

Chapter 67

The future of aluminum

Like the rest of the metals industry, aluminum production requires exploration, mining, transportation, refining, smelting, fabricating and marketing. All of these steps benefit from research that would increase energy efficiency, reduce environmental impacts and create new products. In her 2014 book “Aluminum Dreams: The Making of Light Modernity,” Mimi Sheller describes how the use of aluminum changed many aspects of modern life for the better. But she also noted that the unintended consequences from the widespread use of aluminum included “struggles for sovereignty and resource control in Africa, India and the Caribbean; the unleashing of multinational corporations; and the pollution of the earth through mining and smelting.”¹ Research in new mining, refining and smelting technologies would not address political problems – greed or indifference by governments or corporations do not lend themselves well as laboratory projects, and they are a condition of humanity beyond the scope of the aluminum industry. Reducing energy intake and pollution output is something scientists can study, and any solutions they discovered would affect the entire industry – from natural resource extraction all the way to end products used by mass consumers.

From perspective of the business world, Alcan President and CEO Jacques Bougie looked ahead at the global aluminum industry in an October 1998 paper for the Aluminum Association. Bougie forecast that aluminum consumption would increase by about 3.5%, with 5.7 million tons from new smelters, 2.6 million tons from increasing capacity at existing smelters, and 3.4 million tons from modifications at existing plants that increased production. Bougie also forecast that the secondary scrap and recycling market would grow by 4.5% per year between 1998 and 2015. “Smelter production costs, helped by advances in technology, have dropped throughout the industry, helping to maintain aluminum as a viable, cost-competitive material,” he said. The aluminum beverage can market had grown to a major international business. Seven can manufacturers accounted for 85% of the world production of cans, and two customers accounted for nearly 75% of the demand for those cans – Coca-Cola and Pepsi.²

The same trend in centralization was taking place in demand for aluminum by the automotive industry, according to Bougie, as large manufacturers merged to form larger companies, and new aluminum technology offered an opportunity to reduce pollution and energy consumption. He cited the Ford P2000 utilizing Alcan's proprietary Aluminum Vehicle Technology and the Audi A8 using Alcoa technology as examples. The aluminum industry, however, had a public relations problem, Bougie said. "Critics attack aluminum on the basis of perceived weaknesses exposed through the primary part of the life-cycle analysis - i.e. high energy consumption, assumed toxicity, use of primary resources, etc," he said. "I realize I am preaching today to the converted. Most of us here appreciate that, when life-cycle analyses include all aspects of the product, aluminum stacks up very well against competitive materials from an environmental perspective." Competition by the steel and plastic industries was increasing, Bougie noted. The Steel Alliance had budgeted \$100 million for a print and television campaign promoting the use of steel, particularly in the automotive industry, and the plastics trade association in Germany spent \$11 million in 1997. The aluminum industry spent only \$500,000 on promotional activities, he said. ³

Bauxite and alumina

Alcan, Alcoa, Reynolds, Kaiser, Pechiney and Alusuisse dominated the aluminum industry of the free world by 1967. Acting often like an oligarchy, the Big 6 owned most of the known bauxite deposits, produced most of the world's alumina, smelted most of the primary aluminum, and fabricated most the aluminum shapes and products. Together, the six companies directly owned about 63.9% of the free world's smelting capacity in 1963 and had a share in ownership of an additional 12.7% - with plans underway to expand capacity throughout the world. ⁴ Third World nations were able to counter this arrangement through cartels - a method used by the big aluminum producers since the late 19th century. In August 1968, the Jamaican government raised the idea of creating an economic group representing bauxite-producing nations in South America and the Caribbean, including Suriname, Guyana and the Dominican Republic. By 1972, Jamaica, Suriname and Guyana had signed an agreement to share information on the bauxite industry. The 1970s were a difficult period for all industries, with

cyclical economic fluctuations, repetitive oil price hikes and shortages, and the emergence of resource nationalism – the demand by countries to maximize the benefits of their natural resources by controlling how their resources were developed. Sales of bauxite and alumina accounted for half the exports of countries like Jamaica, Guinea and Guyana. On the other hand, bauxite and alumina accounted for less than 2% and 15% respectively of the overall cost of primary aluminum production. Many countries with bauxite resources looked for a way to integrate downstream into aluminum production, especially if a cheap source of electrical power was available. ⁵

In March 1974, representatives from Australia, Guinea, Guyana, Jamaica, Sierra Leone, Suriname and Yugoslavia met in Conarky, Guinea, to discuss forming a bauxite cartel. The International Bauxite Association was formally created on July 29, 1975. The Dominican Republic, Ghana, Haiti and Indonesia later joined the association. By 1980, the cartel had 11 member nations accounting for 85% of the bauxite traded in the international market and virtually 100% of American imports. Despite this apparent grip on the market, the association did not function as effective as other resource cartels, such as the Organization of the Petroleum Exporting Countries (OPEC). Some members of the International Bauxite Association had enormous reserves, while others had very little. Brazil, with enormous reserves, was expected to become a full-time member by 1982. The association initially suggested floor prices for bauxite, and in 1981 the floor price was raised to \$33 per ton from \$29 in 1980. ⁶ The reaction to the new cartel by large vertically-integrated aluminum companies was not confined to deal-making. They also turned to research. In March 1974 for example, Reynolds Metals announced it had begun testing new methods for producing alumina from laterite ores. The tests were seen as a move to show the growing international cartel of bauxite-producing nations that the U.S. aluminum industry could survive without them. ⁷

A quarter century later, an industry survey projected a dramatic increase in alumina production. According to economists at AME Group, alumina production was expected to more than quadruple from 11.7 million tons per year in 1999 to 56.2 million by 2004, with the growth rates varying widely between regions. Alumina production was

expected to increase in Asia, Latin America, Europe and Australia but to remain unchanged in the former-Soviet Union. The rapid expansion of alumina production was expected to affect the operations of aluminum smelters, but new developments in the processing of bauxite into alumina would also make a difference, including the use of alternative energy sources and the recycling of caustic soda and red mud. Alumina refineries had reduced manpower by 20% from 1989 to 1999. Australia, with a 30% share of the worldwide alumina market, was the lowest-cost producer. The key factors affecting alumina refining costs were bauxite quality, transportation costs, energy costs, energy consumption rate and employee productivity. Australia had the lowest raw bauxite costs, but North America had the lowest energy costs due to the extensive use of natural gas and hydroelectricity. ⁸

The process patented by Karl Josef Bayer in 1892 became the predominant commercial method for refining bauxite into alumina, with some modifications for efficiencies. Around 1900, an alumina refinery typically needed 2.33 tons of coal to process 1 ton of bauxite. By 2004, that had improved to 0.15 tons of coal per ton of bauxite. As a result, bauxite in the early years was typically transported to areas near coal for refining. Energy improvements came from use of heat exchangers and flash tanks for energy recovery and the use of large autoclaves - the larger the reactor, the less heat was needed per unit of production, creating economies of scale. Precipitation tanks also increased in size to 10 times that of the autoclave. Steam was also utilized for heating and agitation, and autoclaves were connected in series to permit continuous operation, decreasing the need for manpower. ⁹

By 1920, Alcoa had developed several improvements, including the continuous digestion, lime and soda, and starch processes. Improvements continued after that - during World War II, the Bayer process recovered on average about 95% of the alumina in bauxite ores, but by 1962 the rate was 97%. ¹⁰ But some research was aimed at replacing the Bayer process altogether. Alcoa's research laboratory in New Kensington, Pa., had 20 employees under the direction of Earl Blough by 1913. Blough was the company's chief chemist and metallurgist, and William Hoopes served as the company's chief electrical engineer. One of Alcoa's major research goals was finding a

cheaper alternative to the Bayer process. That effort was finally suspended in 1919. Other Alcoa research efforts were focused on innovations that would improve production methods, from mining to fabrication. ¹¹ Over the years, successful improvements to the Bayer process were based on economies of scale, not new chemical reactions. Like the Hall-Heroult process for reducing alumina to aluminum, not much changed during the 20th century in the basic method for refining bauxite into alumina – in both cases, the processes derived from late 19th century discoveries.

From 1904 through 1928, Alcoa experimented with a new way to produce alumina called the Hoopes process, more commonly called the dry process. The experiments were conducted at Alcoa's aluminum smelter at Arvida in Quebec. Following the major company split in 1928, the dry process experiments became the property of Aluminium Ltd., but they never proved successful. In 1912, Alcoa entered into a contract with a French company to develop a new type of alumina refining called the Serpek process that would simultaneously produce alumina and ammonia and be cheaper than the Bayer process. The Serpek process never proved practical and the contract was canceled in 1920. On May 31, 1928, Alcoa acquired Prodotti Chimici Napoli, an Italian company that was trying to develop a way to produce alumina from leucite, an Italian mineral, instead of bauxite. The company was transferred to Aluminium Ltd. in 1931. The experiments continued under the Canadian company without result and were canceled in 1935. ¹² The leucite experiments were championed by Arthur Vining Davis, who had worked as Charles Martin Hall's assistant at the Pittsburgh Reduction Co.'s pilot aluminum smelter on Smallman Street in Pittsburgh in 1888 and went on to become chairman of Alcoa. The Italian process involved converting leucite, a silicate of potassium and aluminum, into alumina by leaching the ore with hydrochloric acid, but the process had never been satisfactorily demonstrated before Alcoa paid for it. ¹³

Anaconda's experiments

The Anaconda Company became interested in an alternative to bauxite when it first considered entering the aluminum industry in 1914. Alcoa by then held a firm monopoly over domestic bauxite reserves and was developing mines in British Guiana and Dutch Guiana. To break into

the aluminum industry, Anaconda needed access to aluminum-bearing ore and hoped that source was not limited to bauxite. Anaconda's top metallurgist, Frederick Laist, working with his associate Russel B. Caples, looked into the possibility of producing alumina from slime flotation tailings produced as a waste product at the company's huge reduction works in Anaconda, Mont. The investigation was delayed by World War I and in the end proved infeasible, but the knowledge gained from the investigation led to new ideas about producing alumina from clays mined near Spokane, Wash. The new process was tested at a pilot plant erected in Anaconda in 1915 through 1920. The results of the tests led to the belief that if sufficient alumina could be produced, electric power could be generated in Flathead County to supply an aluminum smelting plant. The whole plan was abandoned when the cost of producing alumina from the Washington clays was compared with the lower cost of bauxite mined in Arkansas. The investigation of clays with higher concentrations of aluminum found near Moscow, Idaho, revived the plan for an alumina refinery in Montana in 1955. By that time, the Anaconda Aluminum Co. plant in Columbia Falls, Mont., was in operation. Plans were made to build another pilot plant in Anaconda in 1957 to test a process for producing alumina from the Idaho clays.¹⁴

The Anaconda Co. announced long-range plans for a clay-processing plant near Spokane on Sept. 23, 1955. The plant relied on construction of a proposed 300 million cubic feet-per-day natural gas pipeline to be run from Canada to Oregon and Washington. In full operation, the clay-processing plant was expected to consume between 25 million and 40 million cubic feet of natural gas per day. But before construction of the plant would start, Anaconda planned on building a pilot plant to test the process.¹⁵ In October 1956, after nearly two years of laboratory study and tests at the AAC smelter, the Anaconda Company announced it had solved a key problem in producing alumina from the Idaho clay deposits and was ready to build a pilot plant capable of converting 50 tons of the clay into alumina.¹⁶ The \$1 million pilot plant would be built near the company's copper smelter in Anaconda and be completed by autumn 1957. The process would involve leaching and high-pressure filtration and was expected to produce alumina at the rate of 10 to 14 tons per day from 50 tons of clay. The clays were already being mined in Idaho and being shipped to Anaconda. If the

pilot plant proved to be commercially viable, the company planned to spend \$35 million constructing a full-scale plant near the clay deposits and then shipping the alumina to its smelter in Columbia Falls. The implications of the new process for both industry and the national defense program were significant – most of the bauxite used in the world’s aluminum industry in the late 1950s came from tropical countries. For the U.S., that meant chiefly Jamaica and Dutch Guiana.¹⁷

Much of the research on how to process clay into alumina took place during World War II when the German submarine campaign threatened the nation’s supply of bauxite from the Caribbean and South America. The Anaconda Company had already secured options on clay reserves in Idaho.¹⁸ By September 1957, construction of the pilot plant was nearing completion. The program drew much attention by other major aluminum producers which had already taken options on clay deposits in the U.S.¹⁹ By February 1963, alumina produced from Idaho clay at Anaconda’s pilot plant was being smelted in two reduction pots at the Columbia Falls aluminum plant, which produced 6,200 pounds of aluminum every 48 hours. The pilot plant had taken six years to develop. According to AAC General Manager James F. Smith, the smelting was in the test stage for about a year to evaluate the economics of the process. According to the Hungry Horse News, “A long-time dream of the American aluminum industry is to be able to use the more conveniently located clays as a source of alumina rather than bauxite from the tropics.”²⁰ Chairman Clyde Weed reported on the company’s progress in producing alumina from clay at the Anaconda Company’s annual stockholders meeting on May 15, 1963. The experimental pilot plant was producing five tons of alumina per day, Weed said, and the process was so promising the company would need to enlarge its smelter at Columbia Falls and its aluminum fabrication plants to accommodate the output. The company’s goal was to establish complete vertical integration – from mining to producing finished aluminum products.²¹

A decade later, however, the Anaconda Company wasn’t using the clay-to-alumina process. The company’s top managers were still interested and were willing to invest settlement money it received from the Chilean government to further develop the process. In 1974, Anaconda accepted \$253 million for the copper mines that the Chilean

government expropriated in 1969. The company was still climbing out of a financial crisis that climaxed with the loss of the Chilean mines, and Anaconda Chairman John Place hoped to use the settlement money to expand the company's aluminum operations, particularly in research and development in the use of non-bauxitic ores to produce alumina. The company owned extensive deposits of kaolin clay in the U.S., he said, and the Jamaican government had substantially raised taxes on bauxite purchased by the company.²² Added taxes and levies imposed by nations that were members of the International Bauxite Association caused bauxite prices to rise by 300% to 400% during the 1970s. The increased costs brought back to life an interest in finding alternative ores for producing alumina. Interest in alternative ores had subsided during the 1960s and early 1970s because of new bauxite deposits developed in Australia and Guinea. The Soviet Union had used non-bauxitic ores for decades out of strategic necessity.²³

Most research on non-bauxitic ores focused on clays that were highest in alumina content and were easily mined. The alumina content ran as high as 40% in Georgia kaolin and 30% in Idaho clays. By September 1977, the U.S. Bureau of Mines, in conjunction with Kaiser Aluminum, had investigated six processes for processing clay, anorthosite and alunite involving use of acid, crystallization, lime-sintering or roasting, and Bayer extraction. The Bureau of Mines focused mostly on kaolin, which was common throughout the Lower 48 states. Idaho clays and Georgia kaolin at Anaconda's pilot plant were calcined and then leached with hydrochloric acid to dissolve the aluminum and iron. The solution was roasted, leaving ferric oxide and alumina, and the hydrochloric acid was recycled. The iron was separated by caustic soda digestion or by soda sintering. Anaconda announced it was nearly ready to build a commercially operating plant when it chose instead to enter into a partnership with Kaiser and Reynolds in 1966 to build a 950,000 ton-per-year alumina refinery in Jamaica. The clay-to-alumina pilot plant was closed down.²⁴

One country that relied on using alumina-bearing clays to produce aluminum was Germany during World War II. Germany turned to its scientists during war-time to find a way to produce a number of important resources by synthetic means, including petroleum products from coal.²⁵ In the U.S., the Olin Corp. acquired Kalunite Inc. of Salt

Lake City in 1943 in an effort to find a more secure alternative to foreign bauxite. Kalunite Inc. had been developing new ways to make alumina from alunite. Olin used nearly \$5 million of Defense Plant Corporation funding to build a processing plant near Salt Lake City capable of producing 26,000 tons of alumina per year. The plant was completed in 1943 and was expected to begin operation by 1944. At the end of World War II, Olin was given an option to purchase the plant, the first such war-surplus industrial plant offer by the government at war's end.²⁶ To put that 26,000 ton-per-year production figure in context, conventional U.S. alumina refineries during World War II were producing more than 4 million tons of alumina per year.²⁷ On March 20, 1961, the Olin Mathieson Chemical Corp. announced that it had discovered a commercially viable way to make alumina from clay at its new \$7.5 million research center in New Haven, Conn. Olin's pilot plant converted aluminum sulfate into alumina.²⁸ But the process was never put into operation on an industrial scale.

Another country that needed aluminum for military purposes but lacked large bauxite reserves was the Soviet Union. The Soviets experimented with ways to produce alumina from non-bauxitic ores in the 1950s. The first experiment employed nepheline, an ore associated with phosphate-bearing rock, and took place on the Kola Peninsula near Kirovsk. The limited success on the Kola Peninsula led to construction of an 800,000 ton-per-year alumina plant in Siberia near Achinsk, but the Achinsk plant was never successful. The experiment's failure was made public in 1976.²⁹ In June 1973, the National Steel Corporation confirmed that it was quietly conducting negotiations with the Soviet Union for access to a new process for converting alunite into alumina. The company, which was a part owner of the NSA-Southwire aluminum smelter in Hawesville, Ky., hoped to take advantage of U.S. alunite deposits at a plant in Cedar City, Utah. Several U.S. companies had taken an interest in the advanced processes used in the Soviet Union's metals processing industry.³⁰

In January 1973, National Steel joined Earth Sciences Inc. of Golden, Colo., to develop alunite as an alternative to bauxite for alumina production. Earth Sciences was mostly made up of graduates from the Colorado School of Mines who had spent 1970 through 1973 exploring alunite deposits in Utah, Arizona and Nevada, and the company held

title to their findings. A spokesman from Reynolds Metals said his company and others were familiar with the Soviet process for alunite, although the U.S. embassy was unaware of the NSA-Southwire negotiations.³¹ In June 1974, the Kaiser Aluminum and Chemical Corp. Chairman Edgar F. Kaiser reportedly traveled to the Soviet Union in an attempt to obtain licenses for Soviet technology used to produce alumina from clay soils instead of bauxite.³² Despite all these efforts and discoveries, the global aluminum industry continued to depend on the mining of bauxite with high aluminum content, refining of bauxite into alumina with a modified version of the Bayer process discovered in 1888, and smelting of alumina into aluminum by the Hall-Heroult reduction process discovered in 1886.

Smelter energy costs

The main costs of using the Hall-Heroult process to smelt alumina into aluminum include raw materials, transportation, labor and energy, with the cost of electrical power playing a larger role than in other metals processing, smelting and refining. Finding cheap electrical power has often been the deciding factor for aluminum companies considering new plants. The most modern aluminum smelters in 2014 utilized about 13 kilowatt-hours to produce one kilogram of aluminum metal, while the global average was 14 kilowatt-hours per kilogram. Current efficiency was the measurement of the part of the electrical current that actually produced aluminum, rather than being lost as heat in transmission, conversion to direct current or heating reduction pots to keep bath in a molten state. According to Faraday's law, 1 kiloamp-hour of electrical current was needed to produce 0.335 kilograms of aluminum, but only 90% to 96% of this amount was realized in industrial applications. In terms of overall energy efficiency, typical modern aluminum reduction cells were 45% to 50% efficient. Modern reduction pots by the 1980s were computer controlled, with alumina and other chemicals automatically fed into the cells by using point-feeders, but the plants still relied on cranes and large vehicles to replace anodes and tap molten metal. The theoretical consumption of alumina in the Hall-Heroult process was 1.89 kilograms per kilogram of aluminum produced, but the practical figure was 1.93 kilograms because the raw material arriving at smelters often contained some impurities, including oxides of sodium, calcium, iron and silica.³³

By 1900, when the emerging aluminum industry was operating in the U.S. and Europe, average energy consumption worldwide ranged from 23 kilowatt-hours per kilogram aluminum produced to more than 50 kilowatt-hours. Energy consumption improved through the century to 19 to 40 kw-hr/kg in 1940, to 17-38 kw-hr/kg in 1960, to 14-19 kw-hr/kg in 2001. The range narrowed at the same time the level decreased owing to the spread of new technology to smelters across the globe. In 1998, energy consumption for U.S. aluminum producers ranged from 14-17 kw-hr/kg. New technologies proposed by the Department of Energy's Office of Industrial Technologies for use sometime in the 21st century included advanced anode and cathode systems expected to consume about 11 kw-hr/kg and alternative technologies expected to consume about 8 kw-hr/kg.³⁴ The U.S. government expressed an interest in improving energy consumption by aluminum smelters. By 1980, about 1 quadrillion BTUs of energy was produced in the U.S. for all uses. About 1% of that total went into the aluminum industry, which purchased about 4% of all electricity generated by U.S. utilities, amounting to about 70 million megawatt-hours annually. The U.S. aluminum industry also consumed 15 million megawatt-hours from its own generating facilities. Significant improvements in energy savings since 1974 had reduced energy demand in the U.S. aluminum industry by more than 10%. These improvements included controlling heat losses in furnaces, reducing electrical use in potlines, employing new ways to use raw materials and increased recycling of aluminum scrap.³⁵

By 1998, the U.S. aluminum industry was the largest in the world, producing more than 22 billion pounds of metal per year worth \$32.7 billion. U.S. aluminum companies employed 85,300 workers with a \$2.7 billion payroll, more than \$1 billion in capital expenditures, a net trade balance of minus \$1.86 billion and a net energy consumption of 360 trillion BTUs.³⁶ North American aluminum smelters in 1999 – including U.S., Canada and Mexico – consumed 63,398 gigawatt-hours of electricity from hydropower, 22,119 gigawatt-hours from coal, 24 gigawatt-hours from oil, zero gigawatt-hours from gas and 1,429 gigawatt-hours from nuclear for a total of 86,970 gigawatt-hours. This included 31,351 gigawatt-hours of self-generated electrical power, 44,770 gigawatt-hours purchased off the grid and 10,849 gigawatt-hours purchased from other sources.³⁷

Of the five top metals produced by industry, aluminum required the most energy (from electricity, coal, natural gas or other forms) – aluminum ingots required 224 million BTUs per ton of metal produced, whereas copper required 112 million, zinc required 65 million, lead required 27 million and steel required 24 million. Energy requirements for the production of one ton of primary aluminum included 2.41 million BTUs for bauxite mining and processing; 44.98 million for alumina refining using the Bayer process; 1.21 million for production of cathodes; 20.83 million for production of anodes; and 174.47 million for electrolytic reduction. With production of cathodes and anodes added to electrolytic reduction, the total for smelting accounted for 80% of the energy requirement to produce aluminum metal. A distinct difference existed between prebake and Soderberg-type reduction plants. Prebake plants consumed significantly more energy and fabrication effort for producing anodes, but prebake plants were more energy-efficient overall. On average, the production of prebake anodes required 20 million BTUs per ton of aluminum produced, compared with only 15.6 million for Soderberg anodes, but this difference was made up with the more efficient reduction pots. Significant gains in energy efficiency at aluminum smelting plants were made by changing from Soderberg to prebake designs, by using larger reduction cells to reduce heat losses, and by reducing resistance in the cathode and anode electrical connections. Pollution control at smelters in 1980 accounted for less than 1% of total energy requirements, or about 2.5 million BTUs per ton of aluminum produced. ³⁸

At a theoretical level, based on the electrolytic chemical reaction taking place within the reduction cell, the minimum amount of energy required to convert alumina to primary aluminum was about 24 million BTUs per ton. In 1980, the Hall-Heroult process averaged only 17% efficiency. Energy savings of 35% to 40% were achieved in the 1970s by increasing the size of reduction cells threefold to reduce heat losses. Another improvement under study in 1980 was the use of refractory hard metals such as titanium diboride as a cathode material to reduce the depth of the molten aluminum inside the reduction cell. About half the energy consumed by reduction pots was wasted by the voltage drop across this pool of molten aluminum. In conventional pots with a carbon-based cathode, the molten aluminum pool was considered unstable, so a large enough depth was maintained to

prevent short-circuiting or the pool rolling over. Another improvement at smelter plants was the use of more efficient solid-state silicon rectifiers instead of mercury arc rectifiers to convert alternating current from the power transmission grid to direct current for the potlines. While aluminum production consumed large quantities of energy, it provided savings over other materials in consumer products – for example aluminum’s high strength-to-weight ratio and the relative ease with which it could be recycled. In 1979, the average U.S. car contained 118 pounds of aluminum. Over the lifetime of the average car, about 290 gallons of gasoline would be saved by the weight reduction brought by the use of aluminum over other materials.

39

Barry Welch, a chemistry professor at the University of Auckland in New Zealand, reviewed the technical limits of new processes for aluminum smelting in a 1999 journal article. The driving cost interests for aluminum production included reducing electrical power costs, reducing capital costs for the aluminum process-reactor and environmental considerations, including compliance costs for fluoride emissions at that time and greenhouse gases looking into the future. Environmental compliance for fluoride emissions could amount to about 10% of the cost of metal production. Welch found in his review of analysis and discussion of proposed smelting alternatives that fundamental energy requirements were the same for all options because they started with the same basic ingredient – alumina – and finished with the same product – molten aluminum metal. The basic ingredients for the alternative processes still included alumina, electrical power, some carbon and possibly some other recyclable chemicals. The output was still aluminum and carbon oxides.⁴⁰

Welch noted that a number of papers had been written about aluminum smelting technologies in the 1980s claiming an achievement of 12.5 kilowatt-hours per kilogram of aluminum produced. Smelting alternatives had been discussed over the past two decades, he noted, including the ASP chloride process, the carbothermal process, the sulfide process, the inert anode or oxygen evolution cell, and the drained cathode or wettable titanium diboride process. The industry also had shifted to high amperage technologies that used more energy but were more cost efficient. The four key elements to a successful

alternative smelting process included a satisfactory chemistry path, a suitable and practical operable reactor system, a suitable material for constructing reactors and electrodes, and the ability to meet stringent environmental standards without driving up costs. Welch concluded that the economic gains of these alternatives were not likely to be dramatic, and the development costs would be considerable – “so much so that it is impractical for any one company to do it alone.”⁴¹ In a March 2000 talk, Welch said advances in the design and operation of Hall-Heroult cells over the past quarter century ensured that the process would continue to predominate over alternative processes. With high current efficiencies and low margins for error in modern cells, further refinements were possible with marginal gain in economic performance, he concluded.⁴²

From hydro to nuclear

Dependence on a large share of the nation’s electrical supply put the U.S. aluminum industry in a vulnerable position as the nation’s population and per capita consumption of electrical power continued to increase. In a Feb. 1, 1995, report for the Engineering and Mining Journal, James V. Thompson predicted that primary aluminum smelting would shift away from the U.S. to other areas of the world. “The long-term trend for the United States and perhaps Europe and Japan is for the aluminum smelting industry to become established offshore in countries that have both bauxite and power,” he wrote. “Some countries with large reserves of petroleum and natural gas in the Middle East have gone into aluminum smelting with imported alumina. The United States and Europe with high labor costs, environmental harassment, high energy costs and no bauxite may soon be relegated to aluminum fabrication only. It is doubtful that anyone has any plans to start a new alumina plant and aluminum smelter in the United States anytime soon.”⁴³ By 1998, about two-thirds of all the aluminum smelters in the world derived their electrical power from hydroelectric dams. Exceptions included nuclear reactors, such as at Dunkerque in France, or abundant low-grade coals, such as in Australia and South Africa.⁴⁴

Alcoa recognized the importance of hydropower to aluminum production early on, building a smelter at Niagara Falls in 1895 when the first major hydroelectric plant in the U.S. went into operation. Alcoa

became the power company's first customer. ⁴⁵ Alcoa continued to look for places to generate hydroelectricity in the U.S. and turned to North Carolina and Tennessee in 1910. Alcoa purchased the Knoxville Power Co., Tallassee Power Co., Western Carolina Power and Transportation Co., Union Development Co., and Union Power and Water Co. and put them together as the Tallassee Power Co., which later became known as Tapoco. Alcoa also built several dams on the Yadkin River after taking over the unfinished L'Aluminium Francais smelter project in Badin, N.C., in 1915. Alcoa Power Generating Inc. continued to sell power from the Yadkin River dams after the Badin smelter shut down permanently in April 2010. ⁴⁶

In 2013, the North Carolina government sued Alcoa, claiming that when Alcoa permanently closed its aluminum plant in Badin, the ownership of the dams on the Yadkin River should have gone to the state. "The benefits of the Yadkin River belong to North Carolina's people," then-Gov. Pat McCrory said at the time the lawsuit was filed. "We should be able to use it for North Carolina water needs and to create North Carolina jobs." A federal judge ruled against the state in 2015 after Alcoa was able to prove it owned portions of the Yadkin River where it operated the four hydroelectric dams. A federal appeals court upheld the lower court's ruling in April 2017. By that time, the four dams had a new owner. On Feb. 2, 2017, Cube Hydro Partners had closed a deal with Alcoa to acquire the High Rock, Tuckertown, Narrows and Falls dams for about \$238 million. Cube Hydro already owned 15 hydroelectric dams in New York, Pennsylvania, West Virginia and Virginia. Arconic, the new business branch created by Alcoa's reorganization, was expected to receive another \$5 million from the sale of the dams. ⁴⁷

Alcoa's investments in hydroelectric facilities also took place in underdeveloped countries, including Dutch Guiana, which provided about 75% of the bauxite used by U.S. aluminum producers during World War II. In 1958, Alcoa, the Dutch Guiana minister-president and the Dutch governor signed the Brokopondo Agreement, named for a town located just north of the proposed Afobakka Dam. The plan was to build an alumina refinery and a hydroelectric dam to power a smelter all at one nearby location. The plans were drafted at Alcoa's Engineering Department at its offices in Pittsburgh. Construction of the

1.2-mile long 189-megawatt dam lasted from 1959 to 1965 and created a 618-square-mile reservoir that displaced about 6,000 people in 43 villages. The Brokopondo Agreement left it up to the Dutch Guianese government to “remove the population, the buildings and other property from the reservoir area.” Electrical power from the dam also was used to light and power Paramaribo, the country’s largest city. The Brokopondo Agreement provided a small portion of the dam’s electrical output to the Dutch Guianese government at 0.4 cents per kilowatt-hour. The industrial complex operated under the name Suralco. The new industrial complex’s first ingots of aluminum metal were poured in 1965, and the first alumina exports were sent to Vancouver, B.C. that same year. Per capita income in Dutch Guiana increased 10% that year, and a middle class began to evolve in the underdeveloped country. ⁴⁸

By 1975, when Dutch Guiana became Suriname and independent of The Netherlands, about 5,000 workers were employed by Alcoa. Many of the workers belonged to a union and their families enjoyed free education and health care. A six-year long civil war in Suriname ended in 1992, and Suralco was able to keep its plants operating during that time. Suralco became part of Alcoa World Alumina and Chemicals, a joint venture created in 1995 by combining Alcoa’s bauxite, alumina and alumina chemicals business with related businesses owned by Alumina Limited of Australia. Alcoa owned a controlling 60% stake in the venture. Economic conditions in Suriname changed as a result of several factors, including depleted bauxite reserves, rising energy costs and the overall transfer of global aluminum production from the U.S. to Asia and the Middle East. Alcoa chose to shut down the smelter, which used most of the dam’s power, in 1999. The company cited environmental concerns and the smelter’s small size. Alcoa also said it wanted to use the power available from the dam instead of oil to produce steam for its alumina refinery, but the Suriname government wanted to purchase the power made available by closing the smelter. To offset the high cost of oil used for its refinery, Alcoa chose to sell the available power from the dam to the Suriname government based on the cost of oil, not the cost of operating the dam. ⁴⁹

By 2010 or 2011, the Suriname government was paying more for power from the Afobakka Dam than Suralco was paying the

government in taxes and other revenue. According to a financial statement Alcoa filed with the U.S. Securities and Exchange Commission in 1996 about its Suriname holdings, “current mine reserves... are expected to be depleted in 2005.” Alcoa announced in 1997 its forecast that easily-obtainable bauxite deposits in Suriname would become depleted. Suralco and government officials had studied lower-quality bauxite reserves in the western part of the country, but a cost-effective way to transport the ore had not been discovered, and Alcoa said its refinery was not equipped to process the lower-quality ore. In 2002, Alcoa entered into a mining and refining venture in Suriname with BHP Billiton in which the partners agreed to spend up to \$8.5 million over two years to develop the bauxite reserves in western Suriname. Alcoa also said it would examine whether to build another dam and a smelter complex near the western reserves. One former Suralco manager said he believed the western bauxite reserves could be economically developed, but Alcoa management had lost interest after management of the Suriname operations was transferred from offices in North America to Brazil. Suriname government officials also said they believed Alcoa had neglected opportunities in Suriname to keep the plants operating. In October 2015, Alcoa and the Suriname minister of natural resources signed a nonbinding memorandum of understanding outlining what steps Alcoa would take if it closed its operations and left the country. Alcoa agreed to clean up its mine and industrial sites to U.S. standards and consider future mining of bauxite reserves in western Suriname. A new alumina refinery located near the western reserves, however, could cost \$3 billion or more. A critic noted that this was the fifth feasibility study of the western reserves and believed Alcoa was just buying time and didn’t want any other company to acquire the bauxite deposits.⁵⁰

According to the October 2015 nonbinding MOU, Alcoa also agreed to give the Afobakka Dam to the Suriname government in 2019, which was 13 years before the Bokopondo Agreement was slated to end. Until then, the Suriname government would have to continue to purchase power from the dam at prices based on the comparable cost of oil with an annual \$3 per barrel increase. The National Assembly rejected the agreement in November 2015. One member of the assembly demanded that the dam be handed over to the government immediately. Another problem facing Suriname was that U.S.

aluminum production had dramatically decreased by 2015, and the cost of shipping bauxite or alumina to plants in Asia or the Middle East was cost-prohibitive. A metals analyst said he doubted if there was even a 5% chance that a new bauxite mine or refinery would be built in Suriname because of overcapacity in China. Suriname business supporters believed the existing Suralco refinery could be upgraded and become a catalyst for future economic growth. But in January 2017, Alcoa announced it would permanently idle its refinery in Paranam, Suriname. The refinery had been shut down since late 2015. Alcoa said the refinery's costs were about 75% higher than its competitors. The Suriname economy, with 560,000 people, was already in a "crisis" mode in 2015, with a 10% decline in gross domestic product and 55% inflation, along with strikes, power outages and floods. ⁵¹

In the U.S., four aluminum smelters were built in the Pacific Northwest to utilize the region's abundant hydropower during World War II, joining two others already operating on the Columbia River. Four more smelters were built in the Pacific Northwest in the two decades following the war, including the Anaconda Aluminum Co. smelter in Columbia Falls, Mont. built near the new Hungry Horse Dam and the headwaters of the Columbia River. But in 1950, with the outbreak of the Korean War, another period of expansion began in a different part of the U.S. With hydroelectric capacity in the Pacific Northwest tapped out, aluminum production moved to the Ohio River Valley, where coal and natural gas were used to generate the electrical power needed for aluminum smelting. The location also benefited from river transport and increased production of alumina and bauxite in the Caribbean, as well as proximity to fabricating companies. By 1958, only 30% of the aluminum produced in the U.S. came from the Pacific Northwest. Cheap electrical power in the Pacific Northwest, once a drawing factor for aluminum companies, became short in supply, and increased capacity meant increased electrical power costs after 1950. ⁵²

The development of new aluminum smelting plants in the Ohio River Valley proved that the industry no longer needed to rely on hydropower, atomic energy, gas or oil for electrical power. The Kaiser smelter in Ravenswood, W.Va., and the Ormet smelter in Hannibal, Ohio, were powered by coal-fired generating plants. Electrical power in

the Pacific Northwest in the 1950s cost about \$2.20 per megawatt-hour compared to \$4 in the Ohio River Valley, but the advantages of cheap river transportation along the Ohio River offset the difference and made coal a competitive source of energy. Furthermore, technical improvements had reduced the amount of coal needed to produce electricity from 1.29 pounds per kilowatt-hour in 1946 to 0.96 pounds by 1955. Behind the decision to build the two large smelter plants in the Ohio River Valley was a six-year study by the American Gas & Electric Co. that found costs for operating gas-fired power plants were expected to increase while most practical hydropower sites were already developed.⁵³ The trend toward coal continued across the globe – by 2014, coal had become the energy source for more than half of the aluminum produced in the world.⁵⁴

The U.S. aluminum industry dominated the global aluminum market prior to 1980 by controlling more than 40% of the world's capacity. By 1987, that position had changed as aluminum imports from Canada doubled during the first half of the 1980s, and nearly 20% of U.S. aluminum capacity was permanently closed between 1978 and 1987. Three economic factors caused this change – higher energy prices, weak market demand and the strong U.S. dollar. During the 1970s, rapidly rising energy costs often linked to oil prices drove up the cost of power to U.S. aluminum plants. One effect was that construction of additional U.S. aluminum production capacity was deferred and in some cases redirected to Canada, Australia and Brazil. No new aluminum smelting capacity was built in the U.S. between 1980 and 1987.⁵⁵

In the Pacific Northwest, power rates increased from \$2.50 per megawatt-hour in 1978 to \$25 by 1984, a 1,000% increase largely attributed to cost over-runs at nuclear power plants, some of which were never built. In southeastern U.S., the price of power from the Tennessee Valley Authority increased from \$20 per megawatt-hour in 1978 to more than \$37 by 1984, but because of take-or-pay clauses, power for some plants increased to about \$88 by 1984. Along the Gulf Coast, where cheap natural gas in 1983 had enabled average power rates lower than in the Pacific Northwest, rising natural gas prices forced power prices up to \$40 per megawatt-hour, and four out of five smelters in that region permanently closed by 1987. In the Ohio Valley,

aluminum smelters using coal-fired power fared much better, with power rates ranging from \$18 to \$30. While energy prices increased as a result of the energy crisis in the 1970s, global demand for aluminum fell by 12% between 1980 and 1983, compounding the power cost problem.⁵⁶

The U.S. aluminum industry embarked on an energy-saving program in 1974 with the goal of reducing energy consumption by 10% by 1980, using the year 1972 as a base year. The industry achieved its goal two years early in 1978 and set another goal of reducing energy consumption by an additional 10% by 1985. The most significant improvement was better “housekeeping” or energy-management measures, as well as certain equipment modifications. Housekeeping measures included shutting down standby furnaces, eliminating steam and heat leaks, and lowering potline temperatures when possible. Some capital investment was required to reduce energy losses in anode and cathode electrical connections.⁵⁷

But the energy-savings effort paled when compared to enormous smelter projects constructed in the Mideast, where energy availability was not a problem and plants could be built from scratch. These new plants featured the most modern smelting equipment and were located next to ocean shipping terminals. By November 2001, the Dubal smelter in Dubai and the Alba smelter in Bahrain on the Persian Gulf boasted the lowest aluminum smelting costs in the world. The average aluminum-smelting cost worldwide in 2001 was about \$1,100 per ton, but Dubal and Alba averaged between \$750 and \$800 per ton. The cost for power at the Dubal and Alba smelters amounted to only 12% to 15% of the overall cost of production, compared to a global average of 20% to 30%. Natural gas, which was plentiful in the Persian Gulf, was used to generate electrical power. The Persian Gulf states accounted for about 4% of world aluminum production. Feasibility studies were being conducted for additional aluminum plants in Saudi Arabia, Qatar, Kuwait and Oman.⁵⁸

The Middle Eastern aluminum plants also benefited from vertical integration in a single location. The aluminum facility at Ras Al Khair in Saudi Arabia, a joint venture between Alcoa and the Saudi Arabian Mining Co., included a 1.8 million ton-per-year alumina refinery, a 740,000 ton-per-year aluminum smelter and a 380,000 ton-per-year

rolling mill, all powered by a 1,400 megawatt gas-fired power plant and located at a shipping terminal on the Persian Gulf. Each of the four potrooms was three-quarters of a mile long and held 180 modern reduction pots. The Al Baitha bauxite mine was connected to Ras Al Khair by a rail line. The vertically-integrated facility, which produced metal in May 2015, was expected to be the lowest-cost aluminum complex in the world.⁵⁹

The anode problem

By 2000, the typical modern aluminum smelter used prebake anodes, and computer-controlled point feeders automatically injected alumina into the molten bath. In the traditional Hall-Heroult process, each reduction cell operated at about 4 to 4.5 volts, which was considerably higher than the theoretical decomposition voltage of alumina. The additional voltage was caused by various unavoidable industrial voltage losses that in turn generated heat and maintained the electrolyte temperature.⁶⁰ The use of electrical resistance to maintain process temperature when smelting alumina into aluminum was patented by Charles S. Bradley in 1883, three years before Charles Martin Hall or Paul L.T. Heroult discovered the electrolytic process still used to produce aluminum. Without internal electrical resistance heating, an external source of heat would be needed to keep bath molten in reduction cells, such as natural gas burners.⁶¹

Some additional heating in the reduction cell was caused by the burning of the anode carbon. For every three atoms of oxygen removed from a single alumina molecule, three atoms of carbon were consumed from the anode to create carbon monoxide, which was converted to carbon dioxide in pot gas system burners. Carbon loss by anodes amounted to about 1.5 kilograms of carbon dioxide per kilogram of aluminum produced.⁶² Modern cells could handle from 100,000 to 300,000 amps in direct current. Older reduction cells using the Soderberg anode design had a low current efficiency of about 86% to 90%, compared to 95% with the prebake anode design. Other design or process problems could reduce current efficiency. Anode effects commonly took place when the alumina concentration in the bath dropped below a threshold value, causing a gas bubble to form between the anode and the bath that increased cell resistance and caused cell voltage to climb to 40 volts or higher. In addition to

consuming unnecessary power, anode effects produced perfluorocarbons, a powerful greenhouse gas. In the most ideal aluminum smelter plant with computer-controlled alumina feeding, anode effects could be reduced from the normal one per day per cell to one every two months.⁶³

The constant consumption of carbon anodes in the early use of the Hall-Heroult process led to development of a new type of anode patented by Carl Wilhelm Soderberg, an engineer from Christiania, Norway, on Dec. 4, 1917. The typical process for creating electrodes at that time involved mixing finely ground raw materials, such as coal, coke or graphite, with a suitable binder, such as coal tar pitch, and then putting the mixture into a mold for baking in a furnace until all the volatile products were driven off and the electrode had the desired density. These prebake anodes needed to be replaced as they burned away. Soderberg's innovation was to build one large single anode of unbaked raw materials. The heat from the reduction process would bake the materials into a hard carbon anode, and carbon paste briquettes could be added from the top to replenish the anode.⁶⁴ The Soderberg anode went into wide use in the aluminum industry in 1923 and was considered the first important breakthrough invention for the industry since the Hall-Heroult discovery in 1886.⁶⁵ Soderberg-type anodes were installed at the Anaconda Aluminum Co. smelter in Columbia Falls when it was built in 1955. The 600 reduction cells were converted to Sumitomo technology in the late 1970s to improve energy efficiency and to reduce fluoride emissions, but they continued to use Soderberg anodes, and the open-topped anodes and lack of hoods over the cells made the anodes a major source of secondary emission problems in potrooms.

The aluminum industry eventually changed back to prebake anodes. The main reason was energy savings. During the 1940s, Alcoa built seven aluminum smelters for the U.S. government using a prebake cell design called the Alcoa N-40. The design was developed at Alcoa's Niagara Falls smelter and was a 50,000-amp, end-riser, center-work design. Smelters built in the 1940s that employed this design were located in Brooklyn and Massena, N.Y.; Riverbank, Calif.; Vancouver and Spokane, Wash.; Jones Mills, Ark.; and Troutdale, Ore. By 2000, the Vancouver and Spokane smelters continued to use the N-40 cells with

modifications. ⁶⁶ During the 1950s, Alcoa built potlines at its smelters in Rockdale, Texas, and Wenatchee, Wash., using prebake reduction cells called the T-51 end-riser design. Later an enlarged version of the T-51 called the P-75 was installed by Alcoa at Massena. Another prebake design called the P-88 was installed by Alcoa at its smelter in Warrick, Ind. During the 1960s, the first quarter-riser design called the P-100 was installed at Rockdale, Wenatchee and Warrick. By 2000, Alcoa was using the P-155 design at five smelters, including Badin, N.C., and Sebree, Ky. The P-155 design employed 170,000-amp, two side-riser, point-feeder technology. The A-697 cell design with 180,000-amp, two side-riser, point-feeder technology developed in 1977 was used at the Mt. Holly, S.C., New Madrid, Mo., and Sao Luis, Brazil smelters. ⁶⁷

In 2000, the U.S. aluminum industry consumed about 1.6 million tons of carbon anodes. The theoretical minimum requirement for consumption of carbon in the smelting of alumina into aluminum was 0.33 kilogram of carbon per kilogram of aluminum produced. In practice, the figure was about 0.45 kilograms, about 35% above the theoretical minimum. Excess carbon usage resulted from the need to protect the iron studs inside the anodes by removing the anodes before they were entirely spent, and from air burning and dusting. Prebaked anodes accounted for more than 82% of anode production in the U.S. in 2000. “New prebaked anode reduction cells have surpassed Soderberg anodes in terms of current efficiency and emission control,” the U.S. Department of Energy’s Office of Industrial Technology reported. “No new Soderberg cells are being built, and those that exist are progressively being replaced, converted or shut down.” Electrical resistance in Soderberg anodes was about 30% higher, and because they were open at the top, Soderberg anodes had a greater dusting potential than prebake anodes. Additional energy was lost in emission control for the 5% to 15% of volatile organic content of green coke used in Soderberg anodes, including wet and dry scrubbing systems. ⁶⁸ According to a 2014 journal article by Halvor Kvande and Per Arne Drablos, briquettes for Soderberg anodes contained twice the amount of coal tar pitch as used to manufacture prebake anodes. Soderberg anodes were difficult to enclose, and polycyclic aromatic hydrocarbon fumes from the self-baking anode escaped into the potroom, including benzo(a)pyrene, a suspected carcinogen. ⁶⁹

According to a September 2003 article by Helge Forberg in ENAL Newsletter, the high cost of converting aluminum plants from Soderberg to prebake anodes could offset any advantages from improved energy efficiency or lower-cost pollution control equipment. Despite low metal prices at the time of the article, the high cost of building new smelters made upgrading existing Soderberg pots a more economical alternative, he said. The debt service for a new smelter with the latest equipment ran to about 36% of total operating costs, a record high. The operating performance of Soderberg reduction pots was good 50 years ago, Forberg noted, when vertical-stud Soderberg pots were introduced during a time of rising aluminum demand, and smelters with Soderberg pots had lower operating costs than the typical plant with prebake pots. The success of a plant with Soderberg anodes depended on the skill of the foremen and operators because Soderberg-type reduction pots were generally operated manually. Soderberg pots acquired a bad image over 25 to 30 years of operation because they weren't run well, Forberg said. ⁷⁰

During the 1970s and 1980s, many Soderberg pots were upgraded with Sumitomo technology, which improved performance, increased production and reduced emissions. This upgrade helped to extend the economic life of many old smelters and showed that revamping of old Soderberg plants could make them competitive, assuming the plants had acceptable power contracts, Forberg said. Properly operated Soderberg pots with good gas skirts and Sumitomo-type bar-breakers to open up the crust could record 95% gas collection. A pot equipped with point feeders could do even better, he said. Using a bath containing lithium would reduce fluoride output even more. A new Soderberg smelter plant with a capacity ranging from 50,000 to 100,000 tons per year could be built without the severe cost penalty associated with a new prebake plant because Soderberg plants did not need a baking furnace and rodding room to create the prebake anodes, which could account for 20% of the cost of a new prebake plant. "Additional cost savings could possibly be found by selecting a simplified plant layout similar to the Harvey Aluminum smelters built many years ago and by basing the operation on the purchase of anode paste," Forberg said. "However, it has to be recognized that the Soderberg pot has some inherent handicaps compared to a prebake pot." ⁷¹

By 1999, according to a report by Gean Overseas Inc., aluminum smelters with Soderberg pots continued to operate around the world, but many were converting to prebake pots. A smelter in Ardal, Norway, built in 1958 and then converted to the Sumitomo process was switching to prebake pots. Analysts expected the aluminum smelter in Mosjoen, Norway, would convert from Soderberg pots to point-feeder prebake pots. The aluminum smelter in Lista, Norway was converting side-worked Soderberg pots to point-feeder technology. The Sunndalsora smelter in Norway was considering leveling its Soderberg line to make room for new prebake lines. An aluminum smelter in Sundsvall, Sweden, with Soderberg pots was adding process-controlled point-feeder technology to its vertical-stud configuration. The Arvida aluminum smelter in Canada planned on shutting down its horizontal-stud Soderberg potline when its new Alma smelter went online. The Baie Comeau smelter in Canada planned to eliminate its Soderberg pots once an expansion project was completed. The giant Krasnoyarsk smelter in Russia was not expected to convert to prebake technology. The giant Bratsk smelter in Russia had 12 potlines using vertical-stud Soderberg pots that were built between 1966 and 1976 and was expected to add a new 105-kiloamp Soderberg potline. The Volgograd aluminum smelter in Russia was completely converting from Soderberg to prebake pots because of its high operation cost, and two of the Soderberg potlines had been closed for good.⁷²

According to the Gean Overseas report, management at the Novokuznetsk smelter in Russia planned to upgrade its horizontal-stud Soderberg potlines to prebake technology with support from Alcoa, thereby doubling its output. The Shelekhovo smelter in Russia, using VAMI-designed 130 kiloamp Soderberg pots, was being looked at by Kaiser and Alumax for a \$600 million upgrade. The small Kandalaksha smelter in Russia was considering increasing its overall capacity while keeping its Soderberg pots operating using Reynolds improvements. The Sumgait smelter in Azerbaijan was considering converting its Soderberg pots to prebake technology. The aluminum smelter in Lanzhou, China, was considering expanding with prebake pots that would eventually replace the plant's older Soderberg pots. Owners of the Hirakud smelter in India were contemplating whether to build a new prebake plant or to double its smaller horizontal-stud Soderberg potline. The Indalco smelter in Belgaum, India, had already shut down

its small Soderberg potlines due to high energy costs. The San Ciprian smelter in Spain was expected to replace its Soderberg pots with prebake pots. The Seydisehir smelter in Turkey was debating converting its pots from Soderberg to prebake technology, but analysts believed the plant would simply add point-feeders to its vertical-stud pots. The Bayside, South Africa, smelter was expanding its existing Soderberg potlines. At Goldendale, Wash., point-feeder technology from Norsk Hydro was being added to the smelter's vertical-stud Soderberg pots. ⁷³

On Jan. 23, 2004, Alcan announced it was permanently halting aluminum production at four Soderberg lines at its 60-year-old Jonquiere smelter in Quebec. "Despite our successful efforts over the years to bring the Jonquiere Soderberg lines up to today's environmental and technological standards, the reality is that this technology has a limited life span," Alcan President and CEO Travis Engen said. The 90,000 ton-per-year Soderberg lines at Jonquiere were the least efficient and had the highest production costs and most difficult environmental challenges of all Alcan lines, Engen said. The remaining prebake lines at Jonquiere would not be affected. ⁷⁴ Beginning in 2009, the Quebec government made it known that environmental legislation would be enacted in 2015 banning the use of Soderberg reduction cells at aluminum smelters. As a result, Alcan closed its Beauharnois smelter in 2009. Alcoa later closed a potline at its Baie-Comeau smelter to be replaced with prebake cells. Rio Tinto Alcan announced in 2011 that it would spend \$300 million modernizing its Kitimat smelter in British Columbia. The first phase of that project included 38 reduction pots using Alcan's AP60 technology, with a capacity of 60,000 tons per year slated to begin production in 2013. The AP60 technology was considered the most environmentally friendly design for primary aluminum production and increased metal output by 40%. ⁷⁵

Perfecting the process

In February 1962, the American Institute of Mining, Metallurgical and Petroleum Engineers reported on research directed at improving or replacing the two basic processes used to make aluminum - the Bayer process used to make alumina from bauxite and the Hall-Heroult process used to make aluminum from alumina. The cost to build a Hall-

Heroult aluminum reduction plant in 1962 was estimated to run about \$700 to \$1,000 per ton of aluminum produced per year. In 1960, Alcan announced development of a new process that would convert bauxite directly into aluminum, bypassing the need to make alumina. A pilot plant to employ the new process was scheduled for completion in early 1962. Meanwhile, scientists in Australia were investigating ways to use sulfuric acid to produce alumina from low-grade bauxite ores. Scientists in Chattanooga, Tenn., were studying ways to use an electric furnace to convert bauxite directly into a metal alloy containing 65% aluminum that could then be smelted into a purer form of aluminum. In December 1961, Kaiser and British Aluminum announced progress in their joint development of new materials for building cathodes for aluminum reduction cells using carbides and borides of titanium and zirconium. The new cathode materials would increase electrical efficiency and increase cell production by 15%. Other cell improvements studied by Kaiser and British Aluminum included using silicon carbide side walls and a new electrolytic bath with 5% lithium fluoride. The improvements were said to increase aluminum production by up to 37.8% with a 27% increase in electrical use. ⁷⁶

Between 1980 and 2000, aluminum companies tried and abandoned one new technology after another in an attempt to smelt aluminum without depending upon the Hall-Heroult process. Among these alternative processes were the ASP chloride process, the carbothermal production option, the use of drained-cathode technology using a wettable titanium-diboride coating, and other methods involving potential materials for inert-anode technology. Among these new ideas was the use of hydrogen dissolved in molten alumina at 700 to 1,000 degrees Celsius. During the early 1980s, a flood of technical papers claimed aluminum could be produced using less than 12.5 kilowatt-hours per kilogram of aluminum produced. Alcoa Laboratories announced in January 1980 that it was investigating ways to smelt alumina that would be more energy efficient, less polluting and require less manpower than the Hall-Heroult process. By 2000, the emphasis was on high-amperage technologies that were less energy efficient but more cost efficient. Plants using new technologies routinely saw 96% efficiency ratings, while older plants could be retrofitted to reach 95% efficiency. The goal for most new technologies was lower cell voltages while maintaining adequate superheat to prevent sludge formation and

electrolyte-concentrations gradients. Over 50 years, cell voltages had been steadily lowered until they reached the 4.1 to 4.2 volts range, at least for cells larger than 200 kiloamps. Computers helped improve cell technology through modeling and process control. The result was not only new cell designs but improvements to older cell designs. Experts felt improvements were still available for reduction-cell technology, but there were diminishing performance gains.⁷⁷

Attempts to create an aluminum reduction cell with an inert anode, instead of a carbon anode that constantly burned away, began in 1886 when Charles Hall tried to use copper anodes. Hall, however, found the copper quickly dissolved in the molten electrolyte. More than a century later, Alcoa announced its scientists were still studying inert anodes. In 2002, Alcoa CEO Alain Belda announced that “the science is proved, so we have an inert anode, but we have not proved the commercial aspects.” The announcement spurred other researchers to try to discover the process Alcoa used, but Alcoa’s work went unpublished and was expected to stay that way for proprietary reasons. The practical goal would be to find material for an anode that could last as long as the reduction cell itself, but conventional wisdom held that all materials had a finite solubility in the corrosive molten cryolite bath at 960 degrees Celsius, and an inert anode was not likely to be discovered.⁷⁸ Over the years, several types of multi-polar electrolytic processes were proposed to replace the bi-polar Hall-Heroult process, but they all assumed a non-consumable or inert electrode could be found. Various compounds had been considered for the process, including aluminum chloride in the ASP process, aluminum sulfide and alumina.⁷⁹

In 1905, Thomas Betts of the U.S. developed a method for aluminum reduction called the three-layer process which did not become an industrial process until 1922. The process, which was also called the Hoopes three-layer process, was used to produce aluminum at a 99.90% purity level. The three-layer process inverted the Hall-Heroult reduction pot design by putting the positively-charged anode at the bottom of the cell and the negatively-charged cathode on top. In addition, whereas the Hall-Heroult process used two liquid layers – molten aluminum on the bottom and molten cryolite on top – the Hoopes cell had a third layer on top of the cryolite that consisted of

high-purity aluminum. The pure aluminum migrated upwards to the negatively-charged cathode and was collected by tapping. Serious technological difficulties, including environmental problems, prevented the process from being utilized until 1932 when the French engineer Robert Gadeau, working for Pechiney, developed a more efficient bath composition and was able to run the process at lower temperatures. Pechiney built an aluminum purifying plant in the French Alps before World War II and by 1980 was able to produce aluminum at 99.99% purity.⁸⁰

The carbothermic process was similar to processes used in the 1880s to produce aluminum-copper alloys with about 15% aluminum. The Cowles Brothers of Niagara Falls produced an aluminum-bronze alloy that was 90 parts copper and 10 parts aluminum by fusing a pile of alumina and copper with electrical current. An abundant supply of the alloy was on the market by 1884.⁸¹ One year after he had discovered the modern method to produce aluminum, Paul Heroult took out another French patent for a process that produced aluminum alloys rather than aluminum metal. A plant using hydropower at Neuhausen, Switzerland, began to produce an aluminum-bronze alloy in 1888.⁸² The carbothermic process called for using heat and carbon to produce aluminum and carbon monoxide in three steps. German scientists in the 1920s were able to produce aluminum-silicon alloys using a similar process with up to 40% to 60% aluminum. About 10,000 tons of these alloys were produced each year up to 1945.⁸³

The first reported attempt to produce pure aluminum with the carbothermic process was made around 1955 by Pechiney, which continued to work on the idea until about 1967 when the research was terminated for technical reasons. Reynolds worked on an electric arc furnace to produce aluminum from 1971 to 1984. Alcan acquired information from Pechiney and continued their research on the idea until the early 1980s. Alcoa tried to develop the carbothermic process to make aluminum-silicon alloys from 1977 to 1982. Alcoa started work on the carbothermic process again in 1998, working with Elkem in Norway.⁸⁴ The carbothermal process was not an electrochemical process – it looked more like the old iron-making blast furnace. Aluminum-carbon would form at lower temperatures than molten aluminum, but the final process temperature was high, about 1,900

degrees Celsius, resulting in heat losses. Carbon monoxide was produced, which was a greenhouse gas. In addition, designing a reactor for the carbothermal process was challenging, and it ranked poorly for energy consumption.⁸⁵

One approach to improving the performance of the Hall-Heroult process was to find the perfect formula for the molten bath. In 1954, Alcoa was the first aluminum producer to begin testing higher concentrations of aluminum-fluoride in the bath in the company's aluminum reduction cells. Work at its Wenatchee, Wash. smelter showed that higher concentrations could improve current efficiency. Further work was conducted at Alcoa's Badin, N.C. plant with even higher concentrations, which led to a disaster as the pots lost their protective edge and "tapped out faster than we could patch them," an Alcoa scientist said. Eleven years later, Alcoa was able to use higher concentrations following experiments at Badin.⁸⁶ Cryolite accounted for about 75% to 80% by weight of the electrolyte in a typical Hall-Heroult aluminum reduction cell. The double fluoride of sodium and aluminum had a melting point of 1,011 degrees Celsius. Aluminum fluoride, which could make up as much as 9% to 12% of the electrolyte bath by weight, was consumed during the normal operation of the cell by three mechanisms. First and foremost, it reacted with the sodium oxide that entered the cell as an impurity in alumina. Secondly, it could be depleted by reacting with any water that entered the reduction cell, which created gaseous hydrogen fluoride that was captured by a plant's dry scrubber system. Thirdly, aluminum fluoride could be lost by vaporization - the most volatile emission was sodium tetrafluoroaluminate vapor.⁸⁷

Alcoa scientists first began to understand the effects of electromagnetic fields from one aluminum reduction pot on another in the early 1950s. Mathematical models for magneto-hydrodynamic calculations were developed that later led to new potroom designs, with side-by-side rather than end-to-end orientation and with anode end risers. Decades later, the new configurations allowed for higher potline current.⁸⁸ Placing the cells transversely rather than lined up end to end compensated for magnetic fields created in the cell, took up less floor space and reduced the length of conductors, which in turn reduced power losses by conductor resistance. Magnetic fields could

be reduced by building the electrical buss bar connections through transverse risers.⁸⁹

Alcoa first tested point-feeder technology at its Wenatchee smelter in 1958, and the technology was used at Alcoa's smelter in Rockdale, Texas, in 1961. Point-feeder technology was developed at Alcoa's laboratory in New Kensington in an attempt to reduce labor costs. As the technology improved over time, it became apparent that point feeders could make aluminum reduction cells more efficient and more environmentally friendly. Small holes were punched in the crust that formed on top of the molten bath at two to six different positions using iron rods driven by fast-acting pressurized air cylinders. Small amounts of alumina were then fed into the holes, which reduced the amount of sludge that formed in the center of the cell. Point-feeder technology was considered one of the most important breakthroughs for the aluminum industry and eventually went into use at every smelter in the world.⁹⁰ The latest version of this technology was the center-worked prebake system which used multiple computer-controlled point-feeders located near the center of the pot between the anode blocks. The system produced much lower secondary emissions in the potrooms.⁹¹

Successes and failures

On Jan. 12, 1973, Alcoa Chairman John D. Harper announced a new electrolytic process using chlorine had been developed that the company claimed would use 30% less electrical power and require less labor for smelting aluminum. Alcoa had spent 15 years and \$25 million studying alternatives to the Hall-Heroult process, Harper said. Aluminum producers consumed about 10% of the total electrical power used by all industry, and energy costs were expected to increase. The new method would not use cryolite, which would eliminate the need to build expensive pollution-control equipment to reduce fluoride emissions. In the new process, alumina would be combined with chlorine in a reactor to make aluminum chloride. A completely sealed reduction cell would convert the aluminum chloride to aluminum metal and chlorine gas. The chlorine gas would be recirculated to make more aluminum chloride. A plant using the new process also could be made smaller. Harper said the new process was successfully tested on a full-scale, and he wanted Alcoa to begin building a 15,000 ton-per-year

commercial plant with a completion date of 1975. That plant would eventually be expanded to 300,000 tons per year, he said.⁹² The process called for dissolving aluminum chloride in an electrolyte consisting of molten sodium chloride, potassium chloride or lithium chloride. The result was aluminum metal and chlorine gas. The process was said to use less anode carbon by employing multi-polar graphite electrodes and run at much lower temperatures, 700 degrees Celsius, and therefore required less heat energy. Alcoa continued to experiment with the chlorine process in 1976 at a pilot plant in Palestine, Texas.⁹³

The new chlorine process ran into problems during the conversion of alumina to aluminum chloride in a fluidized-bed reactor.⁹⁴ The experimental plant was shut down because of the corrosive effects of recirculating chlorine driving up the cost of producing anhydrous aluminum chloride.⁹⁵ The Bonneville Power Administration described another process that used chlorine for producing aluminum from alumina-bearing minerals in July 1976. In the Toth process, an alumina-bearing mineral, such as bauxite or kaolin, was calcined and then chlorinated in the presence of a reductant such as coke. The products were then separated, and the aluminum chloride was reacted with manganese metal to produce aluminum metal and manganese chloride. The manganese chloride was then processed for recovery and recycling of the manganese and the chlorine. Claims were made that the Toth process would reduce the capital cost of new aluminum plants by 50% and consumption of electrical power by 90%. By July 1976, it was reported that progress in research and development of the Toth process had halted, and none of the major aluminum companies felt the process would prove to be commercially feasible.⁹⁶

In fall 1985, Alcoa announced it was abandoning its search for an alternative to the Hall-Heroult process at its Alcoa Smelting Process pilot plant in Texas, which was shut down for a tax write-down of \$138.8 million. As a result, Alcoa showed its first income loss since the Great Depression. According to some experts, the experiment was not a total loss and the chlorine process was still viable, but Alcoa's top management felt that aluminum production was in a downturn all across the global economy. The process had promised to reduce the need for electrical power by one-third, but the project was hurt by

obsessive secrecy, a depleted base of fundamental knowledge and time pressure, which forced it out of the laboratory and into a pilot plant before the process was ready. The project did yield insights into how to improve the Hall-Heroult reduction cell, and by the mid-1980s Alcoa's cells were operating with much improved metal output and reduced electrical power consumption. The fundamental research discovered in the project spun off into the traditional Hall-Heroult pot design. ⁹⁷

In 1994, Kaiser began to experiment with a new type of cathode at its Mead smelter in Spokane, Wash. in cooperation with Reynolds' research and development department. The cathode material was made of titanium diboride plus graphite. The cathode blocks were developed jointly by Reynolds, Kaiser, SGL Carbon and the U.S. Department of Energy's Office of Industrial Technologies and used in prebake pots. According to Kaiser, the higher "wettability" of the cathode meant the anode could be moved closer to the cathode, thus saving 20% in voltage and 10% in overall energy. The process was expected to bring energy consumption down to 1.5 kilowatt-hours per kilogram of aluminum produced at a retrofitting cost of 2.4 cents per pound of capacity. ⁹⁸ Titanium diboride was first promoted as a useful cathode material for aluminum smelting in the 1950s, but the high cost of creating the cathode blocks posed significant economic and practical challenges. Other difficulties were posed by standard operating needs - how to feed alumina to the cell, how to tap cells, how to change out anodes without freezing the bottom of the cell, and how to preheat a cell when starting up. Studies of the oxygen evolution alternative came up with no suitable anode material because of corrosion and contamination by the smelting process. ⁹⁹

Research and development of new technology for the aluminum industry continued to be conducted in partnership with the U.S. Department of Energy's Office of Industrial Technology with the goal of reducing energy consumption and reducing environmental impacts. The U.S. aluminum industry purchased about \$2 billion worth of electrical power annually by 1999, but the average amount of electrical power needed to produce a pound of aluminum had fallen since the end of World War II from 12 kilowatt-hours to 7 kilowatt-hours. ¹⁰⁰ In December 1999, Century Aluminum announced that it had

received a second grant from the Energy Department to study ways to improve the efficiency of aluminum smelters. The Intelligent Pot Control project was a \$2.3 million cooperative study between Century Aluminum, Applied Industrial Solutions and West Virginia University. The project involved using computers and advanced software to control the operating conditions of reduction pots.¹⁰¹

The Energy Department's goals in 2000 included mid-term development of a 13 kilowatt-hour/kilogram of aluminum retrofit cell, long-term development of an 11 kilowatt-hour per kilogram advanced cell, elimination of carbon dioxide emissions, a 20% improvement in Bayer alumina-refining productivity, and development of new uses for wastes and byproducts. Overall goals included a 25% increase in energy efficiency, a 10% reduction in operating costs and a reduction of greenhouse gases by 8 million tons of carbon at 100% production. Midterm goals included use of wettable ceramic-based cathodes, and long-term goals included development of non-carbon anodes, such as a low-temperature inert-metal anode. The Energy Department believed wettable ceramic-based cathodes offered a potential energy savings of 1,500 megawatts per year, assuming full U.S. annual production, a cell efficiency increase of 13% to 20%. Work on wettable ceramic-based cathodes was done in cooperation with Advanced Refractory Technologies, Kaiser and Reynolds. The Energy Department's budget for research into these goals increased from a low of \$1.41 million in 1996 to \$11 million in 2000. The Energy Department worked closely with the Aluminum Association.¹⁰²

By June 2000, significant progress had been reported by Alcoa and Northwest Aluminum in the development of new smelting technologies. The new technologies were expected to lower production costs for primary aluminum by 6 to 11 cents per pound while also reducing environmental impacts. Alcoa's development involved the use of inert anodes, while Northwest Aluminum combined inert anodes with wettable cathodes. The use of inert anodes would eliminate the need for producing carbon anodes, which added 6 cents per pound to the cost of aluminum production and 25% to the cost of new aluminum plants by eliminating the need for prebaked anode manufacturing facilities. Inert anodes would also eliminate the production of carbon dioxide and perfluorocarbons.¹⁰³ In April 2001, Alcoa announced it had

begun the latest testing stage for its new inert-anode smelting technology, and that it planned to have a potline using the new technology operating by the first quarter in 2002. Alcoa started up a single reduction pot using the new technology in April 2001. ¹⁰⁴

One modification to the Hall-Heroult process that was successfully implemented was higher-amperage reduction cells. In 1914, the typical Hall-Heroult cell used 10,000 to 20,000 amp direct current. That increased with new technology to 50,000 amps by 1940, to 155,000 amps at Alcoa's Badin plant in 1963 and 225,000 amps at Alcoa's Tennessee plant in 1969. The reduction cells at the Anaconda Aluminum Co. smelter in Columbia Falls operated at 100,000 amps. The increasing current levels went hand in hand with larger and larger reduction cells, including the popular AP18 design first used by Pechiney in 1976. Eventually the AP18 design cells were able to achieve a world-record 95% current efficiency. Reduction cells grew even larger with the 300,000 amp "superpots," including Alcoa's A817 and Pechiney's AP30 cells. In 1978, Alcoa operated a pilot cell at 280,000 amps at its smelter in Massena. By 1986, Alcoa A817 cells were operating at a smelter in Portland, Australia, but problems led to a magnetic retrofit in 2002. The A817 technology was never used anywhere else due to operational difficulties. Pechiney's AP30 cells began operating in France with 280,000 amps in 1981. The Dunkerque smelter had 264 cells using the AP30 design operating by 1991, and the cells were running at more than 360,000 amps by 2015. Another smelter in France began using Pechiney's AP50 design in 1989 and operated at 500,000 amps. Several Chinese smelters reportedly operated at 400,000 to 500,000 amps. ¹⁰⁵ Companies using Hall-Heroult reduction cells at 175,000 amps in 1980 saw energy consumption between 12.9 and 13.2 kilowatt-hours per kilogram of aluminum produced. By the mid-1980s, a new breed of even larger reduction cells appeared. The trend continued into the 1990s, with reduction cells exceeding 310,000 amps, but they did not achieve the low energy consumption of the smaller 1980s-era cells. ¹⁰⁶

In September 1999, AME Online published results from a survey of aluminum smelters throughout the western world and in China, the former-Soviet Union and Eastern Europe. Upgrading and retrofitting had become a common alternative to building new smelting capacity.

The age of smelters appeared to be less relevant. New developments were bringing industry costs down and increasing capacity overall by 1% per year. AME Online reported that a new technological trend was the use of higher current intensities. The higher current was directly correlated with employee productivity and indirectly with power consumption.¹⁰⁷ In 2010, Rio Tinto Alcan reportedly completed development of a new high-tech aluminum smelting process called AP40 and began using it at the company's smelter in St. Jean de Maurienne in France – the same smelter that had provided a model for the Anaconda Company in 1952 when deciding how to build its aluminum plant in Columbia Falls. The AP40 reduction cells used 400,000 amps and consumed less than 13,150 kilowatts per ton of aluminum produced. Developers needed to address buss bar capabilities, operational quality and process control, with special attention to use of an “operating window” approach to determine the optimal operating point. Benefits included better anode-effect frequency, current efficiency and energy consumption.¹⁰⁸ By 2014, potlines at modern smelters were capable of operating at 1,500 volts and up to 600,000 amps. Reduction cell cathodes typically measured 29.5 to 59 feet long, 9.8 to 16.5 feet wide and 3.2 to 5 feet deep. The depth of the operating cell cavity was much less – about 1.3 to 1.6 feet.¹⁰⁹ By comparison, the aluminum smelter at Columbia Falls ran potlines at 600 volts and 100,000 amps, and pot bottoms were about 24 feet long and 10 feet wide with an 18-inch deep cavity.

In July 2002, Pechiney announced it would provide its environmentally friendly AP30 aluminum smelting technology to several smelters worldwide, including the 500,000 ton-per-year Aluminium Bahrain smelter on the Persian Gulf in Bahrain, which was adding 308,000 tons in capacity; BHP Billiton's Hillside smelter in South Africa, which was adding 132,000 tons in capacity; the Aluminerie Alouette Inc. smelter in Quebec, which was adding 302,000 tons in capacity; and BHP Billiton's 250,000 ton-per-year Mozal smelter in Mozambique, which was adding 500,000 tons incapacity. About 80% of new aluminum smelters worldwide used Pechiney technology.¹¹⁰ Pechiney's AP30 prebake cells used 300,000 amps with larger anodes measuring from 53.8 square feet to 409 square feet resulting in 95% to 96% current efficiency. The AP30 cells also featured magnetic compensation, automatic point-feeders, improved cell hooding, low-ratio bath

chemistry and more mechanization of smelter operations.¹¹¹ On Dec. 15, 2006, Alcan announced plans to spend more than \$2 billion over 10 years upgrading its smelter in Saguenay, Quebec. The new smelter was slated to be running by 2010 and be the first in the world to use Pechiney's AP50 reduction cell technology, which would use 500,000 amps or more and 20% less electricity. That technology later evolved to the more improved AP60.¹¹²

On May 10, 2018, Alcoa and Rio Tinto announced they would form a joint venture with Apple and the Quebec and Canada governments called Elysis backed with a combined \$145 million to develop a new way to smelt alumina into aluminum without producing carbon dioxide and less perfluorocarbons, both greenhouse gases. The new technology would use inert anodes, which researchers had been hunting for since the Hall-Heroult smelting process was discovered in 1886. Alcoa had been testing an inert anode of an undisclosed composition at a technical facility in Pittsburgh since 2009 and reportedly had produced 700 tons using the new technology. Alcoa had published frequently about anodes made of ferrite cermet, but it was believed the company had moved beyond that composition. No clear economic motive existed for pursuing a process that didn't produce carbon dioxide until Apple became interested. Apple sought to be 100% carbon-free in its global operations, but the aluminum it used in its smartphones, tablets and computers accounted for 24% of its manufacturing carbon footprint. The new technology would enable Canada, the world's third-largest aluminum producer, to eliminate greenhouse gas emissions equivalent to 1.8 million light-duty vehicles. The Elysis process also was expected to reduce operating costs by 15% and increase production by 15%. After scaling the technology for industry, the process was expected to be in use commercially by 2024.¹¹³

"This discovery has been long sought in the aluminum industry," Alcoa president and CEO Roy Harvey said. If successful, the new technology would "take aluminum's sustainable advantage to a new level with the potential to improve the carbon footprint of a range of products from cars to consumer electronics," he said. Overall, aluminum production accounted for about 1% of the world's total carbon dioxide emissions. The Hall-Heroult alumina smelting process in use since 1886 took half

a pound of carbon to produce one pound of aluminum, and half a pound of carbon was converted into a pound and a half of carbon dioxide, according to MIT materials scientist Donald Sadoway. Smelting alumina into aluminum with an inert anode would require more energy than with a consumable carbon anode, Sadoway said, but an inert anode would also emit less perfluorocarbons. "The Elysis technology is a potential game-changer for the aluminum industry," Aluminum Association president and chief executive Heidi Brock said. "Aluminum is already a sustainable material, thanks to its recycling profile and use-phase benefits, but by removing much of the carbon impact on the front end of production, it can play an even greater role in tackling global energy challenges." ¹¹⁴

One metals analyst compared aluminum smelting to storing electricity in metal form. Once created from natural sources, aluminum metal can be recycled indefinitely and still be used to produce any product for which new aluminum could have been used. Recycling aluminum requires only 5% of the energy required to make new metal from alumina. Blending recycled aluminum with new metal allows considerable energy savings with little to no change in quality or properties of the product. ¹¹⁵ Sources for recycled aluminum include beverage cans, aircraft, automobiles, bicycles, boats, computers, cookware, gutters, siding, wire and many other products. Aluminum recycling includes collecting and remelting consumer products and scrap from fabricating plants. Scrap – such as ends cut off tubing and extrusions, buttons pushed out of sheet, and turnings produced by milling – typically includes higher-purity material than consumer products such as beverage cans.

In 1967, the Reynolds Metals Co. initiated a program for recycling aluminum cans. Reynolds unsuccessfully tried offering gasoline coupons or earmarking money for charity, but recycling took off when the company offered money for cans. Reynolds collected 2.9 billion aluminum cans for recycling in 1977 and paid out \$20 million. Americans returned 6 billion aluminum beverage cans for recycling that year. It was estimated that Americans threw away 3 billion pounds of aluminum each year by then, an amount equal to the entire U.S. production of aluminum in 1958. It would take an estimated 20 million megawatt-hours of electrical power to make that much wasted

aluminum, or 1% of the power consumed in the U.S. in 1977.¹¹⁶ By 1998, recycling accounted for a record 33% of the total U.S. aluminum production. Of the 102 billion aluminum cans produced in 1998, about 64 billion or 63% of the total were recycled. Almost 90% of automotive aluminum was reclaimed and recycled.¹¹⁷ On April 4, 2007, Novelis Inc. announced it recycled 24 billion aluminum cans in 2006, amounting to about 45% of all the aluminum cans used in the U.S. and Canada each year. Novelis operated recycling plants in Berea, Ky., Oswego, N.Y., and Greensboro, Ga. The Berea plant was the largest in the world. Worldwide, Novelis recycled 38 billion used aluminum cans in 2006, equivalent to 500 tons of aluminum and a record at the time. Recycling one aluminum can saved enough energy to run a television for three hours, Novelis claimed.¹¹⁸

Red mud

In addition to energy efficiency, the future of the aluminum industry depends on its success in dealing with environmental issues. By 1981, pollution-control costs for the U.S. aluminum industry ran to about 3 to 4 cents per pound, or about 5% of the metal's list price. For comparison, pollution control in the copper industry ran to about 20 cents per pound. All mining and mineral-processing industries faced the same task of extracting small amounts of metal from large amounts of typically low-grade ore. Each stage of the aluminum production process, from mining and ore processing to refining and smelting, also affected the surrounding environment. Environmental degradation resulted from vast amounts of waste rock, effluent in natural streams, and gases and particulates in the surrounding atmosphere. Open-pit mine reclamation involved replacing the overburden and topsoil and replanting vegetation. In 1980, more than 80% of the bauxite produced worldwide was mined by open-pit method, which disrupted the local ecology and caused land erosion.¹¹⁹ After mining, bauxite was typically crushed and ground and then digested in an alumina refinery at elevated temperatures in a strong solution of caustic soda. The insoluble impurities formed what was commonly called red mud, which was separated from the solution.¹²⁰ Refineries typically consumed substantial amounts of energy and were often located near sources of cheap energy. Each refinery was tailor-made to suit a particular type of bauxite. One of the largest

environmental concerns for alumina refineries was disposal of red mud. In some places, red mud was deposited on the ocean floor under strictly controlled conditions. A common way to dispose of red mud was to build dykes to enclose the waste. After several years, the waste area could be cultivated to eliminate an eyesore.¹²¹

During the 1930s, Alcoa developed the Combination Process for refining low-grade high-silica bauxites by sintering the red mud waste product for further processing.¹²² Due to the limited supply of high-quality overseas bauxite during World War II, use of the domestic supply of bauxite from Arkansas was increased at Alcoa's East St. Louis Works. Arkansas bauxite, however, had a high silica content that reduced the recoverable aluminum from the ore using the conventional Bayer process. One way to increase the yield of aluminum oxide was to reprocess the red mud waste by sintering it in rotary kilns with limestone and soda ash and returning the clinker, or sintered aggregate, back for a second digestion run. A U.S. government-owned plant using the process during the war experienced several production problems and never produced a large volume of sintered material. By early 1946, the sintering plant was shut down and portions of the plant were sold to Alcoa.¹²³

In 1980, between 40 million and 50 million tons of red mud were created by alumina refineries worldwide. No commercially viable treatment had been discovered to reuse the waste product for road construction or making bricks, so the only solution was to carefully impound the waste.¹²⁴ The environmental impacts of the bauxite and alumina industry on the small Caribbean island of Jamaica were significant. By 1992, Jamaica produced nearly 3 million tons of alumina per year, which created 3 million tons of red mud waste containing a weak caustic soda solution. In the early years, alumina refineries had pumped the waste tailings into unused mines or into valleys rimmed with dikes, but the chemicals in the tailings eventually percolated into underground aquifers and contaminated them. Later, large sealed ponds were constructed with 12 to 14 inches of clay lining the bottoms to prevent the chemicals from escaping the impoundment. The ponds were designed to hold five to seven years of waste tailings production, but the ponds removed arable land from the local economy, and chemicals from the ponds eventually leaked into aquifers.¹²⁵

In the U.S. Virgin Islands, red mud from an alumina refinery was dumped into two lagoons from the early 1960s to 2000. The refinery was originally built by Harvey Aluminum and shared 1,400 acres of former sugar cane fields with an oil refinery owned by Hess Oil. The red mud had a high concentration of iron oxide and a high pH balance, making it caustic. The red mud could also be radioactive. The Virgin Islands Department of Planning and Natural Resources sued several companies in May 2005 over concerns about the red mud getting into the aquifer, contaminating the ocean or mangrove swamps, or getting blown by wind into nearby communities. After six years of legal action, Alcoa World Alumina, St. Croix Renaissance Group and St. Croix Alumina were assigned responsibility for remediation of the contaminated site. A \$3 million escrow account was established to enable the government to enforce and regulate the three companies which were held responsible. Two other defendants, V.I. Alumina Corp. and Lockheed Martin Corp., had not agreed to a settlement. Two companies that had oil refineries in the area, HOVENSA and Hess Oil, also had not agreed to a settlement. Century Aluminum was released from the lawsuit in November 2011 after it was shown it only owned the alumina refinery for one day and it never ran during that brief time.

126

The Aughinish alumina refinery in Ireland was built by Alcan between 1978 and 1983, with a stake held by the Anaconda Company. It was the largest construction project in Europe, employing up to 6,500 workers. Ownership of the refinery changed hands several times. By June 2000, the plant took up 360 acres of the 1,100-acre Aughinish Island on the south side of the Shannon estuary, about 20 miles downstream from Limerick City. The plant employed about 450 workers and produced more than 1.4 million tons of alumina per year using the Bayer process.¹²⁷ In 2007, Rusal acquired the refinery from Glencore. By 2009, the plant was able to process 2.7 million tons of bauxite, with about 70% coming from Guinea, West Africa. Processing capacity was increased by 50% in 2010 to 4.1 million tons of bauxite, and the Aughinish plant became the largest alumina refinery in Europe. The 236-acre disposal area for the refinery's red mud was projected to reach the end of its life by 2012, by which time 23.3 million tons of red mud would have been deposited there. In October 2011, the company announced that it had commissioned a 195-acre

development that could hold 17 million more tons of red mud from the \$1.2 billion refining plant. The new holding area would allow 2 million tons of alumina production per year at the plant through 2030. ¹²⁸

The threat posed by red mud went beyond contamination of aquifers and ocean estuaries to immediate human safety on Oct. 4, 2010, when a dam wall collapsed at the Magyar Aluminium Termelő és Kereskedelmi Zrt alumina refinery in Ajka, Hungary. About 35 million cubic feet of waste from the refinery flooded nearby villages and threatened the Danube River. The red mud deluge formed a three to seven foot high wave as it flowed through the villages of Kolontar and Devecser, initially affecting 15 square miles of land. The spill reached the Danube River on Oct. 7. The highly alkaline waste had been stored in open-air ponds, and Hungary had experienced a particularly wet summer that year, but the cause of the breach was not immediately known. Prime Minister Viktor Orban blamed human error for the accident. The ponds had once been owned by the government, but the refinery had been privatized. The mayor of Devecser reported 80 to 90 people had been hospitalized with chemical burns. Although the mud was not considered hazardous by European Union standards, the caustic material at Ajka, Hungary had a pH of 13. The red mud killed all life in the Marcal River, which ran through the area. While the Hungarian Environmental State Secretary ordered suspension of operations at the plant and reconstruction of the dam wall, the company chairman said production would resume over the Oct. 9-10 weekend. ¹²⁹

The red mud from the Ajka alumina refinery flooded about 400 homes in Devecser, and 40 people were rescued from the village of Somlovasarhely. The red mud was 6 1/2 feet high in the village of Kolontar. Emergency people were treating people for burns to skin and eyes. ¹³⁰ The red mud also flowed into a local stream, then into another river and eventually reached the Danube River near the town of Győr, where it reportedly appeared like a white foam. When contaminated water in the Danube River reached Budapest, it was diluted and could only be detected with a pH meter. In villages near the alumina refinery, the red mud stained skin, clothes, homes and pets red. It also caused burns. ¹³¹ By Oct. 8, pollution levels in the Danube River had declined, but new concerns arose that after water had run off and the sludge

had dried, the red mud could become airborne as dust by winds. Emergency workers dumped clay and acid into streams to neutralize the alkaline waste. Downstream nations, including Croatia, Serbia and Romania, worked on emergency plans. The pH of the materials that reached the Danube River were below 9 and had become diluted, the Hungarian Interior Minister reported, and the spill had not affected drinking water. All life in the Marcal River, however, had been extinguished. ¹³²

By Oct. 10, cracks were appearing in another dam wall at the Ajka refinery. Residents of a nearby town were evacuated, and others were ordered to be prepared to evacuate. Engineers were concerned a second wave could prove to be more toxic because the sludge behind the impounding dam was more concentrated. Engineers were building retaining walls around a corner of a dam that ruptured on Oct. 4, unleashing 184 million gallons of red mud. The 800 residents of Kolontar, the hardest hit town, were evacuated. At least seven people were killed and 120 injured, of which some were hospitalized with serious injuries. The 6,000 residents of Devecser, about 2 1/2 miles north of Kolontar, were told to prepare for evacuation. Ordinarily, the holding ponds at an alumina refinery stored red mud until it dried, at which point it would be considered a relatively safe red-colored clay. But industry experts said the sludge at the Ajka refinery may not have been sufficiently treated, meaning it was highly caustic. Most of what spilled on Oct. 4 reportedly was water, not mud. ¹³³

Atmospheric emissions

The most well-known pollution problem for aluminum smelters has been atmospheric emissions. With no pollution control equipment in place, a theoretical 220,000 ton-per-year aluminum smelter could emit 40 to 60 pounds of fluorides and 112 pounds of complex fluoride compound particulates, such as sodium aluminum fluoride or calcium fluoride, per ton of aluminum produced. That would amount to 44,000 to 66,000 pounds of fluorides and 123,000 pounds of fluoride particulates emitted per day. The same theoretical plant could emit from 5 to 47 parts per million of sulfur dioxide or sulfur trioxide, and 5 parts per million of nitrous oxides. In general, prebake plants had less difficulty in controlling fluoride emissions. It was estimated that

pollution controls added from 5% to 15% to the cost of operating a U.S. smelter.¹³⁴

According to June 2003 data from the International Aluminium Institute, most smelters worldwide removed 96% to 99% of pot gas fluoride and recycled it into the process, emitting only 2.4 pounds of fluoride per ton of aluminum produced for older plants and 1.1 pounds for newer plants. The two main types of fluoride emissions included inorganic fluorides such as sodium fluoride, aluminum fluoride and sodium aluminum fluoride as particulates and hydrogen fluoride as a gas, and organic fluorides such as carbon tetrafluoride and hexafluoroethane as gases. Research showed that vegetation near smelters “quickly recovered when fluoride emissions were reduced to current levels.” But as a precaution, “Most aluminium smelters are surrounded by environmental control zones, normally farmland, and the environment in these is closely monitored,” the Institute reported. For inorganic fluoride emissions, the Institute divided the history of existing aluminum smelters into three progressively improving generations – the first, 1940-1955, saw 12-15 kilograms of fluoride emitted per ton of aluminum produced; the second, 1955-1975, saw 2-6 kilograms per ton; the third, 1975-2003, saw 0.3-1 kilograms per ton.

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Perfluorocarbons created by anode effects were considered “chemically inert” by the Institute but had a high global-warming potential. “It is clear that the more efficiently the electrolytic process can be run, the lower the generation of PFCs,” the Institute said. Another category of emissions, polycyclic aromatic hydrocarbons, were produced by the manufacturing of prebake anodes or by the consumption of Soderberg-type anodes. Emission of polycyclic aromatic hydrocarbons, which were carcinogens, in 2003 averaged 0.05 kilograms per ton of aluminum produced by prebake smelters and 0.25 kilograms per ton for Soderberg plants, with the most modern prebake smelters emitting only 0.01 kilograms per ton. Polycyclic aromatic hydrocarbons emissions in Soderberg plants “have been dramatically reduced” by the introduction of dry anode technology, process improvements and altering the raw materials used, the Institute said. The remedy for sulfur dioxide produced by anode consumption was to use low-sulfur coke for producing anodes and to

use wet scrubbers to catch emissions from prebake furnaces. Carbon dioxide emissions, however, “is a feature of all metal processes which produce metal from ores containing oxides,” the Institute said. Carbon combined with the oxygen in the raw material and was “therefore an unavoidable byproduct of the aluminum smelting process,” the Institute said. Carbon dioxide emissions fell by 10% from 1992 through 2003 through improved production techniques.¹³⁶

In the past decade or more, the focus on atmospheric emissions by the aluminum industry shifted from concerns about fluoride to climate change. According to the Energy Department, total emissions by the U.S. aluminum industry of greenhouse gases – carbon dioxide and perfluorocarbons – decreased by about 27% from 1970 through 1996 at the same time production increased 59%. Most of this decrease was attributed to an increase in secondary aluminum production by recycling and a decrease in primary production, as many U.S. smelters shut down. In 1995, combustion-related emissions from alumina refining and aluminum smelting were estimated at 6.2 million tons of carbon. Consumption of carbon anodes resulted in carbon dioxide emissions of 1.3 million tons of carbon, while process emissions also included about 4.1 million tons of perfluorocarbons.¹³⁷ On average, aluminum smelting produced 1.7 tons of carbon dioxide per ton of aluminum produced. By July 2001, one third of the aluminum produced in the world came from scrap, which produced 0.18 tons of carbon dioxide per ton of aluminum produced. Aluminum recycling not only consumed less energy – it produced much less carbon dioxide.¹³⁸

Technological and operational changes at smelters around the world dramatically reduced emissions of perfluorocarbons, which were potent greenhouse gases. One ton of tetrafluoromethane had the same global warming potential as 6,500 tons of carbon dioxide, and one ton of hexafluoroethane had the same impact as 9,200 tons of carbon dioxide. Both gases were characterized by “strong infrared radiation absorption and relative inertness in the atmosphere,” according to a 1998 article by Bernard Leber in *Light Metals*.¹³⁹ In 1997, the World Aluminium Organization surveyed 60% of the world’s primary aluminum producers for emissions of perfluorocarbons. The survey, which did not include Russia and China, found that perfluorocarbon emissions had decreased by 47% since 1990 in the rate produced per

ton of aluminum.¹⁴⁰ According to a 2001 survey of 65% of the world's primary aluminum smelters by the International Aluminium Institute, average perfluorocarbon emissions per ton of aluminum produced declined by 70% from 1990 to 2000. Overall, the global aluminum industry had reduced total perfluorocarbon emissions by 46% despite a 36% increase in production over that period, the Institute reported.¹⁴¹

President George Bush recognized the U.S. aluminum industry in February 2002 for achieving a 45% reduction in perfluorocarbon gas emissions in 2000 under the Voluntary Aluminum Industrial Partnership, which included Alcan, Alcoa, Century Aluminum, Columbia Falls Aluminum Co., Golden Northwest Aluminum, Kaiser and Noranda. The perfluorocarbon reduction was equivalent in global-warming impact to 1.8 million tons of carbon emissions.¹⁴² In a February 2012 report for the International Aluminium Institute, Carmine Nappi forecast a compounded annual growth rate of 4% for the next two decades, which could double aluminum consumption in about 20 years. While aluminum production was a major carbon dioxide producer and could be impacted by climate change regulations, Nappi suggested the trade-off might be the advantages of lighter-weight motor vehicles emitting less carbon dioxide. On top of that were the benefits of recycling – Nappi pointed out that 75% of all the aluminum that had ever been produced over the past 125 years by multiple generations was still in use in 2012 as it was recycled and put back to use.¹⁴³ Alcoa included sustainability as a branding element to promote its product sales, including its ECOLUM primary aluminum products which were manufactured at aluminum smelters powered by hydroelectricity and its ECODURA billets which were produced with a minimum of 50% recycled content.¹⁴⁴

The cutting edge

By the early decades of the 20th century, Alcoa and companies in Europe had not only developed more efficient ways to produce aluminum ingot, they had also developed new ways to fabricate aluminum into shapes for downstream manufacturers by casting, rolling and extruding. The first mass consumer products were cast kitchen utensils. The Pittsburgh Reduction Co. produced its first extrusions in 1904. Aluminum foil was first produced by Gautschi of France in 1903, and the U.S. Foil Co. started rolling aluminum foil in

1926. The Pittsburgh Reduction Co. began producing aluminum wire at New Kensington in the 1890s, and Hoopes had developed aluminum-conductor steel-reinforced (ACSR) electrical transmission cable by 1908. The Duralumin alloy essential to the birth of the modern aircraft industry was invented in 1908. The clad process for bonding different materials with aluminum sheet was invented in 1926, the direct-chill process for producing ingots and billets in smelter casthouses was invented in 1929, both heli-arc welding and a method for brazing aluminum were developed in 1940, and the cold-pressure welding process was discovered in 1949. More exotic processes followed. In the summer of 1972, both Reynolds and Kaiser reportedly purchased technological information from the Soviet Union for a new way to pour aluminum ingot using an electromagnetic process.¹⁴⁵ In April 1980, researchers at Purdue University and the Massachusetts Institute of Technology reportedly discovered a way to separate and concentrate aluminum compounds from non-bauxitic ores by using ultra-powerful magnets.¹⁴⁶

By the time the world went to war in 1939, aluminum had become the dominant material in aircraft, and the U.S. invested heavily in hydropower plants, protecting bauxite shipping from South America, and building the alumina refineries, aluminum smelters and fabricating plants needed for manufacturing bombers and fighter planes on a mass scale. But vehicular transportation on the nation's roads continued to rely on steel through most of the 20th century. The first sports car featuring an aluminum body was shown at the Berlin International Motor Show in 1899, and the first engine with aluminum parts was developed by Carl Benz in 1901. As the price of aluminum came down after World War II, aluminum was used more and more in mass-produced automobiles. In 1961, British Land Rover produced V-8 engine blocks with aluminum cylinders.¹⁴⁷

Use of aluminum in cars and trucks increased from 3% by weight in 1976 to about 7% in the mid-1990s, but the substitution had been on a part by part basis with no radical design changes. Most substitutions included transmissions, engine blocks and wheels, largely as castings, forgings or extrusions. Researchers in 2001 conceded that the only way aluminum could truly replace steel was with use of aluminum sheet as the primary material for the chassis and body. The first-

generation version of the Honda NSX from 1990 through 2005 was the world's first mass-produced car to feature an all-aluminum body. The sports car was powered by an all-aluminum 3.0-liter V6 engine.¹⁴⁸ The two design approaches to production of an all aluminum car were unibody design, predominantly an all-aluminum stamped body, or space-frame design, using stampings, castings and extrusions. Starting in 1994, the Audi A8 was an example of a luxury, low-volume, all-aluminum space-frame design car. By August 2001, it was unclear which design was more economically suited for mass production. The space-frame was slightly cost-competitive due to high costs for stamping unibodies. Six car designs were analyzed and two key obstacles were found - higher material costs and higher tooling costs for aluminum panels. To be successful, the price of aluminum needed to drop to \$1 per pound. Researchers believed aluminum producers and fabricators needed to partner with automobile manufacturers to make all-aluminum cars possible.¹⁴⁹

In 2015, an Aluminum Association campaign promoted the advantages of using aluminum in construction of automobiles and trucks, from Ford F-150 pickup trucks to luxury cars made by Audi, Mercedes-Benz and Land Rover. The Ford F-150, one of the most popular vehicles in the U.S. and one of the most profitable motor-vehicle lines in the world, would be about 700 pounds or 15% lighter by using a high-strength, military-grade, all-aluminum body. Aluminum by 2015 was the second most-used material in vehicles, after steel. At the end of a vehicle's life, on average 90% of its aluminum was recycled, which translated into energy savings on an economical scale, the Aluminum Association said.¹⁵⁰

On Jan. 6, 2016, it was reported that Rolls-Royce planned to develop and test a new aluminum space-frame underpinning for all its cars that went on sale in 2018. The only Rolls-Royce car at the time with an aluminum body was the Phantom, but it sat on a steel frame like most cars. The goal was to reduce weight to improve fuel economy, power-to-weight ratios and handling.¹⁵¹ According to Brent Dunn in Autobytel online, the top 10 cars with aluminum frames were the Acura NSX, the BMWi8, the Mercedes-Benz SL-Class, the Audi A8 L, the Jaguar XJ, the Tesla Model S60, the Alfa Romeo 4C and the Chevrolet Corvette - all high-end coupes and sports cars.¹⁵² According to a February 2015

Consumer Reports story on aluminum vehicles, difficulties in fabricating aluminum sheet added about \$500 to the cost of a new Ford F-150 truck. After owners had reported problems with paint bubbling and premature corrosion, Ford placed a five-year, unlimited-mileage warranty for corrosion and paint adhesion on the 2015 year F-150 and said body-repair costs would not be any higher than for a steel-body truck. ¹⁵³

Outside of the transportation sector, unusual discoveries and inventions involving aluminum were taking place. In August 2007, scientists at Purdue University announced that an alloy of aluminum and gallium could be used to produce hydrogen from water, creating a nonpolluting fuel. The aluminum was converted to aluminum oxide, freeing up the hydrogen atom in the water. The gallium prevented an aluminum oxide skin from forming, which would stop the process. ¹⁵⁴ In January 2016, Shapeways announced a new aluminum media for 3D printing. This was the company's 54th media product. Like other 3D printing media, the aluminum media came in powder form and was fused together as it was deposited by the printer head. But instead of the selective-laser sintering process used to fuse plastic media, the aluminum media was fused by a selective-laser melting process that used a higher-power laser needed to fully melt the aluminum powder. The result, Shapeways said, was a strong homogeneous metal with a high tolerance that could be created in shapes and designs that would be impossible to create using traditional manufacturing methods. ¹⁵⁵

Perhaps less exotic was the announcement in August 2004 by the Pittsburgh Brewing Co. - maker of Iron City Beer - that it had partnered with Alcoa to begin selling beer in all-aluminum bottles with three times the aluminum of a typical can. The company claimed aluminum bottles would keep beer colder than glass for 50 more minutes and cost only \$1 more per case. About 20,000 cases of the new beer bottles were shipped out in August. The first time the Pittsburgh Brewing Co. teamed up with Alcoa was in 1962 with the first pull-tab beer cans. About 40% of all beer consumed in the U.S. in 2004 was produced in cans, with another 43% in bottles and 8% delivered by tap. A microbrewery in Missoula, Mont., about 120 miles south of the aluminum smelter in Columbia Falls, already sold beer in aluminum bottles, but Pittsburgh Brewing Co. would be the first to ship them

nationally. ¹⁵⁶ Heineken International of The Netherlands was the first brewer in the world to produce beer in aluminum bottles. Big Sky Brewing of Missoula was the first in U.S. The Philipsburg Brewing Co. in Philipsburg, Mont., was offering beer in aluminum bottles by 2015. ¹⁵⁷

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