

U.S. Aluminum Production Energy Requirements: Historical Perspective, Theoretical Limits, and New Opportunities

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ABSTRACT

Energy reduction in the U.S. aluminum industry has been 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 per unit mass over the past forty years. However, this strategic metal remains by many measures one of the most energy-intensive materials to produce. This paper will describe the present practice energy requirements for aluminum production and compares these values to the theoretical minimum energy requirements. The greater the magnitude between practice and theoretical, the greater the potential for research and development (R&D) activities to further reduce energy intensity. These values show that the aluminum industry still has very large opportunities to further reduce its energy intensity, particularly in the production of aluminum from ore. This paper examines current R&D activities and speculates on their potential energy impact.

Introduction

Aluminum is an essential material for a modern manufacturing economy. The U.S. aluminum industry in 2000 was the largest in the world both in terms of metal production and product manufacturing. U.S. industry utilized 10,698,000 metric tons (tonnes) in 2000 to produce over \$39 billion in products. It is growing at an annual rate of 3.6%. U.S. per capita consumption was 35.4 kilograms. The industry operated more than 400 plants in 41 states and directly employed over 145,000 people (The Aluminum Association, 2001).

Primary aluminum is made from alumina refined from bauxite ore. U.S. plants consumed 369×10^{12} Btu of onsite energy to produce over 3,668,000 tonnes of primary metal in 2000. Secondary aluminum is made from recycled aluminum products. Over 3,450,000 tonnes of secondary metal were produced in 2000, consuming 29.5×10^{12} Btu of onsite energy. Secondary aluminum consumes about 8% of the onsite energy required to produce primary aluminum.

Primary aluminum is the most energy-intensive material, on a mass basis, produced in large quantities in the United States. Only paper, gasoline, steel and ethylene manufacturing consume more energy for manufacturing in the United States. Primary aluminum electrolytic cells are the nation's single largest electric energy consumer using 57.6×10^9 kWh annually, or 1.5% of all the electricity consumed by the residential, commercial, and industrial sectors of the U.S. economy. Electricity represents 25% of the costs to produce primary metal.

The U.S. aluminum industry has reduced its energy intensity by 58% over the past forty years, 21% as a result of technical progress and 37% with the growth of recycling. Recycling, with its inherently low energy intensity and strong growth (4.3% annually) rate, will continue to contribute to the lowering of the total energy demand of the industry. The industry has large opportunities to further reduce its energy intensity particularly with technical progress in primary production. The energy consumed in 2000 by the U.S. primary

aluminum industry is over three times greater than the theoretical minimum requirement. This large difference is a measure of the technical potential to reduce energy intensity by R&D activities. Examining the energy consumption and theoretical requirements for individual processes can indicate where valuable R&D resources should be focused to provide the greatest reduction of energy intensity. Realistically, however, technically achievable cost-effective energy savings are much smaller than the difference between theoretical and practice, but they are still very large and significant.

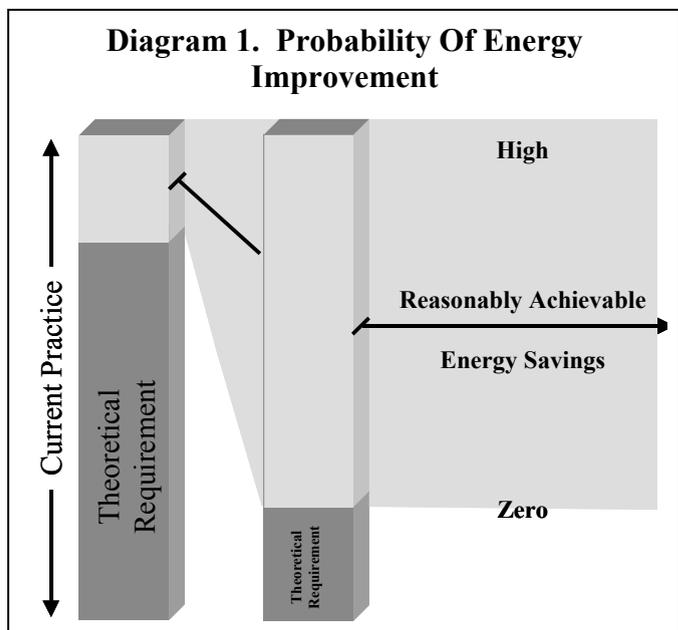
This paper provides an overview and builds on the information and data presented in a comprehensive study entitled: *U.S. Energy Requirements for Aluminum Production, Historical Perspective, Theoretical Limits and New Opportunities* (Choate, W. T. and Green, J. A. S.). This in-depth study provides energy performance benchmarks for primary, secondary and forming processes. It can be used for evaluating new process developments, tracking progress toward performance targets, and facilitating comparisons of energy use. It also provides a basic description of the processes involved, their interrelationships, effects on energy consumed and environmental impact of manufacturing aluminum metal and its products. This paper focuses on R&D activities associated with primary metal production, the area with the largest opportunities to save energy.

Minima, Energy Metrics and Research Opportunities

When examining R&D options for energy reduction in industrial processes, two values are indicative of the magnitude of potential savings for that process - the theoretical minimum and the current practice value. The theoretical minimum energy for chemically transforming a material is determined from the net chemical reaction used to manufacture the material. The theoretical minimum energy to transform a material from one shape to another shape (e.g., ingot to sheet) is based on the thermal and mechanical properties of the material. Neither chemical nor mechanical theoretical minimums can be realized. They are simplistic, thermodynamically ideal and require an infinite time to complete; however, these minima do provide benchmarks that no process will better.

The difference between the theoretical minimum and the current practice value is a useful measure of the size of the opportunities for R&D energy efficiency improvement. Two processes whose current practices consume the same amount of energy but whose theoretical requirements are different are shown in Diagram 1. It is more likely that the process with the largest difference will yield the greatest reduction in energy use for a given level of research effort.

A full accounting of the energy impact of manufacturing should include the energy used to produce the electricity, the fuels, and fuels used as raw materials (e.g., coke



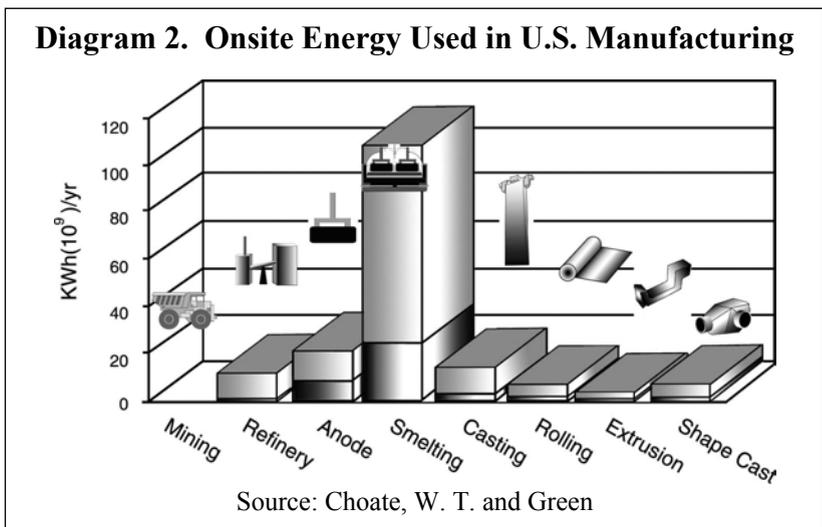
used in aluminum production). These “secondary” or “tacit” energy requirements are commonly confused with reported onsite energy values. Onsite values are based on physical in-plant measurements. Tacit energy values are a function of the onsite energy measurements and have assumptions associated with their values. These assumptions make it difficult to compare processes or industries without knowing the basis used to set tacit energy values. The difference between tacit and onsite values for many fuels is relatively small, roughly 3%. However, tacit electric energy values vary widely. Average U.S. grid electricity requires about 9,780 Btu to produce one kWh of onsite electricity (3,412 Btu). Electricity produced directly from coal requires 10,290 Btu/kWh, whereas hydroelectric is assumed to be 3,412 Btu/kWh. In 2000, the U.S. aluminum smelting and anode baking operations obtained 50.2% of their electricity from hydro facilities – an average tacit value of 6,850 Btu/kWh (Choate, W. T. and Green, J. A. S.). This paper, for clarity, distinguishes between onsite energy values and tacit energy values with the use of a “tf” superscript (*e.g.*, 1.0^{tf} kWh). Electric tacit values are calculated using 6,850 Btu/kWh for smelting and anode making and 9,780 for all other operations.

Plant operations and industrial R&D focuses on the value of onsite energy savings. Tacit values, however, are very important from a regional, national, and global energy perspective and are seldom analyzed or accounted for within an individual plant site. In the near term, as life cycle analyses and ISO 14000 become criteria in the purchase of materials, the tacit energy requirements for manufacturing will become more significant. When trying to measure the impact of energy-saving R&D consideration of both tacit and onsite energy values is important.

U.S. Energy Use in Aluminum Metal Production and Forming Operations

The total energy associated with primary metal production from ore was approximately 23.78(45.15^{tf}) kWh/kg of aluminum (Al) in 2000 and consisted of: 8.20(14.05^{tf}) kWh/kg aluminum for raw materials and 15.58(31.10^{tf}) kWh/kg Al for electrolytic reduction (Choate, W. T. and Green, J. S. A.). Recovering aluminum from scrap consumes about 6% of the energy required to produce primary aluminum. Hence, recycling in the United States saved more than 150 x (10⁹) kWh of energy in 2000. Nearly half, 48.5%, of U.S. produced metal in 2000 was from recycled material. The growth of the secondary metal market is due in large measure to economics. Aluminum is easily melted at relatively low temperatures, 700°C to 800°C (pure aluminum melts at 660°C).

Diagram 2 shows the amounts of total onsite energy used in the major metal production and forming operations of the U.S. aluminum industry. The casting band includes all secondary aluminum



production. The upper portion of each band shows the energy used over the theoretical minimum requirement and is an indication of how large the opportunity is for energy reduction. Electrolytic cells (anode making and smelting) account for 64% (75^{tf}%) of the energy used by the U.S. aluminum industry.

Of all post-smelting processes (i.e., melting, fluxing, casting, heat treatment, rolling, extruding, shaping and finishing) those associated with furnaces and heating account for 27% (16^{tf}%) of industry energy use. This paper focuses only on primary metal production.

Primary Metal Production

Primary aluminum production requires roughly 5.9 kg of earth to be mined to produce 5.1 kg of bauxite, which is refined into 1.93 kg of alumina, then is processed with 0.45 kg of carbon to produce 1.00 kg of aluminum.

The energy demand associated with the extraction of bauxite is typical of most overburden removal mining operations. The average energy requirement is 0.06 kWh per kilogram of mined bauxite for typical extraction (The Aluminum Association, 1998) or approximately 0.32(0.34^{tf}) kWh/kg of aluminum. Bauxite for aluminum production is no longer mined in the United States.

The United States refines imported bauxite to provide roughly half of its alumina smelting feedstock. The other half is obtained by the direct importation of alumina. Theoretically, 1.89 kg of alumina is required to produce 1.00 kg of aluminum. In practice, 1.93 kilograms are used, a very small portion of the alumina supply is lost to handling. The energy required to produce alumina from bauxite in 1985 was estimated to range from 2 kWh/kg to 9 kWh/kg of alumina (Burkin, A. R.). This range reflects both bauxite quality (alumina content) and refinery design. The average energy associated with the U.S. alumina feedstock is approximately 7.27(7.87^{tf}) kWh/kg Al (The Aluminum Association, 1998).

Anode Energy Requirements

Approximately 0.61(5.90^{tf}) kWh of energy were required to manufacture the 0.45 kg of carbon anode needed to produce 1.00 kg of aluminum in 2000. Anode consumption rates in practice are 35% higher than the stoichiometric requirement. Excess carbon usage results from the need to protect the iron electrical connections, from air burning, and from dusting. 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.

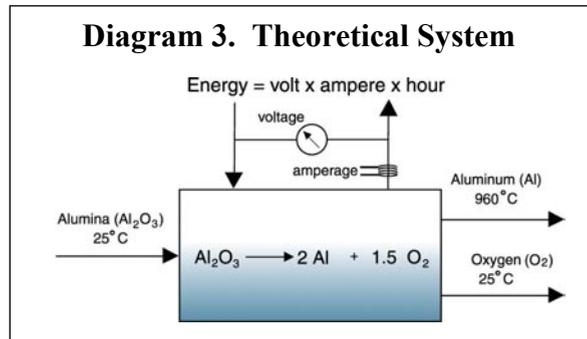
The most commonly used anode blocks are typically baked in a natural gas-fired furnace to about 1250°C. The minimum theoretical energy requirement to manufacture a carbon anode is the energy necessary to convert the coal tar pitch by destructive distillation to a coke-based binder. Approximately one-third of the pitch binder mass is lost in the baking process (UCAR Carbon Company, Inc). The fuel energy value of the lost pitch, 0.75 kWh/kg of anode, provides an approximation of the theoretical energy required. In addition, the tacit or inherent energy of 11.55^{tf} kWh/kg of carbon anode must be included. Therefore, the total theoretical minimum energy for carbon anode production is 4.1^{tf} kWh/kg of aluminum.

Reduction Energy Requirements

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).

Molten aluminum is the product of primary reduction processes. This paper 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 (Diagram 3). Changes in the operating temperature of a cell have a minor effect on the theoretical energy requirements.

For example, 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. 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. Theoretically, it is possible to capture all the energy associated with these gaseous emissions.



Three energy factors must be examined in the production of aluminum; energy required to drive the reduction reaction forward, energy required to maintain the system at constant pressure and temperature, and energy required to change the temperature of the reactants and/or products. The thermodynamics and chemical equilibrium of reactions are described by the Gibbs equation: $\Delta G = \Delta H - T\Delta S$. The energy required to drive the reaction forward is the Gibbs free energy (ΔG). For alumina reduction, ΔG is less than the heat of reaction (ΔH) and additional energy ($\Delta H - \Delta G$) must be added to the system to maintain the system temperature. Otherwise, the system would cool as the reaction progresses. (Reduction cells operate at atmospheric conditions and no pressure change results from the reduction.) The energy required to change the temperature of reactants and products is calculated from their heat capacities (C_p).

The theoretical Hall-Héroult reaction ($2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2$) 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. The energy required to drive the reaction forward (ΔG) is 5.11 kWh/kg, the thermal energy required to maintain the system temperature is 0.49 kWh/kg and the thermal energy associated with the molten aluminum is 0.39 kWh/kg Al. The theoretical minimum energy requirement is 5.99 kWh/kg Al. (Note: if the CO₂ gas emission at 960°C is included then the total theoretical minimum energy requirement is 6.16 kWh/kg Al).

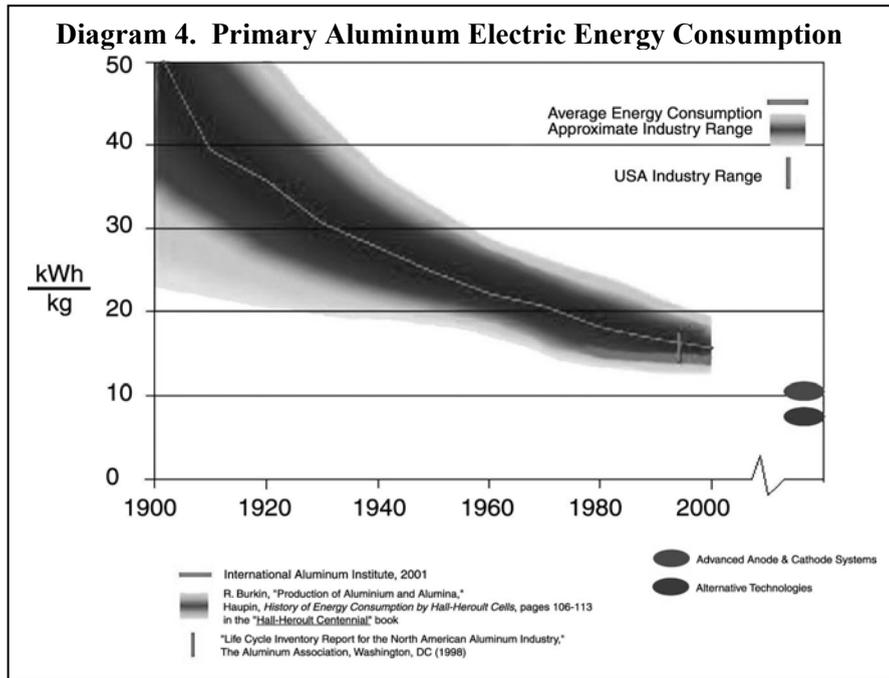
Faraday's law provides the minimum amperage requirement for electrolytic reduction, 2,980 Ah/kg Al. The Gibbs free energy divided by the Faraday amperage provides the minimum voltage required to drive the reaction forward. Cell voltage and current efficiency are variables that are controllable by design 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 actual carbon anode cell operations, current efficiencies of less than 100% result from reverse oxidation reactions between part of the aluminum metal

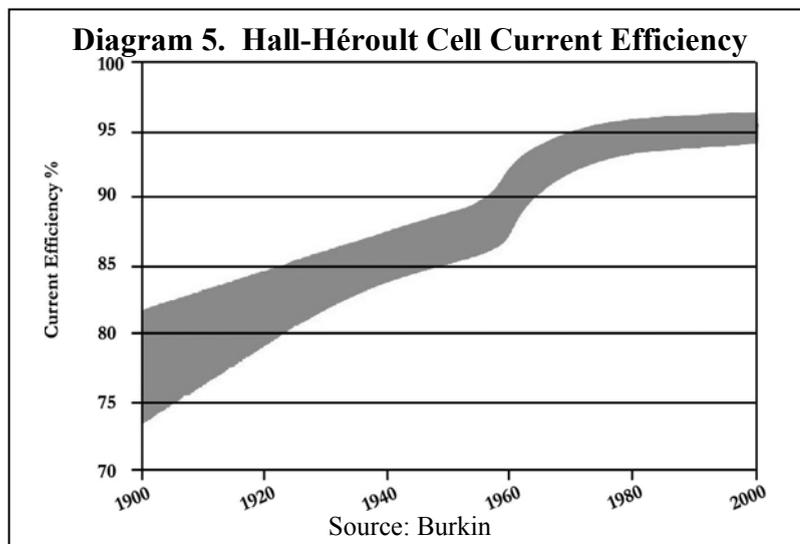
that is dissolved in the cryolite and carbon dioxide gas produced ($2 \text{ Al} + 3 \text{ CO}_2 \rightarrow \text{Al}_2\text{O}_3 + 3 \text{ CO}$) and to a lesser extent between the carbon dioxide gas and the carbon anode ($\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$). Current efficiency losses 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 Al. The onsite energy efficiency levels of present state-of-the-art carbon anode reduction cells are on the order of 46%. Diagram 4, *Primary Aluminum Electric Energy Consumption 1900 to 2000*, shows the significant electrical energy improvements made between 1900 and 2000. Onsite electricity use varies from less than 13 kWh/kg Al for state-of-the-art plants up to more than 20 kWh/kg Al (U.S. plants in 1995 averaged 15.4 kWh/kg Al (The Aluminum Association, 1998)). Compared to



theoretical values, U.S. facilities are averaging roughly 35% energy efficiency.

There is a minimum cell amperage required to produce aluminum (2980 Ah/kg Al). Production in the United States operates at about 95% current efficiency. The aluminum industry has significantly improved current efficiency (Diagram 5). The high current efficiency of existing technologies leaves little



opportunity for lowering amperage. Since current efficiency is high, lowering cell voltage presents the best opportunities for improving energy efficiency.

The electric current flows through the cell and cell components can be described as a set of resistors in series. The cell reaction voltage is a function of temperature and at 960°C is fixed at 1.2 V(dc) (DOE, 1999) 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.

Opportunities for Changes to Primary Aluminum Production

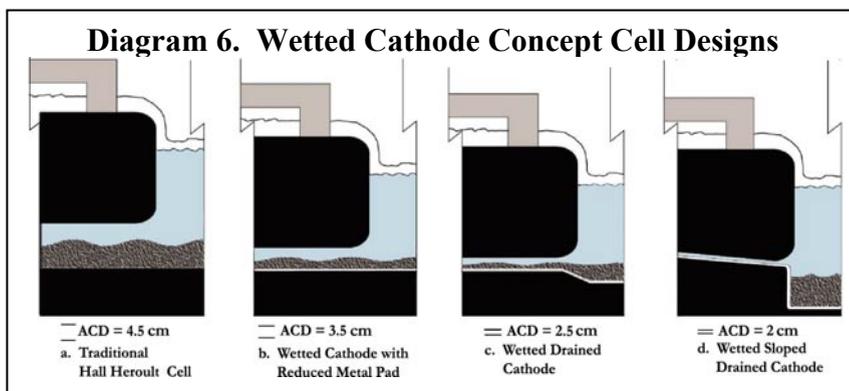
The Hall-Héroult cell is a system and improving one component does not necessarily result in an improved cell or a more energy-efficient operation, since all components must perform together as a whole system. Two innovative technological changes, the wetted drained cathode and the inert anode, are on the near-term horizon for improving energy and environmental performance. These technologies can, with cell modifications, be retrofit into existing potlines and supporting infrastructure. Mid- and longer-term technologies include; multipolar cells using Hall-Héroult chemistry with inert anode and wetted cathode technology; carbothermic alumina reduction; and multipolar cells reducing aluminum chloride made from kaolinite clays.

Wetted Cathodes

Wetted drained cathodes allow the anode-cathode-distance (ACD) to be reduced and are expected to result in a 21% reduction in the electrolysis energy required to aluminum. Molten aluminum does not wet the carbon lining of a Hall-Héroult cell. Titanium diboride (TiB_2) has been found to be a wettable cathodic material, and several approaches to incorporate TiB_2 into a Hall-Héroult cell are being studied (Brown, G. D., Taylor, M. P., Hardie, G. J., Shaw, R.W.). Cathodes made wettable with TiB_2 provide up to 300 mV reduction in junction resistance, but more importantly could allow for designs that stabilize or remove the metal pad and reduce ACD. Wetted cathodes also appear to increase cell life, which is a considerable benefit in terms of costs and spent cell lining wastes. Recent evidence also suggests that wetted cathodes reduce the formation of sludge (undissolved alumina) on the cell bottom and improve cell operations (Taylor, Mark P., Hardie, Gregory J., McFadden, Fiona J. Stevens, Uru, William).

The modern Hall-Héroult cell has an ACD of 4.5 cm and a voltage drop of 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. Several concepts for wetted and draining cells have been proposed (Diagram 6). These configurations are attractive since they can be



incorporated as a retrofit to existing facilities and some are currently being evaluated in commercial cells (Boxall, Larry, Cooke, Arthur V., and Hayden, Wayne). Reducing the ACD is limited by the ability to transport dissolved alumina to the electrode and aluminum and gas away from the electrode. This requires retrofit designs to account for the change in bath dynamics and 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. Sloping the electrode interface slightly (Diagram 6 (d)) removes products and supplies reactants more effectively by using the buoyancy of the gas to aid in transporting materials. It is estimated that under the best conditions, the ACD for a sloped configuration could be reduced as low as 2.0 cm (U.S. Patent 4,602,990). In which case the voltage associated with the bath would be 0.78 V(dc). The total voltage required would decrease to 3.63 V(dc), which provides a 21% reduction in cell energy.

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, productivity, and energy efficiency of the cell. However, 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 produced aluminum. An inert anode would enable greater control of the critical ACD, which represents the largest voltage drop in the cell. When used in conjunction with a drained cathode, it is estimated that an inert anode may save up to 22^{tf}% of the energy required for reducing aluminum. Inert anodes offer a major environmental advantage as a result of oxygen (O₂) being discharged rather than carbon dioxide (CO₂). Future carbon credits and/or CO₂ taxes are an unknown, but potentially large economic force that could hasten the development of inert anodes.

Inert anode technology could potentially be retrofit with limited changes into existing cells 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.

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

The theoretical minimum energy requirement of 9.03 kWh/kg Al for an idealized Hall-Héroult cell using an inert anode can be calculated from the thermodynamics of the reaction $2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al} + 3\text{O}_2$ (Note: if the O₂ gas emission at 960°C is included then the total theoretical minimum energy requirement is 9.30 kWh/kg Al). The theoretical energy requirement for an inert anode reaction is 45% higher than the carbon anode requirement. This makes the inert anode reaction voltage about 1 V(dc) higher. However, three factors are likely to provide the inert anode with an overall improved, operational energy performance than carbon anodes:

- a) *Elimination of Carbon Anode Manufacturing* - Carbon anodes require 5.90^{ff} kWh/kg Al for manufacture while inert anodes will require approximately 0.75 kWh/kg Al.
- b) *Reduction of Anode Polarization Overvoltage* – Inert anodes can be shaped to allow for better release of the O₂ generated and experimental evidence has shown that the oxygen evolved in the bath has a different froth/foam dynamic than carbon dioxide and these physical properties, in practice, also contribute to a lower anode overvoltage (DOE, 1999).
- c) *Reduction in ACD* - a stable anode surface combined with a wetted cathode will allow for a greater reduction in ACD.

Overall inert anodes when combined with a wetted cathode, 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), 5% cell productivity increases and a 43% reduction of carbon dioxide equivalent greenhouse gas emissions (DOE and The Aluminum Association, 1998)

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

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 arrangement makes aluminum reduction a capital-intensive process. Multipolar electrolytic cells would greatly increase productivity-per-unit-reactor volume and provide better control of heat losses. The concept has been successfully demonstrated for aluminum chloride reduction (Rao, D. Bhogeswara, Choudry, U. V., Erstfeld, T. E., Williams, R. J., and Chang, Y. A.). Alcoa Inc. in 1976 began operation of a multipolar, prototype plant with a capacity of over 18,000 kg Al per day. Alcoa obtained 90% current efficiency at 9.26 kWh/kg Al, 40% more efficient than a Hall-Héroult cell. The prototype plant was eventually shutdown because of the combination of the aluminum chloride production costs, 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 (Haupin, Warren).

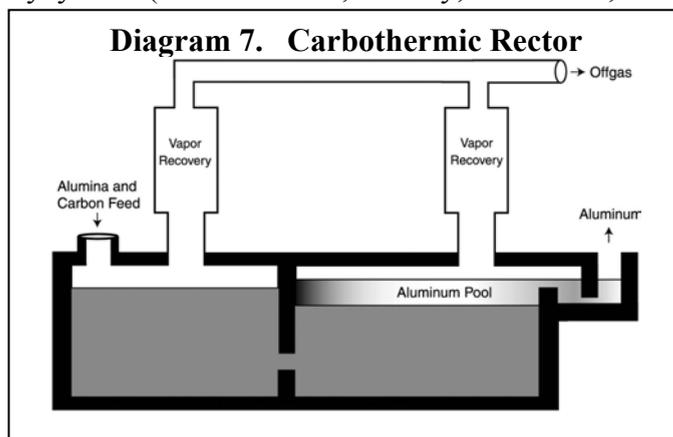
Multipolar chloride reduction technology using low-cost alumina-containing kaolinite clays has potential advantages: raw materials are widely available and indigenous to the United States; high-speed, high-conversion reactions with lower electrical demand; no “bauxite residue”; and use of conventional materials-of-construction (i.e., mild steel). While significant elements of the kaolinite process have been studied and developed, no integrated production of aluminum from kaolinite clays has yet been attempted (Toth Aluminum Corporation).

A Hall-Héroult multipolar design, involving multiple inert anodes and wettable cathodes arrayed vertically in a fluoride electrolyte cell, is currently being explored (Brown, Craig). In this concept, the operating temperature is 750°C – compared to Hall-Héroult technology at 960°C. 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.

Carbothermic Alumina Reduction

Carbothermic technology is projected to produce aluminum from ore at 34.65^{ff} kWh/kg Al or 20% less than Hall-Héroult technology. Carbothermic reduction of alumina is a non-electrochemical process. The technology has been an industry objective and the subject of extensive research for more than forty years. (Garcia-Osorio, Vianey, Lindstad*, Tor, Ydstie, B. Erik). It produces aluminum by a chemical reaction in a furnace/reactor. This provides a small footprint and makes it much less dependent on the economies of scale (large and long potlines). It is expected have capital costs 60% lower and operating costs 25% lower than a modern Hall-Héroult cell. The technology could significantly change the structure of the aluminum industry, allowing “mini-mills” to locate adjacent to casting facilities. These “mini-mills” could provide molten aluminum and/or specifically alloyed metal directly to casting operations, providing additional energy, economic, and environmental benefits to the industry.



The carbothermic process is a multi-step, high-temperature, chemical-reaction. Current work is directed toward a two-stage reactor with vapor recovery (Diagram 7). The first stage net reaction at ~1,900°C forms a carbide ($2 \text{Al}_2\text{O}_3 + 9 \text{C} \rightarrow \text{Al}_4\text{C}_3 + 6 \text{CO}$) and the second stage ~2,000°C uses the carbide and additional alumina to produce aluminum ($\text{Al}_4\text{C}_3 + \text{Al}_2\text{O}_3 \rightarrow 6 \text{Al} + 3 \text{CO}$). The thermo-dynamics are complex and careful process control is required to minimize back reactions. Recovery of the gas phase metal components is required for the reactor to have viable economics. Carbon is consumed during the reaction process and gives the process a lower theoretical energy requirement (7.32 kWh/kg Al) than the direct reduction of alumina. If an 85% thermal and 95% reaction efficiency were assumed a carbothermic reactor would require 9.07 kWh/kg Al, a 40% reduction in energy (Johansen , Kai, Aune, Jan A., Bruno, Marshall, Schei, Anders). Additional energy reduction could come from capturing the fuel value of the carbon monoxide byproduct.

The carbothermic reaction results in the generation of carbon-based greenhouse gases (GHG), mainly carbon monoxide (CO), at twice the rate of the Hall-Héroult reaction. However, the carbothermic process requires electricity only for heating and not for electrolysis. The total greenhouse gas (GHG) emissions from “utility-to-metal” for the carbothermic process are roughly 8% less than a modern Hall-Héroult cell.

Summary and Conclusion

The energy efficiency of primary metal production will be improved with the adoption of new cell and alternative reduction technologies. Table 1 summarizes the energy performance of potential near and midterm technologies. The energy values shown are for

the complete process including ore and anode production. Many technical hurdles remain to be solved in these new processes before they become commonplace in the industry.

Table 1. Comparison Ore-to-Metal Process Technologies

Energy Input kWh/kg Al		Modern Prebaked Hall-Héroult	Wetted Cathode ACD=2.0	Inert Anode Wetted Cathode ACD=2.0	Carbothermic Reduction	Kaolinite AlCl ₃ Reduction	
Onsite Energy Demands	Raw Materials	Bauxite-alumina	7.59	7.59	7.59		
		Kaolinite				8.14	
		Anode Materials	0.61	0.61	0.75		
		Reaction Carbon				0.08	
		TOTAL	8.20	8.20	8.34	7.59	8.89
	Reaction Energy	Thermal Reaction				7.71	-1.90
		Furnace Losses				1.36	0.40
		Electrolysis	3.76	3.76	6.90		6.48
		Cell Ohmic	10.67	7.62	6.20		2.93
		TOTAL Reaction	14.43	11.38	13.11		11.47
TOTAL kWh/kg Al		22.63	19.58	21.45	16.74	16.91	
Percent Energy Savings		Reactions	21%	9%	37%	45%	
		Reactions and anode	20%	8%	40%	42%	
		Reactions, anodes, and ore	13%	5%	26%	25%	
Tacit Energy Demands	Raw Materials	Bauxite-alumina	8.21 ^{tf}	8.21 ^{tf}	8.21 ^{tf}	8.21 ^{tf}	
		Kaolinite					8.81 ^{tf}
		Anode Materials	5.90 ^{tf}	5.90 ^{tf}	0.75 ^{tf}		0.75 ^{tf}
		Reaction Carbon				8.25 ^{tf}	11.12 ^{tf}
		TOTAL	14.10 ^{tf}	14.01 ^{tf}	8.96 ^{tf}	16.44 ^{tf}	20.65 ^{tf}
	Reaction Energy	Thermal Reaction				15.48 ^{tf}	-1.90 ^{tf}
		Furnace Losses				2.73 ^{tf}	0.60 ^{tf}
		Electrolysis	7.56 ^{tf}	7.56 ^{tf}	13.85 ^{tf}		13.02 ^{tf}
		Cell Ohmic	21.41 ^{tf}	15.29 ^{tf}	12.46 ^{tf}		5.88 ^{tf}
		TOTAL Reaction	28.97 ^{tf}	22.85 ^{tf}	26.31 ^{tf}	18.21 ^{tf}	17.59 ^{tf}
TOTAL kWh/kg Al		43.07 ^{tf}	36.95 ^{tf}	35.27 ^{tf}	34.65 ^{tf}	38.24 ^{tf}	
Percent Energy Savings		Reactions	21 ^{tf} %	9 ^{tf} %	37 ^{tf} %	24 ^{tf} %	
		Reactions and anode	18 ^{tf} %	22 ^{tf} %	48 ^{tf} %	35 ^{tf} %	
		Reactions, anodes, and ore	14 ^{tf} %	18 ^{tf} %	20 ^{tf} %	11 ^{tf} %	

Wetted drained cathode technology offers the most significant near-term potential for energy efficiency improvements, but its adoption will be gradual. Typical cell life is seven to ten years. The industry will likely optimize the capital invested in existing cells before retrofitting with new wetted technologies. 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.

Mid-term technologies, carbothermic and the aluminum chloride reduction processes, appear to offer a significant improvement in energy efficiency. However, industry will require significant demonstration time before adopting these alternative reduction technology.

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