

# U.S. Energy Requirements for Aluminum Production

Historical Perspective, Theoretical Limits  
and New Opportunities

Prepared under contract to:  
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Energy Efficiency and Renewable Energy  
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**U.S. Energy Requirements for Aluminum Production:  
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## **Preface**

This report provides reliable and comprehensive statistical data over the period 1960 to 2000 for the evaluation of energy trends and issues in the aluminum industry. It should be noted, however, that 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 snowpacks 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 significant increases to the market price of electricity during this time. This price increase in the Pacific Northwest made it more economical for aluminum smelters to stop 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% of all U.S. primary aluminum capacity, shut down.

In light of the issues facing aluminum production in the Pacific Northwest. Much of the detailed statistical data for the years 2001 and 2002 are neither finalized nor available. It is currently too early to accurately assess the long-term impact of the shutdown and changing conditions on the aluminum industry. It remains to be seen whether the shutdown 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. 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.

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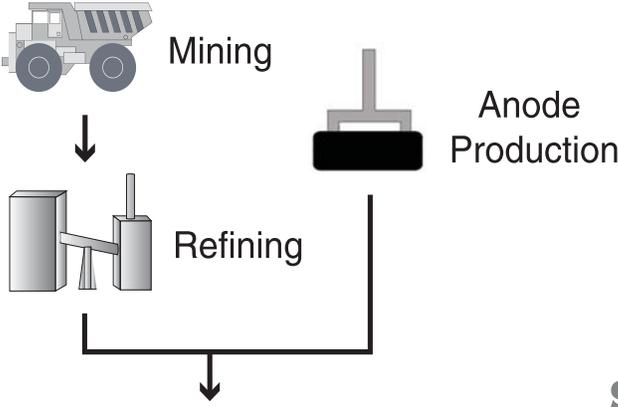
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# Primary Metal



# Secondary Metal

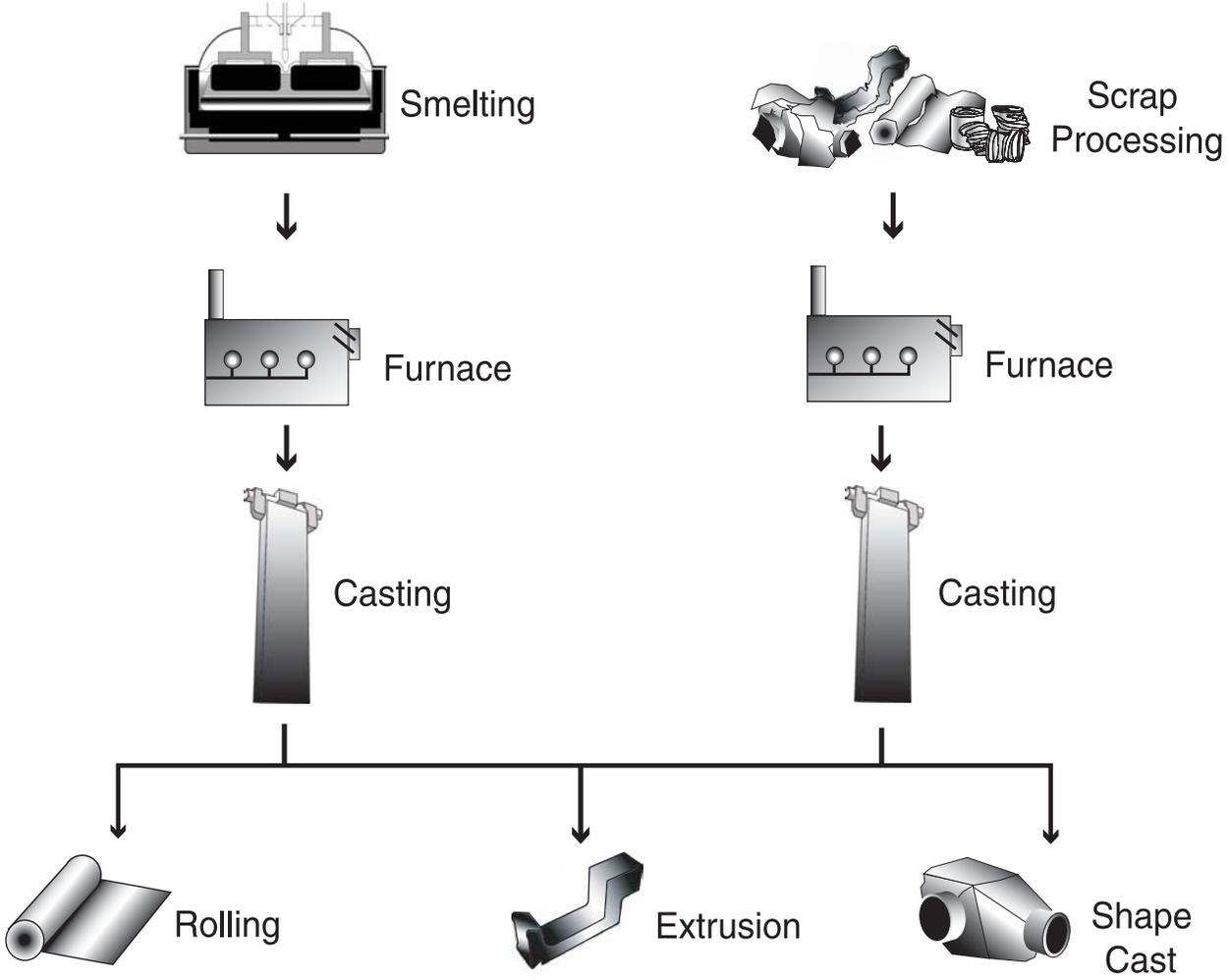


Diagram A - Aluminum Industry Flow Diagram

## Executive Summary

The United States aluminum industry is the world's largest, processing over 10.7 million metric tons of metal and producing about \$39 billion in products and exports in 2000. It operates more than 300 plants in 35 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 21% and 37% respectively to the total 58% 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 industries. The U.S. aluminum industry directly consumes  $61.5 \times 10^9$  kilowatt hours (0.21 quad) of electricity annually or 1.6% 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 7,023,000 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  $185 \times 10^9$  kilowatt hours (0.63 quad). The difference between the gross annual energy required and the theoretical minimum requirement amounts to over  $140 \times 10^9$  kilowatt hours (0.48 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. Diagram A - Aluminum Industry Flow Diagram 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**

<b>U.S. Total Energy Requirements &amp; Potential Savings</b>	<b>U.S. Annual Production 2000</b> Metric tons	<b>Theoretical Minimum Energy Requirement</b> kWh (10 <sup>9</sup> )/yr (quad)	<b>Total U.S. Process Energy Required</b> kWh (10 <sup>9</sup> )/yr (quad)	<b>Total U.S. Gross Energy<sup>tf</sup> Required</b> kWh (10 <sup>9</sup> )/yr (quad)	<b>Potential Gross U.S. Energy<sup>tf</sup> Savings</b> kWh (10 <sup>9</sup> )/yr (quad)
Bauxite Mining					
Alumina Refining	3,985,000	0.52 (0.002)	15.00 (0.051)	16.24 (0.055)	15.72 (0.054)
Anodes Production	1,668,000	15.36 (0.052)	21.36 (0.073)	21.86 (0.075)	6.49 (0.022)
Aluminum Smelting	3,741,000	22.41 (0.076)	58.29 (0.199)	116.36 (0.397)	93.95 (0.321)
Primary Casting	3,668,000	1.23 (0.004)	3.70 (0.013)	4.56 (0.016)	3.34 (0.011)
Secondary Casting	3,450,000	1.15 (0.004)	8.63 (0.029)	9.64 (0.033)	8.49 (0.029)
Rolling	5,498,000	1.76 (0.006)	3.45 (0.012)	6.66 (0.023)	4.90 (0.017)
Extrusion	1,719,000	0.75 (0.003)	2.23 (0.008)	2.59 (0.009)	1.84 (0.006)
Shape Casting	2,513,000	0.84 (0.003)	6.42 (0.022)	6.63 (0.023)	5.79 (0.020)
<b>Total</b>		<b>44 (0.150)</b>	<b>119 (0.406)</b>	<b>185 (0.630)</b>	<b>141 (0.479)</b>

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.

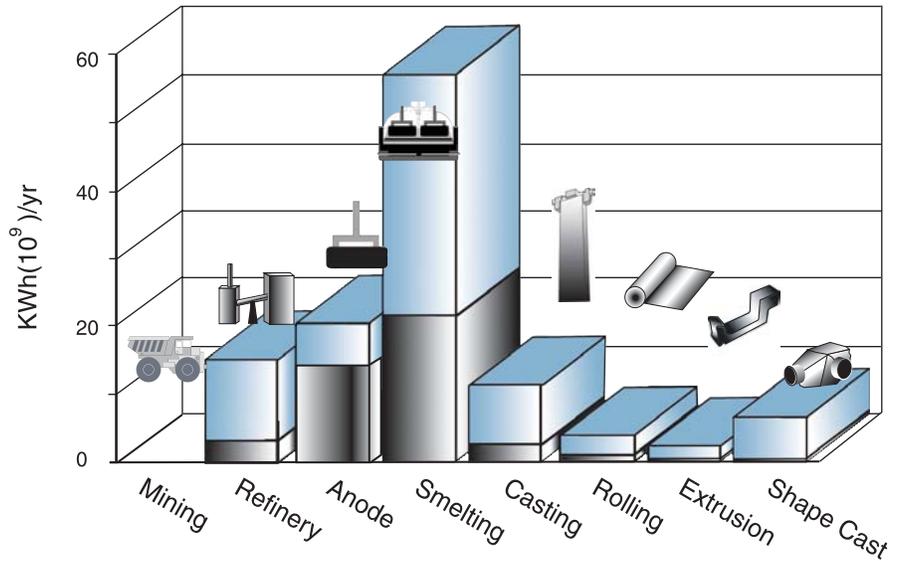
The amount of energy used onsite in the major processing operations of the U.S. aluminum industry are shown in Diagram B - Process Energy Used in U.S. Manufacturing of Aluminum Products. The bottom band on each bar shows the theoretical energy requirement, while the top band of each bar shows the energy 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 49% 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 energy and has the potential for the greatest energy reduction of all operations. Electricity is required for smelting and accounts for over 98% 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%.

Process heating accounts for 25% 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 nearly half of all U.S. produced aluminum. It requires less than 6% of the energy to produce aluminum from mined materials 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.



**Diagram B - Process Energy Used in U.S. Manufacturing of Aluminum Products**

The magnitude of the top bands of the energy bars in Diagram 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% reduction from 2000 practices.

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.

## **I.0 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 both in terms of production and consumption. The U.S. aluminum industry utilized 10,698,000 metric tons in 2000 to produce an enormous variety of products. U.S. per capita consumption was 35.4 kilograms. The industry operated more than 300 plants in 35 states and employed over 145,000 people to make aluminum products.<sup>1</sup> 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.

Energy is an essential input to all manufacturing of materials and products. Decreasing energy usage correlates with improving manufacturing economics and environmental impacts. 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 58% (Appendix L). However, even with the large reduction in energy intensity, the industry consumes nearly three times the theoretical energy required. Significant opportunities for further energy improvements still remain.

## **I.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*<sup>2</sup>).

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% 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<sup>3,4</sup> 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 48% of the aluminum produced by U.S. industry in 2000 came from recycled material. Forty years ago, recycled material was used to generate less than 18% of U.S. produced aluminum (Appendix G). Recovering aluminum from wastes and scraps requires less than 6% 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.

## 2.0 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 of 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 reported values. Onsite and tacit values used in this report are explained in Section 2.2. The United States does not mine ore for aluminum production, and 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 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 ( $2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al} + 3\text{O}_2$ ), 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 slow. 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 will better (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 <sup>5</sup>” has selected a goal of 11 kWh/kg of aluminum as its smelting current practice value for the year 2020. This represents a 27% reduction over 1995’s current value of 15.4 kWh/kg of aluminum. This future target value was reached by industry experts in a deliberative process. The industry can envision this as an obtainable goal, and this goal sets the industry practical minimum smelting energy 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% 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% increase in the onsite energy consumption of the Hall-Héroult 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 one kilowatt-hour of onsite electricity is equivalent to saving over three kilowatt-hours 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 9,780 Btu of energy to deliver 1 kWh of onsite electricity (3,412 Btu) for use. Electricity production from coal requires 10,290 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, 10,290 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% electric energy. A modern smelter operating from a hydroelectric utility requires 14.4 kWh/kg of aluminum produced of onsite energy and 14.4 kWh/kg of aluminum of tacit energy, whereas an identical smelter operating from a coal-fired utility requires 14.4 kWh/kg of aluminum of onsite energy and 36.0 kWh/kg of aluminum of tacit energy (Appendix C, Table C-3). The U.S. primary aluminum industry has more than half of its capacity connected to hydroelectric facilities. This report uses an average tacit value of 6,850 Btu per onsite kWh of electricity for smelting and anode production facilities, and 9,780 Btu per onsite kWh for all other operations (Appendix D). This report, for clarity, distinguishes between onsite operating energy values and the secondary energy values that include tacit/feedstock contributions with the use of a superscript (*Any value that includes tacit and/or feedstock components is denoted with the superscript “tf”, e.g., 1.0<sup>tf</sup> 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 for 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 benefits derived in one area do not shift the impact burden to other places within a product’s life cycle.

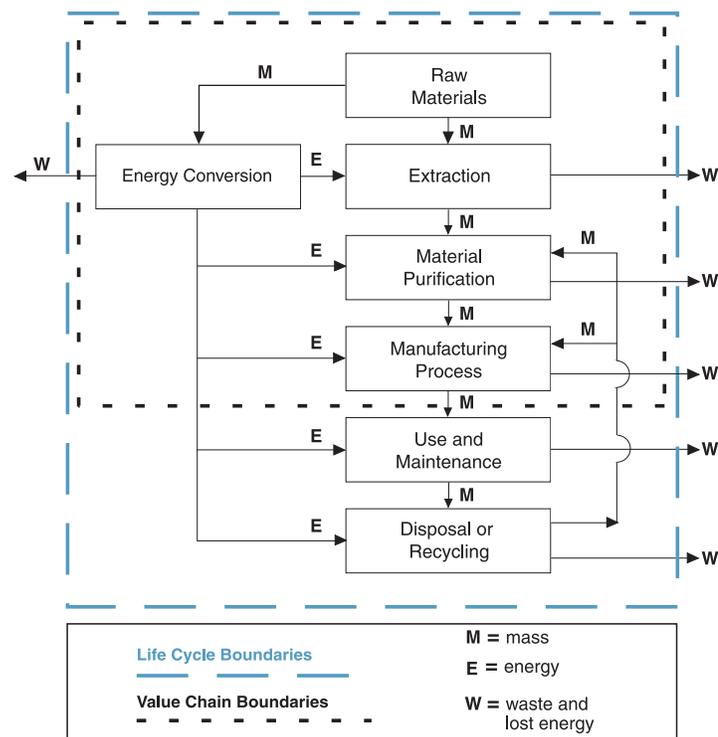
The LCA “use and maintenance” factor for aluminum varies by end-product and in many applications is more significant in terms of energy and environmental impact than production. Aluminum, in some cases, provides LCA “use and maintenance” energy savings that are significantly greater than the energy used 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.

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 nearly 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. Diagram 2.4 - Boundaries for Life Cycle and Value Chain Assessments shows the global boundaries of an LCA study and the boundaries for this study’s value chain.

Value chain analysis allows for the capture of the direct energy and feedstock inputs of each processing step (link) and builds the 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.



**Diagram 2.4 - Boundaries for Life Cycle and Value Chain Assessments**

## 2.5 Transportation Energy

The transportation energy associated with acquiring raw materials and distribution on intermediate products is important for a full Life Cycle Assessment. 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.

Transportation energy calculations for raw materials that are mined globally are highly variable. They are a function of 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% of the total energy associated with primary aluminum production in the United States.<sup>6</sup>

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 transport 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% 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. These other emission quantities are typically small when 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*<sup>7</sup> 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 CO<sub>2</sub> is the standard, and emissions are expressed in terms of a million metric tons of CO<sub>2</sub> equivalent or 10<sup>6</sup>TCDE. This report uses carbon dioxide equivalents (CDE). Emissions are also commonly expressed in terms of a million metric tons of carbon equivalent (10<sup>6</sup>TCE). Carbon comprises 12/44 of the mass of carbon dioxide; to convert from CO<sub>2</sub> equivalent to C equivalent, multiply 0.273 by the CO<sub>2</sub> equivalent .

### 3.0 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 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 second most abundant element in the Earth's crust after silicon. Aluminum 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 aluminum industry's raw materials and product markets are global. Global primary aluminum production has been growing at a rate of 2.2% annually over the last ten years.<sup>8</sup> The U.S. aluminum total supply grew at an annual rate of 3.6% over the period of 1990 to 2000 (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 the world manufacturing.

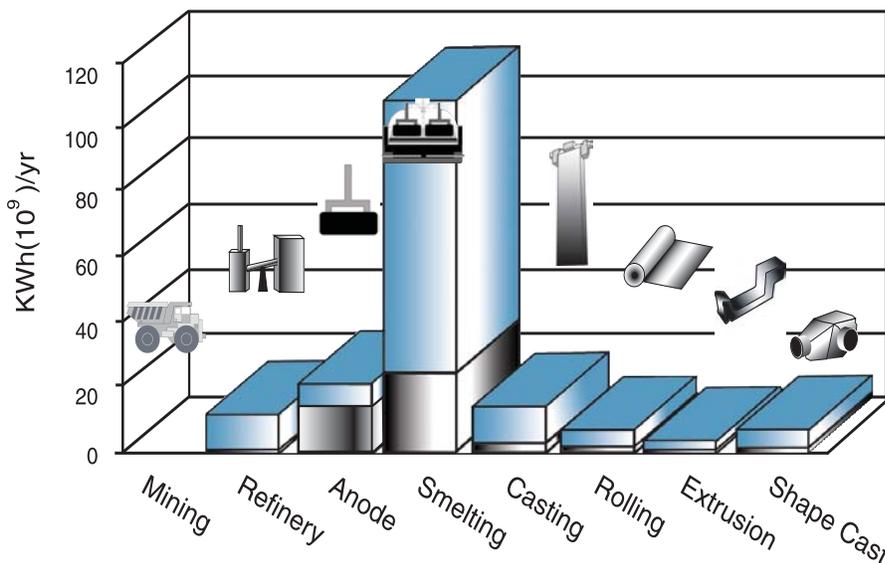
The global estimate for economically recoverable bauxite reserves is 22,000,000,000 metric tons. This quantity can supply demand for the next century. Two countries have nearly half of the world's identified bauxite resources (Guinea has 25% and Australia has 20%). Bauxite is no longer mined in the United States as a commercial feedstock for aluminum production. Domestic ore, which accounts for less than 1% of the U.S. requirement for bauxite, is used in the production of non-metallurgical products such as abrasives, chemicals, flame retardants, and refractories.<sup>9</sup>

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. Australia is the largest refiner of bauxite. 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 toward 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 produced by the electrolysis (smelting) of alumina. The electrolysis process is used globally. Companies choose their smelting locations where production conditions are favorable. Favorable conditions include the availability of skilled labor, proximity to

a consumer market, a highly-developed infrastructure and, especially, low cost and reliable energy. Nearly 53% of the energy used worldwide for electrolysis of aluminum comes from hydroelectric power (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 1970's and restructuring continues to this day. Australia and Canada have emerged as major metal producers; other countries entering the world market include Brazil, China, Norway, Venezuela, 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 nearly 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).



**Diagram 3.0 - Energy<sup>tf</sup> Consumption of U.S. Aluminum Operations**

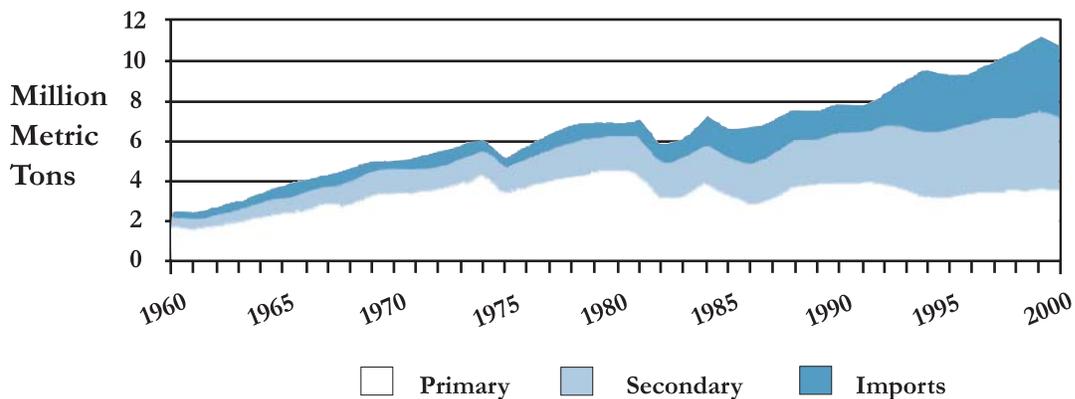
Primary and secondary aluminum are used to manufacture numerous products ranging from aircraft components to household and packaging foils. Each product requires processing and many of these involve heating, melting, alloying and mechanical working. Diagram 3.0 - Energy<sup>tf</sup> Consumption of U.S. Aluminum Operations shows the tacit energy consumption of the major processes in the aluminum production chain.

Production of primary aluminum accounts for 86<sup>th</sup>% of the energy consumed by U.S. industry; production of secondary aluminum for 5<sup>th</sup>%; rolling for 4<sup>th</sup>%; extrusion for 1<sup>st</sup>%; and shape casting for the remaining 4<sup>th</sup>% (Appendix F, Table F-4).

Two operations, electrolysis and the heating/melting of aluminum, account for over 74(79<sup>th</sup>)% 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 10,698,000 metric tons in 2000 originated from three basic sources: primary aluminum (domestically produced), secondary aluminum (recycled domestic material), and aluminum imports. This consisted of 3,668,000 metric tons of primary aluminum, 3,450,000 metric tons of secondary aluminum and 3,580,000 metric tons of imported aluminum.<sup>10</sup> From 1990 to 2000, the annual U.S. growth of these supplies was -0.8%, 4.3% and 10% respectively. Since 1990, the total U.S. supply has risen at an annual rate of about 3.6%. Diagram 3.1 shows the distribution of these supplies over the past 40 years (Appendix G).



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

**Diagram 3.1 - U.S. Aluminum Supply 1960 to 2000**

The United States is the 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% of the primary aluminum produced. By 2000, the U.S. share of world production had decreased to 15.3%. U.S. primary production peaked in 1980, and over the past twenty 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 2000, almost 3,450,000 metric tons of aluminum were recovered. For the years 1991 through 2000, the secondary production of aluminum has grown at an annual rate of 4.3% (Appendix G). Recently, the secondary aluminum growth rate has been slowing because of a combination of maturing scrap collection programs and slowing market growth of scrap sources. This is expected to change. Use of aluminum in the automotive industry grew at nearly 10% annually between 1990 and 2000. This large and growing supply is now beginning to enter the scrap markets and will produce new growth in secondary aluminum.

Imported aluminum is the fastest growing source of U.S. supply with an annual rate of 10% over the 1990 to 2000 time frame (Appendix G). New primary aluminum facilities are being located outside the United States, near new sources of low-cost electricity.

## 4.0 Primary Aluminum Raw Materials

*The total energy associated with producing the raw materials required for aluminum production from bauxite ore was approximately 8.20(14.11<sup>th</sup>) kWh/kg of aluminum in 2000. This accounts for 28% of the total energy required to produce primary aluminum metal and consists of:*

*0.32( 0.34<sup>th</sup>) kWh per kg aluminum for bauxite mining,*

*7.27( 7.87<sup>th</sup>) kWh per kg aluminum for bauxite refining to alumina, and*

*0.66( 5.90<sup>th</sup>) 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 the 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 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

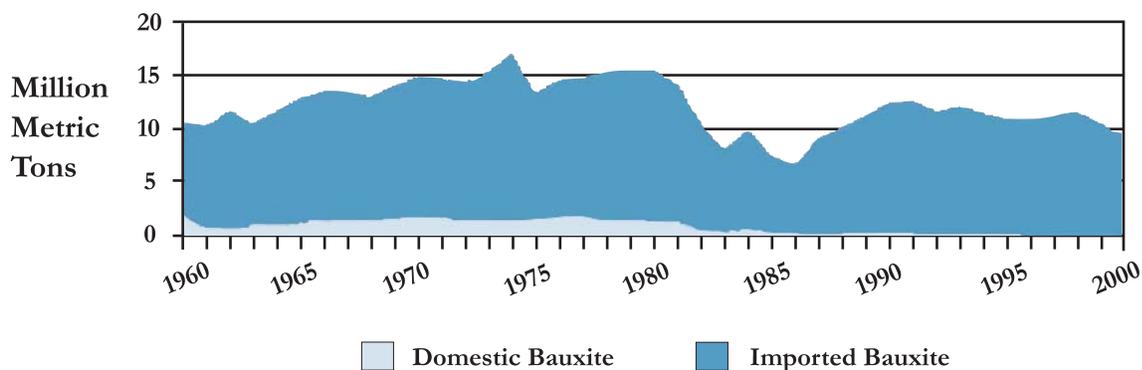
Aluminum is never found as a free metal, but it is commonly found as aluminum oxides or silicates. The oxides are used for producing aluminum. The silicates of aluminum is mixed with other metals such as sodium, potassium, iron, calcium, and magnesium. These silicates are not useful ores since it is chemically difficult and expensive to extract aluminum from them. The aluminum oxides commonly found as naturally occurring minerals include

- corundum, alumina ( $\text{Al}_2\text{O}_3$ )
- böehmite ( $\alpha\text{-Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ , a monohydrate containing 85 weight % alumina)
- diaspore ( $\beta\text{-Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ , the same chemical formula as böehmite with a different crystal structure)
- gibbsite ( $\alpha\text{-Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , a trihydrate containing 65.4 weight % 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%) is metallurgical and used as feedstock for the manufacture of aluminum.

The United States mines less than 1% of the bauxite it uses annually. Domestic ore is mined by one company from surface mines in Alabama and Georgia. Virtually all U.S. mined bauxite is used in the production of non-metallurgical products, such as abrasives, chemicals, and refractories.<sup>8</sup> In 2000, the United States imported a total of 9,120,000 metric tons of bauxite. Each kilogram of primary aluminum required approximately 5.1 kilograms of bauxite for its production. Approximately 7,800,000 metric tons of the imported bauxite were refined for the primary production of aluminum.



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

**Diagram 4.1 - U.S. Bauxite Supply 1960 to 2000**

Diagram 4.1 graphically shows the U.S. bauxite supply (Appendix H).

Nearly all bauxite consumed in the United States is imported. In 2000, the United States imported 9,120,000 metric tons of bauxite. About 95% of the imported bauxite is refined to produce alumina. Approximately 90% of the refined alumina is used to produce primary aluminum.

#### 4.1.1 Bauxite Energy Requirements (Onsite and Theoretical)

*Approximately 0.32(0.34<sup>f</sup>) kWh of process energy were required in 2000 to produce the 5.1 kilograms of bauxite needed to produce 1.0 kilogram of aluminum. Approximately 16.7 kilograms of CO<sub>2</sub> equivalent 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.

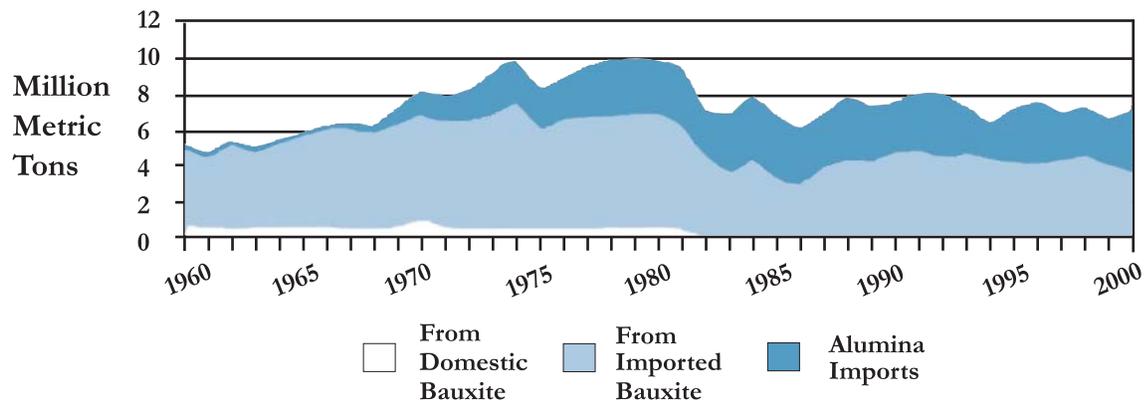
Approximately 5.1 kilograms of bauxite are required to produce a kilogram of aluminum. The energy requirement per kilogram of mined bauxite is 0.06 kWh for typical extraction.<sup>11</sup> Since electricity accounts for less than 1% of the energy used in bauxite production, the tacit addition is negligible (Appendix F, Table F-1).

Calculation of a theoretical minimum energy requirement for mining bauxite is dependent on the system boundaries applied and 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 of carbon dioxide equivalents are emitted for each kilogram of bauxite mined.

## 4.2 Alumina

Theoretically, from the stoichiometric equation ( $2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2$ ), 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 1.9 kilograms of alumina for production of each kilogram of aluminum. The United States produced 3,970,000 metric tons of alumina from bauxite and imported an additional 3,500,000 metric tons of alumina to make aluminum in 2000.



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

**Diagram 4.2 - U.S. Alumina Supply 1960 to 2000**

Diagram 4.2 graphically shows alumina supply sources. The United States had four Bayer refineries in operation in 2000. These refiners processed about 8,664,000 metric tons of bauxite into 3,970,000 metric tons of alumina. About 10% of the alumina produced is used to manufacture abrasive, refractory and other products. Approximately 3,571,000 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 3,500,000 metric tons of alumina were imported (Appendix H).

All commercial alumina ( $\text{Al}_2\text{O}_3$ ) 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 ( $180^\circ\text{C}$  to  $250^\circ\text{C}$ ) 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  $100^\circ\text{C}$ , while böehmite and diaspore are soluble in caustic soda above  $200^\circ\text{C}$ . The treatment of böehmite and diaspore requires higher temperatures and longer digestion times, and therefore is more expensive than treatment of gibbsite. The aluminum oxides in the bauxite react to form soluble sodium aluminate or “green liquor” ( $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O} + 2\text{NaOH} \rightarrow 2\text{NaAlO}_2 + 2\text{H}_2\text{O}$  and  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} + 2\text{NaOH} \rightarrow 2\text{NaAlO}_2 + 4\text{H}_2\text{O}$ ). 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 that 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 ( $2\text{NaAlO}_2 + 4\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} + 2\text{NaOH}$ ). 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  $980^\circ\text{C}$  to  $1,300^\circ\text{C}$  to remove the water of crystallization ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O}$ ) and produce the dry white powder, alumina. 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.

Bauxite residue (red mud) is a by-product 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.<sup>12</sup> 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 the production of ceramic bricks or tiles, the use as roadbed material or as filler material for plastics, or the 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. In locations where bauxite residue has been applied, there has been a significant increase in crop yield and a significant reduction in the amount of phosphorous being leached into local waterways.

#### 4.2.1 Alumina Energy Requirements

*Approximately 7.27(7.87<sup>tf</sup>) kWh of energy were required and 1.62 kg of CO<sub>2</sub> equivalent were released to refine the 1.93 kg of alumina from bauxite needed to produce one kilogram of aluminum in 2000.*

The energy required to produce alumina from bauxite in 1985 was estimated to range from 2 kWh/kg to 9 kWh/kg of alumina.<sup>13</sup> 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.<sup>14</sup> The most recent available refining data lists 3.76 kWh/kg of alumina for 1995.<sup>15</sup> 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.<sup>16</sup> The alumina energy requirement can be estimated as 3.76 kWh/kg of alumina times 1.93 kg alumina per kg aluminum or 7.27 kWh/kg of aluminum, a tacit value of 7.87<sup>tf</sup> kWh/kg of aluminum.

The *Alumina Technology Roadmap* provides insight into the high-priority research and development needs of the global alumina industry.<sup>17</sup> The Roadmap recognizes the need and the opportunity for a 25% 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 of carbon dioxide equivalents 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 requirement for the digestion, clarification, and precipitation steps is 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 third reaction, calcination, require energy to drive off the hydrated water ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O}$ ). The theoretical minimum energy requirement to calcine (dehydrate the alumina) is 0.13 kWh/kg of aluminum produced (Appendix J, Table J-10).

#### 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 ( $2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2$ ) 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 impurities are dissolved 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% 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. Anode carbon dust is unavailable for aluminum production.

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.

Two different anode technologies are utilized by U.S. industry. “Prebaked” carbon anodes account for more than 82% of 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 emission control. 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% 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% moisture and 5% to 15% 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, to drive off volatile matter, and to increase the density, strength and conductivity of the product.<sup>18</sup> Worldwide, about 25% of all raw coke is calcined and about 70% 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 0.61(0.74<sup>tr</sup>) kWh of energy were required and 0.12 kg of CO<sub>2</sub> equivalent were released in the manufacturing of the 0.45 kg of carbon anode needed to produce one kilogram of aluminum in 2000.*

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 1250°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% of the energy input to the prebake ovens. The remaining 54% of the energy needed comes from fuel. Only about 30% of the input energy goes into making the anode, 24% is lost from oven surfaces, 29% goes up the stack and 17% is lost in other ways. New prebake furnace ovens with computer controls are

more efficient with both regenerative and recuperative elements.<sup>19</sup>

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

**Table 4.3.1 - Energy Associated with Carbon Anode Manufacturing**

	kWh/kg anode	kWh/kg of aluminum
	a	0.45 x a
pitch	0.003(2.58 <sup>tf</sup> )	0.001(1.15 <sup>tf</sup> )
coke	0.11(8.97 <sup>tf</sup> )	0.05(4.00 <sup>tf</sup> )
anode	1.36(1.66 <sup>tf</sup> )	0.61(0.74 <sup>tf</sup> )
<b>TOTAL</b>	<b>1.47(13.21<sup>tf</sup>)</b>	<b>0.66(5.89<sup>tf</sup>)</b>

The process energy used to produce a carbon anode is 1.36(1.66<sup>tf</sup>) kWh/kg of anode from the most recent available U.S. data for 1995.<sup>20</sup> The total energy (see Appendix I) to produce a carbon anode is shown in Table 4.3.1 - Energy Associated with Carbon Anode Manufacturing. 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.

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% higher electrical resistivity and a greater dusting propensity than a prebaked anode.<sup>21</sup> The cell emission control system is also more complex than for a prebake cell, since emission systems must be designed to handle the 5% to 15% volatile organic material content of the green coke.<sup>22</sup> Some plants employ both wet and dry gas scrubbing systems to meet 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.<sup>23</sup> A portion of this loss consists of volatile components, while the remainder is the carbonization of the pitch. Pitch contains approximately 85% carbon. Approximately 79% of the pitch is actually carbonized, while 21% 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<sup>tf</sup> 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 prebaked carbon anodes is 12.30<sup>tf</sup> kWh/kg of carbon anode. Theoretically, 0.33 kg of carbon anode are required to produce a kilogram of aluminum. Therefore, the minimum theoretical energy requirement to produce anodes is 4.1 kWh/kg of aluminum.

## 5.0 Primary Aluminum Production

*The total energy associated with primary aluminum production from bauxite ore was approximately 23.78(45.21<sup>th</sup>) kWh/kg of aluminum in 2000. This consisted of:*

*8.20(14.11<sup>th</sup>) kWh/kg aluminum for raw materials and*

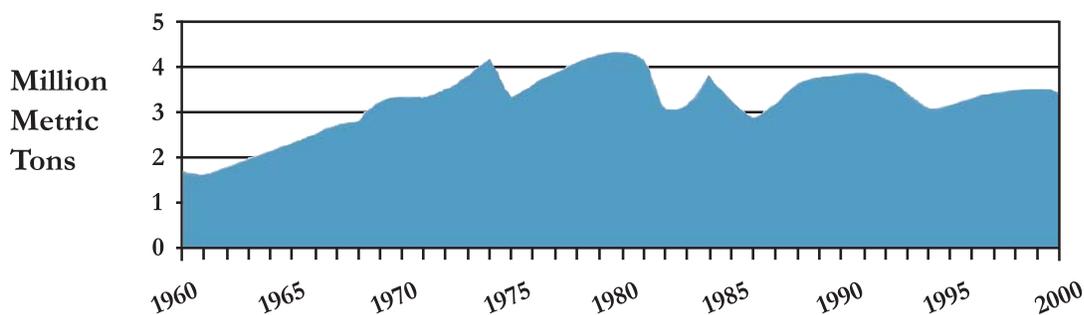
*15.58(31.10<sup>th</sup>) kWh/kg aluminum for electrolytic reduction.*

Alumina is insoluble in all ordinary chemical reagents at room temperature and its melting point is high, above 2000°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 in use. 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

Eleven companies in 2000 operated 23 primary aluminum production facilities in the United States. These facilities had a production capacity of approximately 4,280,600 metric tons and produced 3,668,000 metric tons. These facilities operated at approximately 86% capacity in 2000.<sup>24</sup>



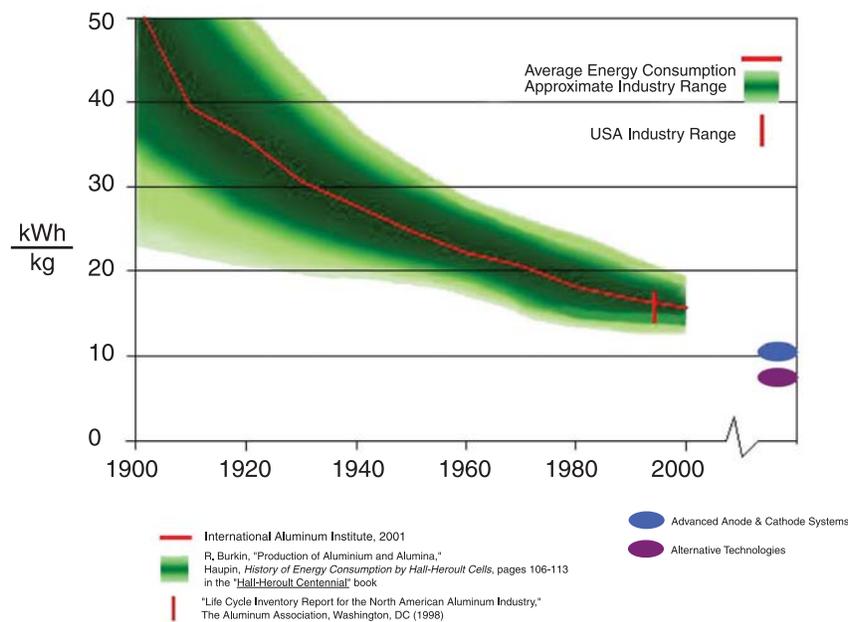
Source: Aluminum statistical review for 2000, The Aluminum Association, 2001, p.7

**Diagram 5.1 - U.S. Production of Primary Aluminum 1960 to 2000**

Production variations in the United States are more representative of the costs to produce aluminum than of the domestic demand. Primary aluminum is traded on a global market, and global demand has been growing steadily at more than 2.2% annually for the past ten years. The United States accounted for 15.3% of the world's primary aluminum production in 2000.

## 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% to 78%.”<sup>25</sup> The Hall-Héroult process is still electric energy intensive.



**Diagram 5.2a - Primary Aluminum Electric Energy Consumption 1900 to 2000**

Since electricity costs are an important portion (about one third) of the total production costs, energy efficiency continues to be a major area of focus for the aluminum industry.

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. Diagram 5.2a - Primary Aluminum Electric Energy Consumption 1900 to 2000 shows the significant electrical energy improvements made between

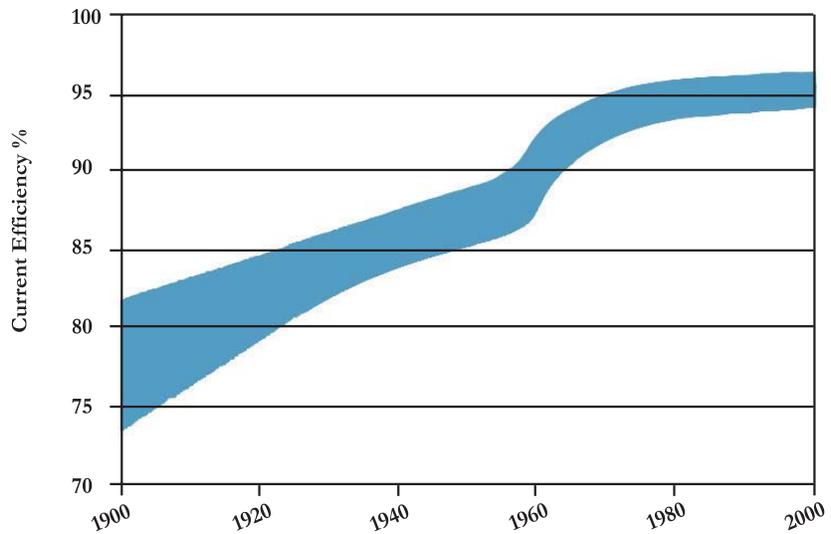
1900 and 2000. Total electricity use (excluding tacit generation and transmission losses) varies from less than 13 kWh/kg of aluminum for the state-of-the-art plants up to more than 20 kWh/kg for older Söderberg facilities (U.S. plants in 1995 averaged around 15.4 kWh/kg Al). The theoretical minimum 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% 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 new cell.<sup>26</sup> 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 new equipment and techniques for smaller and more frequent alumina additions. This, combined with higher amperage, lower current density and larger cells, has dramatically improved current efficiencies and productivity.

**Table 5.2 - Typical Parameters of Aluminum Reduction Cells 1948 vs. 1999** <sup>26</sup>

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 <sup>2</sup> )	1.2 - 1.3	0.8 - 0.85
Area of Cavity (m <sup>3</sup> )	8	40 - 45
Nominal Anode Area (m <sup>2</sup> )	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 <sub>4</sub>	~ 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 <sup>6</sup> ) metric tons	~ 1	~ 20

There is a minimum cell amperage (electrical current) required to produce aluminum (the next section details this minimum). Production in the United States now operates at about 95% current efficiency. The aluminum industry, as shown in Diagram 5.2b - Primary Aluminum Current Efficiency 1900 to 2000, has significantly improved current efficiency. 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 best opportunities for improving Hall-Héroult efficiencies. The voltage requirements of a cell are described in section 5.4.2.



Source: Production of Aluminum and Alumina <sup>3</sup>

**Diagram 5.2b - Primary Aluminum Current Efficiency 1900 to 2000**

### 5.3 Theoretical Minimum Energy for Reduction

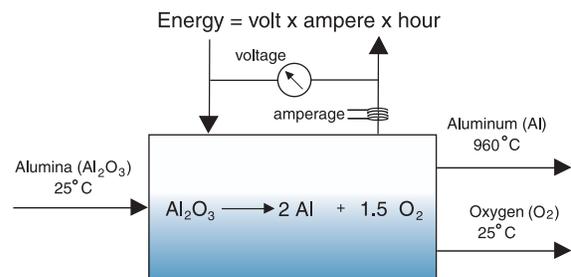
All current primary production facilities and most alternative processes for aluminum production use alumina as their raw material. Any process that starts with alumina to make aluminum has the same theoretical energy requirement. Different processes do not offer any theoretical energy advantage. However, 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.

Molten aluminum is the product of primary reduction processes. 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. Diagram 5.3 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% 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% to 3% 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 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 ( $2 \text{ Al}_2\text{O}_3 \rightarrow 4 \text{ Al} + 3 \text{ O}_2$ ) and is given by the change in the Gibbs free energy value ( $\Delta G$ ). The energy required to maintain system equilibrium is the difference between the heat of reaction ( $\Delta H$ ) and the Gibbs free energy value ( $\Delta G$ ), 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 precedes. Hence, for the alumina reduction reaction, the  $\Delta H$  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



**Diagram 5.3 - Alumina to Aluminum Theoretical Minimum Energy**

values for these thermodynamic measures and details the calculations used to determine the theoretical minimum energy requirement are given in Appendix J for the elements and compounds common to aluminum processing. 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 ( $\Delta G$ ) 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 Diagram 5.3, the energy required to drive the reaction forward ( $\Delta G$ ) 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  $960^\circ\text{C}$  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-Hérout Carbon Anode Reduction

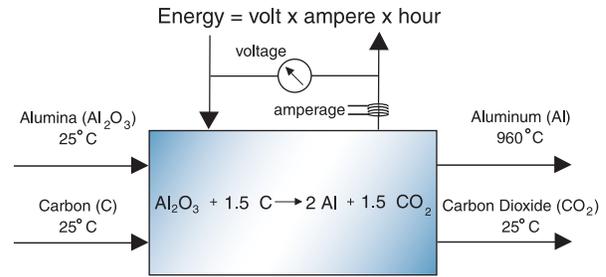
*The theoretical minimum energy requirement for producing molten aluminum at  $960^\circ\text{C}$  in a Hall-Hérout cell with a carbon anode is 5.99 kWh/kg.*

All commercial aluminum production uses a carbon anode in a Hall-Hérout 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-Hérout 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-Hérout process is  $2 \text{ Al}_2\text{O}_3 + 3 \text{ C} \rightarrow 4 \text{ Al} + 3 \text{ CO}_2$ . Diagram 5.3.1 shows an idealized Hall-Hérout cell for the production of aluminum. In this cell, it is assumed that the reactants (alumina and carbon) enter the cell at  $25^\circ\text{C}$ , the carbon dioxide byproduct leaves the cell at  $25^\circ\text{C}$ , 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 ( $\Delta G$ ) 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. The theoretical minimum energy requirement for the reduction of alumina in a carbon anode cell is 5.99 kWh/kg of aluminum. (Note: if the CO<sub>2</sub> gas emission at 960°C is included, the total theoretical minimum energy requirement is 6.16 kWh/kg of aluminum).



**Diagram 5.3.1 - Alumina and Carbon to Aluminum Theoretical Minimum Energy**

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

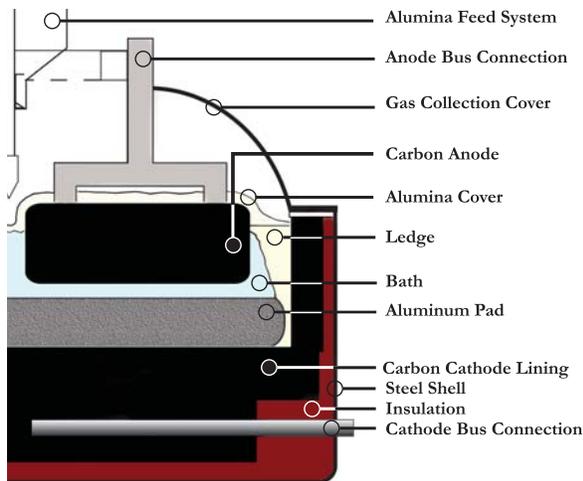
Today's state-of-the-art reduction cells are achieving current efficiency levels of 96% and energy consumption levels of 13.0 kWh/kg of aluminum.<sup>27</sup> The theoretical minimum energy requirement at 100 percent current efficiency is 5.99 kWh/kg of aluminum. The energy efficiency levels of present state-of-the-art carbon anode reduction cells are about 46%.

## 5.4 Hall-Héroult Reduction Process

The engineering, materials, and process knowledge of existing components and processes form the foundations for developing new components, processes, and techniques for producing aluminum. The Hall-Héroult cell is a system and improving one component does not necessarily result in an improved cell or a more energy-efficient operation, since all components must perform together as a whole system. On a practical level, it is helpful to understand the Hall-Héroult process in terms of its components, operation and interrelationships. This section describes a typical prebake anode operation and provides practical information on the Hall-Héroult process so the reader can understand the impact that component and system changes have on cell performance.

### 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 to 12 m long, 3 m to 4 m wide and 1 m to 1.5 m deep. 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



**Diagram 5.4.1 - Typical Cell**

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% 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.

Electric current enters the cell through the carbon anode and flows through 3 cm to 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.

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 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. Replacing anodes disrupts cell operations. 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.

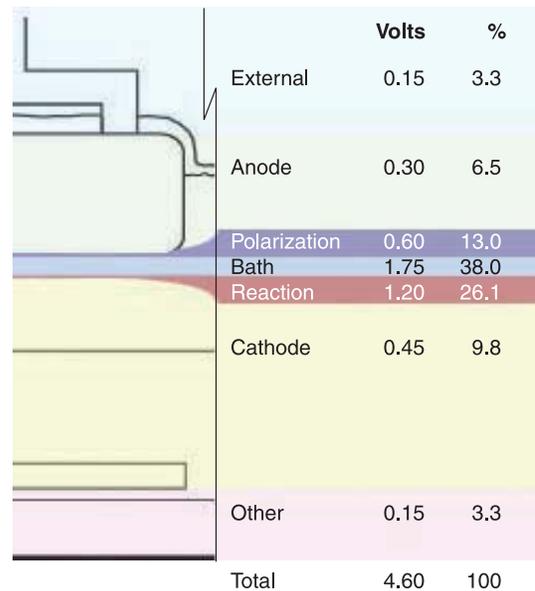
### 5.4.2 Voltage Requirements

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). Modern Hall-Héroult cells operate at high (95+%) current efficiencies. The approximate voltage components of a conventional cell are shown in Diagram 5.4.2 - Voltage Distribution in a Hall-Héroult Cell.

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).<sup>28</sup> 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.



**Diagram 5.4.2 - Voltage Distribution in a Hall-Héroult Cell**

### 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 ( $\text{Na}_3\text{AlF}_6$ ). This is modified with the addition of aluminum fluoride ( $\text{AlF}_3$ ), calcium fluoride ( $\text{CaF}_2$ ) 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 ( $\text{AlF}_3$ ) 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  $\text{NaF}$  to  $\text{AlF}_3$  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 to 5 cm. The electrolytic bath occupies the space between the carbon anode and 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 values flowing through a cell create electromagnetic forces that cause the pad to rotate, and this motion deforms the molten aluminum/cryolite interface. The electromagnetic forces cause local metal velocities of about 5 cm/sec to occur. 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 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 and can 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 allows 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).

### **Cathode**

The bottom lining of the cell also serves as a cathode and carries current from the molten metal pad. Since 10% 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  $TiB_2$  coatings may offer an opportunity to increase the graphitic content of cathode blocks, and lower cell resistance, without reducing cell life. Under optimal conditions, the life of a cathode or cell is in the range of 7 to 10 years.

### **Current Density**

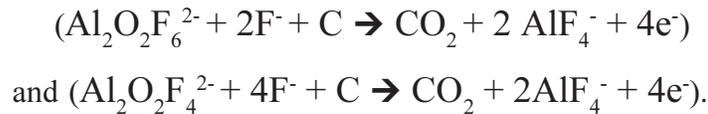
Current density is a measure of the productivity of a cell. It is calculated by dividing the amperage supplied to an anode by the geometric face area of the anode. It is generally expressed in amperes per square centimeter ( $A/cm^2$ ). Most potlines operate in the range of  $0.8 A/cm^2$  to  $1.0 A/cm^2$ . 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 ( $\text{Al}^{3+}$ ) or oxygen ( $\text{O}^{2-}$ ) 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 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.<sup>29</sup>

Polarization effects at the cathode contribute much less to overvoltage than at the anode. The cathode reactions are ( $\text{AlF}_6^{3-} + 3\text{e}^- \rightarrow \text{Al} + 6\text{F}^-$ ) and ( $\text{AlF}_4^- + 3\text{e}^- \rightarrow \text{Al} + 4\text{F}^-$ ). The aluminum ion complexes  $\text{AlF}_6^{3-}$  and  $\text{AlF}_4^-$  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% alumina dissolved in a typical bath. The normal operating level is about 3% alumina. If the level goes above 4%, some of the added alumina may not dissolve rapidly and can settle to form a sludge on the cell bottom thereby reducing cell conductivity. If it falls below 1% alumina the cell is starved of the reactant and an “anode effect” ensues. When this occurs, the production of metal is interrupted and fluorine ( $\text{F}$ ), hydrogen fluoride ( $\text{HF}$ ), and other perfluorocarbon gases are discharged instead of carbon dioxide. 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 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

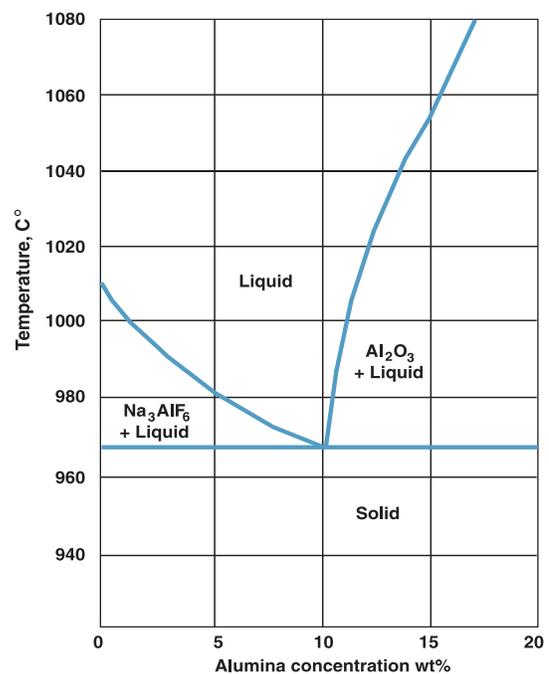
analysis to provide control of alumina concentration in the bath and alumina feed rate.

Alumina is fed by automatic handling and conveyor systems. The alumina must dissolve rapidly and its specifications are complex with numerous tradeoffs. The alumina 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 than and have replaced most feeding systems in both prebaked and Söderberg cells.

### Cell Operating Temperature

Bath chemistry controls the operating temperature of the Hall-Héroult process. Most commercial cells operate near 960°C (1233°K). Reducing the cell operating temperature is an obvious approach to saving energy and reducing capital costs by lowering insulation requirements. However, controlling the operating variables of a cell becomes more critical as temperature is lowered. Dissolved alumina must be available for reduction in the bath to have high cell productivity, minimize energy consuming concentration polarization, and avoid anode effects. Lowering the cell temperature lowers the solubility range for alumina in a cryolite bath. The solubility or phase diagram for a cryolite alumina system is V-shaped with temperature on the y-axis and alumina concentration on the x-axis. Diagram 5.4.3 shows the phase diagram for pure cryolite and alumina. Cells must operate within the V; operations to the left will precipitate cryolite, and those to the right will precipitate alumina. Decreasing the temperature narrows the cell operating range with respect to alumina solubility. In practice, bath chemistry is modified with the addition of aluminum fluoride, calcium fluoride and



**Diagram 5.4.3 Cryolite - Alumina Phase Diagram**

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% to 45% of the total heat loss in a cell.<sup>30</sup> 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 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*,<sup>5</sup> compiled by the U.S. Department of Energy, Office of Industrial Technologies Program, and *Life Cycle Inventory Report for the North American Aluminum Industry*,<sup>6</sup> 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 (CO<sub>2</sub>) and carbon monoxide (CO); process upset perfluorocarbons emissions; and hydrogen fluoride (HF) formed from the inclusion of moisture (H<sub>2</sub>O) 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 3.79 kg of carbon dioxide for each kilogram of aluminum produced (Appendix E, Table E-2).

A total of 5.31 kilograms of CO<sub>2</sub> is generated from the reduction process for each kilogram of aluminum produced in the 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 carbon dioxide for each kilogram of aluminum produced, while potlines using electricity from hydro-power plants produce close to zero carbon dioxide 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 (CF<sub>4</sub>) and hexafluoroethane (C<sub>2</sub>F<sub>6</sub>) 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 carbon dioxide. The GWP of CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub> is 6,500 and 9,200 respectively. In other words, 1 kg of CF<sub>4</sub> released to the atmosphere is equivalent in its warming potential to 6,500 kg of CO<sub>2</sub>.

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 1,096 metric tons of tetrafluoromethane and 90 metric tons of hexafluoroethane in 2000.<sup>31</sup> In 1995, the aluminum industry entered into a “Voluntary Aluminum Industry Partnership” (VAIP) with the EPA to reduce perfluorocarbon emissions by 46% during the next decade. Reductions in primary aluminum production and efficiency improvements to reduce anode effects have reduced emissions of tetrafluoromethane and hexafluoroethane since 1990 by 55% and 64%, respectively. The U.S. aluminum industry and EPA are continuing the VAIP to seek further GHG reductions beyond the original achievements. The total 2000 U.S. aluminum perfluorocarbon emissions are 2.2 CO<sub>2</sub> 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 CO<sub>2</sub> emissions for the carbon anode manufacturing amount to approximately 0.12 kg of CO<sub>2</sub> equivalents per kg of aluminum. More specific information on this topic can be found in the comprehensive life cycle information published by The Aluminum Association.<sup>6</sup>

### **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<sub>3</sub>, and to render the remaining material inert through vitrification.

## 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 of 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 continued adoption of improved cell designs, improved feeding systems, improved bath composition, improved control systems, and other technical and practice advancements. This trend has resulted in a gradual decline in energy consumption in the range of 0.2% to 0.5% 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%, the goal is generally to reduce the overvoltage in the aluminum cells to increase overall electric efficiency.

A number of technological and engineering improvement options exist and are being adopted by 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.

### 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 18<sup>to</sup>% 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% current efficiency with the voltage distribution shown in Diagram 5.4.2. The combination of an inert anode with a wetted cathode could provide a 22<sup>to</sup>% reduction in energy consumption and the elimination of cell CO<sub>2</sub> emissions. These technologies are described in Section 6.0 - Advanced Hall-Héroult Cells 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 technology

processes could displace existing Hall-Héroult cells in the future. These processes are described in Section 7 - Alternative Primary Aluminum Processes. Both processes could potentially change where and how the 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) CO<sub>2</sub> emissions. The carbothermic process is anticipated to save 20<sup>th</sup>% in energy and be economical at a much smaller scale than Hall-Héroult facilities. The kaolinite reduction process is anticipated to save about 11<sup>th</sup>% 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 on-site energy demands,

**Table 5.6.1 - Ore-to-Metal Comparison of Near and Midterm 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 <sub>3</sub> Reduction	
<b>Onsite Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	7.59	7.59	7.59		
		Kaolinite				8.14	
		Anode Materials	0.61	0.61	0.75	0.75	
		Reaction Carbon					
	<b>TOTAL</b>	<b>8.20</b>	<b>8.20</b>	<b>8.34</b>	<b>7.59</b>	<b>8.89</b>	
	<b>Reaction Energy</b>	Reaction Thermal				7.71	-1.90
		Furnace Losses				1.36	0.40
		Reaction Electrolysis	3.76	3.76	6.90		6.48
		Cell Ohmic	10.67	7.62	6.20		2.93
		<b>TOTAL Reaction</b>	<b>14.43</b>	<b>11.38</b>	<b>13.11</b>	<b>9.07</b>	<b>7.91</b>
<b>TOTAL Onsite kWh/kg Al</b>		<b>22.63</b>	<b>19.58</b>	<b>21.45</b>	<b>16.66</b>	<b>16.80</b>	
<b>Percent Energy Savings</b>							
	Reactions		21%	9%	37%	45%	
	Reactions and anode		20%	8%	40%	42%	
	Reactions, anodes and ore		13%	5%	26%	26%	
<b>Tacit Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	
		Kaolinite					8.81 <sup>tf</sup>
		Anode Materials	5.89 <sup>tf</sup>	5.89 <sup>tf</sup>	0.75 <sup>tf</sup>		0.75 <sup>tf</sup>
		Reaction Carbon				8.25 <sup>tf</sup>	11.10 <sup>tf</sup>
	<b>TOTAL</b>	<b>14.10<sup>tf</sup></b>	<b>14.10<sup>tf</sup></b>	<b>8.96<sup>tf</sup></b>	<b>16.44<sup>tf</sup></b>	<b>20.65<sup>tf</sup></b>	
	<b>Reaction Energy</b>	Reaction Thermal				15.48 <sup>tf</sup>	-1.90 <sup>tf</sup>
		Furnace Losses				2.73 <sup>tf</sup>	0.60 <sup>tf</sup>
		Reaction Electrolysis	7.56 <sup>tf</sup>	7.56 <sup>tf</sup>	13.85 <sup>tf</sup>		13.02 <sup>tf</sup>
		Cell Ohmic	21.41 <sup>tf</sup>	15.29 <sup>tf</sup>	12.46 <sup>tf</sup>		5.88 <sup>tf</sup>
		<b>TOTAL Reaction</b>	<b>28.97<sup>tf</sup></b>	<b>22.85<sup>tf</sup></b>	<b>26.31<sup>tf</sup></b>	<b>18.21<sup>tf</sup></b>	<b>17.59<sup>tf</sup></b>
<b>TOTAL Tacit kWh/kg Al</b>		<b>43.07<sup>tf</sup></b>	<b>36.95<sup>tf</sup></b>	<b>35.27<sup>tf</sup></b>	<b>34.65<sup>tf</sup></b>	<b>38.24<sup>tf</sup></b>	
<b>Percent Energy Savings</b>							
	Reactions		21 <sup>th</sup> %	9 <sup>th</sup> %	37 <sup>th</sup> %	39 <sup>th</sup> %	
	Reactions and anode		18 <sup>th</sup> %	22 <sup>th</sup> %	48 <sup>th</sup> %	47 <sup>th</sup> %	
	Reactions, anodes and ore		14 <sup>th</sup> %	18 <sup>th</sup> %	20 <sup>th</sup> %	11 <sup>th</sup> %	

domestically available ore, and lower-cost raw materials.

Table 5.6.1 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, Table M-1 and Table M-2). These voltage changes are supported by theory and reported experimentation and provide a good estimation 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.

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 they are proven and existing cells need rebuilding. Industry will require significant demonstration time before adopting any alternative to Hall-Héroult technology.

## 6.0 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 existing cells. Inert anodes could be adopted more quickly by industry since 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(18%) reduction in the electrolysis energy required to produce aluminum.*

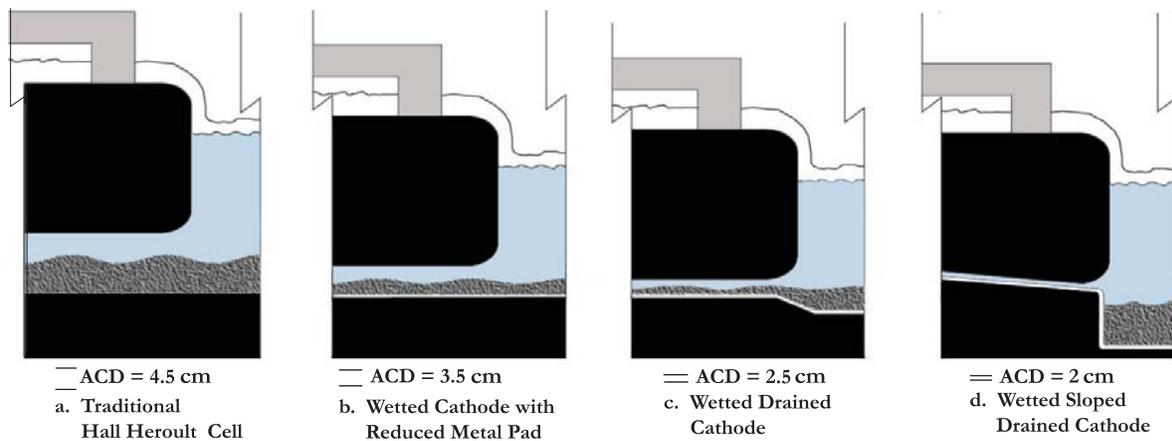
Molten aluminum does not wet the carbon lining of a Hall-Héroult cell. The aluminum pad rests on an extremely thin sheet of cryolite bath. This creates an electrical junction similar to the air gap between two metal bars and causes a small voltage drop. If the bars are clamped tighter - providing better contact - the junction voltage 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 ( $\text{TiB}_2$ ) has been found to be a wettable cathodic material, and several approaches to incorporate  $\text{TiB}_2$  into a Hall-Héroult cell are being studied.<sup>32</sup> Cathodes made wettable with  $\text{TiB}_2$  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  $\text{TiB}_2$  material. Recent evidence also suggests that wetted cathodes reduce the formation of sludge (undissolved alumina) on the cell bottom and improve cell operations.<sup>33</sup>

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

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

The decrease in ACD is shown for each configuration. These configurations are attractive since they can be incorporated as a retrofit to existing facilities. Some of these configurations are currently being evaluated in commercial cells and could soon be available.<sup>34</sup> 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.



**Diagram 6.1 - Conceptual Wetted Cathode Cells**

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 of various wetted designs can be estimated (Appendix M, Table M-1) for the different cell configuration shown in Diagram 6.1.

The modern Hall-Héroult cell, shown in Diagram 6.1 (a) has an ACD of 4.5 cm and a voltage distribution similar to that shown in Diagram 5.4.3. The traditional cell voltage distribution has 1.75 V(dc) associated with the ACD. The ACD voltage drop accounts for approximately 38% of the total 4.60 V(dc) drop across the cell. A wetted cathode provides better electrical contact between the metal pad and the cathode. It allows operation with a thinner metal pad which results in a flatter pad surface. This allows the ACD to be decreased. If the ACD were lowered from 4.5 cm to 3.5 cm, as shown in Diagram 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% reduction in 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 2.5cm, as shown in Diagram 6.1 (c), the voltage associated with the bath would be proportionally lowered to 0.97 V(dc). The total voltage would decrease to 3.82V(dc), which would provide a 16% reduction in 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.<sup>35, 36</sup> If the ACD were 2 cm, the voltage associated with the resistance of the bath would be 0.78 V(dc). The total voltage required would decrease to 3.63 V(dc), which would provide nearly a 20% reduction in electrical energy usage.

**Table 6.1.1 - Energy Consumption Associated with Various Wetted Cathode Arrangements (kWh/kgAl)**

Energy Input kWh/kg Al		Modern Prebaked Hall-Hérault ACD = 4.5	Wetted Cathode ACD = 3.5	Wetted Cathode ACD = 2.5	Wetted Cathode ACD = 2.0
<b>Onsite Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	7.59	7.59	7.59
		Anode Materials	0.61	0.61	0.61
		TOTAL	8.20	8.20	8.20
	<b>Reaction Energy</b>	Reaction Electrolysis	3.76	3.76	3.76
		Cell Ohmic	10.67	9.45	8.23
		TOTAL Reaction	14.43	13.21	11.99
TOTAL Onsite kWh/kg Al		22.63	21.41	20.19	
<b>Percent Energy Savings</b>					
		Reactions	8%	17%	21%
		Reactions and anode	8%	16%	20%
		Reactions, anodes and ore	5%	11%	13%
<b>Tacit Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>
		Anode Materials	5.89 <sup>tf</sup>	5.89 <sup>tf</sup>	5.89 <sup>tf</sup>
		TOTAL	14.10 <sup>tf</sup>	14.10 <sup>tf</sup>	14.10 <sup>tf</sup>
	<b>Reaction Energy</b>	Reaction Electrolysis	7.56 <sup>tf</sup>	7.56 <sup>tf</sup>	7.56 <sup>tf</sup>
		Cell Ohmic	21.41 <sup>tf</sup>	18.96 <sup>tf</sup>	16.51 <sup>tf</sup>
		TOTAL Reaction	28.97 <sup>tf</sup>	26.52 <sup>tf</sup>	24.07 <sup>tf</sup>
TOTAL Onsite kWh/kg Al		43.07 <sup>tf</sup>	40.62 <sup>tf</sup>	38.17 <sup>tf</sup>	
<b>Percent Energy Savings</b>					
		Reactions	8 <sup>tf</sup> %	17 <sup>tf</sup> %	21 <sup>tf</sup> %
		Reactions and anode	7 <sup>tf</sup> %	14 <sup>tf</sup> %	18 <sup>tf</sup> %
		Reactions, anodes and ore	6 <sup>tf</sup> %	11 <sup>tf</sup> %	14 <sup>tf</sup> %

Table 6.1.1 lists the data and measures the impact of the wetted cathode arrangements. Depending upon the cell design, the reduction energy impact is expected to be as high as 18<sup>th</sup>%.

### **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, 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 emission from the bath. Wetted cathode technology does not change the emissions related to process upsets or bath emissions. The electrolytic 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. Wetted and traditional cathodes will produce 1.22 kg of carbon dioxide from the reduction reaction ( $2 \text{ Al}_2\text{O}_3 + 3 \text{ C} \rightarrow 4 \text{ Al} + 3 \text{ CO}_2$ ), 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 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 Al) for a modern Hall-Héroult cell emits 3.55 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 nearly 22% to 2.8 kg CDE/kg of aluminum produced. This lowers the total CDE emissions associated with a wetted-sloped cathode cell from 8.26 kg CDE/kg to 5.86 kg CDE/kg of aluminum produced (Appendix E, Table E-4).

#### **Cell Waste Products**

Longer cell life is one of the benefits of using wetted cathodes. 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.<sup>37</sup> The material demands of an inert anode require that it be highly conductive and thermally and mechanically stable at 800°C to 1000°C, not react or dissolve to any significant extent in cryolite, and not react or corrode in the 800°C to 1000°C oxygen containing atmosphere. Few materials are truly inert under the extreme conditions of a cell. Undesirable inert anode reactions, dissolution, or corrosion with the bath must occur at a very slow

rate since they result in anode material contaminating the aluminum product.

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 (Diagram 5.4.2 Voltage Distribution in a Hall-Héroult). When used in conjunction with a drained cathode, it is estimated that an inert anode may save up to 22<sup>nd</sup>0% 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 (O<sub>2</sub>) being discharged rather than carbon dioxide (CO<sub>2</sub>). 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 existing cells with limited changes and use existing alumina and aluminum handling infrastructures. Some electrical infrastructure changes would be required since the inert anode will operate at a higher voltage than 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.<sup>38</sup> 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.

### 6.2.1 Theoretical Energy for Hall-Héroult Inert Anode

The theoretical minimum energy requirement for an idealized 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 Diagram 6.2.1 assumes that the reactant (alumina) enters the cell at 25°C, the oxygen byproduct leaves

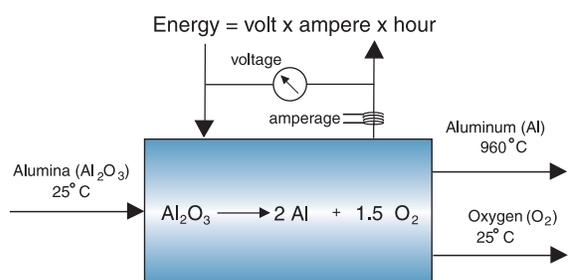


Diagram 6.2.1 - Theoretical Energy Schematic for Inert Anode

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, no parasitic reactions, no limitations to the ionic species reacting at the electrodes, and no heat/energy losses external to the system. The results show that the energy required to drive the reaction forward ( $\Delta G$ ) 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 theoretical minimum energy requirement for an inert anode is 9.03 kWh/kg of aluminum. (Note: if the O<sub>2</sub> 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% 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 that is 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 45% higher than the carbon anode requirement. This makes the inert anode reaction voltage 1 V(dc) higher than a carbon anode Hall-Héroult cell. However, three factors are expected to provide the inert anode with an overall improved operational energy performance than 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 6.2.2 and calculations are presented in Appendix M, Table M-2.

The Hall-Héroult carbon and inert anode process 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).<sup>39</sup> 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.

#### **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 5.90<sup>f</sup> 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. A conservative estimate of

**Table 6.2.2 - Energy Impact of Inert Anode Technology**

Energy Input kWh/kg Al		Modern Prebaked Hall-Hérout ACD = 4.5	Inert Anode a) Elimination of Carbon Anode ACD = 4.5	Inert Anode a) Elimination of Carbon Anode b) Low Polarization ACD = 4.5	Inert Anode a) Elimination of Carbon Anode b) Low Polarization c) Wetted Cathode ACD = 2.0
<b>Onsite Energy Demands</b>	<b>Raw Materials</b>				
	Bauxite-alumina	7.59	7.59	7.59	7.59
	Anode Materials	0.61	0.75	0.75	0.75
	TOTAL	8.20	8.34	8.34	8.34
	<b>Reaction Energy</b>				
	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 kWh/kg Al	22.63	25.91	24.49	21.45	
<b>Percent Energy Savings</b>	Reactions		-22%	-12%	9%
	Reactions and anode		-22%	-12%	8%
	Reactions, anodes and ore		-14%	-8%	6%
<b>Tacit Energy Demands</b>	<b>Raw Materials</b>				
	Bauxite-alumina	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>
	Anode Materials	5.90 <sup>tf</sup>	0.75 <sup>tf</sup>	0.75 <sup>tf</sup>	0.75 <sup>tf</sup>
	TOTAL	14.11 <sup>tf</sup>	8.96 <sup>tf</sup>	8.96 <sup>tf</sup>	8.96 <sup>tf</sup>
	<b>Reaction Energy</b>				
	Reaction Electrolysis	7.56 <sup>tf</sup>	13.85 <sup>tf</sup>	13.85 <sup>tf</sup>	13.85 <sup>tf</sup>
	Cell Ohmic	21.41 <sup>tf</sup>	21.41 <sup>tf</sup>	18.58 <sup>tf</sup>	12.46 <sup>tf</sup>
TOTAL Reaction	28.97 <sup>tf</sup>	35.27 <sup>tf</sup>	32.43 <sup>tf</sup>	26.31 <sup>tf</sup>	
TOTAL Onsite kWh/kg Al	43.08 <sup>tf</sup>	44.22 <sup>tf</sup>	41.39 <sup>tf</sup>	35.27 <sup>tf</sup>	
<b>Percent Energy Savings</b>	Reactions		-22 <sup>tf</sup> %	-12 <sup>tf</sup> %	9 <sup>tf</sup> %
	Reactions and anode		-3 <sup>tf</sup> %	5 <sup>tf</sup> %	22 <sup>tf</sup> %
	Reactions, anodes and ore		-3 <sup>tf</sup> %	4 <sup>tf</sup> %	18 <sup>tf</sup> %

the energy associated with the manufacturing of inert anodes is made in Appendix M, Table M-3. Since actual values for manufacturing inert anodes are unknown at this time, this estimate, approximately 0.75 kWh/kg of aluminum, provides a basis for comparing processes. The total energy associated with an inert anode operating cell is 0.75<sup>tf</sup> kWh/kg for anode manufacturing, 3.14 kWh/kg for the onsite additional voltage requirement, and 3.15<sup>tf</sup> kWh/kg for the generation and transmission losses associated with the additional anode voltage. The inert anode requires 7.04<sup>tf</sup> kWh/kg of aluminum produced, 18<sup>tf</sup>% more than the tacit energy associated with the Hall-Hérout carbon-anode requirement.

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 are jostled and moved 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% lighter than carbon dioxide, less mass moves through the electrode area. The physical properties, in practice, contribute to a lower anode

overtoltage.<sup>40</sup> The inert anode can also be shaped to allow for better release of the oxygen generated (Diagram 6.2.2). 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% energy improvement.

### Inert Anode - Wetted Cathode Combination

A more stable inert anode surface will allow the anode-cathode-distance (ACD) to be reduced and 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 traditional Hall-Héroult cells, are expected to provide

- 10% operating cost reductions (elimination of carbon anode plant and labor costs associated with replacing anodes)<sup>41</sup>
- 5% cell productivity increases<sup>41</sup>
- 43% reduction 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, materials of construction have ruled out multipolar cells using molten fluoride electrolytes.

Two variations of electrochemical multipolar cells are possible: one system uses independent pairs of electrodes immersed in the same cell; the second 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. 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

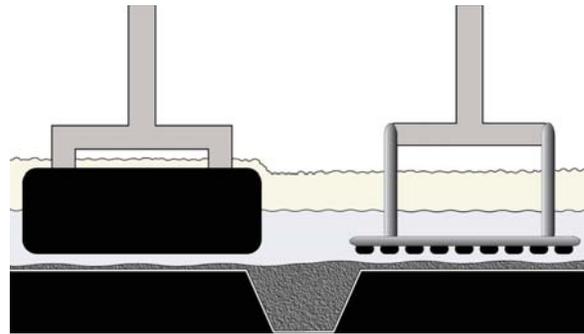


Diagram 6.2.2 - Inert Anode

bypass current efficiency losses. A simplified conceptual system diagram of the two variations in multipolar cells is shown in Diagram 6.3. Multipolar cell designs are complicated by the need to remove liquid metal and collect the gaseous reaction products.

The bipolar-multipolar concept was successfully demonstrated for electrolytic aluminum chloride reduction.<sup>42</sup> 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% current efficiency at 9.26 kWh/kg of aluminum. The Alcoa multipolar cell was electrically 40% more efficient than a present day Hall-Héroult cell.

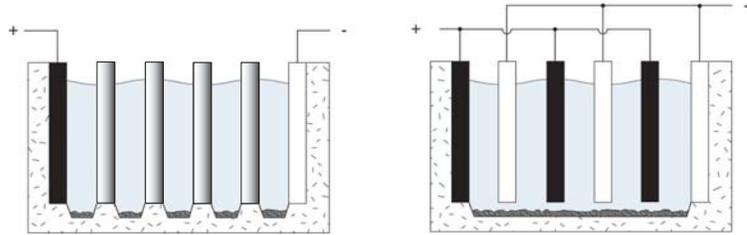


Diagram 6.3 - Multipolar Cells

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 biphenyl byproducts, the reactor capital costs, and general maintenance costs.<sup>43</sup>

The Alcoa cell had distinct technical advantages over the classic Hall-Héroult: 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% to 10% of purified aluminum chloride ( $\text{AlCl}_3$ ), 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  $0.8 \text{ A/cm}^2$  to  $2.3 \text{ A/cm}^2$  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, is currently being explored.<sup>44</sup> In this concept, the operating temperature is  $750^\circ\text{C}$ , much lower than Hall-Héroult technology. Alumina saturation at the lower temperature of the electrolyte bath is maintained by controlling a suspension of fine alumina particles in the bath. This technology offers 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.

## 7.0 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. Industry adoption of these processes for producing aluminum has not yet occurred, 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.<sup>45</sup> Carbothermic technology is projected to produce aluminum from ore at 34.7<sup>tf</sup> kWh/kg or 20% below a modern Hall-Héroult carbon-anode technology (Table 7.1.2).

Carbothermic reduction produces aluminum using a chemical reaction that takes place within a reactor. This volumetric reaction requires much less physical space than the area reaction of Hall-Héroult.

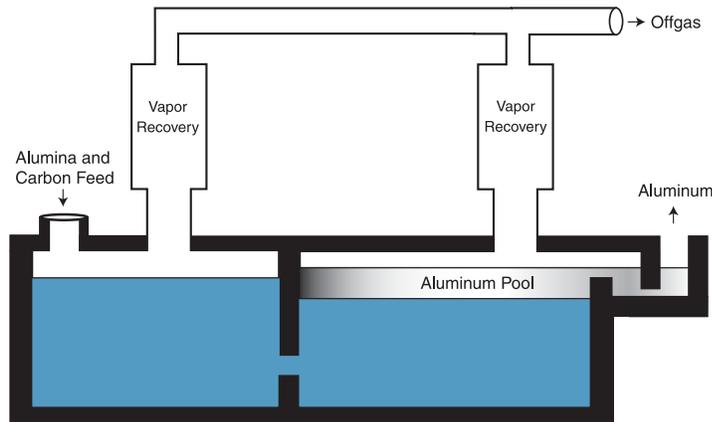
These properties give carbothermic technology a small footprint and make it much less dependent on the economies of scale (large and long potlines) required for an economically efficient Hall-Héroult facility. If successful, this technology could significantly change the structure of the aluminum industry, 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 casting operations. This would provide additional energy, economic, and environmental benefits to the industry.

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 (Diagram 7.1). The first stage net reaction is one in which alumina and carbon form an alumina-aluminum carbide slag at ~1,900°C ( $2\text{Al}_2\text{O}_3 + 9\text{C} \rightarrow \text{Al}_4\text{C}_3 + 6\text{CO}$ ). The second net reaction ( $\text{Al}_4\text{C}_3 + \text{Al}_2\text{O}_3 \rightarrow 6\text{Al} + 3\text{CO}$ ) forms aluminum metal by reduction of aluminum carbide, and occurs at ~2,000°C. The thermodynamics (temperatures and chemical equilibria) are

#### 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.*

very complex. A significant portion of aluminum evolves as gas phase components (Al and  $\text{Al}_2\text{O}$ ) at these operating temperatures. Careful process control is necessary to minimize the generation of volatiles. Recovery of these components in the form of  $\text{Al}_4\text{C}_3$  in a vapor recovery system is required for the process to be economically viable. If the Al and  $\text{Al}_2\text{O}$  back react with CO to  $\text{Al}_2\text{O}_3$  then productivity of the process is decreased and the  $\text{Al}_4\text{C}_3$  required to satisfy the process stoichiometry is deficient.



**Diagram 7.1 - Carbothermic Reactor**

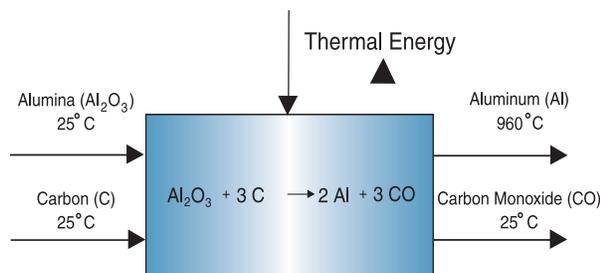
The complex thermodynamic controls, sophisticated equipment, and construction materials required to successfully develop an economical commercial system have eluded industry. Current R&D efforts are reevaluating carbothermic technology in hopes of capitalizing on new, advanced, high-intensity, electric-arc furnace technology, advanced thermodynamic and system modeling techniques, and an improved understanding of the process dynamics.<sup>46</sup>

### 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  $25^\circ\text{C}$ , the carbon monoxide byproduct leaves at  $25^\circ\text{C}$ , and the aluminum product leaves the reactor system as molten metal at  $960^\circ\text{C}$ . The assumed molten metal temperature is lower than the actual reactor metal discharge



**Diagram 7.1.1 - Carbothermic Theoretical Minimum Energy**

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  $960^\circ\text{C}$  is used throughout this report. The theoretical reaction occurs under perfect conditions: when there are no

reverse reactions, no parasitic reactions, and no heat/energy losses external to the system.

Appendix J, Table J-3 details the calculation of theoretical minimum energy for the carbothermic reaction. The results show that the energy required to drive the reaction forward ( $\Delta G$ ) 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 is 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% 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% thermal efficiency. If the thermodynamics of the reaction and offgas recovery can be controlled within 95% of the theoretical requirements, the electrical energy required for an operating carbothermic reactor would be 9.07 kWh/kg of aluminum produced ( $7.32 \text{ kWh/kg} / (0.85 \times 0.95)$ ). This represents a 37% reduction in energy use when compared to the 14.3 kWh/kg of aluminum from a modern Hall-Héroult Cell. Table 7.1.2 Comparison of Hall-Héroult and Carbothermic Reduction 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. Carbothermic technology could bring

- a reduction in capital costs by 50% or more as a result of volumetric processing through high-intensity smelting;
- a reduction in production costs by 25% through lower electrical demand and elimination of carbon anode manufacturing and handling;
- the production of a high purity CO/CO<sub>2</sub> 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 7.1.2 - Comparison of Hall-Héroult and Carbothermic Reduction**

<b>Energy Input kWh/kg Al</b>		<b>Modern Prebaked Hall-Héroult</b>	<b>Carbothermic Reduction</b>	
<b>Onsite Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	7.59	7.59
		Kaolinite		
		Anode Materials	0.61	
		Reaction Carbon		
	TOTAL	8.20	7.59	
	<b>Reaction Energy</b>	Reaction Thermal		7.71
		Furnace Losses		1.36
		Reaction Electrolysis	3.76	
		Cell Ohmic	10.67	
		TOTAL Reaction	14.43	9.07
TOTAL Onsite kWh/kg Al		22.63	16.66	
<b>Percent Energy Savings</b>		Reactions	37%	
		Reactions and anode	40%	
		Reactions, anodes and ore	26%	
<b>Tacit Energy Demands</b>	<b>Raw Materials</b>	Bauxite-alumina	8.21 <sup>tf</sup>	8.21 <sup>tf</sup>
		Kaolinite		
		Anode Materials	5.89 <sup>tf</sup>	
		Reaction Carbon		8.24 <sup>tf</sup>
	TOTAL	14.10 <sup>tf</sup>	16.45 <sup>tf</sup>	
	<b>Reaction Energy</b>	Reaction Thermal		15.48 <sup>tf</sup>
		Furnace Losses		2.73 <sup>tf</sup>
		Reaction Electrolysis	7.56 <sup>tf</sup>	
		Cell Ohmic	21.41 <sup>tf</sup>	
		TOTAL Reaction	28.97 <sup>tf</sup>	18.21 <sup>tf</sup>
TOTAL Tacit kWh/kg Al		43.07 <sup>tf</sup>	34.66 <sup>tf</sup>	
<b>Percent Energy Savings</b>		Reactions	37 <sup>tf</sup> %	
		Reactions and anode	48 <sup>tf</sup> %	
		Reactions, anodes and ore	20 <sup>tf</sup> %	

### 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 0.49 kg CDE/kWh (Appendix E, Table E-1). Half of the U.S. primary industry operates on hydroelectric power, and the aluminum industry average electrical generation emission rate is 0.25 kg CDE/kWh. The carbothermic reaction results in the generation of carbon-based greenhouse gases (GHG), mainly

**Table 7.1.3 - Carbon Dioxide Equivalent Comparison of Hall-Héroult and Carbothermic**

Emissions Sources	Carbothermic		Modern Hall-Héroult	
		kgCDE/kgAl		kgCDE/kgAl
Carbon Anode		--		1.65
Carbon Reaction		2.45		--
<b>Electricity Generation</b>				
kWh/kg Al	9.07		14.43	
kg CDE/kWh	0.486		0.246	
		4.41		3.55
<b>Process</b>			Perfluorocarbon	2.2
<b>Total</b>		6.86		7.42

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 greenhouse gas (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 7.1.3 (Appendix E, Table E-4) shows the lower electrical demand of carbothermic technology resulting in a lower total CDE than a Hall-Héroult system.

## 7.2 Kaolinite Reduction Technology

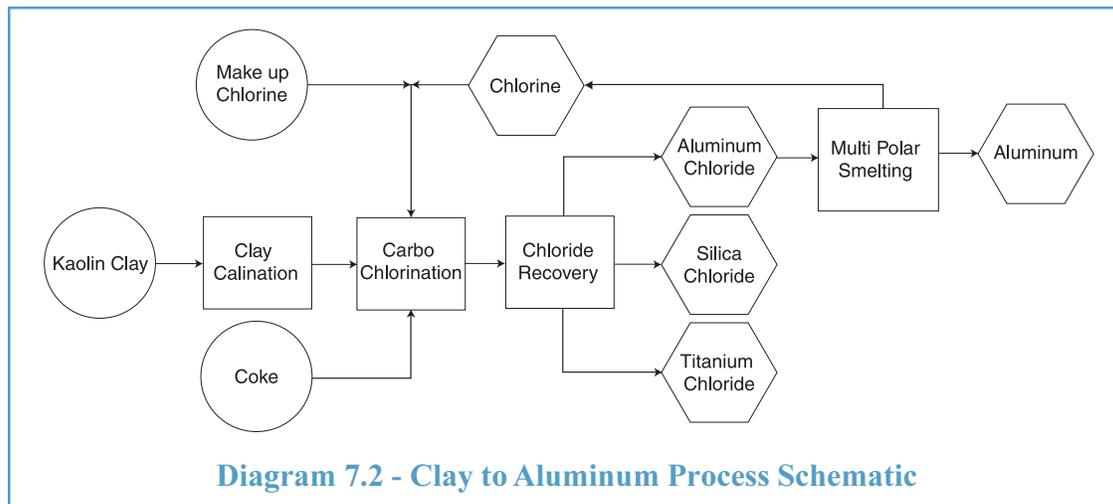
Production of pure aluminum by reduction of aluminum chloride is associated with its discovery in 1825 and predates the Hall-Héroult process. Alumina conversion to aluminum chloride and reduction to aluminum using bipolar technology was demonstrated in the late 1970’s, but it was not commercialized because of problems with product purity and projected high capital and operating costs (Section 6.3). 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
- 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 ( $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ )), significant amounts of titanium dioxide (1% to 5%), 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 technology are shown in Diagram 7.2.<sup>47</sup>



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 the 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 ( $3\text{SiCl}_4 + 2\text{Al}_2\text{O}_3 \rightarrow 4\text{AlCl}_3 + 3\text{SiO}_2$ ). 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 ( $4\text{SiCl}_4 + 5\text{O}_2 \rightarrow 2\text{SiO}_2 + 3\text{O}_2 + 8\text{Cl}_2$ ).

The crude aluminum chloride must be purified for ease of operation of the electrolytic reduction cells and for final aluminum quality. The main impurity is iron, which is present as ferric chloride at levels as high as  $\sim 50,000$  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 ( $2\text{AlCl}_3 \rightarrow 2\text{Al} + 3\text{Cl}_2$ ). 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, no parasitic reactions, and no heat/energy losses external to the system. These assumptions yield a theoretical minimum energy requirement of aluminum production from kaolinite of 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, no parasitic reactions, no 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 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 an overall kaolinite to aluminum theoretical energy requirement that is lower than the minimum energy requirement for the aluminum chloride reduction process.

### 7.2.2 Comparative Benefits for Kaolinite Reduction and Hall-Héroult Cells

The kaolinite reduction process offers potential advantages when compared to the Hall-Héroult process. Table 7.2.2 shows the onsite and tacit energy comparison. The combined clay carbo-chlorination and bipolar aluminum chloride smelting process is estimated to be 35% more tacit energy efficient than Hall-Héroult, 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% lower than a modern Hall-Héroult cell. The large tacit energy

**Table 7.2.2 - Comparison of Hall-Héroult and Kaolinite Reduction**

<b>Energy Input kWh/kg Al</b>		Modern Prebaked Hall-Héroult	Kaolinite AlCl <sub>3</sub> Reduction
<b>Onsite Energy Demands</b>	<b>Raw Materials</b>		
	Bauxite-alumina	7.59	8.14
	Kaolinite		0.75
	Anode Materials	0.61	
	Reaction Carbon		
	TOTAL	8.20	8.89
	<b>Reaction Energy</b>		
	Reaction Thermal		-1.90
	Furnace Losses		0.40
	Reaction Electrolysis	3.76	6.48
Cell Ohmic	10.67	2.93	
TOTAL Reaction	14.43	7.91	
TOTAL Onsite kWh/kg Al		22.63	16.80
<b>Percent Energy Savings</b>			
Reactions			45%
Reactions and anode			42%
Reactions, anodes and ore			26%
<b>Tacit Energy Demands</b>	<b>Raw Materials</b>		
	Bauxite-alumina	8.21 <sup>tf</sup>	8.81 <sup>tf</sup>
	Kaolinite		0.75 <sup>tf</sup>
	Anode Materials	5.89 <sup>tf</sup>	
	Reaction Carbon		11.10 <sup>tf</sup>
	TOTAL	14.10 <sup>tf</sup>	20.66 <sup>tf</sup>
	<b>Reaction Energy</b>		
	Reaction Thermal		-1.90 <sup>tf</sup>
	Furnace Losses		0.60 <sup>tf</sup>
	Reaction Electrolysis	7.56 <sup>tf</sup>	13.02 <sup>tf</sup>
Cell Ohmic	21.41 <sup>tf</sup>	5.88 <sup>tf</sup>	
TOTAL Reaction	28.97 <sup>tf</sup>	17.59 <sup>tf</sup>	
TOTAL Tacit kWh/kg Al		43.07 <sup>tf</sup>	38.25 <sup>tf</sup>
<b>Percent Energy Savings</b>			
Reactions			39 <sup>tf</sup> %
Reactions and anode			47 <sup>tf</sup> %
Reactions, anodes and ore			11 <sup>tf</sup> %

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% 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 63% more energy compared to those in a modern Hall-Héroult process (Appendix M, Table M-4). 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-Hérault systems.

It is important to emphasize that while the 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**

Appendix E, Table E-4 tabulates the carbon dioxide equivalent (CDE) emissions for the kaolinite to aluminum process. Operating off the average U.S. electrical grid this process would produce 17% more CDE emissions than Hall-Hérault. However, the same plant operating on the average U.S. smelter grid (50.2% hydroelectric) would actually result in 8% lower CDE emissions than Hall-Hérault facilities.

## 8.0 Secondary Aluminum (Recycling)

The production of primary aluminum ingots from bauxite ore requires approximately 23.8(45.2<sup>tf</sup>) kWh/kg of aluminum. Recovering aluminum from scrap to produce secondary aluminum ingot consumes about 6% of the energy required to produce primary aluminum.<sup>48</sup> 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  $150 \times 10^9$  kilowatt hours (0.51 quad) of energy in 2000, the equivalent of 17,200 Megawatts. Each kilogram of aluminum that is recovered by recycling saves 43.6<sup>tf</sup> kWh of the 46.4<sup>tf</sup> 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 1900's, 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% of the nation's total aluminum supply (401,000 metric tons). Over the next 40 years, production of recycled aluminum rose 760% to 3,450,000 metric tons. During those same 40 years, the total U.S. aluminum metal supply increased 346% (Appendix G). In 2000, 68 plants in the United States produced secondary ingots. Nearly half – 48.5% – of the aluminum metal produced in the United States in 2000 was from recycled material.<sup>49</sup>

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). Only about 6% of the energy required to produce a primary aluminum ingot from bauxite ore is needed to produce a recycled aluminum ingot. In addition, to achieve a given output of ingot, recycled aluminum requires only about 10% 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.

Diagram 8.0 - U.S. Aluminum Market shows the annual growth rates of the three sources of metal supply between 1990 and 2000 period, together with the growth in the major aluminum product markets. Recycling is growing at more than 4.3% per year while U.S. primary production is in decline (Appendix G).

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, wire, cable, 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 U.S. recycling statistics.

## 8.1 Secondary Aluminum Production

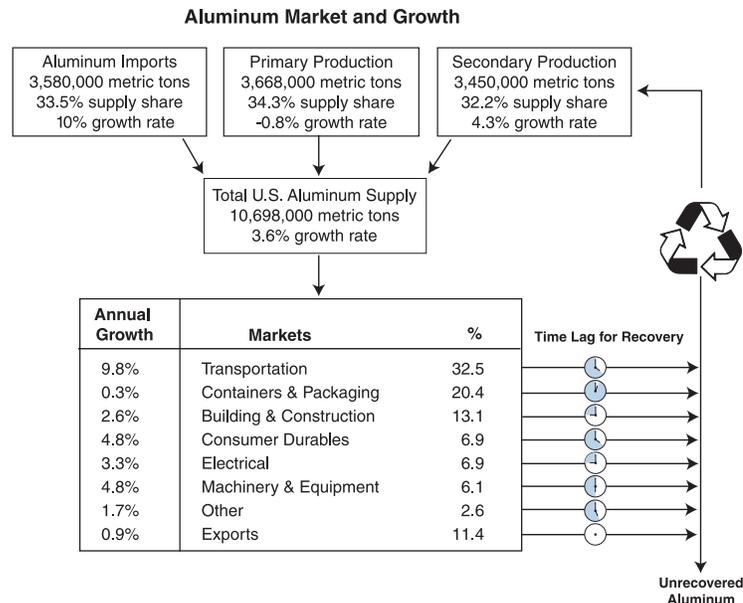
Secondary aluminum producers represent a separate and vital segment of the aluminum industry whose principal activities are converting purchased scrap and recovering metal from skim and dross generated in molten metal operations into usable aluminum alloy products. Recycling in primary aluminum operations 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 the remanufacture 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 for the remanufacture of 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 consuming.

Casting alloys are the largest and 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 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



Source: Aluminum statistical review for 2000, The Aluminum Association, 2001, p. 23

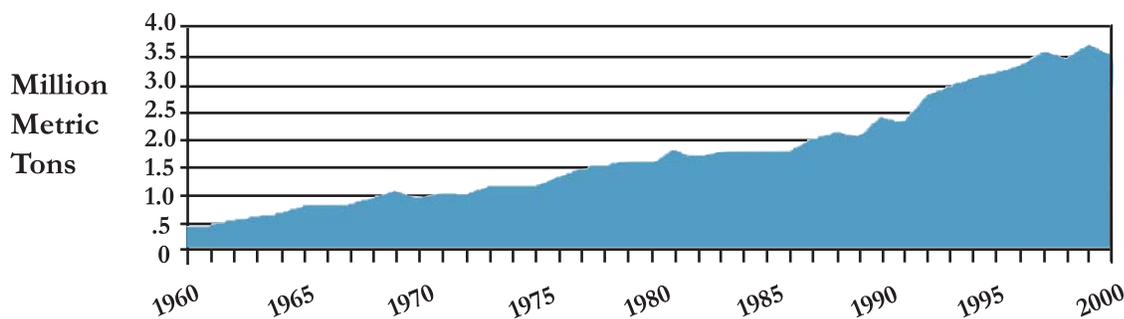
**Diagram 8.0 - U.S. Aluminum Market**

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 salable alloy compositions will become common practice.

New scrap sorting technology is developing, including technologies that relate to the recovery of aluminum from the large transportation and white goods markets.<sup>50</sup> New technologies with computer screening are using color segregation and laser-induced-breakdown spectroscopy (LIBS) to sort wrought from cast and, in some instances, alloy from alloy. 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. One third of the U.S. supply of aluminum in 2000 was from secondary metal. In 2000, the United States produced 3,450,000 metric tons of secondary aluminum. This market had an annual growth rate of 4.3% over the last ten years (Diagram 8.2 and Appendix G).



Source: Aluminum statistical review for 2000, The Aluminum Association, 2001, p. 7

**Diagram 8.2 - U.S. Production of Secondary Aluminum 1960 to 2000**

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

The urban mine has accumulated scrap products for the past hundred years and it continues to do so. 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% of scrapped automobiles’ weight in 2000, but represents 35% to 50% of its scrap value. This source will grow rapidly as new automobile designs continue to utilize a greater proportion of aluminum.

Because large amounts of aluminum are stored in long-life products (accumulated within the “urban mine”) and because of the continued growth in aluminum demand, recycling will continue to grow

and be a significant contributor to the U.S. metal supply. In fact, recycling is projected to overtake bauxite mining and primary production as the main source of aluminum in the United States in the near future with imported primary metal providing the balance of U.S. industry needs.

### **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 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%. Rotary kilns and conveyor furnaces operate in essentially the same efficiency range. Induction melting is more efficient at approximately 90% 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 extraction of recoverable aluminum from skim and dross obtained from foundries and primary and secondary molten metal processing is typically performed in secondary producers. While other dross treatment processes have been developed, rotary furnaces in which dross and salts are mixed and heated remain in most common use. 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
- 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% 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 primary aluminum, is used in this report for secondary aluminum to easily compare aluminum process technologies. 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 a molten 960°C metal is 0.39 kWh/kg. The theoretical energy requirement for melting aluminum scrap is less than 6.5% of the theoretical energy requirement for the primary production of aluminum. The theoretical energy required to raise a substance from room temperature to its melting point, melt the material, and raise the molten aluminum to a higher temperature is calculated, and the formulae and values are presented in Appendix K. Pure aluminum melts at 660°C and the energy required to melt pure aluminum is 0.30 kWh/kg, 23% 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 in 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 recycling volume. Consumer awareness requires the continuing education and promotion of the energy and environmental benefits of recycling to the public, and incentives 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%. Improved technology can be applied to increase scrap recovery rates, especially with regard to aluminum in municipal solid waste. Recycling energy requirements can be reduced by making incremental improvements in existing furnaces. These improvements can be made by recuperating stock gas energy for preheating combustion air and metal feedstock by making burner and furnace design modifications and by controlling furnace practice and operating conditions.<sup>51, 52</sup> New technologies must also be developed to ensure more significant progress.

## 9.0 Aluminum Processing

The aluminum industry can be divided into metal-producing and product-producing sectors. The metal-producing sector manufactures approximately 3,668,000 metric tons of primary metal and 3,450,000 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.<sup>53</sup> Wire rod and bar, forgings, impacts, and powder products total more than 700,000 metric tons, about 7% of the aluminum product market, and have not been studied as a part of this report.

Recoveries (yield) in each product processing sector are less than 100%. Handled, melted, and worked tonnage exceeds that implied by the product statistics. The manufacture of circles and blanks from aluminum sheet, for example, may recover as little as 35% 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 permit the shipment of molten metal 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, and 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 include 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.<sup>54</sup> In addition, a gas furnace increases metal losses due to oxidation. Gas furnaces have 5% to 8% metal loss compared to 0.5% to 3% 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. Recuperation of the 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.

### **Skimming**

Oxide naturally forms on the surface of molten aluminum, resulting initially in a thin protective film. With time and temperature increases, 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%. 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.<sup>55</sup> 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 1950's 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 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%. 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% energy efficient, while gas-fired crucibles are 15% to 28% energy efficient, and electrically heated crucibles are 83% 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.<sup>56</sup>

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.

## **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.

Ingot 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 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 3,668,000 metric tons of primary aluminum were cast into ingots in 2000 (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% and requires about 1.01(1.24<sup>th</sup>) kWh/kg of cast ingot product (Appendix F, Table F-2).

*Primary Ingot Casting Distribution of Energy Consumption (Appendix F, Table F-10)*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	79(66 <sup>th</sup> )%	21(34 <sup>th</sup> )%	0(0 <sup>th</sup> )%

Secondary ingot casting is nearly identical to primary casting in terms of on-site process energy usage. The tacit energy requirements appear different due to the origin of the electrical power. Secondary aluminum ingot casting is assumed to operate on tacit energy from the national electrical grid. Primary aluminum ingot casting is assumed to occur at the primary metal smelters. Over half of the U.S. primary metal producers operate on hydroelectric power, and their electric tacit energy values are significantly lower than the average U.S. grid numbers. Secondary aluminum was cast into 3,450,000 metric tons of ingots in 2000. Secondary ingot casting has typical yields of 96% and requires about 2.50(2.79<sup>th</sup>) kWh/kg of product.

*Secondary Ingot Casting Distribution of Energy Consumption (Appendix F, Table F-10)*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	77(74 <sup>th</sup> )%	5(9 <sup>th</sup> )%	18(18 <sup>th</sup> )%

### 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.

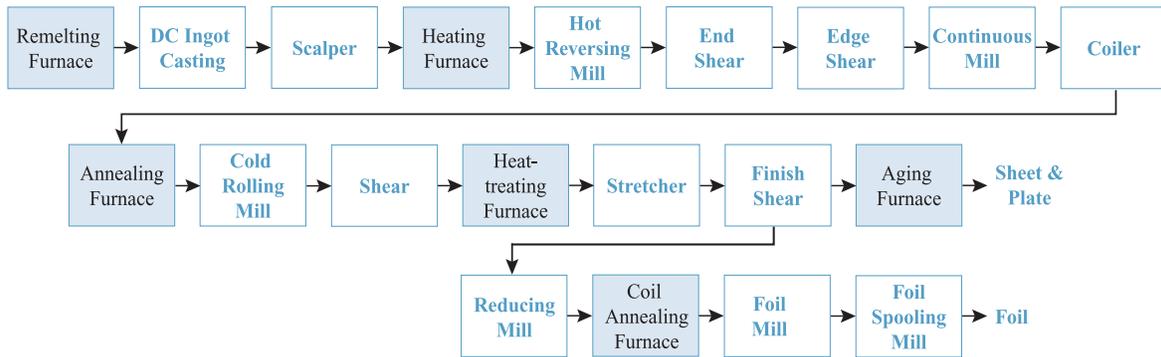
Molten metal fluxing and filtration processes continue to undergo changes leading to greater efficiencies, higher product quality, reduced environmental impact, and reduced costs.

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). Diagram 9.3 shows the unit operations of a typical rolling mill.



**Diagram 9.3 - 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. Nearly 2,749,000 metric tons of cold rolled products were produced in 2000 (Appendix F, Table F-4). Cold rolling has typical yields of about 84% and requires about 0.64(1.30<sup>th</sup>) kWh/kg of rolled product.

*Cold Rolling Distribution of Energy Consumption (Appendix F, Table F-10)*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	42(27 <sup>th</sup> )%	55(70 <sup>th</sup> )%	3(3 <sup>th</sup> )%

In 2000, nearly 2,749,000 metric tons of hot-rolled products were produced (Appendix F, Table F-4). Hot rolling has typical yields of about 82% and requires about 0.62(1.13<sup>th</sup>) kWh/kg of rolled product.

*Hot Rolling Distribution of Energy Consumption (Appendix F, Table F-10)*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	57(41 <sup>th</sup> )%	43(59 <sup>th</sup> )%	0(0 <sup>th</sup> )%

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:

- 1) the energy required to heat starting stock to the rolling temperature, and
- 2) 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  $\epsilon$  is the strain or deformation defined as  $\epsilon = \ln(t_i/t_f)$ ,  $t_i$  where  $t_i$  represents the initial and  $t_f$  the final dimension,  $\sigma$  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 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% and the electric/hydraulic system efficiency is 75%, 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 50% overall energy efficiency and hot rolling at about 52% 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.<sup>57</sup> 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.

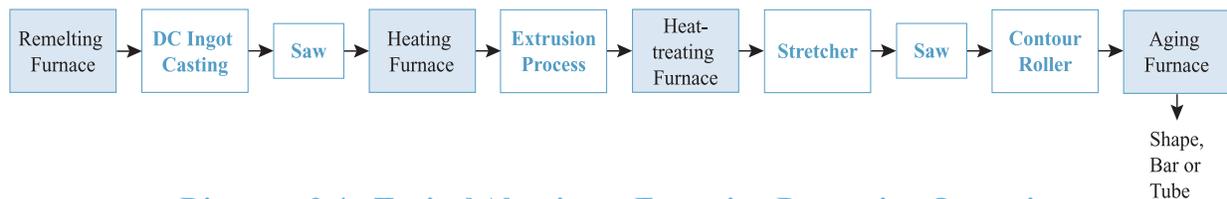
Continuous strip casting is in wide current use for some sheet and foil specifications and has demonstrated energy savings of more than 25% relative to conventional ingot rolling. These casters convert molten metal directly into reroll gauge sheet at 1 mm to 12 mm thickness. Continuous strip casters 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 results 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 advance 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. Diagram 9.4 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.



**Diagram 9.4 - 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 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% 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 affect acceptability.

#### 9.4.1 Energy Requirements for Extruding Aluminum

The United States produced over 1,719,000 metric tons of extruded aluminum products in 2000 (Appendix F, Table F-4). Extrusion processes have typical yields of 69% and require about 1.30(1.51<sup>st</sup>) kWh/kg of extruded product.

*Extrusion Distribution of Energy Consumption (Appendix F, Table F-10)*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	87(27 <sup>th</sup> )%	7(70 <sup>th</sup> )%	3(3 <sup>rd</sup> )%

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:

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

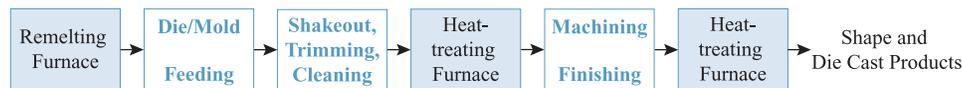
The hotter the material is, the lower the deformation energy required. The simpler the die, the lower the extrusion-energy requirement. The heat capacity equations needed to calculate the energy requirements for heating pure aluminum are listed in Appendix K. The energy required to deform the material 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  $F = A_o(\sigma_m/\eta) \epsilon$ , where the strain  $\epsilon$ , corresponds to the reduction area,  $\epsilon = \ln(A_o/A_f)$ ,  $\sigma_m$  is the mean stress for the strain,  $A_o$  is the original cross-sectional area, and  $\eta$  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% for heating and 75% for the electric/hydraulic system. These assumptions imply that overall extrusion facilities operate at about 34% 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. Diagram 9.5 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.

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.



**Diagram 9.5 - Typical Aluminum Product Shape Casting Operations**

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, and 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 2,513,000 metric tons of shape-cast products were produced in 2000. Shape casting has typical yields of only 45% and requires about 2.56(2.64<sup>tf</sup>) kWh/kg of cast product. The energy consumed is almost exclusively related to furnace and heating operations (Appendix F, Table F-4).

*Shape Casting Distribution of Energy Consumption*

Energy Category	Fossil-thermal	Electrical	Other-fuels
Percent	0(13 <sup>tf</sup> )%	100(81 <sup>tf</sup> )%	0(6 <sup>tf</sup> )%

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% overall heating efficiency and a 75% electric/hydraulic system efficiency are assumed. These assumptions imply that shape-casting facilities operate at about 23% 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 and heat-treatable high integrity pressure die castings that utilize lower impurity compositions, vacuum, and dry lubrication are being produced.

## 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 temperature required 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.

## Notes

- <sup>1</sup> *Aluminum Statistical Review for 2000* (Washington, D.C.: The Aluminum Association, Inc., 2001) 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.
- <sup>2</sup> *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.
- <sup>3</sup> *Production of Aluminium and Alumina*, ed. A.R. Burkin (Chichester: John Wiley & Sons, 1987)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.
- <sup>4</sup> 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."
- <sup>5</sup> *Aluminum Industry Vision, Sustainable Solutions for a Dynamic World*, 22.
- <sup>6</sup> *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.
- <sup>7</sup> *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.
- <sup>8</sup> *Aluminum Statistical Review for 2000*, 43.
- <sup>9</sup> "Bauxite and Alumina Statistics and Information," U.S.Geological Survey, Minerals Information, Available: [<http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/>].
- <sup>10</sup> *Aluminum Statistical Review for 2000*, 7.
- <sup>11</sup> *Life Cycle Inventory Report for the North American Aluminum Industry*, E-3.

- <sup>12</sup> *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.
- <sup>13</sup> *Production of Aluminium and Alumina*, 38.
- <sup>14</sup> *Energy and Environmental Profile of the U.S. Aluminum Industry*, 29.
- <sup>15</sup> *Life Cycle Inventory Report for the North American Aluminum Industry*, E-8.
- <sup>16</sup> *Life Cycle Inventory Report for the North American Aluminum Industry*, E-8.
- <sup>17</sup> *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.
- <sup>18</sup> Paul J. Ellis, "Tutorial: Petroleum Coke Calcining and Uses of Calcined Petroleum Coke," 13. Speech given at AIChE 2000 Spring National Meeting, 3<sup>rd</sup> International Conference on Refining Processes, March, 2000.
- <sup>19</sup> *Production of Aluminium and Alumina*, 57.
- <sup>20</sup> *Life Cycle Inventory Report for the North American Aluminum Industry*, E-6.
- <sup>21</sup> *Production of Aluminium and Alumina*, 49.
- <sup>22</sup> Ellis, 13.
- <sup>23</sup> "The Manufacture of Carbon and Graphite," Chapter in *Industrial Graphite Engineering Handbook*, (Parma, OH: UCAR Carbon Company, Inc, 2001) 1-6.
- <sup>24</sup> *Aluminum Statistical Review for 2000*, 10-11.
- <sup>25</sup> Warren Haupin, "History of Electrical Consumption by Hall-Héroult Cells," Chapter in *Hall-Héroult Centennial*, ed. W. Peterson and R. Miller (New York: the Metallurgical Society of AIME, 1986) 106. This article provides a detailed historical review of energy usage in the Hall-Héroult process from the first cells to 1986.
- <sup>26</sup> R.P. Pawlek, "75 Years of Development of Aluminum Electrolysis Cells," *Aluminium*, 75.9 (1999): 734-743.
- <sup>27</sup> Barry J. Welch, "Aluminum Production Paths in the New Millennium," *Journal on Metals* 51.5 (February 1999): 24-28.
- <sup>28</sup> *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.

- <sup>29</sup> Noel Jarrett, W.B. Frank, and Rudolf Keller, "Advances in Aluminum Smelting," *Metallurgical Treatises AIME* VI.93 (1981): 137.
- <sup>30</sup> *Production of Aluminium and Alumina*, 63.
- <sup>31</sup> U.S. Environmental Protection Agency, Office of Air and Radiation, Web site. Available: [www.epa.gov/globalwarming/].
- <sup>32</sup> G. D. Brown, M. P. Taylor, G. J. Hardie, and R.W. Shaw, from Comalco Aluminum Ltd., "TiB<sub>2</sub> Coated Aluminum Reduction Cells: Status and Future Direction of Coated Cells in Comalco." Paper presented at the Queenstown Aluminum Smelting Conference, 26 Nov 1998.
- <sup>33</sup> Mark P. Taylor, Gregory J. Hardie, Fiona J. Stevens McFadden, and William Uru from Comalco Aluminum Ltd., "Use of Refractory Hard Cathodes to Reduce Energy Consumption in Aluminum Smelting." Paper presented at the Second International Conference on Processing Materials for Properties, TMS 2000 Technical Program.
- <sup>34</sup> *Use of Refractory Hard Cathodes to Reduce Energy Consumption in Aluminum Smelting*.
- <sup>35</sup> Larry Boxall, Arthur V. Cooke, and Wayne Hayden, "TiB<sub>2</sub> Cathode Material: Application in Conventional VSS Cells," *Journal of Light Metals* 36.11 (November 1984): 35-39.
- <sup>36</sup> Low Energy Aluminum Reduction Cell With Induced Bath Flow, U.S. Patent 4,602,990.
- <sup>37</sup> *Report of the American Society of Mechanical Engineers' : Technical Working Group on Inert Anode Technologies*, 28.
- <sup>38</sup> Thomas M. Leeuwen, "An Aluminum Revolution," *Desk Notes*, (Credit Suisse First Boston Corporation: 22 June 2000).
- <sup>39</sup> *Report of the American Society of Mechanical Engineers' : Technical Working Group on Inert Anode Technologies*, Appendix A-9. Inert anode voltage equation,  $E = 2.922 - 0.0005712 \times T$ , where E is in V(dc) and T is in degrees Kelvin.
- <sup>40</sup> *Report of the American Society of Mechanical Engineers' : Technical Working Group on Inert Anode Technologies*, Appendix A-9: Thermodynamics of Electrochemical Reduction of Aluminum.
- <sup>41</sup> *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.
- <sup>42</sup> D. Bhogeswara Rao, U.V. Choudry, T.E. Erstfeld, R.J. Williams, and Y.A. Chang, "Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen from Nonterrestrial Sources," Chapter in *Space Resources and Space Settlements* (Moffett Field, California: NASA Ames Research Center Summer Study, 1977) 15.

- <sup>43</sup> Warren Haupin, "Reflections on the Hall-Héroult Process," Editorial in *Molten Salts Bulletin*, ed. 59 (Marseille: Ecole Polytechnique, Universitarire de Marseille).
- <sup>44</sup> Craig Brown, "Next Generation Vertical Electrode Cell," *Journal on Metals* 53.5 (May 2001): 39-42.
- <sup>45</sup> Vianey Garcia-Osorio and B. Erik Ydstie (the Department of Chemical Engineering Carnegie Mellon University) and Tor Lindstad (SINTEF MAterials Technology), "Dynamic Model for Vapor Recovery in Carbothermic Aluminum Process."
- <sup>46</sup> Kai Johansen, Jan A. Aune, Marshal Bruno, and Anders Schei, "Carbothermic Aluminum - Alcoa and Elkem's New Approach Based on Reactor Technology to Meet Process Requirements." Paper presented at the Sixth International Congress on Molten Slags, Fluxes, and Salts, Stockholm, June 2000.
- <sup>47</sup> "Toth Aluminum Corporations's Bipolar Clay-Aluminum Technology and Project," *Seminar Edition*. Paper presented at TMS annual meeting, New Orleans, 11 February 2001.
- <sup>48</sup> *Life Cycle Inventory Report for the North American Aluminum*, E-12.
- <sup>49</sup> *Aluminum Statistical Review for 2000*, 11.
- <sup>50</sup> "New Technology is a Breakthrough for Automotive Aluminum Recycling," *Aluminum Now* November/December 2000: 28.
- <sup>51</sup> "Melt Loss Reduction in Recycling Processes," J.H.L. Van Linden, Katholieke Universiteit Leuven, May, 1988.
- <sup>52</sup> "Aluminum Dross - Liability into Opportunity," E.L. Rooy, *Light Metal Age*, June, 1995.
- <sup>53</sup> *Aluminum Statistical Review for 2000*, 17-19.
- <sup>54</sup> *Metal Melting Practices and Procedure for Efficiency and Effectiveness*, 20
- <sup>55</sup> *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.
- <sup>56</sup> *Applications for Advanced Ceramics in Aluminum Production: Needs and Opportunities* (Washington, D.C.: The Aluminum Association, Inc., February 2001).
- <sup>57</sup> Shaun Hamer, Bruno Taraglio, and Chris Romanowski, "Continuous Casting and Rolling of Aluminum: Analysis of Capacity, Product Ranges, and Technology," *Light Metal Age* 60.9-10 (October 2002): 6.

## Glossary

**ALUMINA** - Alumina is the oxide of aluminum ( $\text{Al}_2\text{O}_3$ ) and the compound from which aluminum metal is commercially obtained.

**ALUMINUM** - Aluminum is 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%).

Atomic Number	13
Atomic Mass	26.982
Melting Point	993.52°K
Boiling Point	2698°K

**ANODE** - The anode is 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. The distance affects the voltage and energy requirement of a cell.

**ANODE EFFECT** - Anode effect is 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** - Bath is an aluminum-industry idiom referring to the cryolite-based electrolyte pool in the reduction cell.

**BAUXITE** - Found as a collection of small, reddish-brown nodules in a light brown, earthy matrix, bauxite is the prime source of alumina. Commercial bauxite ore contains 30 to 60 weight percent of alumina.

**BAYER PROCESS** - The Bayer process, developed by Karl Bayer in 1888, refines bauxite ore into alumina grains. It is the process currently in use worldwide.

**CALCINING** - Calcining is 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)** - Carbon Dioxide Equivalents (CDE) is 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 ( $10^6\text{TCDE}$ ).

**CARBON EQUIVALENTS (CE)** - Carbon Equivalents (CE) is 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** - Carbothermic reduction is an alternative process to electrolytic reduction. The carbothermic process reduces alumina in a high-temperature furnace with carbon.

**CASTINGS** - Castings describe 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** - The cathode is 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** - Chloride reduction is an alternative process to alumina electrolytic reduction in which aluminum chloride is used as the feed to the reduction cell.

**COKE** - Coke is a carbon product of the crude oil refining industry. Green or raw coke contains 8% to 10% moisture and 5% to 15% volatile organic materials. Coke is calcined in thermal kilns to remove moisture and volatile organic materials.

**CRYOLITE** - Cryolite ( $\text{Na}_3\text{AlF}_6$ ) is 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** - Dross is 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** - Dusting is 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** - Electrolysis is 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** - An electrolyte is a nonmetallic electrical conductor in which current is carried by the movement of ions.

**EXTRUSION** - Extrusion is the process of forcing the metal ingot (or billet) to flow through a die to create a new cross-section.

**FEEDSTOCK ENERGY** - Feedstock energy 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<sub>2</sub> is the common standard, and emissions are expressed in terms of a million metric tons of CO<sub>2</sub> equivalent or 10<sup>6</sup>TCDE.

**GREENHOUSE GASES (GHG)** - Greenhouse gases are atmospheric gases that contribute to climate change, by increasing the ability of the atmosphere to trap heat.

**HALL-HÉROULT PROCESS** - Charles Martin Hall and Paul Lewis Toussaint Héroult independently developed and patented the electrolytic process for reduction of alumina in 1886. This process is commonly referred to using both names, the Hall-Héroult 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 kilowatt-hour (kWh) is a unit of energy.

**LIFE CYCLE ASSESSMENT (LCA)** - Life Cycle Assessment (LCA) is 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** - Onsite energy is 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** - Pad is the aluminum industry idiom used to describe the body of molten aluminum that accumulates within the Hall-Héroult electrolytic cell.

**POLARIZATION** - Polarization describes 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** - Pot is an aluminum industry idiom used to describe an electrolytic cell. The term was derived from the shape of the first cells.

**POTLINE** - Potline is an aluminum industry idiom that describes the arrangement of a long row of interconnected electrolytic cells (pots).

**POTLINING** - Potlining is an aluminum industry idiom that describes the refractory and carbon materials used to line the interior of the cell (pot).

**PRIMARY ALUMINUM** - Primary aluminum or primary metal refers to aluminum metal produced directly from alumina feedstock by chemical reduction.

**QUAD** - A common abbreviation for a quadrillion Btu. (1 quad equals  $10^{15}$  Btu.)

**RED MUD** - Red mud is the residue of insoluble materials that results from extracting alumina from bauxite ore. It is also referred to as “bauxite residue.”

**REDUCTION CELL** - A reduction cell is a container holding single or multiple anodes, cathodes and an electrolytic bath used for reducing a material.

**REVERBERATORY FURNACE** - The reverberatory furnace is the most common furnace type used 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** - Rolling describes the process that results in the reduction of the cross-sectional area of a metal shape as it is passed through rotating rolls.

**SECONDARY ALUMINUM** - Secondary aluminum metal is produced from recycled aluminum products and wastes.

**TACIT ENERGY** - Tacit energy is 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** - Urban mining describes the large source of aluminum available through urban recycling programs as compared to bauxite mining.

**VALUE CHAIN ANALYSIS** - Value chain analysis is 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 with a processing facility, the onsite energy. Gross Energy<sup>f</sup> 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) and the energy required to produce fuels.

<b>THEORETICAL, PROCESS, AND GROSS ENERGY REQUIREMENTS</b>	Ratio of Material to Produce Primary Aluminum kg/kg of Aluminum	Theoretical Minimum Energy Requirement kWh/kg of Aluminum	Process Energy Required kWh/kg of Aluminum	Overall Process Energy Efficiency %	Gross Energy <sup>f</sup> Required kWh/kg of Aluminum	Overall Gross Energy <sup>f</sup> Efficiency %
Bauxite Mining	5.10	0.00	0.32	0%	0.34	0%
Alumina Refining	1.93	0.25	7.27	3%	7.87	3%
Anode Production	0.45	4.11	5.71	72%	5.84	70%
Aluminum Smelting	1.00	5.99	15.58	38%	31.10	19%
Primary Casting		0.33	1.01	33%	1.24	27%
Secondary Casting		0.33	2.50	13%	2.79	12%
Rolling		0.32	0.63	51%	1.21	26%
Extrusion		0.44	1.30	34%	1.50	29%
Shape Casting		0.33	2.56	13%	2.64	13%

<b>UNITED STATES TOTAL ENERGY REQUIREMENTS and POTENTIAL SAVINGS</b>	U.S. Annual Production 2000 metric tons	Theoretical Minimum Energy Requirement ( kWh (10 <sup>9</sup> )/yr )	U.S. Process Energy Required ( kWh (10 <sup>9</sup> )/yr )	Potential Process U.S. Energy SAVINGS ( kWh (10 <sup>9</sup> )/yr )	Total U.S. Gross Energy <sup>f</sup> Required ( kWh (10 <sup>9</sup> )/yr )	Potential Gross U.S. Energy <sup>f</sup> SAVINGS ( kWh (10 <sup>9</sup> )/yr )
Bauxite Mining*						
Alumina Refining*	3,985,000	0.52	15.00	14.48	16.24	15.72
Anode Production	1,668,000	15.36	21.36	6.00	21.86	6.49
Aluminum Smelting	3,741,000	22.41	58.29	35.88	116.36	93.95
Primary Casting	3,668,000	1.23	3.70	2.47	4.56	3.34
Secondary Casting	3,450,000	1.15	8.63	7.47	9.64	8.49
Rolling	5,498,000	1.76	3.45	1.69	6.66	4.90
Extrusion	1,719,000	0.75	2.23	1.48	2.59	1.84
Shape Casting	2,513,000	0.84	6.42	5.58	6.63	5.79
<b>Total</b>		<b>44.02</b>	<b>119.08</b>	<b>75.06</b>	<b>184.53</b>	<b>140.51</b>

\*Note: Bauxite is no longer mined in the United States in quantities large enough for commercial aluminum production; 56% of the alumina needed to produce aluminum in the United States was imported in 2000

## Appendix B

### Energy Intensity of Materials Produced in the United States

**Aluminum, by several measures, is one of the most energy-intensive materials produced.**

**TABLE B-1 Energy Requirements to Produce Materials in the United States (2000)**

The data in Table B-1 are the onsite energy requirements to produce these products. These values do not include the energy content of fuels used as materials or the generation and transmission losses associated with electricity production.

*Note: Aluminum is the most energy-intensive major material manufactured in the U.S. on a per unit mass basis*

	a	b	c	a	b	c
	Btu/yr	Btu/lb	2000 lb/yr	Data Sources		
Paper & Paper Board	2.67E+15	15,125	1.76E+11	MECS	b*c	MECS
Gasoline	2.16E+15	2,659	8.14E+11	b*c	Drexel	EIA2
Iron & Steel	1.83E+15	8,700	2.10E+11	Steel, pg 23	Steel, pg 23	Steel, pg 27
Ethylene	4.46E+14	8,107	5.51E+10	b*c	E&E, pg 28	ACC, pg 24
<b>Aluminum, primary ingot</b>	<b>3.61E+14</b>	<b>44,711</b>	<b>8.07E+09</b>	b*c	Appendix F Table F-1	Appendix G
Distillate	3.31E+14	990	3.34E+11	b*c	Drexel	EIA2
Ammonia	4.02E+14	12,150	3.31E+10	b*c	E&E, pg 32	ACC, pg 24
Propylene	4.29E+13	1,351	3.18E+10	b*c	E&E, pg 28	ACC, pg 24
Jet Fuel	1.48E+14	990	1.50E+11	b*c	Drexel	EIA2
Coal	1.30E+14	60	2.15E+12	b*c	EIA1	EIA1
Benzene	2.22E+13	1,255	1.77E+10	b*c	E&E, pg 30	ACC, pg 24

**TABLE B-2 Gross Energy Requirements to Produce Materials in the United States (2000)**

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 a renewable resource, and petroleum calcined coke used as a raw material in aluminum production has a 15,250 Btu/lb.

	a	b	c	a	b	c
	Btu/yr	Btu/lb	2000 lb/yr	Data Sources		
Paper & Paper Board	2.67E+15	15,125	1.76E+11	MECS	b*c	MECS
Gasoline	2.03E+15	2,659	7.64E+11	b*c	Drexel	EIA2
Iron & Steel	1.83E+15	8,700	2.10E+11	Steel, pg 23	Steel, pg 23	Steel, pg 27
Ethylene	1.74E+15	31,664	5.51E+10	b*c	E&E, pg 28	ACC, pg 24
Propylene	8.90E+14	28,000	3.18E+10	b*c	E&E, pg 28	ACC, pg 24
Ammonia	6.95E+14	20,985	3.31E+10	b*c	E&E, pg 32	ACC, pg 24
<b>Aluminum, primary ingot</b>	<b>5.75E+14</b>	<b>69,902</b>	<b>8.07E+09</b>	a*b	Appendix F Table F-1	Appendix G
Benzene	5.38E+14	30,475	1.77E+10	b*c	E&E, pg 30	ACC, pg 24
Distillate	3.31E+14	990	3.34E+11	a*b	Drexel	EIA2
Coal	1.29E+14	60	2.15E+12	b*c	EIA1	EIA1
Jet Fuel	1.48E+14	990	1.50E+11	b*c	Drexel	EIA2

**SOURCES for TABLES B-1 and B-2**

- ACC - Guide to The Business of Chemistry, American Chemical Council, 2002
- 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
- EIA1 - Coal Industry Annual 2000, Energy Information Agency, DOE
- EIA2 - Petroleum Annual 2000, 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

## 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 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**

Appendix F Input Unit	Calorific Energy Values "Primary-Energy"			Process Energy Values "Secondary-Energy"			Tacit Energy	
	Btu per Common Unit	Btu per Input Unit	Data Source	Btu per Common Unit Required to Produce	Btu per Input Unit	data Source	Btu per Appendix F input unit	Appendix F Input Unit
<b>FUELS</b>								
Fuels and Fuels used as materials								
Fuel Oil, medium	139,000 Btu/gal	43,380	cogeneration.net	5,000 Btu/gal	1,321	Drexel	44,700	kg
Fuel Oil, light	150,000 Btu/gal	46,813	cogeneration.net	5,000 Btu/gal	1,321	Drexel	48,130	kg
Diesel	5,670,000 Btu/bbl	35,667	EIA	5,200 Btu/gal	1,374	CEC	37,040	L
Kerosene	5,670,000 Btu/bbl	35,667	AEO2002a	5,200 Btu/gal	1,374	CEC	37,040	L
Gasoline	5,204,000 Btu/bbl	32,736	AEO2002a	12,000 Btu/gal	3,170	CEC	35,910	L
Natural Gas	1,027 Btu/ft3	36,268	AEO2002a	30 Btu/ft3	1,059	CEC	37,330	m3
Bituminous/Sub	11,110 Btu/lb	24,493	CIA2000	60 Btu/lb	132	E&E, Mining	24,630	kg
Calcined Coke	15,250 Btu/lb	33,620	MidCon	179 Btu/lb	395	E&E pg 52	34,010	kg
Pitch	6,065,000 Btu/bbl	38,152	E&E pg 52	18 Btu/lb	40	E&E pg 52	38,190	kg
Green Coke	14,200 Btu/lb	31,305	MidCon	Btu/lb	500	Drexel	31,810	kg
Propane	3,824,000 Btu/bbl	24,055	EGGUS	Btu/lb			24,050	L
Coal	10,201 Btu/lb	22,488	AEO2002a	60 Btu/lb	132		22,620	kg
<b>ELECTRICITY</b>								
Electric	1 kWh	3412	ISO	Hydroelectric Utility	0	ISO	3,412	kWh
Avg U.S. Electric*	1 kWh	3412	ISO	Average U.S. Grid	6,368	tacit Btu	9,780	kWh
Primary Al Electric**	1 kWh	3412	ISO	Average U.S. Smelter	3,438	tacit Btu	6,850	kWh
Coal-Fired Electric	1 kWh	3412	ISO	Coal-Fired Utility	6,879	tacit Btu	10,290	kWh

\* tacit Btu accounts for generation and transmission energy losses for average U.S. generation

\*\* tacit Btu for electrolysis and anode manufacture is lower than general electricity because of the large 50.2% hydro component

**SOURCES**

- AEO2002a- Annual Energy Outlook 2002, Energy Information Agency, Dec 2001 pg 248
- 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 - documents from DOE - OIT these are the "Energy and Environmental Profiles", Aluminum and Mining
- 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.

**Appendix C**  
**Energy Values for Energy Sources and Materials**

**TABLE C - 2 Impact of Process ("secondary energy") on the Conversion factors on kWh/yr Consumed Worldwide for U.S. Aluminum Production**

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. Bauxite is refined in the United States to supply 44% of the alumina needed and imports the remaining 56% required for aluminum production.

<b>kWh/yr of Fuels Consumed Worldwide for U.S. Aluminum Processing excluding Electricity and Coke feedstock energy</b>											
	Mining	Refining	Anode w/ feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL
<b>No Process ("secondary energy") inputs for fuels</b>											
kWh/yr	1.20E+09	2.64E+10	1.82E+09	6.79E+08	2.93E+09	8.23E+09	9.78E+08	7.87E+08	2.07E+09	6.41E+09	<b>5.15E+10</b>
<b>with Process ("secondary energy") inputs for fuels</b>											
kWh/yr	1.25E+09	2.72E+10	1.88E+09	6.97E+08	3.01E+09	8.50E+09	1.01E+09	8.14E+08	2.13E+09	6.60E+09	<b>5.31E+10</b>
<b>Percent Process ("secondary energy") Fuel Contribution</b>	4%	3%	3%	3%	3%	3%	3%	3%	3%	3%	<b>3%</b>

**TABLE C - 3 Impact of Electric Tacit Conversion factors on kWh/yr Consumed Worldwide for U.S. Aluminum Production**

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. This report uses an average tacit based on the electric fuel sources of aluminum smelting operations (Appendix D Table D-1).

	Mining	Refining	Anode w/ feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL
<b>AVERAGE U.S. Aluminum Processing Facilities</b>											
6,850 Btu of energy required to produce 1 kWh of onsite electrical power for an average U.S. Aluminum Smelting, Anode and Primary Casting Facility											
9,780 Btu of energy required to produce 1 kWh of onsite electrical power for all other U.S. Aluminum Facilities											
kWh/yr	1.27E+09	2.94E+10	2.19E+10	1.16E+11	4.56E+09	9.64E+09	3.09E+09	3.56E+09	2.59E+09	6.63E+09	<b>1.99E+11</b>
<b>Percent increase relative to a facilities with 100% hydroelectric energy resource</b>	4%	8%	2%	100%	23%	12%	81%	104%	16%	3%	<b>50%</b>
<b>U.S. Aluminum Processing Facilities with 100% electrical power generated by hydroelectric utilities</b>											
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	1.22E+09	2.72E+10	2.14E+10	5.83E+10	3.70E+09	8.63E+09	1.71E+09	1.75E+09	2.23E+09	6.42E+09	<b>1.32E+11</b>
<b>U.S. Aluminum Processing Facilities with 100% electrical power generated by coal-fired utilities</b>											
10,290 Btu of energy required to produce 1 kWh of onsite electrical power from coal resources for all U.S. Aluminum Facilities											
kWh/yr	1.27E+09	2.98E+10	2.21E+10	1.46E+11	4.96E+09	9.84E+09	3.47E+09	4.05E+09	2.67E+09	6.63E+09	<b>2.31E+11</b>
<b>Percent increase relative to a facilities with 100% hydroelectric energy resource</b>	4%	10%	3%	150%	34%	14%	103%	132%	20%	3%	<b>3%</b>

## Appendix D Hydroelectric Distribution and Electrical Energy Values

### Electric Tacit 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 50.2% of aluminum smelting capacity utilizes hydroelectric power\*.

**TABLE D-1**

Electrical Energy Source	U. S. Primary Aluminum Capacity*		Average US Grid	Heat Rate **	Carbon Emission Coefficient ***
	metric tons	%		Btu / kWh 2000	Mt/Qbtu
				9,780	13.56
Hydro	2,147,520	50.2%		3,412	0
Coal	1,932,560	45.2%		10,291	21.25
Oil	13,328	0.3%		9,542	19.08
Natural Gas	46,648	1.1%		10,903	12.50
Nuclear	139,944	3.3%		10,623	0
<b>Total</b>	<b>4,280,000</b>	<b>100.0%</b>			
Weighted averages based on Aluminum Capacity				6,855	9.79

\* The distribution of electrical sources for U.S. Primary Aluminum capacity is obtained by subtracting the Canadian capacity of 2.4 million metric tons, which is 100% hydroelectric, from the North American Totals presented in Table D-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 2000," Energy Information Administration, August 2001 pg 221.

\*\*\* **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

**This Report Uses:**

**6,850** Tacit Btu per kWh for anode manufacture, smelting and primary ingot casting  
**9,780** Tacit Btu per kWh for all other electricity consumed in aluminum processing

### ELECTRICAL POWER USED IN PRIMARY ALUMINIUM PRODUCTION WORLDWIDE

Table D-2 and D-3 source: International Aluminium Institute  
 New Zealand House  
 Haymarket  
 London SW1Y 4TE  
 United Kingdom

Date of issue: 20 September 2001

**TABLE D-2**

Energy Sources of Electrical Power in 2000

Electrical Power Used (gigawatt hours)

Electric Energy Source	Africa	North America		Latin America	Asia	Europe	Oceania	Total	Grand Total
	GWh	GWh	%	GWh	GWh	GWh	GWh	GWh	%
Hydro	6,914	59,324	68%	30,491	3,682	28,449	7,328	136,188	52%
Coal	10,844	25,292	29%	0	9,786	14,286	2,697	81,905	32%
Oil	0	150	0%	518	468	1,052	0	2,188	1%
Natural Gas	0	587	1%	2,119	15,806	4,894	0	23,406	9%
Nuclear	0	1,826	2%	99	8	14,004	0	15,937	6%
<b>Total</b>	<b>17,758</b>	<b>87,179</b>	<b>100%</b>	<b>33,227</b>	<b>29,750</b>	<b>62,685</b>	<b>29,025</b>	<b>259,624</b>	<b>100%</b>

**TABLE D-3**

Sources of Supply of Electrical Power in 2000

Electrical Power Used (gigawatt hours)

Electric Source of Supply	Africa	North America		Latin America	Asia	Europe	Oceania	Total	Grand Total
	GWh	GWh	%	GWh	GWh	GWh	GWh	GWh	%
Self-generated	0	29,574	34%	4,124	28,147	2,391	1,108	65,344	25%
Purchased - Grid	17,758	47,948	55%	29,103	1,603	58,690	27,917	183,019	70%
Purchased - Other	0	9,657	11%	0	0	1,604	0	11,261	4%
<b>Total</b>	<b>17,758</b>	<b>87,179</b>	<b>100%</b>	<b>33,227</b>	<b>29,750</b>	<b>62,685</b>	<b>29,025</b>	<b>259,624</b>	<b>100%</b>
Self-generated - other purposes †	0	0		172	2,417	1	0	2,590	

## Appendix E Emission Data and Calculations

**Table E-1 Carbon Dioxide (CO<sub>2</sub>) Equivalent Emission Coefficients for Fuels Associated with Aluminum Production**

This table presents the carbon dioxide equivalent emission values for the fuels and materials associated with the production of aluminum metal and aluminum products

FUEL	Appendix F		Carbon Emission Coefficient Mt/Qbtu	Carbon Emission Coefficient Source	Percent Carbon (EGGUS)	API Gravity (EGGUS)	Density Pounds/gal (EGGUS)	Million Btu/bbl (EGGUS)	Kilogram Carbon Dioxide Equivalent per input unit	FUEL
	input unit	Btu per input unit								
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	5.825	3.52E+00	Fuel Oil, medium	
Fuel Oil, light (#2)	kg	37,040	19.95	b	86.3	35.5	5.825	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	37,040	19.72	EGG2000	86.6	58.6	5.253	2.55E+00	Kerosene	
Gasoline	L	35,910	19.34	EGG2000				1.98E+00	Gasoline	
Natural Gas	m3	37,330	14.47	EGG2000				2.33E+00	Natural Gas	
Bituminous/Sub	kg	24,630	25.81	EGGUS		n/a		3.47E+00	Bituminous/Sub	
Calcined Coke	kg	34,010	27.85	c	85.8	25.6	6.024	2.89E+00	Calcined Coke	
Pitch	kg	38,190	20.62	d	92.3	n/a		3.25E+00	Pitch	
Green Coke	kg	31,810	27.85	EGG2000				1.52E+00	Green Coke	
Propane	L	24,050	17.20	EGGUS				2.14E+00	Propane	
Coal	kg	22,620	25.76	EGG2000					Coal	
<b>Electricity</b>										
Hydro Electric	kWh	3,412	0.0	EGG2000				0.00E+00	Hydro Electric	
Average U.S. Electric	kWh	9,780	13.56	EGG2000				4.86E-01	Average U.S. Electric	
Primary Al Electric	kWh	6,850	9.79	e				2.46E-01	Primary Al Electric	
Coal-Fired Electric	kWh	10,290	21.25	EGG2000				8.02E-01	Coal-Fired Electric	

\* Mt/Qbtu - million metric tons per Quadrillion Btu (10<sup>6</sup> metric tons / 10<sup>15</sup> Btu)

### 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).



## Appendix E Emission Data and Calculations

### TABLE E-3 Carbon Dioxide (CO<sub>2</sub>) Equivalent Emissions Associated with Aluminum Production

Table E-3 uses the units of Energy Input from Table F-2 and calculates the Carbon Dioxide Equivalent emissions for each Energy Input base on the CDE values for fuels presented in Table E-1

Input/Output	Primary Ingot Casting		Secondary Ingot Casting		Hot Rolling		Cold Rolling		Extrusion		Shape Casting	
	units	yield	units	yield	units	yield	units	yield	units	yield	units	yield
Electrolysis Metal	1,020											
Alloy Additives	kg		21									
Scrap	kg		676									
Primary Ingot	kg		346									
Secondary Ingot	kg	1,000	1,000	96%	498	82%	474	84%	559	69%	2,200	45%
Product	kg	1,000	1,000	98%	723	82%	722	84%	885	69%	1,000	45%
	kg				1,000	82%	1,000	84%	1,000	69%	2,200	45%
	kg											
<b>Energy Inputs per 1,000 kg</b>												
Fuel Oil, medium	kg	17.4	42.3	149	0.040	0.109	0.038	0	0.002	0		
Fuel Oil, light (#2)	kg	0.184	31,464	85	0.007	0			0.417	1		
Diesel	L				0.007	0			0.028	0		
Kerosene	L	0.075	12,757	32	0.007	0	2.150	5	0.044	0		
Gasoline	L	51.8	126.0	250	33.4	66	24.8	49	103.0	204		
Natural Gas	m3											
Bituminous/Sub	kg											
Calced Coke	kg											
Pitch	kg											
Green Coke	kg	0.798	1,941	3	0.034	0	0.238	0	4.460	7		
Propane	L								11,200	24		
Coal	kg	211	115,000	55.92	265	128.87	349	169.72	93	45.23		
Electric	kWh											
<b>TOTAL per 1000 kg</b>	CO <sub>2</sub> Eq	2.17E+02	5.75E+02		1.95E+02		2.25E+02		2.81E+02		4.77E+02	
<b>Total Material Production in the U.S. for Aluminum Manufacturing</b>	metric tons	3,668,000	3,450,000		2,749,000		2,749,000		1,719,000		2,513,000	
<b>Total U.S. Production Carbon Dioxide Emissions</b>	metric tons CO <sub>2</sub> Eq	796,520	1,984,340		536,647		617,903		483,461		1,199,468	
<b>kg of Carbon Dioxide Equivalent per kilogram of Product</b>	kg/kg Al	8.41	0.58		0.20		0.22		0.28		0.48	

## Appendix E Emission Data and Calculations

**TABLE E-4 Carbon Dioxide (CO<sub>2</sub>) Equivalent Emissions Associated with New Aluminum Production Technologies**

Table E-4 provide the ore-to-metal Carbon Dioxide Equivalent emissions for a modern Hall-Heroult cell to the CDE emissions of Hall-Heroult improvements and alternative technologies.

Carbon Dioxide (CO <sub>2</sub> ) Equivalent Emissions Associated with New Aluminum Production Technologies	Typical modern Hall-Heroult cell operating at 95% current efficiency and with an ACD = 4.5 cm	Typical modern Hall-Heroult 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 ACD = 2.0 cm using Wetted Cathode technology	Carbothermic Reduction with a reaction efficiency of 95% and a furnace efficiency of 85% Electric Furnace operating on the Average U.S. grid	Chloride Reduction of kaolinite clays electrolysis current efficiency 95%, reaction efficiency 95% and heating efficiencies 85% efficiency Onsite Electric Furnace and electrolysis cell operating on the Average U.S. grid	
Mineral Material	kWh/kg Al	kgCO <sub>2</sub> /kg Al	kWh/kg Al	kgCO <sub>2</sub> /kg Al	kWh/kg Al	kgCO <sub>2</sub> /kg Al
Tacit Energy required	8.21	1.71	8.21	1.71	8.21	1.83
<b>Onsite Reaction Energy Requirements</b>						
Reaction Thermal Furnace Losses						
Reaction Electrolysis	3.76	0.93	3.76	0.93	3.75	-0.92
Cell Ohmic	10.67	2.62	7.62	1.87	0.66	0.19
TOTAL Reaction Energy	14.43	3.55	11.38	2.80	9.07	3.15
<b>Anode Related Emissions</b>						
Anode manufacturing	0.61	0.12	0.61	0.12		
Anode Use						
Anode Reaction	0.33 kg	1.22		1.22		
Anode Excess (Air Burning)	0.11 kg	0.30		0.30		
Total Anode		1.65		1.65		
<b>Process Related Emissions</b>						
Carbon Reactant					0.66 kg	0.89 kg
Perfluorocarbon		2.20		0.55		0.00
<b>TOTAL CO<sub>2</sub> Emissions</b>						
Mineral Material		1.71		1.71		1.83
Reactions		3.55		2.80		3.85
Carbon		1.65		1.65		3.27
Process		2.20		0.55		0.00
TOTAL		9.11		6.71		8.95



**Appendix F**  
**U.S. Energy Use by Aluminum Processing Area**

**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	1,000	1,000
	yield 98%	yield 96%	yield 82%	yield 84%	yield 69%	yield 45%
<b>Energy Inputs per 1,000 kg</b>						
Fuel Oil, medium	units	units	units	units	units	units
Fuel Oil, light	17.4	42.3	0.040	0.038	0.002	0.002
Diesel	0.184	31,464	0.007	0.008	0.417	0.417
Kerosene		1,981,346	0.007	0.007	0.028	0.028
Gasoline	0.075	1,122,230	0.007	2,150	0.044	0.044
Natural Gas	51.8	417,597	33.4	24.8	103,000	240,000
Bituminous/Sub		4,569,793	1,211,358	899,451	3,735,624	8,704,367
Coke						
Propane	0.798	1,941	0.034	0.238	4,460	107,285
Anthracite					11,200	251,866
Electric	211	115	265	349	93	4
	719,932	392,380	904,180	1,190,788	317,316	13,750
<b>TOTAL ENERGY INPUTS (Energy per kg of Output)</b>	Btu/kg	8,530	2,118	2,168	4,430	8,718
	kWh/kg	2.50	0.62	0.64	1.30	2.56
<b>TACIT ENERGY INPUTS (Energy per kg of Output)</b>	Btu/kg	9,536	3,841	4,423	5,133	8,999
	kWh/kg	2.79	1.13	1.30	1.50	2.64

## Appendix F U.S. Energy Use by Aluminum Processing Area

**Table F-3**

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 775C. 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%.

**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		0.13	12.30	5.99	0.33	0.33	0.31	0.33	0.44	0.33
ratioed to Al		0.25	4.11	5.99	0.33	0.33	0.31	0.33	0.44	0.33
Current Practice Onsite Process Efficiency %		3%	72%	38%	33%	13%	50%	52%	34%	13%

**Table F-4**

Table F-4 lists the United States' production quantities, 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 56% 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.

**U.S. Energy Use in the Production of Domestic Aluminum.**

	Mining	Refining	Anode w/ feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL ENERGY
<b>Material Production within the United States</b> metric tons	0	3,985,000	1,668,000	3,741,000	3,668,000	3,450,000	2,749,000	2,749,000	1,719,000	2,513,000	
<b>On-Site Energy Consumed in Production for United States Aluminum Industry</b>											
kWh/kg		3.76	12.80	15.58	1.01	2.50	0.62	0.64	1.30	2.56	
ratioed* to Al		7.27	5.71	15.58	1.01	2.50	0.62	0.64	1.30	2.56	
Total kWh/yr		1.50E+10	2.14E+10	5.83E+10	3.70E+09	8.63E+09	1.71E+09	1.75E+09	2.23E+09	6.42E+09	1.19E+11
Proportion of U.S. Energy Used		13%	18%	49%	3%	7%	1%	1%	2%	5%	100%
<b>Total TACIT Energy Consumed in Production for the United States Aluminum Industry</b>											
kWh/kg		4.08	13.10	31.10	1.24	2.79	1.13	1.30	1.50	2.64	
ratioed* to Al		7.87	5.84	31.10	1.24	2.79	1.13	1.30	1.50	2.64	
Total kWh/yr		1.62E+10	2.19E+10	1.16E+11	4.56E+09	9.64E+09	3.09E+09	3.56E+09	2.59E+09	6.63E+09	1.85E+11
Proportion of U.S. Energy Used		8.8%	11.8%	63.1%	2.5%	5.2%	1.7%	1.9%	1.4%	3.6%	100%
<b>Theoretical Magnitude of Opportunities for U.S. Energy Savings</b>											
kWh/yr		1.45E+10	6.00E+09	3.59E+10	2.47E+09	7.47E+09	8.58E+08	8.36E+08	1.48E+09	5.58E+09	7.51E+10
Tacit kWh/yr		1.57E+10	6.50E+09	9.39E+10	3.34E+09	8.49E+09	2.25E+09	2.65E+09	1.84E+09	5.79E+09	1.41E+11

# Appendix F U.S. Energy Use by Aluminum Processing Area

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

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%, and
- c: electrolysis electrical energy were reduced from 15 to 11 kWh/kg of aluminum

U.S. Aluminum Industry	kWh/yr	Quads/yr	MW	Households	bbl crude per year
Total Energy Use	on-site tacit	1.19E+11 1.85E+11	0.41 0.63	13,600 21,100	13,600,000 21,100,000
Theoretical Requirement	on-site tacit	4.40E+10 4.40E+10	0.15 0.15	5,000 5,100	5,000,000 5,100,000
Energy Efficiency	on-site tacit	37% 24%			
a: Theoretical Opportunity	on-site tacit	7.51E+10 1.41E+11	0.26 0.48	8,600 16,000	8,600,000 16,000,000
b: Practical Goal (Vision)	on-site tacit	3.57E+10 5.54E+10	0.12 0.19	4,080 6,330	4,100 6,400
c: Electrolysis savings of 4 kWh/kg	on-site tacit	1.50E+10 3.00E+10	0.05 0.10	1,708 3,429	1,800 3,500
					8,900,000 17,700,000

**Energy Saved with Recycling**

Tacit Energy Values  
 46.4 kWh/kg to produce Primary Metal Ingot  
 2.8 kWh/kg to produce Secondary Metal Ingot  
 6.0% Secondary to Primary Energy  
 3,450,000 kg of Secondary Metal produced in 2000  
 1.50E+11 kWh/yr ENERGY SAVED 2000  
 0.51 Quads Saved per Year 2000  
 17,200 MW SAVED 2000

**Table F-6 Energy Impact of Recycling**

Table F-6 shows the 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-7 U.S. Electric On-site Energy Consumption in the Aluminum Industry**

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

	Refining	Anode w/ feedstock	Electrolysis	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting	TOTAL ELECTRIC ENERGY
metric tons 2000	3,985,000	1,668,000	3,741,000	3,668,000	3,450,000	2,749,000	2,749,000	1,719,000	2,513,000	
	0.109 kWh/kg	0.266 kWh/kg	15.400 kWh/kg	0.211 kWh/kg	0.115 kWh/kg	0.265 kWh/kg	0.349 kWh/kg	0.093 kWh/kg	0.004 kWh/kg	
	4.34E+08 kWh/yr	4.44E+08 kWh/yr	5.76E+10 kWh/yr	7.74E+08 kWh/yr	3.97E+08 kWh/yr	7.28E+08 kWh/yr	9.59E+08 kWh/yr	1.60E+08 kWh/yr	1.01E+07 kWh/yr	6.15E+10 kWh/yr
Total U.S. Al Industry Electrical Use	6.15E+10 kWh/yr									0.21
on-site	7,023 MW									
	7,023,000 households									
tacit	72,700,000 bbl crude									
				Net US Generation	3,800E+12					
				Aluminum's % of U.S. net	1.6%					
										Source: eia.doe.gov/cneaf/electricity



## Appendix F

### U.S. Energy Use by Aluminum Processing Area

**Table F-10** Table F-10 divides energy uses in aluminum casting and semi-fabrication manufacturing operations into three areas. The following percentage 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 includes all other fuels and it is assumed these are fuels used in non-heating operations such as transportation and collection of materials. (Note: rounding causes some totals to differ from 100%)

	Primary Casting	Secondary Casting	Hot Rolling	Cold Rolling	Extrusion	Shape Casting
% onsite electric	21%	5%	43%	55%	7%	0%
% heating	79%	77%	57%	42%	87%	100%
miscellaneous fuels	0%	18%	0%	3%	6%	0%
% tact electric	34%	9%	59%	70%	70%	13%
% heating	66%	74%	41%	27%	27%	81%
miscellaneous fuels	0%	18%	0%	3%	3%	6%

## Appendix G

### U.S. Primary, Secondary and Imported Aluminum Quantities, 1960-2000

Source: Aluminum Statistical review for 2000, The Aluminum Association, 2001, p. 7

Thousand Metric Dry Tons

Year	U.S. Primary Aluminum Production	U.S. Secondary Aluminum Production	U.S. Aluminum Imports	U.S. Total Aluminum Supply
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
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
Average Growth Rate 1991 through 2000	-0.8%	4.3%	10.0%	3.6%
Percent of Total Supply	34%	32%	33%	100%

The growth rates utilized in this report are based on a linear regression of the ten year period 1991 through 2000 data. Linearizing the data provides a better value for average growth over the period than a simple comparison of 1991 to 2000.

#### Ten Year Period 1991 through 2000 Growth

	Primary	Secondary	Imports	Supply
<b>Linear regression for 1991 through 2000</b>				
slope	-28.6	127.5	230.0	328.9
intercept	60,698	-251,298	-456,225	-646,826
<b>Linearized values</b>				
1990	3,844	2,469	1,439	7,752
2000	3,559	3,744	3,738	11,041
<b>Linearized growth from 1991 to 2000</b>				
Avg Growth	-0.8%	4.3%	10.0%	3.6%
U.S. Aluminum production Growth (primary & secondary Combined)				1.47%

## Appendix H

### U.S. Bauxite and Alumina Quantities, 1960 - 2000

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

Thousand Metric Dry Tons

Year	Imports of Bauxite	U.S. mined Bauxite	Exports of Bauxite	Net Bauxite Supply	Estimated Alumina Production for Bauxite	Imports of Alumina	Exports of Alumina	Estimated Net Alumina for Electrolysis
1960	8,879	2,030	29	10,880	4,755	80		4,359
1961	9,354	1,248	153	10,449	4,566	171		4,281
1962	10,745	1,391	263	11,873	5,189	158		4,828
1963	9,408	1,549	206	10,751	4,698	173		4,401
1964	10,518	1,627	283	11,862	5,184	191		4,856
1965	11,601	1,681	149	13,133	5,739	206	290	5,081
1966	11,928	1,825	63	13,690	5,983	443	290	5,537
1967	12,010	1,681	2	13,689	5,982	865	499	5,750
1968	11,359	1,692	7	13,044	5,700	1,190	780	5,540
1969	12,355	1,873	5	14,223	6,215	1,730	885	6,439
1970	13,039	2,115	3	15,151	6,621	2,340	998	7,301
1971	12,837	2,020	35	14,822	6,477	2,190	980	7,039
1972	12,803	1,841	29	14,615	6,387	2,590	797	7,541
1973	13,618	1,909	12	15,515	6,780	3,090	694	8,498
1974	15,216	1,980	16	17,180	7,508	3,290	927	9,120
1975	11,714	1,801	20	13,495	5,897	3,180	933	7,555
1976	12,749	1,989	15	14,723	6,434	3,290	1,050	8,031
1977	12,989	2,013	26	14,976	6,545	3,760	857	8,793
1978	13,847	1,669	13	15,503	6,775	3,970	878	9,189
1979	13,780	1,821	15	15,586	6,811	3,840	849	9,121
1980	14,087	1,559	21	15,625	6,828	4,360	1,140	9,365
1981	12,802	1,510	20	14,292	6,246	3,980	730	8,871
1982	10,122	732	49	10,805	4,722	3,180	590	6,840
1983	7,601	679	74	8,206	3,586	4,030	602	6,655
1984	9,435	856	82	10,209	4,461	4,290	648	7,657
1985	7,158	674	56	7,776	3,398	3,830	316	6,572
1986	6,456	510	69	6,897	3,014	3,600	487	5,826
1987	9,156	576	201	9,531	4,165	4,070	1,130	6,689
1988	9,944	588	63	10,469	4,575	4,630	1,040	7,707
1989	10,893	W	44	10,849	4,741	4,310	1,330	7,247
1990	12,142	W	53	12,089	5,283	4,070	1,260	7,565
1991	12,300	W	58	12,242	5,350	4,590	1,350	8,055
1992	11,400	W	68	11,332	4,952	4,700	1,140	8,017
1993	11,900	W	92	11,808	5,160	3,940	1,240	7,344
1994	11,200	W	137	11,063	4,835	3,120	1,040	6,431
1995	10,800	W	120	10,680	4,667	4,000	1,040	7,160
1996	10,700	W	154	10,546	4,609	4,320	918	7,550
1997	11,300	W	97	11,203	4,896	3,830	1,270	6,966
1998	11,600	W	108	11,492	5,022	4,050	1,280	7,290
1999	10,400	W	168	10,232	4,471	3,810	1,230	6,604
2000	9,300	W	180	9,120	3,985	4,500	1,000	7,087

A                      B                      C                      D                      E                      F                      G                      H                      I

W - data withheld

**Note:** 3,985,000 metric tons or 56% of the 7,087,000 metric tons of alumina needed to produce aluminum in the United States was refined in the United States in 2000.

#### Calculated Columns

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  $F = 0.95 \times 0.46 \times \text{Column E}$ .

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

# Appendix I

## Energy Requirements for Carbon Anodes

**Table I-1**

The following table shows the onsite, process and feedstock energy values that are part of making a carbon electrode 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.

Energy Associated with Aluminum Industry Carbon Anode Manufacturing	Mass of Material Input	Material Input Energy	kWh per kg anode	kWh per kg aluminum
	Values from Appendix F Table F-1 kg/kg Anode	Values from Appendix C Table C-1 Btu/kg		
<b>Pitch</b>				
mass	0.231			
feedstock energy		8,813	2.58	1.15
process energy		9	0.003	0.001
<b>Calcined Coke</b>				
mass	0.820			
feedstock energy		27,569	8.08	3.60
process energy		324	0.095	0.04
<b>Green Coke</b>				
mass	0.085			
feedstock energy		2,664	0.78	0.35
process energy		43	0.012	0.01
<b>Carbon Anode Baking</b>				
process energy (Appendix F Table F-1)			1.66	0.74
<b>TOTAL Raw Materials and Energy</b>				
mass	1.136			
feedstock energy		39,046	11.44	5.10
process energy		375	1.77	0.79
		<b>TOTAL Tacit Energy Input</b>	<b>13.21</b>	<b>5.89</b>

**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	0.11	8.97	0.05	4.00
Baking	1.36	1.66	0.61	0.74
<b>Total</b>	<b>1.47</b>	<b>13.21</b>	<b>0.66</b>	<b>5.89</b>

## Appendix J

# Theoretical Energy Data and Calculations for Reactions

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 calculate 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  $^a G = ^a H - T ^a S$ , and the numeric values are given in Table J-6. The energy required to drive the reaction forward is the Gibbs free energy value ( $^a G$ ). The energy required to maintain system equilibrium is the difference between the heat of reaction ( $^a H$ ) and the Gibbs free energy value ( $^a G$ ), which equals the entropy term ( $T ^a S$ ). 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 precedes. (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.

# Appendix J

## Theoretical Energy Data and Calculations

**Table J-1 Theoretical Minimum Energy for Hall Heroult Carbon Anode System**

Reactants Temp	2 Al <sub>2</sub> O <sub>3</sub> 25	3 C 25	Products Temp	4 Al 960	3 CO <sub>2</sub> 25
↑		↑		↑	
<div style="border: 1px solid black; padding: 10px; margin: 0 auto; width: 80%;"> <p style="text-align: center;">Carbon Anode Cell</p> </div>					
<p>Reaction Thermodynamics at 298 C</p> <p>( 2 Al<sub>2</sub>O<sub>3</sub> + 3 C ) to ( 4 Al + 3 CO<sub>2</sub> ) = Net</p>					
		delta G		-282,779	
		delta H		-282,155	
		delta S		153.2	
		4.1		27.1	
<p>Process Theoretical Minimum Energy Requirements</p>					
		Thermal Energy for Temperature Maintenance (delta H - delta G)		118,395	
		Thermal Energy for Al at 960 C		129,711	
		<b>Theoretical Minimum</b>		11,311	
		kWh/kg		5.11	
		Electrolytic Work Requirement (delta G)		0.49	
		Thermal Energy for CO <sub>2</sub> at 960 C		0.39	
		<b>Theoretical Minimum</b>		5.99	
		Thermal Energy for CO <sub>2</sub> 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 Heroult Inert Anode System**

Reactants Temp	Al <sub>2</sub> O <sub>3</sub> 25	Products Temp	2 Al 960	1.5 O <sub>2</sub> 25	
↑		↑		↑	
<div style="border: 1px solid black; padding: 10px; margin: 0 auto; width: 80%;"> <p style="text-align: center;">Inert Anode Cell</p> </div>					
<p>Reaction Thermodynamics at 298 C</p> <p>( Al<sub>2</sub>O<sub>3</sub> ) to ( 2 Al + 1.5 O<sub>2</sub> ) = Net</p>					
		delta G		-378,179	
		delta H		-400,500	
		delta S		12	
		0		14	
		0		74	
<p>Process Theoretical Minimum Energy Requirements</p>					
		Thermal Energy for Temperature Maintenance (delta H - delta G)		189,089	
		Thermal Energy for Al at 960 C		200,250	
		<b>Theoretical Minimum</b>		11,155	
		kWh/kg		8.16	
		Electrolytic Work Requirement (delta G)		0.48	
		Thermal Energy for O <sub>2</sub> at 960 C		0.39	
		<b>Theoretical Minimum</b>		9.03	
		Thermal Energy for O <sub>2</sub> 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

# Appendix J

## Theoretical Energy Data and Calculations

**Table J-3 Theoretical Minimum Energy for Carbothermic Reduction**

<p>Reactants Temp</p> <p style="text-align: center;">Al<sub>2</sub>O<sub>3</sub> 25</p> <p style="text-align: center;">3 C 25</p>		<p>Products Temp</p> <p style="text-align: center;">2 Al 960</p> <p style="text-align: center;">3 CO 25</p>	<p><b>Reaction Thermodynamics at 298 C</b></p> <p>( Al<sub>2</sub>O<sub>3</sub> + 3 C ) to ( 2 Al + 3 CO ) = Net</p>	<p><b>products- reactants</b></p> <p>call/gm mole Al</p> <p>139,878</p> <p>160,626</p> <p>21,347</p>
			<p>delta G -378,179    0    0    -98,424</p> <p>delta H -400,500    0    0    -79,247</p> <p>delta S 12.2    4.1    13.5    141.9</p>	
			<p><b>Process Theoretical Minimum Energy Requirements</b></p>	
			<p>Thermal Energy for Temperature Maintenance (delta H - delta G)</p> <p>Thermal Energy for Al at 960 C</p> <p><b>Theoretical Minimum</b></p> <p>Thermal Energy for CO at 960 C</p>	<p>kWh/kg</p> <p>6.03</p> <p>0.90</p> <p>0.39</p> <p>7.32</p> <p>0.19</p>

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**

<p>Reactants Temp</p> <p style="text-align: center;">2AlCl<sub>3</sub> 25</p>		<p>Products Temp</p> <p style="text-align: center;">2 Al 960</p> <p style="text-align: center;">3 Cl<sub>2</sub> 25</p>	<p><b>Reaction Thermodynamics at 298 C</b></p> <p>( 2AlCl<sub>3</sub> ) to ( 2 Al + 3 Cl<sub>2</sub> ) = Net</p>	<p><b>products- reactants</b></p> <p>call/gm mole Al</p> <p>150,287</p> <p>168,308</p> <p>18,664</p>
			<p>delta G -300,574    0    0</p> <p>delta H -336,616    0    0</p> <p>delta S 48.1    13.5    159.9</p>	
			<p><b>Process Theoretical Minimum Energy Requirements</b></p>	
			<p>Thermal Energy for Temperature Maintenance (delta H - delta G)</p> <p>Thermal Energy for Al at 960 C</p> <p><b>Theoretical Minimum</b></p> <p>Thermal Energy for Cl<sub>2</sub> at 960 C</p>	<p>kWh/kg</p> <p>6.48</p> <p>0.78</p> <p>0.39</p> <p>7.66</p> <p>0.19</p>

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

# Appendix J

## Theoretical Energy Data and Calculations

**Table J-5 Theoretical Minimum Energy for Kaolinite / Aluminum Chloride Reduction**

Reactants Temp	Net Aluminum Reaction CarboChlorination (900 C)				Products Temp	product- reactants call/gm mole Al		
7 Al <sub>2</sub> O <sub>3</sub> .2SiO <sub>2</sub> 25	14 C +	21 Cl <sub>2</sub>	) to (	6 AlCl <sub>3</sub> +	6 SiCl <sub>4</sub>	+ 7 CO	Net	
	delta G	-2,374,053	0	0	-901,721	-884,799	-229,655	-659,819
	delta H	-2,531,520	0	0	-1,009,847	-942,161	-184,910	-658,363
	delta S	19	1,119	144	474	331	357	-50,323
	Chloride Reduction (700 C)							Net
	( 2AlCl <sub>3</sub>	) to ( 2 Al + 3 Cl <sub>2</sub> ) =						150,287
	delta G	-300,574	0	0				168,308
	delta H	-336,616	0	0				18,664
	delta S	48	14	160				
<b>Process Theoretical Minimum Energy Requirements</b>								
Thermal Energy for CO <sub>2</sub> at 960 C								
Thermal Energy for CO at 960 C								
Thermal Energy for Temperature Maintenance (delta H - delta G)								
Thermal Energy for AlCl <sub>3</sub> Production								
Electrolytic Work Requirement (delta G)								
Thermal Energy for Al at 960 C								
<b>Theoretical Minimum</b>								
Thermal Energy for CO <sub>2</sub> at 960 C								
Thermal Energy for CO at 960 C								

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

## Appendix J Theoretical Energy Data and Calculations

**TABLE J-6 Thermochemistry Data for Elements and Compounds Associated with Aluminum Production**

	CAS RN	Molecular Weights	Chemical formula	H (s)		G (s)		S (s)		Cp (s)	
				J/mol	cal/mol	J/mol	cal/mol	J/mol K	cal/mol K	J/mol K	cal/mol K
Aluminum	7429-90-5	26.98	Al	0	0	0	0	28.3	6.764	24.35	5.82
Aluminum Chloride	7446-70-0	133.34	AlCl <sub>3</sub>	-704,200	-168,308	-628,800	-150,287	100.7	24.061	91.84	21.95
Corundum	1334-28-1	101.96	Al <sub>2</sub> O <sub>3</sub>	-1,675,700	-400,500	-1,582,300	-378,179	50.9	12.165	79	18.88
Gibbsite*	155.96	Al <sub>2</sub> O <sub>3</sub> ·3H <sub>2</sub> O		-1,293,100	-309,058	-1,154,900	-276,028				
Kaolinite*	1332-58-7	Al <sub>2</sub> O <sub>3</sub> ·SiO <sub>2</sub> ·2H <sub>2</sub> O		-4,119,000	-984,465	-3,793,900	-906,764				
Kaolinite, meta	162.04	Al <sub>2</sub> O <sub>3</sub> ·SiO <sub>2</sub>		-843,840		-791,351					
Graphite	7440-44-0	12.01	C	0	0	0	0	5.7	1.361		
Chlorine	70.91	Cl <sub>2</sub> (g)		0	0	0	0	222.9	53.286		
Carbon Monoxide	630-08-0	28.01	CO (g)	-110,523	-26,416	-137,268	-32,808	197.9	47.301		
Carbon Dioxide	124-38-9	44.01	CO <sub>2</sub> (g)	-393,513	-94,052	-394,383	-94,260	213.6	51.061		
Oxygen	7782-44-7	32.00	O <sub>2</sub> (g)	0	0	0	0	205.0	49.003		
Water	18.00	H <sub>2</sub> O (g)		-241,826	-57,798	-228,582	-54,632	188.8	45.132	33.598	
Silica Dioxide	14808-60-7	60.08	SiO <sub>2</sub>	-910,700	-217,663			41.46	9.909		
Silicon tetrachloride	10026-04-7	169.90	SiCl <sub>4</sub> (g)	-657,000	-157,027	-617,000	-147,467	330.70	79.039	90.3	21.6

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 Formations Values as a Function of Temperature**

Temp C	Temp K	Heats of Formation - calories per gram mole					
		Al <sub>2</sub> O <sub>3</sub>	C	Al	CO <sub>2</sub>	CO	O <sub>2</sub>
25	298	-400,300	0	0	-94,050	-26,400	0
727	1,000	-404,400	2,310	18,710	-94,400	-26,750	9,249
827	1,100	-404,000	3,320	21,710	-94,250	-26,900	10,515
927	1,200	-403,600	3,850	24,740	-94,300	-27,000	11,843
960	1,233	-403,500	4,030	25,750	-94,300	-27,100	12,295
1,027	1,300	-403,200	4,390	27,790	-94,300	-27,300	13,233
1,127	1,400	-402,800	4,930	30,850	-94,300	-27,350	14,685

Source: \*values from "Technical Working Group on Inert Anode Technologies" Appendix A-9 page 11



## Appendix K Aluminum Heat Capacity and Heat of Fusion Data

**Heat Capacity (cal/mol\*K) = A + B\*t + C\*t^2 + D\*t^3 + E/t^2**

**Standard Enthalpy (kcal/mol) = A\*t+B\*t/2+(C\*t^3)/3+(D\*t^4)/4-E/t+F-H**

**Standard Entropy (cal/mol\*K) = A\*ln(t)+B\*t+(C\*t^2)/2+(D\*t^3)/3-E/(2\*t^2)+G**

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

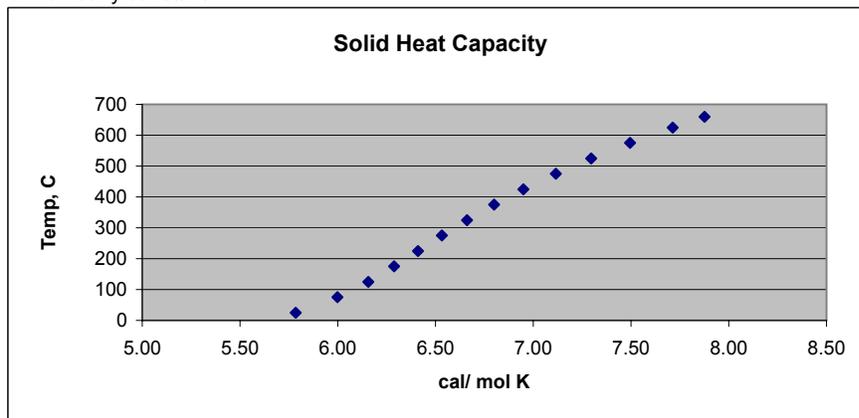
Source : <http://webbook.nist.gov> (Standard Reference Data Program)

<b>SOLID</b> formula for temperature range 298 to 933.45 K (1 atm)								
	A	B	C	D	E	F	G	H
Aluminum	6.71348	-1.29418	2.04599	0.819161	-0.066294	-2.18623	14.7968	0
<b>LIQUID</b> formula for temperature range 933.45 to 2790.812 K (1atm)								
	A	B	C	D	E			
Aluminum	7.588681	9.40685E-09	4.26987E-09	6.43922E-09	1.30976E-09	-0.226024	17.5429	2.524381

### 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
C	K					
25	298	<b>Solid</b>	5.79		0.00	0.00
660	933		7.88		0.19	0.19
660		<b>Fusion</b>	94.5	cal/gm	0.11	
660	933	<b>Liquid</b>	7.59			0.30
775	1048		7.59		0.04	0.33
960	1233		7.59		0.06	0.39
2000	2273		7.59		0.34	0.73
Smelting			25 to 960 C		Total	
Furnace Melting		25 to 775 C		Total		0.33

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



## Appendix L

**TABLE L-1 Impact of Secondary Metal Production on the Nominal Energy Requirements to Produce Aluminum**

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.

Year	U.S. Primary Aluminum Production in thousand Metric Tonnes	Smelting Energy kWh per kilogram	U.S. Secondary Aluminum Production in thousand Metric Tonnes	Market Percent of Secondary metal	Total Energy ore-to-metal To Produce Combined Metals kWh/kg	Effective Smelting Energy To Produce Combined Metals kWh/kg
1960	1,828	<b>23.1</b>	401	18%	50.6	19.2
1961	1,727	22.9	445		48.7	18.5
1962	1,921	22.7	533		47.6	18.1
1963	2,098	22.6	601		47.0	17.9
1964	2,316	22.4	648		46.9	17.8
1965	2,499	22.3	774		45.5	17.3
1966	2,693	22.1	833		45.2	17.2
1967	2,966	21.9	821		45.9	17.5
1968	2,953	21.8	935		44.2	16.8
1969	3,441	21.6	1,067		44.1	16.8
1970	3,607	<b>21.4</b>	937	20%	45.5	17.3
1971	3,561	21.0	1,004		43.9	16.7
1972	3,740	20.6	1,022		43.4	16.5
1973	4,109	20.2	1,127		42.5	16.1
1974	4,448	19.9	1,163		42.1	16.0
1975	3,519	19.5	1,121		39.5	15.0
1976	3,857	19.1	1,334		38.0	14.5
1977	4,117	18.7	1,456		37.0	14.1
1978	4,358	18.3	1,518		36.3	13.8
1979	4,557	17.9	1,612		35.4	13.5
1980	4,653	<b>17.5</b>	1,577	25%	35.0	13.3
1981	4,489	17.4	1,790		33.3	12.7
1982	3,274	17.2	1,666		30.7	11.8
1983	3,353	17.1	1,773		30.0	11.5
1984	4,099	16.9	1,760		31.8	12.1
1985	3,500	16.8	1,762		30.0	11.5
1986	3,039	16.6	1,773		28.3	10.9
1987	3,347	16.5	1,986		27.9	10.7
1988	3,945	16.3	2,122		28.6	11.0
1989	4,030	16.2	2,054		28.9	11.1
1990	4,048	<b>16.1</b>	2,393	39%	27.2	10.5
1991	4,121	16.0	2,286		27.6	10.6
1992	4,042	15.9	2,756		25.5	9.8
1993	3,695	15.8	2,944		23.8	9.2
1994	3,299	15.7	3,086		22.0	8.6
1995	3,375	15.6	3,188		21.8	8.5
1996	3,577	15.5	3,307		21.9	8.5
1997	3,603	15.4	3,547		21.1	8.2
1998	3,713	15.3	3,442		21.6	8.4
1999	3,779	15.2	3,695		20.9	8.1
2000	3,668	<b>15.1</b>	3,450	47%	21.1	8.2

**Forty Year Total Change in U.S. Energy Intensity**

1960	50.6	
2000	21.1	58.2%

## Appendix M

**TABLE M-1 Impact of Wetted Cathode Technology on Primary Metal Electrolysis**

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.

Wetted Cathode Technology	Typical modern "prebaked" Hall-Heroult cell operating at 95% current efficiency and with an ACD = 4.5 cm		Typical modern "prebaked" Hall-Heroult cell operating at 95% current efficiency and retrofitted with a wetted cathode surface and a reduced ACD (ACD = 3.5 cm)		Typical modern "prebaked" Hall-Heroult cell operating at 95% current efficiency and retrofitted with a wetted cathode surface, aluminum sump, and a reduced ACD (ACD = 2.5 cm)		Typical modern "prebaked" Hall-Heroult cell operating at 95% current efficiency and retrofitted with a sloped and wetted cathode surface, aluminum sump, and a reduced ACD (ACD = 2.0 cm)	
	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al	V (dc)	kWh/kg Al
<b>Energy Requirements</b>								
Reaction	1.20	3.76	1.20	3.76	1.20	3.76	1.20	3.76
Additional Energy Requirements								
External								
Anode	0.15	0.47	0.15	0.47	0.15	0.47	0.15	0.47
Anode Polarization	0.30	0.94	0.30	0.94	0.30	0.94	0.30	0.94
Cathode Polarization	0.55	1.73	0.55	1.73	0.55	1.73	0.55	1.73
Cryolite Bath	0.05	0.16	0.05	0.16	0.05	0.16	0.05	0.16
Cathode	1.75	5.49	1.36	4.27	0.97	3.05	0.78	2.44
Other	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
<b>ONSITE Energy Values</b>								
Cell Total	4.60	14.43	4.21	13.21	3.82	11.99	3.63	11.38
% Energy Savings			<b>8%</b>		<b>17%</b>		<b>21%</b>	
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			<b>8%</b>		<b>16%</b>		<b>20%</b>	
<b>TACIT Energy Values</b>								
Cell Total	4.60	28.97	4.21	26.52	3.82	24.07	3.63	22.85
% Energy Savings			<b>8%</b>		<b>17%</b>		<b>21%</b>	
Anode Manufacturing		5.89		5.89		5.89		5.89
Total onsite cell and anode		34.86		32.41		29.96		28.74
% Energy Savings			<b>7%</b>		<b>14%</b>		<b>18%</b>	



## Appendix M

**TABLE M-3 Estimate of the Energy Requirement to Manufacture 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 cm<sup>2</sup> as a basis the following can be calculated:

0.85 A/cm<sup>2</sup> is the a typical current density for a modern Hall-Heroult Cell current density

2980 Ah/kg Al is the theoretical amperage required to produce aluminum.

95% efficiency is typical of a modern Hall-Heroult 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 cm<sup>2</sup> over a two year period is calculated to be:

14.82 kg of Carbon per cm<sup>2</sup> over a two year operating period.

33.23 kg of aluminum per cm<sup>2</sup> over a two year operating period

From Appendix I

5.89 Tacit kWh/kg of aluminum produced is the energy associated with carbon anode. The total energy associated with the two year operation of the 1 cm<sup>2</sup> of carbon anode can be calculated.

196 kWh of tacit energy are consumed for anode manufacture and use.

2.27 gm/cm<sup>3</sup> is the density of a anode carbon. The height of the 1 cm<sup>2</sup> of carbon can be calculated as:

6529 cm height of carbon anode with a 1 cm<sup>2</sup> base or anode face

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 cm<sup>2</sup> of anode face and that it requires five times the total tacit energy of a carbon anode (which includes its fuel value) to manufacture. It can be calculated that:

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

## Appendix M

**TABLE M-4 Estimate of the Energy Requirement to Manufacture Aluminum Using Different Technologies**

Aluminum Production Technologies	Typical modern Hall-Heroult pre baked anode cell operating at 95% Current efficiency and with an ACD = 4.5 cm	Typical modern Hall-Heroult 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 ACD = 2.0 cm using Wetted Cathode technology	Carbothermic Reduction with a reaction efficiency of 95% and a furnace efficiency of 85%	Chloride Reduction of kaolinite clays: electrolysis current efficiency 95%, reaction efficiency 95% and heating efficiencies 85% efficiency
<b>Raw Materials</b>					
Onsite Energy required	kWh/kg Al	kWh/kg Al	kWh/kg Al	kWh/kg Al	kWh/kg Al
Tacit Energy required	alumina alumina	alumina alumina	alumina alumina	alumina alumina	see note B kaolinite kaolinite
	7.59 8.21	7.59 8.21	7.59 8.21	7.59 8.21	8.14 8.81
<b>Onsite Reaction Energy Requirements</b>					
Reaction Thermal	kWh/kg Al	kWh/kg Al	kWh/kg Al	kWh/kg Al	kWh/kg Al
Furnace Losses					
Reaction Electrolysis	V (dc) 1.20 3.40	V (dc) 1.20 2.43	V (dc) 2.20 1.98		
Cell Ohmic	3.76 10.67	3.76 7.62	6.90 6.20		2.07 0.93
TOTAL Reaction Energy	14.43	11.38	13.11	9.07	3.00
Anode Manufacturing	0.61	0.61	0.75	0	0.75
<b>% Onsite Energy Savings</b>		<b>20%</b>	<b>8%</b>	<b>40%</b>	<b>42%</b>
<b>TOTAL Onsite Energy Requirements including Raw Materials</b>					
Raw Ore Materials	7.59	7.59	7.59	7.59	8.14
Reactions	14.43	11.38	13.11	9.07	7.91
Carbon/Electrodes	0.61	0.61	0.75	0	0.75
<b>% Total Energy Savings</b>		<b>13%</b>	<b>5%</b>	<b>26%</b>	<b>26%</b>
<b>TOTAL TACIT Energy Requirements including Raw Materials</b>					
Raw Ore Materials	8.21	8.21	8.21	8.21	8.81
Reactions	28.97	22.85	26.31	18.21	16.64
Carbon/Electrodes	5.89	5.89	0.75	8.24	11.85
<b>% Total Energy Savings</b>		<b>14%</b>	<b>18%</b>	<b>20%</b>	<b>13%</b>

Note A: The Carbothermic reaction requires twice the carbon as the Hall-Heroult reaction. The Hall-Heroult 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% by weight aluminum. 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. Kaolinitic clays contain valuable titanium, in addition to their silicon content. These materials will likely be recovered in the processing plant and account of approximately 35% of kaolinitic clay content. This report allocates 65% of the total raw material energy requirement to the kaolinitic 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)