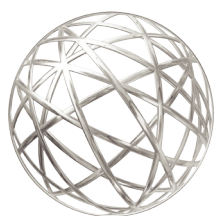


SUSTAINABLE BAUXITE RESIDUE MANAGEMENT GUIDANCE



INTERNATIONAL
ALUMINIUM

International Aluminium Institute (IAI)

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Current IAI membership represents all major regions of global bauxite, alumina and aluminium production. Since its foundation in 1972, members of the IAI have been companies engaged in the production of bauxite, alumina, aluminium, the recycling of aluminium, or fabrication of aluminium or as joint venture partners in such. The key objectives of the Institute are to:

- Increase the market for aluminium by enhancing world-wide awareness of its unique and valuable qualities;
- Provide the global forum for aluminium producers on matters of common concern and liaising with regional and national aluminium associations to achieve efficient and cost-effective co-operation;
- Identify issues of relevance to the production, use and recycling of aluminium and promoting appropriate research and other action concerning them;
- Encourage and assisting continuous progress in the healthy, safe and environmentally sound production of aluminium;
- Collect statistical and other relevant information and communicating it to the industry and its principal stakeholders; and
- Communicate the views and positions of the aluminium industry to international agencies and other relevant parties.

Through the IAI, the aluminium industry aims to promote a wider understanding of its activities and demonstrate both its responsibility in producing the metal and the potential benefits to be realised through their use in sustainable applications and through recycling.

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EXECUTIVE SUMMARY

Aluminium metal does not occur naturally, but is principally produced by refining bauxite ore to aluminium oxide (alumina) in the Bayer process, which is then reduced electrolytically to metal in the Hall Héroult process. After extraction of the aluminium minerals from bauxite, the residual minerals and some weak Bayer process liquor become 'bauxite residue' or 'red mud', which is deposited in 'Bauxite Residue Storage Facilities' (BRSF).

Bauxite residue is alkaline, and needs to be contained in safe and physically stable BRSFs until closed and rehabilitated into a safe and stable landform able to support vegetation and other land-uses.

Residue contains potentially valuable materials and properties, and some residue is used as a bulk material or as a raw material for other products. For the present and near future, however, the majority of residue is

stored in BRSFs. The universal objective of the alumina industry is to manage residue safely in these BRSFs and convert them to safe and stable landforms after closure, while seeking to utilise residue and ultimately create a zero-residue process.

Bauxite residue production rates are primarily related to the alumina content of the bauxite processed and the alumina production rate. A typical and global average residue to alumina production ratio is 1.23 tonnes of residue per tonne of alumina produced, but can range between 0.55 and 2.21. Residue is mainly composed of iron, silica, alumina, titanium and calcium minerals, but also contains sodium salts from the weak Bayer liquor associated with it. Many other minerals are included in residue at minor or trace concentrations. Bauxite residue is generally fine, although it usually contains a minor

quantity (or 'fraction') of coarse particles or 'sand', which is sometimes separated.

Bauxite residue solids are washed before discharge from the refinery by a Counter Current Decantation (CCD) process to recover caustic liquor to the Bayer process and reduce it in the residue. It may be further washed and dried on filters. The technologies for washing and drying have improved since the Bayer process began more than a century ago, and residue has become much higher in solids and much lower in caustic over this time. The caustic in residue can be neutralised in several ways to make residue areas safer during operation and quicker and easier to rehabilitate after closure.

The technologies for depositing and dewatering residue to make physically stable BRSFs have improved over the history of the Bayer process and continue to be improved. This has been aided by improved washing and dewatering processes prior to deposition. These improved technologies have dramatically reduced the land area required for residue storage, along with the risks associated with less dense storage.

The use of press filters prior to deposition to achieve solids concentrations above 70 % allows 'Dry Storage', where residue can be worked like soil and stacked at high angles, increasing the storage density, and further reducing risks of dam failures and environmental contamination. Similar results can be achieved by working the residue in-situ with machines ('farming'). Once a deposition method is adopted in a refinery, it can (and often is) updated to newer improved technology, but some upgrades can be prohibitively expensive or adoption is limited by other factors.

The design of a refinery's washing and thickening processes and Bauxite Residue Area are based on the properties of the residue and the geological, environmental and social context of the BRSF. During the design process, stakeholders need to be engaged, ecosystems baselined and environmental impacts assessed, risks identified and managed, and compliance with legislation assured. Thorough review, consultation, informed design and long-term planning are key to a safe and low risk operation to the local community and environment and ultimately the refinery owner.

Clear management accountability for residue management is key to maintaining performance against a residue management plan. Mapping and communication of responsibilities is required, as is a clear and wide understanding of the Residue management plan and related performance metrics (KPIs). A rigorous system for monitoring and tracking of the relevant refinery and BRSF processes and conditions are a prerequisite for meeting the design intent.

As a bulk material, and as a collection of potential raw materials to feed other production processes, bauxite residue utilisation has been extensively studied with significant quantities presently being used, although this remains a minor part of all residue produced. Many opportunities have been identified and have or are being developed, but while technically feasible, are often not economically viable. Residue use as a raw material for cement production is a major part of that presently utilised, and widespread development is focused on growing its bulk consumption in this area. The recovery of iron, titanium, residual alumina and other minerals remains a research focus, while the extraction of rare earths and precious metals also continue to be studied. Economic viability and the volume of residue produced remain limitations on utilisation of a larger proportion of the residue produced.

Once a BRSF is filled to its final design capacity or a refinery is shut-down, a process of closure and rehabilitation begins, with the ultimate objective of leaving a stable and safe landform which can support revegetation and will be progressively naturalised into the local environment. Rehabilitation is facilitated and accelerated by the reduction of sodium and alkalinity in residue, and this is a greater focus in the industry. Numerous studies and examples have demonstrated the ability to convert BRSFs into stable landforms which can support revegetation and the development of a healthy ecosystem, which itself facilitates the naturalisation of the BRSF over time. Various approaches have been proven to work. The nature of the residue, history of the BRSF and local climatic and environmental context and resources available to the operators can drive the choice of the best approach.

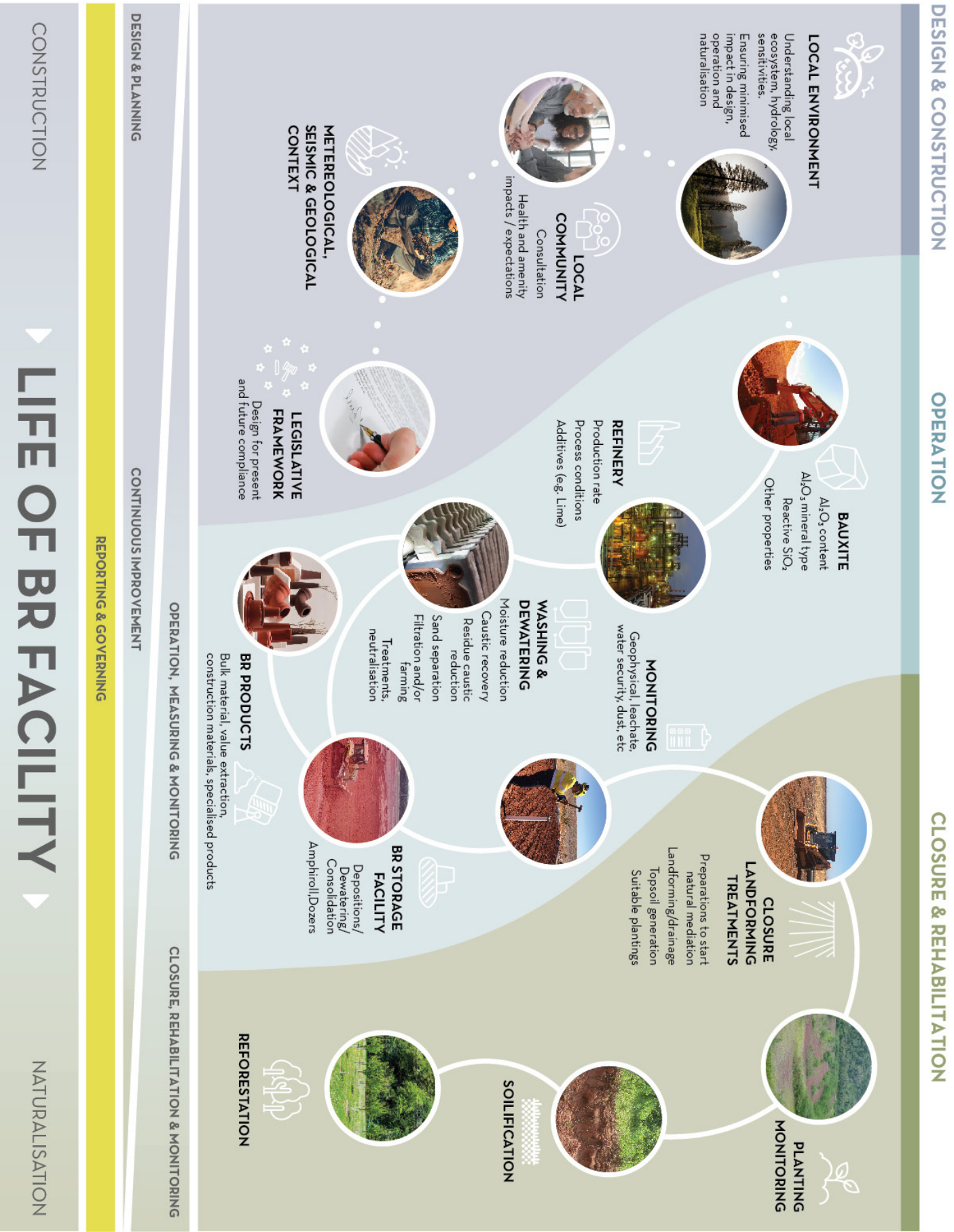


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1

INTRODUCTION



KEY POINTS

- Aluminium metal does not occur naturally, but is principally produced by refining bauxite ore to aluminium oxide (alumina) in an alumina refinery (using the Bayer process). The alumina is then converted to metal in the Hall Héroult aluminium smelting process.
- After extraction of the aluminium minerals from bauxite, the residual minerals along with some weak Bayer process liquor become 'bauxite residue' or 'red mud', which is deposited in 'Bauxite Residue Storage Facilities' (BRSF).
- The first Bayer process refinery operated in the late 1800s, and there are now in the order of 100 operating alumina refineries in the world, producing about 134 million tonnes/year of metallurgical alumina and roughly 150 million tonnes/year of residue.
- As it leaves the Bayer process, bauxite residue is alkaline, and must be contained in safe and stable storage areas where it cannot impact on the local environment and community until the area is closed and rehabilitated.
- Over time and with the aid of treatments and the elements, the stored residue will be converted into a safe and stable landform able to support vegetation and other land-uses.
- Residue contains some potentially valuable materials and properties and some is used as a raw material for other products. Many new uses are being developed, but the majority of residue is stored in BRSFs.

This document is a revision of the Bauxite Residue Management Best Practice document¹ published by the IAI in 2015. Apart from an update on the characteristics of bauxite residue, how it is produced, and how the alumina industry is managing it, this revision aims to provide an understanding for a wider, less technical, audience. It is not meant to be a text book or prescriptive method for bauxite residue management. It does not cover every aspect of bauxite residue management in detail, which would require a much larger and more detailed analysis, and the IAI recommend the references cited throughout

the document, and the large body of information in the public domain, as a source of more detail.

Global annual aluminium production was just over 64 million tonnes in 2020, and is forecast to grow to 88 million tonnes by 2050². Aluminium is the 3rd most abundant element after oxygen and silicon in the earth's crust, but it does not occur naturally as a metal. Aluminium rich ores (principally bauxite) are refined to produce alumina (Al_2O_3), which is then reduced electrolytically to primary metallic aluminium using the Hall Héroult process (see figure 1).

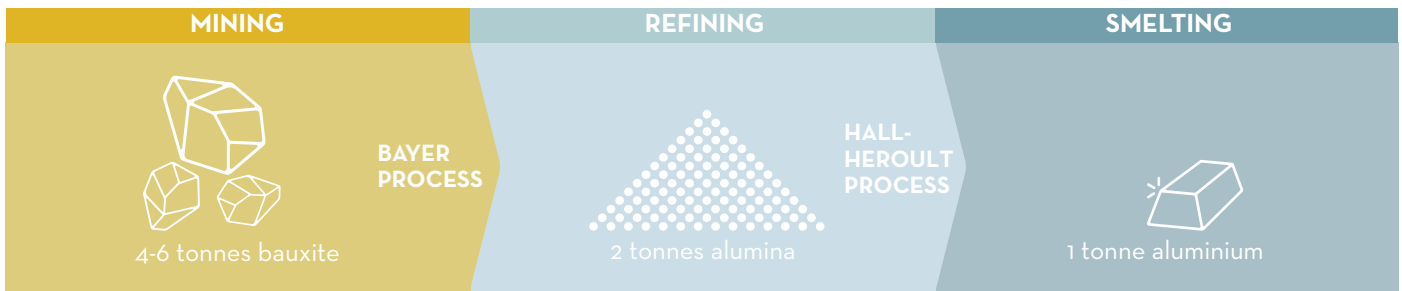
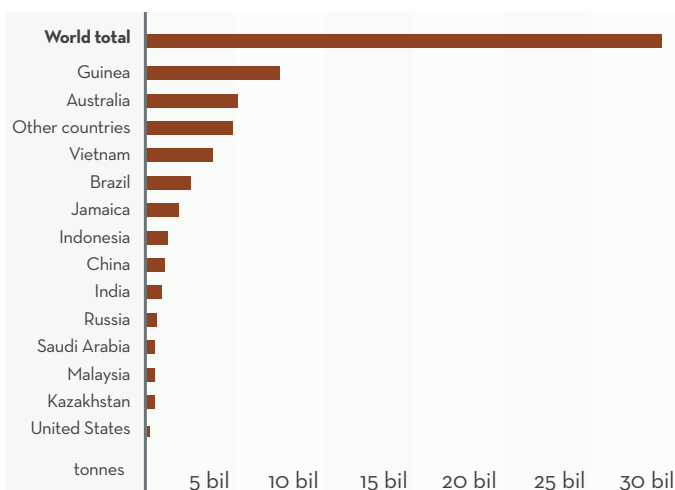


Figure 1. Bauxite to Aluminium Mass Ratios²

Bauxite occurs widely around the world, with global reserves estimated at 30 billion tonnes, and resources of between 55 to 75 billion tonnes³. It is mined in many countries including Australia, Brazil, China, Ghana, Greece,

Guinea, Guyana, Hungary, India, Indonesia, Jamaica, Sierra Leone, Suriname, Venezuela and Vietnam. In 2020 global bauxite production was estimated as 371 million tonnes³. See Figures 2 and 3.

World bauxite reserves 2020



Bauxite production worldwide 2010 - 2020

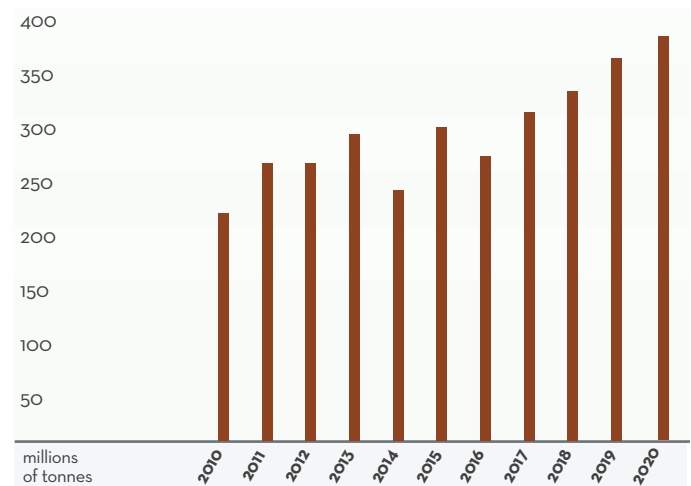


Figure 2. 2020 World Bauxite Reserves and Production³

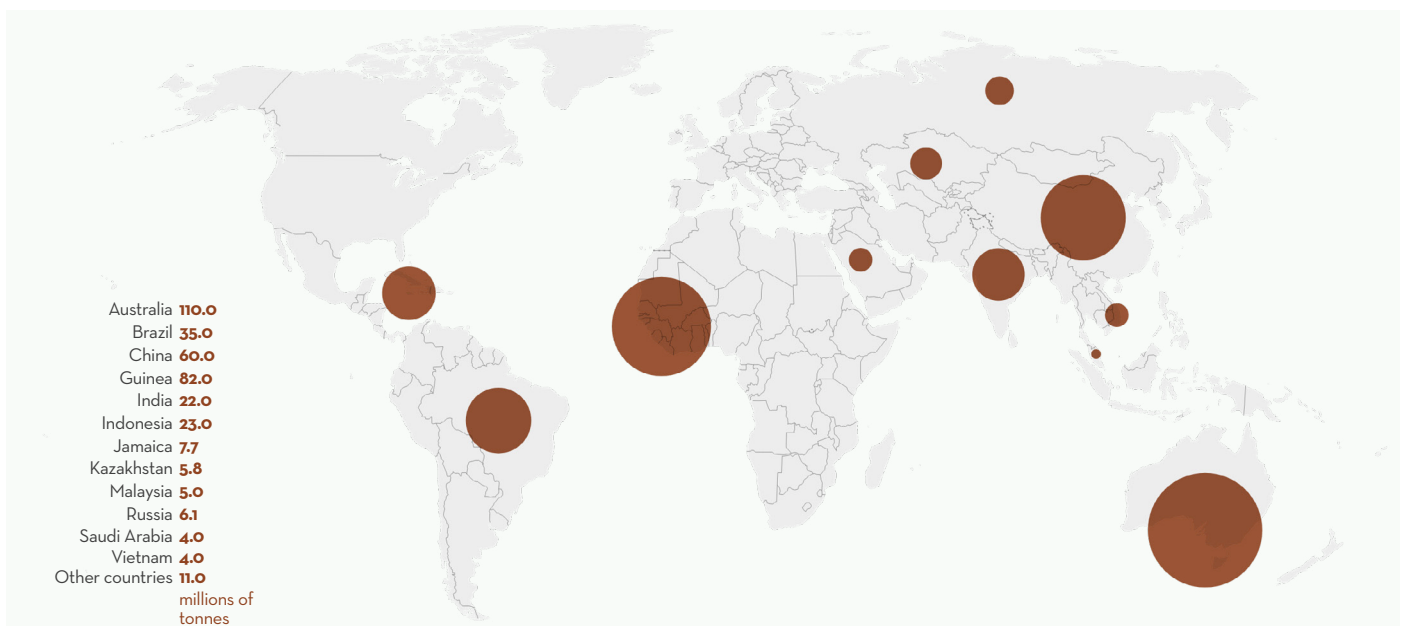


Figure 3. Global Bauxite Producing Countries³

Over 95% of the estimated 2020 global alumina production of 134 million tonnes⁴ is from bauxite refined in the Bayer process, and will probably remain so for decades to come. The balance of production uses other minerals and/or processes (e.g. nepheline, or bauxite in the Sinter process).

There are in the order of 100 alumina refineries presently operating globally, with China being the world's largest alumina producer. The number of Chinese refineries has grown rapidly, increasing from 7 in 2001 to about 49 in 2019⁴. New alumina refineries and expansions of existing ones are added periodically to meet the growing demand for aluminium. See figure 4.

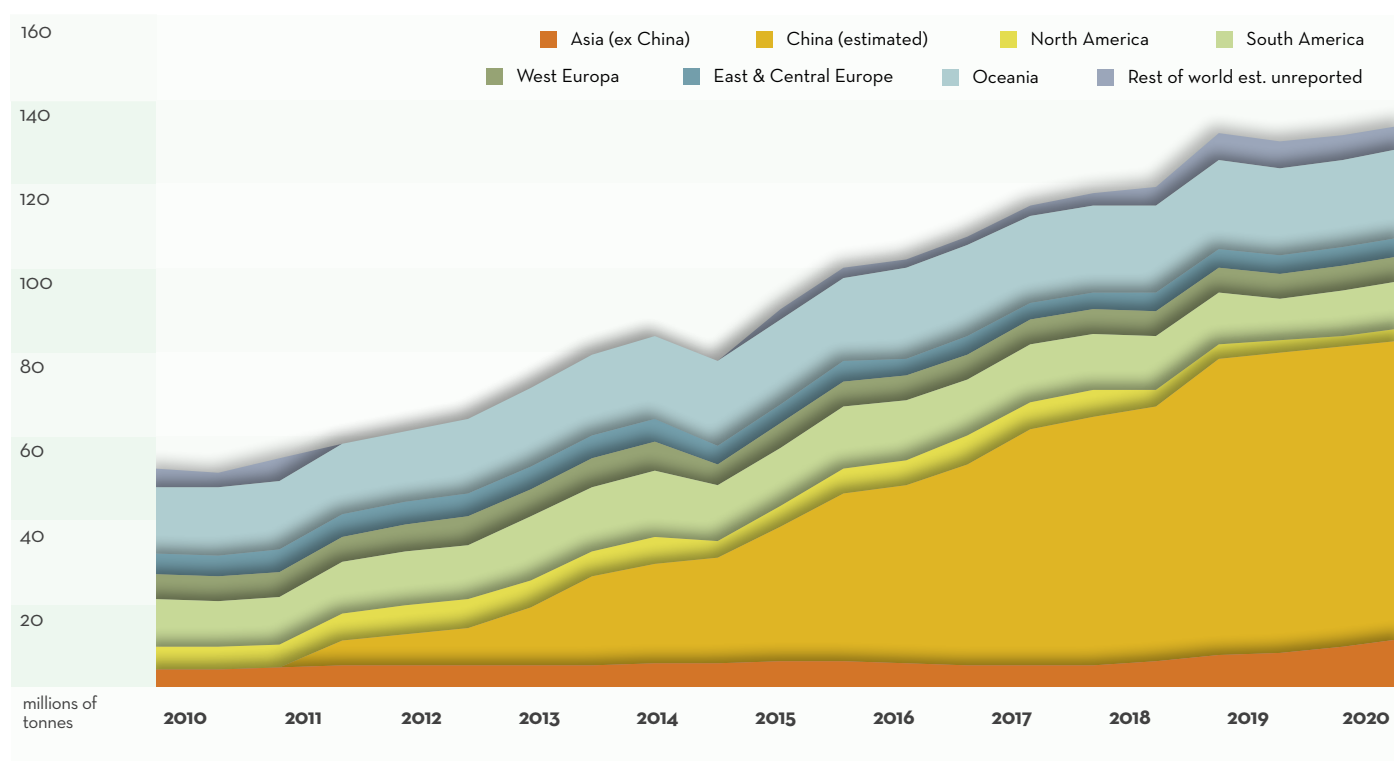


Figure 4. Annual Alumina Production²

In the Bayer process, bauxite is heated to elevated temperatures (up to 280 °C) under pressure with a caustic soda (sodium hydroxide or NaOH) solution (or 'Bayer liquor') to

selectively dissolve alumina as sodium aluminate, leaving the bulk of other minerals undissolved, and forming the main solid element of Bauxite Residue (BR). See figure 5.

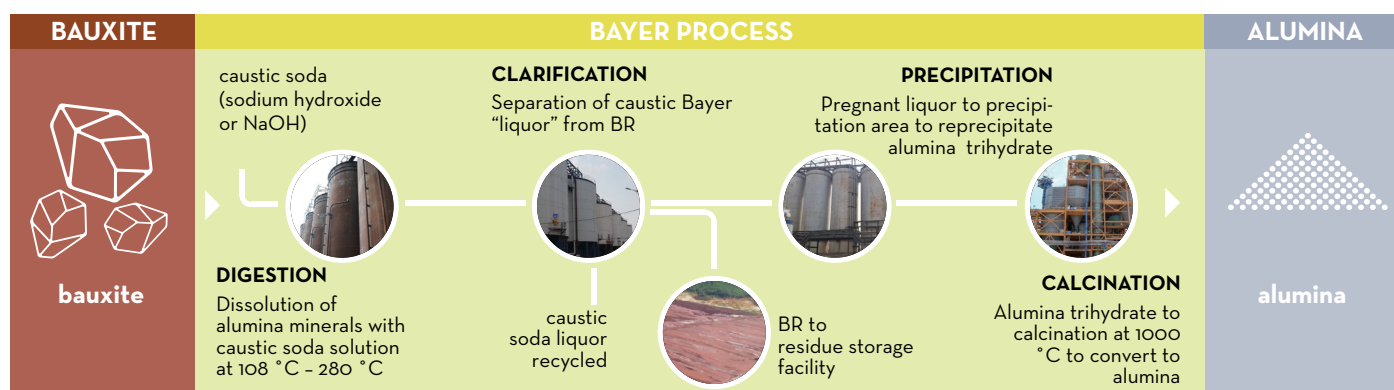
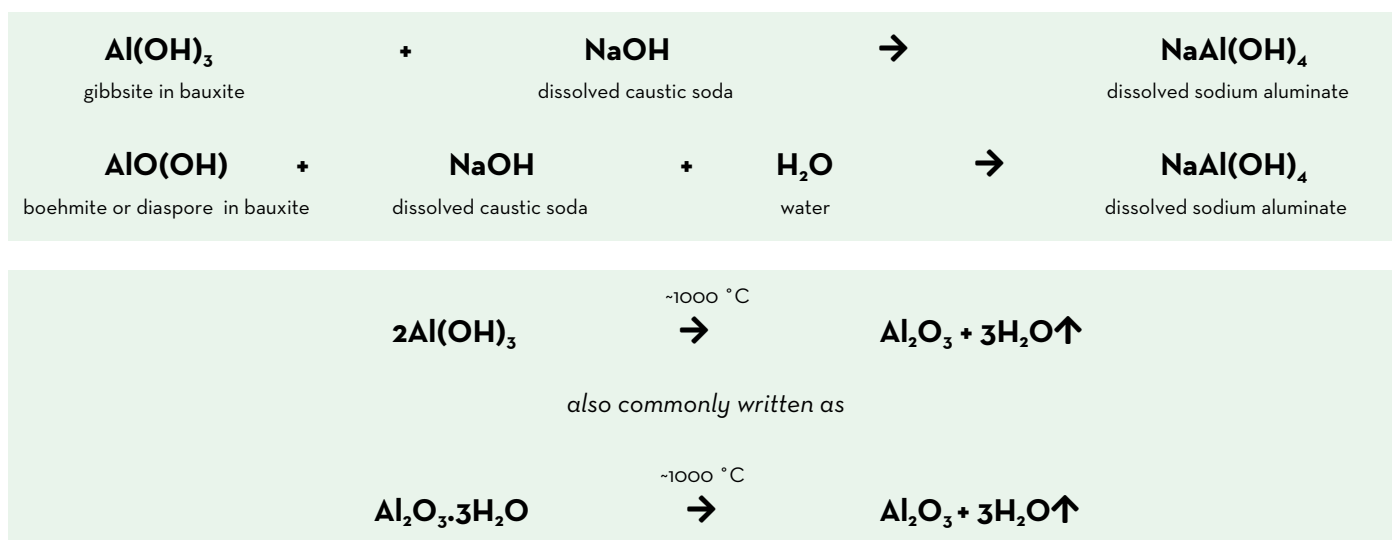


Figure 5. Simplified Bayer Process

Simplified equations for the dissolution of alumina, as the minerals gibbsite, boehmite and diasporite from bauxite follow.



The sodium aluminate solution is then filtered and aluminium hydroxide (a.k.a. alumina 'trihydrate', $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, hydrate, or gibbsite Al(OH)_3) crystals are precipitated in seeded reactors or 'precipitators'. The majority (>90 %) of aluminium hydroxide produced is heated (or 'calcined') to around 1000 °C to remove the 'water of hydration' in gibbsite to produce alumina. A minor proportion is utilised as the uncalcined hydroxide.

Over 90 % of global alumina production is used to produce aluminium metal, and is termed 'metallurgical' or 'smelting grade' alumina (SGA). The balance of alumina and aluminium hydroxide produced is the key raw material for water treatment agents, such as zeolites, activated

alumina, refractory materials, ceramics, abrasives, tiles, and glass³.

As a by-product of alumina production by the Bayer process, a mixture of minerals in bauxite (other than those containing 'available' alumina), along with some alkaline process liquor is produced. This mix of minerals and liquor is commonly called 'red mud' or 'bauxite residue'. Bauxite residue has consequently been produced since the Bayer process was first used in the late nineteenth century. Its production has grown with alumina production, with a production rate of over 150 million tonnes in 2020, and estimated accumulated total production to reach 4 billion tonnes by 2022⁴. See figure 6.

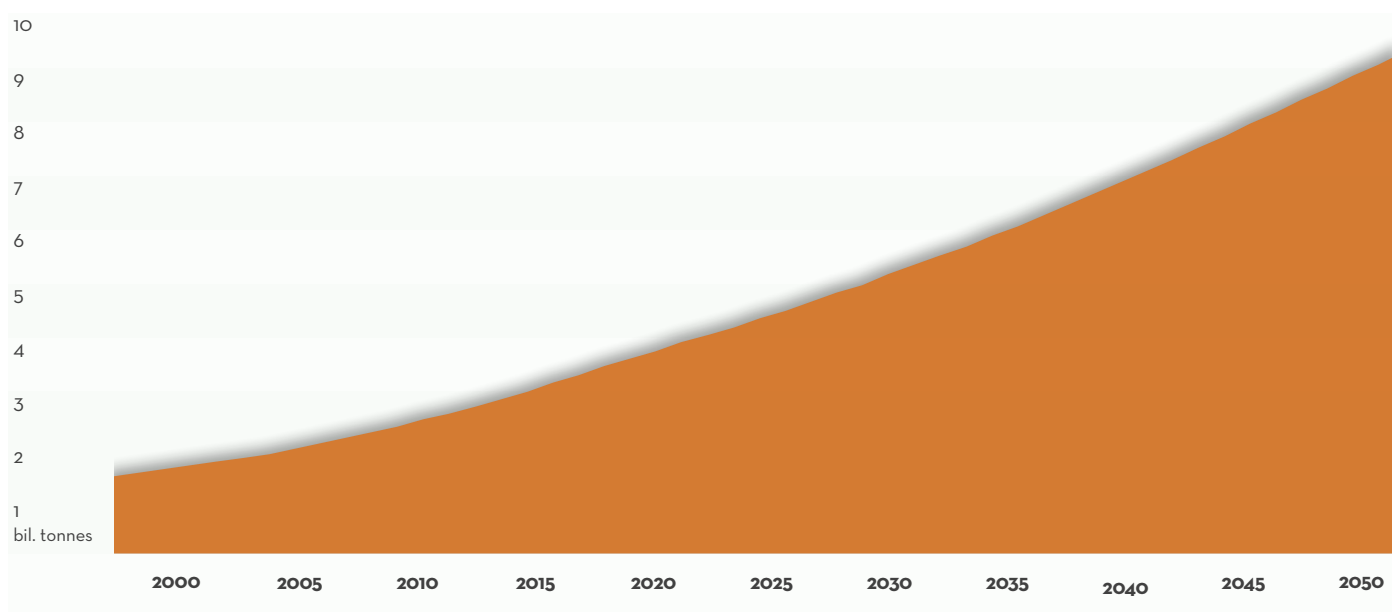


Figure 6. Cumulative Bauxite Residue Produced and Projected Growth

In addition to those now operating, there are also roughly 30 Bayer refineries that have closed along with their bauxite residue storage areas, in various states of rehabilitation and management. Of the nearly 4 billion tonnes produced, a proportion is in storage facilities now closed

and rehabilitated into safe and stable landforms, progressively neutralised and consolidated by the rehabilitation process and the effects of biological action, weathering and time. See figure 7.



Figure 7. Bauxite Residue Facility Transformation to Safe and Stable Landform

The alumina industry's universal objective is to safely deposit residue in a way that maintains a low social and environmental impact during operation, and returns residue after closure to a geophysically, environmentally and socially safe landform. The industry continues to search, with growing success, for technically and economically viable options for residue value extraction and utilisation with the ideal future state of producing zero residue.

Residue management is not “one-size fits all” and technology selection and management practices have histories, and are adapted to specific and local circumstances. The solutions and practices used at each refinery will be fur-

ther influenced by local climatic, geographic and environmental conditions as well as government policies, regulatory frameworks and community factors.

Innovative residue treatments can change residue properties, allowing different long-term storage, rehabilitation, and utilisation options. The alumina industry has a long record of adopting innovative storage and closure solutions as they are developed and proven. R&D into improved storage and remediation solutions for the existing residue inventories is ongoing by most alumina producers, and many research institutions in alumina producing regions of the world.

2 BAUXITE RESIDUE PRODUCTION AND PROPERTIES



KEY POINTS

- Bauxite residue production rates are primarily related to the alumina content of the bauxite processed and the alumina production rate, while processing conditions in the Bayer refinery are a secondary factor.
- A global average residue to alumina production ratio is 1.23.
- Residue is mainly composed of iron, silica, alumina, titanium and calcium minerals. It also contains sodium salts (including caustic soda) from the weak Bayer liquor associated with it.
- Many other minerals are included in residue at minor or trace levels. Many have potential value.
- Low levels of radioactive minerals occur naturally in some bauxites and these largely end up in residue. Generally speaking, levels of radioactivity are below safe limits.
- The water content, pH and particle size of residue (key factors in its management) can vary significantly between refineries.
- Bauxite residue solids are generally fine, although it can contain a minor quantity of coarse particles or ‘sand’, which is sometimes separated.

2.1 Residue Production Rate

The amount of bauxite residue produced by an alumina refinery is primarily dependent on the refinery’s alumina production rate and the ‘available’ alumina content of the bauxite. The type of alumina minerals present (e.g. gibbsite, boehmite or diaspore) and refinery processing conditions are a secondary, but significant factor. The “residue

factor” (or ‘mud factor’), is usually expressed as the tonnes of dry residue per tonne of alumina produced, and in 2015 had a range of between 0.7 and 2, with an industry weighted average of around 1.23⁴. Figure 8 shows the historical and projected annual production of bauxite residue.

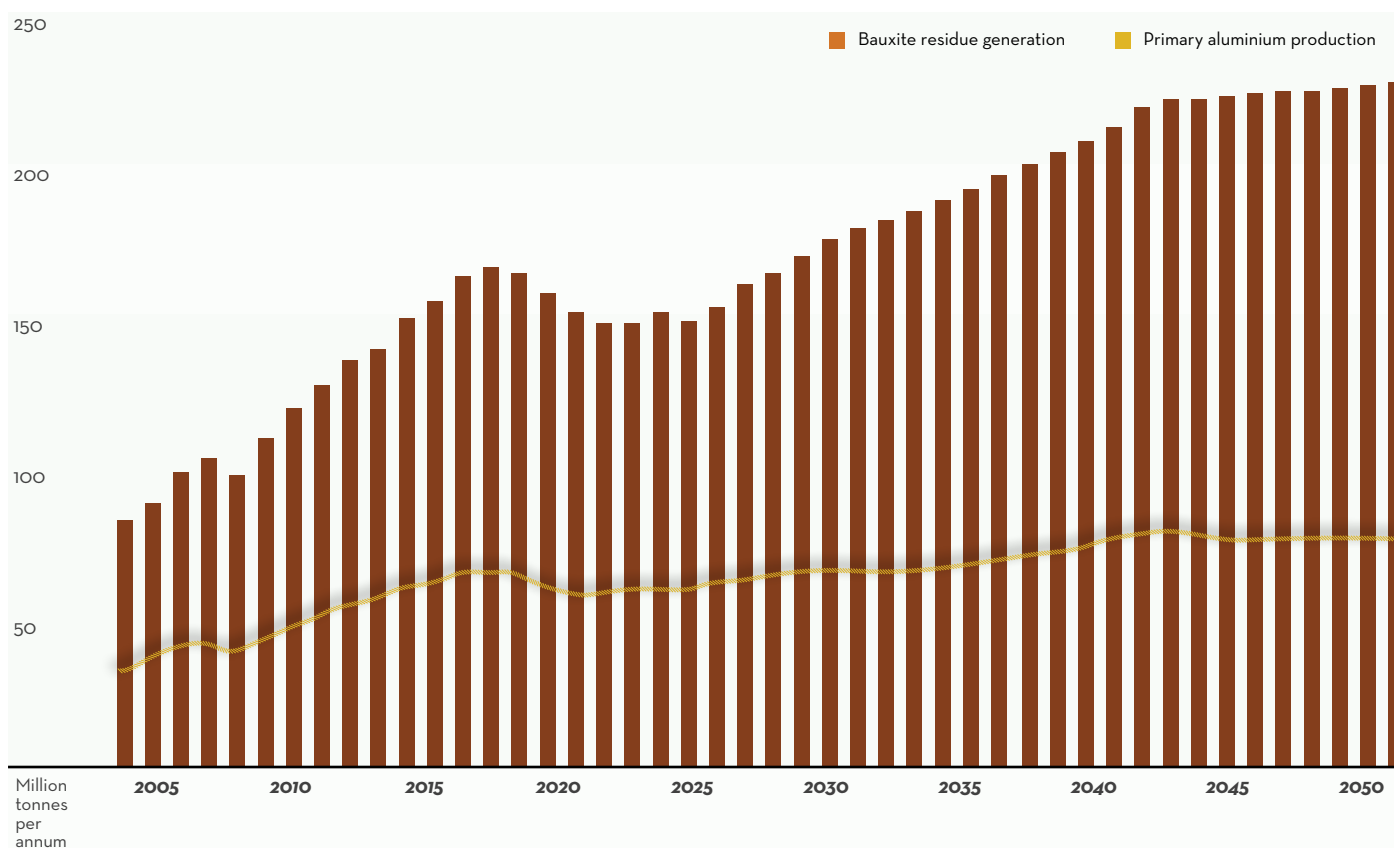


Figure 8. Annual bauxite residue generation and primary aluminium production: history and projections⁶

2.2 Composition

The major metal element of bauxite residues are iron, titanium, silicon, aluminium, sodium and calcium. As a matter of convention, and to simplify calculations, these are expressed as oxide equivalents. For example, the aluminium content of any mineral is calculated as if the aluminium was there as Al_2O_3 . In reality, these elements exist as various minerals, some of which have multiple elemental components. Calcium largely originates from lime additions to the Bayer process, and is present as a range of calcium compounds such as calcite, tri-calcium aluminate (TCA), and in some cases calcium oxalate.

Minor components include a wide range of other elements (present as various minerals and compounds) which vary with the bauxite's origin. The iron oxide hematite (a ubiquitous mineral in bauxite) gives residue its characteristic red colour, and its common name 'red mud'. Typical chemical and mineralogical compositions are shown in Tables 1 and 2.

Component	Typical range (%)
Fe_2O_3	5 - 60
Al_2O_3	5 - 30
TiO_2	0.3 - 15
CaO	2 - 14
SiO_2	3 - 50
Na_2O	1 - 10

Table 1 – Chemical composition range (%) of bauxite residue's main components.

Component	Typical range (%)
Sodalite ($3\text{Na}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{Na}_2\text{SO}_4$)	4 - 40
Goethite (FeOOH)	10 - 30
Hematite (Fe_2O_3)	10 - 30
Magnetite (Fe_3O_4)	0 - 8
Silica (SiO_2) crystalline and amorphous	3 - 20
Calcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$)	2 - 20
Boehmite (AlOOH)	0 - 20
Titanium Dioxide (TiO_2) anatase and rutile	0 - 15
Muscovite ($\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$)	0 - 15
Calcite (CaCO_3)	2 - 20
Kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$)	0 - 5
Gibbsite ($\text{Al}(\text{OH})_3$)	0 - 5
Perovskite (CaTiO_3)	0 - 12
Cancrinite ($\text{Na}_6[\text{Al}_6\text{Si}_6\text{O}_{24}]\cdot 2\text{CaCO}_3$)	0 - 50
Diaspore (AlOOH)	0 - 5

Table 2 – Mineralogical composition ranges for bauxite residues

A wide range of other trace components are also present in bauxite. Minerals of arsenic, beryllium, cadmium, chromium, copper, gallium, lead, manganese, mercury, nickel, potassium, thorium, uranium, vanadium, zinc, and a wide range of rare earth elements are common. Some of the elements remain un-dissolved and unaltered through the Bayer process and as part of the bauxite residue. Some are soluble in Bayer process liquor, and either accumulate in liquor, or precipitate in the residue or in product

aluminium hydroxide. Depending on the processing conditions, some elements will be more or less extracted into the liquor or transformed in the bauxite residue.

Non-metallic elements found in residue include phosphorus and sulfur. A wide variety of organic (carbon based) materials and compounds are also usually present, produced by or derived from flora and fauna living on and penetrating into (as roots and soil biota) the bauxite deposit. Organic compounds include carbohydrates, alcohols, phenols, and the sodium salts of polybasic and hydroxy-acids. Residues also contain traces of organic process additives such as flocculants and antifoams.

In addition to the solid minerals and compounds, dilute Bayer liquor containing sodium hydroxide (or 'caustic soda'), sodium aluminate and other sodium compounds remains associated with residue solids. Alumina refineries try to maximise caustic soda recovery from residue for recycling into the refinery's recirculating liquor stream. The efficiency of the caustic recovery process in each refinery (washing and solid liquid separation), the character of the bauxite, and processing conditions largely determines the residual caustic and alkalinity of the residue slurry. Over time, sodium hydroxide and aluminate (along with other hydroxy-salts), are partially neutralised by carbon dioxide from the air to form sodium and other carbonates, resulting in both a lower pH and a lower human and environmental risk.

Bauxites have very low levels of "naturally occurring radioactive materials" (NORMs) due to the common occurrence of uranium (^{238}U) and thorium (^{232}Th) series minerals. Bauxite ^{238}U and ^{232}Th results in very low levels of radioactivity, at or below that naturally occurring in many regions of the world.

After bauxite processing, most of the uranium and thorium ends up in the residue, concentrating radioactivity in the residue in proportion to the alumina minerals extracted. This is sometimes called 'Technologically Enhanced Naturally Occurring Radioactive Material' (TENORM). More detailed information on bauxite and residue radioactivity is presented in Chapter 4.

2.3 Physical Characteristics

While the specific bauxite used and the specific comminution and processing conditions of each refinery will have an impact on each residue's physical properties, the general properties of bauxite and general conditions of the Bayer process result in a material that has a fine particle size distribution which can be like powder when dry, or like clay when wet.

There is often a significant fraction of coarse particles (> 100 μm) in residue, often referred to as 'sand', which may be separated from the finer residue, which is usually referred to as 'mud'. Historically, sand and mud were separated to facilitate washing, but these size fractions are less often separated today. If un-separated, the permeability of the bauxite residue is increased. Bauxites from some regions, such as Western Australia, are especially high in sand, and in some instances can account for up to 50% of the residue.

Slurries of residue exhibit thixotropic behaviour, meaning that although they do not flow if undisturbed, they become more liquid when vibrated or mixed ('sheared'). This is an important characteristic, and impacts several aspects of the way it is separated from process liquor, transported, deposited and consolidated.

Apart from varying composition and particle sizes of different residues, all of which have some influence, the biggest impact on a residue slurry's handling properties is its solids content, expressed as % solids (w/w) or grams per litre (g/L). As solids content increases, the slurry's viscosity rises exponentially. The yield stress is an expression of the force required to mobilise a slurry. For a typical residue slurry, yield stress increases dramatically above 50% solids, making it far more difficult to move by pumping or agitation. See figure 9.

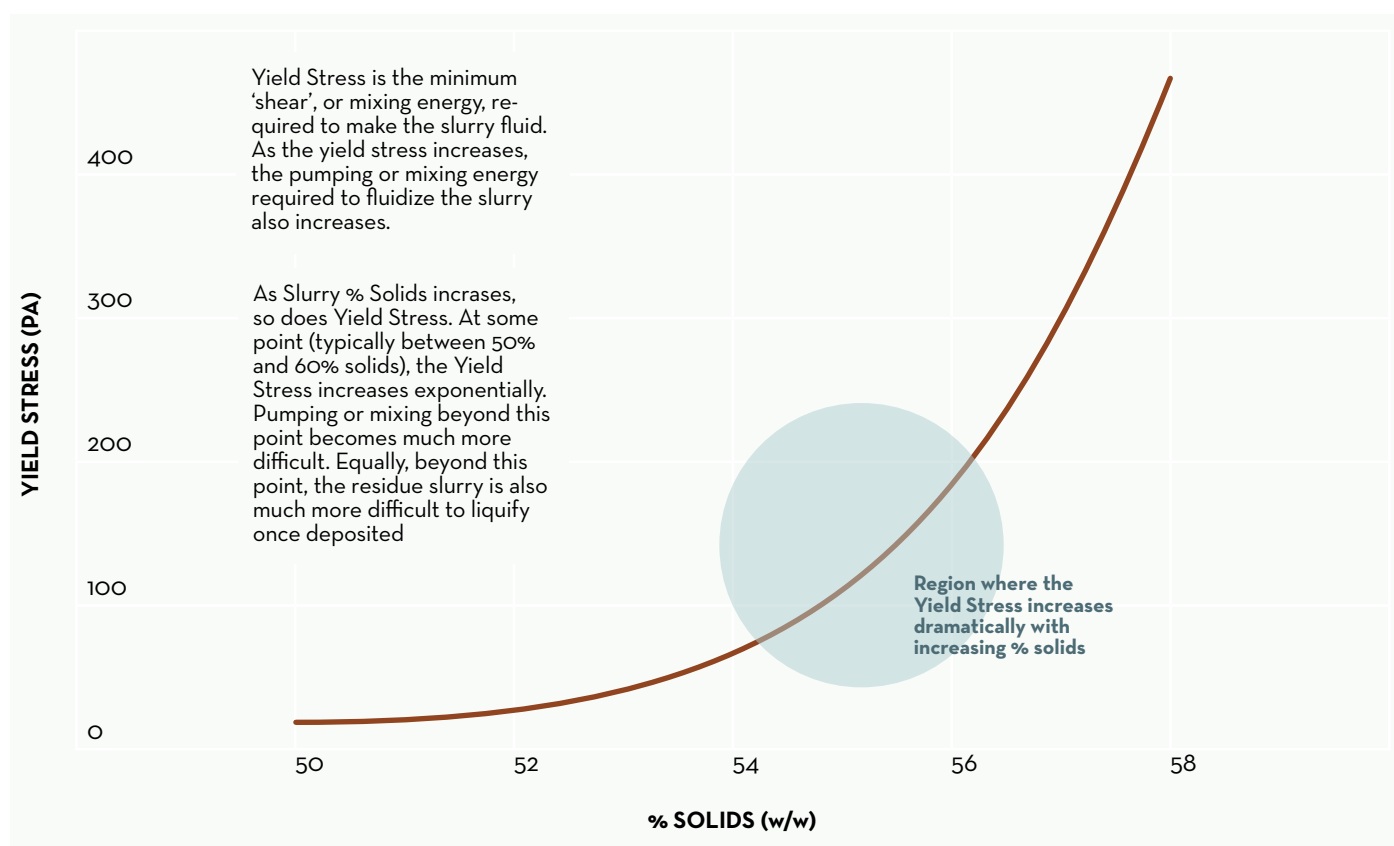


Figure 9. Typical Bauxite Residue Yield Stress Curve

3

BAUXITE RESIDUE WASHING AND NEUTRALISATION



KEY POINTS

- The residual material after digestion of alumina minerals from the bauxite that make up residue are washed before discharge by a Counter Current Decantation (CCD) process to recover caustic liquor to the Bayer process and reduce it in the residue. Following the CCD washing of residue, it can be further washed and dried on filters.
- These technologies have improved since the first Bayer process refineries operated, and residue has consequently become higher in solids and lower in caustic.
- The caustic in residue can be neutralised in several ways to make the residue areas safer during operation and quicker and easier to rehabilitate.

3.1 Residue Washing and Thickening

Washing residue to reduce associated caustic soda and to return the caustic soda to the refinery is usually achieved by a combination of washing (with water or liquor with a lower caustic) and solid liquid separation processes. The technology for washing and thickening has developed in a series of small and large iterations in the last 100+ years. Residue filters and multi-chamber washers gave way to high rate decanters, super thickeners, deep cone washers, vacuum disc and drum filters, and plate and frame filters. These advances have increased the economically optimal residue solids content from around 20% to above 75% and greatly reduced the economically optimum caustic soda content in residue.

Today, the primary technology in Bayer refineries for washing and caustic recovery is called 'Counter Current Decantation' (CCD) where the solid residue flows through a series of vessels in the opposite direction to the wash water stream. The solids and the liquid are separated by settling, with the settled solids exiting via the vessel underflow and the liquid exiting through the overflow. At one end of a chain of settling vessels, the underflow output is a high-density slurry (typically >40% solids), with residue solids associated with a dilute (low caustic concentration) liquor, while at the other end, a liquor high in caustic, but with almost no solids (<1 g/L) is discharged from the overflow. Figure 10 shows a typical 'CCD' arrangement for washing residue.

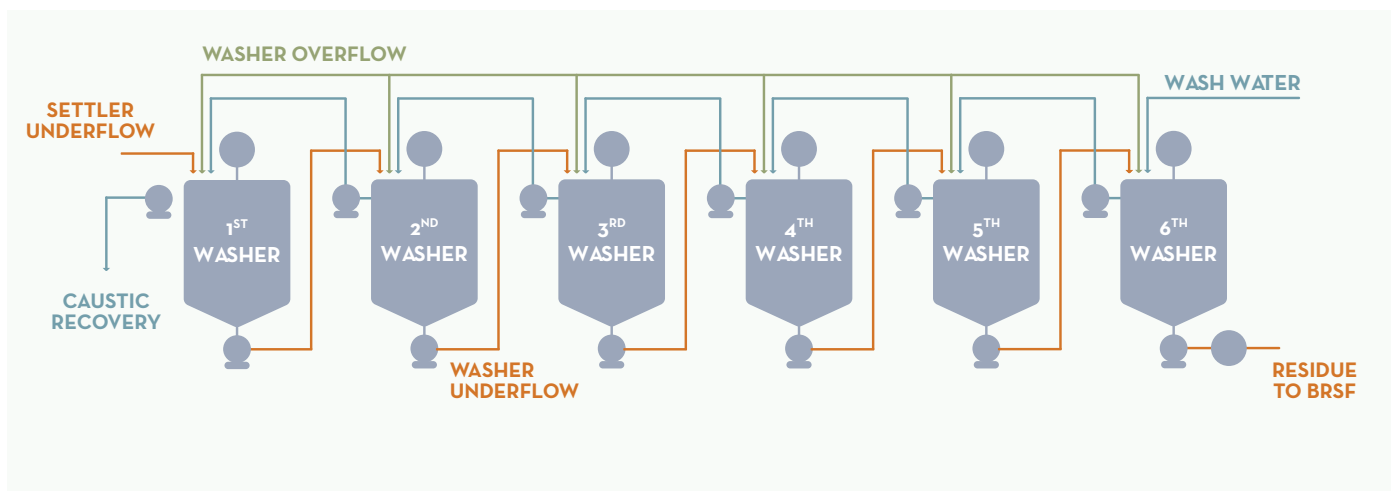


Figure 10. Typical Counter-Current Decantation (CCD) Residue Washing Arrangement

The practical limit to how thick this technology can make the residue slurry prior to storage is the point at which the residue slurry is too thick to be pumped from the thickening vessel onwards to a filter, or directly to the BRSF. This limit varies with each residue and washing and pumping technologies, but is usually around 50% solids concentra-

tion. To increase the density of the residue slurry from a maximum of ~50% solids achievable from the CCD, either the residue is allowed to consolidate in the BRSF with time and/or 'farmed', or increasingly, filtered to dewater the slurry before deposition.

3.2 Neutralisation

The caustic soda in residue deposited into a BRSF reacts over time with atmospheric CO_2 or that dissolved in rainwater, converting sodium hydroxide (caustic) to sodium carbonate, and reducing residue pH. This process is slow due to the general impermeability of residue. 'Farming' residue accelerates this process by exposing fresh residue to atmospheric CO_2 . UC RUSAL's Aughinish Alumina in Ireland for example, utilise this reaction by ploughing the residue repeatedly to carbonate any residual caustic to prepare it for revegetation.

Residue causticity and alkalinity is also neutralised naturally by organic acids generated by many biological processes and organisms, once revegetation commences and a microbiological ecosystem develops.

Some refineries actively neutralise residue slurry or residue supernatant liquor's causticity and alkalinity using agents such as mineral acids (normally sulfuric or hydrochloric), concentrated carbon dioxide gas, sulfur dioxide gas, sea water.

In some jurisdictions, untreated bauxite residue may be classified as a hazardous material, which can increase the complexity and cost of managing it. In such circumstances, neutralisation offers the benefit of reducing this complexity. This is not the case in Europe, where all bauxite residues produced are classified as non-hazardous.

Residue neutralisation reduces risks associated with residue's pH during operation, and facilitates rehabilitation after closure. Neutralisation is more or less complex and costly for refineries depending on their location and proximity to the sea, sources of carbon dioxide or flue gases and other factors. Figure 11 illustrates common approaches to residue neutralisation.

'Neutralisation' by seawater can lower the pH to between 8 and 8.5, and lowers the concentration of hydroxyl and aluminate anions present, resulting in the formation of calcium and magnesium compounds (e.g. calcite, aragonite, brucite, hydrotalcite, hydrocalumite). The calcium, magnesium and potassium, coupled with rain, reduce sodium, and together with the lower pH, aid revegetation.

Neutralisation by seawater is known to produce a useful material, such as in the case of the Virotec's Basecon™ process, where a non-hazardous product 'Bauxsol®' is the product of a reaction of bauxite residue with brines containing high concentrations of magnesium and calcium salts.

In some coastal locations (e.g. Queensland Alumina Ltd. and Rio Tinto Yarwun refineries in Gladstone, Australia), seawater is used to reduce the pH of the residue liquor. The chemical reactions between residue liquor and seawater allow the resulting seawater/weak liquor mix to be released back to the sea. While seawater neutralisation

results in a more environmentally friendly residue in storage, it does limit some of the options for residue reuse, due to the relatively high initial salinity. Any residual aluminium and caustic soda contents in the residue before treatment are also practically unrecoverable. Seawater neutralisation requires the discharge of seawater /treated liquor mix back to the local environment, and meeting strict environmental discharge licences.

Even lower residual pHs can be achieved using mineral acids or acidic gasses, and residues with a pH of 7.5 have been achieved using hydrochloric acid. Residue pH re-

duction using sulfur dioxide in flue gases has been used by Eurallumina in Sardinia.

Despite the potential for improvements in technology, it can be prohibitively expensive for a refinery to change the method and nature of residue deposited once established. Factors such as proximity to the sea; suitable land availability; residue characteristics; aspects of the climate where the refinery is located; availability of economic pH reduction sources (e.g. carbon dioxide, sulfur dioxide, sea water, acid), can all affect decision making.



Figure 11. Bauxite Residue Neutralisation

3.3 Case Study: Seawater Neutralisation of Bauxite Residue at QAL

Queensland Alumina Limited (QAL) in Gladstone, Australia has been operating since 1967, currently producing 3.95 million tonnes per year of smelter grade alumina and 3.5 - 3.8 million tonnes per year of bauxite residue. At QAL, sea water has been used to some degree to neutralise residue since the early 1970's.

An improved neutralisation facility was commissioned in 2007, allowing residue at a solids concentration of 350 g/L to be stacked and farmed, increasing the stored dry density from 0.7 to 1.3 tonnes/m³. After discharge from the neutralisation facility, the residue slurry is pumped to and poured into bays, before being 'farmed' using amphibious scrollers before being further compacted by specialised (low ground pressure) dozers. The increased density achieved both reduces stored residue volume and also provides good foundations for future wall raises.



Figure 1.
Amphibious Residue Scroller

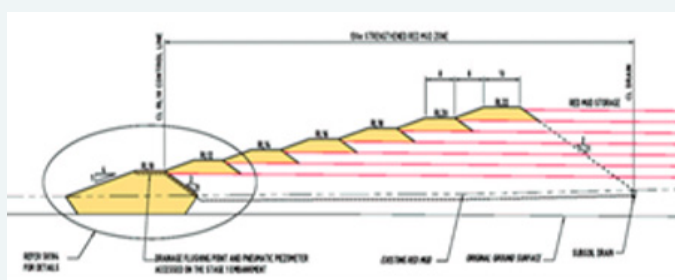


Figure 2.
Upstream Dam Construction as
a result of Mud Farming

The supernatant seawater from the Neutralisation facility has a pH lower than 8.5, solid content of less than 30 mg/L and dissolved aluminium lower than 5 mg/L. The neutralisation process relies on the seawater Mg concentration which can be reduced by rain events. Acid neutralisation has been built into the neutralisation facility, and is employed during these periods. The supernatant flow continuously discharges to the environment after a labyrinth and 50m long diffuser pipe. The discharge and several points in the receiving environment are continuously monitored for Dissolved Oxygen (D.O.), salinity and conductivity.

Benefits of improved seawater neutralisation include reduced residue alkalinity and less dust due to the salt crust which forms on the residue surface. It has reduced costs and demand for other materials by allowing the residue to be used for wall construction, potentially lowering closure costs and liability by safely encapsulating the original un-neutralised mud.



Figure 3
1. Neutralisation Facility 2. Seawater Intake 3. Labyrinth and diffuser 4. Discharge point
● Continuous Monitoring Points

4

HEALTH AND SAFETY



KEY POINTS

The human health aspects of bauxite residue management include:

- Occupational health of workers during normal operations.
- Environmental health focused on airborne emissions during normal operations and any impact on the health of nearby communities.
- Residue reuse and the health of those working with or using the products.
- Containment failure and the health of emergency responders and community members.

4.1 Occupational health of workers during normal operations

4.1.1 Alkali

While much of the valuable caustic soda (sodium hydroxide) introduced to Bayer refineries to digest bauxite is recovered, some is lost to bauxite residue unchanged, and transformed by the Bayer process into sodium aluminate. Without a specific caustic neutralisation process, this results in bauxite residue slurries initially being strongly alkaline. Over time, contact with carbon dioxide in the air or dissolved in rainwater results in further conversion of residual caustic to sodium carbonate, lowering the pH¹.

While general access to residue areas does not require personal protective equipment (PPE) to prevent alkali ir-

ritation (skin, eyes, respiratory tract) or chemical burns, contact with bauxite residue slurries and access to residue areas under conditions where a significant airborne dust loading is raised, requires suitable PPE. Refineries employ various strategies to minimise dust, and in some cases to allow carbonation of residual caustic⁵.

4.1.2 Naturally occurring radioactive material (NORM)

Bauxite is a low-level naturally occurring radioactive material (NORM), due to its uranium (²³⁸U), thorium (²³²Th), and potassium (⁴⁰K) content⁶. The contribution of ⁴⁰K to activity concentration is relatively small – essentially neg-

ligible. NORM in the ore almost entirely ends up in the solid residue after refining.

Calculated average radioactive element activities (head of decay chain) for bauxite, sand residue and mud residue have been reported for three refineries in Western Australia. The highest average ^{238}U results were 0.41 Bq/g for bauxite, 0.17 Bq/g for sand residue, and 0.66 Bq/g for mud residue. The highest average ^{232}Th results were 0.76 Bq/g for bauxite, 0.71 Bq/g for sand residue, and 1.80 Bq/g for mud residue⁶.

These average activity concentrations are higher than those generally reported for residues globally, and most bauxite residues will have activity concentrations below these. Materials with activity concentrations below the international benchmark of 1 Bq/g (applied to each head of chain) may be excluded from radiological regulation⁶. Although there is the potential for some residues to exceed this benchmark, processes may be exempted from radiological regulation where occupational above-background workforce exposures do not exceed 1 mSv/year, the upper limit of exposure also prescribed for members of the public. This was the case for the three refineries in Western Australia with all such exposures below 1 mSv/year (total gamma, radon progeny and gross alpha), including those recorded for residue area employees⁶.

4.1.3 Cancer incidence and mortality

A cancer incidence and mortality study was undertaken for a cohort of employees (including those working in the residue areas) at three bauxite mines and three alumina refineries in Western Australia⁷, the only such study in the industry to date. The most recently published analysis of this ongoing cohort found mortality from all causes to be significantly lower than that for the Australian male population (standardised mortality ratio = 0.68; 95 % confidence interval [CI] = 0.60 to 0.77). Mortality was also significantly lower for circulatory diseases, respiratory diseases, injury/trauma, and “other or unknown causes”. Mortality for all cancers combined was not significantly different.

The only significantly increased mortality rate was for pleural mesothelioma – attributed to historic exposure to asbestos (not in residue areas). The incidence of all cancers combined was not significantly different to that of the comparison population (standardised incidence ratio = 0.92; 95 % CI = 0.82 to 1.03). There were increased incidence rates for pleural mesothelioma, melanoma and thyroid cancer. Mesothelioma was mostly attributed to exposures that had occurred outside the aluminium industry and not to work in residue areas. Subsequent analysis at one of the refineries found no statistically significant increase in melanoma incidence when state rather than national comparison data was used (unpublished data).

There was an increased incidence of thyroid cancer in those who had ever worked in an office, but no excess in those who had ever worked in production or maintenance roles. There was no evidence of an excess risk of any cancer type with cumulative bauxite or alumina exposure. There was some evidence of an exposure-response relationship between cumulative inhalable bauxite exposure and non-malignant respiratory disease mortality and between cumulative inhalable alumina exposure and cerebrovascular disease mortality. However, these associations were based on very few cases and the non-malignant respiratory diseases were a heterogeneous mixture. Further follow-up is required to clarify these preliminary findings. In summary, there is no evidence to date of cancer or mortality risks attributed to work in bauxite residue areas.

4.1.4 Inception cohort and bauxite

An inception cohort study tracked the respiratory health of new starters over 13 years at bauxite mines and alumina refineries in Western Australia⁸. The study reported no significant impact of cumulative respirable bauxite exposure on respiratory symptoms and lung function. The study did not look at bauxite residue exposures specifically although most of the components are shared.

4.1.5 Air emissions during normal operations and nearby community health

The ground level concentrations (GLCs) of air emissions from alumina refineries, including residue areas, are typically assessed using air quality monitoring and air dispersion computer modelling. Short-term GLCs are used to assess the risks of acute health effects. Annual average GLCs are used to assess the risks of chronic health effects and incremental carcinogenic risks.

Health Risk Assessments (HRAs) compare GLCs with health guideline values for each of the emissions, and conservatively estimate the risk of acute health effects, the risk of chronic health effects and the incremental risk of cancers. HRAs at alumina refineries, including residue areas, have recently been reviewed⁹. The risks of acute health effects at the studied refineries were adequately controlled and the risks of chronic health effects including cancer were found to be negligible.

A study specifically on the health risks of fugitive dust from bauxite residue areas found PM₁₀ was the dominant contributor to acute health risk⁹. Constituent metals present in bauxite residue dust typically made up less than 2 % of the acute health risk. The risks of chronic health effects and cancer were small. GLCs of PM_{2.5} near residue areas in Western Australia are typically only about 6 % of GLCs for PM₁₀, so compliance with PM₁₀ standards will deliver compliance with PM_{2.5} standards.

While it is possible for PM₁₀ GLCs to be above short-term health standards very close to residue areas, with good dust control management, these periods should be uncommon and minor, and unlikely to create significant additional health risks.

There is the potential for coarse dust (TSP – total suspended particulates) to settle on surfaces at neighbouring residences, especially over time. This amenity impact can lead residents to worry about the potential for health effects.

Non-inhalation pathways have been assessed in alumina refinery HRAs. These pathways include soil ingestion, dermal absorption, vegetable ingestion and water ingestion. Metal exposures via these pathways were found to make minor contributions to health risks compared to the inhalation pathway⁹.

4.1.6 EU legislation relating to titanium dioxide

New European Union (EU) legislation (Regulation EC 1272/2008 of the European Parliament and Council, 18th February 2020), covers the classification, labelling and packaging of substances and mixtures sold in the EU, and is relevant to both bauxite and bauxite residue. It relates to the hazardous nature of titanium dioxide in mixtures, and will come into force in member countries on the 1st October 2021. The legislation specifically covers titanium dioxide; other titanium containing species are not included in the assessment.

The legislation will mean that powders containing more than 1 % respirable ('having an aerodynamic particle diameter of 10 µm or less') titanium dioxide will be classified as possible carcinogens (STOT RE 2 classification). There will also be an impact on all powder mixtures with more than 1 % titanium dioxide, regardless of the size of the titanium dioxide particles.

Almost all commercial bauxites in the world contain more than 1 % titanium dioxide, normally as the minerals anatase or rutile. The titanium dioxide present in the bauxite is generally coarse, and the amount with an aerodynamic

particle size of 10 µm or less, is invariably much lower than 1 %. However, as a precautionary measure, from 1st October 2021, bauxites sold into the EU should carry the EUH phrase 212: "Warning! Hazardous respirable dust may be formed when used. Do not breathe dust."

The sale of bauxite residue will be similarly affected. Virtually all bauxite residues contain some titanium dioxide and the majority contain more than 1 %. Consequently, from 1st October 2021, bauxite residues sold in the EU should carry EUH phrase 212. Bauxite residue that contains more than 1 % titanium dioxide with an aerodynamic particle diameter of 10 µm or less will be classified as a class 2 carcinogen by inhalation, requiring the additional H351 (inhalation) warning label; "Warning! Suspected of causing cancer by inhalation.", and the GHS08 pictogram.

EU waste categorisation criteria are also in the process of being amended, and the presence of more than 1 % titanium dioxide with an aerodynamic particle diameter of 10 µm or less, could mean that such bauxite residues will be regarded as a hazardous waste.

The new legislation gives no guidance as to how the aerodynamic particle diameter of the powder should be measured, so the International Aluminium Institute along with the alumina industry has begun studying how best to measure this characteristic, and how much of the titanium dioxide present has an aerodynamic particle diameter of 10 µm or less. The work to date suggests that titanium dioxide particles with an aerodynamic particle diameter of 10 µm or less are much less than 1 %, but the work is ongoing.

There are legal challenges to the legislation in the European Court of Justice which will take several years, and which could change the legislation. Whilst only applicable to the EU, this new legislation could influence regulators in other jurisdictions when they consider updating their regulations.

More detailed document(s) on this subject will be issued by the IAI in due course.

4.2 Residue utilisation and related Health and Safety risks

Products or applications using bauxite residue as a dominant input have various levels of treatments or processing to ensure they are suitable and safe for purpose. These treatments often address the same attributes which present health or safety risks. High causticity and salinity, for example, are generally problematic for many uses of residue, and need to be addressed by washing, neutralisation or dilution before use.

Generally speaking, processes and products will have their own risk assessment processes where health and safety risks are identified and managed accordingly. Rather than list specific or general risks here, we refer readers to relevant studies for specific applications.

5

DEPOSITION AND CONSOLIDATION METHODS



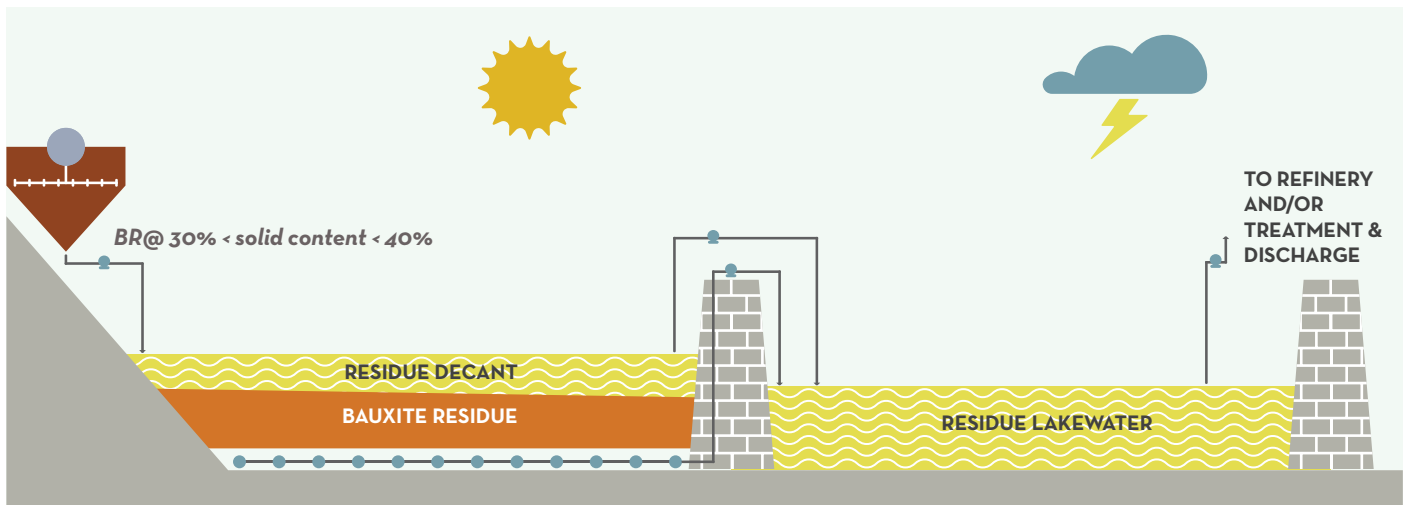
KEY POINTS

- The vast majority of residue produced and to be produced in the near future will be deposited in residue storage facilities and ultimately converted to a safe and stable landform capable of supporting vegetation.
- The technologies for depositing, dewatering and consolidating residue in BRSFs to make them geophysically stable has improved over the history of the alumina industry, and continues to be improved. This has been facilitated by improved washing and dewatering processes prior to storage.
- The improved deposition and dewatering technologies have dramatically reduced the land area requirement for residue storage, along with the risks associated with less dense storage approaches.
- The use of press filters prior to storage to achieve solids concentrations above 70% allows 'Dry Storage', where residue can be worked like soil, increasing the storage density and geophysical stability, further reducing risks.
- Once a storage method is adopted in a refinery, it can be (and often is) updated to newer improved technology, but some upgrades can be prohibitively expensive or adoption is limited by other factors. Similar results can be achieved by different methods.

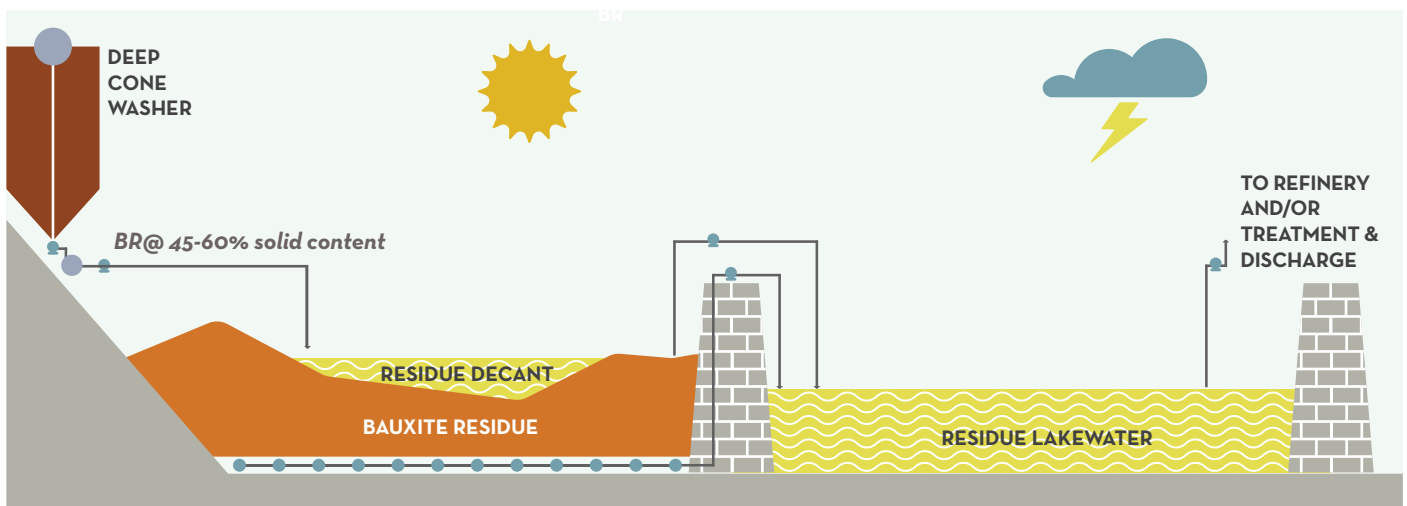
Only a minor proportion of bauxite residue produced finds its way outside of refineries' residue areas, so the overwhelming majority is stored in Bauxite Residue Storage Facilities (BRSFs). The processes used for handling and storage of bauxite residue is determined by factors such as the age of the refinery, land availability, proximity to the sea, local topography, climate, logistics, nature of the residue, and regulations.

In the early years of the alumina industry, refineries would dispose of residue on the operating site or on adjoining land, taking advantage of depressions, valleys and mine workings. Where convenient landforms did not exist,

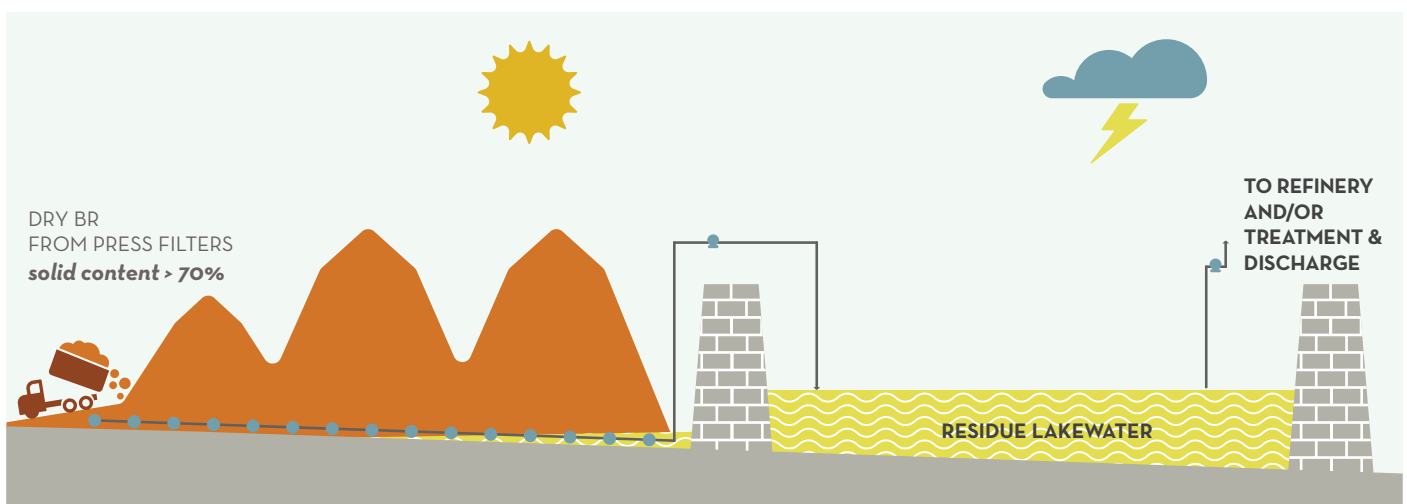
bunded areas or 'impoundments' were created. These storage areas were rarely lined, so alkaline liquor could leak from the deposited residue. Over time, major improvements have been made in the design and management of residue facilities to minimise the risk of environmental contamination and to make its transformation to a safe and stable landform at the end of its life easier and faster. Improved containment of the weak residue liquor with the use of HDPE and improved clay liners is an example. The alumina industry has devoted considerable thought and science to safe residue area management and closure strategies, which are now a key requisite of all modern operations.



LAGOONING



DRY STACKING



DRY STORAGE

Figure 12. Drying and Consolidation Technologies used in BRSF Operation

Through its magnesium and calcium salts, seawater can neutralise residue alkalinity and fix soluble metals, rendering residue more chemically stable, and for many decades it was considered to have a low impact on the marine environment. Discharging bauxite residue into the sea, rivers

or estuaries, was practised at a small number of refinery sites worldwide, but in accordance with the 1976 Barcelona convention and 1996 London Protocol, this practice has been stopped.

5.1 Lagooning or Ponding

Lagooning was the deposition method for most early alumina refineries. It involves pumping a dilute slurry (typically between 18-22 % solids) into depressions, old mine workings, areas impounded by dykes or levees, or dammed valleys. Sometimes these lagoons were lined to avoid seepage to groundwater, but most early operations were not. The solids would consolidate with time, expressing the liquor associated with the residue which was returned to the refinery. Over a prolonged period, the lagoon would be filled, solids consolidated under gravi-

ty with time, and the area could be rehabilitated. Figure 12 shows simplified schemes for Lagooning, Dry Stacking and Dry Storage technologies.

Due to the low solids density and the requirement to store large volumes of supernatant and rainwater, Lagooning requires a large land area, and as refinery production rates increased along with the need for better land utilisation, higher solids density solutions have been widely adopted.

5.2 Dry (or 'Mud') Stacking

As the land area constraints of Lagooning have called for higher density approaches, 'stacking' progressively became the dominant deposition method.

The concept of stacking tailings was first practiced in the mid-1960s when 'Thickened Tailings Disposal' was developed and first practiced. Its objective is to increase the



Figure 13. Mud Farming with 'Amphirole', and Bull Dozer working dry residue



residue solids concentration to a critical level at which the slurry yield stress begins to increase exponentially. At this point the slurry will still flow when pumped and when discharged at the BRSF, but without the solids settling out, due to the higher slurry viscosity. The residue slurry flow will stop at a gentle angle forming a 'beach' angle of between 2 - 6 % depending on the climate, with steeper slopes achieved in drier climates.

Using this method, a much larger volume of residue can be stored in the same area, so less total land area, levees, dykes or dams are required. When sufficiently thickened,

residue will not readily re-slurry, so rainfall will run-off the surface, permitting atmospheric drying and aiding consolidation. The higher solids concentrations allow more process liquor to be returned to the refinery, lowering the refinery's caustic soda consumption as discharge with residue. Where residue is continuously discharged onto a stack from a single point, it became known as 'wet stacking' and was adopted in wet and low-temperature climates.

For a stackable residue, it must be thickened to a high enough solids concentration that it will form a slope

above the horizontal when discharged as a slurry. The target solids content will depend on the characteristics of the residue, in particular its particle size distribution. As discussed above, at some alumina refineries, the fine residue (mud) is separated from the coarse 'sand' residue while in other plants the fractions are not separated. The

fine fraction of the bauxite residue may be thickened to a high density (48-55 % solids, or higher) by advanced thickener and flocculation technologies at the alumina refinery.

When residue is 'stacked' rainwater will tend to run off, minimising liquid stored in the storage area. The water re-



Figure 14. BRSF divided into bays, where it is deposited, farmed and dried sequentially.

claimed from the surface is pumped back to the refinery to recover the soluble sodium salts, or treated and discharged to the local environment. Stacked residue areas are often "under-drained" to improve the consolidation of the residue and recover further residue water. The combination of stacking and a well-drained deposit leads to a more stable landform.

Moisture and residual liquor in stored residue can be reduced by 'farming'. This involves working the residue surface with machines such as special bulldozers, or 'Amphiroles', a vehicle which is driven by screws which compact and leave trenches in the residue surface. Figure 13 shows examples of an 'Amphirole' and a specialised bulldozer for farming residue. The compaction and creation of channels accelerates dewatering and drainage of the residue in-situ. Residue is progressively deposited in layers of a few hundred millimetres deep, worked and left to dry before a new layer is added, farmed and dried. The larger residue

area is divided into sub areas or 'bays' at different stages of the farming cycle to maximise the operation's efficiency. Figure 14 shows a BRSF divided into bays in different stages of deposition, farming and drying.

The residue may be deposited with high moisture contents, so the vehicles used to make the troughs need to be able to 'float' on the wet residue surface. Solids contents of 60 - 65 % can be achieved by this process. Mud farming also promotes carbonation (by atmospheric CO_2) of any residual caustic, reducing the residue's pH.

In hotter, drier climates, higher evaporation rates can be utilised by 'thin layer stacking'. The residue is spread in layers of 0.3 to 0.5 m, over a wide area and is not covered with fresh residue until it has reached its target dryness of around 70 %.

Thickening technologies were developed to dewater

the residue slurry to solids content of up to 50 % and sometimes more. The slurries from these technologies approach the maximum solids content that can still be

pumped, and beyond this density other methods of transport from refinery to residue areas are required.

5.3 Dry Storage

Bauxite residue can be vacuum or press filtered to form a cake which handles like a solid (> 60 % solids). Water or steam can be used as a filter cake wash to reduce the alkalinity before being transported, stored or used. Plate and frame filters have been used for this purpose since the 1930s, and rotary vacuum filters since the 1960s. Improvements in equipment, especially press filtration, have led to higher solid content residues (more than 70 %) which are easier to handle. Press filters have been used for more than a decade in some refineries outside of China, and are now widely used in Chinese refineries, where

the majority of residue is now Dry Stored. Figure 15 shows a simplified press filter arrangement for thickening bauxite residue, and figure 16 shows residue being dry stored after press filtration.

Other technologies are being tested such as Hyperbaric (Hi-Bar) steam filtration (an enhanced disc filter) for residue, with solid contents of 77 % claimed. The ongoing search for better residue washing and drying technology continues.

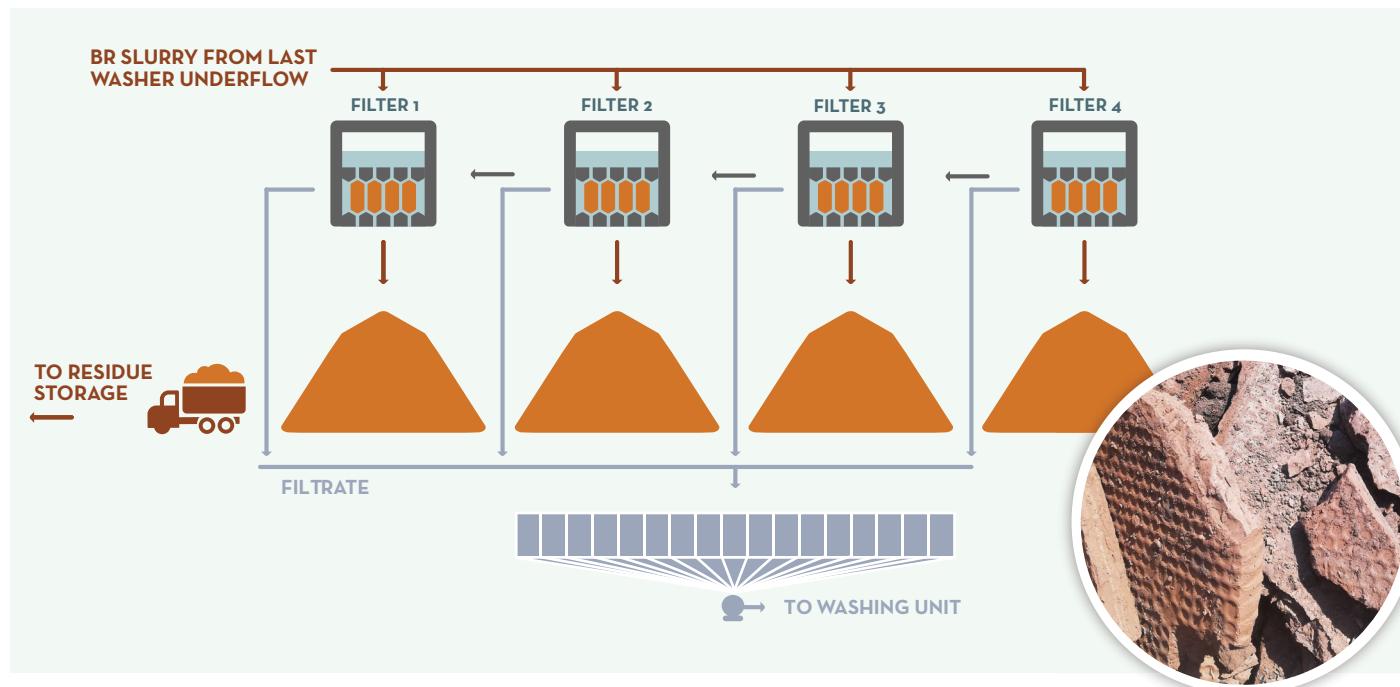


Figure 15. Simple Residue Press Filter Arrangement (L) and Press Filtered Residue (> 70 % solid content) (R)



Figure 16. Dry Stacking Residue from Press Filters

5.4 Case Study - Jamaican Innovations in Tailings Management

Jamalco has been refining alumina from bauxite in the Bayer process in Jamaica since 1972. Residue is deposited into residue storage areas for solar drying to an elevated density. Like many similar operations, Jamalco progressively manages and expands residue storage facilities to meet projected production rates. These facilities are costly to construct and manage, and equally challenging to close.

In 2017 the latest technologies (including Residue Filtration, and Accelerated Mechanical Consolidation (AMC) or Mud Farming and expansion of the existing high-density system) were evaluated. After a detailed review, AMC was adopted as it offered equivalent performance to residue filtration but at a lower overall cost.

AMC is the mechanical working of residue after deposition to force entrained water to the surface where it can be drained off and evaporated. The process requires repeated traverses of the MudMaster® (Twin Screw Archimedes Tractor) to effect drainage and consolidation, leading to a higher residue density and increased water recovery. AMC requires rigorous scheduling of tailings production, deposition and residue operations to maximise performance. The results achieved would not have been possible without the close co-operation of partners Phibion and Nalco.

Nalco (now Ecolab) has provided bauxite residue solutions in many refineries globally using its specialised chemistries. Nalco's work with Phibion at Jamalco required customised chemistries, which provided the residue rheology and hydrophilic characteristics that facilitates AMC.

Accelerated Mechanical Consolidation (AMC or Mud Farming) has two phases; the production phase where residue is poured to a depth of about 1 metre; and the recovery phase where the residue is ploughed several times with the Mud Master to achieve residue



Residue pouring (L) and early farming with Mud Master (R)



Mud farming at an Advanced Stage



Dried Mud after AMC (L), and Mud Master machine (R)

consolidation and strength.

The application of AMC at Jamalco has safely reduced newly deposited residue volume by over 30 %, increased final residue density by 20 %; and increased the strength of deposited residue to >30 kPa.

AMC has been transformational for Jamalco:

- Delivering a very high-density residue technology with zero capital expenditure;
- Integrated with existing operations with zero disruption;
- Delivered nearly all of the benefits of filtration without the cost;
- Allowed deferment of new residue storage facilities;
- Allowed incorporation of residue harvesting into normal operations to permit re-contouring of residue topography; and
- Underpinned the refinery's ongoing viability, sustaining employment for thousands and contributing to the economic and social well-being of Jamaica.

AMC is the mechanical working of residue after deposition to force entrained water to the surface where it can be drained off and evaporated. The process requires repeated traverses of the MudMaster® (Twin Screw Archimedes Tractor) to effect drainage and consolidation, leading to a higher residue density and increased water recovery. AMC requires rigorous scheduling of tailings production, deposition and residue operations to maximise performance. The results achieved would not have been possible without the close co-operation of partners Phibion and Nalco.

5.5 Case Study: CBA move towards conversion from wet to dry storage

Since 1955, Companhia Brasileira de Alumínio (CBA) has produced high-quality aluminium by integrated and sustainable processes. Able to generate 100 % of its energy demand from its own hydroelectric plants, CBA mines bauxite, and processes it into alumina, primary aluminum and downstream products. In close partnership with its customers, CBA tailors packaging and transport solutions and services, for lighter and longer life products.



CBA Complex at Alumínio City (L), São Paulo, Brasil; Palmital Residue Storage Area (R)

As part of its continuous improvement strategy, CBA is converting its bauxite residue storage facility from wet to dry deposition via filter press installation. An important and necessary step in this project is the removal of the existing liquor inventory inside the residue area to allow the sequential storage and stacking of the dry material in the same area.

CBA has invested in projects to further improve its residue management process. An ongoing project will use filter presses to dewater materials sent to Palmital Dam in Alumínio, located in the state of São Paulo, shifting from wet storage (~45 % solids concentration) to dry storage (75 % solids concentration). By investing approximately R\$ 300 million, in addition to further increasing the dam's safety, the project increases the BRSF life by 20 years, and increases the caustic soda recycled to the refinery. This project is forecast to start-up in 2023.

Removing the existing liquor inventory in the Palmital BRSF must be achieved before the filters start-up. The best way to achieve this is recycling the liquor to the refinery, recovering caustic and dissolved alumina. However, the liquor is high in impurities, which must be removed before returning it to the refinery process.

CBA has developed a causticization process to remove carbonate from the liquor, with high efficiency reaction conditions and a 10 tph filter press to separate the calcium carbonate produced from the treated liquor. This technology was commissioned in 2016, allowing the return of more than 1.5 million m³ of liquor to the refinery, or around 70 % of total liquor volume in Palmital Dam, with minimal impact on the refinery.



10 tph Sodium Carbonate Filter Press (L) and Calcium Carbonate Discharge (R)

The high purity calcium carbonate produced has a very low moisture content, and a study showed this material to be an excellent soil pH amendment. Currently, CBA applies this material at the Mirai mine, in Minas Gerais state, in the rehabilitation of mined areas.



Sodium Carbonate Application at the Mirai Mine in Minas Gerai.

In 2021 the first step in conversion from wet to dry storage, the liquor reduction will be completed and Palmital Dam will be ready to receive press filtered bauxite residue in an even more sustainable operation.

5.6 Case Study: Norsk Hydro Brasil's Alunorte Residue Filter Press Retrofit

The Alunorte refinery, with annual production capacity of 6.3 million tonnes, uses enhanced dry-stacking storage technology, which includes an improved residue filtration step and a mechanical compaction. Alunorte is now using press filtration technology before transporting the residue to its BRSF. This press filter technology produces a filtered cake with lower moisture content (22 %), which allows for the cake's further mechanical compaction and storage on steeper slopes, reducing storage area requirements and its environmental footprint.



External (L) and Internal (R) Views of The Alunorte Filter Press Building

5.7 Case Study: Implementation of Residue Dry Storage at CHALCO Zhongzhou

The dry storage process for bauxite residue has relatively low requirements for drying area, and is less sensitive to climatic, topographical and geological conditions. The physical properties of the residue as a press filter cake are significantly improved compared to wet residue, which allows using residue for dam construction, and due to the higher safe stacking density, improves land use efficiency. The dry storage process has become the industry standard for Chinese refineries, especially for new projects.

The Aluminum Corporation of China's (CHALCO) Zhongzhou refinery (the former Zhongzhou Branch, CHALCO) is located in Xiuwu, Jiaozuo, Henan, China. About 2.3 million tonnes of bauxite residue is produced annually. The wet stacking method previously used, has been changed to the benchmark dry stacking method using press filters. As a result, the land use efficiency has increased by 30 - 40 %, with both environmental and economic benefits.

A diaphragm pump is used to send the residue slurry from the underflow of the last washer to a filter press process in the BRSF area, where it enters a filter feed tank, before being forwarded through a feed pump to the press filter. Finally, the filtered residue is transported to the designated storage location by truck or conveyor belt.

The filter plate area used is 600 - 800 m², the moisture content of filter cake typically controlled between 27 - 30 %, with the operating efficiency of the filter press above 95 %.



Filter Press Discharge



Residue Dry Storage at
CHALCO Zhongzhou

6 DESIGN AND PLANNING FOR A BAUXITE RESIDUE STORAGE AREA



KEY POINTS

- The design of a refinery's washing and thickening processes and Bauxite Residue Facility must be based on the properties of the residue and the geological, environmental and social context of the BRSF.
- Stakeholders are engaged, ecosystems baselined and environmental impacts assessed, risks identified and managed, and compliance with legislation assured.
- Thorough review, consultation, informed design and long-term planning is key to a safe and low risk operation to the local community and environment and ultimately the refinery owner.
- Design for geophysical stability of residue dam walls are a critical consideration. Recent disasters caused by tailings dam failures including the Hungarian Ajka residue dam failure have brought ever further focus and regulation of this aspect of BRSF design. A widespread review of BRSF stability, more rigorous regulation and monitoring along with industry moves towards higher density residue storage have dramatically lowered the risk of further incidents in BRSFs.

The design of a bauxite residue storage facility (BRSF), and its operating and closure plan are based on the chemical and physical properties of the residue and the geological, environmental and social setting at and around the proposed site. Planning will always involve the regulatory authorities, local communities and other key stakeholders. Figure 17 maps out key considerations and relationships in the design and planning of BRSFs.

Potential environmental, social, economic, health and safety risks must be identified¹⁰, and plans for environmental management, monitoring, closure and rehabilitation must result in acceptable environmental outcomes and risk mitigation for the life of the operation and beyond closure.

A risk assessment process is established early in the planning of a new BRSF, reflecting current risk assessment

methodology (e.g. AS/NZS 4360:2004)¹¹. Risk assessments should establish the geographical, social and environmental context, identify hazards, analyse and characterise the risks against the design criteria, and identify the options for mitigation of significant risks. Particular consideration is given to the likelihood of earthquakes, tsunamis, hurricanes, and severe storms which might impact on the integrity of the BRSF.

Existing local conditions are measured and recorded for establishing an environmental baseline prior to development of a BRSF. These include; groundwater levels and quality, water content and geochemistry of foundation soils and rocks, air quality, fauna and flora, background radiation levels, underlying geology and hydrogeology and any history of extreme weather events.



Figure 17. BRSF Planning, Design and Operating Elements and Relationships

The physical and chemical characteristics of the bauxite residue are measured, monitored against target KPIs and reported over time. Changes to these characteristics are carefully assessed to determine any potential impacts on existing practices and future management of the site.

BRSF operators take responsibility for meeting performance standards set by government regulators, and always look for continuous improvement. Negative environmental impacts on land, water, air, fauna and flora are avoided where possible, and any impacts on the area's environmental values should meet objectives agreed with stakeholders. Public health and safety are always a high priority.

Rigorous monitoring and transparent reporting drive and demonstrate progress towards, and achievement of agreed environmental outcomes, and corrective action where not achieved. The organisation responsible for the BRSF implements a suitable management system (including contingency plans) with adequate training and

resourcing, and with transparency about compliance with the management plan.

Successful bauxite residue management is achieved by the planning, design, operations and closure teams having an integrated action plan and open communication. Monitoring aspects of operational performance (e.g. ground and surface water management), reporting relevant KPIs and responding to deviations from them are key to success.

Having and reviewing an integrated life cycle plan is important to keep focus on long term objectives. Ensuring there is enough space available to reliably deliver the wider and longer term BRSF and operational process design is an important element. Figure 19 illustrates the key elements required for BRSF design and operating success.

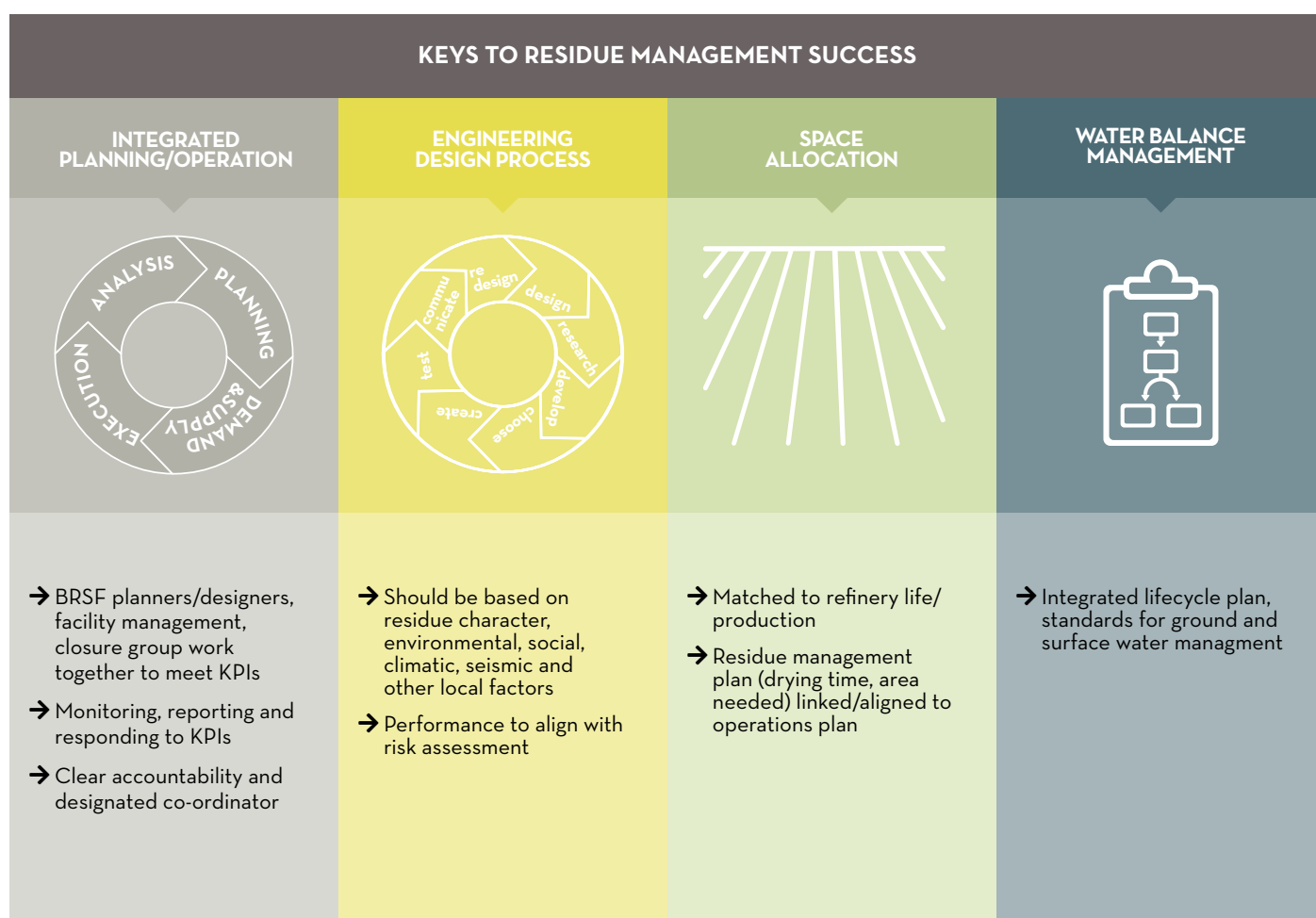


Figure 18. Keys to BRSF Management Success

6.1 Storage Facility Design Criteria

Due to the long-life and long-term nature of BRSFs, and to ensure they have a low human and environmental impact, a broad set of criteria are considered by the design process. Design criteria of a bauxite residue storage facility

include; residue characteristics and production rates, operating life, water balances, history of extreme meteorological and seismic events, and proximity and potential impacts on local communities and environments.

6.2 Physical Stability

A critical aspect of BRSF design is ensuring the physical stability of walls and embankments to minimise the risk of failure and outflow of residue into the surrounding area. This requires an understanding of the geological foundations on which these structures are built and the selection of materials to ensure their stability in the case of extreme local weather or seismic events.

This aspect of BRSF design and monitoring is understandably heavily regulated, and the standards of design, construction and monitoring through their life-cycle are carefully considered and reviewed. In this respect, BRSFs are in many ways the same as the ‘tailings dams’ used for containment of mining and mineral processing residues from other products such as copper, gold, nickel, coal, etc. For this reason, design standards and regulation are common or similar and there is collaboration and alignment on both the design and operation, and regulatory best practice.

A number of tailing dam failures across the mining industry















RESIDUE AREA DESIGN CRITERIA						
METEOROLOGICAL, SEISMIC & GEOLOGICAL CONTEXT	LEGISLATIVE FRAMEWORK	LOCAL COMMUNITY	LOCAL ENVIRONMENT	REFINERY	WASHING AND DEWATERING	BR STORAGE FACILITY
						
						
<ul style="list-style-type: none"> → Rainfall/evaporation rates → History of extreme weather → Seismic history → Local geology, geophysics, topography 	<ul style="list-style-type: none"> → Public health and safety → Community and environmental compliance targets 	<ul style="list-style-type: none"> → Proximity to habitations, recreational facilities → Impacts on other businesses → Air quality baseline and sensitivities → Rehabilitation expectations → Public amenity impact expectations 	<ul style="list-style-type: none"> → Proximity to local ecosystems → Groundwater systems and environment, social, agricultural or industrial importance 	<ul style="list-style-type: none"> → Residue production rates (annual rates and variance) → Life of operation 	<ul style="list-style-type: none"> → Geochemical properties influencing operation and closure choices → Solids content → Sand separation 	<ul style="list-style-type: none"> → Water return capacity/limits → Rehabilitation expectations

Figure 19. BRSF Design Criteria

dustries have demonstrated the devastating impact of failures, especially where communities are downstream. Deaths, injuries, severe property and environmental destruction can result.

The 2010 Ajka residue dam failure in Hungary and its tragic and disastrous impact on the local community and environment was one of the very few such failures in the Alumina industry, although a number of tailings failures in other industries have underlined the risks and modes of failures to be managed.

Apart from seismic activity, heavy rainfall events causing water to overflow embankments is a common cause of

tailings facility failures. This is the reason why BRSFs (and tailings storage facilities generally) are required to have a safety limit to water storage levels to ensure that a period of exceptional rainfall, will not result in water overflowing walls uncontrollably. When water overflows in an uncontrolled way, the embankments can be eroded and breached, and a residue slurry may be mobilised by the running water, resulting in a flowing residue slurry.

As refineries become older than their design life, and BRSFs may exceed their original design capacity, appropriate reviews and engineering studies are required to ensure BRSFs have stable foundations and appropriate water storage buffers.

6.3 Construction

Residue storage facilities are designed and constructed by suitably qualified and experienced organisations, with equally appropriate supervision, and quality control over

construction materials and practices. Design specifications should meet appropriate standards and reflect local conditions, and construction fully quality controlled.

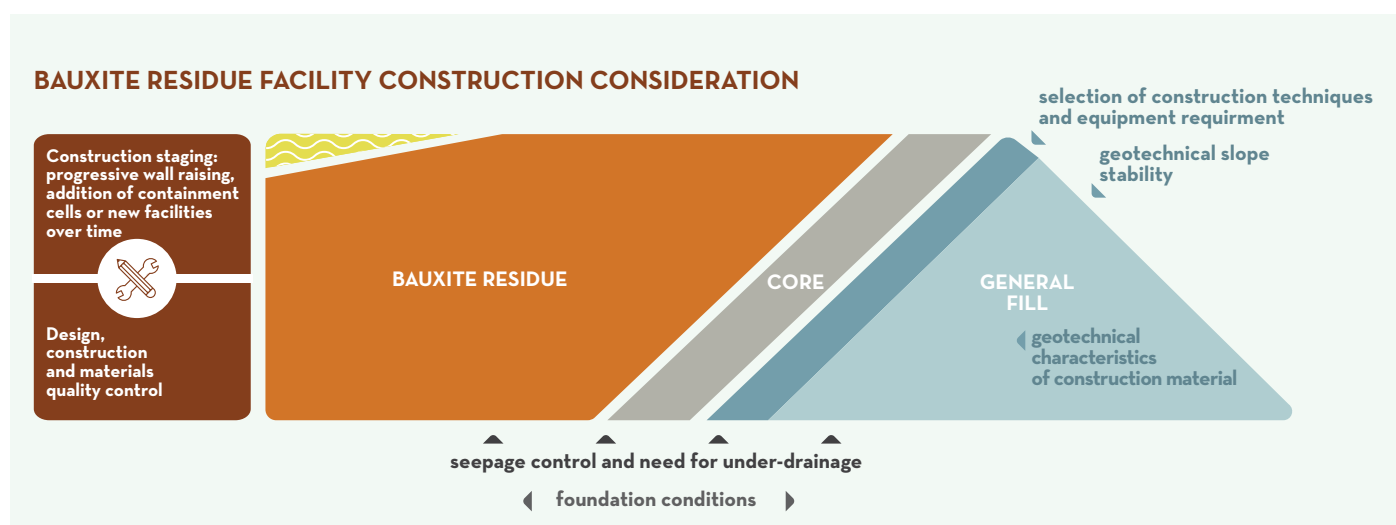


Figure 20. Example of design elements for BRSF

6.4 Seepage control

Control of any seepage of alkaline residue water to the underlying soil, geological structures and water table is an important objective. The hydraulic characteristics of the BRSF foundation and storage walls are key factors, as is the presence and value of groundwater under and near-

by to the BRSF. Boreholes are usually drilled around the BRSF and ground water is tested regularly to monitor and identify any seepage.

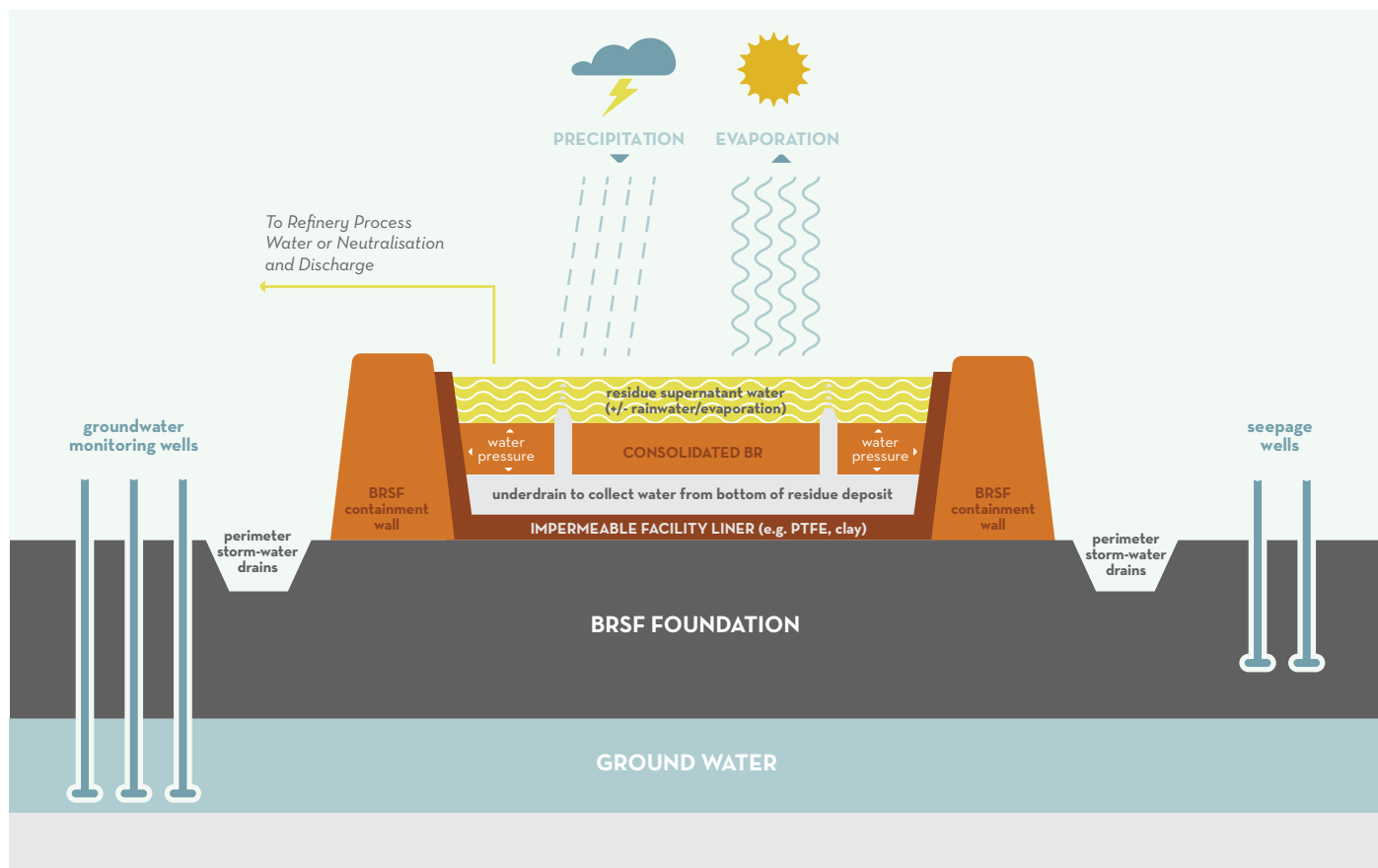


Figure 21. Example of Seepage management in BRSF design

6.5 Case Study: Using Filtered Bauxite Residue for an Engineered Landfill at EGA

Emirates Global Aluminium is the world's largest 'premium aluminium' producer, and makes about 4 % of global aluminium production. In 2019, EGA commissioned its first alumina refinery, the 2 mtpa Al Taweelah refinery on the coast of Abu Dhabi, and began operating its Bauxite Residue Storage Area (BRSF), located some 35 km inland. Regulatory approval for the refinery's construction required a commitment to research residue re-use while applying the highest standards in residue management.

Abu Dhabi Ports (ADPC), which owns the land on which the Al Taweelah refinery and BRSF is built, provided very specific criteria for its design and operation. To meet these requirements, rigorous engineering design followed by operational excellence was required.

EGA contracted Golder Associates (Melbourne, Australia) in early 2016 for Front End Engineering Design (FEED) and Detailed Design, including initial lab work to determine the Maximum Dry Density (MDD), Optimum Moisture Content, and other critical residue properties. The scope included drawings, specifications, construction guidance for the HDPE and Geo-Synthetic Clay Liner, embankments, and an Operations Manual.

The BRSF is designed to be 20 meters high, in four 5-metre lifts, constructed progressively using filtered bauxite residue. The first stage is designed to last 7-8 years. The operating team's challenge is to increase compacted residue densities and filling efficiencies, extending its life and delaying or eliminating any required expansion.

The key elements of the Al Taweelah BRSF management process were the initial laboratory testing and trial pad, the compaction monitoring process, and dust suppression management.

Initial Laboratory Testing and Trial Pad

Bauxite residue management began in March, 2019, with all residue transported to the BRSF in the first 7 weeks spread as a first layer, to quickly cover the sand base. A local soil laboratory sampled residue and tested for density, to measure the compaction equipment performance, and the minimum compactor passes required to achieve 95 % of the trial field density.



Compaction Monitoring Process (L) and BRSF Bay Layout (R)

Residue is placed and compacted in 300mm layers, which is monitored continuously. The 60-hectare BRSF is divided into 8 to 10 smaller bays for sequential residue placement and compaction. Bay access is via a central haul road with secondary haul roads and access ramps. In-situ density checks are critical to achieving BRSF operations objectives. After placement, rolling and compaction, density is tested using either a Nuclear Density Meter

(NDM) or sand cone (ASTM D6938). Surface runoff and settlement is monitored continuously, with external topographical surveys performed at least every quarter, while surveying for daily operations is performed in-house. Monitoring is to ensure residue thickness is 300 mm +/- 20 mm, and records are submitted to Al Taweelah BRSF Civil Engineer and registered land surveyor on a monthly basis.

Dust Suppression Management

Al Taweelah's BRSF is located in a desert. Although well buffered, surrounding land holdings are at risk of residue dusting due to sand storms and ambient temperatures of up to 50 °C. Water is not readily available at the BRSF site, so sustainable management of the 2 principal dust suppressants is crucial:

1. Neutralised slurry, a byproduct of the refinery process, trucked to the BRSF, stored in settlement ponds, and decanted to a Clarified Liquid Pond, and
2. Seawater, which is also trucked to the site, and stored in a dust suppression pond.

Laboratory simulations show that neutralised slurry is a better dust suppressant (and the first option) compared to seawater, forming a crust on the dried residue surface. Seawater is used when neutralised slurry is unavailable. The table below shows the relative demand for dust suppressants (neutralised slurry vs. seawater) and the effect on daily demand.

Average water demand for phase 1 dust suppression				
Scenario	Neutralised slurry liquid (m³/d)		Seawater (m³/d)	
	September-May	June-August	September-May	June-August
Upper limit	198	396	175	468
Mean	145	246	203	322
Lower limit	60	64	124	126

Two weather stations on site provide data on dust particle loadings (PM10) upstream and downstream of the BRSF. EGA reports dust loading and wind direction data quarterly to the environmental regulators as part of the environmental operating permit requirements.

6.6 Bauxite Residue Transportation

The handling characteristics of the residue along with the dewatering method are major factors in the choice of transport options for conveying the residue from the refinery to the BRSF. The moisture content of residue changes its handling (rheological or flowability) behaviour, when vibrated, agitated or pumped. This means that while at rest, the material may look solid, but when shaken (such as in the tray of a moving truck or in a pipe or the impellor of a pump), it will begin to behave like a liquid.

If press filters are employed to dry the residue to solid contents around 70 %, the material will almost always be above the point where it can flow, and can be trucked or put on a conveyor belt without the risk of liquefaction. The use of vacuum filters to achieve solids contents of around 60 % can also allow trucking, but depending on the residue's specific properties, it may require a different type of truck and approach to handling.

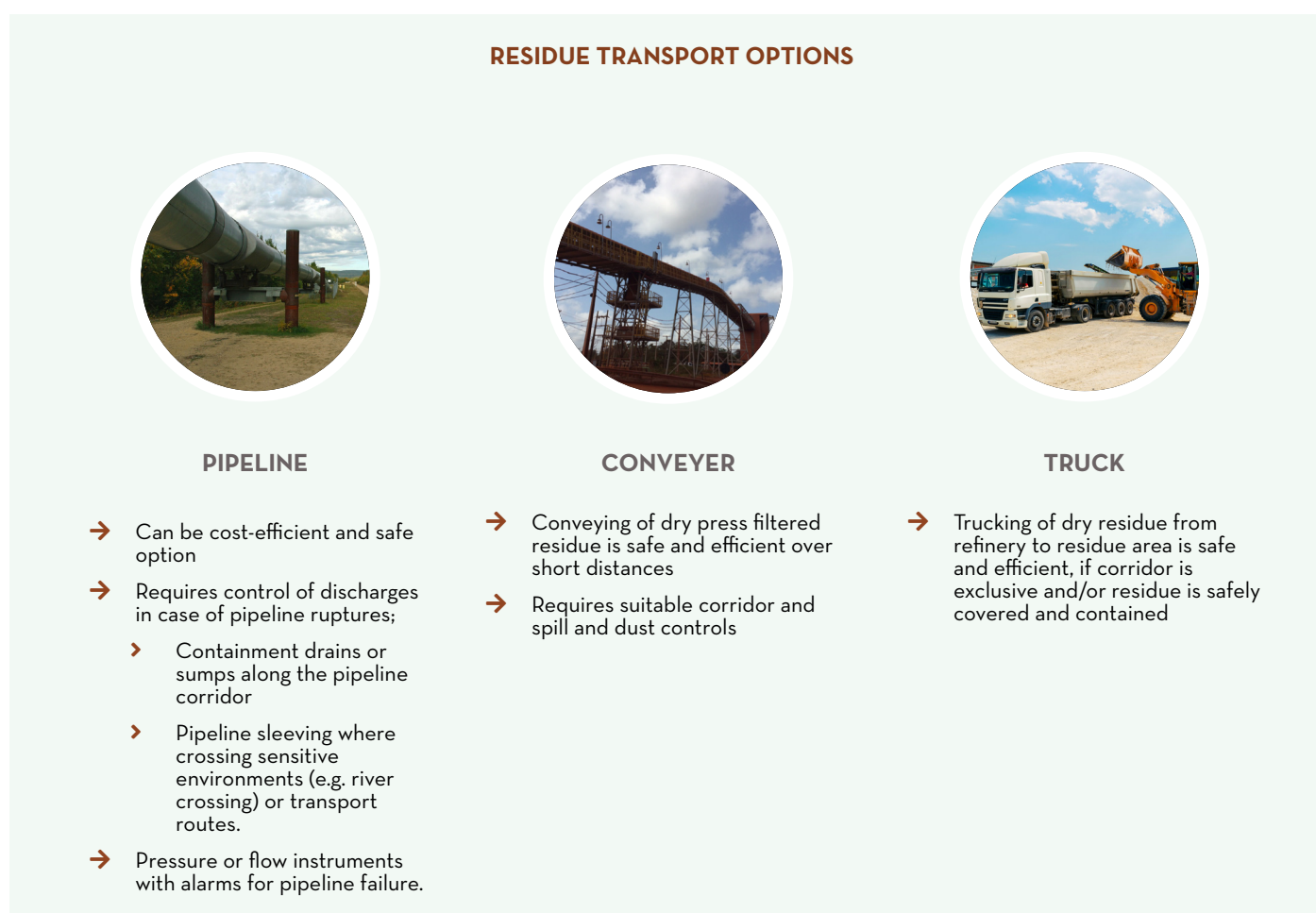


Figure 22. Residue Transport Options

Residue can be transported from refinery to BRSF in several different ways including slurry pumping in pipelines, conveyor belts (where residue is dry enough) and trucking. The distance to the BRSF, and whether an exclusive pipeline or conveyor corridor, or road for trucking is possible are also considerations in the choice of transport route and methods. Figure 22 illustrates the transport options commonly used in the alumina industry.

Where distances are relatively short between refineries

and residue areas, pumping has many advantages, but as distances increase, while still possible and can be practiced safely, pumping becomes more technically challenging, and costs and risks increase.

Where press or vacuum filters are employed to produce 'dry' residue, they are often sited at the refinery, and the dry material trucked or moved on a conveyor to the residue area. Alternatively, the filters may be sited at the residue area, and residue slurry from the refinery may be

pumped to the BRSF where it is then filtered 'dry' and moved short distances by trucks or earthmoving equipment for deposition.

The combination of the transport corridor design and transport method should allow protection of the environment and any nearby communities, agricultural or business activity, against the effect of spills due to possible pipeline leaks, failures or accidental breaks. Access to a pipeline and space for the clearing of spills and blockages is essential. Pipeline routes need to be inspected regularly.

Where trucking or conveying of residue is practiced, elimination or minimization of solid spills and dust is a key objective. Where possible, site transport roads or pedes-

trian paths and active residue pipelines are separated. It is also necessary to be able to contain and control any leaks or spills through the use of technology designed to sense failures and stop pumping, bunding and sumps, and removal of the pipeline from trafficked areas.

A reliable system for real-time monitoring of residue transportation is always required. Pipeline spill or trucking accident plans are prepared and tested and all responses to failures/incidents are recorded for continuous improvement.

6.7 Case Study: Low Visibility Technology for Residue Transport at Al Taweelah

At the Al Taweelah refinery, transportation by truck along a public highway is currently the only way of moving residue to the BRSF. Visibility or ‘visual range’ is the longest distance at which an object can be recognised against the horizon, and “good” visibility is the ability to see and recognise objects more than 5 km distant. The UAE sometimes experiences low visibility, due to heavy fog, dust storms or rainfall, increasing the risk to commuting staff, and to residue trucks travelling between the refinery and BRSF.

In March 2018, Al Taweelah’s EHS Steering Committee commissioned a study to provide guidance on safe travel to work in reduced visibility, and in Q3, 2018 issued the Safe Work Practice (SWP) “Safe Journey in Low Visibility”, which referenced “General guidance for employers and workers in inclement weather conditions” and “Technical Guideline Dealing with Adverse Weather Conditions”, by the Abu Dhabi Occupational Safety and Health Center (OSHAD).

Al Taweelah’s leadership also reinforced safety in residue trucking during low visibility, and in parallel with the ‘Safe Journey’ SWP development, residue trucking in low visibility was considered. Among the documents researched were “Minimum Acceptable Visibility (MAV) on Highways due to Smoke” and “Best Practices for Road Weather Management”, published by U.S. highway authorities. These guides present the theory and calculations for MAV, including studies done by U.S. States on low visibility warning and communication systems, control strategies for various road conditions, and insights into low visibility sensing and reporting systems.

After review of low visibility best practice, a review of available technology and vendors followed. Biral was found the most suitable option from a technical and performance standpoint, and their UAE partner (Microstep – MIS FZE), had a record of successful local installations for private and government entities. www.microstep-mis.com

Visibility Distance	Advisories on DMS	Other strategies
Less than 900 feet (274.3 metres)	“FOG WARNING”	Speed limit at 65 mph (104.5 kph)
Less than 660 feet (201.2 metres)	“FOG” alternating with “SLOW, USE LOW BEAMS”	“55 MPH” (88.4 kph) on VSL signs “TRUCKS KEEP RIGHT” on DMS
Less than 450 feet (137.2 metres)	“FOG” alternating with “SLOW, USE LOW BEAMS”	“45 MPH” (72.4 kph) on VSL signs “TRUCKS KEEP RIGHT” on DMS
Less than 280 feet (85.3 metres)	“DENSE FOG” alternating with “SLOW, USE LOW BEAMS”	“35 MPH” (56.3 kph) on VSL signs “TRUCKS KEEP RIGHT” on DMS Street lighting extinguished
Less than 175 feet (53.3 metres)	1-10 CLOSED, KEEP RIGHT, EXIT	1/2 MILE Road Closure by Highway Patrol

The Microstep-MIS scope of work included an early warning system using self-powered fog sensors, and coordination with the Government for installation along the route. The devices were eventually installed on EGA property, so the need for Government approval/ coordination diminished. Government regulations and traffic safety rules have evolved, and the installation of highway notice boards with visibility sensors has led independently to more science-based management of traffic during low visibility.

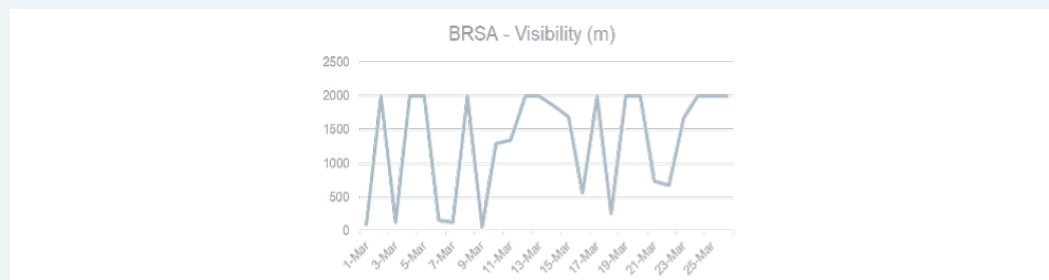
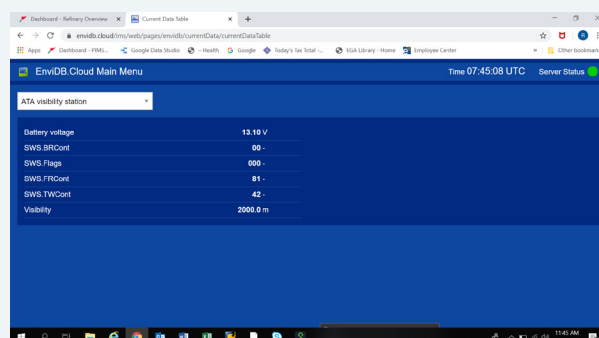
Based on U.S. and OSHAD guidance, “Low Visibility” is below 400 m, and an email alert is sent once readings below this value from the installed sensors are received, with sign

panels set to give visual alerts.. Visibility below 100 metres is considered catastrophic or “No Visibility”, and hauling is stopped until visibility is restored. Al Taweelah’s residue production is directed to an emergency stockpile during low visibility periods, and reloaded once trucking resumes.

A third party manages EGA’s visibility information via the IMS EnviDB.Cloud, now on Al Taweelah’s Process Information Management System (PIMS), for broad organizational access.

The data generated allows visibility to be a planning input. Real time data allows timely trucking suspension during low visibility, and restart with adequate visibility on a scientific and data basis. The visibility sensor systems have proven valuable for the management of bauxite residue trucking, as well as for other aspects of refinery management.

Microstep - MIS installed the pilor visibility sensor at the entrance to the Al Taweelah alumina refinery in December 2018. After rigorous testing and ironing out os systems issues and gaining organisational acceptance, it was agreed that a second visibility sensor unit be installed at the BRSF in September 2019. Losistical and liability/land ownership issues have mitigated against the installation of additional intermediate visibility sensors. Microstep -MIS has since provided extensive training in the use and basic trouble shooting of the system and provides systems assistance on an ongoing basis.



7

GOVERNANCE AND PERFORMANCE TRACKING



KEY POINTS

- Clear accountability for residue management is key to maintaining performance against a residue management plan.
- Mapping and communication of responsibilities and accountabilities is required, as is a clear and wide understanding of the Residue management plan and related performance metrics (KPIs).
- A rigorous system for monitoring and tracking of the relevant refinery and BRSF processes and conditions are a prerequisite for meeting the design intention.
- Performance tracking is necessary to ensure compliance with residue management plans and to trigger remedial action when operations do not meet critical metrics.
- Tracking systems should ensure data is reliable and appropriate. It should be documented, with training provided to those required to maintain and use it, and it should be audited to ensure its fidelity.

7.1 Governance

Important to success in managing residue is clear management accountability for bauxite residue activities at all levels, especially the senior level, which requires a thorough understanding of design, operating and closure plans and objectives¹².

An operating manual is maintained for every BRSE, aligned with the facility's design objectives, to guide daily opera-

tion and forward operations and maintenance planning. The manual will describe, and the operators will receive training in, the facility's daily operation, residue deposition procedures, water management, dust control, critical operating practices such as pump and pipeline management and facility equipment maintenance, along with reporting requirements.

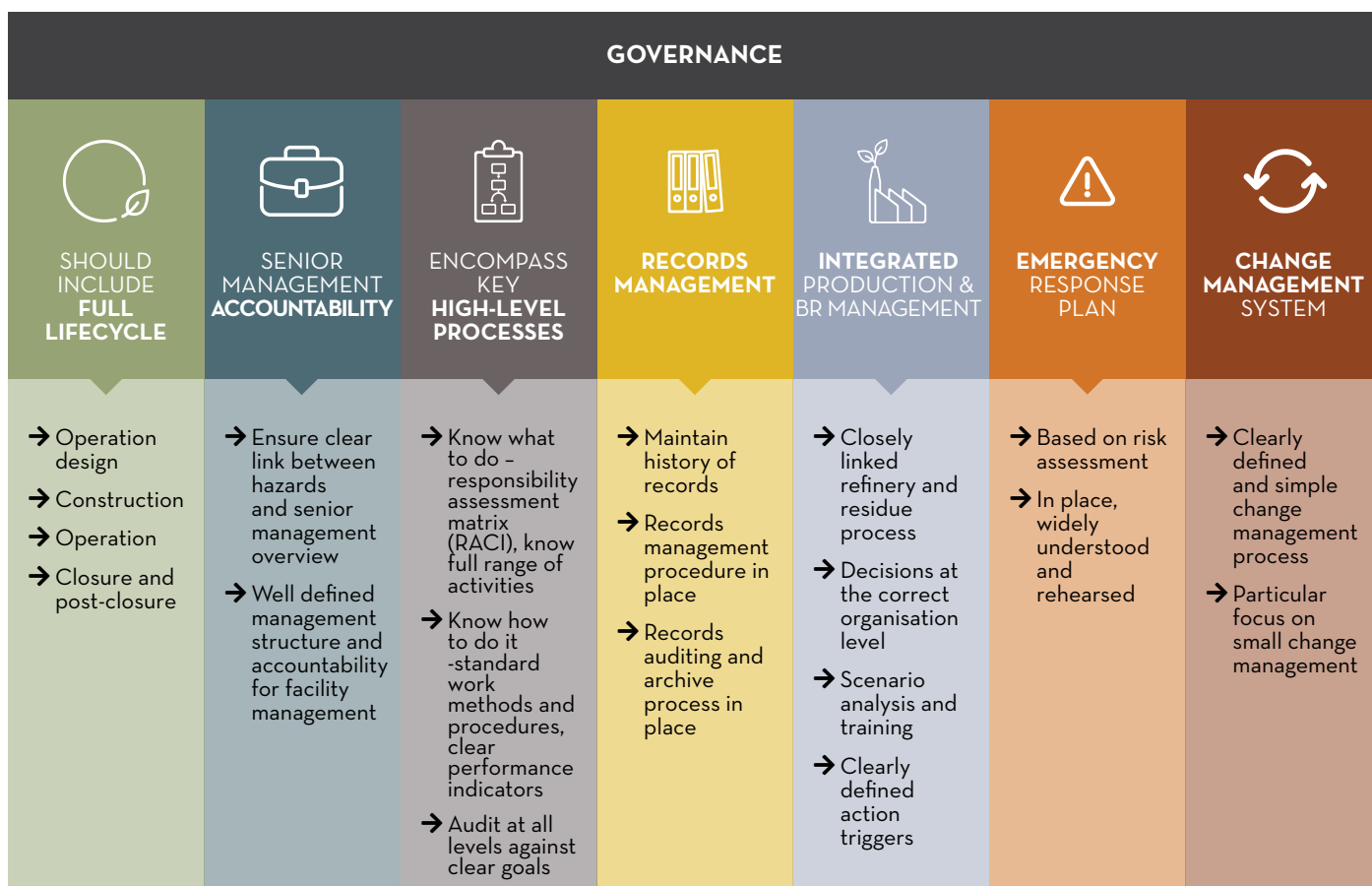


Figure 23. Elements of Good BRSF Governance.

Governance will cover the full BRSF lifecycle including design, construction, operation, closure and post-closure. It will cover knowing what to do (responsibility assessment matrix or ‘RACI’), and how to do it (standard work methods and procedures) and have clear performance indicators, and audited at all levels against clear goals.

There will be a Change Management System, with a clearly defined and simple change management process, with particular focus on the management of small changes. An Emergency Response Plan based on a risk assessment

should be in place, widely understood and rehearsed.

Senior management accountability ensures a clear link between hazards and senior management overview, with well-defined management structures and accountability for facility management. Integrated production and residue management organisations ensure that refinery and residue processes and metrics are closely linked with decisions made at the correct organisational level. A records management system will maintain the history of records, including records auditing and archive process.

7.2 Inspections and monitoring

Monitoring of bauxite residue facilities will include key indicators such as the properties of the residue sent from the refinery, the BRSF’s physical stability, the performance of the transport, deposition and consolidation processes, airborne dust loadings, groundwater beneath and surrounding the BRSF, and surface and ground water upstream and downstream of the facility. The complete list of inspections and metrics to be collected and monitored are usually prescribed by local regulatory agencies

and by the original engineering design and operating plan.

Frequent inspections of all bauxite residue storage facilities and associated pumping and pipeline systems are undertaken and recorded. Unusual conditions or maintenance requirements are documented and appropriate action taken, including reporting to regulators and the community.

MONITORING



Figure 24. BRSF Monitoring Targets

7.3 Emergency Response Plan

Bauxite residue storage facilities should have an emergency response plan, ensuring that in the unlikely event of failure, actions can be taken to minimise the risk to people on and off site, and to the environment, by responding in an organised and systematic manner. In some regions,

where BRSFs have been designated hazardous sites, regulations require emergency plans be provided to regulatory authorities. Elements of an emergency response plan are illustrated in figure 25.



Figure 25. Emergency Response Plan Elements

7.4 Performance Tracking

Performance tracking is key to achieving target performance and alignment with the BRSF design and operating plan. Vigilance is required to ensure departures from plans are identified early to allow timely review and corrective responses.

Tracking provides useful feedback to operations, enabling the delivery of the short-term operational plan. All levels of operational management should know and understand

their roles and responsibilities in performance tracking, and key residue management criteria.

Performance tracking quantifies adherence to the BRSF management plan through a combination of regular field observations by trained staff, and automatic data from suitable instruments. Optimal deposition controls for each operation are analysed, and tasks required for sustained BRSF performance are documented and justified.

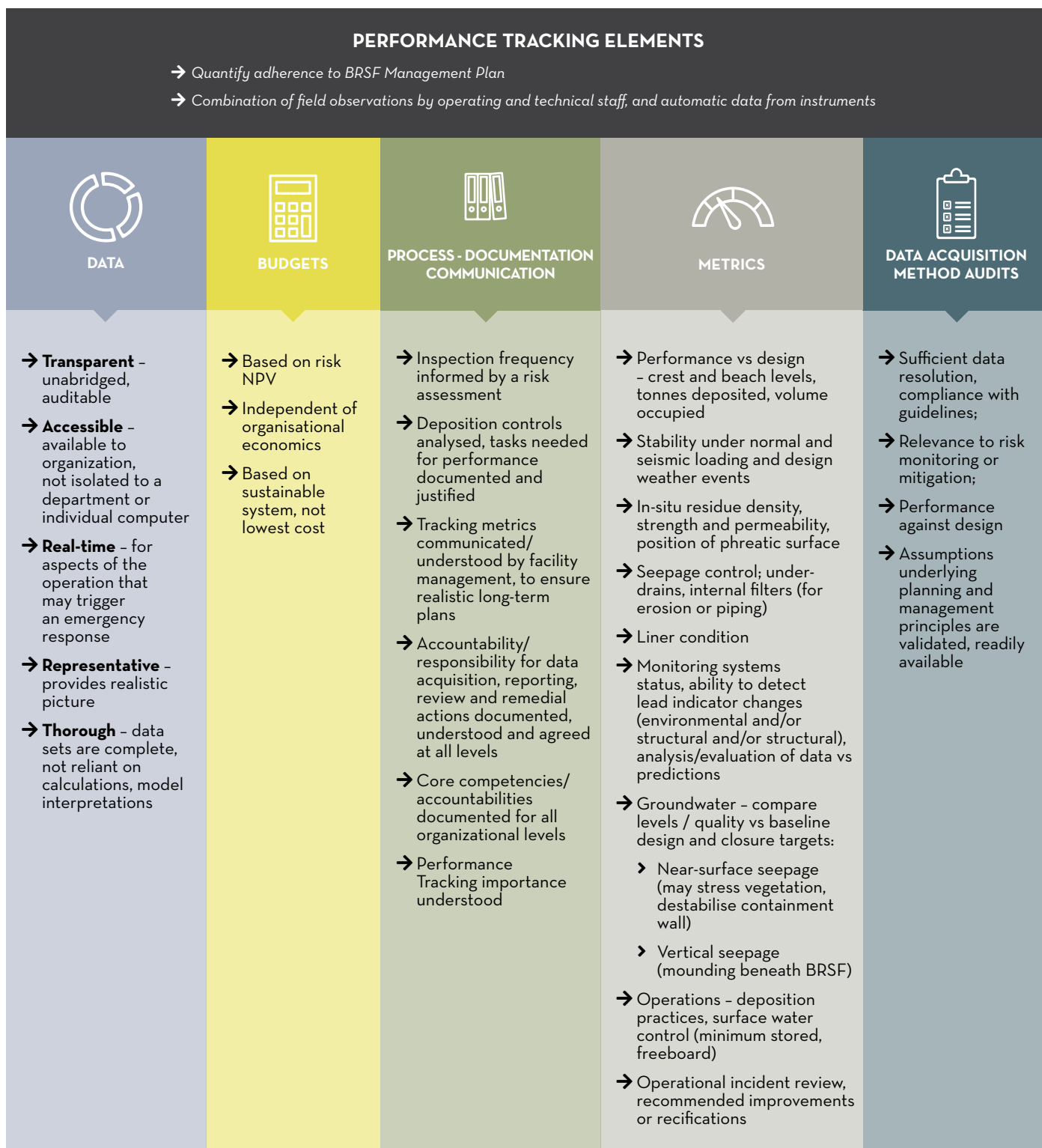


Figure 26. Performance Tracking Elements

The importance of Performance Tracking metrics needs to be communicated to and understood by BRSF management and staff, to ensure realistic long-term plans and forecasts. The accountability and responsibility for data acquisition, reporting, review and remedial actions for key metrics are documented, understood and agreed at all levels.

Documentation of core competencies and accountabilities for all organisational levels is key to sustaining performance tracking and reporting, and the importance of Performance Tracking needs to be fully understood. Regular reviews of the information flow should ensure ongoing adherence to the tracking system. A KPI system provides an easily tracked, progressive performance tool. Figure 26

lists key elements of performance tracking systems.

Data and KPIs should be transparent, accessible to the appropriate staff, real-time (particularly those that may trigger an emergency response), representative (a realistic view of actual conditions and performance) and thorough.

Policy and planning ensure the structure of the organisation and available resources are aligned with its ability to sustain the long-term plan. Training and accountability are clearly defined to ensure all levels of the organisation are adequately qualified to undertake performance tracking responsibilities.

Data is collected in a manner that is appropriate (thorough and representative) and managed to ensure it is transparent and readily accessible, allowing effective communication between all organisational levels.

Budgets for performance tracking should always be based on the significance of the risk and loss scenarios, including any risk to workers, communities and the environment, and guaranteed regardless of economic context. Automated data acquisition is preferred over manual sampling to better ensure reliable data tracking over a wider range of conditions. While costs are always a constraint, an appropriate and reliable data acquisition system which offers the best risk management is always the best investment.

Internal auditing of important aspects of residue management performance is required to ensure the monitoring system is providing an accurate picture of real operations. External audits are typically undertaken annually (if not more frequently) by an independent, qualified third party. Internal and independent audits will generally include data acquisition methods to ensure sufficient data resolution, compliance with guidelines and relevance to the risks and expected performance. Assumptions used in planning and management need to be validated, readily available and reassessed as required.

Audits should generally be undertaken at an appropriate frequency by an independent third party to ensure sus-

tained operational alignment with long-term plan and continued validation of key underlying assumptions.

A typical review will consider the following¹²:

- performance against design – crest and beach levels, residue tonnage stored and volume occupied
- assessment of stability under normal and seismic loading and design meteorological events, in situ residue parameters (density, strength and permeability) and position of phreatic (aquifer) surfaces
- performance of seepage control measures such as under-drains (for seepage control), or internal filters (which control internal erosion or piping)
- liner condition, where used
- history of extreme meteorological events
- status and condition of monitoring systems, their performance in detecting changes in lead indicators (environmental and/or structural), and the analysis and evaluation of monitoring data against predicted trends
- groundwater monitoring results – comparison of the groundwater levels and quality against the ‘baseline’ data and against design and closure criteria, considering:
 - near-surface lateral seepage which may stress vegetation or destabilise a containment wall
 - vertical seepage which may cause localised mounding beneath the storage facility
- operational performance – residue deposition practices (thin layer) and surface water control (minimum stored water and maintenance of required freeboard)
- assessment of operational incidents, and recommendations for improvements or modifications to rectify shortcomings.

7.5 Tailings Management Systems and Regulations

The standards and processes related to the safe management of BRSFs are closely related (if not common) to those of other mine tailings containment facilities. While some attributes and regulations may be different for some technologies and operating practices, BRSF’s are considered tailings facilities in many jurisdictions and covered by the same standards and regulations.

The alumina industry in general look to leading mining industry organisations to ensure their systems and standards meet or exceed practices in the wider mining industries, and to learn from the wider experience base.

The Mining Association of Canada (MAC) has been a leader in the development of systems and standards for

the management of tailings facilities for mining in Canada, and its management principles and standards are widely referenced in the alumina industry.

In 2020 the Global Industry Standard on Tailings Management was released¹³. The Standard sets a precedent for the safe management of tailings facilities, towards the goal of zero harm. It is directed at operators and applies to tailings facilities, both existing and to-be-built.

A critical aspect of BRSF design is ensuring the physical stability of walls and embankments to minimise the risk of failure and outflow of residue into the surrounding area. This requires an understanding of the foundations on which these structures are built and the selection of materials which will ensure stability in the case of extreme local weather or seismic events.

This aspect of BRSF design and monitoring is understandably heavily regulated and the standards of design, con-

struction and of their monitoring through their life are carefully considered and reviewed.

Heavy rainfall causing walls to overflow is a common cause of wall failures, and the reason why BRSFs are required to have a safety limit to water storage levels.

Figures 27 and 28 illustrate the life cycle management process and layers of a tailings management system respectively.

7.5.1 Continuous Improvement

Residue management goals require a culture of continuous improvement. Inter-operational benchmarking uses agreed, standardised industry measures to allow benchmarking with similar operations.

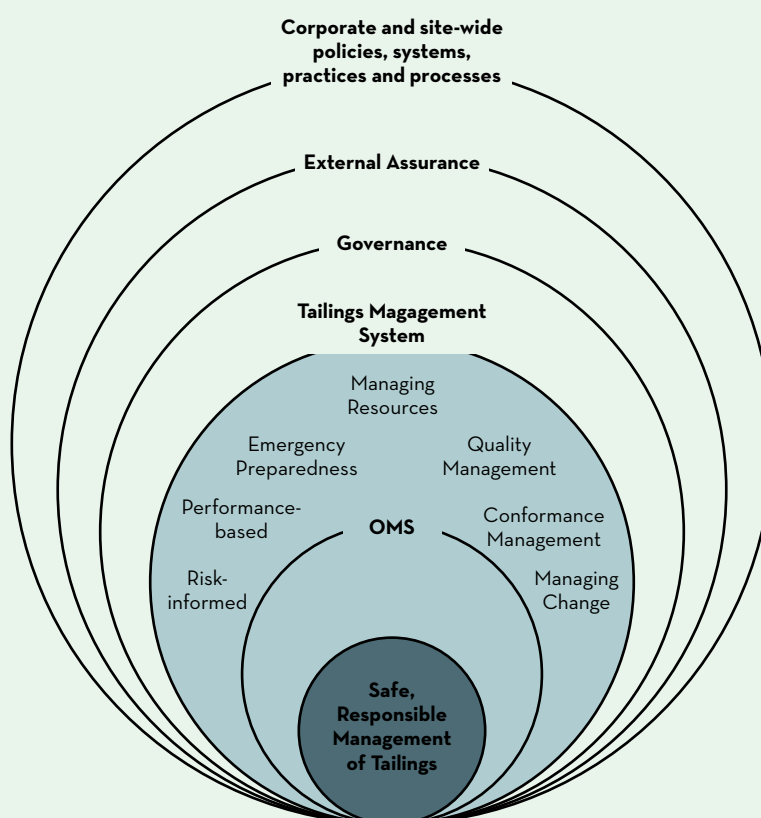


Figure 27. Layers of a Tailings Operations Management System (OMS)

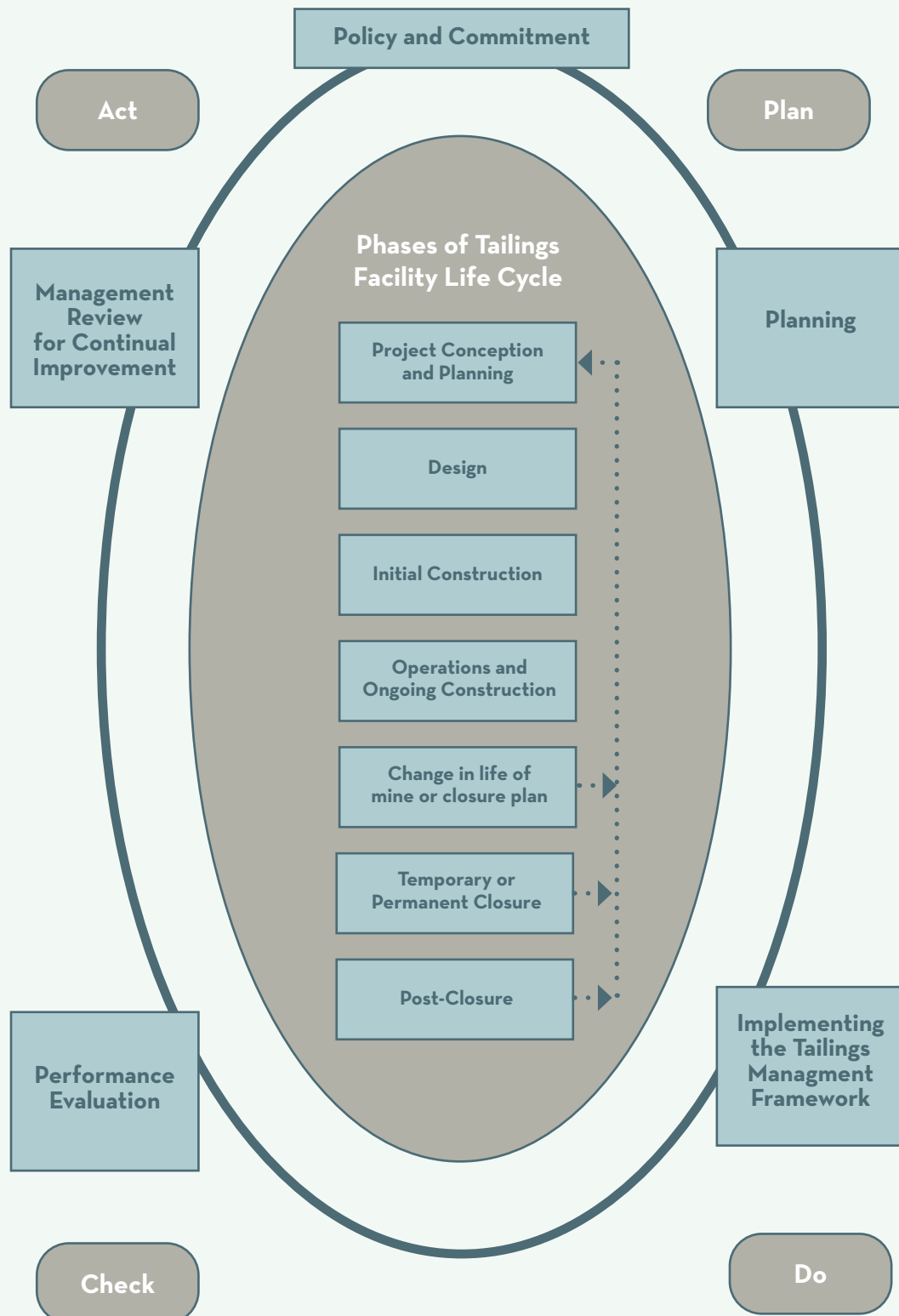


Figure 28. Management through the phases of the life of a Tailings Facility (Reproduced from MAC)

7.6 Case Study: Use of InSAR for monitoring dam safety, South32

In recent years, Space-borne Interferometric Synthetic Aperture Radar (InSAR, also abbreviated as IFSAR or ISAR) has become commercially available as an advanced tool for monitoring ground movements. Using the phase differences between two SAR images of the same area at different times, InSAR can be used to construct a Digital Elevation Model (DEM) and/or measure the ground movements that occurred during the time interval.

In 2019, South32 adopted InSAR to provide regular, remote monitoring of all its tailings and water storage facilities, and to support the extensive geotechnical instrumentation networks and routine inspections undertaken by site personnel.

Utilizing both ascending and descending satellite data via a specialist service provider, South32 can receive an update of movements at each operation every 12 days, using the European Space Agency's Sentinel 1 satellite.

Following extensive data processing to remove atmospheric aberration effects, repeated satellite passes allows ground movements to be measured to within a 1 cm accuracy. The data can then be displayed as either vectors of ground movement or separate horizontal and vertical movements. Due to the site-wide coverage, the InSAR readings can quickly direct site personnel to particular areas of a tailings storage facility for closer inspection. This is particularly useful for our operations with large TSFs, which comprise in excess of 50km of perimeter embankments.

A recent development allows time histories and transects to be displayed graphically for any point or section across the site. Shown below is a 12-day time step history for a section drawn across a valley and up a dam wall. The InSAR accuracy depicts +/- 2 cm seasonal surface movement of the natural ground surface (left side of plot) to pressive settlement up the dam crest; 16 cm, from commencement of construction of an upstream raise to commissioning.



The effectiveness of InSAR as a predictive tool in avoiding a dam wall failure requires a comprehensive assessment of the brittle/ductile behaviour of the tailings and foundation materials. In particular, ductile behaviour allowing much earlier identification of accelerating slope movements compared with brittle failure. South32 has thus undertaken extensive investigations of all of its High consequence (ANCOLD rated) tailings storage facilities to quantify the behaviour and give confidence to the monitoring programmes.

8 CLOSURE AND REHABILITATION



KEY POINTS

- Once a BRSF is filled to design capacity or the associated refinery is shut down, the process of closing the facility begins. Conceptual plans are made when the facility is designed, but are updated when the facility is closed to ensure it addresses changes in the social, environmental, regulatory, technical and economic contexts.
- The residue deposit is shaped for purpose, drainage and geophysical stability, and prepared to support its long-term land use objectives.
- The surface of the deposit is usually prepared to support sustainable revegetation using either raw residue with amendments and/or imported topsoil to kick-start the process of natural transformation.
- Remediation and rehabilitation is facilitated and accelerated by reduction of sodium and particularly caustic in residue.
- Numerous studies and examples have demonstrated the ability to convert BRSFs into stable landforms which can support revegetation and the development of a healthy ecosystem, which itself facilitates the naturalisation of BRSF over time.
- Various approaches have been proven to work. The nature of the residue, history of the BRSF and local climatic and environmental context and resources available to the operators all drive the choice of the best approach.

When BRSFs are filled to their design capacity and/or the associated refinery is shut down, a process begins to ‘close’ and ‘rehabilitate’ the residue deposit. BRSFs can also be managed as sub-areas which are progressively closed as they are filled to design capacity. The economies of scale, and the need to get maximum residue storage on available land footprints means the industry trend is to have larger working residue areas and to close and rehabilitate larger areas, less often. There is however, no right or wrong in this choice and refineries make this choice based on history and context, and various approaches can deliver good results. Figure 29 provides a high-level timeline for closure and rehabilitation.

After the last residue is deposited, a multistage and multifaceted process begins to stabilise and prepare the area for revegetation or other land use. BRSFs have a closure plan at some level of detail when they are designed, and these plans are usually updated at various points in the life of the facility. The most detailed planning and design step is usually kept till immediately before and/or during closure. During the long life of a residue area, changes occur in design capacity, residue deposition methods, environmental, social or regulatory context, available technologies, best practices and materials available at the time of closure. It is common that the plan for closure prepared during the original BRSF design will no longer be

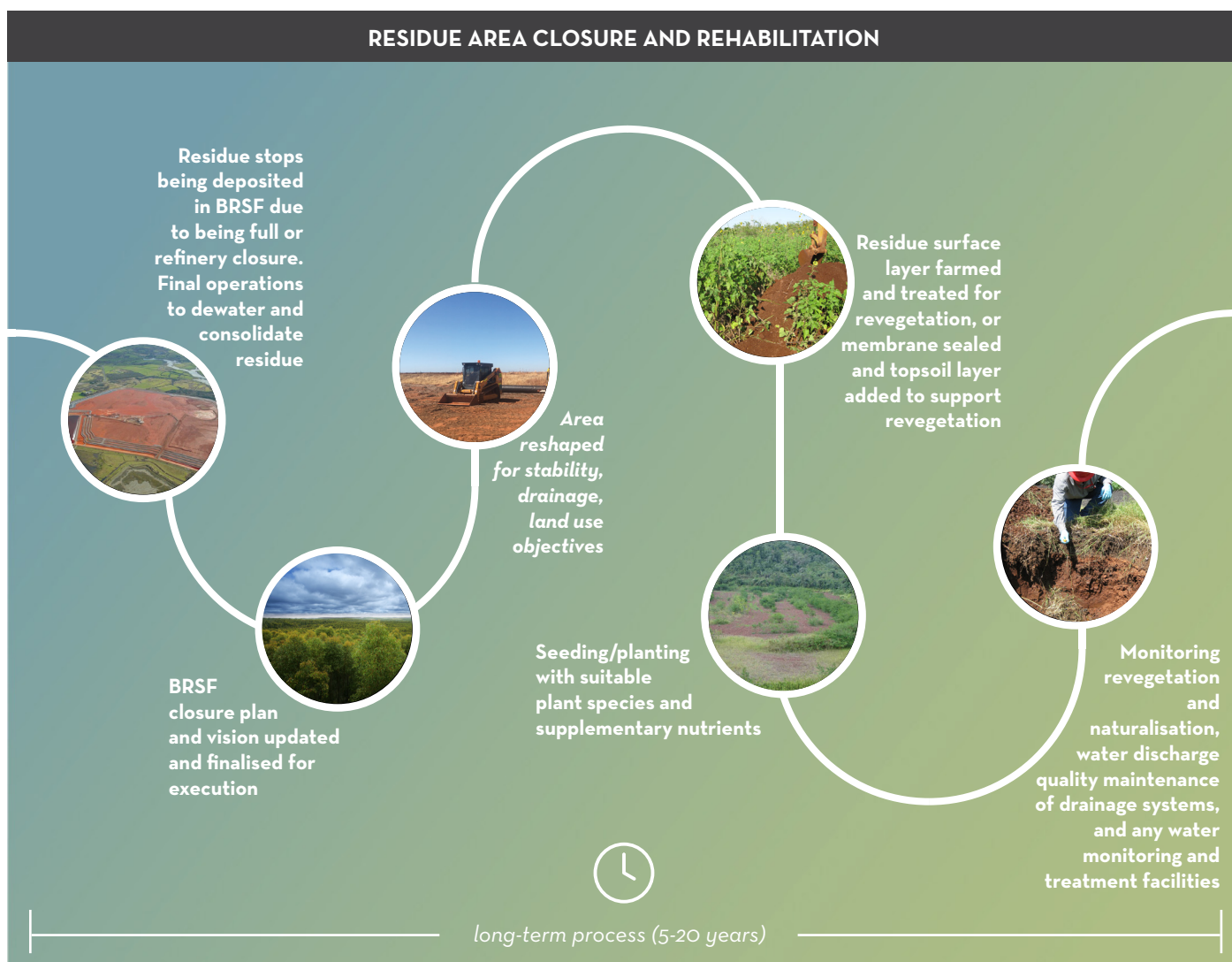


Figure 29. BRSF General Closure and Rehabilitation Steps

optimum, and the available options need to be studied to achieve the best environmental and business outcomes.

By nature, a closure plan needs to have the long-term objective of converting the area to a safe and stable land-form from geophysical, environmental and health and safety perspectives. The contours of the area need to be considered and there is often some reshaping of the deposit to provide stable slopes resistant to erosion and landslips, to provide good drainage, including from any under-drainage system and often with some overall visual aesthetic or land use in mind.

A key challenge to remediation of closed bauxite residue areas are often its high pH and high sodium content. A central objective of the rehabilitation process is to mitigate these effects, so that vegetation can be established, which will by its activity and along with the elements and time, continue to remediate these properties.

After shaping the area, the preparation of the residue surface for revegetation begins. This can be an agricultural process of working the surface and adding treatments (e.g. gypsum, organic material, fertilisers and possibly some topsoil). It may also be the laying of an impermeable membrane or sand layer to act as a capillary break. This is to stop salts, dissolved in residue water drawn up from the untreated residue by evaporation, that prevent plant growth and soil bacteria development. A capping layer of imported topsoil may be added to support revegetation. The methods employed for this process have evolved with time, and the conversion of residue to topsoil by working and adding amendments has become more successful and more commonly practiced, and continues to be studied and optimised.

Initial revegetation is usually with alkali and sodium tolerant plant species. Accumulated experience with BRSF rehabilitation has allowed amendment choice, addition

rate and species selection to be progressively optimised. In time, as the residue is converted to soil, other plant species can be introduced or will naturally colonise the area, and there are good examples of this as older closed BRSFs become more naturalised.

The collection and treatment (where necessary) of any water expressed from the body of the residue, or rainfall run-off is also an important consideration. This residue water is usually channeled into streams which are moni-

tored and treated before discharge to the local environment. The treatment of these flows can be active, or more passive (for example through wetlands). Over time, as the residue weathers and ages, discharges become less alkaline and more natural processes take over in the remediation of discharges.

Figure 30 shows an example of revegetation at a site in Guyana.

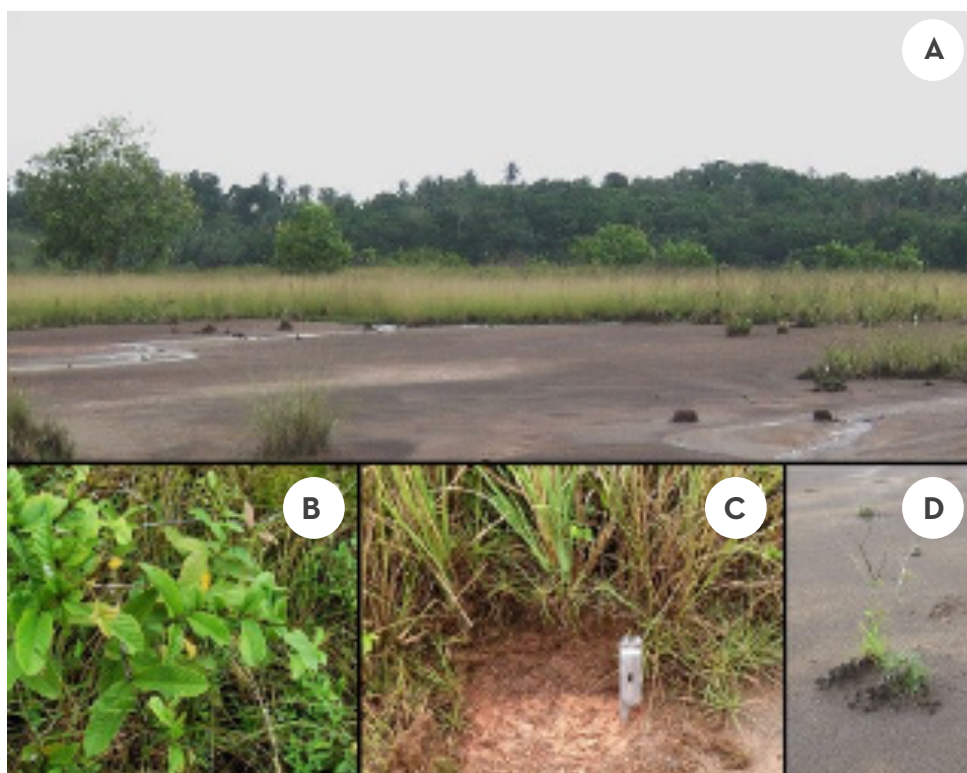


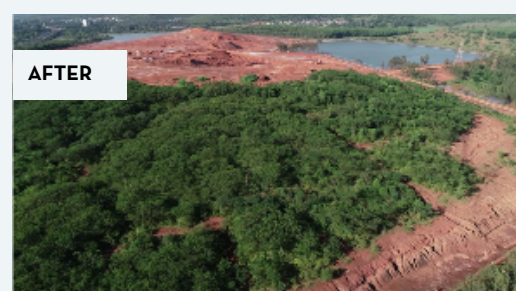
Figure 30. Example of revegetation on bauxite residue at Linden, Guyana.
(a) Sharp boundary between typical cover and barren residue;
(b) large-leafed guava and creeper in dense grass;
(c) profile showing brown, sandy, humus enriched topsoil over pink residue;
(d) isolated tuft of grass self-established beyond vegetation fringe.

8.1 Case Study: Rehabilitation of Hindalco Belagavi Bauxite Residue Storage Area

The rehabilitation of Bauxite Residue Storage Facilities (BRSFs) is often constrained by the high sodium content, low rainwater infiltration, and low hydraulic conductivity. The pH of untreated residue is usually more than 11. In 2002-03 Hindalco entered into a joint development project with The Energy and Resources Institute (TERI) for revegetation of closed BRSFs.

The first phase of the project was carried out in 2002-03 at TERI's research center at Gual Pahari in Haryana on 3 tonnes of bauxite residue from Hindalco Belagavi. This work was to identify suitable amendments and plant species for rehabilitation of a BRSF at Belgaum. Based on the encouraging trial results, 1 ha of BRSF-1 at the Belagavi Refinery was rehabilitated during 2003-04.

The procedure involved tilling of the top residue layer and adding amendments to make the residue more supportive of vegetative growth and bacterial inoculation. The bacteria multiply under the prevailing conditions and help modify the residue pH. After blending the top residue layer with amendments, pits of suitable size were dug up to 3 metres apart.



These pits are then filled with residue suitably modified with amendments and bacteria before tree species selected for their high tolerance to alkalinity are planted. The space between the trees is then planted with different varieties of alkali tolerant grasses. Since 2003-04, ~12 ha of BRSF has been treated and revegetated, and a further 0.6 ha is planned for 2020.

Rehabilitation of the closed BRSF at the Belagavi Alumina Refinery illustrates Hindalco Industries' capability and commitment to responsible residue management, with 12.5 ha BRSF rehabilitated to date. Rehabilitation of the BRSF enables rebuilding of the ecosystem, a positive indication of the sustainability of revegetation on the BRSF, and improving the surrounding environment. The initiative has enhanced the trust and reputation of the refinery with the surrounding community. Revegetation also has also reduced water demand for residue surface dust suppression.

8.2 Case Study: Rehabilitation of Alcoa Kwinana's A, B & C Residue Storage Areas

Operating since 1963, Alcoa's Kwinana refinery sits on the shores of Cockburn Sound, twenty kms south of Fremantle, Western Australia (W.A.). Its bauxite Residue Storage Areas (RSAs) A, B and C operated between 1963 and 1976, with approximately 13.4 million tonnes of residue deposited. The areas were progressively de-watered between 1974 and 2000, reducing the deposit's alkalinity, and assisting its consolidation. Areas A, B, and C sit on land leased from the State Government, which requires it to be made suitable for uses such as light industry, beyond its use for residue storage. Parts were handed back in March 2000 and are Alcoa's first residue areas to be closed in W.A.

Areas A, B and C were formed by damming small local depressions with embankments of up to 20 metres high. The subsurface under and around the areas is mainly coastal sand and limestone with variable permeability, requiring a low permeability clay seal to restrict alkaline seepage. The clay liner was formed by mixing 75 mm of imported clay with local sand and compacting to a 150 mm layer. On top of this sand/clay mix, 380 mm of compacted clay was placed in two roughly equal layers. A 300 mm sand layer was placed over the clay liner as protection against extreme weather and traffic.

Areas A, B, and C were initially filled by 'wet' deposition of a residue mud and sand mixture. The coarse sand fraction tended to settle around the perimeter of the deposit, with fine mud concentrated toward the centre. After filling the areas, the surface was drained and the deposit allowed to consolidate. The perimeter sand was pushed over the central, predominantly mud areas to provide a capping layer that allowed machinery traffic for dust control and revegetation activities. The sand cap varied in thickness from several metres near the perimeter to less than a metre near the centre. Between 1972 and 1992, the sand capping layer was progressively drained using surface ditches, and the deposit de-watered by eductor pumping systems, supplemented with windmill pumping. Surface vegetation including grasses, shrubs and trees was established, and some agricultural trials carried out.

In 1990, Alcoa studied placement of more residue sand to allow re-contouring of the areas, making them more suited to a wider range of land uses, including light industry. A plan for this re-contouring over 10 to 12 years was developed in consultation with the government, commenced in 1992 and completed in 2000. During the installation of this sand cap, sub-surface drainage was installed, using a network of perforated pipes to collect rainfall infiltration and preventing any perched water table from rising to where it could affect surface vegetation.

The original surface of Areas A, B, and C was successfully re-vegetated, however, settlement resulted in depressed central areas that were difficult to drain and had high seasonal water tables, resulting in some salt and alkalinity damage to vegetation. Subsequent re-contouring of the surface, and sub-surface drainage provided a better basis for sustainable vegetation, and the open area has since been successfully re-vegetated.

Foundation conditions for building structures on Areas A, B, and C are variable due to the layers of mud and sand in the residue profile. Sand layers are reasonably well consolidated but mud layers will compress under additional loads, which could result in settlement of foundations or structures. While significant geotechnical data is available for the areas, studies for more specific development proposals are still required.

Groundwater contamination beneath and around Areas A, B, and C was first detected in 1973 as a plume of alkaline contamination, confined to the bottom third of the 20-metre-deep aquifer and extending several hundred metres beyond the northern boundary of Area A. A groundwater recovery system was installed, successfully capturing the contamination. Groundwater recovery and monitoring continues, and Alcoa reports annually to the State Government on the area's groundwater quality.

Drainage has been installed to capture alkalinity leached by rainfall from the residue sand cap, including perimeter drains for runoff and sub-surface drains at the base of the sand cap, to collect rainfall leaching through it. The alkaline water recovered is returned to the refinery for reuse.

In 1998 the W.A. Minister for Planning announced an area including part of Areas ABC was the preferred site for the Kwinana Motorplex, a new a motor sport facility. Construction was completed and an official opening held in 2000.

Special design considerations were applied to the Motorplex to accommodate its history, with no heavy structures placed on the deposits, and residue areas used for car parking and speedway car marshalling areas. Stormwater drainage systems were installed to protect and complement the existing sub-surface drainage systems, and security fencing and signage erected around sump areas that collect peak rainfall run-off. An easement allows Alcoa access to continue monitoring and recovery of contaminated groundwater.



The Kwinana Motorplex

Since the opening of the Motorplex, there have been no management issues related to it being a former residue storage area. The development provides a very good example of the redevelopment of closed alumina refinery residue areas.

8.3 Case study: In Situ Remediation of Bauxite Residue, Alcoa, Australia

Environmentally sound rehabilitation, revegetation, and closure of bauxite residue storage facilities requires a suitable plant growth medium in the surface residue layers. This has typically been achieved by placing imported capping layers (usually topsoil plus a clay or PVC liner) over the residue surface, in which vegetation is then established.

A partnership between the University of Western Australia (UWA), International Aluminium Institute and Alcoa Australia to develop and optimise in situ remediation has provided a new approach by transforming bauxite residue into a productive, stable soil in which vegetation can be directly established. The method uses chemical, physical, and biological amendments, along with natural weathering to form soil. This low cost approach decreases the environmental risk of failures and unplanned releases by progressively improving the properties of the stored residue, while avoiding issues of cap erosion or failure.

In situ remediation involves rapid soil formation. Soil science techniques and analyses have been used to understand the processes driving residue remediation, particularly the extent to which various amendments drive and accelerate the transformation. The effect of amendments is also in part influenced by site-specific factors such as initial residue properties, climate, and environmental setting; all of which guide natural soil formation from typical geological materials.

Although a number of refineries around the world have conducted in situ remediation trials and programs as early as the 1970s, these activities had not been comprehensively analysed and synthesised to identify the most effective amendments for rapid remediation, or the effect of site-specific factors especially over the longer term.

Dr Talitha Santini's PhD and postdoctoral projects in the early 2010s examined the medium to long term (up to 40 years) responses of bauxite residue to various amendments at sites in Brazil, USA, Guyana, Ireland, Germany, China, and Australia. The work confirmed the role of traditional caps in limiting in situ residue remediation, and identified high rainfall (or irrigation), tillage or Amphiroling, and additions of organic matter, gypsum, or sand as key remediation accelerants.

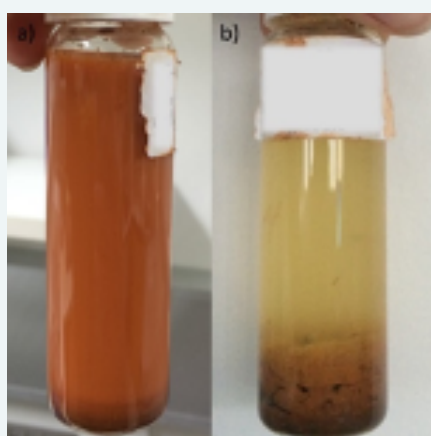
The study of residue microbial communities in this work revealed the low diversity, low biomass communities in fresh residues, and the marked shifts in community composition in response to remediation. This raised the possibility that microbial communities might not only respond to remediation, but could be active in the process.



Successful in situ residue remediation using sewage sludge and clay at Sherwin, Texas showing (a) dense vegetation at surface, and (b) well developed soil profile in residue.)

Subsequent work by Dr Santini's research group in the later 2010s optimised this microbial remediation. Microbes ferment added organic carbon (simple sugars such as glucose, or complex organics such as plant mulches and composts) to produce organic acids and CO₂, neutralising residue pH and addressing one of residue's most stubborn properties, while improving particle aggregation and other residue properties.

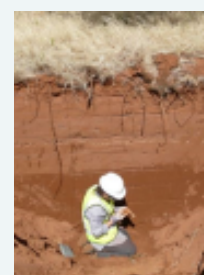
This microbial activity has now been combined with beneficial amendments from previous experience, such as irrigation, tillage, organic matter, and gypsum, to optimise the formulation for rapid remediation. This optimised approach is currently being tested in large field trials at Alcoa Kwinana's residue storage area in Perth, Western Australia. The field trials have revealed synergies between microbial activity and other amendments to rapidly deliver multiple improvements in pH, salinity, solid phase alkalinity, and nutrient content.



Lab bioremediation showing residue suspension before (a) and after (b) treatment. Note improved clarity and solids aggregation at base of vial (b).

Future work will further scale up the current field trials to larger (≥ 1 ha) areas, and implement at other refineries around the world to test responses with different site-specific conditions and locally available amendments such as different agricultural or industrial by-products, as organic carbon sources.

Beyond the benefits for closure of legacy and active residue sites, the development of rapid in situ residue remediation, may allow a new residue utilisation option in the form of soil products from bauxite residue. In situ remediation to transform residue, coupled with periodic harvesting of the remediated residue (soil) product, could allow gradual draw down of residue stored in legacy and existing sites, and the avoidance of long-term storage facilities at new and future refineries.



Field trials established in 2019 (L), Bioreactor treatment pit (M), and field sampling of weathered bauxite residue at Pinjarra, Western Australia (R)

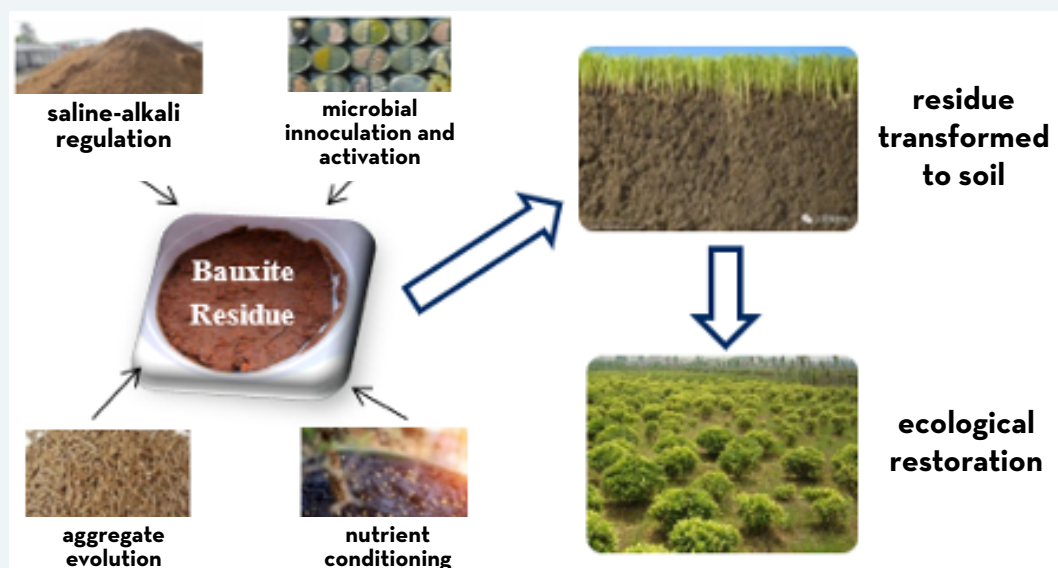
A full list of journal papers from this project is available at Dr Santini's website:

<https://research-repository.uwa.edu.au/en/persons/talitha-santini/publications/>.

For a copy of publications, please contact Dr. Santini at: talitha.santini@uwa.edu.au

8.4 Case Study: CHALCO's BRSF Ecological Restoration Process

Technology for the ecological restoration of bauxite residue storage facilities and side slopes was developed by Zhengzhou Non-ferrous Metal Research Institute Co. Ltd of CHALCO (ZZRI). The technology consists of saline-alkali regulation, microbial inoculation and activation, aggregate evolution and nutrient conditioning. The pH value and salt content of bauxite residues are reduced significantly using the technology. At the same time, the structure of the residue is improved, greatly increasing the porosity and stability of soil aggregates. Treated using this technology, the remediation of bauxite residue and its transformation to soil is greatly accelerated, providing the basic conditions for its ecological restoration.



CHALCO ZZRI Bauxite Residue Ecological Restoration Process

In 2018, a demonstration of CHALCO ZZRI's in-situ ecological restoration was carried out in the fifth bauxite residue storage area of CHINALCO Mining Co., Ltd (the former Henan Branch, CHALCO). In the first year after restoration, soil fertility and heavy metal content both met the Chinese standard for first-class dryland, and the green coverage rate of pioneer crops was more than 95 %. Native vegetation can grow naturally without intervention in the third year after restoration.



In-situ Restoration at CHINALCO Mining (L) and Slope Restoration at Zunyi Aluminum (R)

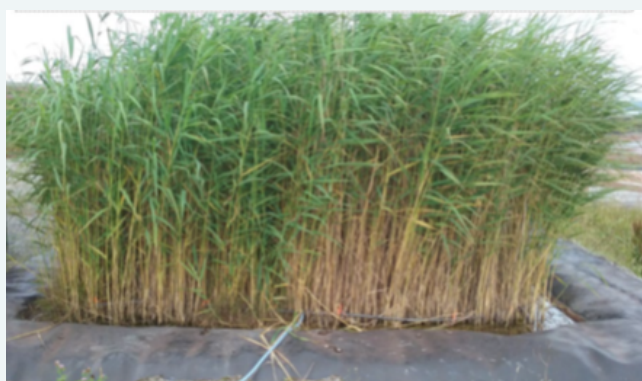
In 2019, the demonstration ecological restoration of residue area slopes was carried out in the the residue storage area of the refinery of Zunyi Aluminum Co., Limited. The vegetation in demonstration areas grows well and can self-propagate. The green coverage rate was calculated to be more than 90 % and the average vegetation height more than 25cm in the second year of restoration.

8.5 Case Study: Residue leachate treatment, Rusal Aughinish

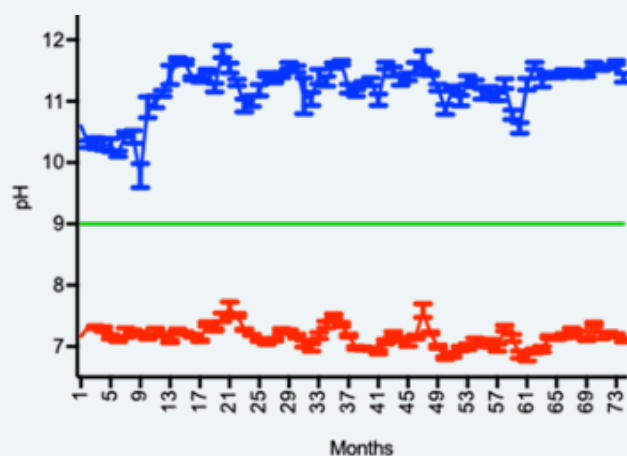
Rusal Aughinish located in Askeaton, Ireland has developed and sponsored a research programme to study and prove the passive treatment of bauxite residue leachate through a constructed wetland, as a long-term treatment option. The wetlands' purpose is to reduce the alkaline wastewater to pH levels of < 9 .

Partnering with the International Aluminium Institute and the University of Limerick, the research programme conducted a series of laboratory-based trials before establishing the alumina industry's first constructed wetland trial on site. The wetland optimises conditions for biological activity which mitigates the leachate alkalinity and other parameters to allow safe release of the leachate into the environment. The growth of wetland vegetation ensures a continued supply of organic matter to act as food sources for the biological communities which generate the neutralisation agents.

Designed to receive typical alkaline residue leachates of around pH 11, the wetland system has been operational for 7 years. Continuous monitoring has demonstrated the sustained ability to decrease pH and other key parameters to target levels for environmental discharge. The process's advantages are in the natural processes and structures utilised, and its simplicity and robustness. Upscaled versions of the constructed wetland are currently being implemented.



Rusal Aughinish Constructed Wetland Trial



Performance of Rusal Aughinish constructed wetland in effluent pH reduction

8.6 Case Study: Bauxite residue rehabilitation, Rusal Aughinish

The establishment of soil covers, vegetation growth and wider ecosystem development is recognised as the most effective way to stabilise mineral residue deposits and for effective landscaping once a residue area is decommissioned.

For over 20 years Rusal Aughinish has implemented a research programme with the University of Limerick to develop strategies for converting the bauxite residue into a soil medium that supports plant growth. The establishment of soil biota and functions lead to a soil-vegetation system that is self-regulating and therefore sustainable.

The research programme has identified novel approaches to physically and chemically modify the residue, and accelerate its transformation into a soil-like media. The residue is 'farmed' to enhance carbonation and decrease alkalinity before additions of gypsum and organic address the sodic and nutrient balance. Measurement of rehabilitation success is not just the visual 'greened with grass', but are assessed using completion-criteria-indicators, based on scientific evidence.

The novel residue/ soil displays chemical and biological characteristics typical of soil analogues, hosts populations of soil biological communities and supports the growth of several indigenous vegetation species.

In addition, the rehabilitation strategy not only achieves target values for critical soil parameters, but the initiation of 'soilification' means that conditions are sustained or improved over a 20 year timeframe. These include

- Stable soil pH
- Soil aggregation
- Establishment of key soil faunal groups such as earthworms
- Establishment of soil microbial communities
- Wider pedogenesis (soil development)

Crucially, over a 20 year period, rehabilitated residue has received no further management or intervention and facilitates the establishment of a grass-scrubland ecosystem. Rusal continues to refine its best practice bauxite residue rehabilitation through an active research program and adaptive management to guide progressive rehabilitation and continuous improvement.



Rehabilitated residue at Rusal Aughinish showing diverse grassland growth



Rehabilitated residue showing diverse grassland growth (L), Sample of rehabilitated residue with demonstration of soil structure, aggregation and root development (R)

8.7 Case Study: Rio Tinto/U.Q.'s Bauxite Residue into Soil Technology

Since 2015, Rio Tinto has partnered with the bauxite residue research team in the Sustainable Minerals Institute at the University of Queensland (U.Q.), led by Pfr. Longbin Huang (<https://researchers.uq.edu.au/researcher/1341>), to develop an integrated and field operable process for rapidly converting bauxite residues into soil. The process allows rehabilitation of strongly alkaline and saline bauxite residues at industrial scale within 2-3 years. This technology is based on integrated mineral and biological processes as described in the University of Queensland's provisional patent, PO025964AU (Treatment of bauxite residue), and has been built on the framework of ecological engineering of mineral wastes (Huang, Baumgartl, & Mulligan, 2012; Huang & You, 2018).

The work progressed from initial laboratory studies to a scaled-up trial using 1 m³ Industrial Bulk Containers at the closed Gove refinery in the Northern Territory of Australia. Recently, the process has been demonstrated at Queensland Alumina Limited in a field trial on seawater neutralised residues, which are still alkaline and highly saline. With the progress of soil formation in the treated bauxite residues, diverse pioneer plant species have naturally colonised the treated area, in addition to the sown and transplanted species. The photos below show the establishment of vegetation cover within 2 years of commencing bauxite residue treatments.

This approach utilises locally available and renewable/recycled organic matter, and requires only limited quantities of transported materials, important for remote sites where suitable material may not be available locally. The operational process can be easily adapted from established broadacre farming practices, and will create opportunities for local communities, especially the indigenous people at Gove (Nhulunbuy), Northern Territory, to participate in its implementation, through farming, supplying plant biomass, in field operations and land management.

The costs associated with materials and field operations have been estimated to be substantially lower than topsoil-dependent approaches for rehabilitation of bauxite residue storage facilities. This technology is operationally repeatable, with the expected outcomes to be seen 2 to 3 years after commencement.

A large-scale pilot trial has commenced at the Gove site, to formulate and optimise a field operational guide, to be incorporated into the rehabilitation strategy for the closure of Gove's bauxite residue areas. The pilot trial is to be completed by 2024.



Vegetation growth in Gove bauxite residue IBC trial within seven months of treatment.



Pioneer plant roots colonising treated bauxite residue in the Gove IBC trial. Roots extended the full depth of the amended residue (approx. 90 cm).



Soil-plant system development directly in QAL bauxite residue under field conditions. The vegetation is composed of naturally colonised grasses and shrubs and sown plant species, within 2 years after commencing field treatments.

Huang, L., Baumgartl, T., & Mulligan, D. (2012). Is rhizosphere remediation sufficient for sustainable revegetation of mine tailings? *Annals of Botany*, 110(2), 223-238. doi:10.1093/aob/mcs115

Huang, L., & You, F. (2018). Ecological engineering of soil-plant systems to rehabilitate bauxite residues: current progress, barriers and innovations. Paper presented at the Alumi-na2018 - The 11th AQW International Conference, Gladstone, Qld, Australia.

You, F., Zhang, L., Ye, J., & Huang, L. (2019). Microbial decomposition of biomass residues mitigated hydrogeochemical dynamics in strongly alkaline bauxite residues. *Science of The Total Environment*, 663, 216-226. doi: <https://doi.org/10.1016/j.scitotenv.2019.01.317>

9 BAUXITE RESIDUE UTILISATION



KEY POINTS

- As a bulk material, and as a collection of valuable elements and materials to feed other products, residue utilisation has been widely studied, with significant quantities presently being used, although these volumes are presently a minor part of residue produced.
- Many opportunities have been identified and have or are being developed. The recovery of iron, titanium, residual alumina and other minerals have been a focus, while the extraction of rare earths and precious metals continued to be studied.
- Bauxite residue's use as a raw material for Portland and other kinds of cement and concrete has been one of the largest present uses, and could provide a market for large volumes of residue. Studies in this area are supported by the IAI.
- Economic viability and the volume of residue produced remain constraints on utilisation of a large proportion of residue produced.

Throughout the history of its production, alumina refineries have looked for opportunities to utilise bauxite residue by recovering valuable minerals from it, using it as a bulk raw material, or transforming it into other products. Given the costs and risks associated with managing it, alumina producers have always had strong economic and business risk motivations to find uses for it, which have only grown with time¹⁴.

Hundreds of patents have been issued, and thousands of

studies undertaken on different applications, but only a small number have been commercialised. Although significant volumes, the residue utilised remains a small part of that produced. Most residue applications studied are technically feasible, but not economically viable. A small number of applications are economically viable, but will not substantially reduce the large volumes of residue produced annually. For a particular refinery, an application may be an opportunity to utilise some residue (and mitigate management costs), but without significantly reduc-

ing the volume of residue to manage.

Many large volume residue applications involve replacing other virgin low-cost raw materials (e.g. sand, gravel, clay) and while the concept is usually technically feasible, the costs, complexity and/or perceived risks associated with residue's properties undermine the case to use it. The cases where the properties of bauxite residue give unique benefits in a large volume application are rare. Obstacles to utilisation of untreated residue include sodium content, alkalinity, its particle size, metal constituents and rarely, low-level radioactivity.

Workers utilising bauxite residue in typical commercial applications are not exposed to crystalline silica, metals or radiation at levels considered to be harmful, provided safe methods of work are adopted, such as would be used during work with conventional materials. However, perceived risks may remain high even after studies demonstrate that they are not, and this is an ongoing challenge for some large volume applications, such as agricultural soil amendments.

In general, the economics of residue utilisation should consider all the costs of storing it in a BRSF. These costs include the construction (and extensions) of the BRSF, ongoing operating costs, closure and rehabilitation and monitoring of closed sites.

The Chinese alumina industry as a whole has one of the world's best records for utilisation to date. The 2012 Chinese publication 'multipurpose use of bulk industrial solid waste 5-year plan' (which covers bauxite residue) set a tar-

get for bulk industrial solid waste utilisation of 50 %. The national goal for bauxite residue was a utilisation rate of 15 % by 2015 and 20 % by 2020. The utilisation rate in 2012 in China was estimated at 4 % of the 40 million tonnes of that produced in that year, although some refineries were achieving a much higher figure. Several refineries in China are now operating significant iron recovery schemes.

The bauxite residue utilised annually is currently estimated at 3 million tonnes per year, and growing. The largest current applications are in cement production in a number of countries (particularly India, Greece and China) and iron recovery, mostly in China. Most other applications are small proportions of the annual residue volume produced.

The figure of 3 million tonnes /year does not include that used in the construction of BRSF infrastructure (such as walls and roads, as a substitute for imported construction materials), which is a significant and growing application. With higher density stacking, more residue with the required mechanical properties has become available, and is being increasingly utilised. If this 'use' is considered, the utilisation rate is obviously higher than the 3 million tonnes per year.

The alumina industry has always been open to collaborate with other companies or research institutes, to develop new residue applications. Refineries are often not in competition with each other in bulk applications for residue, as these applications are limited by freight costs to short distances from each refinery.

9.1 Applications

The thousands of publications and the many studies and applications for residue utilisation cannot possibly be covered or even fully summarised here, and only a high-level break-down of the main application areas is provided below. A literature search will uncover many of these studies, and it is recommended that those interested in the detail look to those sources.

Residue uses can be classified in a number of different ways and into a number of different categories. The following is one simple approach, and is used here to analyse the range of applications that are currently applied or under development.

Residue use is examined below, categorised as follows;

- as a **bulk material** for its properties, with or without

additions and/or simple treatments, (e.g. covering landfill, soil and mine waste amendments, road base, cement addition);

- by **extracting the value of mineral components** (e.g. iron, titanium, rare-earths);
- by processing to produce a **construction material**, (e.g. bricks, tiles, geopolymers, wood substitute, pigments); or
- using more **advanced processing** to develop a specialised property or application (e.g. aggregates, proppants, water treatment reagents, catalysts).

Figure 30 illustrates these nominal categories for residue utilisation.

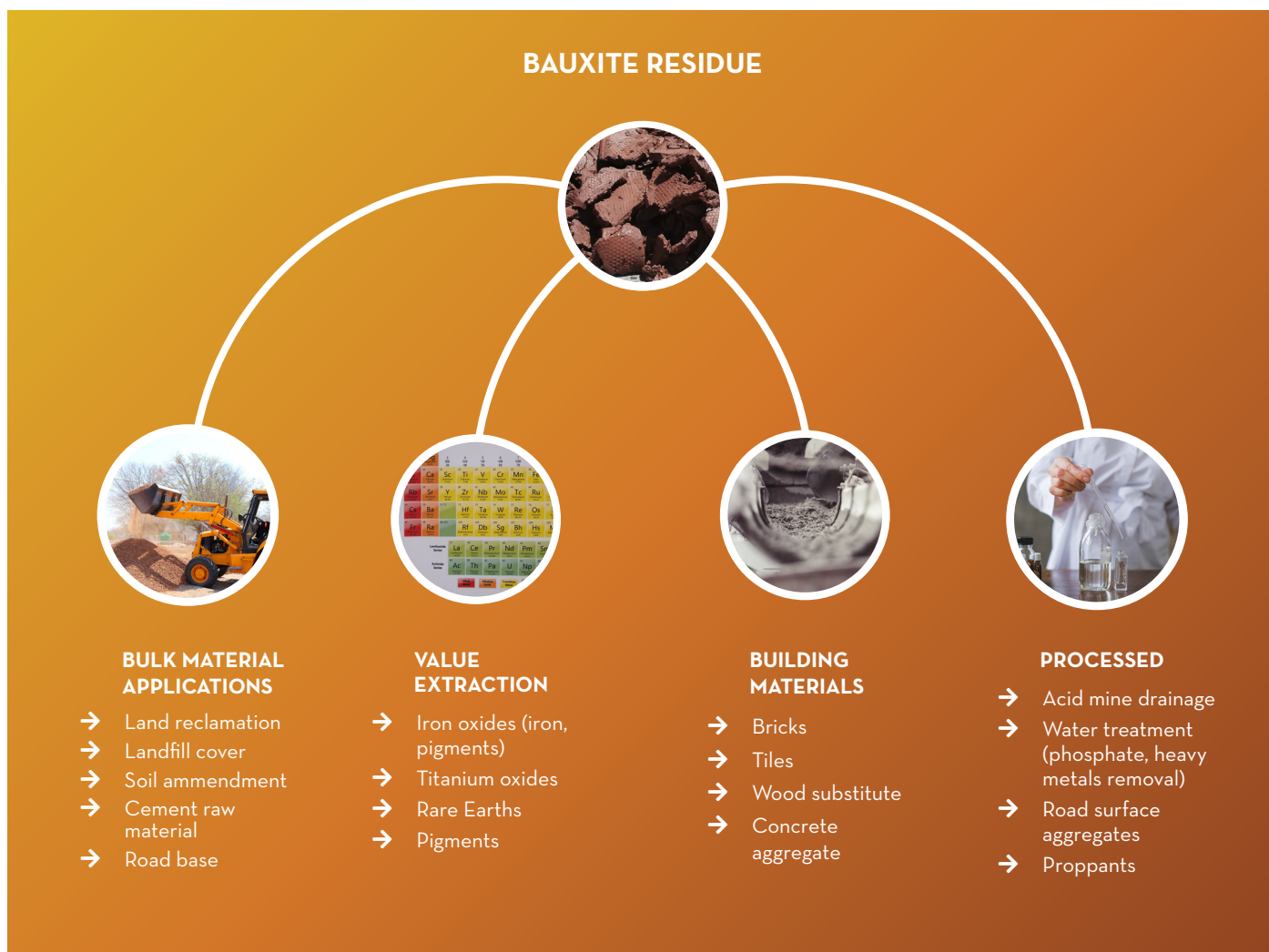


Figure 30. Examples of uses for Bauxite Residue

9.1.1 Bulk Material

When dewatered, compacted and mixed with a suitable binder, residue makes a good road base, and has long been used to do so within BRSFs. In France, bauxite residue mixed with other materials (Bauxaline®), has been used in the construction of roads, and Red Sand® from Alcoa's refineries were used in construction of the Perth to Bunbury Highway in Western Australia.

Bauxite residue's impermeability when dewatered and compacted is useful for the construction of BRSF containment walls, and it is now widely utilised for this purpose. Where separated, the coarse fraction of residue ('sand') can be used for road construction in the BRSF, as a drainage layer under the residue, or as a capping material for residue sites. Residue 'sand' is easier to wash, drains better, so has lower residual sodium.

Residue's relative impermeability can be used in the capping of municipal landfills. Bauxaline® from the Gardanne

refinery has been used extensively in the Marseille area, and at one site the methane gas evolved is collected under a Bauxaline® covering layer. For a similar application in Louisiana, pH reduced residue is mixed with clay.

Soil Amendment

Applications of raw bauxite residue is best considered for emergency responses to soils requiring a highly alkaline, buffered material to contain a spill, plume or other contamination. It is however, not usually useful for long term management of acid mine drainage, acid sulfate soils or similar, as its buffering capacity is typically limited compared to that of the source of acidity, and may cause contamination itself if that buffer capacity is exceeded.

Residue as a soil amendment for growing plants should first be neutralized and desalinated to remove excess Na^+ , $\text{Al}(\text{OH})_4^-$, CO_3^{2-} , and other ions soluble at high pH. In amended and neutralized form, residue's greatest potential is with structurally poor, sandy soils with a range

of deficiencies (structure, water-holding capacity, nutrient retention, organic matter, etc). Due its limited buffering capacity, its use for pH correction provides only marginal, short-term benefits, generally better addressed with agricultural lime. Greater interception and retention of nutrients (nitrogen, phosphorous) may be another benefit of residue applications; although it does not fix the root cause of nutrient over-application.

The greatest benefits are most likely where soils see little to no human intervention (e.g., farming), and the local biota is given the time (years to decades) to properly integrate the new suite of physical, chemical and hydrological properties. For use in agriculture, land-management practices need be adjusted to benefit from neutralized residue. For example, adjusting nutrient management practices, going from till to no-till systems to allow soil structure to develop, fallow-periods, crop-rotation, weed & pest management, run-off management & erosion control, etc.

Development of best management practices for soils amended with neutralized residue will require the help of local agricultural extension agencies. The long-term effects on the local ecosystem of neutralized residue applications should be well understood. This includes the risks from displacing native fauna and flora while inviting unwanted pests, weeds, and other species; soil water and aquifer balance; increased run-off potential due to lower hydraulic conductivities; nutrient availability; increased residual acidity potential from easily soluble Al-minerals introduced by the residue; accumulation of unwanted elements due to natural weathering processes or manmade activities; and in semi-arid regions the increased fire risks from greater biomass production, among many other potential consequences.

Introduction of neutralized/amended bauxite residue to any native soil system requires a period of study and monitoring of the long-term implications. Like any new land management option, it requires trials, oversight, and monitoring over 10-15 years to assure agricultural extension agencies and potential users understand how the application of the new technique/amendment/land-management practice is beneficial to the operator, the environment, and the downstream end-users.

Some potential benefits of residue addition to acidic and sandy soils have been demonstrated in Western Australia by Alcoa. Bauxite residue with 5 % gypsum added at around 250 t/ha to sandy soil improves water retention and nutrient utilisation, greatly improving ammonium and phosphorus retention, and reducing fertiliser demand.

Phosphate retention by Alcoa's carbon dioxide neutralised residue (Alkaloam®) has been demonstrated in the Peel Estuary in Western Australia. In addition to stronger phosphorus adsorption, it reduces phosphorus leach-

ing, reducing agricultural phosphorous flow into the local marine environment, reducing algal blooms.

Residue has been used to treat acid sulfate soils by the Gladstone Port Authority in Queensland, Australia, and the QAL BRSFs are themselves considered an acceptable depository for acid sulfate soils from local construction activities.

Uncertainty about the leachability of metals and radionuclides and their movement into the food chain from bauxite residue has inspired extensive studies. One study looked at levels of ^{40}K , ^{226}Ra , ^{228}Ra , ^{228}Th , and ^{228}U in crops grown in soil with residue additions. No uptake was detected even at additions of 480 t/ha, although other studies are ongoing and further work is required.

9.1.2 Value Extraction

Residue's mineral components are a clear value recovery opportunity. The composition of the bauxite from which the residue is derived has a significant bearing on the proportion of the minerals present and along with the refinery process, has an impact on the viability of extraction. The iron, titanium, silicon and residual sodium are the highest proportion by weight but are in the commodity value category, while the extraction of the trace amounts of high-value Rare Earths or precious metals are at the other end of the value scale. Whether these minerals are cost effective to recover will depend of the cost of recovery and the quality of product. Both hurdles can prove challenging.

Residue's high iron oxide content (up to 60 %), has inspired numerous studies into many methods for iron recovery. Presently, the greatest recovery of iron from residue occurs in some refineries in China, where para-magnetic hematite is magnetically separated from residue and used in nearby iron foundries.

Apart from magnetic separation, many of the paths to recover iron from residue studied reduce the iron minerals with agents such as hydrogen, carbon monoxide, town gas, coke or biomass, at a range of temperatures and conditions. Some of these processes also recover other by-products such as titanium, residual alumina and sodium.

Rare earths elements (REEs) are divided into light rare earths such as lanthanum, cerium, neodymium, samarium, praseodymium, promethium and europium, and heavy rare earths; gadolinium, terbium, holmium, erbium, lutetium, thulium, ytterbium, dysprosium. Scandium and yttrium are also classified as rare earths. The concentration of these elements in residues vary, but (for example) a typical Jamaican residue (which can be 5-10 times higher in REEs than bauxites from other regions) contains (in

ppm): scandium 135, lanthanum 500, cerium 650, neodymium 250, samarium 65, europium 15, terbium 10, ytterbium 30, lutetium 5, tantalum 10. The growing demand for rare earth elements has increased interest in their recovery from residue.

Each rare earth element or oxide has its own applications. Neodymium and praseodymium in powerful magnets, cerium and lanthanum in auto-exhaust catalysts, scandium in aluminium alloys for aircrafts and europium and terbium as phosphors for plasma screens. With growing electric vehicle production, demand for samarium for battery alloys is also growing. In 2010 approximately 130,000 tonnes of REEs were produced, which had increased to around 240,000 by 2020³. REEs recovered from residue could fill a substantial part of the world's demand, and if pursued, could facilitate recovery of other residue components (e.g. silica for fillers, titanium and iron).

REE extraction is typically by acid leaching, followed by solvent extraction of the resulting liquor. UC Rusal have trialed processes developed by VAMI to extract scandium from residue since the 1980s at the Uralsk and Bogoslovsk refineries.

A number of studies and proposals have been made to eliminate bauxite residue, so that none need be deposited in BRSFs, where all elements of residue are separated and turned into various products, anticipating a positive business case overall. Although this notion has been studied for many decades by multiple organisations, and even piloted at industrial scale several times, the economics have so far failed to motivate any full scale or ongoing industrialisation.

9.1.3 Building and Construction Materials

Residue mixtures with clay, shale, sand, and fly ash have been widely evaluated for brick production. High levels of sodium reduce the durability of the bricks produced, so substitution of sodium with calcium is generally required. Bricks with a residue content of over 90 % have been made at firing temperatures of around 1000°C. Both inorganic (e.g. quicklime, gypsum) and organic (e.g. PVA and PMMA) binders have been used. A sports pavilion in Jamaica using residue bricks is still in use today.

Residue's high iron content and fineness has attracted interest as a pigment. 2 - 5 % of high iron oxide bauxite residue added to bricks can provide a uniform red colour.

Bauxite residue use in Portland cement production			
Status	Bauxite residue source	User(s)	Quantity used (kt/y)
Actual usage			
Now	Mykolayiv, Ukraine	Formerly 10 plants (now 6)	~250
Now	Distomon, Greece	3 cement plants in Greece, 1 cement plant in Cyprus	~80
Now	Shangdong, China	Integrated cement plant	?
Now	China - several plants	Local cement plans	?
Now	India - several plants	Approximately 40 cement plants	>2100
Potential			
Potential	Distomon, Greece	Trial Lafarge, 3500 tonnes	300
Potential	India	Various	2500
Abandoned			
2011	Ewarton, Jamaica	St Catherine cement plant	100
2003/2004	Showa Denko, Japan	Trial 700 tonnes	
1986/1987	Ewarton, Jamaica	Caribbean Cement Limited, Kingston	40 - 50

Table 3 - Bauxite residue use in Portland cement production

Small additions to red tiles was once a significant use, but demand for these tiles (for windows sills and floors), has shrunk considerably. Roof tiles have been manufactured in Turkey from residue from the Seydisehir alumina refinery.

Bauxite residue has been used as a pigment in plastics. A plant in Larne, Northern Ireland operated for many years after the Bayer refinery closed utilising residue to produce a pigment for tiles, paints, and plastics. At the AMPR Institute in Bhopal, India, a mix of 50 % residue with natural fibres and polyester resin produced a wood substitute for building applications, which demonstrated high strength, water resistance, weatherability and fire resistance.

Geopolymers are a substitute in some applications, and have a number of advantages over ordinary Portland cement, including a lower CO₂ footprint. Geopolymer formation involves the dissolution of silica and alumina in an alkali, before polymerisation of a $-(\text{Si-O-Al-O})_n-$ polymer chain. The aluminium and silicon in a highly alkaline residue mix offers opportunities to produce construction materials. The IAI has published a report on bauxite residue in special cements which is available from the IAI website.

9.1.3.1 Portland Cement

The prospects for using bauxite residue in Portland cement has been explored for over 80 years with many promising technical studies and several successful large-scale commercial initiatives. The iron and aluminium compounds contained in the bauxite residue provide valuable additions in the production of Portland cement at a low cost.

The IAI has sponsored work in this area. A detailed report on using Bauxite Residue in Portland Cement Clinker and a Technology Roadmap to maximise the use of bauxite residue in cement and concrete products¹⁵ were published in 2020. They are available from the IAI website and are recommended reading for those looking for more details.

The best estimates are that about 3 million tonnes of bauxite residue are currently used annually in the production of Portland Cement clinker. The cement plants currently utilising residue in clinker production are based in China, Ukraine, India, Russia, Georgia, Moldova, Cyprus and Greece.

From operating experience, bauxite residue can be satisfactorily used in cement clinker production, with only slight changes to their operating process. With the appropriate bauxite residue, an input rate of 2.5 to 5 % can be accommodated.

From the industrial experience to date, key requirements are:

- a relatively low moisture content - of less than 30 % (and preferably less than 15 %) has been used in several cement plants, which can readily be achieved by using a press filter, and/or by air drying (lower moistures also reduce transport costs);
- a sodium content of <2.5 % (as Na₂O) has been indicated, but will depend on the composition of other raw material inputs;
- the appropriate aluminium to iron ratio - an iron oxide to alumina ratio of 0.8:1.2 in the raw mix was found to give the best results in one study, although some plants will use residue to supplement iron level while others use it for the alumina content;
- and reasonable proximity to the cement plant - up to 1200 km has been found to be acceptable in one case, although generally shorter distances are economic limits.

Table 3 summarises the current usage along with some pending applications and abandoned ventures. There is scope for many more clinker producers to use bauxite residue leading to improved environmental footprints of both the aluminium and cement industries.

9.1.3.2 Supplementary Cementitious Materials (SCM) for blended cements

Bauxite residue, in some cases after treatment, can improve the packing characteristics or rheological behaviour and can play a valuable role in mortars or concrete as a replacement of clinker or in combination with pozzolanic and hydraulic additives. There have been many studies demonstrating the possible benefit and some of the most significant ones are outlined in the IAI report on Opportunities for use of bauxite residue in SCM. The IAI Technology Roadmap to maximise the use of bauxite residue in cement and concrete products¹⁵ discusses the potential for using bauxite residue in SCM for blended cements, should the barriers be overcome. Utilisation rates of up to 10 % of residue would allow for over 130 Mtpa or nearly 85 % of BR production to be used on a regional basis.

9.1.4 Processing into Specialised Materials

Bauxite residue's ability to absorb and retain metals has been widely studied, particularly from mine or mineral processing wastewater. Residue from the Eurallumina refinery in Sardinia neutralised with seawater was proven to have high metal absorption rates, including arsenic. An Australian company, Virotec, neutralises residue with magnesium and calcium salt brines to produce Bauxsol®

which has useful metal absorption properties.

In Korea, pellets made by heat treatment of mixtures of bauxite residue, polypropylene, sodium metasilicate, magnesium chloride and fly ash at 600 °C, showed good heavy metal absorption, especially for lead, copper and cadmium. Bauxite residue from San Ciprian mixed with gypsum was found to remove copper, zinc, nickel and cadmium from waste streams.

Both Bauxsol® and acid treated bauxite residue effectively remove phosphate and in China partial neutralisation with hydrochloric acid and subsequent heat treatment

have shown over 99 % removal of the phosphorus in water. Trials in UK sewage treatment plants have shown that low levels of phosphorus (<0.06 mg/L) can be achieved by treating effluent with Bauxsol®, to meet EU standards for effluent phosphorus levels, otherwise difficult to achieve.

Catalysts are widely used in the chemical and petrochemical industries to facilitate and accelerate chemical reactions. Residue has been demonstrated as an effective catalyst for some applications and development work in this area is ongoing.

9.2 Case Study: READYGRIT® - Extracting Value from Bauxite Residue

Darling Range bauxite mined by Alcoa in Western Australia (W.A.) is typically 30-49 % alumina, 23 % iron oxides and 15-23 % quartz. After its alumina is extracted, the bauxite residue has a coarse size fraction (>150 µm, called 'sand'), and a fine fraction (<150 µm, called 'mud'). The 'sand' fraction is about 40 % of the residue produced at Alcoa's W.A. refineries, and is mainly silicon, iron and aluminium rich minerals. Although washed to remove excess caustic, it retains some associated alkaline water, resulting in a pH of ~13.5.

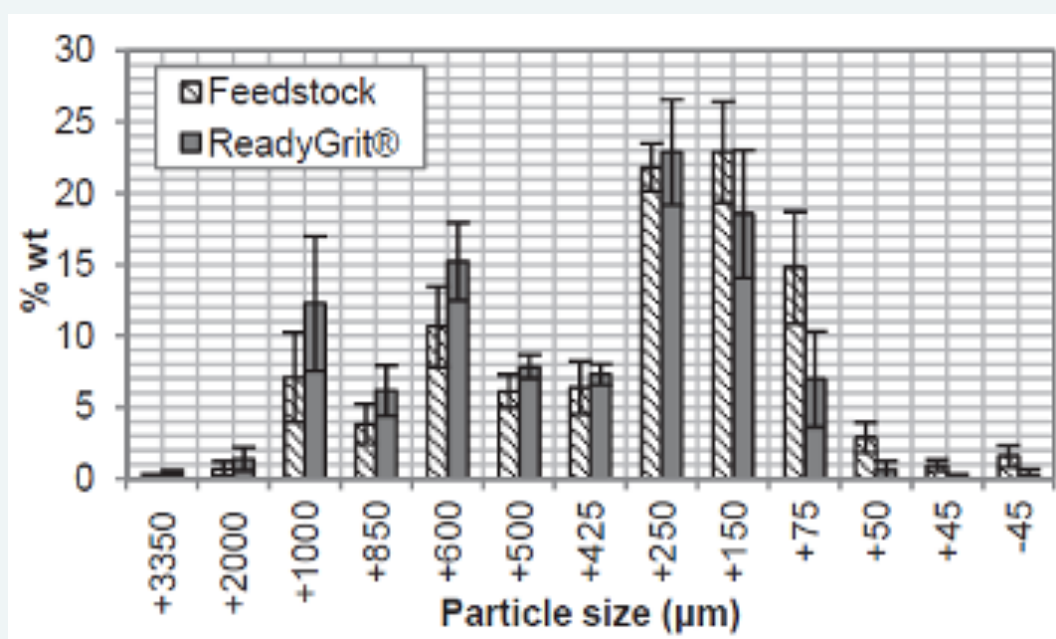
Alcoa has partnered with GMA Garnet to develop a process transforming residue sand into an environmentally benign product named ReadyGrit® (or Red Sand™), an alternative to quarried sand for some applications (15). For some uses, further washing of residue sand to remove fine material, and pH neutralization is required. Typical particle size distributions (PSDs) of the feedstock sand and ReadyGrit® are given below.

Neutralisation of residual liquid alkalinity by reaction with CO₂ can reduce the residue pH to < 10. Some alkalinity is due to low levels of tricalcium aluminate (TCA₆), the result of lime addition to the alumina refining process, and CO₂ will also react with this residual TCA₆ to form calcite and with aging, bayerite. Not all TCA₆ is converted, and the residual may slowly dissolve, releasing sodium hydroxide, and increasing the pH again. The TCA₆ is in the feedstock fines and can be largely removed by washing and screening, reducing the pH of ReadyGrit®.

A pilot plant was designed and constructed to produce ReadyGrit® from bauxite residue to a particle size distribution (PSD) and alkalinity specification for testing, evaluation and demonstration in a range of applications. The pilot production process included;

Fine mud and TCA₆ removal to a size specification with cyclones and screens.

- Counter current washing with water to reduce soluble salts.
- Neutralisation of alkalinity with CO₂ to reduce pH.
- Amendment with gypsum (0.25 % to 0.5 %) to lower pH to < 9, for low pH applications.
- Dry stacking of the product ready for trucking off site.



Particle Size Distribution of Feedstock Residue Sand and ReadyGrit® Product



ReadyGrit® was tested for dry density and soaked and unsoaked Californian Bearing Ratio (CBR), with results similar to naturally occurring sands used as road sub base materials, meeting the W.A. Main Roads criteria. Its leaching characteristics were measured by various assessment methods to understand its potential environmental impacts, and the results used in application environmental assessments. ReadyGrit® was also assessed against different guidelines in Australia and Europe for its health, safety and environmental impacts.



In summary, Alcoa's washing and neutralisation process transforms its bauxite residue into a product for use in road construction, top dressing and industrial fill, replacing traditional sand and limestone materials. Field trials demonstrate that ReadyGrit® satisfies market specifications for these applications. The process has been successfully piloted at Alcoa's Wagerup and Kwinana refineries, and the product trialed in road construction, bunker sand, top dressing, and industrial fill. ReadyGrit® demonstrates a product successfully produced and utilised from bauxite residue, while significantly reducing the volume of residue stored.

Readygrit® - Extracting Value From Bauxite Residue. Lee. F, Attiwell. S, Cooling. D, Myers. L, Nyeboer. H, Malley. I, Hay. P, Irons. R, Tate. D. Perth : 10th International Alumina Quality Workshop, 2015.

9.3 Case Study: Norsk Hydro's R&D Program for Bauxite Residue Utilisation

A major driver of Norsk Hydro's innovation is its broad knowledge and control of the entire value chain; bauxite mining, alumina refining, primary aluminium production, alloy technology, and finished products and recycling. A key to Hydro's 114-year-long success is that R&D has gone hand in hand with full-scale production.

Hydro's Bauxite & Alumina business continuously invests in innovative technology and R&D to improve Hydro's competitive position. A significant Bauxite & Alumina R&D department has been built in the state of Para, Brazil, with a major focus on the improvement of its environmental impact such as supporting biodiversity within, and rehabilitation of, its operating footprint, and utilization of bauxite residue.

Part of Hydro's R&D is done in-house, and part is collaborative, working with local, national and international institutions: local (SENAI Innovation Institute and Federal University of Para), national (São Paulo University and The Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering) and international (CSIRO, Drend Solutions).

Norsk Hydro participates in national and international collaborations studying uses for bauxite residue, with an objective to develop a bauxite residue-based product in the next ten years. The bauxite residue utilization program aligns with Norsk Hydro's ambition to create a fair and circular society by producing responsibly, offering zero-carbon aluminium, circular solutions and more renewable energy. Hydro's R&D objective is to develop bauxite residue products for large volume applications into economically strong and large-scale industries. Project areas are summarised below.

Sector	R&D Projects Underway
Steel Industry	Iron Recovery from Bauxite Residue
Agriculture	Soil Conditioners from Bauxite Residue
Civil Construction	Low CO ₂ emission cement
	Synthetic bauxite residue aggregate for concrete
	Bauxite residue as iron and alumina source for Portland clinker
	Incorporation of bauxite residue into cementitious products
Oil & Gas	Proppants using bauxite residue

Iron recovery and soil conditioner from bauxite residue

Hydro and SENAI Innovation Institute-Mineral Technologies partnered in 2019 to study two applications of Bauxite Residue (BR) in parallel: iron recovery and soil amendment.

Different technologies have been studied for iron recovery from residue, including magnetic and gravity separations, and flotation. Preliminary results of magnetic separation show an overall iron recovery of 11.5 %, and a 59 % Fe₂O₃ product. Coarser feed particles report to the product, while fines are not recovered, demonstrating that particle size is a key variable in wet magnetic separation of paramagnetic materials. An 11.5 % recovery rate would produce 0.3 – 0.6 million tonnes/year of iron.

(Light Metals 2020): https://link.springer.com/chapter/10.1007/978-3-030-36408-3_14

BR can be a sustainable and economically viable option for soil fertility improvement in countries where agriculture is socially and economically important, such as Brazil. This project uses biology to partially neutralise BR alkalinity, allowing its safe application as a soil conditioner for fertility improvement in acidic tropical soils. Microcosm testwork has assessed the effect of adding local agro-industrial organic residues to BR along with fertile soil as a microbial inoculum to generate acidity. This approach resulted in fast BR pH reduction (from 10 to 6.5 in 2 days). Preliminary results confirmed that the local organic residues and soil additions improved BR's physical and chemical characteristics, supporting further study into its agronomic value.

(Light Metals 2020): https://link.springer.com/chapter/10.1007/978-3-030-36408-3_15

Low CO₂ emission cement

In rapidly developing countries, concrete is the dominant construction material, and its production accounts for 5 to 8 % of global CO₂ emissions, with cement 95 % of this total. In 2014, emerging countries including China, India, Russia, South Africa and Brazil, accounted for 81 % of global production, while industrialised countries accounted for only 9 %. Developing countries are projected to demand 2.5 times more cement-based products by 2050, making cement around 30 % of global anthropogenic CO₂ emissions.

In 2020 Hydro and the Federal University of Para (UFPA) partnered to develop a cement product using bauxite residue from Hydro's Alunorte refinery and other raw materials from the Pará region. The project's objective is a cement which reduces both energy consumption (by up to 50 %), and CO₂ emissions (up to 70 %). Replacing limestone with bauxite residue, along with other innovations, results in a cement with better mechanical properties and durability, which is cost competitive with the cement currently mass-produced.

Synthetic bauxite residue aggregate for concrete

Hydro and the Federal University of Para (UFPA) began a project in 2020 to produce synthetic aggregates using bauxite residue, clay and silica, for use in concrete structures in civil construction in the region. Conventional coarse aggregates are usually pebble and gravel. There are several types of natural aggregates on the market with different applications that vary according to their density, such as in beams, columns, structural blocks, floors, curbs and joints. The study includes the development and optimization of the production technology, evaluation of the performance and durability of the aggregate and concrete, and tests of structural elements made from the concrete.

Bauxite residue as iron and alumina source for Portland clinker

Using alternative raw materials (bauxite, iron ore, clays, etc) as sources of iron and alumina, for Portland clinker production is already applied in several locations globally. In addition to the environmental benefits for the alumina industry of using bauxite residue, it reduces the environmental impact of limestone and clay mining, the main cement raw materials. The local availability of the raw material is another advantage, where other sources of iron and alumina need to be transported over long distances.

The main factor for success is often logistics, since the cost of transport, as well as environmental and regulatory restrictions, may make residue less competitive than conventional raw materials. The cement industry in the region has been engaged in testing Alunorte bauxite residue in their cement products.

Incorporation of bauxite residue into cementitious products

Hydro and São Paulo University (USP) agreed in 2020 to develop building materials and components based on criteria that consider technical and production safety issues, availability of inputs close to the consumer market, performance in use, durability and life cycle analysis, especially in products using residue as a raw material. The project's premise is to integrate scientific, geo-economic and construction performance concepts for the systematic development of bauxite residue applications.

Proppants using bauxite residue

Proppants are used in the extraction of oil and gas from shale formations by hydraulic fracturing. Hydro and Drend Solutions agreed in 2020 to develop a proppant from bauxite residue that meets internationally accepted standards, both in terms of their hydraulic fracturing performance and environmental safety.

9.4 Case Study: MYTILINEOS Metallurgy Business Unit ‘Remining’ of Bauxite Residue

MYTILINEOS Metallurgy Business Unit’s plant “Aluminium of Greece” (AoG) is the leading producer of alumina and aluminium in S.E. Europe, and the only vertically integrated bauxite, alumina and aluminium production plant in Europe. AoG mines 650 kt of Greek bauxite, processes more than 1.4 mt of Greek and 0.4 mt of tropical bauxite, to produce 835 kt of alumina and 190 kt of aluminium and about 800 kt of bauxite residue each year.

The handling of the bauxite residue consists for AoG one of the fundamental challenges for its sustainability, and a constant effort within its ESG framework. Over the years, the company has invested in advanced technological equipment that allow the treatment of bauxite tailings, while it participates in several European projects aimed at finding future applications for the bauxite residue.

AoG was the first company in the world to adopt the high-pressure filtration technology for the handling of the produced bauxite residue. The company’s investment decision to install filter presses reflected its vision to minimise the company’s environmental footprint in the most safe and efficient way via the adoption of the Best Available Techniques in bauxite residue handling (BAT). The filter presses allowed AoG to lower the moisture of the produced bauxite residue, and hence to safely deposit it on land (meeting this way the EC waste directives), and easily transport it to other sites for utilisation. AoG installed the first filter press in 2006, while a second filter press was installed in 2008, after a full year of continuous testing and improvements (2007). The project was completed in 2009 with the installation of two more filter presses while incremental debottlenecking and optimisations were carried out along the way. Since 2012, 100 % of the produced bauxite residue has been filter pressed and deposited as dry filter cake (moisture below 28 %) on the residue storage site, which is located next to the refinery. The deposition of BR takes place in line with environmental permits and geotechnical studies.



AoG Press Filter and Building, Residue Stockpile and Residue Storage Facility

The adoption of the high-pressure filtration technology allowed AoG to increase the utilisation of the bauxite residues in cement production, an application which nowadays is widely studied and has been progressively adopted by alumina refineries all over the world as the

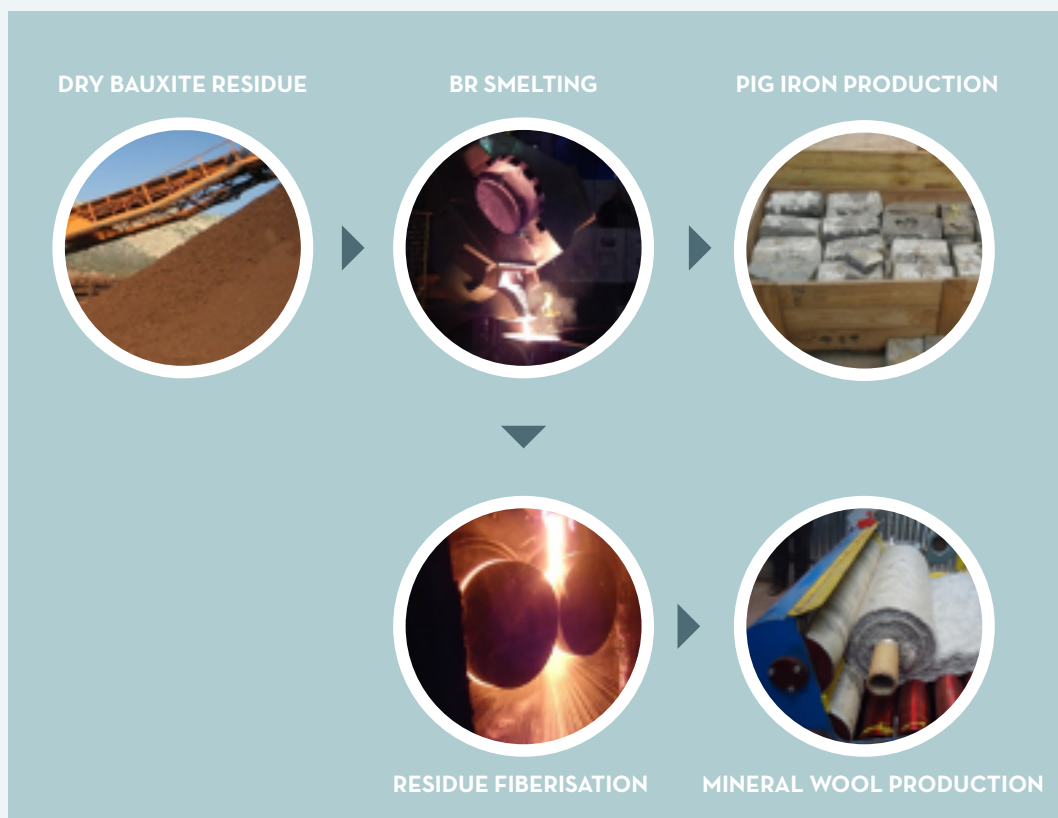
most prominent sustainable solution for the utilisation of the produced BR. The company's shipments, initially addressed to nearby cement plants, were extended in 2018 to Cyprus. AoG's BR has been used at rates of 1.5 - 3 % in the production of cement clinker, resulting overall in the re-use of more than 330 kt (on dry basis) of BR in cement production over this eight-years-time period.

Sodium (Na) and chromium (Cr) content, along with moisture, are the most common technical constraints to greater BR utilisation in cement production, although none of them is crucial. On the other hand, logistic costs, and legal complexity of BR shipments become key issues. European Community (EC) waste transport legislation requires specific permits for the BR shipments, increasing the complexity and costs. Cement producers are only willing to utilise BR, as long as it constitutes a lower-cost alternative in respect to other raw materials.

Except for the utilisation of BR in cement production, over the years, AoG has also undertaken several pilot-scale research projects, aiming to find new sustainable applications for BR reuse.

In 2012, the company installed an Electric Arc Furnace and a Melt Fiberizing unit to pilot the ENEXAL residue treatment process. Over the two-years project, more than 30 t of residue were treated, and more than 5 t of pig iron were produced and then re-used as an up- to- 20 % steel-scrap substitute in secondary steel production. A good-quality fibre of bright color and high mechanical resistance was produced by the molten slag, confirming that ENEXAL was a zero-waste process.

The production of both pig iron and mineral wool could generate revenues that match and exceed the operational costs of a potential production unit. However, given that pig iron revenues alone can only cover up to 35 % of the operational costs, and that the mineral wool market could only absorb a quantity of 60 -100 kt/year in a 1000 km radius, in case



of full BR processing (~300 kt of pig iron and ~400 kt of mineral wool product/year) the process becomes non-viable.

The Greek bauxite residue BR constitutes a significant source of Rare Earth Elements (REE) Scandium (Sc) and Gallium (Ga). According to primary calculations, extracting REE from Mytilineos - AoG's annual residue production can meet about 10 % of European REE demand (8000 tpa - 2014 data). Extracting gallium from both the BR and Bayer liquor from a single European alumina refinery would amount to global levels of gallium production (annual world production 284 t in 2012).

In 2020 AoG installed a hydrometallurgical pilot plant to extract Sc from BR, applying the SCALE process. More than 10 t of BR have been leached with sulfuric acid until now, producing a Sc-bearing pregnant leaching solution (PLS) and a neutralised Bauxite Residue. The next step of the project involves processing the PLS with II-VI's SIR ion-exchange technology to produce a solution that can reach up to 25 wt% concentration in Sc.



BR leaching in SCALE pilot at AoG



II-VI SIR pilot at AoG

9.5 Case Study: Iron Recovery from Bauxite Residue at CHALCO's Guangxi Branch (Pingguo)

CHALCO's Guangxi refinery is located in Pingguo, Baise, in the Guangxi Zhuang Autonomous Region. The refinery was established in 1987, as the Pingguo Aluminum Company, and presently has five Bayer production lines. Construction of the first line began in 1991, and was first put into operation in 1995.

The process for the Magnetic separation of bauxite residue to recover iron concentrate from all bauxite residue was commissioned in 2011, with deep magnetic separation (a technology developed by CHALCO) implemented in 2015. CHALCO's Guangxi branch has developed into a modern large-scale enterprise integrating mining and alumina production, with a production rate of 2.5 million tonnes of alumina and 700 thousand tonnes of iron concentrate after more than 20 years of process optimization and production expansion.

Magnetic separation is used in bauxite residue iron recovery producing a product with a total Fe in iron concentrate of $\geq 55\%$, and a moisture content of $\leq 16\%$. Iron oxide in residue is recovered efficiently at low cost, and the volume required for residue storage is reduced through the application of bauxite residue iron separation technology.



Bauxite Residue stacking area in Guangxi Branch of CHALCO



CHALCO Iron Concentrate



CHALCO Pingguo Residue Iron Separation Facility



10 IAI SPONSORED RESIDUE STUDIES

KEY POINTS

- Work in the the bauxite residue remediation field has been underway for some time in both collaborative activities and individual company research efforts.
- The IAI has invested its members' funds in facilitating research and development into areas that are key and common issues for the global alumina industry. The details of these studies can be found on the IAI's website

10.1 AMIRA P1038

The AMIRA International project P1038 identified possible ways in which the “in situ” remediation of bauxite residues might be undertaken and identified bioremediation based on strategies developed for saline-sodic soil as the most promising research direction.

Following a review of AMIRA Project P1038, the IAI Board decided to fund further research by the University of Western Australia's School of Earth and Environment on

the in situ Remediation of bauxite residue.

The overall project aimed to address the need for the development of methods for modifying the existing stored residue by a combination of neutralisation and concretion, without major disturbance to the bulk mass, with a view to improving the long-term chemical and physical stability.

10.2 Leaching assessment study and methodologies

A study on leaching assessment methodologies for storage and use of bauxite residues⁴ was delivered by H.A. Van Der Sloot and D.S. Kosson in 2010 under consultancy to the IAI. The study's objective was to build further knowledge and understanding of the primary environmental concerns such as the effect of waterborne releases, and subsequent transport and potential impacts re-

sulting from leaching.

The objective of this report was to review the current status, understanding and approaches to leaching assessment that may facilitate improvements in use and storage of bauxite residue, emphasising emerging assessment techniques in the European Union and the United States.

10.3 Bioassays for assessing rehabilitation of bauxite residue

This Rio Tinto, Alteo, University of Limerick and IAI project assessed metal availability and uptake in a range of different residue treatments. The aim was to understand the potential for translocation through the food chain. This was done through plant and earthworm bioassays on

fresh and rehabilitated bauxite residue. Results show that bauxite residue which has undergone some rehabilitation demonstrates no phytotoxic risk nor food chain contamination risk in plants.

10.4 Constructed wetlands for treatment of alkaline leachate

Please refer to Case study 8.5 Residue leachate treatment, Rusal Aughinish for more information.

10.5 In situ remediation of bauxite residue

Please refer to Case study 8.3 for more information.

10.6 In situ remediation of lime sintered bauxite residue

In the past, lime sintered bauxite residue accounted for 10 % of the total bauxite residue produced in China. Although the production share of lime sintered residue has now declined, large quantities of lime sintered residue continue to be stored and await remediation and closure.

This project between CHALCO, IAI and University of Western Australia applied and optimised microbially-assisted in situ bioremediation for diasporic-derived bauxite residues, including lime sintered and un-sintered (Bayer) residues.

10.7 Opportunities for bauxite residue reuse in cement

A working group comprised of members from IAI, seven alumina producers and external consultants has been exploring opportunities to use bauxite residue in different cements. Having undertaken extensive literature reviews at an earlier stage, a Technology Roadmap to maximise the use of bauxite residue in cement and concrete products was published in 2020¹². The roadmap provides information that addresses concerns, prejudices, technical and legislative barriers to bauxite residue use.

In addition, a Bauxite Residue in Cement Calculation Tool has been developed by École de technologie supérieure, Rio Tinto and IAI. The energy, environmental and financial benefits of using bauxite residue in the cement and concrete industry are not well understood. The Tool evaluates electricity use, fuel consumption, expected emissions and related costs per tonne of material produced, comparing all possible scenarios of adding the residue to the baseline of the normal operation of the cement plant. The tool is available to download from the IAI website.

10.8 Alumina Technology Roadmap update

An Alumina Technology Roadmap website, incorporating not only core process and environmental objectives but also changing shareholder expectations and underlying

industry trends in manufacturing, automation and end to end optimisation is being developed by the Alumina Quality Workshop with support from IAI.

10.9 Geotechnical stability of filtered residue

The stacking of the filter cake presents a new field of geotechnical engineering. The material is considerably different to normally consolidated residue, and as such it is uncertain whether conventional testing and analysis can be applied to large deposits. The challenge is to determine the level to which the stacked material needs to be worked (compacted), and to have the appropriate tools

available to check and forecast the overall condition (stability) of the stack as it is developed. An extensive testing program led by the University of Western Australia is currently underway. Other partners involved in the project include IAI, Alcoa, Rio Tinto, BHP Billiton, Alumina Quality Workshop and MRIWA.

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