

# Bauxite Residue Management: Best Practice

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## **International Aluminium Institute (IAI)**

Current IAI membership represents over 60% of global bauxite, alumina and aluminium production. Since its foundation in 1972 (as the International Primary Aluminium Institute), the 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. While the Institute works closely with the national and regional aluminium associations, with which it shares many members, the associations themselves are not members of the IAI.

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 principle stakeholders.
- 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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## **European Aluminium (EA)**

The EA, founded in 1981, represents the whole value chain of the aluminium industry in Europe. European Aluminium actively engages with decision-makers and the wider stakeholder community to promote the outstanding properties of aluminium, secure growth and optimise the contribution our metal can make to meeting Europe's sustainability challenges. Through environmental and technical expertise, economic and statistical analysis, scientific research, education and sharing of best practices, public affairs and communication activities, EA promotes the use of aluminium as a permanent material that is part of the solution to achieving sustainable goals.

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Disclaimer: The information contained in this publication is presented to the best of the Institute's knowledge, but without warranty. The application of the methods, systems and processes for the management of bauxite residue outlined in this publication is beyond the Institute's control and responsibility and should be taken in compliance with local and national regulatory requirements.

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## I. Introduction

Bauxite residue has been produced since the development of the alumina/aluminium industry in the late nineteenth century. It is one of the largest industrial by-products in modern society with global levels estimated at around 3,000 million tonnes at the end of 2010 (Power et al, 2009). Developing and implementing effective storage and remediation programmes remains essential as the inventory grows by approximately 120 million tonnes per annum.

The chemical and physical properties of bauxite residues are determined by the nature of the bauxite and the effect of the Bayer process. The technology and operating procedures at individual refineries will impact the water content and pH value of the material being discharged - two key factors in bauxite residue management.

This document elaborates on the aluminium industry's objective to ensure bauxite residue management is based on global best practice, providing safe storage and achieving acceptable low social and environmental impacts during operation and post-closure.

Best practice is the best way of doing things for a given site at a given time. Best practice principles and approaches should evolve to accommodate innovative solutions as they are developed.

'Best practice' is not a single "one-size fits all" prescription to bauxite residue management: it involves managing each risk with best available technology appropriate to the circumstances. This will be influenced by local climatic, geographic and environmental conditions as well as government policies, the regulatory framework and, importantly, community factors.

Development of technological applications for bauxite residue treatment could change the material discharged, allowing for different long term storage, remediation, and re-use options (for example, filtration developments). Significant research in remediation solutions for existing residue material is being undertaken. High alkalinity in much of the stockpiled material is a critical aspect to be resolved.

The best practice recommendations are the result of a series of workshops held in conjunction with the Alumina Quality Workshop (AQW) in Perth 2012 and the China Non-Ferrous Metals Industry Association (CNIA) in Nanning 2012. Operational and technical experts from the global alumina industry identified the design and operational criteria that recognise and promote best practices for the sustainable management of bauxite residue storage facilities. We would like to thank Ken Evans, Chris Handley, Leon Munro and David Smirk for their work in helping to put these recommendations together. We would also like to thank Bruce Brown, Gary Bentel, Don Glenister, David Honey, Leon Munro, David Smirk and Steve Vlahos for facilitating the workshops.

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## II. Properties of Bauxite Residue

### a. Background

Aluminium is a material with global annual production of some 45 million tonnes in 2011 and an estimate of nearly 50 millions tonnes in 2013. Aluminium metal does not occur naturally although elemental



aluminium ranks after oxygen and silicon in abundance in the earth's crust. Aluminium is a constituent of many rocks, minerals and ores and has to be extracted and converted to metal through a combination of chemical and electrolytic processes. The normal precursor to aluminium metal is aluminium oxide (alumina) although routes based on aluminium chlorides have also been developed and employed on a very small scale. Over 95% of the alumina manufactured globally is derived from bauxite by the Bayer process. There is some limited manufacture of alumina using other processes, for example the VAMI and sinter route processes in Russia and China. Bauxite and nepheline syenite are the principal raw material sources but experimental work is

continuing using kaolin and high alumina containing clays. Residual materials arise during these alumina manufacturing processes: those using the Bayer process extraction of bauxite are termed 'red mud' whilst those from different routes using other aluminous materials give rise to 'bellite/white muds'.

Bauxite ore is readily available and contains aluminium oxides and hydroxides in levels between 30 and 65% (measured as aluminium oxide). Current estimates of known world reserves are some 30 billion tonnes with indications of unproven reserves being much higher. 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 the Bayer process, bauxite is heated under high temperature and pressure conditions in caustic soda to form a solution of sodium aluminate leaving behind an insoluble residue. The sodium aluminate is then filtered and aluminium hydroxide crystals are encouraged to precipitate. The aluminium hydroxide is sometimes sold as is or can be calcined to form aluminium oxide (alumina).



Over 90% of the alumina produced in the world is used to manufacture aluminium metal, this is termed metallurgical or smelter grade alumina (SGA); the remainder is termed non-metallurgical grade alumina (NMGA). Large quantities of aluminium hydroxide are used to make water treatment chemicals (alum, polyaluminium chloride and sodium aluminate), zeolites, activated alumina, whilst specialty grades of alumina are used in a wide range of applications such as refractory products, ceramic materials, abrasives, tiles, and glass.

### b. Production of bauxite residue

The amount of bauxite residue produced by an alumina plant or refinery is primarily dependent on the sources of the bauxite and secondarily on the extraction conditions used by the plant. In the extreme, this can vary from 0.3 to as high as 2.5 tonnes of residue per tonne of alumina produced, though typically it lies between 0.7 and 2 tonnes of residue per tonne of alumina produced. The most important factors are aluminium content of the bauxite, the type of aluminium oxide/hydroxide present (e.g. gibbsite, boehmite or diaspore), and the temperature and pressure conditions used for the extraction. The last two factors are dictated by the nature and form of the alumina present, the local cost for energy, and the cost and distance the bauxite needs to be transported. Bauxites high in boehmite need higher processing temperatures and diasporic bauxites even more aggressive conditions of temperature and causticity. A processing temperature of 140–150°C is generally used for bauxites high in gibbsite, a temperature of 220–270°C for boehmitic bauxites and a temperature of 250–280°C for diasporic bauxites.

The Bayer process has been used since 1893 and there are approximately 60 Bayer alumina plants in the world currently in operation outside China. The number of alumina refineries in China is growing

extremely rapidly and has increased from 7 in 2001 to 49 in 2011. The total operating plants are therefore over one hundred. New alumina plants and expansions are being added as the demand for aluminium continues with long term annual growth rate in excess of 6% projected. It is estimated that the annual generation of bauxite residue from all these plants is of the order of 120 million tonnes a year.

There are approximately 30 Bayer alumina refineries that have closed and have left associated legacy bauxite residue sites. It is estimated that the amount of bauxite residue stored in operating and closed sites is some 3 billion tonnes.

### c. Composition

Bauxite residue is mainly composed of iron oxides, titanium oxide, silicon oxide and un-dissolved alumina together with a wide range of other oxides which will vary according to the country of origin of the bauxite. The high concentration of iron compounds in the bauxite gives the by-product its characteristic red colour, and hence its common name 'red mud'. A typical chemical composition is shown in Table 1 and a typical mineralogical composition is shown in Table 2.

Table 1 – Chemical composition range (%) for bauxite residue for main components

| Component               | Typical range (%) |
|-------------------------|-------------------|
| $\text{Fe}_2\text{O}_3$ | 20 - 45           |
| $\text{Al}_2\text{O}_3$ | 10 - 22           |
| $\text{TiO}_2$          | 4 - 20            |
| $\text{CaO}$            | 0 - 14            |
| $\text{SiO}_2$          | 5 - 30            |
| $\text{Na}_2\text{O}$   | 2 - 8             |

Table 2 – Mineralogical composition range for bauxite residues

| 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 ( $\text{FeOOH}$ )   | 10 - 30           |
| Hematite ( $\text{Fe}_2\text{O}_3$ )  | 10 - 30           |
| Magnetite ( $\text{Fe}_3\text{O}_4$ )   | 0 - 8             |
| Silica ( $\text{SiO}_2$ ) 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 ( $\text{AlOOH}$ )   | 0 - 20            |
| Titanium Dioxide ( $\text{TiO}_2$ ) anatase and rutile  | 2 - 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 ( $\text{CaCO}_3$ )   | 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 ( $\text{CaTiO}_3$ )   | 0 - 12            |
| Cancrinite ( $\text{Na}_6[\text{Al}_6\text{Si}_6\text{O}_{24}] \cdot 2\text{CaCO}_3$ )                            | 0 - 50            |
| Diaspore ( $\text{AlOOH}$ )   | 0 - 5             |

In addition there are various other minerals sometimes found including hydrogarnet, chantalite, hydroxycancrinite, and sodium titanate.

A wide range of other components are present at trace levels in the bauxite, most especially metallic oxides such as those of arsenic, beryllium, cadmium, chromium, copper, gallium, lead, manganese, mercury, nickel, potassium, thorium, uranium, vanadium, zinc and a wide range of rare earth elements (discussed later). Some of the elements remain un-dissolved so are eliminated with the bauxite residue, whilst some are soluble in the Bayer process and either build up in the Bayer liquor, or precipitate along with the aluminium hydroxide. Depending on the temperature used in the extraction process some elements will increase in concentrations and other will be lower in the bauxite residue.

Non-metallic elements that may occur in the bauxite residue are phosphorus and sulfur.

A wide variety of organic compounds can also be present, these are derived from vegetable and organic matter in the bauxite and include carbohydrates, alcohols, phenols, and the sodium salts of polybasic and hydroxyacids such as humic, fulvic, succinic, acetic or oxalic acids. In addition, small quantities of some of the sodium compounds resulting from the sodium hydroxide used in the extraction process will remain depending on the dewatering and washing systems used.

The Bayer process requires the introduction of caustic soda as the major compound in alumina production. A key focus of alumina refineries is to maximise the recovery of the valuable caustic soda from the residues in order to reuse it during the extraction process. Apart from the residual caustic soda remaining after this recovery process, the ore residues contain only traces of additives used in the process such as flocculants. The residual soluble sodium species, predominantly a mixture of sodium aluminate and sodium carbonate, give rise to an elevated pH for bauxite residue slurries. Over time the residual sodium species are partially neutralised by carbon dioxide from the air to form sodium carbonate and other metal carbonate species, resulting in both a lower pH as well as an improved hazard profile.

#### *Radioactivity*

Bauxites contain very low levels of naturally occurring radioactive materials (NORM); due to the presence of the uranium ( $^{238}\text{U}$ ) series and the thorium ( $^{232}\text{Th}$ ) series, which are both found in most mineral raw materials. The levels of  $^{238}\text{U}$  and  $^{232}\text{Th}$  in bauxite are normally in the mg/kg range and give rise to extremely low levels of radioactivity, at or below naturally occurring radioactivity found in granite rocks in many regions of the world.

During the Bayer process, most of the uranium and thorium remains in the un-dissolved residue. The concentration of the radioactive species will therefore be proportionately higher in the bauxite residue than the initial ore; this is sometimes referred to as technologically enhanced naturally occurring radioactive material (TENORM). Some typical radioactive concentrations in bauxites due to  $^{238}\text{U}$  range from 0.03 to 0.6 Bq/g and due to  $^{232}\text{Th}$  from 0.03 to 0.76 Bq/g; whilst in bauxite residues the levels due to  $^{238}\text{U}$  are typically from 0.08 to 0.66 Bq/g and  $^{232}\text{Th}$  are typically from 0.07 to 1.8 Bq/g. This compares with the average level in soil for  $^{238}\text{U}$  and  $^{232}\text{Th}$  of 0.033 and 0.045 Bq/g respectively (UNSCEAR). The impact of these levels of radioactivity has been considered in a number of potential applications for bauxite residue and is discussed in the section on bauxite residue utilisation. Occupational above-background exposures at bauxite mines and alumina refineries in Western Australia have been found not to exceed 1mSv/year, the upper-limit of exposure prescribed for members of the public.

#### **d. Characteristics**

The bauxite used will have a major impact on the characteristics, particle size distribution, and behaviour of the residue; the coarse fraction (greater than 100  $\mu\text{m}$ ) which is high in quartz may be separated from the finer silty muds (typically 80% less than 10  $\mu\text{m}$ ). Sometimes these coarse fractions are given particular names such as 'red oxide sand' or 'sand residue,' and the fine fractions are termed 'red mud'. These coarse and fine fractions are handled very differently in the plant. The coarse fraction sands are often used for road construction in the residue areas, to provide a drainage layer under the mud, or as a capping material for the residue sites. The coarse fraction is much easier to wash, has much better draining behaviour so has a lower residual caustic content. However, if left un-separated, then the draining behaviour of the bauxite residue is much improved. Bauxites from some regions, such as Western Australia, are especially high in the coarse sands and in some instances these can account for 50% of the content of bauxite.

### III. Long Term Planning and Design

The basis for planning of a bauxite residue storage area (BRSA) should be a comprehensive characterisation of the chemical and physical properties of the residue material and the geological, environmental and social setting at and around the proposed site. Planning should involve the regulatory authorities and local communities/stakeholders.

All potential environmental, social, economic, health and safety risks must be identified and plans for environmental management, monitoring, closure and rehabilitation must result in acceptable best practice environmental outcomes and constitute best practice for mitigating these risks for the life of the operation and thereafter.

A risk assessment process should be established at an early stage of the planning of a (new) BRSA, reflecting current risk assessment methodology as recommended by AS/NZS 4360:2004 <sup>(1)</sup>

- establish the context – geographically, socially and environmentally, and decide on the design criteria
- identify the hazards – what can happen, where and when, and how and why?
- analyse the risks – identify existing controls, determine the likelihoods and consequences, and the level of risk
- evaluate the risks – compare them against the design criteria, carry out sensitivity analyses to highlight both the key and unimportant risks, set priorities, and decide whether the risks need to be addressed
- address the selected risks – identify and assess options for mitigation, prepare and implement treatment plans, and analyse and evaluate the residual risk.

Particular consideration should be given to the likelihood of earthquakes, tsunamis, hurricanes, and severe storms which might have an impact on the integrity of the system.

Existing conditions that need to be measured and recorded for establishing baseline environmental data prior to development of a BRSA should include:

- groundwater levels and quality
- water content and geochemistry of foundation soils and rocks
- air quality
- fauna and flora
- natural and background radiation levels where radioactivity is associated with the source bauxite material.
- underlying geology and hydrogeology
- history of extreme meteorological events

Physical and chemical characteristics of the bauxite residue should be identified, monitored and reported over time – with changes to these characteristics being carefully assessed to determine any potential impacts on existing practices and future management of the site.

Operators must take responsibility for meeting performance standards set by government regulators and are expected to pursue continual improvement where practicable.

Negative environmental impacts on land, water, air and biota should be avoided where feasible, and any impacts on environmental values should meet approved outcomes.

Public health and safety should not be compromised. Rigorous monitoring and public reporting programmes should be used to demonstrate progress towards, and achievement of, agreed environmental outcomes, such that it will be possible to take corrective or enforcement action if the environmental outcomes are not achieved.

The facility responsible for the bauxite residue should demonstrate capability through implementation of suitable management systems (including contingency plans) with adequate training and resourcing to ensure best practice is implemented on the site.

#### **a. Storage Facility Design Criteria <sup>(2)</sup>**

Key design criteria of a bauxite residue storage facility include:

- minimum, maximum and average residue rates at which the delivery system will operate (m<sup>3</sup>/h)
- geochemical characteristics which may influence the selection of the most appropriate design for operation and closure
- solids concentrations and average solids concentration (percentage by mass)
- annual and life-of-operation residue tonnages
- the rated maximum capacity of the return water system (m<sup>3</sup>/hour)
- history of extreme meteorological events
- proximity to habitation and water courses
- propensity of seismic activities and tsunamis
- public health and safety, community and environmental compliance targets, defined in consultation with stakeholders, including seepage, ground water quality, decommissioning, rehabilitation/closure requirements, air quality and radioactivity
- operating and maintenance requirements.

#### **b. Construction <sup>(2)</sup>**

The storage facility designed and constructed by suitably qualified and experienced contractors/staff, with an appropriate supervision and quality control of construction materials – in accordance with design specifications meeting international/national standards and reflecting local conditions.

The principal considerations for design of a bauxite residue containment structure are:

- foundation conditions
- geotechnical parameters of the construction materials
- geotechnical slope stability
- seepage and the need for internal drainage or clay cores and cut-offs into the foundation beneath the containment wall
- staged construction, either by progressive wall raising, addition of containment cells or construction of new facilities over time
- selection of construction techniques and equipment requirement
- quality assurance of construction process.

#### **c. Seepage control <sup>(2)</sup>**

The following aspects need to be considered in the design to adequately control seepage:

- hydraulic characteristics of the foundation beneath the residue storage facility, including the presence and value of groundwater, and the need for a liner
- hydraulic characteristics of the containment wall, including the need for a clay core and cut-off into the foundation beneath the containment wall
- the impact of seepage from the residue on surface and ground water
- prevention of low permeability lenses or layers forming on the residue beach that could cause future seepage or stability concerns
- under-drainage to remove gravity drainage from the deposited residue.
- decant systems designed and operated to limit the storage of supernatant water and incident rainfall off the surface of the residue, and hence limit seepage.

#### **d. Bauxite Residue Transportation <sup>(2)</sup>**

*Only slurry pipeline transportation is covered in this document.*

Residue is often pumped as slurry along a pipeline to the storage facility. The slurry pipeline corridor should be designed to protect the environment against spills due to possible pipeline leaks/failures and breaks, and the clearing of pipeline blockages. There should be regular inspections of pipeline routes

Methods for controlling the discharge of residue if such incidents occur include:

- construction of containment drains or sumps along the pipeline corridor
- sleeving of the pipeline with a larger diameter pipe for situations where the residue pipeline is traversing sensitive environments (for example, a river crossing) or crossing transport routes
- use of differential pressure sensor or flow measurement instrumentation and alarm system to alert operators in case of pipeline failure.

## Best Practice Recommendations

### Integrated planning

- \* residue planning designers, facility management and closure group must work together and communicate to achieve key performance indicators (KPIs).
- \* accountability and designated co-ordinator important.

### Storage design

- \* capacity should be based on performance and align with risk assessment.

### Water Balance

- \* integrate a life cycle plan.
- \* establish standards for ground and surface water management.

### Space

- space should be adequate to match refinery life/production expectations. Residue storage plan (include drying time, area needed) needs to be linked/aligned to operations plan (e.g. increase in capacity).



Bauxite residue storage area, Rusal Aughinish, Ireland

## IV. Governance

There should be clear management accountability of bauxite residue activities at a senior level, with a thorough understanding of design, operating and closure objectives.

An operating manual should be maintained for each storage facility – and aligned with the design objectives of the facility – to guide facility operators with the daily operation, as well as with forward planning of the facility's operation and maintenance.

The operating manual should describe, and the operators should receive training in:

- the facility's daily operation
- residue deposition — layer drying to maximise strength and minimise seepage
- water - management of the decant pond and efficient water use to maximise stability
- dust control
- procedures requiring specific precautionary measures, such as the correct order of valve opening/closing to avoid blockage of residue pipelines
- procedures for changing and flushing residue pipelines
- key indicators used to monitor the facility's successful operation
- operator's role and responsibilities in support of residue management plan
- scheduled and preventative maintenance to keep critical equipment operational
- recording and storing of monitoring and performance data
- reporting any exceptional, untoward or unexpected observation to a supervisor, and to follow through with emergency and risk management actions.

Monitoring of bauxite residue facilities should include:

- installation of groundwater monitoring equipment beneath and surrounding the facility
- surface and groundwater quality sampling, upstream and downstream of the facility

Daily inspection of all bauxite residue storage facilities and associated pumping and pipeline systems should be undertaken and observations recorded. Unusual observations or maintenance requirements must be documented and appropriate action taken, including reporting to regulators and the community.

Inspections should include:

- position of the decant pond and observations relating to freeboard requirements (water levels with respect to dam crest levels)
- visual and operating checks of lead indicators, such as damp, seepage and erosion
- status of leak detection systems and secondary containment systems
- status of automatic flow measurement and fault alarms
- dam/levee/dyke integrity
- condition of pump and pipeline systems
- assessment of impacts to birds and other wildlife or livestock

### **a. Emergency Action Plan <sup>(2)</sup>**

All bauxite residue storage facilities should have an emergency action plan. This will ensure that in the unlikely event of a failure, appropriate actions can be taken to minimise the safety risk to people on and off the site, and to minimise any impacts to the environment by responding to the incident in an organised and systematic manner. In the EU, where a residue disposal area has been designated as a hazardous site then EU regulations require that the emergency plan information must be provided to the regulatory authorities.

The emergency action plan should:

- identify conditions that could result in an emergency, such as severe storms, tsunamis, sabotage
- describe procedures to isolate people from hazards, including the warning and evacuation of downstream communities
- identify response plans to mitigate impacts, such as clean-up plans and resources required to implement the emergency action and response plans
- identify emergency response training requirements for key people and document the location of emergency warning alarms and maintenance requirements to ensure serviceability at all times.

## Best Practice Recommendations

Governance should cover full facility lifecycle including;

- \* operation design,
- \* construction,
- \* operation and,
- \* closure and post-closure

Governance should encompass the following high level processes;

- \* know what to do - responsibility assessment matrix (RACI), know full range of activities
- \* know how to do it - standard work methods and procedures, clear performance indicators
- \* audit at all levels against clear goals

Change Management System

- \* clearly defined change management process - particular focus on the management of small changes
- \* clear and simple change management process

Emergency Response Plan

- \* emergency response plan based on risk assessment is in place and rehearsed

Senior Management Accountability

- \* ensure clear link between hazards and senior management overview
- \* well defined management structures and accountability for facility management

Integrated Production and Residue Management

- \* refinery and residue process closely linked
- \* decisions made at the correct level in the organisation
- \* scenario analysis and training
- \* clearly defined action triggers

Records Management

- \* maintain history of records
- \* put records management procedure in place
- \* put records auditing and archive process in place



## V. Performance Tracking

Performance Tracking is required by any operation striving to achieve best practice in residue management in order to sustain operational alignment with plan and design intent.

Vigilance is required ensuring that evidence of deviation from residue management plans is captured early to provide adequate opportunity to review and, as necessary, develop contingency plans in a timely manner.

It involves:

1. quantification of the extent to which the deposition management plan is implemented.
2. a combination of constant field observation by appropriately trained operational and technical support personnel in conjunction with automatic data feed through suitable, calibrated equipment. The frequency of inspections should be determined after undertaking a risk assessment.

It is intended to provide useful feedback to operational staff to enable the short-term deposition management plan to be implemented. All levels of operational management need to be aware of and fully understand their roles and responsibilities with respect to performance tracking and key residue management criteria.

The key aspects of Performance Tracking data needs to be communicated to and understood by facility level management in order to ensure the establishment of realistic long-term plans and forecasts. Similarly, the accountability and responsibility for data acquisition, reporting, management and actions required by key data indicators need to be clearly documented, understood and agreed at all levels.

A document outlining required core competencies and accountabilities reflecting all levels of an organisation is essential for sustaining performance tracking and reporting. Furthermore, the importance of sustaining quality Performance Tracking obligations needs to be fully understood and appreciated. Regular assessments of the adequacy of the information flow are required to ensure ongoing adherence to the intent of the system. A KPI-type system is strongly recommended to provide an easily tracked, progressive performance tool.

Data management should be:

- transparent - unabridged and all spreadsheets auditable to the source of the raw data
- accessible – freely available to any appropriately qualified member of an organisation, and not held in isolation within a single department or individual computer. Real-time data tracking is required for all aspects of the operation that may lead to the requirement of an emergency response scenario to ensure timely warning of the foreseen risk;
- representative –all data collected needs to provide a realistic picture of actual conditions and performance measures and (as far as practicable) not derived or reverse-calculated from theoretical models until such time as alignment of field data with such models has been adequately validated;
- thorough –as far as practicable, all data sets are themselves complete, and not reliant on subsequent calculations or interpretations from models or external parties in order to be understood, applied or for control or flow loops to be closed.

Budget allocation for performance tracking should be assigned based on risk aversion, NPV and loss scenarios and not limited by short-term views. Although there are many simple, effective and relatively cheap methods of manually tracking field data, automated data acquisition systems are preferred over operator-sampled to better ensure sustained data tracking under a wider range of conditions. Therefore, the most appropriate and reliable means of data acquisition should be selected and not simply the cheapest or easiest.

Auditing, both internal and independent third party should include the methodologies employed for performance tracking data acquisition to ensure:

- sufficient data resolution and compliant with that required by applicable guidelines;
- relevance to risk mitigation or assessment;
- overall performance against design.

Assumptions underlying planning and management principles need to be fully validated, readily available and reassessed subsequent to changes in operations or residue quality and/or quantity.

The review should consider <sup>(2)</sup>:

- 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 surface
- 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
- 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.

### Best Practice Recommendations

Policy and planning -

- \* ensure the structure of the organisation and available resources align with and compliment its ability to sustain the long-term plan.

Training and accountability

- \* clearly defined to ensure all levels of the organisation are adequately qualified to undertake performance tracking responsibilities; information collected and collated in a meaningful way to ensure the intent of performance tracking activities are met to support both short- and long-term goals and consistent with the long-term plan that is in place.

Data management

- \* data to be collected in a manner that is appropriate (thorough and representative) and managed to ensure effective communication between all levels (transparent and readily accessible).

Budget

- \* ensure justification of expenditure is undertaken to implement and maintain Performance Tracking tools and equipment

Performance auditing

- \* undertaken at an appropriate frequency by an independent third party to ensure sustained operational alignment with long-term plan and continued validation of key underlying assumptions.
- \* ongoing internal auditing of all aspects of residue management performance is required with external audits undertaken at least annually by a suitably qualified third party, who is not part of the usual operational support group to avoid possible conflict of interest issues.

Forward planning

- \* best-practice goals should be developed to drive a culture of continuous improvement. Inter-operational benchmarking should be undertaken using agreed, standardised measures (such as annual deposition intensity within active disposal area) to ensure alignment of similar disposal techniques with state of the art performance capabilities.

## VI. Bauxite Residue Disposal and Storage

### a. Processing prior to disposal and storage

Caustic soda is a key input and cost within the extraction process and plants have always sought to recover as much as possible for reuse within the Bayer process. The desire to produce a residue with an even lower residual soda level has pushed this trend even further. There has been a progressive improvement and recovery is now normally greater than 96%.

Kelly filters and multi-chamber washers have given way to Super thickeners, deep cone washers, vacuum disc filters, vacuum drum filters, plate and frame filters; the solids content of the residue produced has risen from perhaps 20% to about 77%.

### b. Transportation

The handling characteristics and the dewatering method are major factors in the method used to convey the bauxite residue. If the solids content is above about 75% a handleable cake is obtained which can be trucked or put on a conveyor belt. If the residue contains greater than 28% moisture then it shows thixotropic behaviour so that its viscosity falls when subjected to vibration or mechanical agitation.

### c. Disposal and storage methods

Only a very small proportion of the bauxite residues produced are currently re-used in any way. The topic of utilisation of bauxite residues is addressed later. The manner in which the bauxite residue is handled and stored is determined by factors such as the age of the plant, land availability, proximity to the sea, presence of local features (such as old mines), climate, logistics, nature of the residue, and regulations.

Historically, plants would dispose of the bauxite residue either on the operating site itself or on adjoining land. Advantage was taken to fill depressions, valleys and mine workings. Where suitable areas did not exist, bunded areas (often called impoundments) were created; these areas were rarely lined so, in many cases, highly alkaline liquor leached from the landfill. As time progressed, considerable improvements have been made in the management, control and monitoring of these residue areas in order to minimise risk of offsite contamination and to make restoration at the end of its life easier and more effective. As the industry has developed considerable planning and thought is given to closure strategies which are now a key requisite of all modern operations.

#### *Seawater Discharge*

Discharge of bauxite residue to sea either by pipeline from the coast or into deep ocean trenches was practised at a small number of facilities. This method is progressively being phased out although studies carried out in both the Mediterranean and Pacific Ocean show that the method has minimal adverse effect on the marine environment. Disposal into the Mississippi River and Severn Estuary was carried out by the Gramercy and Newport alumina plants but ceased in the mid 1970s.

#### *Lagooning or Ponding*

Lagooning involves pumping a relatively dilute slurry (solids content between 15-30%, most often between 18-22%) into depressions, old mine workings, areas impound by dykes or levees, or dammed valleys. This has been the traditional method of disposal for almost all the early alumina plants.

In some cases these were lined to avoid seepage into groundwater, but in most of the early cases they were not. The solids would settle out and the liquor returned to the plant for reuse or evaporated using demisters. Over a prolonged period the pond would be filled, the solids would consolidate and the area could be rehabilitated. This rehabilitation could be achieved either by capping the area or using an approach such as gypsum treatment to encourage re-vegetation. Profiling of the surface was normally designed so that rainwater would runoff the rehabilitated area and not allowed to become contaminated. Very often the alkaline leachate from the area would still need to be collected and disposed of in a safe manner for many decades; this might involve collection, neutralisation and filtration to remove precipitated solids, or returning the leachate to the refinery or directly into the public sewage system for treatment.

A significant risk may exist with this method of disposal as any impounded area may well contain

unconsolidated muds and a considerable amount of highly alkaline liquid. If the dam fails because of an earth tremor, excessive rain, tsunamis, poor construction or maintenance then the contents may liquefy and muds and process liquids flow through the breach. In this liquid state the muds may flow a considerable distance. Another major disadvantage of this disposal method is the sterilisation of the land that has been used when the area is filled and the ongoing cost of collection, treatment and monitoring of the leachate and monitoring of the site and surrounding area.

### *Mud/Dry Stacking*

Where lagooning was not possible because of space limitations, stacking was adopted as a disposal procedure. For example in the UK, an early method of 'dry mud stacking' was adopted in 1941 by the British Aluminium Company plant at Burntisland. A plate and frame press was used and the mud was transported by road to a nearby disposal site which had formerly been old shale workings. In the mid 1960s, Giuliani GmbH at their plant in Ludswighafen in Germany used dry mud stacking after the mud had been filtered using a rotary vacuum filter.

The more general concept of stacking industrial tailings goes back to the mid-1960s when the Thickened Tailings Disposal system was developed by Dr E I Robinsky and has evolved over the years. It was first adopted in Ontario, Canada in the mid 1970s at the Kidd Creek Mines. The Thickened Tailings Disposal system involves reducing the water content of the tailings to below a critical level to give a higher solids residue and returning more of the process liquid to the plant. When the tailings are released, they will still flow but without segregation. The flow will stop at a gentle angle and the target was to attain a slope of 2-6% depending on the climate. In very dry climates, steeper slopes could be achieved. A much larger quantity of solids could be stored in a given available area and the levees, dykes or dams are consequently less expensive to construct. Another advantage is that when sufficiently thickened, the residue will not readily re-slurry so rainfall will runoff the surface and be collected and removed permitting atmospheric drying and aiding consolidation. The Robinsky method in which mud is continuously discharged onto a stack from a single position became known as 'wet stacking' and was adopted in wet and low-temperature climates.

The requirement for a stackable mud is that it is thickened to a high enough degree that the resulting yield stress will cause it to stack at a positive angle to the horizontal. 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 mud is separated from the coarse sandy process whilst in other plants the fractions are not separated for disposal. The fine fraction of the bauxite residue may be thickened to a high density slurry (48-55% solids or higher) by advanced thickener and flocculation technologies at the alumina plant.

When stored as a stackable deposit rainwater will tend to run off, thereby minimising liquid stored in the disposal area. The water reclaimed from the surface is pumped back to the plant to recover the soluble sodium salts. Stacked residue areas are often "under-drained" to improve the consolidation of the residue and recover further water for re-use in the refinery. The combination of stacking in a well drained deposit leads to a very stable deposit of residue.

Considerable water reduction can be obtained by 'farming' the muds. In one variant of this method, trenches are dug at intervals, say 25 m, across the mud deposit and water allowed to drain into the trenches and flow away. The muds can start off with very high moisture contents and the vehicles used need to be amphibious. Water reduction in the surface layers can be encouraged by traversing the site with vehicles with very large rollers (amphiroles) which 'squeeze' water out of the surface layers of muds. The trenches are then regularly deepened as more water drains away and the material consolidates and can be moved to another location for storage. The solids content of these materials are of the order of 60-65%. Mud farming has also been used in a beneficial way to promote carbonation and thereby reduce the pH of the muds; in a typical procedure, the muds are ploughed and harrowed daily for a period to increase contact between the air and mud.

In hotter climates where evaporation can play a greater role, 'thin layer stacking' occurs. This was adopted in the mid 1980s in Jamaica and Western Australia, in 1992 in Gove and in 2007 in QAL. Where climatically viable, it is the preferred method of disposal and is used in many newly built refineries. In this system the mud is spread in relatively thin layers, perhaps 0.5 m, over a wide area and is not covered with fresh mud until it has reached its target dryness, ~ 70%.



Mud farming, Rusal Aughinish, Ireland

‘Super-thickening’ technology has been developed by Alcoa using large diameter gravity thickeners to dewater the slurry to give a solids content of > 50%. These high-solids content residue can still be pumped but normally with the use of surfactants.

#### *Dry Disposal*

Bauxite residue can be vacuumed or high-pressure filtered to form a semi-dry cake (> 65% solids); if necessary water or steam can be used to reduce the alkalinity before being transported, stored or used. Plate and frame filters have been used since the 1930 whilst rotary vacuum filters have been used since the 1960s. Improvements in equipment, especially pressure filtration, have led to higher solid content materials (more than 70% at Gardanne and Distomon) which are easier to handle. Some trials have also been undertaken with Hyperbaric (Hi-Bar) steam filtration. The equipment is an enhancement of the disc filter principle using a pressure difference of up to 6 bar and which have successfully used for fine coal slurries. It has been claimed that a solids content of 77% can be achieved.

#### **d. Neutralisation**

Partial or complete neutralisation of the residues is sometimes implemented; this can be achieved by the use of acids (normally sulfuric acid or hydrochloric acid), carbon dioxide, sulfur dioxide, sea water or concentrated brines (Virotec process). Partial neutralisation of the bauxite residue reduces the potential hazard associated with the deposit and can aid re-vegetation of the land during restoration. They can be attractive options for some plants but are dependent on the location of the plant and proximity to the sea, or sources of carbon dioxide or flue gases. In the case of the Virotec process, a non-hazardous product termed Bauxsol® is produced by reacting the bauxite residue with concentrated brines.

In some coastal locations (such as the Queensland Alumina Limited and the Rio Tinto Alcan Yarwun facilities – both located in Gladstone, Queensland), seawater is used to reduce the pH of the alkaline leachate. In most instances the leachate is treated to such a level that it can be released back to the sea or estuary. The residual soluble sodium species in the bauxite residue react over time with the carbon dioxide in the air to form sodium carbonate/bicarbonate thereby reducing the pH of the muds. This has the additional merit from a climate change perspective of locking up carbon dioxide. Given a sufficient period it will reduce the pH of a surface of a dried out pond to less than 10.

Means of accelerating this have been considered for many years. Sulfur dioxide pH reduction using flue gases has been used by some plants, for example Eurallumina, Sardinia since the mid-1970s with beneficial results.

Partial neutralisation by seawater can effectively lower the pH to between 8 and 8.5 and lowers the concentration of hydroxyl and aluminate anions resulting in the formation of calcium and magnesium compounds such as calcite, aragonite, brucite, hydrotalcites, aluminohydrocalcite, hydrocalumite, pyroaurite. The addition of calcium, magnesium and potassium together with the lower pH aid re-vegetation though rain is required to reduce the sodium level further. Even lower residual pHs can be achieved using mineral acids and residues with a pH of 7.5 have been achieved using hydrochloric acid.

## Best Practice Recommendations

Despite the improvements in technology, it must be accepted that it is often extremely difficult for a plant to change the method of bauxite disposal. Factors such as proximity to the sea; availability of sufficient suitable land area; nature and characteristics of the residue; amount of annual rainfall; the sun and wind evaporative characteristics of the climate where the plant is located; availability of economic pH reduction sources such as carbon dioxide, sulfur dioxide, sea water, acid all effect the decision making. Some of these are impossible to change whilst others could lead to the plant becoming uneconomic.

It is essential for each plant to undertake a risk assessment taking into account the solid liquid characteristics of the residue, the quantity stored, the hazardous nature of the stored material (especially pH), the height and type of dam/dyke used to impound the material, the risk in that area for the possibility of earth tremors, heavy rain, hurricanes, cyclones, tsunamis, sabotage etc.

It is generally accepted within the industry that the disposal of bauxite residue to sea/estuaries will cease by 2016.

### The nature of bauxite residue

- \* there should be an overarching goal to reduce and/or stabilise the residual soda content in residue (and associated stored liquors).
- \* where possible a site should neutralise residue to prevent classification as a hazardous material/waste.

### Residue Transportation

- \* where possible separate site transport roads and active residue pipelines.
- \* control, contain or isolate residue pipelines through burst discs, bunding or removal from trafficked areas.
- \* establish a benchmark for monitoring of distribution/transportation system
- \* prepare and test pipeline spill plans and all response to failures/incidents.

### Discharge Control & Deposition Management

- \* define optimal deposition controls for each operation.
- \* document and justify tasks required for sustained BRSA performance.



Filter press at Gardanne refinery

## VII. Utilisation of Bauxite Residue

Throughout the entire history of alumina production there has been a desire to utilise the bauxite residue created in the Bayer Process either by recovering additional products from it or using it. Karl Josef Bayer's original patent in 1887 on processing bauxite to make aluminium hydroxide makes reference to its possible use in iron production. His first patent involved calcination of bauxite as the first step whilst in the later 1892 patent he referred to the use of caustic soda as the extractant. As storage, remediation, rehabilitation and monitoring costs rise, land space becomes a premium, (and disposal to sea is being phased out) then the drive to utilise bauxite residue as much as possible strengthens.

Hundreds of patents have been issued and thousands of trials have been undertaken on different uses, some of these applications have been commercialised but matching the tonnage arising annually with possible commercial applications has been, and continues to be, a major challenge. In many cases the possible uses involve replacing another low cost raw material so whilst the concept may be technically feasible, the costs and risks of using bauxite residue are not justified. It is critical that all the costs are considered: the ongoing costs of maintaining the site, security, HSE implications, risk of ongoing storage issues, rehabilitation and monitoring of closed sites must also be taken into account when considering the feasibility of particular applications.

The Chinese Ministry of Industry and Information department published the 'multipurpose use of bulk industrial solid waste 5-year plan' (the twelfth of its kind) on 5th January 2012. The ministry has established a utilisation rate of bulk industrial solid waste of 50%. Bauxite residue falls into this category and the national goal is for a utilisation rate of 15% by 2015 with a target of 20% by 2020. The utilisation rate of bauxite residue in 2012 in China has been estimated at 4% of the 40 million tonnes of bauxite residue produced although some alumina plants were achieving a much higher figure. Several plants in China are now operating significant iron recovery schemes.

### Applications

The proposed uses fall into a number of different categories: extracting some of the components, e.g. iron or rare-earths; using it as a source of a particular component, (eg. iron and alumina in cement); using the material for a specific characteristic, (e.g. colour); as a construction material, (e.g. bricks, tiles, aggregate blocks, wood substitute); or as bulk impermeable material for covering landfill. The majority of patents filed have involved bauxite residue being used in the construction, building or agricultural industries.

Considerable effort has been expended in finding applications for bauxite residue but a number of key factors affect the feasibility and economics of its adoption. The classification as hazardous or non-hazardous is important to the economics and the possible exclusion in certain applications. In addition to the chemical composition, other parameters that affect the utilisation in various applications are the residual sodium species still remaining, the particle size and the moisture content.

#### a. Potential applications

The main application areas that have been evaluated are briefly summarised below and an outline of the extent of work undertaken is described.

##### *Cement production*

Work on using bauxite residue in Portland cement has been underway for over 75 years. The aluminium and iron content provide valuable benefits to the cement in terms of strength and setting characteristics of the cement although the presence of sodium ions can be a problem. The chromium content of the bauxite residue, even though low, can be an issue if too high a proportion is used.

Iron rich, special setting cements with improved strength (when compared to Portland cement) have been made with levels of up to 50% bauxite residue from Renukoot, India together with bauxite and gypsum.

Substantial quantities of the bauxite residue from the AdG alumina plant in Distomon, Greece that were formerly disposed of in the sea, are now destined for the local cement industry.

##### *Road construction*

When dewatered, compacted and mixed with a suitable binder, bauxite residue makes a good road

building material and has been used to construct haul roads on bauxite residue areas for very many years. In the south of France, bauxite residue from the Gardanne alumina refinery (the product is termed Bauxaline®), has been used in the construction of several roads and platforms.

Some 25,000 cubic metres of Red Sand® from Alcoa were used in construction of the Perth to Bunbury Highway which opened in 2009. Trials are currently underway in Jamaica using bauxite residue from Ewarton by the Jamaican National Works Agency.

#### *Levee/dyke construction*

The good impermeability of bauxite residue when dewatered and compacted is an advantage in the construction of levees and dyke walls and is used in the construction of impoundment areas for containing bauxite residue. The material is sometimes mixed with other waste materials, e.g. fly ash, and then capped with clay to reduce water ingress and promote vegetative growth. This practice has been widely adopted across the world.

#### *Brick production*

Mixtures with clay, shale, sand, and fly ash have been proposed and evaluated for brick manufacture by various teams of workers and has been undertaken using bauxite residue from Jamaica, Sardinia, Hungary, and Korea. The presence of high levels of sodium ions will reduce the long term weathering resistance and durability of the bricks so the replacement of sodium ions by calcium can significantly improve the properties. Bricks have been made with a bauxite residue content of over 90% when using a firing temperature of approximately a 1000°C. Formulation made with both inorganic and organic binders have been successfully manufactured: inorganic binders used include quicklime, limestone, cement, and gypsum; and organic ones have included PVA and PMMA.

Lightweight aggregates have also been manufactured by incorporating foaming agents into the mixes normally with fly ash. Meanwhile, roof tiles have been manufactured in Turkey from bauxite residue from the Seydisehir alumina plant.

In the mid 1990s a project to build a sports pavilion using bricks made predominantly from bauxite residue was set up by the Jamaica Bauxite Institute and the Jamaican Building Research Institute using bauxite residue from Ewarton. Bricks made by a silicate bonded system and red mud pozzolanic cement gave good characteristics and the building is still in use today. The trace radioactive material remaining in bauxite residue gave rise to some concerns in Jamaica but an investigation showed that using 100% bauxite residue gave a dose equivalent to just over 2 mSv/year and was judged to be acceptable. Other work on Hungarian bauxites has recommended a maximum addition of 15% bauxite residue to avoid exceeding a level of 0.3 mSv/y.

#### *Soil amelioration*

Addition of bauxite residue to acidic and sandy soils can be beneficial in many ways and considerable work in this area has been undertaken in Western Australia by Alcoa. Bauxite residue at a level of over 250 t/ha was added to sandy soil together with 5% gypsum. The additions imparted to the soil, improved water retention and nutrient utilisation ability. Greatly increased ammonium and phosphorus retention were found showing how the usage of fertiliser could be reduced.

The benefits of good phosphate retention for bauxite residue partially neutralised to below pH 8 have been shown to very beneficial by Alcoa in the Peel-Harvey Estuary in Western Australia. The bauxite residue was commercialised in 1993 under the name Alkaloam® which is the material made after the carbonation of fine bauxite residue by carbon dioxide. In addition to ensuring stronger phosphorus adsorption, it has the benefit of reducing the leachability of phosphorus and thereby the amount of phosphorous escaping into the Peel Inlet and Harvey Estuary and hence the occurrence of algal blooms and fish kills. Alkaloam® also acts in a similar way to agricultural lime. After washing, the carbonated coarse bauxite residue is termed Red Sand®; this is used as a general fill construction including road base construction.

Concerns were raised with respect to leachability of heavy metals and radionuclides from the bauxite residue and a considerable amount of work was carried out to determine whether this was a problem. All the research studies indicated that there was no problem in leachability of heavy metals or radioactivity. One of the studies looked at levels of <sup>40</sup>K, <sup>226</sup>Ra, <sup>228</sup>Ra, <sup>228</sup>Th, and <sup>228</sup>U which might arise from the bauxite

residue in crops grown and no uptake of these elements was detected even up to additions of 480 t/ha of bauxite residue.

Saline residue has been used to treat acid sulfate soils for the Gladstone Port Authority and the QAL tailings dams themselves are considered an acceptable means of disposing of acid sulfate soils from construction activities.

#### *Marshland restoration*

Parts of Louisiana are denuded every year and land lost because of sediment erosion; bauxite residue from Gramercy has been considered as a sediment replacement material.

#### *Landfill covering material*

Another application that utilises the impermeability of bauxite residue when dewatered is the capping of landfills, especially municipal site; this has been extensively used in the Marseille area using Bauxaline® from Gardanne. In one site in the Gardanne area, the waste methane gas that evolves is collected under the Bauxaline® covering layer. Similar practices have been done in Louisiana where the pH reduced bauxite residue is mixed with clay.

#### *Iron production*

The high iron oxide content of bauxite residue, up to 60%, has meant that this has been an area to attract a lot of activity and experimental work. Many methods have been proposed, and the list below is just a small fraction of them:

- production of iron powder by reduction with hydrogen, carbon monoxide or town gas at 300 – 400°C;
- recovery of 90% of the iron has been achieved by using an electric arc furnace to heat a mixture of bauxite residue and coke at 1600 -1700°C;
- iron, aluminium and titanium were extracted from Jamaican bauxite residues by calcining bauxite residue with sodium carbonate and then dissolving out the sodium aluminate with water – iron was then recovered by magnetic separation after conversion to a ferromagnetic state by a reduction process;
- charging a shaft kiln from the top with bauxite residue and then introducing hydrogen, ammonia and fuel gas from the bottom;
- chlorination of bauxite residue and then going through a step wise removal of titanium and aluminium chlorides;
- treatment with carbon monoxide and hydrogen at < 350°C, then addition of calcium chloride and heating to 530–600°C, treatment with water allowed the iron, titania and silica to be separated.

The coarse component of bauxite residue, red oxide sand, has been used as an iron ore source when better quality raw materials have been unavailable, for example during war time.

#### *Acid mine drainage and heavy metal absorption*

The ability of bauxite residues to react with heavy metals, most especially from mine and mineralogical processing sites, has been examined by several groups around the world. In Italy using residues from the Eurallumina plant, good heavy metal absorption results were obtained by neutralising the material with seawater. In some formulations, the bauxite residue was mixed with fly ash which improved the absorption of arsenic.

An Australian company, Virotec, has undertaken a considerable amount of work using brines rather than sea water to produce a partially neutralised material, termed Bauxsol®, which has good heavy metal absorption characteristics.

In Korea, work showed how pellets made by heat treatment of mixtures of bauxite residue, polypropylene, sodium metasilicate, magnesium chloride and fly ash at 600°C, has good heavy metal absorption properties, especially for lead, copper and cadmium.

Work on bauxite residue from San Ciprian mixed with gypsum was found to have a good capability to remove copper, zinc, nickel and cadmium from waste streams.

### *Phosphate removal*

Both Bauxsol® and acid treated bauxite residue have been shown to be effective at removing phosphate and in China partial neutralisation with hydrochloric acid and subsequent heat treatment studies have shown over 99% removal of the phosphorus in water. Trials at sewage treatment plants in the UK have shown that very low levels of phosphorus (<0.06 mg/L) can be achieved in the final effluent using Bauxsol® in pellet form as a phosphate absorber; this allows effluent waters to meet the EU Habitats Directive for phosphorus levels which is difficult to achieve by conventional means.

### *Refractory in steel manufacturing*

In Romania some 60-70,000 tonne/year of bauxite residue from the Tulcea plant is used locally, in steel production as a titaniferous material that is fed into the furnaces to reduce the ilmenite consumption needed for protection of the hearth refractories against erosion.

### *Pigment application*

The high iron content and finely divided state of the red mud has attracted an interest as a pigment in a wide variety of materials.

Additions to bricks of a few percent of high iron oxide bauxite residue, 2-5%, have been done to reduce the cost of the raw materials and provide a uniform red colouration to the bricks. Small addition to red tiles was at one stage moderately significant but the demand for these tiles, once widely used for windows sills and floors has now shrunk considerably.

Bauxite residue has been used as a pigment in plastics, in particular PVC for waste water pipes.

A plant operated in Larne, Northern Ireland for many years utilising the kilns after the Bayer plant closed to manufacture a pigment for the tile, paint, and plastic industries.

### *Catalyst manufacture*

Considerable interest has been shown in the ability of bauxite residue to act as a low cost, high surface area, 'disposable', iron oxide and titania catalyst. Work has been done confirming the ability of bauxite residue to act as a catalyst to suppress adverse coke formation in the processing of heavy hydro-carbonaceous feedstocks in petroleum refining.

Other work has been done in the hydro-dechlorination, hydrogenation and exhaust gas clean up.

### *Wood substitute*

Good results have been achieved at the Advanced Materials and Processes Research Institute in Bhopal using bauxite residue from Nalco at a loading of 50% with natural fibre and polyester resin to make a wood substitute product for building applications. Products with high strength, and good water resistance, weatherability and fire resistance have been obtained.

### *Geopolymer*

Geopolymers have a number of potential advantages over conventional Portland cement, in particular, reduced production of carbon dioxide during manufacture. The formation of geopolymers involves the dissolution of silica and alumina species in an alkali and then effecting polymerisation of a  $-(\text{Si-O-Al-O})_n-$  polymer chain. The presence in bauxite residue of aluminium, and silicon species in a highly alkaline could offer attractive opportunities for its the manufacture of construction materials.

### *Extraction of rare-earth and other metals*

The strongly growing markets and the very high prices that have been experienced in recent years for certain rare earths elements have re-awakened interest in their extraction from bauxite residue. Rare earths elements (REEs) are divided into light rare earths such as lanthanum, cerium, neodymium, samarium, praseodymium, promethium and europium, and the heavy rare earths gadolinium, terbium, holmium, erbium, lutetium, thulium, ytterbium, dysprosium. Then there are two rare earths which are not part of the lanthanides series namely scandium and yttrium. Bauxite residues will vary in composition of these elements but a typical Jamaican bauxite residue has been found to contain (all values in mg/kg): scandium 135, lanthanum 500, cerium 650, neodymium 250, samarium 65, europium 15, terbium 10, ytterbium 30, lutetium 5, tantalum 10.

There was considerable interest in extracting the REEs from Jamaican bauxite residues during the 1980s but prices fell and the schemes in the main were dropped. The routes were typically based on acid extraction to leave most of the iron and titanium behind followed by selective solvent extraction of the resulting liquor. VAMI, in conjunction with the Uralsk alumina plant, operated a magneto – hydrochemical route to extract scandium oxide from bauxite residue in the 1980s and more recently an acid extraction route has been successfully trialled at Bogoslovsk alumina plant. Currently there is considerable activity in China in reclaiming these elements from bauxite residue with several small scale plants operating. A new project was announced in early 2013 based on a joint venture between the Jamaica Bauxite Institute and Nippon Light Metals to extract REEs from bauxite residue in Jamaica; construction of a pilot plant at the Jamaica Bauxite Institute laboratories is due for completion in mid 2013. In late 2012, Orbite Aluminae filed patents to extract REEs from bauxite residue and clay using a hydrochloric acid extraction route and in early 2013 announced a joint venture with Veolia Environmental Services with the intention of building a plant to recover and recycle the REEs, as well as the other components, found in bauxite residue.

Each rare earth has its own particular use so growth will not be uniform across all of them. A very large market exists for neodymium and praseodymium in powerful magnets for mobile phones etc. Cerium and lanthanum are incorporated into the alumina wash coat for auto-emission catalysts. There is a major growing use of scandium in alloys with aluminium for aircrafts. Europium and terbium are extensively used for phosphors for plasma screens. Another major use exists in alloys for batteries so if the electric car takes off another huge growth area – this time samarium. Usage of REEs in 2010 was 134,000 tonnes; forecast use by 2015 is 165,000 tonnes with some forecasts even higher. Recovery of rare earths from bauxite residue could form a valuable part of this tonnage. The by-products formed as result of these acid recovery processes will be very different in nature from the bauxite residues currently disposed of and will encourage efforts to recover the other components present in the bauxite residue for example silica for use as a filler as well as the valuable titanium and iron.



Building at the Jamaica Bauxite Institute with bricks made from bauxite residue

## **b. Commercial application with significant potential**

Many of the above applications, whilst technically of interest and clearly feasible, are not capable of utilising significant tonnages of bauxite residue. Other applications, such as rare-earth and scandium recovery might be economically very attractive, but they have no impact on reducing the large volumes of bauxite residue created annually to manufacture alumina unless the recovery of iron, titanium and silicon dioxide is carried out as part of the same process. This is not to say that for a particular plant, they don't present an opportunity that will help mitigate disposal costs, but they will not have a significant effect on the volume of bauxite residue that a plant will need to deal with.

There are few instances where the constituents or properties of bauxite residue give unique benefits, so the possible large tonnage applications are only likely to occur in certain cases. They must provide raw material or a combination of properties which are more economic than other wastes or virgin raw materials whilst still taking into account the risks and perceived concerns about using bauxite residue. Risks include those presented by alkalinity, crystalline silica, metal constituents and low level radioactivity. Alkalinity can be addressed by partial neutralisation or improved processing and washing. Workers utilising bauxite residue in typical commercial applications are not exposed to crystalline silica, metals or low-level radiation at levels considered to be harmful to humans, provided safe methods of work are adopted such as would be used during work with conventional materials. Some bauxite residues may not be suitable for residential building materials because of low level radiation. It is worth noting that perceived concerns may well remain high even when experts advise people that the risks are low.

No data is published on the tonnage of bauxite residue utilised annually but the IAI plans to carry out regular surveys of its members in the future; the currently estimated utilisation is approximately 2 million tonnes per year, however, this figure is growing rapidly with new initiatives, especially in China.

The largest current usages are in: cement production, with an estimated 400,000 t/y used in Greece, Ukraine, Georgia, Moldova, Belorussia; and iron recovery, particularly in China. Capping landfills is undertaken in France but usage is variable and is restricted to a relatively small radius of the alumina plant; usage is up to 100,000 t/y. Usage of bauxite residue from Tulcea, Romania for refractory products is approximately 50,000 t/y. Large tonnages have been used, frequently with fly ash, for road construction for example on highways in France but there are large tonnages used internally within alumina plants/residue disposal areas for road and dyke/levee construction. Soil amelioration of acidic and sandy soils offers many opportunities as does the recovery of selective components, such as iron and titanium, from bauxite residue and then producing a benign waste that can be used as a soil conditioner.

The largest potential future uses are seen as:

- soil amelioration;
- cement production;
- iron recovery;
- landfill restoration;
- road construction;
- building materials, most probably not as the major component but as a sizeable fraction to ensure that all fears regarding radioactivity are allayed.

Sizeable tonnages could also be used in refractory linings and the amelioration of contaminated landfills or old mine workings.

Consideration by the alumina industry should be given for joint work with other companies or research institutes, possibly with government support, to accelerate the adoption for some of these applications. In almost all instances plants will not be competing with each other as utilisation will only be within a few hundred kilometres of each plant. One of the greatest benefits of increased bauxite residue utilisation of red mud would be the significant contribution to enhanced sustainability of the aluminium/alumina industries.

## VIII. Remediation and Rehabilitation

The most important barrier to remediation, re-use and long term sustainability of bauxite residue management is its high alkalinity. Continuing research on residue pH reduction/remediation is being funded by the International Aluminium Institute under the co-ordination of the IAI Bauxite & Alumina Committee (BAC) and the Alumina Technical Panel (ATP).

Work in the remediation field has been underway for some time in both collaborative activities and individual company research efforts. The recently completed AMIRA International project P1038 was a literature review with the aim to identify, on the basis of the open (public) literature, possible ways in which the “in situ” remediation of bauxite residues might be undertaken and in particular to define specific objectives for the industry in the context of the most promising research pathways. This review suggested that the most promising pathway for in situ rehabilitation would appear to be bioremediation based on strategies developed for saline-sodic soil, with a focus on enhanced surface rehabilitation techniques.

Following a review of AMIRA Project P1038, the IAI Board has accepted the recommendation of the BAC/ ATP to fund further research by the University of Western Australia’s School of Earth and Environment on the In Situ Remediation of bauxite residue. Work already conducted by the School of Earth and Environment (where professorial position is co-funded by Alcoa and BHP Billiton) has been working in this direction. The overall project is aimed at addressing 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 chemical and physical stability in the long term. This might be achieved by means of accelerated leaching, natural biological amelioration as an extension of surface rehabilitation, or concretion reactions if enough is known about the chemistry and geo-mechanics of the deposits.

The Stage 2 - In Situ Remediation of bauxite residue project is expected to be completed by 2014.



Photographs of partial establishment of vegetation on bauxite residue at Linden, Guyana. (a) Sharp boundary between typical cover of grasses and forbs and barren residue within older bauxite residue storage area (note that dark green trees behind grasses are part of native vegetation beyond perimeter of residue deposit); (b) detail of vegetation showing large-leafed guava (*Psidium guajava*) and a clover-like creeper (lower right) within a dense sward of grass; (c) profile showing brown, sandy, humus enriched topsoil over pink, clayey bauxite residue; (d) isolated tuft of grass that has established itself beyond the fringe of vegetation.

## Case study: From red to green in ten years – bauxite residue remediation in Jamaica <sup>(3)</sup>

Alcan (now Rio Tinto Alcan) had a long history in Jamaica, constructing the first alumina plant (Kirkvine) there in 1952, and a second in 1959, in Ewarton. In 2001 Alcan sold its bauxite mines and alumina plants in Jamaica but kept responsibility for many of the bauxite residue sites with the intention of safely remediating them to an agreed standard and transferring ownership to the Government of Jamaica. The agreed objective was maximum biodiversity rather than housing or agricultural use.

### Kirkvine

Some thirteen red mud ponds were to be closed: six were classified as ‘open’ ponds and no restoration had been attempted, one had been partially restored and seven had been classified as ‘closed’ ponds and had been substantially restored or naturally revegetated previously. In addition, there was an asbestos repository and a concrete tomb for storing oxalate that needed to be remediated.

At Kirkvine, the bauxite residue (typical concentration 47%  $\text{Fe}_2\text{O}_3$ , 16%  $\text{Al}_2\text{O}_3$ , 7%  $\text{CaO}$ , 6%  $\text{TiO}_2$ , 4%  $\text{SiO}_2$ , 3%  $\text{Na}_2\text{O}$ , 2%  $\text{P}_2\text{O}_5$ , and 14% LOI) had been deposited in depressions left after bauxite mining. When deposited, the residue had a solids content of approximately about 20% but it was discharged in a way that in most cases, when full and aged, no residual pond water remained resulting in a relatively dry surface and the pH was about 11.

### Kirkvine Pond 6 Trials

In 1996, trials were undertaken on this 4 ha pond where red mud disposal had just stopped. Four large plots, 30 m by 18 m, and 16 small plots, 2 m by 2 m, were treated with different levels of gypsum and fertiliser. The dry red mud was ploughed twice to a depth of about 15 cm to break up the surface and then traversed with a D-6 caterpillar to further break up the large lumps. The final target was a mixture of sizes from 2 - 5 cm with fine material between them to aid germination. It was believed that the presence of the coarser material would ensure good permeability and would minimise release of entrapped sodium. The gypsum used had an analysis of: calcium sulfate 46%, anhydrite 47%, silica 3.7%, magnesia 0.8%, pH 7.8.

The four large plots were treated with gypsum loadings of 10, 20, 40 and 60 t/ha whilst the smaller plots were treated with 40, 60, 80 and 100 t/ha of gypsum.

Soil electrical conductivity showed that whilst there was a substantial reduction in pH value as the treated level was raised from 10 to 20 t/ha, there was only a modest improvement as the level was increased to 40 t/ha and almost no improvement when the level was raised further to 60 t/ha.

Just over a year after the gypsum was spread onto the large plots, poultry manure was spread at a dosage level of 4 t/ha on half the plots and 2 t/ha on the other half; ammonium sulfate was spread at a level of 0.062 t/ha. Three months later, hand seeding was carried using the following mixture of seeds:

**Cynodon dactylon** (Bermuda Grass) 21 kg/ha  
**Brachiaria decumbens** (Brachiaria) 31 kg/ha  
**Leucaena leucocephala** (Leucaena or Lead Tree) 10 kg/ha  
**Ricinus communis** (Castor Bean) 4 kg/ha  
**Haematoxylum campechianum** (Logwood) 1 kg/ha

Bermuda Grass was chosen as the main species based on the pH and electrical conductivity values and previous experience at Aljam. Brachiaria decumbens had been used previously for rehabilitating mined out bauxite lands and was also used for comparison. Logwood Trees already surrounded the area and some wind blown seeds had already germinated. The bulkier Bermuda Grass seeds germinated much more rapidly than the Brachiaria but despite the slow germination within three months the Brachiaria had grown to a height of 0.6 m with roots 0.1 m deep. The Bermuda Grass was prolific, growing about 0.2 m with 0.1 m deep roots. Logwood, Castor Bean and Leucaena had all grown to about 0.12 m height in the same period but the leaves of the Leucaena were chlorotic.

In 2004 a study was undertaken by the University of the West Indies on the vegetative development and of the five species sown in 1998 only **Haematoxylum campechianum** (Logwood) and **Leucaena leucocephala** (Lead Tree) were encountered. This was surprising as two years after planting in 1998 the Bermuda Grass was re-

ported to have had an excellent growth rate as well as being the most abundant plant species. In addition, the germination and growth rates for Lead Tree at that time was slow with leaves appearing chlorotic. The 2004 study showed at least 53 plant species belonging to 28 families, dominated by Lead Trees and the grass **Panicum maximum**. The success of the Lead Tree is attributable to its nitrogen fixation ability. In addition it utilises a seed release mechanism which gives distinct advantages where soils are depleted in nitrogen and the vegetation cover is sparse. The growth form of the vegetation, slender trees, grasses, climbers and runners with rhizomes and stolons is typical of an early pioneer stage in succession and community development.

The rhizosphere within the vegetation community appeared to be presently limited by depth as the maximum depth at which roots were encountered was 1.4 m although a surface area spread of 0.93 m radius was recorded. Unfortunately, there was concern that the earlier study had not included some plants which had since the comparison speaks to the five species sown within the pond and does not include the species associated with the pond on the slope of the depression. The vast increase in number from 5 to 53 must therefore be revised to only 12 of the 53 species. Much of the vegetation encountered may be considered characteristic of the terra rossa soils of the bauxite plains of Manchester and St. Ann.

Following this assessment, the parts of Pond 6 where vegetation had been poor were reinvigorated in 2005 by the addition of gypsum at a rate of 40 t/ha, chicken manure at 0.6 kg/m<sup>2</sup> and reseeded with *Brachiaria*, *Bonavis-ta* Bean and Guinea Grass. By 2011 there had been a dramatic improvement in the growth – this improvement was across the entire area. A further vegetation review on Pond 6 undertaken in 2011 encountered 56 species, which is a composition comparable to a ‘dry limestone forest’ in Jamaica.



Kirkvine Pond 6, 2005 (left)  
Kirkvine Pond 6, 2011 (below)



The results of the topsoil free method encouraged Rio Tinto Alcan to adopt a similar method on the remaining six ponds which still comprised bare red mud. A major reason for using the method was the acute shortage of topsoil in the area; it was illogical from a sustainability viewpoint to utilise scarce good quality topsoil for remediating contaminated land. Three of these ponds still contained areas under water which needed to be drained before re-profiling could commence; the maximum depth, however, was < 2 m. The process was carried sequentially on the ponds so the lessons from the first could be applied to subsequent ponds.

## Best Practice Recommendations

Factors to be considered when planning the closure, decommissioning and rehabilitation of a bauxite residue storage facility are:

- \* environment and climate in which the residue storage facility is located
- \* post-closure land use
- \* long-term landform stability, including geotechnical and erosional stability
- \* managing surface runoff and ponding, and the need for a closure spillway
- \* long-term seepage to the environment of potentially contaminated water
- \* potential for dust generation both before and after rehabilitation
- \* surface treatment and vegetation of the top of the residue storage facility
- \* profiling, surface treatment and vegetation of outer batter slopes.
- \* post closure land use e.g. restored to original flora, maximum biodiversity, productive crops, recreation
- \* if deemed necessary, collection and treatment of leachate (e.g. neutralisation, constructed wetlands)
- \* ongoing testing and monitoring of surface and ground water regimes to meet regulatory requirements
- \* ongoing management, security and controls of sites when the refinery no longer exists.

### Plan

- \* defined closure plan developed with community input
- \* closure costs identified and allocated
- \* clear closure plan owner identified
- \* defined community engagement process

### Cost

- \* need to consider residue as a potential resource: both for direct uses, eg soil amelioration, land capping, and uses for the closed residue sites.
- \* transparent accounting of resources for closure required so that the best low cost sustainable regime can be implemented.

### Education

- \* interaction with the regulators – often no prior experience of bauxite residue, so it may be necessary to ‘educate’ them.
- \* chemical/environmental education of the general public.
- \* highlight successful examples of closed facilities

### Residue Composition

- \* recover as much sodium as possible
- \* list all constituents; where possible convert into harmless stable form.

## IX. Recent Studies on Bauxite Residues

### a. Leaching assessment methodologies

A report on leaching assessment methodologies for disposal and use of bauxite residues <sup>(4)</sup> was prepared by H.A. Van Der Sloot and D.S. Kosson in 2010 under a consultancy project for the IAI. The objective was to build further knowledge and understanding of the issue of sustainability within the bauxite-alumina segments of the aluminium industry.

Primary environmental concerns are waterborne releases, and subsequent transport and potential impacts resulting 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 disposal of bauxite residue, emphasizing emerging assessment techniques in the European Union and the United States.

The following are recommendations for the aluminum industry that follow as a result of this review:

- Establish a baseline leaching characterisation programme for bauxite residue produced at different facilities. This would allow comparisons and understanding of the similarities and differences among bauxite residue producers and provide a foundation for improving treatment, use and disposal practices, as well as quality control. Baseline leaching characterisation would include pH dependence, percolation and mass transfer testing. Additional testing should include physical properties sufficient to understand geotechnical and hydraulic performance.
- Establish a common database of leaching and related properties that can be tied to the similarities and differences in bauxite residue production processes, sources and management scenarios. This database should also include field observations of pore water and leachate from representative bauxite residue management scenarios. A custom LeachXS database would be suitable for such a database.
- If information on lysimeter studies or field data on either landfill or beneficial use are available those observations should be evaluated in context with the more extended laboratory test data. If such information is not available or is insufficient, it is advisable to obtain field test data to verify the basis for estimating long-term performance.
- Experience can be obtained from information in other areas (soil, waste, construction) to facilitate the prediction of long term release from bauxite residue disposal and beneficial use. This relates to effects of carbonation, oxidation, preferential flow and interaction between materials in a mixture.
- Establish guidance on quality control monitoring for bauxite residue that include simplified leaching assessment and meets the needs of likely use and disposal scenarios.
- Develop and validate to the extent practical a geochemical speciation model for bauxite residue. This would facilitate simulation-based evaluation of performance under different use and disposal conditions, including blending of bauxite residue with other materials, prior to carrying out confirmatory testing, and thereby allow consideration of a wider range of applications at reduced testing costs.

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## Bauxite Residue Voluntary Objectives

International Aluminium Institute (IAI)  
Adopted 17 May 2011

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The IAI Board of Directors (on the recommendation of the IAI Bauxite & Alumina Committee) adopted the following five voluntary objectives to address bauxite residue management.

### **Objective 1 – Assured Integrity of Current Residue storage facilities:**

To re-assess the integrity of all existing residue storage facilities including closed/legacy sites – and ensure adequate monitoring, management and control processes in order to avoid future incidents;

### **Objective 2 – Provision of Industry based support:**

To continue to identify and make available a pool of industry experts to (a) assist authorities on management of legacy sites and (b) provide operational support to industry participants for specific activities if requested;

### **Objective 3 – Best practice management:**

To manage bauxite residue according to industry best practices, (including high storage density/ low causticity storage and neutralisation where feasible), and reflecting local climatic, geographic, regulatory, residue properties and other conditions;

### **Objective 4 – Conclusion of bauxite residue solids disposal to marine and aquatic environment:**

The industry commits to the conclusion of the few remaining aquatic and marine disposal activities by 2016;

### **Objective 5 – Improved technology:**

Through collaborative and individual actions, to continue research and development into innovative industry-wide remediation, rehabilitation, re-use and benign storage options for bauxite residue – and to disseminate the research results on a global basis.

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The voluntary objectives have been incorporated into the IAI's Aluminium for Future Generations Sustainable Development Programme (AFFG). Launched in 2003 in partnership with the regional and national aluminium associations the AFFG initiative comprises voluntary objectives in social, economic and environmental performance across all the key phases of aluminium's life cycle. There are currently 19 voluntary objectives, agreed by the IAI's Board of Directors. The industry's performance is measured annually against quantitative metrics or sustainable development indicators. Work is being undertaken to further strengthen the global industry performance in the field on bauxite residue management, including utilisation/reuse options and the remediation/rehabilitation of residue storage facilities.