New technology to the rescue for aluminum

The goals are a 50% reduction in capital per unit of production and a 40% reduction in operating costs. Much of the enabling technology already exists in other industries.

André R. Teissier-duCros

The aluminum industry is in crisis. And yet aluminum is the only metal whose consumption is growing, with diversified applications for which it has a clear advantage over other materials. The industry's crisis is caused by a growing discrepancy between strategic constraints and technological choices. Restructuring the industry requires rethinking the way industry does its technological development, putting a higher priority on "open, external R&D" than on "closed-shop, internal R&D." Much of the technology that can be called to the rescue already exists in other industries or applications. The aluminum industry has to recognize its needs and look for the solutions, some of which I discuss here.

Applications for aluminum exploit its diverse properties. Its structural properties allow it to be used in housing and construction, in automobile manufacture, and in the aerospace industry. Its malleability makes it ideal for packaging and home products such as insulation backing. Its electrical conductivity makes it suitable for some wire and cable applications; aluminum's share of this market is 50% and growing. Annual world production is 18 million metric tons (MT) compared with 700 million MT for steel and less than 10 million MT for copper. However, if world per capita consumption of aluminum equaled Japan's, we would need 140 million MT annually!

Aluminum production

Aluminum is produced by electrolysis of alumina through a consumable carbon anode by the Hall–Heroult process. Alumina is itself separated from bauxite, a natural ore, by the Bayer solvent extraction process. The major manufacturers of aluminum are listed in Table 1 along with their production capacity. These seven leaders have plants that produce a total of 40% of the world capacity.

Table 1. **Major manufacturers of aluminum**

Company	Country	Capacity, thousand metric tons
Alcoa	U.S.	2000
Alcan	Canada	1600
Reynolds	U.S.	1000
Pechiney	France	800
Alumax	U.S.	750
Hydro Aluminum	Norway	600
Kaiser	U.S.	500

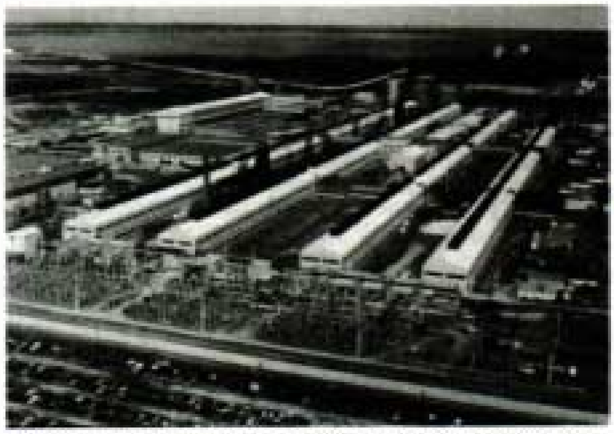

***Figure 1.* An aluminum plant.** Each of the electrolytic cells is arranged in electrical series in "potlines," and the plant may align several potlines. Each cell provides electrochemical resistance.

An aluminum plant is shown in Figure 1. The economics of building a state-of-the-art plant like this from scratch are outlined in the box. Aluminum production is the most capital-intensive industry in the world. As you can see, it is also highly energy intensive, requiring 6 kWh to produce each pound of aluminum.

This plant we're proposing to build is quite large. Could it be smaller? Plant size has not been growing until now for two main reasons: economies of scale, to reduce energy consumption; and the critical size of the carbon plant where the anodes are made, which consumes roughly 9 MT/year of petroleum coke and pitch.

How much does it cost to produce aluminum? This is a touchy subject because 70% of world aluminum smelters are operating at a loss, but I have broken down the cost into its constituents in Figure 2 (p. 32). Today 220 smelters are

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One state-of-the-art aluminum smelter

Investment cost	$1.5 billion
Capacity	230,000 MT/year
Sales revenue at $1100/MT	$250 million
Energy consumed at 14,000 kWh/MT	3.2 million MWh

listed worldwide, but many are cocooned or closed down. Alumina is assumed to be a commodity whose price is the same worldwide. Any price differential comes from shipment costs, which favor smelters on a seacoast or along a large river. The price of energy, however, varies enormously according to countries, to nature of contracts, and to economic priorities in the country.

Two technologies have been used during this century to produce aluminum: the prebaked anode technology and the Soderberg technology (Figure 3). In both cases, alumina, mixed with cryolite (sodium–aluminum fluoride) to form a eutectic of lower melting point, is electrolyzed in a refractory pot between a cathode of carbon blocks and an anode of compacted and baked granules of petroleum coke mixed with pitch as a binder. Alumina and carbon are converted to aluminum and carbon dioxide.

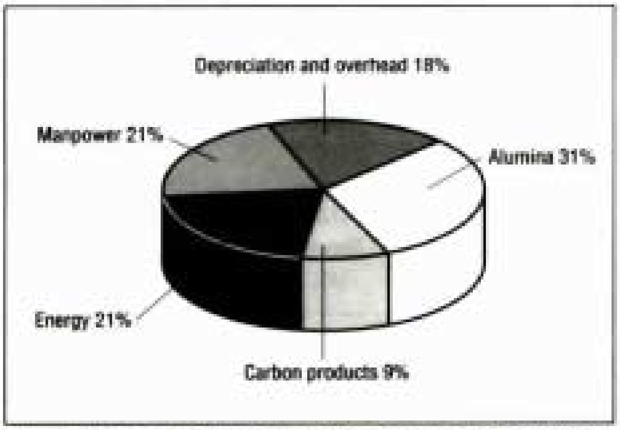


***Figure 2.* The operating cost of a state-of-the-art factory where the total cost per ton is $1215.** These percentages are approximations since depreciation can range from 14% to 17%, energy costs 18% to 22%, and alumina cost is 27% to 32%.

In the prebaked method, anodes are compounded and baked separately in an anode plant with a process comparable to that used in brick manufacture. This was the original technology imagined by the inventors, Charles Martin Hall and Paul Heroult, in 1880.

In 1927, a Scandinavian engineer, Carl Wilhelm Soderberg, demonstrated a concept of continuous anode. An enormous "sleeve" or "casing" above the pot is filled with green premixed anode paste that is baked by the heat of the pot itself as the paste goes down, following consumption of the anode. The continuous anode is held by steel studs or spikes scattered throughout: these are pulled out one after the other and replaced.

Soderberg's ingenious design eliminated half of the anode plant, simplified the process, and provided at the time a higher Faraday efficiency because of larger surface and lower current density. But it is dangerous: Organic gases emitted by anode baking are mixed with fluoride and metal compounds emitted by the pot. Anode consumption, bound to be irregular on such a large scale, translates into local overheating and generates pockets of gas that act as insulators and must be eliminated by human intervention. What with prevailing heat and toxic atmosphere, a mismanaged Soderberg plant is very close to Hell.

Toward greater efficiency

The efficiency of a smelter can be measured in two ways: the yield of metal per kWh consumed, and the Faraday efficiency, which measures what percentage of electrical energy has been used to convert alumina into aluminum. The first gives an economic performance, the second an electrochemical performance. When the Soderberg technology was introduced, its higher efficiency and lower capital cost prevailed. From 1927 to the late 1960s, the Soderberg technology was more efficient until the prebaked technology finally prevailed.

Between these dates, enormous R&D budgets were spent by the larger aluminum producers. The race was led by Alcoa, and the main challengers were Alusuisse and, post–World War II, Pechiney in France; later Kaiser, Reynolds, and Hydro Aluminum joined in the competition.

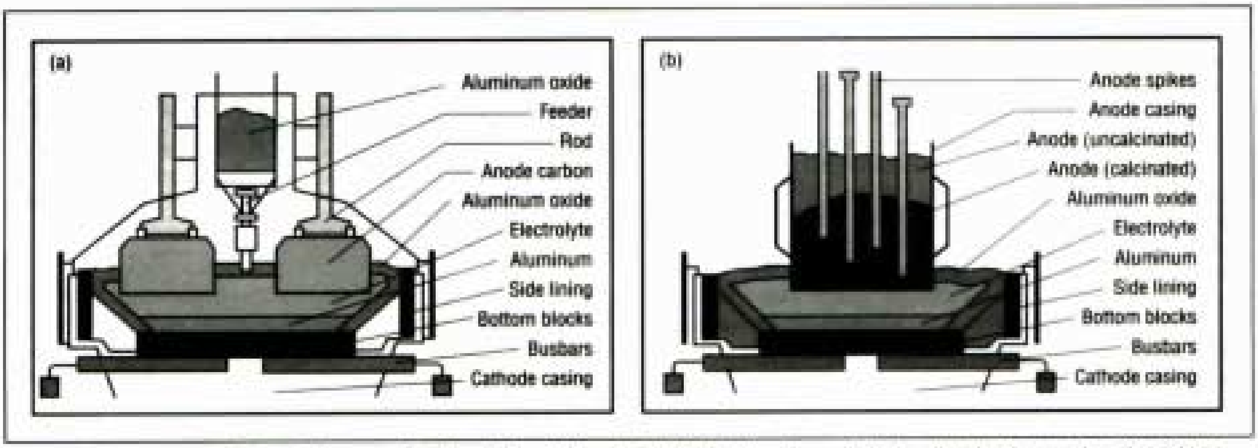


***Figure 3.* The two competing aluminum production technologies.** On the left is the older prebaked-cell technology and on the right is the Soderberg technology. After years of in-house development work, the older prebaked-cell technology prevailed and is the one in use today.

the Soderberg process was rendered obsolete, it was a triumph of internal R&D.

The technology advances

Until the late 1980s, priority was put on energy efficiency even though it meant larger size and capital intensity. The world industry, shaken by the 1973 energy crisis, discovered the French aluminum technology promoted by Pechiney. For decades France, a pioneer in aluminum, had a protected market justified by high energy costs. A massive effort was made domestically to increase metal yield per kilowatt hour. A technology breakthrough was introduced in the late 1960s with the Pechiney AP 16 and 18 pots of 180,000 amperes. This was obtained by computer modeling of magnetic fields in the pot, a typical project for internal corporate R&D.

a market. Pechiney sought economies of scale to further optimize its control of magnetic fields in and around the pot. Its plants are 280,000 and 300,000 A (versus 255,000 A for Alcoa), with nominal capacities of 230,000 MT.

Between 1970 and today, Pechiney has supplied the technology for about half of the smelters built in the world. Aluminum smelting technology became available "off the shelf," and newcomers such as Venezuela, Arab Emirates, and Australia have imported the technology from Pechiney but also from Kaiser, Reynolds, and Alusuisse. Alcoa still prefers to do internal R&D to meet or beat Pechiney and keeps its technology to itself.

Finding new technologies

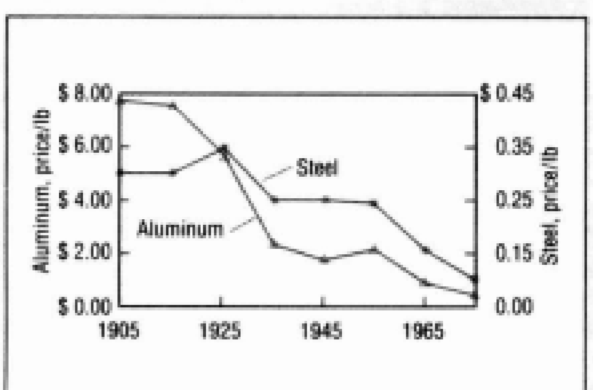
Technology priorities now aim at increasing added value, reducing costs other than energy, and reducing

Economics

World aluminum consumption doubled every decade from 1900 to 1980. The industry, led by Alcoa from the 1910s to 1973, followed a price umbrella set by Alcoa, based on a remarkably simple and sound policy: Prices were to be stable, then slowly descending against prices of steel and copper, the two main competitors.

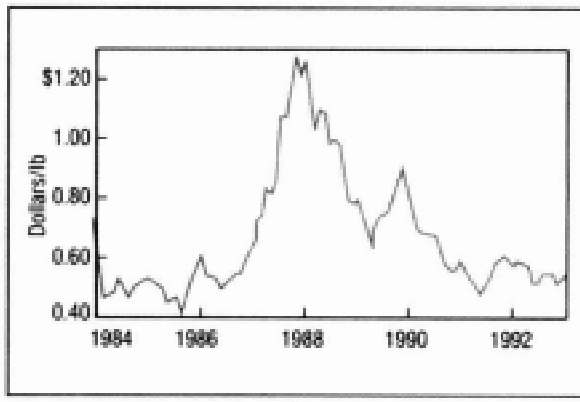
Any manufacturer betting on aluminum against other metals was sure to gain a cost advantage with time against the more conservative competitors. Thus, aluminum growth was market driven. Promotion of aluminum uses by Alcoa in packaging and automobiles, by Reynolds in house products, by Alcan or Southwire in wire and cable, and by others led to safe and predictable results with this kind of price policy, which could be enforced only because Alcoa was the market dominant supplier by far.

It was too good to last. Between 1938 and 1958, Alcoa was the victim of the biggest antitrust litigation ever. From 1905 to 1945 aluminum prices went down faster than steel prices; the period in which Alcoa's so-called monopoly was broken after 1945 coincided with an increase of prices in constant 1994 dollars and an increase relative to steel prices as well.



Alcoa was finally condemned for price fixing in 1958, although it took until the 1973 energy crisis for Alcoa's competitors to lose the habit of aligning on Alcoa's prices.

In 1978, the London Metals Exchange (LME) began quoting aluminum, and you see here what happened to the U.S. market spot price: instability, increases in the late 1980s, then collapse in the 1990s.



If prices are unstable, a downturn tends to favor the low-cost supplier that can afford to keep running at full capacity. And everyone wants to run at full capacity because of tremendous depreciation costs. Therefore aluminum was dumped in the LME inventories, creating a price war. This simply amplified the downturn, generated high inventories and market glut, and further reduced profits.

Smelters reacted to this situation in two ways. First, they asked utilities to share in the risk of downturns by having kWh prices indexed on LME prices. This gives them more resilience in a price war, which favors the price war. Second, they negotiated long-term contracts with key customers, which has the effect of freezing metal prices. Such contracts reduce the volume of the free market, which therefore tends to be more volatile: LME price downturns are amplified.

Alcoa was the first to realize that the costly R&D Taj Mahal that it had built did not make sense anymore, and the company scaled it down dramatically in the 1980s. Alusuisse dismantled its R&D lab, the core of which became an independent and successful R&D firm, R&D Carbon.

One might expect that with the scaling down of internal R&D, industry progress would stop. But that's not what happened. Left to themselves, individual smelters started tinkering with their own developments. With prices remaining at an all-time low of $1100–1200/MT, U.S. smelters succeeded in reducing costs and introducing new technologies. In 1991, it was estimated that 80% of the world's smelters were running in the red. In 1992, despite the same low prices, the figure fell to 70%, with significant improvements in North America.

that is, the pot efficiency. The anode technology is neglected. And yet the anode is at the heart of unsolved problems. The Faraday Index reaches 96%, but carbon efficiency (i.e., carbon consumption in excess of theoretical consumption as translated from the reaction formula) is 40–50%; however, most of the plant malfunctions are caused by irregular and changing anode quality. Small producers, such as National Southwire, which owns only one smelter, have demonstrated improvements in anode technology and in mechanization of anode operations while producing high-purity aluminum that goes directly from the ladle to continuous rod casting, and on to wire processing.

I believe that the aluminum industry will have to change in the next few years. It will want to aim at building smaller units, which can address specific regional markets. This is important in developing countries that must favor their domestic manufacturing industries. The carbon plant, the main factor in increased capacity, must be scaled down. Companies will need to offer directly the alloy, or high-purity metal, or semiproducts, such as rod, sheet or foil, or extruded profile, which a more local customer wants. Small-scale integration will allow lower cost and higher added value in the finished product.

My firm has identified seven independent technology goals that when implemented would result in a smelter with the following parameters:

- A smelter of 70,000–100,000 MT capacity;
- Intermediate intensity: 160,000–180,000 A;
- Investment cost per MT of capacity: about $3500;
- Operating cost per MT of metal: less than $1000, perhaps as low as $850, at the best sites;
- Site selection: on the sea, and near a long-term partner in electric power, or with an integrated power plant.

The seven goals can be pursued independently, and I believe that an active search for outside technologies for transfer to the industry will permit each goal to be met.

Scale down the carbon plant. The basic process used in the carbon anode plant, illustrated in Figure 4, is ancient, and evokes the technology used for making bricks. Trial and error led to expedient additions of grinders, screeners, and mixers to the process that became today's state of the art. The result is a complex process that is still prone to irregular quality. A faulty anode means a higher spontaneous air burn, a loss of energy and carbon product, and a risk of malfunction.

Early tech transfer in the aluminum industry

The first technologies transferred from another industry occurred in the 1950s. One is the continuous anode paste kneader, transferred from—no joke—the chocolate industry, and developed by Buss AG, a Swiss firm, of course. The other is the invention by a very small French manufacturer of gantry cranes, ECL. It is a connecting clamp that allows the use of a master–slave robot carried by an insulated gantry crane which mechanizes anode changing and other pot-tending functions including alumina feeding. The pot-tending machine replaces anode changing from a tractor or by a hand-operated crane. The gains in productivity and human safety are tremendous. As a result of this invention, ECL has grown to 500 employees and become the absolute market leader among industry-specific suppliers. These firms and others who followed can tell you the best stories about the NIH—Not Invented Here—syndrome. It took 20 years for the pot-tending machine to become the prevailing technique used by almost all new prebake smelters.

Pennsylvania Crusher Company, ... shown the way to better control of particle size. R&D Carbon redesigned the carbon plant (Figure 5), using a process transferred from asphalt technology and the road-surfacing industry; this carbon plant is now promoted by ABB Engineering. The techniques used to prepare mixes are simpler and less elaborate than the prevailing ones. Pennsylvania Crusher suggested changes, which it transferred from experience with fine crushing of coke in coal-fired power plants. These changes could eliminate several steps of grinding and screening.

Toward an isotropic anode. We foresee the use of powder generation technology to produce an "isotropic" anode instead of the granular structure of the current anode. This would be produced by sintering a carbon powder, itself generated by solid coalescence of carbon in a liquid phase. This technology could also be inherited from the steel industry.

Continuous alumina feeding. The pot is permanently breaking down alumina into aluminum and carbon dioxide. The right amount of alumina must be maintained so that each electron volt available ideally feeds the electrochemical reaction to maximize Faraday efficiency. Unfor-

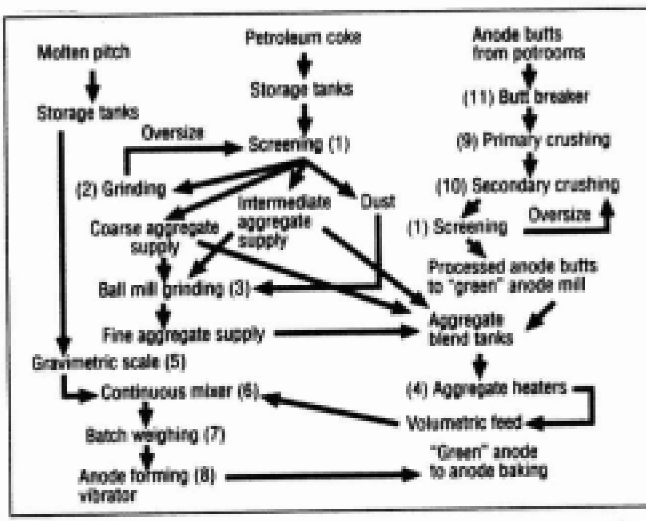


Figure 4. Functional chart of the plant that is currently used to produce the carbon anode.

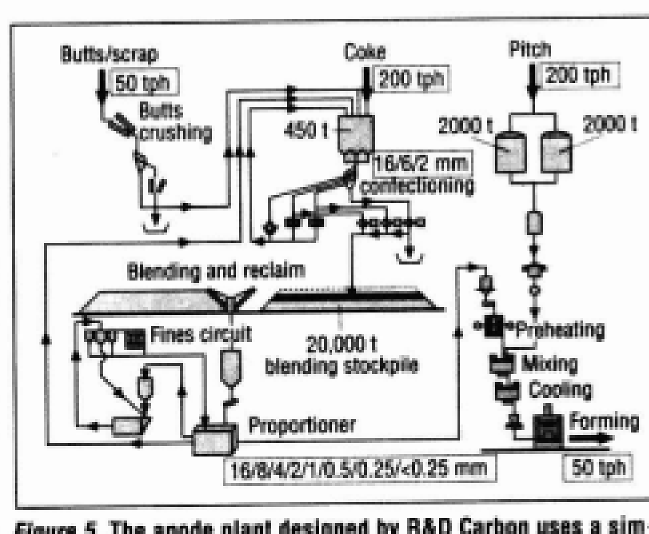


***Figure 5.* The anode plant designed by R&D Carbon uses a simpler process.** The process was borrowed from the asphalt processing industry.

crust at the surface of the pot. Alumina must be fed through that crust. It must be broken at regular intervals to let through an injection of fresh alumina.

The bottleneck here is a subsystem called the point feeder. The best current technology is the Pechiney design shown in Figure 6. This device combines a pneumatic hammer with a small hopper. There are three point feeders per pot, which break the crust and feed the oxide every 2 minutes or so. In between, the Faraday efficiency drifts down slightly. If the frequency of the feed could be higher, efficiency would increase. Unfortunately this device has an Achilles' heel: Its air cylinder uses polymer seals and elastomer hoses that do not function well in the presence of alumina powder and high temperature. A seal technology that uses only metals and minerals and is totally refractory is available; it comes from the automotive industry. A new design can eliminate the hoses. These improvements are common in machine design, but the industry has to be willing to go elsewhere and seek the needed expertise.

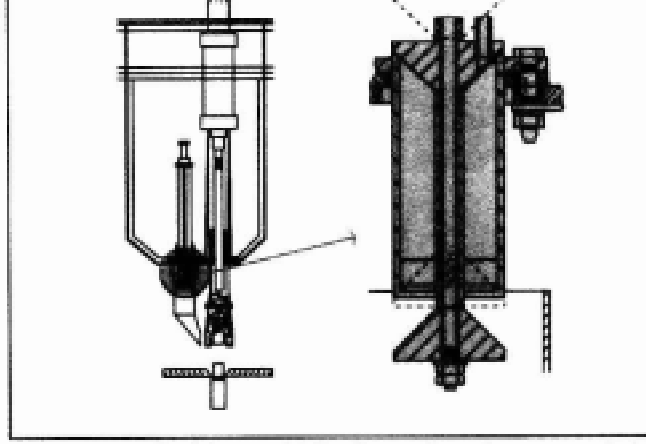


Figure 6. **The Pechiney point feeder system.** Improvements in materials could lead to more even operation and higher Faraday efficiencies.

Heat insulation. In a rare example of university–aluminum industry cooperation, Hydro Aluminium, the Scandinavian producer, has sponsored in a local Technology Center the development of an unexpected energy-saving device. Because smelting occurs at temperatures of about 1400 °F, a lot of energy is lost through heat. A heat exchanger using a heat-conducting fluid as media covers each pot. Hydro Aluminium demonstrated in its pilot operation that 11% of the previously lost heat can be converted into usable cogenerated energy.

Metal recovery in dross. The dross is the slag composed of metal, oxide, and salts at the surface of molten metal. The invention of dross cooling plus metal recovery in rotary furnaces came from MFS Engineering Company, a small Canadian engineering firm previously active—again—in the steel industry. Even more high tech is the transfer from plasma torch technology: Plasma Energy Corporation promotes remelting of dross in a controlled atmosphere to recover the metal. The process has been used with success by Alcan and by Oralco Aluminum.

Environmental protection. The industry leaders in reducing the air pollution from aluminum smelters are a Swedish firm, Flakt Industri, and a French firm, Procedair. Their technology consists of scrubbers cleaning fumes from various toxic components notably fluorine, SO_x, VOCs, and metal compounds.

Disposing of the solid residue remains a problem. But several technology transfers are in the making, aimed at completely neutralizing the solid residue into a vitrified material safe to dump or even to reuse. Vitrification is again obtained by plasma processing. One possibility would be the technology developed in Europe by LAB, an engineering firm cooperating with Europlasma, a spin-off of an aerospace company.

Improved pot shelf life. The problem here is that the extreme thermal stress on the pot limits its life. The pot lining must be replaced at regular intervals, and the spent lining is a hazardous pollutant. A breakthrough in materials technology and in design could solve this problem. I do not believe that the breakthrough needed will come from the aluminum industry itself.

The future

My company is monitoring these developments for our clients in the aluminum industry, and we are confident that in the coming decade aluminum consumption, driven by strategic priorities and a commitment to low prices, will increase much more than current projections. The industry will be less research oriented but more innovative. In Table 2 are the absolute cost of aluminum and its constituents in three cases from the worst to the ideal but feasible case, which applies to several smelters now at project stage. An operating cost of $805/MT is feasible. If anyone wants to put some money into such a smelter, please give me a call!

This article is based on a presentation to the spring 1994 meeting of the Commercial Development Association.

Table 2. **Production costs for aluminum, 1993–1995**

Factors	Cost[a] Ideal	Realistic	Worst
Depreciation	92	185	240
Alumina	300	375	400
Carbon products	87	110	120
Energy	100	250	600
Labor	60	180	360
Equipment & supplies	160	240	240
Shipping	6	40	80
Total	805	1380	2040

[a] All figures are in U.S. dollars per metric ton.

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