

# LIFE CYCLE INVENTORY DATA AND ENVIRONMENTAL METRICS FOR THE PRIMARY ALUMINIUM INDUSTRY

Appendix B

Appendix C

Appendix D

**2015 DATA**

**FINAL**

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## Appendix B: Unit Process Descriptions

Significant inventory inputs and outputs are reported in ***bold italic*** within the following unit process descriptions.

### 1. BAUXITE MINING

Inventory analysis unit process description
<p>This unit process begins with the removal of overburden from a bauxite rich mining site. Reusable topsoil is normally stored for later mine site restoration.</p> <p>The operations associated with this unit process include:</p> <ul style="list-style-type: none"> <li>• the extraction of bauxite rich minerals from the site;</li> <li>• beneficiation activities such as washing, screening, or drying;</li> <li>• treatment of mining site residues and waste; and</li> <li>• site restoration activities such as landscaping, topsoil replacement and replanting.</li> </ul> <p>The output of this unit process is the <b><i>bauxite</i></b> that is transported to an alumina refinery.</p>

Bauxite mining activities mainly take place in tropical and subtropical areas of the earth. Almost all bauxite is extracted using open pit mining methods. The known reserves of alumina containing ore will sustain the present rate of mining for over 100 years.

Commercial ***bauxite*** can be separated into ores composed of mostly alumina trihydrates and those composed of alumina monohydrates. The bauxite with trihydrate alumina contains approximately 50% alumina by weight, while monohydrates are approximately 30%. Monohydrates are normally found close to the surface (e.g. Australian ores), while trihydrates tend to be at deeper levels (e.g. Brazilian ores).

The only significant processing difference in bauxite mining is the need for beneficiation. Beneficiation is required with ores from forested areas, while the grassland type typically does not require washing. The ***waste water*** from washing is normally retained in a settling pond and recycled for continual reuse.

For further information on bauxite mining processes, refer to <http://bauxite.world-aluminium.org/>.

## ALUMINA PRODUCTION

### Inventory analysis unit process description

This unit process begins with unloading of process materials to their storage areas on site.

The operations associated with this unit process include:

- bauxite grinding, digestion and processing of liquors;
- alumina precipitation and calcination;
- maintenance and repair of plant and equipment; and
- treatment of process air, liquids and solids.

The output of this unit process is smelter grade **alumina** transported to an electrolysis plant (primary aluminium smelter).

In alumina production, also commonly named alumina refining, **bauxite** is converted to **alumina** (aluminium oxide) using the Bayer Process, which uses **caustic soda** and **calcined lime** (*limestone*) as input reactants. **Bauxite** is ground and blended into a liquor containing sodium carbonate and sodium hydroxide. The slurry is heated and pumped to digesters, which are heated pressure tanks. In digestion, iron and silicon impurities form insoluble oxides called **bauxite residue**. The **bauxite residue** settles out and a rich concentration of sodium aluminate is filtered and seeded to form hydrate alumina crystals in precipitators. These crystals are then heated in a calcining process. The heat in the calciners drive off combined water, leaving alumina. **Fresh water** (surface and groundwater) or **sea water** is used as cooling agent.

The major differences in processing are at the calcination stage. Two types of kilns are used: rotary and fluid bed. The fluid bed or stationary kiln is newer and significantly more energy efficient. Energy requirements (**coal, diesel oil, heavy oil, natural gas, electricity**) have been halved over the last two decades with the introduction of higher pressure digesters and fluid flash calciners.

Air emissions mostly arise from the calcination stage (**particulates; nitrous oxides (as NO<sub>2</sub>)** and **sulfur dioxide** from fuel combustion; **mercury** from the ore), while water emissions come from cooling use (**fresh water, sea water, oil and grease/total hydrocarbons**) or are linked with the digestion stage (**suspended solids, mercury** from the ore). Most of the **bauxite residue (red mud)** is currently deposited as solid waste, while a small but growing fraction is reused. **Other (by-products for external recycling)** are reaction chemicals. **Other landfill wastes** are typically inert components from **bauxite** such as sand, or waste chemicals.

For further information on alumina refining processes refer to <http://bauxite.world-aluminium.org/>.

For further information on the management of bauxite residue, please refer to [http://www.world-aluminium.org/media/filer\\_public/2013/06/11/bauxite\\_residue\\_management\\_-\\_best\\_practice\\_1.pdf](http://www.world-aluminium.org/media/filer_public/2013/06/11/bauxite_residue_management_-_best_practice_1.pdf).

## 2. ANODE PRODUCTION

Inventory analysis unit process description
<p>This unit process begins with the unloading of process materials to their storage areas on site.</p> <p>The operations associated with this unit process include:</p> <ul style="list-style-type: none"> <li>• recovery of spent anode materials;</li> <li>• anode mix preparation, anode block or briquette forming and baking;</li> <li>• rodding of baked anodes;</li> <li>• maintenance and repair of plant and equipment; and</li> <li>• treatment of process air, liquids and solids.</li> </ul> <p>The outputs of this unit process are rodded <b>Prebake anodes</b> or <b>Søderberg paste</b> briquettes transported to an electrolysis plant.</p>

There are two types of aluminium smelting technologies that are distinguished by the type of anode that is used in the reduction process: *Søderberg* and *Prebake*.

*Søderberg* processes use a single anode, which covers most of the top surface of a reduction cell (pot). Anode paste in the form of carbon briquettes is fed to the top of the anode and as it is consumed in the electrolysis process, the paste moves downwards by gravity. Heat from the pot bakes the paste into a monolithic mass before it gets to the electrolytic bath interface.

*Prebake* processes use prefired blocks of solid carbon suspended from **steel** axial busbars, which hold the anodes in place and also conduct the current for electrolysis.

The process for making the aggregate for paste briquettes or pre-baked anodes is identical. **Petrol coke** is calcined, ground and blended with **pitch** to form a paste that is subsequently formed into blocks or briquettes and allowed to cool. While the briquettes are sent direct to the pots for consumption, the blocks are then sent to a separate baking furnace.

Baking furnace technology has evolved from simple pits that discharged volatiles directly to the atmosphere during the baking cycle to closed loop designs that convert the caloric heat of the volatile into a process fuel that reduces process energy consumption. Baking furnaces use **refractory materials** for linings and **fresh water** (surface and groundwater) as a cooling agent. Baking furnaces account for most of energy consumption (**coal, diesel oil, heavy oil, natural gas, electricity**) in the pre-baked anode production process.

Air emissions such as **gaseous fluoride (as F)** and **particulate fluoride (as F)** arise from the recycling of spent anode materials (“anode butts”) recovered from electrolysis processes (see below). **Particulates, nitrous oxides (as NO<sub>2</sub>)** and **sulfur dioxide** emissions typically arise from fuel combustion. **Total polycyclic aromatic hydrocarbons (PAH)**, which includes **benzo-a-pyrene**, are air emissions generated from the basic anode production process.

Water emissions of **fluoride (as F)** and **polycyclic aromatic hydrocarbons (6 Borneff components)** are generated in the same way as their air emission equivalents above. The 6 Borneff components used as a marker for total PAH are: Fluoranthene, Benzo(k)fluoranthene, Benzo(b)fluoranthene, Indeno(1,2,3-cd)pyrene, Benzo(a)pyrene and Benzo(ghi)perylene. **Suspended solids** and **oil and grease/total hydrocarbons** are also monitored in water discharges.

The common practice for pollution control of anode baking furnaces is scrubbing with alumina and returning the alumina to the electrolysis process. In the case of separate anode baking plants this is replaced by coke and lime scrubbing, which is then returned to the process. For paste plants the common pollution prevention is coke scrubbing and returning the coke to the process. There are some plants still using water scrubbing, but this is not common and does not follow best practice. **Fresh water** emissions from paste and anode plants come from cooling processes.

By-products for external recycling includes used **steel** recovered from anode bars or used **refractory material** from baking furnaces. Various **other** by-products are also recovered, e.g. carbon recovered for re-use.

Solid waste(for landfilling): **waste carbon or mix** is a residue from anode production; **scrubber sludges** arising from water scrubbing used for control of air emissions mentioned above, and **refractory** waste from baking furnaces. **Other landfill wastes** arise as various residues, e.g. carbon fines.

For further information on anode production processes refer to <http://primary.world-aluminium.org/>.

## ELECTROLYSIS

Inventory analysis unit process description
<p>This unit process begins with the unloading of process materials to their storage areas on site.</p> <p>The operations associated with this unit process include:</p> <ul style="list-style-type: none"> <li>• recovery, preparation and handling of process materials;</li> <li>• manufacture of major process equipment (e.g. cathodes);</li> <li>• process control activities (metal, bath, heat);</li> <li>• maintenance and repair of plant and equipment; and</li> <li>• treatment of process air, liquids and solids.</li> </ul> <p>The output of this unit process is <b>electrolysis metal</b> transported to an ingot casting facility.</p>

The electrolysis process is also commonly known as “reduction” or, together with anode production, “aluminium smelting”.

Molten aluminium is produced from **alumina** through the Hall-Héroult electrolytic process that sees the **alumina** dissolved in a molten cryolite (**aluminium fluoride**) “bath” and a direct electric current passed through the solution, thereby decomposing the **alumina** into **aluminium** and oxygen. Aluminium is tapped from the reduction cell (pot) at daily intervals and the oxygen combines with the carbon of the anode to form **carbon dioxide (non-fuel combustion source)**.

The pot consists of a **steel** shell lined with **refractory materials** insulation and with a hearth of **cathode carbon**. The cathode is filled with a cryolite bath and **alumina** and an anode is suspended in the bath to complete the circuit for the pot. Once started, a pot will run continuously for the life of the cathode, which may last for in excess of 10 years. At the end of its life each pot is completely refurbished. **Steel** from used cathodes is recovered for recycling. **Refractory materials** are either recycled as by-products or landfilled (**refractory waste – landfill**). Spent pot linings (SPL), which include a carbon-based and a refractory-based part are either recycled as by-products or landfilled.

The electrical current through a pot varies from 60 to over 500 kiloamperes (kA) at a voltage range of 4.2 to 5.0 volts, depending on cell design. Pots produce around 7 to 7.5 kg of aluminium per kA per day at an operating efficiency of 85 to 95%. **Electricity** is the dominant energy source consumed during electrolysis.

Aluminium smelters typically employ air pollution control systems to reduce emissions to the atmosphere. The primary system is typically a scrubber. Many plants use dry scrubbers with **alumina** as an adsorbent that is subsequently fed to the pots and allows for the recovery of scrubbed materials. Other plants use wet scrubbers, which recirculate an alkaline solution to adsorb gases: the wet scrubbing process uses **fresh water** (surface and groundwater) or **sea water** as input and results in corresponding **fresh water** or **sea water** discharges. Unlike dry scrubbers, wet scrubbers adsorb carbon dioxide, nitrogen oxide and sulphur dioxide that are entrained

in the waste water liquor (which is subsequently treated prior to final discharge). **Scrubber sludges** are landfilled.

Specific aluminium electrolysis process air emissions are ***gaseous fluoride (as F)***, ***particulate fluoride (as F)***, which arise from the molten bath; ***total polycyclic aromatic hydrocarbons***, which includes ***benzo-a-pyrene***, which arise from anode consumption. ***Tetrafluoromethane*** and ***Hexafluoroethane***, commonly reported as perfluorocarbons or PFCs, are gases usually generated through an uncontrolled anode voltage excursion known as an "anode effect". ***Particulates, nitrous oxides (as NO<sub>2</sub>)*** and ***sulfur dioxide*** emissions typically arise from fuel combustion.

Water emissions of ***fluoride (as F)*** and ***polycyclic aromatic hydrocarbons (6 Borneff components)*** are generated in the same way as their air emission equivalents above. The 6 Borneff components used as a marker for total PAH are: Fluoranthene, Benzo(k)fluoranthene, Benzo(b)fluoranthene, Indeno(1,2,3-cd)pyrene, Benzo(a)pyrene and Benzo(ghi)perylene. ***Suspended solids*** and ***oil and grease/total hydrocarbons*** are also monitored in water discharges.

Solid waste: ***other landfill wastes*** typically consist of around 60% "environmental abatement" wastes (such as dry scrubber filter bags) and 40% "municipal" wastes (Aluminum Association, 1998).

For further information on electrolytic processes refer to <http://primary.world-aluminium.org>.

## INGOT CASTING

Inventory analysis unit process description
<p>This unit process begins with the unloading of process materials to their storage areas on site.</p> <p>The operations associated with this unit process include:</p> <ul style="list-style-type: none"> <li>• pre-treatment of hot metal (cleaning and auxiliary heating);</li> <li>• recovery and handling of internal process scrap;</li> <li>• batching, metal treatment and casting operations;</li> <li>• homogenizing, sawing and packaging activities;</li> <li>• maintenance and repair of plant and equipment; and</li> <li>• treatment of process air, liquids and solids.</li> </ul> <p>The output of this unit process is packaged aluminium ingots or alloyed hot metal transported to an aluminium fabricating facility.</p>

Molten **electrolysis metal** siphoned from the pots is sent to a resident casting complex found in each smelter. In some cases, due to proximity, molten metal is transported directly to a shape casting foundry. **Remelt ingot** and **outside scrap** may also be used as metal input. Molten metal is transferred to a holding furnace and the composition is adjusted to the specific alloy requested by a customer, by use of **alloy additives**. In some instances, depending on the application and on the bath composition in the pots, some initial hot metal treatment to remove impurities may be done.

When the alloying is complete, the melt is stirred and sometimes fluxed with flushing gases to remove impurities and reduce gas content. As a result, the liquid metal in the furnace is covered by a layer consisting of liquid aluminium, aluminium oxide skins and gas bubbles, (typically called **dross**) which is skimmed off. The dross is normally further processed, primarily to recover the aluminium content.

Depending on the application, the metal is processed through an inline degasser combined with an inline filter to remove impurities (mainly hydrogen, sodium and non-metal inclusions). For inline degassing, flushing gases typically consist of nitrogen or argon with the addition of chlorine. Metal is then cast into ingots in a variety of methods: open moulds (typically for **remelt ingot**), through direct chill moulds for various fabrication shapes, electromagnetic moulds for some sheet ingots, and through continuous casters for aluminium coils. **Fresh water** (surface or groundwater) is used for cooling (often with re-circulation through a cooling tower and water treatment plant) and is subsequently discharged, where **suspended solids** and **oil and grease/total hydrocarbons**) are monitored.

Energy carriers for ingot casting are **electricity**, **natural gas** or **heavy oil**. **Diesel oil** is normally used for internal plant transport.

While recovery and handling of internal process scrap is usually included in the ingot casting operation as mentioned above, some casthouses prefer to sell it to independent recyclers (**scrap sold** as by-product for



external recycling). **Dross**, **filter dust** from melting furnace air filtration and **refractory** material from furnace internal linings are either recovered as by-products for external recycling, or landfilled.

Solid waste: **other landfill wastes** typically consist of around 80% "environmental abatement" wastes (such as metal filter box and baghouse filters) and 20% "municipal" wastes (Aluminum Association, 1998).

**Particulates, nitrous oxides (as NO<sub>2</sub>)** and **sulfur dioxide** emissions typically arise from fuel combustion.

For further information on aluminium casting processes refer to <http://primary.world-aluminium.org>.



### **Appendix C: IAI Surveys**

Copies of the IAI Surveys used to collect industry data for the inventory can be downloaded from the World Aluminium website at the following link:

<http://www.world-aluminium.org/publications/tagged/life%20cycle/>

### Appendix D: Impact Category Descriptions

Impact Category	Impact Category Description
Acidification Potential (AP)	This relates to the increase in quantity of acidifying substances in the low atmosphere, which cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification potential is caused by direct outlets of acids or by outlets of gases that form acid in contact with air humidity and are deposited to soil and water. Examples are: SO <sub>2</sub> , NO <sub>x</sub> and Ammonia.
Depletion of fossil energy resources	This impact category quantifies the extraction of fossil fuels due to inputs into the system like coal, crude oil, natural gas or uranium.
Eutrophication Potential (EP)	Aqueous eutrophication (also known as nutrification) is characterized by the introduction of macro-nutrients (e.g. in the form of phosphatised and nitrogenous compounds), which leads to the proliferation of algae and the associated adverse biological effects. This phenomenon can lead to a reduction in the content of dissolved oxygen in the water which may result in the death of flora and fauna.
Greenhouse Gas emission (GWP 100 years)	Greenhouse gases (e.g. CO <sub>2</sub> , CH <sub>4</sub> and C <sub>2</sub> F <sub>6</sub> ) are components of the atmosphere that contribute to the greenhouse effect by absorbing, and subsequently re-emitting, outgoing long wave heat radiation, thus increasing the lower atmosphere temperature. The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterisation factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission.
Ozone Layer Depletion Potential (ODP, steady state)	Stratospheric ozone depletion (especially above poles) causes a larger fraction of UV-B radiation to reach the earth surface and results mainly from a catalytic destruction of ozone by atomic chlorine and bromine. The main source of these halogen atoms in the stratosphere is photodissociation of chlorofluorocarbon (CFC) compounds, commonly called freons, and of bromofluorocarbon compounds known as halons. These compounds are transported into the stratosphere after being emitted at the surface.
Photo-oxidant Creation Potential (POCP)	Photo-oxidant formation is the formation of reactive substances (mainly ozone), created by high concentrations of pollution and daylight UV rays at the earth's surface. There is a great deal of evidence to show that high concentrations (ppm) of these substances (mainly ozone) are injurious to human health and ecosystems and may also damage crops. The majority of tropospheric ozone formation occurs when nitrogen oxides (NO <sub>x</sub> ), carbon monoxide (CO) and volatile organic compounds (VOCs), such as xylene, react in the atmosphere in the presence of sunlight. NO <sub>x</sub> and VOCs are called ozone precursors.
Water Scarcity	Water scarcity is the extent to which demand for water compares with the replenishment of water in an area (e.g. a drainage basin). This impact category quantifies the contribution of the water inputs and water outputs to water scarcity.