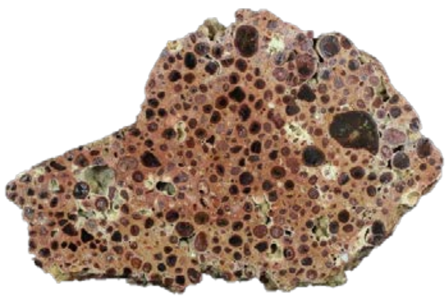
Learn About ...

ALUMINUM

Element 13 is the most abundant metal in the Earth’s crust, with a name deriving from the Latin *alumen*, meaning “bitter salt.” Aluminum is a soft, silvery, ductile metal. Aluminum is present in over 270 minerals and makes up 8.3% of the Earth’s crust by weight, the third most abundant element in the crust after oxygen (45.5%) and silicon (25.7%). Most aluminum-containing minerals contain a sulfate (SO_4^{2-}) or phosphate (PO_4^{3-}) group. An ore called bauxite contains a great number of aluminum-containing minerals. One of these compounds, alum (a compound containing two sulfate groups, aluminum, water, and a positively charged ion such as potassium) dates the first uses of aluminum back to 5000 BC, when it was used to set dyes for cloth and to preserve leather.



Bauxite is an ore that contains many aluminum-based minerals.
Photo credit: fossilera.com

Danish chemist Hans Christian Ørsted was the first to successfully isolate elemental aluminum, in 1824. He obtained the metal by heating dry aluminum chloride with potassium metal.

$$AlCl_3 + 3\,K \longrightarrow Al + 3\,KCl$$

In the 1850s, German chemist Robert Wilhelm Bunsen and French chemist Henri Étienne Sainte-Claire Deville independently developed ways to use an electric current to isolate aluminum, but the process was expensive because of the cost of both potassium metal and electricity.

Despite its value exceeding that of gold, aluminum was used to make the capstone for DC’s Washington Monument in 1884. Engineers wanted a metal that would act as a lightning rod but would also not tarnish. Although several modifications have been made to the structure, the aluminum capstone remains in place to this day.

Two engineers inspecting the aluminum capstone on the Washington monument in 1934.
Photo credit: Library of Congress

Two other scientists, working independently, developed what is now known as the Hall-Héroult process for inexpensively extracting aluminum, which is still in use today. Working in France, engineer Paul Héroult made his electrolytic aluminum process discovery in 1886. That same year, American chemist Charles Martin Hall, who was finishing his studies at Oberlin College, fabricated his own apparatus at home with the help of his sister Julia.

The first step in the commercial production of aluminum is the separation of aluminum oxide from the iron oxide in bauxite. This is accomplished by dissolving the aluminum oxide in a concentrated sodium hydroxide solution. Aluminum ions form a soluble complex ion with hydroxide ions, while iron ions do not.

$$Al_2O_3 \cdot xH_2O(s) + 2\ OH^-(aq) \rightleftharpoons 2\ Al(OH)_4^-(aq) + (x\text{–}3)\ H_2O(l)$$

After the insoluble iron oxide is filtered from the solution, $Al(OH)_3$ is precipitated from the solution by adding acid to lower the pH to about 6. Then the precipitate is heated to produce dry Al_2O_3 (alumina).

$$2\ Al(OH)_3(s) \xrightarrow{\text{heat}} Al_2O_3(s) + 3\ H_2O(g)$$

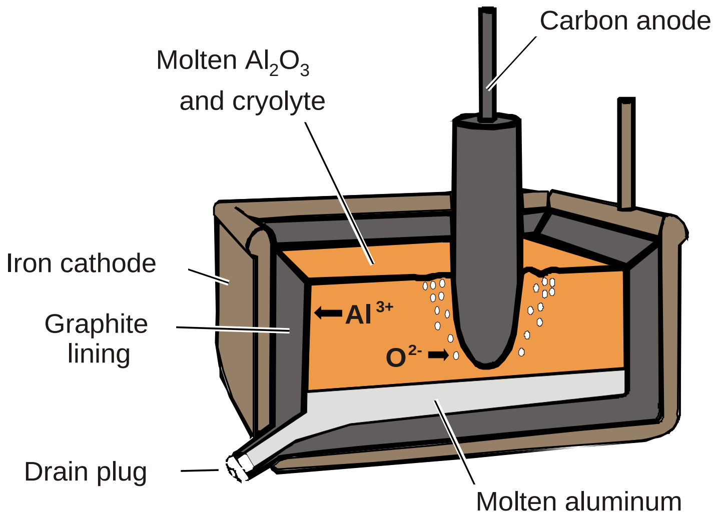
In the Hall-Héroult process, aluminum metal is obtained by electrolytic reduction of alumina. Pure alumina melts at over 2000°C. To produce an electrolyte at lower temperature, alumina is dissolved in molten cryolite at 1000°C. The electrolyte is placed in an iron vat lined with graphite. The vat serves as the cathode. Carbon anodes are inserted into the electrolyte from the top. The oxygen produced at the anodes reacts with them, forming carbon dioxide and carbon monoxide. Therefore, the anodes are consumed and need to be replaced periodically. Molten aluminum metal is produced at the cathode, and it sinks to the bottom of the vat. The principal cell reactions are represented by these equations:

$$\text{cathode:}\quad 4\ Al^{3+} + 12\ e^- \longrightarrow 4\ Al(l)$$

$$\text{anode:}\quad 6\ O^{2-} \longrightarrow 3\ O_2(g) + 12\ e^-$$

$$\text{net:}\quad 4\ Al^{3+} + 6\ O^{2-} \longrightarrow 4\ Al(l) + 3\ O_2(g)$$

At intervals, a plug is removed from the vat and the molten aluminum is drained. The heat required to keep the mixture molten is provided by resistive heating of the electrolyte by the current passing through the cell. Typical cells use a potential of 4 to 5 volts and a current of 100,000 amperes.



By the 1890s, aluminum was being used in many everyday items, including cookware, eyeglasses, and aluminum foil. With an electrical conductivity 60% that of copper and a much lower density, it is used extensively for electrical transmission lines. It can be mixed with numerous other metals to form alloys, which are harder than either of their components while still retaining the desired properties of aluminum: the ability to be easily machined or cast, lightness (density 2.70 g/cm^3), and the fact that it's non-toxic.

The beverage cans we drink out of are also made from an aluminum alloy, usually containing 92 to 99% aluminum. However, manufacturers of canned beverages have added an inner coating to their cans to prevent the carbonated contents from dissolving the can. Cans vary in composition and are generally nonreactive compounds.

Aluminum became a vital resource with the beginning of World War II in September 1939. Aircraft frames were constructed from aluminum (earlier planes used wood) making them lighter. Today alloys are still used in many airplane components, including frames, fuel tanks, and fuselage casings. They are not limited to airplanes—they have also found value in high-speed trains, as well as in cars.

Although aluminum is not considered a precious metal, small elemental replacements within aluminum-containing compounds make something else precious: gemstones! They are created when aluminum ions are replaced by those of a different metal. For example, aluminum oxide, Al_2O_3, is one of the most common forms of aluminum. When some of the aluminum sites are replaced by iron and titanium the result is a sapphire. When some of the aluminum sites are replaces by chromium the result is a ruby. Other gemstones can be formed with similar replacements in aluminum-based compounds, leading to a rainbow of gemstones.

Left to Right: Sapphire, Ruby, Emerald, Aquamarine.
Photo credit: gemselect.com

Despite its presence in nearly every area of our life, aluminum harvesting remains a very energy-intensive process, accounting for 5% of the electricity used in the United States. Given that no cost-effective replacements for the Hall-Héroult process have been discovered, a greater attention has instead been placed on recycling aluminum. The energetic cost of recycling an aluminum can is far lower than forming a brand new one and thus a higher rate of recycling helps reduce energy usage. To incentivize recycling, some states place a small 5- to 10-cent tax on each aluminum beverage can. When the can is returned to the store, the money is returned.

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