Ingot		346	498	474	559	
Secondary Ingot			723	722	885	2,200
Product			1,000	1,000	1,000	1,000
		Yield: 98%	Yield: 82%	Yield: 84%	Yield: 69%	Yield: 45%
Energy Inputs per 1,000 kg	<i>units</i>	<i>Btu</i>	<i>units</i>	<i>Btu</i>	<i>units</i>	<i>Btu</i>
Fuel Oil, medium		42.3	0.040	0.038	0.002	0.002
Fuel Oil, light	17.4	1,981,346	1,441	1,362	0.417	109
Diesel	0.184	1,122,230	249		0.028	14,873
Kerosene			0.007	2.150	0.044	988
Gasoline	0.075	417,115	0.007	24.8	103.000	1,442
Natural Gas	51.8	4,569,793	33.4	899,451		3,735,624
Bituminous/Sub						240,000
Coke						8,704,367
Propane	0.798	19,196	0.034	0.238	4.460	107,285
Anthracite					11,200	252,829
Electric	211	392,380	265	349	93	317,316
						4
						13,750
TOTAL ENERGY INPUTS (Energy per kg of Output)						
Btu/kg	3,441	8,530	2,118	2,168	4,430	8,718
kWh/kg	1.01	2.50	0.62	0.64	1.30	2.56
TACIT ENERGY INPUTS (Energy per kg of Output)						
Btu/kg	4,967	9,591	3,971	4,594	5,180	9,001
kWh/kg	1.46	2.81	1.16	1.35	1.52	2.64

Table F.3 lists the theoretical minimum energy requirements to produce raw materials and aluminum products. It also shows the process efficiency for each operation. Mining, refining, anode manufacturing and electrolysis minimum energy values are based on the net chemical changes that result from these processes. Primary casting, secondary casting, and shape casting minimum energy values are based on the energy required to produce molten pure aluminum at 775 °C. The minimum energy requirements for rolling and extrusion operations are estimated from their yield and onsite energy consumption values in Table F.2, and from an overall assumed electric and hydraulic system efficiencies of 75% and thermal furnace and heating efficiencies of 50%.

Table F.3: Theoretical Minimum Energy Requirements to Produce Raw Materials and Aluminum Products

	Mining	Refining	Anode w/ Feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting
kWh/kg		0.14	12.97	5.99	0.33	0.33	0.31	0.33	0.44	0.33
Ratioed to Al		0.27	4.40	5.99	0.33	0.33	0.31	0.33	0.44	0.33
Current Practice Onsite Process Efficiency %		4%	77%	38%	33%	13%	50%	52%	34%	13%

Table F.4 lists U.S. production quantities, and energy and tacit energy consumption associated with producing aluminum products within the United States. The United States does not consume energy to produce metallurgical bauxite, and consumes only 79% of the energy required for alumina. This report distinguishes between the worldwide energy values and the United States values in order to measure the impact of market or process changes to the energy demands within the United States. Table F.9 lists the worldwide values. The theoretical magnitude of the potential U.S. energy savings can be measured by subtracting the theoretical energy requirements from the actual energy consumption numbers.

Table F.4: U.S. Energy Use in the Production of Domestic Aluminum

	Mining	Refining	Anode w/ Feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling *	Extrusion *	Shape Casting	TOTAL ENERGY
Material Production within the United States										
metric tons (2003)	0	3,488,400	1,230,000	2,758,000	2,704,000	2,820,000	2,421,300	2,421,300	1,826,000	2,413,000
On-Site Energy Consumed in Production for the U.S. Aluminum Industry										
ratioed* to Al		3.76	12.80	15.58	1.01	2.50	0.62	0.64	1.30	2.56
Total		7.27	5.71	15.58	1.01	2.50	0.62	0.64	1.30	2.56
Proportion of U.S. Energy Used		14%	17%	46%	3%	8%	2%	2%	3%	7%
					80%	Total U.S. Primary proportion				100%
Total TACIT Energy Consumed in Production for the U.S. Aluminum Industry										
ratioed* to Al		4.09	13.37	46.54	1.46	2.81	1.16	1.35	1.52	2.64
Total		7.90	5.96	46.54	1.46	2.81	1.16	1.35	1.52	2.64
Proportion of U.S. Energy Used		1.43E+10	1.64E+10	1.28E+11	3.94E+09	7.93E+09	2.82E+09	3.26E+09	2.77E+09	6.37E+09
		7.7%	8.8%	69.0%	2.1%	4.3%	1.5%	1.8%	1.5%	3.4%
					87.6%	Total U.S. Primary proportion				100%
Theoretical Magnitude of Opportunities for U.S. Energy Savings										
Tacit kWh/yr		1,26E+10	-1.99E+08	2.65E+10	1.83E+09	6.11E+09	7.56E+08	7.36E+08	1.57E+09	5.36E+09
		1.38E+10	4.98E+08	1.12E+11	3.04E+09	6.99E+09	2.07E+09	2.46E+09	1.97E+09	5.56E+09
										1.48E+11

* Data is from 2000. These are the latest numbers available that are specific to the U.S. production. After 2000, the numbers are based on North American data and not specifically the U.S. data.

Table F.5 shows the total energy values consumed by the U.S. aluminum industry and the energy savings possible if:

- a. it was possible to reduce energy consumption to the theoretical limit,
- b. energy were reduced by 30%, or
- c. electrolysis electrical energy were reduced from 15 to 11 kWh/kg of aluminum

Table F.5: Total U.S. Aluminum Industry Energy Consumption and Potential Savings

U.S. Aluminum Industry	kWh/yr	Quads/yr	MW	Households	bbl crude per year
Total Energy Use	on-site	9.32E+10	0.32	10,600	10,600,000
	tacit	1.86E+11	0.64	21,300	21,300,000
Theoretical Requirement	on-site	3.79E+10	0.13	4,300	4,300,000
	tacit	3.79E+10	0.13	4,400	4,400,000
Energy Efficiency	on-site	41%			
	tacit	20%			
a. Theoretical Opportunity					
	on-site	5.53E+10	0.19	6,300	6,300,000
	tacit	1.48E+11	0.51	16,900	16,900,000
b. Practical Goal (Vision)					
	on-site	2.80E+10	0.10	3,180	3,200
	tacit	5.58E+10	0.19	6,390	6,400
c. Electrolysis Savings of 4 kWh/kg					
	on-site	1.10E+10	0.04	1,259	1,300
	tacit	2.46E+10	0.08	2,813	2,900

Table F.6 shows 94% reduction in energy consumption associated with secondary metal production. Recycling aluminum essentially recaptures all the energy associated with mining, refining and smelting.

Table F.6: Energy Impact of Recycling

Energy Saved with Recycling	(Tacit Energy Values)
62.2 kWh/kg to produce Primary Metal Ingot	
2.8 kWh/kg to produce Secondary Metal Ingot	
4.5% Secondary to Primary Energy	
2,820,000 kg of Secondary Metal produced in 2003	
1.67E+11 kWh/yr Energy Saved in 2003	
0.57 Quads Saved per Year 2003	
19,100 MW SAVED 2003	

Table F.7 shows the electric energy consumption of the U.S. aluminum industry and compares it to the total electric energy produced in the United States.

Table F.7: U.S. Electric On-site Energy Consumption in the Aluminum Industry

	Refining	Anode w/ Feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL ELECTRIC ENERGY
metric tons (2003)	3,488,400	1,230,000	2,758,000	2,704,000	2,820,000	2,421,300	2,421,300	1,826,000	2,413,000	
kWh/kg	0.109	0.266	15,400	0.211	0.115	0.265	0.349	0.093	0.004	
kWh/yr	3.80E+08	3.27E+08	4.25E+10	5.71E+08	3.24E+08	6.42E+08	8.45E+08	1.70E+08	9.72E+06	4.57E+10
Total U.S. Al Industry Electrical Use:										
	on-site	5,222	kWh/yr							0.16
		5,222,000	MW							
	total	54,000,000	households	Net U.S. Generation:	3.858E+12	kWh/yr				(Source: eia.doe.gov/cneaff/electricity)
			bbl crude	Aluminum's % of U.S. Net:	1.2%					

Electrolysis and process heating are the two most energy-intensive process areas of the aluminum industry. Electrolysis accounts for 46% of all onsite and 69% of all tacit energy use. Process heating accounts for 27% of all onsite and 13% of all tacit energy use in the industry.

Table F.8: Smelting and Heating Fractions of Total U.S. Aluminum Industry Energy Consumed

Smelting Fraction of Total U.S. Aluminum Industry Energy Consumed										
Electrolysis										
Onsite	Tacit								Total Industry	Percent of Industry
		kWh/yr	4.30E+10						9.32E+10	46%
		kWh/yr	1.28E+11						1.86E+11	69%
Aluminum Metal Process Heating/Melting Fraction of Total U.S. Aluminum Industry Energy Consumed										
Casting Extrusion Hot Rolling Cold Total Process Heating										
Onsite	Tacit								Total Industry	Percent of Industry
		Btu/kg Al	9,244	1,212	905	4,096	8,704	2,42E+04	9.32E+10	27%
		kWh/kg Al	2.71	0.36	0.27	1.20	2.55	7.08E+00	1.86E+11	13%
		kWh/yr	1.50E+10	8.60E+08	6.42E+08	2.19E+09	6.16E+09	2.48E+10		
Note: The tacit increase for process heating is negligible										

Table F.9 lists the worldwide production quantities, energy, and tacit energy consumption associated with producing aluminum products within the United States. These values provide a full measure of the energy associated with producing aluminum and aluminum products. The actual energy consumed within the United States is lower since no aluminum metallurgical bauxite is mined in the United States, and only 47% of the alumina required is refined in the United States.

Table F.9: Total Worldwide Production and Energy Consumption Associated with Producing Aluminum in the United States

	Mining*	Refining*	Anode* w/ Feedstock	Electrolysis*	Primary Casting	Secondary Casting	Hot Rolling†	Cold Rolling†	Extrusion†	Shape Casting	TOTAL ENERGY	
* ratios to primary aluminum	5.70	1.93	0.45	1.00								
Total Worldwide Production Required to Produce Aluminum in the United States												
metric tons (2003)	14,053,000	5,323,000	1,230,000	2,758,000	2,704,000	2,820,000	2,421,300	2,421,300	1,826,000	2,413,000		
Total On-Site Energy Consumed in Worldwide Production for U.S. Aluminum Industry												
ratioed* to Al	KWh/kg	3.76	12.80	15.6	1.01	2.50	0.62	0.64	1.30	2.56		
Total	KWh/kg Al	0.32	5.71	15.6	1.01	2.50	0.62	0.64	1.30	2.56		
% Relative to Electrolysis*	KWh/yr	8.92E+08	1.57E+10	4.30E+10	2.73E+09	7.05E+09	1.50E+09	1.54E+09	2.37E+09	6.17E+09	1.01E+11	
Proportion of Energy Used		2.1%	36.6%	100.0%	6.3%	16.4%	3.5%	3.6%	5.5%	14.3%	100.0%	
		0.9%	15.6%	42.5%	2.7%	7.0%	1.5%	1.5%	2.3%	6.1%		
Total TACIT Energy Consumed in Worldwide Production for the U.S. Aluminum Industry												
ratioed* to Al	KWh/kg	0.07	4.09	46.5	1.5	2.8	1.2	1.3	1.5	2.6		
Total	KWh/kg Al	0.34	7.90	46.5	1.5	2.8	1.2	1.3	1.5	2.6		
% relative to Electrolysis	KWh/yr	9.38E+08	2.18E+10	1.28E+11	3.94E+09	7.93E+09	2.82E+09	3.26E+09	2.77E+09	6.37E+09	1.95E+11	
Proportion of Energy Used		0.7%	17.0%	100.0%	3.1%	6.2%	2.2%	2.5%	2.2%	5.0%	100.0%	
		0.5%	11.2%	66.0%	2.0%	4.1%	1.4%	1.7%	1.4%	3.3%		
					82% Total Primary proportion							
					88% Total Primary proportion							

† Data is from 2000. This is the last year numbers specific to U.S. production are available. After 2000, the numbers are based on North American data, and not specifically U.S. data.

Table F.10 divides energy uses in aluminum casting and semi-fabrication manufacturing operations into three areas: electric, heating and miscellaneous fuels. The following percentages of energy use are derived from the energy values listed in Table F.2. Fuel oils, natural gas and propane are assumed to be associated with heating (thermal operations). Miscellaneous fuels include all other fuels and it is assumed that these are fuels used in non-heating operations, such as transportation and collection of materials. (Note: rounding causes some totals to differ from 100%)

Table F.10: Percent Break-Up of Different Types of Energy Used in Aluminum Production Operations

	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting
Onsite:						
% onsite electric	21%	5%	43%	55%	7%	0%
% heating	79%	77%	57%	42%	87%	100%
miscellaneous fuels	0%	18%	0%	3%	6%	0%
Tacit:						
% tacit electric	36%	9%	62%	72%	72%	14%
% heating	63%	73%	38%	25%	25%	80%
miscellaneous fuels	0%	17%	0%	3%	3%	6%

Appendix G: U.S. Primary, Secondary and Imported Aluminum Quantities, 1960-2003

Table G.1: U.S. Supply of Aluminum from 1960 to 2003 (in Thousand Metric Dry Tons)

Year	U.S. Primary Aluminum	U.S. Secondary Aluminum	U.S. Aluminum Imports	U.S. Total Aluminum
1960	1,828	401	178	2,407
1961	1,727	445	230	2,402
1962	1,921	533	341	2,795
1963	2,098	601	419	3,118
1964	2,316	648	409	3,373
1965	2,499	774	543	3,816
1966	2,693	833	591	4,117
1967	2,966	821	466	4,253
1968	2,953	935	684	4,572
1969	3,441	1,067	484	4,992
1970	3,607	937	406	4,950
1971	3,561	1,004	582	5,147
1972	3,740	1,022	684	5,446
1973	4,109	1,127	523	5,759
1974	4,448	1,163	511	6,122
1975	3,519	1,121	453	5,093
1976	3,857	1,334	608	5,799
1977	4,117	1,456	683	6,256
1978	4,358	1,518	907	6,783
1979	4,557	1,612	711	6,880
1980	4,653	1,577	603	6,833
1981	4,489	1,790	782	7,061
1982	3,274	1,666	823	5,763
1983	3,353	1,773	1,023	6,149
1984	4,099	1,760	1,376	7,235
1985	3,500	1,762	1,332	6,594
1986	3,039	1,773	1,843	6,655
1987	3,347	1,986	1,702	7,035
1988	3,945	2,122	1,467	7,534
1989	4,030	2,054	1,353	7,437
1990	4,048	2,393	1,421	7,862
1991	4,121	2,286	1,398	7,805

Table G.1: U.S. Supply of Aluminum from 1960 to 2003 (in Thousand Metric Dry Tons) *(Continued)*

Year	U.S. Primary Aluminum	U.S. Secondary Aluminum	U.S. Aluminum Imports	U.S. Total Aluminum
1992	4,042	2,756	1,573	8,371
1993	3,695	2,944	2,327	8,966
1994	3,299	3,086	3,136	9,521
1995	3,375	3,188	2,701	9,264
1996	3,577	3,307	2,572	9,456
1997	3,603	3,547	2,804	9,954
1998	3,713	3,442	3,264	10,419
1999	3,779	3,695	3,680	11,154
2000	3,668	3,450	3,580	10,698
2001	2,637	2,970	3,487	9,094
2002	2,705	2,927	3,947	9,579
2003	2,704	2,820	4,068	9,592
Average Growth Rate 1993 through 2003				
	-2.5%	-0.4%	5.1%	0.6%
Percent of Total Supply (2003)				
	28%	29%	42%	100%

Source: Aluminum Statistical Review for 2003, The Aluminum Association, 2004, p. 7

The growth rates utilized in this report are based on a linear regression of data over ten year period from 1993 through 2003. Linearizing the data provides a better value for average growth over the period than a simple comparison of 1993 to 2003.

	Primary	Secondary	Imports	Supply
Linear regression for 1993 through 2003				
slope	-83.5	-13.4	156.4	59.4
intercept	170,211	30,026	-309,163	-108,927
Linearized values				
1993	3,759	3,283	2,452	9,494
2003	2,924	3,149	4,015	10,088
Linearized growth from 1993 to 2003				
Avg Growth	-2.5%	-0.4%	5.1%	0.6%
U.S. Aluminum Production Growth (Primary & Secondary Combined)				-1.47%

Appendix H: U.S. Bauxite and Alumina Quantities, 1960-2003

Table H.1: U.S. Supply of Bauxite and Alumina from 1960 to 2003 (in Thousand Metric Dry Tons)

A	B	C	D	E	F	G	H	I
Year	Imports of Bauxite	U.S. Mined Bauxite	Exports of Bauxite	Net Bauxite Supply	Estimated Alumina Production from Bauxite	Imports of Alumina	Exports of Alumina	Estimated Net Alumina for Electrolysis
1960	8,879	2,030	29	10,880	4,651	80		4,266
1961	9,354	1,248	153	10,449	4,467	171		4,191
1962	10,745	1,391	263	11,873	5,076	158		4,726
1963	9,408	1,549	206	10,751	4,596	173		4,309
1964	10,518	1,627	283	11,862	5,071	191		4,755
1965	11,601	1,681	149	13,133	5,614	206	290	4,969
1966	11,928	1,825	63	13,690	5,852	443	290	5,420
1967	12,010	1,681	2	13,689	5,852	865	499	5,633
1968	11,359	1,692	7	13,044	5,576	1,190	780	5,429
1969	12,355	1,873	5	14,223	6,080	1,730	885	6,317
1970	13,039	2,115	3	15,151	6,477	2,340	998	7,171
1971	12,837	2,020	35	14,822	6,336	2,190	980	6,913
1972	12,803	1,841	29	14,615	6,248	2,590	797	7,416
1973	13,618	1,909	12	15,515	6,633	3,090	694	8,365
1974	15,216	1,980	16	17,180	7,344	3,290	927	8,973
1975	11,714	1,801	20	13,495	5,769	3,180	933	7,439
1976	12,749	1,989	15	14,723	6,294	3,290	1,050	7,905
1977	12,989	2,013	26	14,976	6,402	3,760	857	8,665
1978	13,847	1,669	13	15,503	6,628	3,970	878	9,057
1979	13,780	1,821	15	15,586	6,663	3,840	849	8,988
1980	14,087	1,559	21	15,625	6,680	4,360	1,140	9,232
1981	12,802	1,510	20	14,292	6,110	3,980	730	8,749
1982	10,122	732	49	10,805	4,619	3,180	590	6,747
1983	7,601	679	74	8,206	3,508	4,030	602	6,585
1984	9,435	856	82	10,209	4,364	4,290	648	7,570
1985	7,158	674	56	7,776	3,324	3,830	316	6,506
1986	6,456	510	69	6,897	2,948	3,600	487	5,767
1987	9,156	576	201	9,531	4,075	4,070	1,130	6,607
1988	9,944	588	63	10,469	4,475	4,630	1,040	7,618
1989	10,893	W	44	10,849	4,638	4,310	1,330	7,154

Table H.1: U.S. Supply of Bauxite and Alumina from 1960 to 2003 (in Thousand Metric Dry Tons) *(Continued)*

A	B	C	D	E	F	G	H	I
Year	Imports of Bauxite	U.S. Mined Bauxite	Exports of Bauxite	Net Bauxite Supply	Estimated Alumina Production from Bauxite	Imports of Alumina	Exports of Alumina	Estimated Net Alumina for Electrolysis
1990	12,142	W	53	12,089	5,168	4,070	1,260	7,461
1991	12,300	W	58	12,242	5,233	4,590	1,350	7,950
1992	11,400	W	68	11,332	4,844	4,700	1,140	7,920
1993	11,900	W	92	11,808	5,048	3,940	1,240	7,243
1994	11,200	W	137	11,063	4,729	3,120	1,040	6,336
1995	10,800	W	120	10,680	4,566	4,000	1,040	7,069
1996	10,700	W	154	10,546	4,508	4,320	918	7,460
1997	11,300	W	97	11,203	4,789	3,830	1,270	6,870
1998	11,600	W	108	11,492	4,913	4,050	1,280	7,192
1999	10,400	W	168	10,232	4,374	3,810	1,230	6,517
2000	9,030	W	147	8,883	3,797	3,820	1,090	6,148
2001	8,670	W	88	8,582	3,669	3,100	1,250	5,152
2002	7,710	W	52	7,658	3,274	3,010	1,270	4,686
2003	8,300	W	140	8,160	3,488	2,300	1,000	4,310
W - data withheld								

Source: United States Geological Survey, Minerals Information, Statistical Compendium

Note: 3,488,000 metric tons or 79% of the 4,310,000 metric tons of alumina needed to produce aluminum in the United States was refined in the United States in 2003.

Calculations

Column F is calculated based on USGS data. The average alumina content for bauxite is 45%, and 95% of bauxite is converted to alumina. The calculation is $F = 0.95 \times 0.45 \times E$. The numbers produced in Column F may be slightly over-estimating since slightly less than 100% of the alumina content of bauxite is actually recovered.

Column I is calculated based on USGS data. 90% of alumina produced is metallurgical alumina used in aluminum production. The calculation is $I = 0.9 \times (F + G - H)$.

Appendix I: Energy Requirements for Carbon Anodes

The following table shows the onsite, process and feedstock energy values that are part of making a carbon electrode (anode) for reduction of alumina to aluminum. Pitch and coke require process energy for their manufacture, and they have a fuel or feedstock energy value that must be accounted for in order to fully evaluate the energy associated with producing aluminum.

Table I.1: Energy Associated with Aluminum Industry Carbon Anode Manufacturing

	Mass of Material Input* <i>kg/1000 kg Anode</i>	Material Input Energy** <i>Btu/kg</i>	kWh per kg Anode	kWh per kg Aluminum
Pitch				
Mass	231			
Feedstock Energy		8,813	2.58	1.15
Process Energy		9	0.003	0.001
Calcined Coke				
Mass	820			
Feedstock Energy		27,569	8.08	3.60
Process Energy		395	0.12	0.05
Green Coke				
Mass	85			
Feedstock Energy		2,664	0.78	0.35
Process Energy		43	0.01	0.01
Carbon Anode Baking				
Process Energy*			1.93	0.86
TOTAL Raw Materials and Energy				
Mass (kg/1000 kg Anode)	1,136			
Feedstock Energy (kWh)		39,046	11.44	5.10
Process Energy (kWh)		446	2.06	0.92
TOTAL Tacit Energy Input			13.50	6.02

* Values from Appendix F, Table F.1 ** Values from Appendix C, Table C.1

Table I.2: Onsite and Tacit Energy Associated with Carbon Anode Production

	kWh per kg of Anode		kWh per kg of Aluminum	
		tf		tf
Pitch	0.003	2.58	0.001	1.15
Coke	0.13	8.99	0.06	4.01
Baking	1.36	1.93	0.61	0.86
Total	1.49	13.50	0.66	6.02

Appendix J: Theoretical Energy Data and Calculations

The theoretical minimum energy requirement for producing any chemical is determined based on the net chemical reaction used to produce the product. It is defined as the energy required to synthesize a substance in its standard state from substances also in their standard states. It can be calculated by summing the reaction energies of the products minus the energies of the reactants.

This report calculates the theoretical minimum energy by assuming the reactants enter and the byproducts leave the system at room temperature and that molten aluminum leaves the system at 960 °C. This report has chosen 960 °C (1233 °K) as the molten metal temperature. This value is an approximation of the average operating cell temperatures of industrial cells.

Some studies assume that the gases evolved during reduction leave the system at the molten metal temperature. In these studies, the theoretical minimum is 2.5% to 3% higher than the numbers calculated here. The additional energy for heating of the emissions is shown in the individual tables. Theoretically, it is possible to capture all the energy associated with these gaseous emissions. However, there is currently no available, economic means of recovering this energy. In practice, the emission gas stream is diluted with air in the cells to lower the temperature that the cell hoods and ducts are exposed to. The emission gas is collected from hundreds of hooded pots and treated before release to the atmosphere. Only a very small portion of the heat is actually absorbed and returned to the system.

The minimum theoretical energy requirement for aluminum production requires the evaluation of three energy factors: the energy required to drive the reduction reaction forward, the energy required to maintain the system at constant pressure and temperature, and the energy required to change the temperature of the reactant and/or product. The thermodynamics and chemical equilibrium of reactions are described by the equation $\Delta G = \Delta H - T \Delta S$ and the numeric values are given in Table J.6. The energy required to drive the reaction forward is the Gibbs free energy value (ΔG). The energy required to maintain system equilibrium is the difference between the heat of reaction (ΔH) and the Gibbs free energy value (ΔG), which equals the entropy term ($T\Delta S$). Since the Gibbs free energy requirement is less than the heat of reaction for alumina reduction, additional energy must be added to the system to maintain the system temperature. Otherwise, the system would cool as the reaction proceeds. (Reduction cells operate at atmospheric conditions and no pressure change results during reduction.) The numeric values for G, H and S are given in Table J.6.

A detailed discussion of the theoretical requirements is made in *Current and Energy Efficiency of Hall-Héroult Cells - Past, Present and Future*, by Warren Haupin and William Frank, published in Light Metal Age, June 2002.

Table J.1: Theoretical Minimum Energy for Hall Héroult Carbon Anode System

Reactants Temp		Products Temp		Reaction Thermodynamics at 298 K		(products - reactants)
						cal/gm mole Al
2 Al ₂ O ₃	25°C	4 Al	960°C	(2 Al ₂ O ₃ + 3 C)	to (4 Al + 3 CO ₂) = Net	118,395
				delta G	0	129,711
				delta H	0	11,311
				delta S	4.1	
3 C	25°C				27.1	
					153.2	
Process Theoretical Minimum Energy Requirements						
kWh/kg						
Electrolytic Work Requirement (delta G)						
5.11						
Thermal Energy for Temperature Maintenance (delta H - delta G)						
0.49						
Thermal Energy for Al at 960°C						
0.39						
Theoretical Minimum						
5.99						
Thermal Energy for CO ₂ at 960°C						
0.17						

Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.2: Theoretical Minimum Energy for Hall Héroult Inert Anode System

Reactants Temp		Products Temp		Reaction Thermodynamics at 298 K		(products - reactants)
						cal/gm mole Al
Al ₂ O ₃	25°C	2 Al	960°C	(Al ₂ O ₃)	to (2 Al + 1.5 O ₂) = Net	189,089
				delta G	-378,179	200,250
				delta H	-400,500	11,155
				delta S	12	
					14	
					74	
Process Theoretical Minimum Energy Requirements						
kWh/kg						
Electrolytic Work Requirement (delta G)						
8.16						
Thermal Energy for Temperature Maintenance (delta H - delta G)						
0.48						
Thermal Energy for Al at 960°C						
0.39						
Theoretical Minimum						
9.03						
Thermal Energy for O ₂ at 960°C						
0.27						

Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.3: Theoretical Minimum Energy for Carbothermic Reduction

Reactants		Reaction Thermodynamics at 298 K		Products	
Temp		($2 \text{ Al}_2\text{O}_3 + 3 \text{ C}$)	to	($2 \text{ Al} + 3 \text{ CO}$)	Net
25°C	Al_2O_3	delta G	-378,179	0	-98,424
25°C	3 C	delta H	-400,500	0	-79,247
		delta S	12.2	4.1	141.9

Process Theoretical Minimum Energy Requirements	
	Work Requirement (delta G)
	6.03
	Thermal Energy for Temperature Maintenance (delta H - delta G)
	0.90
	Thermal Energy for Al at 960°C
	0.39
	Theoretical Minimum
	7.32
	Thermal Energy for CO at 960°C
	0.19

Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.4: Theoretical Minimum Energy for Reduction of Aluminum Chloride

Reactants		Reaction Thermodynamics at 298 K		Products	
Temp		(2 AlCl_3)	to	($2 \text{ Al} + 3 \text{ Cl}_2$)	Net
25°C	2 AlCl_3	delta G	-300,574	0	0
		delta H	-336,616	0	0
		delta S	48.1	13.5	159.9

Process Theoretical Minimum Energy Requirements	
	Electrolytic Work Requirement (delta G)
	6.48
	Thermal Energy for Temperature Maintenance (delta H - delta G)
	0.78
	Thermal Energy for Al at 960°C
	0.39
	Theoretical Minimum
	7.65
	Thermal Energy for Cl_2 at 960°C
	0.19

Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.5: Theoretical Minimum Energy for Kaolinite / Aluminum Chloride Reduction

Reactants Temp		Products Temp	
7 Al ₂ O ₃ ·2SiO ₂	25°C	14 Al	960°C
Kaolinite			
to			
Aluminum Chloride			
to			
14 C	25°C	7 CO ₂	25°C
Reduction System			

Net Aluminum Reaction:		(products – reactants)	
CarboChlorination (900°C)			
$(3 \text{ Al}_2\text{O}_3 \cdot 2\text{SiO}_2 + 14 \text{ C} + 21 \text{ Cl}_2) \text{ to } (6 \text{ AlCl}_3 + 6 \text{ SiCl}_4 + 7 \text{ CO} + 7 \text{ CO}_2) = \text{Net}$			
delta G	-2,374,053	0	-901,721
delta H	-2,531,520	0	-1,009,847
delta S	19	1,119	144
		474	331
		357	

Chloride Reduction (700°C)		(2 AlCl₃) to (2 Al + 3 Cl₂) = Net	
delta G	-300,574	0	0
delta H	-336,616	0	0
delta S	48	14	160

Process Theoretical Minimum Energy Requirements		
		kWh/kg
	Thermal Work for AlCl ₃ Production	-1.90
	Electrolytic Work Requirement (delta G)	6.48
	Thermal Energy for Temperature Maintenance (delta H – delta G)	0.78
	Thermal Energy for Al at 960°C	0.39
	Theoretical Minimum	5.76
	Thermal Energy for CO ₂ at 960°C	0.11
	Thermal Energy for CO at 960°C	0.25

Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.6: Thermochemistry Data for Elements and Compounds Associated with Aluminum Production

CAS RN	Molecular Weight	Chemical Formula	H (s) J/mol	G (s) J/mol	S (s) J/mol K	Cp (s) J/mol K
Aluminum	26.98	Al	0	0	28.3	24.35
Aluminum Chloride	133.34	AlCl ₃	-704,200	-628,800	100.7	91.84
Corundum	101.96	Al ₂ O ₃	-1,675,700	-1,582,300	50.9	79
Gibbsite*	155.96	Al ₂ O ₃ ·3H ₂ O	-1,293,100	-1,154,900		
Kaolinite*	1332-58-7	Al ₂ O ₃ ·SiO ₂ ·2H ₂ O	-4,119,000	-3,793,900		
Kaolinite, meta	162.04	Al ₂ O ₃ ·SiO ₂	-843,840	-791,351		
Graphite	12.01	C	0	0	5.7	1.361
Chlorine	70.91	Cl ₂ (g)	0	0	222.9	53.286
Carbon Monoxide	28.01	CO (g)	-110,523	-137,268	197.9	47.301
Carbon Dioxide	44.01	CO ₂ (g)	-393,513	-394,383	213.6	51.061
Oxygen	32.00	O ₂ (g)	0	0	205.0	49.003
Water	18.00	H ₂ O (g)	-241,826	-228,582	188.8	45.132
Silica Dioxide	60.08	SiO ₂	-910,700	-217,663	41.46	9.909
Silicon tetrachloride	10026-04-7	SiCl ₄ (g)	-657,000	-157,027	330.70	79.039

Source: Handbook of Chemistry and Physics, David R Lide, Editor, 80th Edition CRC

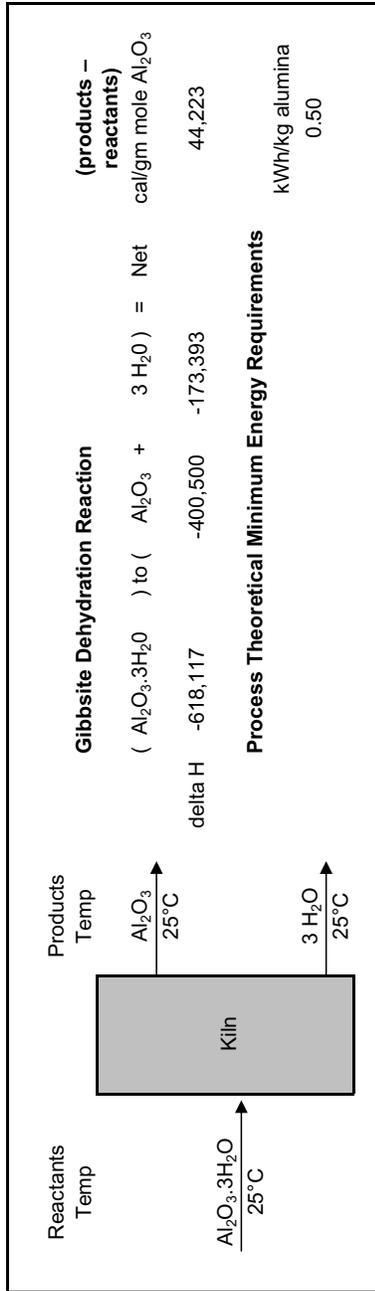
*Source: Advances in Physical Geochemistry, Edited by Saxena, S.K. - data courtesy of Mr. Bruce Hemingway at U.S.G.S.

Table J.7: Changes in Heat of Formation Values as a Function of Temperature

Temperature °C	Heats of Formation in calories per gram mole				
	Al ₂ O ₃ *	C*	Al*	CO ₂ *	O ₂
25	-400,300	0	0	-94,050	0
727	-404,400	2,310	18,710	-94,400	9,249
827	-404,000	3,320	21,710	-94,250	10,515
927	-403,600	3,850	24,740	-94,300	11,843
960	-403,500	4,030	25,750	-94,300	12,295
1,027	-403,200	4,390	27,790	-94,300	13,233
1,127	-402,800	4,930	30,850	-94,300	14,685

Source: *Values from "Technical Working Group on Inert Anode Technologies" Appendix A.9, page 11

Table J.8: Theoretical Minimum Energy for Gibbsite Dehydration



Note: Thermodynamic values for G, H and S are from Table J.6. Heat capacity data are from Table J.9 and Appendix K

Table J.9: Heat of Capacity Equations for Gases Associated with Aluminum Production

Standard Molar Heat Capacity, $C = a + bT + cT^2$	(T in degrees K)		
cal/ mol K	a	$b \times 10^3$	$c \times 10^7$
O_2	6.148	3.102	-9.23
CO	6.420	1.665	-1.96
CO_2	6.214	10.396	-35.45
Cl_2	7.576	2.424	-0.65

Source: A Different Approach to Thermodynamics, W. F. Ludar, 1967

Appendix K: Aluminum Heat Capacity and Heat of Fusion Data

$$\text{Heat Capacity (cal/mol.K)} = A + B.t + C.t^2 + D.t^3 + \frac{E}{t^2}$$

$$\text{Standard Enthalpy (kcal/mol)} = A.t + \frac{(B.t)}{2} + \frac{(C.t^3)}{3} + \frac{(D.t^4)}{4} - \frac{E}{t} + F - H$$

$$\text{Standard Entropy (cal/mol.K)} = A.\ln(t) + B.t + \frac{(C.t^2)}{2} + \frac{(D.t^3)}{3} - \frac{E}{(2.t^2)} + G$$

where, $t = K/1000$ and A, B, C, D, E, F, G and H are constants

Source: <http://webbook.nist.gov> (Standard Reference Data Program)

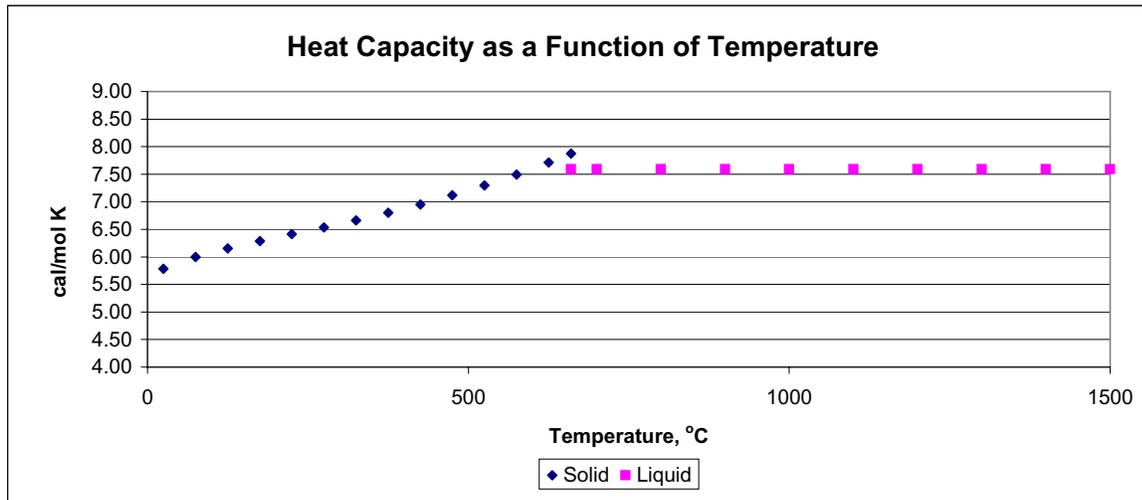
Formula Constants for Aluminum

Solid (298 to 933.45 K, 1 atm):							
<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>	<i>H</i>
6.71348	-1.29418	2.04599	0.819161	-0.066294	-2.18623	14.7968	0
Liquid (933.45 to 2790.812 K, 1atm):							
<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>	<i>H</i>
7.588681	9.40685E-09	4.26987E-09	6.43922E-09	1.30976E-09	-0.226024	17.5429	2.524381

Table K.1: Aluminum Energy Requirements for Heating and Melting

Temperature			Heat Capacity at Temperature (cal/mol K)	Energy for Step Change (kWh/kg)	Cumulative Energy to Raise from 25 °C (kWh/kg)	Energy for Step Change (Btu/lb)	Cumulative Energy to Raise from 25 °C (Btu/lb)
(°C)	(K)						
25	298	Solid	5.79	0.00	0.00	-	-
660	933		7.88	0.19	0.19	286	286
660		Fusion	94.5 (cal/gm)	0.11		170	
660	933	Liquid	7.59		0.29		456
775	1048		7.59	0.04	0.33	58	515
960	1233		7.59	0.06	0.39	94	608
2000	2273		7.59	0.34	0.73	526	1,134
Smelting 25 °C to 960 °C				Total	0.39		608
Furnace Melting 25 °C to 775 °C				Total	0.33		515

Note: Heat capacity for solid aluminum varies significantly with temperature, whereas for molten aluminum, it is nearly constant.



Appendix L: Impact of Secondary Metal Production on Energy Requirements for U.S. Aluminum Production

The nominal U.S. energy required to produce aluminum metal has been rapidly declining as secondary aluminum production has grown. Secondary aluminum requires only 6% of the energy necessary to manufacture primary aluminum (Appendix F, Table F.6). The total U.S. ore-to-metal primary energy values include: refining of half the alumina supply, anode manufacture, electrolysis and ingot casting. Combining the energy requirements for U.S. production of primary and secondary metals lowers the average energy associated with U.S. aluminum metal from over 40 kWh/kg for primary alone to about 21 kWh/kg for the combined metals.

Table L.1: Impact of Secondary Metal Production on the Nominal Energy Requirements to Produce Aluminum

Year	U.S. Primary Aluminum Production <i>(thousand metric tonnes)</i>	Smelting Energy <i>(kWh per kilogram)</i>	U.S. Secondary Aluminum Production <i>(thousand metric tonnes)</i>	Market Percent of Secondary Metal	Total Energy Ore-to-Metal to Produce Combined Metals <i>(kWh/kg)</i>	Effective Smelting Energy to Produce Combined Metals <i>(kWh/kg)</i>
1960	1,828	23.1	401	18%	69.7	19.2
1961	1,727	22.9	445		67.2	18.5
1962	1,921	22.7	533		65.7	18.1
1963	2,098	22.6	601		64.7	17.9
1964	2,316	22.4	648		64.6	17.8
1965	2,499	22.3	774		62.7	17.3
1966	2,693	22.1	833		62.2	17.2
1967	2,966	21.9	821		63.3	17.5
1968	2,953	21.8	935		61.0	16.8
1969	3,441	21.6	1,067		60.8	16.8
1970	3,607	21.4	937	21%	62.7	17.3
1971	3,561	21.0	1,004		60.5	16.7
1972	3,740	20.6	1,022		59.8	16.5
1973	4,109	20.2	1,127		58.6	16.1
1974	4,448	19.9	1,163		58.0	16.0
1975	3,519	19.5	1,121		54.5	15.0
1976	3,857	19.1	1,334		52.3	14.5
1977	4,117	18.7	1,456		50.9	14.1
1978	4,358	18.3	1,518		50.1	13.8
1979	4,557	17.9	1,612		48.8	13.5
1980	4,653	17.5	1,577	25%	48.2	13.3
1981	4,489	17.4	1,790		45.8	12.7
1982	3,274	17.2	1,666		42.2	11.8
1983	3,353	17.1	1,773		41.3	11.5
1984	4,099	16.9	1,760		43.8	12.1
1985	3,500	16.8	1,762		41.3	11.5
1986	3,039	16.6	1,773		38.9	10.9
1987	3,347	16.5	1,986		38.4	10.7
1988	3,945	16.3	2,122		39.4	11.0
1989	4,030	16.2	2,054		39.7	11.1
1990	4,048	16.1	2,393	37%	37.4	10.5
1991	4,121	16.0	2,286		38.0	10.6
1992	4,042	15.9	2,756		35.0	9.8
1993	3,695	15.8	2,944		32.7	9.2
1994	3,299	15.7	3,086		30.2	8.6
1995	3,375	15.6	3,188		29.9	8.5
1996	3,577	15.5	3,307		30.0	8.5
1997	3,603	15.4	3,547		28.9	8.2
1998	3,713	15.3	3,442		29.6	8.4
1999	3,779	15.2	3,695		28.7	8.1
2000	3,668	15.1	3,450	48%	29.0	8.2
2001	2,637	15.0	2,970		26.4	7.5
2002	2,705	14.9	2,927		26.7	7.6
2003	2,704	14.8	2,820	51%	27.1	7.7
Forty-Three Year Total Change in U.S. Energy Intensity:						
	1960	69.7 (kWh/kg)				
	2003	27.1 (kWh/kg)		61.2%		

Appendix M: Impact of Using Different Technologies on Energy Requirements for Producing Aluminum

Wetted cathodes allow the anode-cathode-distance to be reduced. This results in a lowering of the voltage requirement for amperage to pass through the cryolite bath. The following table shows the effect lowering the anode-cathode-distance has on energy consumption.

Table M.1: Impact of Wetted Cathode Technology on Primary Metal Electrolysis

WETTED CATHODE TECHNOLOGY	Typical modern "prebaked" Hall- Héroult cell operating at 95% current efficiency		Typical modern "prebaked" Hall- Héroult cell operating at 95% current efficiency and retrofitted with a wetted cathode surface and reduced ACD		Typical modern "prebaked" Hall- Héroult cell operating at 95% current efficiency and retrofitted with a wetted cathode surface, aluminum sump and reduced ACD		Typical modern "prebaked" Hall- Héroult cell operating at 95% current efficiency and retrofitted with a sloped and wetted cathode surface, aluminum sump, and reduced ACD	
	ACD = 4.5 cm		ACD = 3.5 cm		ACD = 2.5 cm		ACD = 2.0 cm	
Energy Requirements	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al
Reaction	1.20	3.76	1.20	3.76	1.20	3.76	1.20	3.76
Additional Energy Requirements:								
External	0.15	0.47	0.15	0.47	0.15	0.47	0.15	0.47
Anode	0.30	0.94	0.30	0.94	0.30	0.94	0.30	0.94
Anode Polarization	0.55	1.73	0.55	1.73	0.55	1.73	0.55	1.73
Cathode Polarization	0.05	0.16	0.05	0.16	0.05	0.16	0.05	0.16
Cryolite Bath	1.75	5.49	1.36	4.27	0.97	3.05	0.78	2.44
Cathode	0.45	1.41	0.45	1.41	0.45	1.41	0.45	1.41
Other	0.15	0.47	0.15	0.47	0.15	0.47	0.15	0.47
ONSITE Energy Values								
Cell Total	4.60	14.43	4.21	13.21	3.82	11.99	3.63	11.38
% Energy Savings			8%		17%		21%	
Anode Manufacturing		0.61		0.61		0.61		0.61
Total onsite cell and anode		15.04		13.82		12.60		11.99
% Energy Savings			8%		16%		20%	
TACIT Energy Values								
Cell Total	4.60	32.23	4.21	29.50	3.82	26.78	3.63	25.41
% Energy Savings			8%		17%		21%	
Anode Manufacturing		6.02		6.02		6.02		6.02
Total onsite cell and anode		38.25		35.52		32.80		31.44
% Energy Savings			7%		14%		18%	

Table M.2: Impact of Inert Anode and Wetted Cathode Technology on Primary Metal Electrolysis

INERT ANODE and WETTED CATHODE TECHNOLOGY	A		B		C		D	
	Typical modern Hall-Héroult cell operating at 95% current efficiency and ACD of 4.5 cm		Inert Anode direct substitution operating at 95% current efficiency		Inert Anode operating at 95% current efficiency with polarization differences reported for oxygen generation		Inert Anode operating at 95% current efficiency, with oxygen polarization differences and an ACD of 2cm using Wetted Cathode	
Energy Requirements	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al
Reaction	1.20	3.76	2.20	6.90	2.20	6.90	2.20	6.90
Additional Energy Requirements:								
External	0.15	0.47	0.15	0.47	0.15	0.47	0.15	0.47
Anode	0.30	0.94	0.30	0.94	0.30	0.94	0.30	0.94
Anode Polarization	0.55	1.73	0.55	1.73	0.10	0.31	0.10	0.31
Cathode Polarization	0.05	0.16	0.05	0.16	0.05	0.16	0.05	0.16
Cryolite Bath	1.75	5.49	1.75	5.49	1.75	5.49	0.78	2.44
Cathode	0.45	1.41	0.45	1.41	0.45	1.41	0.45	1.41
Other	0.15	0.47	0.15	0.47	0.15	0.47	0.15	0.47
ONSITE Energy Values								
Cell Total	4.60	14.43	5.60	17.57	5.15	16.15	4.18	13.11
% Energy Savings			-22%		-12%		9%	
Anode Manufacturing		0.61		0.77		0.77		0.77
Total onsite cell and anode		15.04		18.33		16.92		13.87
% Energy Savings			-22%		-13%		8%	
TACIT Energy Values								
Cell Total	4.60	32.23	5.60	39.23	5.15	36.08	4.18	29.27
% Energy Savings			-22%		-12%		9%	
Anode Manufacturing		6.02		0.77		0.77		0.77
Total onsite cell and anode		38.25		40.00		36.84		30.03
% Energy Savings			-5%		4%		21%	

Inert Anodes by themselves require additional reaction voltage as can be seen by comparing columns A and B. However, this additional energy requirement is offset by the elimination of carbon anode manufacturing, along with the elimination of the feedstock energy associated with carbon. The estimate for the energy associated with the manufacture of inert anode is shown in Table M.3. Column C shows the impact that results from the lower anode polarization and the ability to design to release gas more effectively. Wetted cathodes combined with inert anodes can provide additional savings as shown in column D.

Table M.3: Estimate of Energy Requirement for Manufacturing an Inert Anode

The energy requirements for manufacturing an inert anode are significantly less than the total manufacturing energy of the many consumable carbon anodes that it replaces. Below is an estimate of the energy required to manufacture an inert anode. Assuming an inert anode has a cell life of two years, the equivalent carbon energy requirements can be calculated. Using 1 cm² as a basis, the following can be calculated:

- 0.85 A/cm² is the typical current density for a modern Hall-Héroult Cell current density.
- 2980 Ah/kg Al is the theoretical amperage required to produce aluminum.
- 95% is the typical efficiency of a modern Hall-Héroult carbon anode cell.
- 0.446 kilograms of carbon are required to produce one kilogram of aluminum.

From the above data, the amount of carbon consumed and aluminum produced per cm² over a two year period is calculated to be:

- 14.82 kg of carbon are consumed per cm² over a two year operating period
- 33.23 kg of aluminum are produced per cm² over a two year operating period.

From Appendix I:

- 6.02 kWh/kg of Al produced is the tacit energy associated with carbon anode. The total energy associated with the two-year operation of the 1 cm² of carbon anode can be calculated.
- 200 kWh of tacit energy are consumed for anode manufacture and use.
- 2.27 gm/cm³ is the density of a carbon anode. The height of the 1 cm² of carbon can be calculated as below.
- 6529 cm is the height of carbon anode with a 1 cm² base or anode face for two years of operation

The materials under consideration for inert anodes have no inherent fuel value as does the carbon anode. The tacit energy requirement associated with the manufacturing of an inert anode is related to the extraction of materials and the inert anode manufacturing process. Assuming that the inert anode is 5 cm thick per cm² of anode face and that it requires 5 times the total tacit energy of a carbon anode (which includes its fuel value) to manufacture, it can be calculated that:

0.77 tacit kWh/kg of aluminum will be required to produce an inert anode.

Table M.4: Estimate of Energy Requirement to Manufacture Aluminum Using Different Technologies

ALUMINUM PRODUCTION TECHNOLOGIES	Typical modern Hall-Heroult prebaked anode cell operating at 95% current efficiency & with ACD of 4.5 cm	Typical modern Hall-Heroult cell operating at 95% current efficiency, retrofitted with a sloped & wetted cathode surface, aluminum sump, & a reduced ACD of 2.0 cm	Inert Anode operating at 95% current efficiency with oxygen polarization differences & ACD of 2.0 cm using Wetted Cathode technology	Carbothermic Reduction with a reaction efficiency of 95% and a furnace efficiency of 80%	Chloride Reduction of Kaolinite Clays: electrolysis current efficiency 95% & heating efficiency 85%
Raw Materials	kWh/kg Al				
Onsite Energy Required	alumina 7.59	alumina 7.59	alumina 7.59	alumina 7.59	see Note B kaolinite 8.14
Tacit Energy Required	alumina 8.24	alumina 8.24	alumina 8.24	alumina 8.24	kaolinite 8.84
Onsite Reaction Energy Requirements					
Reaction Thermal Furnace Losses	V (dc)				
Reaction Electrolysis	1.20	1.20	2.20	7.71	-1.90
Cell Ohmic	3.40	2.43	1.98	1.93	see Note C V (dc) 2.07 0.93
TOTAL Reaction Energy	4.60	3.63	4.18	9.63	3.00
Anode Manufacturing	0.61	0.61	0.77	0	0.77
Onsite Energy Savings	20%				
Total Onsite Energy Requirements Including Raw Materials					
Raw Ore Materials	7.59	7.59	7.59	7.59	8.14
Reactions	14.43	11.38	13.11	9.63	7.91
Carbon / Electrodes	0.61	0.61	0.77	0	see note D 0.77
Total Energy Savings	13%				
Total Tacit Energy Requirements Including Raw Materials					
Raw Ore Materials	8.24	8.24	8.24	8.24	8.84
Reactions	32.23	25.41	29.27	21.52	18.60
Carbon / Electrodes	6.02	6.02	0.77	8.43	see note D 12.13
Total Energy Savings	15%				
			18%	18%	15%

- Note A: The Carbothermic reaction requires twice the carbon as the Hall-Hérout reaction. The Hall-Hérout reaction on a theoretical basis requires 0.33 kg C / kg Al. In this estimate, it is assumed that the carbothermic reaction utilized carbon at a 95% efficiency. Unlike a carbon anode, the carbon used does not require the energy associated with carbon anode manufacturing. Hence only the fuel or "secondary energy" requirement of the carbon are used.*
- Note B: Kaolinite contains 27.2% aluminum by weight. Bauxite contains 45% aluminum by weight. Both materials contain about the same percentage of impurities. For this estimate, it is assumed that the processing and calcination energy of kaolinite is the same as bauxite. However, 66% more kaolinite must be processed to produce a kilogram of aluminum than bauxite. Kaolinic clays contain valuable titanium, in addition to their silicon content. These materials will likely be recovered in the processing plant and account for approximately 35% of kaolinic clay content. This report allocates 65% of the total raw material energy requirement to the kaolinite material used for aluminum manufacturing.*
- Note C: The Carbo-Chlorination reaction is exothermic (-1.90 kWh/kg Al). However, Toth Aluminum reports that based on pilot plant experience and the challenges of capturing the off-gas energy, a small quantity of energy (0.4 kWh/Kg Al) is required to maintain the reaction system temperature.*
- Note D: The Carbo-Chlorination reaction requires 0.89 kg of carbon per kg of aluminum produced. In this estimate, it is assumed that the Carbo-Chlorination reaction utilized carbon at a 95% efficiency. It is also assumed that the energy required and fuel value of the carbon is the same on a weight basis as the carbon utilized for Carbothermic Reduction of Aluminum. (see note A)*