



## **Residue Management Sustainability Review Aughinish Alumina Limited**

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**Prepared for Aughinish Alumina Limited**

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## Executive Summary

Aughinish Alumina Limited (AAL) has submitted an Integrated Pollution Control (IPC) Licence Review Application to the EPA to upgrade and expand the Bauxite Residue Disposal Area (BRDA) at the alumina refinery on Aughinish Island, Askeaton, County Limerick.

In response the EPA has requested additional technical and economic information to enable this review. In summary, these areas were:

1. *Undertake a detailed investigation of the sustainability of the current disposal practices for production waste at the plant with particular emphasis on the ultimate, long-term, environmental burden of the land area covered by the red mud stack.*
2. *Undertake a detailed feasibility assessment (technical and economic) of the alternatives to the current practice of land disposal of red mud with particular reference to options used in similar plants elsewhere in the world.*
3. *Assess the feasibility of neutralising the red mud and using the neutralized sand as a raw material in construction or other beneficial end-use.*

To satisfy this request, the review compared the proposal against 14 different 'Sustainability Indicators for Tailings Management' ranging from site selection through design and operation aspects to final Closure and After-use. It then examined practices for residue disposal employed by the leading Alumina Producers globally. It also examined the key issues regarding residue neutralization and the means by which it could best be implemented at AAL. Finally it examined the state of residue re-use globally and the outlook for greater re-use.

The review identified that the practices used by AAL incorporate the key elements of best practice bauxite residue management (BAT). These include:

- Minimizing the quantity of residue for disposal by processing exclusively high grade bauxite with a low residue content (residue factor of 0.7 t/t versus up to 2.5 t/t internationally)
- Minimising the land-fill footprint by utilizing dry disposal of filtered mud. Dry tailings disposal on an engineered land-fill adjacent to the alumina refinery is the disposal practice of choice for new alumina refineries since the early 1980's. While there is a gradual conversion of older refineries to high density dry or semi-dry disposal due to the advent of high-density thickening technology, AAL is one of the few alumina refineries equipped with higher performance vacuum filters that enable a greater degree of residue dewatering than deep cone thickeners prior to residue disposal. Consequently AAL is discharging one of the highest density or driest residue streams in the industry.
- Minimising the residual alkalinity in the residue. A key design feature of the AAL refinery is that the amount of lime added to the process streams is lower on a specific basis when compared to other equivalent alumina refineries. This means that the net amount of residual solid phase alkalinity that is contained within the bauxite residue is also lower reducing the overall environmental risk posed by the residue.

- Minimizing the environmental impact of surface run-off and any groundwater seepage by locating the BRDA adjacent to a large estuary and overlying a non-productive saline groundwater body.
- Further minimising the environmental foot-print by the careful design and astute operational practices employed. In this regard AAL's design and operational practices are referenced extensively in the EU Commission's BREF on the management of tailings.

From a sustainability perspective, the principal environmental burden on the land from the practice of bauxite residue land-filling is the requirement to manage the slow release of residual alkalinity contained within the residue. From the preliminary investigation of the chemistry and review of previous investigations, the leaching of this residual alkalinity by rainfall requires the exchange of a number of pore volumes of water. The alkalinity is present as soluble alkalinity and in solid form bound with Calcium and Silica compounds. However, the low permeability of the residue limits fresh rainwater ingress and thus limits the rate of natural leaching. While this is beneficial in terms of ensuring slow release rates, it extends the time-frame for complete leaching to occur. As this leaching process cannot be accelerated the implications are that management of this leachate will be required for an extended period. The present estimate of 5 years post closure for the combined rainwater run-off and perimeter leachate to reduce below pH 9.0 requires to be validated via the recently constructed Closure Demonstration Cells. In the meantime it would be prudent to research as part of the ongoing BRDA Closure Plan the feasibility of a wetlands or similar means to attenuate BRDA leachate peaks above pH 9.0 that could possibly occur during periods of low rainwater dilution.

Neutralisation of the residue can reduce the residual alkalinity present. However, the same issues that create the long leaching period mean that neutralization will have a long reaction time to reach 100% completion. In a high-density disposal system there is insufficient time for this to occur and hence only a partial neutralization is possible eliminating up to 20% of the residual alkalinity. This partial neutralization can occur rapidly and would result in a residue leachate pH of 10.5-11.0 prior to surface dilution. It is thus unlikely that residue neutralization in a high-density disposal system will eliminate the need for subsequent neutralization of run-off waters. Adoption of (partial) residue neutralization would however reduce the quantities of neutralizing agents to achieve a leachate with pH<9.0 and would also reduce the time required to achieve a leachate suitable for direct discharge. Thus, partial neutralization and continued high density disposal of the residue is recommended as the best means of minimizing the environmental burden (reduced land area demands) and reducing the period of time required for leaching to eliminate the residual alkalinity (reduced residual alkalinity).

A range of options for residue neutralization was evaluated including seawater, carbon dioxide and acid. All options are subject to the reaction rate issues described previously. Also:

- Sea-water neutralization requires the circulation of unmanageable volumes of intake and discharge flows;
- Carbon dioxide requires major capital investment but provides a minimal greenhouse benefit; and
- Sulphuric acid appears the most feasible from a technical and economic perspective.

The water management burden of the BRDA can be managed quite separately from the potential post closure land-uses available. While amenity is the selected post-closure land-use due to the SAC status of the adjacent lands, it is feasible also to consider an agricultural land-use such as fodder cropping or bio-mass carbon capture. The BRDA 180 hectare land-bank comprising a closed, lined and contained soil system with run-off collection, storage and treatment therefore represents an asset with economic potential. The feasibility to exploit this potential commercially needs to be examined through vegetation trials in the Closure Demonstration Cells. From an environmental perspective the important aspect is that the area is managed post closure such that the rate of change due to erosive processes, soil formation and vegetation growth does not exceed the rate of downward leaching of the residue. Ensuring that this is maintained is the key to ensuring the sustainability of the post-closure land-use.

The present land-fill practice and associated on-going requirement to borrow 80 hectares of agricultural land for 20 year intervals represents a loss of productive agriculture potential in the area. However this loss is temporary as it enables the current investment and economic and social benefits of a modern alumina refinery employing 700 people directly and another 800 indirectly. This facility also includes a serviced industrial site, an internationally important port and a modern gas fired power plant that will support economic activity in the region well beyond the life-time of the original alumina refinery. For AAL, satisfying the social and economic needs of the community and managing any associated environmental burden while creating an "asset" of enduring value meets the criteria of sustainable development. With the adoption of a neutralization process the operation will become a global leader in bauxite residue management.

In terms of international practices for bauxite residue disposal, of the 70 alumina refineries globally only 3 are known not to be land-filling. These plants are employing marine disposal of their bauxite residue. This sea-disposal practice arose at those locations due to a shortage of suitable land for land-filling and also an awareness of the alkali neutralizing capacity of sea-water. However, there is reluctance by Government Regulators and Environmental NGO's globally to condone or facilitate this practice and the three facilities in question are reaching the end of their permitted operation. They must phase out this practice by 2015. The review of international practices also indicates that no alumina refinery disposes of bauxite residue by sending it back to the mine due to the unfavourable environmental and economic consequences. In AAL's case the incremental cost of shipping the residue back to the bauxite mines for disposal would be unsustainable economically and would close the alumina refinery immediately. An engineered landfill, similar to that at the refinery, would have to be constructed at the mine site to ensure no detrimental impact on the environment.

The placement of neutralized residue in a dedicated area (Phase 2 BRDA) is preferred due to the potential effects of capillary rise from un-neutralized residue that has already been deposited that may bring un-neutralized leachate in contact with neutralized residue. However, from a closure perspective, the total time required to achieve a leachate pH to enable direct discharge will still be determined by leachate from the Phase 1 BRDA.

The alumina industry is collaborating to fund research into residue with the objective to identify beneficial uses. To date the most promising applications still remain niche focused. There is an opportunity to re-use process sands as a washed foundation

material but due to internal re-use at AAL there is limited economic or environmental benefit.

Successful implementation of partial residue neutralization combined with AAL's encouragement of potential users locally to take an active role in developing the potential applications, are most likely key to facilitating the up-take of bauxite residue for beneficial uses.

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## **1.0 Introduction**

The Aughinish Alumina Limited (AAL) refinery is located on Aughinish Island, an island on the southern shore of the Shannon Estuary on the west coast of Ireland.

The refinery commenced operations in 1983 and imports bauxite from Guinea and Brazil and refines, using the Bayer Process, over 1.8 Mtpa of alumina.

The alumina refining process dissolves the finely ground bauxite ore into a solution of hot caustic soda under elevated pressure. The dissolved alumina is separated from undigested compounds and filtered and crystallised to produce alumina hydrate. Calcination of the alumina hydrate at high temperature removes any residual water. The alumina powder is exported overseas for smelting into aluminium metal.

The undigested compounds, or bauxite residue, are washed and filtered to high density to recover residual caustic soda prior to pumping to the dedicated Bauxite Residue Disposal Area (BRDA).

Since commissioning over 16,700,000 tonnes of bauxite residue have been placed in the BRDA.

Rainfall runoff at the BRDA is neutralized with sulphuric acid and clarified to permit discharge to the River Shannon in accordance with regulatory requirements.

### **1. 1 Application for an extension to the BRDA**

Aughinish Alumina Ltd (AAL) submitted an Integrated Pollution Control (IPC) Licence Review Application #754 on the 20<sup>th</sup> June 2005 to the Environmental Protection Agency (Ireland). The application details a proposal for:

- An 80ha, ten stage upstream embankment extension (Phase 2 BRDA) to the existing Phase 1 BRDA;
- An additional three stages (i.e. Stages 8 to 10 inclusive) of upstream embankments on the existing 104ha, Phase 1 BRDA (such that it will match the relative elevations of the upstream embankment extension of the Phase 2 BRDA);
- Relocation of the salt cake disposal area to a composite lined facility within the Phase 1 BRDA;
- Removal of a disused sludge pond within the Phase 1 BRDA; and
- Upgrading the BRDA water management system to accommodate the rainfall drainage from the expanded facility.

### **1. 2 Comments by the Environmental Protection Agency**

A letter to AAL dated 11<sup>th</sup> December 2006 the EPA stated that *“the Agency is not convinced that sufficient consideration has been given to the environmental issues and impacts associated with the continued long-term treatment and disposal options for waste at your facility.”*

The EPA outlined three areas where additional technical and economic information would be required that would allow the EPA to address its statutory obligations (EPA, 2006). These areas are:

1. *Undertake a detailed investigation of the sustainability of the current disposal practices for production waste at the plant with particular emphasis on the ultimate, long-term, environmental burden of the land area covered by the red mud stack.*
2. *Undertake a detailed feasibility assessment (technical and economic) of the alternatives to the current practice of land disposal of red mud with particular reference to options used in similar plants elsewhere in the world.*
3. *Assess the feasibility of neutralising the red mud and using the neutralized sand as a raw material in construction or other beneficial end-use.*

Further correspondence from the EPA and AAL dated 5<sup>th</sup> February 2007 confirmed that while EPA is satisfied “in principle” with the scope of this investigation they highlighted that their key requirement is to assess “... from a sustainability point of view, whether the waste management technology proposed is an appropriate and sustainable technology in the context of the local receiving environment, particularly having regard to future requirements (aftercare, after-use, and future landfill void requirements). In your program of studies you will need to confirm that the environmental footprint of the proposed solid waste emissions management technology (untreated mud disposal to land based landfill) is the least practicable (most sustainable) for this sector given the proximity to very sensitive receptors in this area (water, human, land, protected habitats/species, etc.)”

### **1. 3 Scope of the Sustainability Review**

To address the issues raised by the EPA, this review benchmarks the residue management practices and alternative use strategies employed at a range of international alumina refining operations and compares them with residue management practices currently used at AAL. The review will incorporate three main areas:

- An assessment of the sustainability of the current AAL residue management practices with emphasis on the ultimate, long-term, environmental impact on the land area covered by the residue deposit;
- A review of alternative management technologies as used by the alumina industry elsewhere and developments in alternative uses for bauxite residue as a sustainable means of managing residue; and
- A technical review of the applicability of residue neutralization at AAL.

This is a desktop review based on data provided to the Environmental Protection Agency (Ireland) and on information obtained from the public domain, technical journals or approved direct correspondence with key personnel within the alumina industry.

The review will draw upon detailed background information contained in the appendices:

- Appendix A – Current Residue Management Practices at Aughinish Alumina Ltd

- Appendix B – Industry Residue Management Systems – Detailing the types of tailings disposal systems utilized around the world.
- Appendix C - Bauxite Residue Operations Reference – Detailing bauxite residue management practices at a range of international alumina refineries, location specific issues, alternative use programs and closure intentions.
- Appendix D – Commercial Bauxite Residue Re-Use – Detailing commercial successful avenues for the alternative use of bauxite residue.
- Appendix E – Neutralization of Bauxite Residue, Technical and Economic Evaluation

This review was prepared using publicly available information. While technical papers were reviewed a significant part of the information presented has been extracted from Environmental Impact Assessment information from a range of sources. The accessibility of this information depends not only on the values of the parent organization but also on the environmental legislation in the host country. Those organizations and environmental regulators that make such information available are to be commended.

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## 2.0 Principles of Sustainable Tailings Management

Tailings or residues from industrial processes, by definition, are materials that are not valued, required or currently needed by society in the same way as the finished products that are formed during the industrial process. Residues are not “consumed” by society but are “accepted” as a consequence of the need for the finished product.

The degree of “acceptance” of a residue is not a uniform, predictable issue but an evolving viewpoint in society that is subject to changing levels of awareness, education, operator performance and legislative changes. As such, regular review of community attitudes and operational practices developed at similar operations elsewhere is recommended to ensure current practices contribute to this degree of “acceptance”.

As a general rule, society has a poor understanding as to the nature and risk associated with a tailings facility. It is the responsibility of a tailings facility operator to ensure that all stakeholders understand these risks. In addition the risk the tailings facility represents to society and to the environment should not only be low but also acceptable.

Ensuring that these risks are identified and managed is best achieved through a systematic approach to the site selection, design, operation and closure of a tailings facility and through the implementation of risk-based management strategies that account for the viewpoints and expectations of the communities in which a tailings owner will operate.

Companies that embrace sustainable development can create value by reducing their risk profile, improving productivity, and sustaining access to land, capital, markets and skilled people – coupled with regulatory compliance. In the absence of a formal definition, this approach is termed a “license to operate”.

The ideals of such a process are best described in the framework document “Enduring Value” by the Australian Minerals Industry Framework for Sustainable Development. DITR (2006) states that when applied to tailings management, “Enduring Value” requires operators to undertake a broad range of initiatives, including:

- implement an environmental management system focused on continual improvement to review, prevent, mitigate or ameliorate adverse environmental impacts;
- provide for the safe storage and disposal of residual wastes and process residues;
- rehabilitate land disturbed or occupied by operations in accordance with appropriate post-operations land uses;
- consult with interested and affected parties in the identification, assessment and management of all significant social, health, safety, environmental and economic impacts associated with the activities; and
- Inform potentially affected parties of significant risks from operations and of the measures that will be taken to manage the potential risks effectively.



## **2. 1 Elements of Sustainable Tailings Management**

The adoption of sustainable tailings management does not suggest that this process will result in a tailings deposit that is benign or free from environmental issues or management. Rather it suggests that, using the best available knowledge and with wide consultation, the tailings facility will be well understood, have known and predictable risk and have a well-resourced and sustainable closure plan.

Best approach to closure planning clearly defines, at the earliest possible stage in the design, the post-closure land use and the final closure landform, and then demonstrates the commitment to achieve these goals, through regular transparent reporting against leading indicator criteria. Leading practice will also demonstrate a commitment to achieving stable and self-sustaining landforms by testing closure engineering concepts well before closure occurs, so that the closure design can be confidently and cost-effectively engineered (DITR, 2006).

With this information it is then possible to assess what the net impact on an environment and what possible sequential land uses are feasible and what systems and controls are required to sustain this plan.

The application of sustainable tailings management principles should provide the necessary framework to avoid failures in a closure plan that can lead to unacceptable environmental consequences. Based on the Strategic Framework for Tailings Management (MCMR and MC, 2003), the key issues that need to be addressed for closure:

- Containing/encapsulating the tailings to prevent their escape to the environment;
- Minimizing seepage of contaminated water from the tailings storage facility to surface and ground waters;
- Providing a stabilized surface cover to prevent erosion from the tailings storage facility;
- Designing the final landform to minimize post-closure maintenance; and
- Ensuring adequate sequential land-use controls.

Therefore, the key elements of a sustainable tailings management system are systems and designs that at closure can demonstrate appropriate (DITR, 2006):

- Site selection techniques for the proposed facility
- Engineering design of containment structures
- Identification and impact of resource consumption for the facility
- Design criteria for water management
- Risk based engineering design and assessment of Probability of Failure
- Risk and controls to minimize airborne emissions
- Modeling of hydrological/hydro-geological Impacts
- Planning to execute the closure requirements
- Relinquishment Criteria
- Landform & Aesthetics

- Post Closure Management and Acceptance
- Operational Tailings System
- Operational Controls to ensure alignment of operations with “Design Closure”
- Consultation with stakeholders
- Site operation with a Certified Environmental Management System ISO14001

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### **3.0 Sustainability of AAL Residue Operations**

The AAL design for the expanded BRDA has been reviewed and compared to the key elements of sustainable tailings management listed above. While technical papers were reviewed a significant part of the information presented has been extracted from Environmental Impact Assessment information.

#### **3.1 Site Selection**

AAL reviewed several alternative locations for the BRDA development as part of the Environmental Impact Statement (AAL, 2005b). The proposed site was selected because:

- Most of the other AAL owned land around the refinery is designated candidate Special Areas of Conservation (cSAC);
- Other land owned by AAL that is not subject to cSAC designation is not large enough to meet the necessary storage requirements; is more elevated and therefore not aesthetically amenable to the development;
- Acquiring property to support a greenfield BRDA would impose avoidable higher costs on AAL for land acquisition, duplication of facilities, operational management due to longer pumping and haulage distances;
- Alternatively, haulage of residue materials would require transport on public roads and thus exposing the public and adjacent environment to avoidable risks;
- Groundwater under the BRDA is either brackish or flows into a brackish environment that represents a suitable receiving environment for any leachate reporting to groundwater from the BRDA.

Adapting the design to a smaller footprint would necessitate a higher final BRDA elevation, potentially steeper and less sustainable final landform or shorter operational life.

The site selected is the most appropriate location for the development that satisfies the needs of AAL, minimises the risks to the community and reduces total cost exposure.

#### **3.2 Engineering Design of Containment Structures**

A residue disposal facility requires competent geotechnical design by a qualified engineer. It is outside of the scope of this report to assess the geotechnical integrity of the BRDA. However, AAL have retained Golders Associates, a recognized practitioner in the design of tailings dams and with specific experience in the design of bauxite residue facilities. Golders have provided evidence, included in the Environmental Impact Statement documentation that demonstrate that they have the necessary qualified personnel to provide the necessary design and appropriate investigation programs (Golders, 2005a; Golders, 2005b; AAL, 2005c)

### **Seepage Control Design**

The BRDA has been constructed in stages to reflect the progressive development of the alumina refinery and also the gradual accumulation of residue generated by the operation since 1983. As such, the BRDA reflects a temporal aspect to its design where the design requirements of the day have changed as industry and engineering standards have changed.

Prior to construction the design standard of the day was to utilize the existing low permeability deposits such as estuarine subsoil as a barrier to prevent seepage. At the time the BRDA was designed (pre 1983) there was no specific environmental containment legislation or guidelines for landfill or tailings sites in existence for a local authority regulator (AAL, 2005b)

With the Phase 1 BRDA Extension, constructed in 1996 the EPA required that the standard landfill containment design guidelines be applied to the tailings extension design. Part of the reason for this decision was the zone of outcropping limestone which has significantly higher permeability and therefore a composite lining system including screened glacial till and/or geosynthetic clay liner (GCL) and HDPE geomembrane was constructed in this area (Golders, 2005b; AAL 2005b, AAL, 2005d).

The Phase 2 BRDA will be similarly constructed as a composite lined HDPE geomembrane and GCL liner and/or screened glacial till (Golders, 2005a)

The design of the upstream embankment lifts and seepage prevention liner using composite materials in a bauxite residue area is the equal of the best application of this technology in the alumina industry (Jamalco 2005; AWA 2005).

### **3. 3 Water Management Design Criteria**

The design basis for the BRDA is to provide water storage up to a 1 in 200 year design storm and the design requirement for drainage from the upper interceptor channel to the Perimeter Interceptor Channel is 1 in 10,000 year.

Information on the rainfall return design criteria applied within the alumina industry is limited. Alcoa World Alumina state that the residue disposal facility at Jamalco, Jamaica has adopted a 1 in 100 year design return period for runoff storage. As it is likely that this design criterion is applied as a company standard it is likely that other Alcoa facilities operate to a similar design criteria (Jamalco, 2005). Also, Alcan Gove has adopted a design return period for runoff storage of 1 in 200 years for the residue facility (Alcan, 2004).

The application of a 1 in 10,000 year design criteria to a spillway/drainage structure is common as an analogy of the PMF or Probable Maximum Flood concept. Such an approach is commonly used within the minerals industry to apply to very long life drainage structures to prevent failure of runoff storage structures.

Based on the rainfall return design criteria utilized within the alumina industry the design criteria applied by AAL are within the range of accepted methods. In addition, the EU BREF document "Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities, July 2004" states that best available technology (BAT) is to use:

- The once in a 100-year flood as the design flood for the sizing of the emergency discharge capacity of a low hazard dam;
- The once in a 5,000 – 10,000-year flood as the design flood for the sizing of the emergency discharge capacity of a high hazard dam.

As part of normal licensing processes it is expected that the EPA, most likely by using an independent third party reviewer, will review the detailed engineering aspects of the entire Phase 2 BRDA including the water management design criteria before they issue approval for construction to commence.

### **3. 4 Risk Based Design and Probability of Failure**

The traditional geotechnical approach to tailings design is to apply a Factor of Safety approach to stability assessments. While this approach does provide a deterministic assessment of the stability of the tailings system, it does not quantify the probability of failure in a way that could be readily understood by all stakeholders.

DITR (2006) compares the probability of failure concept with the traditional Factor of Safety approach:

While the Factor of Safety concept is traditional and well accepted by tailings operators, Probability of Failure is usually not well understood; for example there are usually difficulties in accepting that “failure” is a possibility;

- A Factor of Safety >1 can be interpreted as a failure that cannot occur yet as it is based on assumptions and with a limited data set this is not necessarily correct. There will always be a finite chance of failure even though it is likely to be extremely small;
- A Factor of Safety assessment is a poor model of variable conditions and uncertainty whereas a Probability of Failure approach is a good model of uncertainty and variable conditions;
- A Factor of Safety approach is not amenable to costing as it either fails or it does not. A Probability of Failure approach enables a better assessment of costing where  $\text{Cost} = (\text{Probability of Failure}) * \text{Cost of Remediation}$ .

AAL have completed a series of slope stability analysis using standard industry techniques for the final height of the upstream embankment stages (Stage 10). In all scenarios the Factor of Safety exceeded 1.0. In addition, a Probability of Failure assessment has been completed for a variety of failure modes and potential breakout pathways (AAL, 2006). The main failure modes or events identified leading to the loss of red mud and/or water into the environment:

- Loss of containment, through slope or foundation failure, or erosion;
- Overtopping through blockage of pipes, spillways or channels, or settlement;
- Failure through wave surge.

This information was submitted to EPA 27<sup>th</sup> April, 2006.

### **3. 5 Minimize Airborne Emissions**

The generation and dispersion of dust from bauxite residue disposal areas is well recognised within the alumina industry as an environmental issue.

Post closure there are two issues that could theoretically impact on the sustainability of the BRDA closure plan. These are:

- Control of dust during the establishment phase of the vegetation cover (including dust from areas should the cover fail locally);
- Radiation associated with isotopes within the residue dust.

The sprinkler irrigation for dust management is designed in accordance with a similar design basis as systems used at other alumina refineries (AWA, 2005). The sprinkler spacing distance chosen is 50% (30m spacing vs. 60m spacing) of the next directly comparable system (AAL, 2005d). Therefore as the sprinkler coverage has a greater density the likelihood is that the dust suppression will be more effective. This has been employed successfully at AAL for the past 5 years.

The sprinkler irrigation system will be retained as a source of irrigation water until the closure vegetation cover is established. Should there be local failure of the vegetation cover any dust from the area could be controlled from this system (AAL, 2005d).

Dust from residue areas can contain Naturally Occurring Radioactive Materials (NORM). This is due to the mineralogy of the bauxite ore containing trace amounts of radioactive isotopes and, while they do not participate in and are not affected by the alumina refining process, they are concentrated due to the removal of the alumina hydrate.

Radiation levels have been independently assessed at AAL and this was reviewed by the Radiological Protection Institute of Ireland (Statutory Authority). The maximum potential worst-case exposure for a person working full time within the BRDA on exposed residue was reported as 0.64 millisieverts per year and levels beyond the BRDA boundary will be well below this (RPII, 2005). This level was well within guideline limits and not a cause for concern (AAL 2005d). These values are based on an operational BRDA. In a post-closure environment with a full vegetation cover, these levels would be expected to be significantly lower (AAL, 2005d).

In a closed condition, provided that the vegetative cover is stable and undamaged there should be minimal dust associated with the BRDA.

### **3. 6 Hydrological/Hydrogeological Modelling**

#### **Hydrological Modeling – Surface Run-off Quality**

Fresh water leaching of bauxite residue will reduce the alkalinity of the residue and leachate over time but due to the very low permeability of the residue and the slow rate of dissolution of solid phase alkalinity this process is extremely slow.

AAL bauxite residue alkalinity is mostly made up of soluble Sodium Aluminate, Sodium Hydroxide or Sodium Carbonate and solid phase Tri-calcium Aluminate (TCA) and Hydrogarnet. These latter compounds are formed most due to the addition of lime within the bauxite digestion process where:

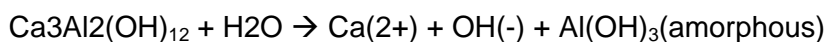
- Sodium aluminate is expressed as  $\text{NaAlO}_2$

- Sodium Hydroxide is expressed as NaOH
- Sodium Carbonate is expressed as NaCO<sub>3</sub>
- TCA is expressed as Ca<sub>3</sub>Al<sub>2</sub>(OH)<sub>12</sub>
- Hydrogarnet is expressed as Ca<sub>3</sub>Al<sub>2</sub>(SiO<sub>4</sub>)<sub>n</sub>(OH)<sub>12-4n</sub>

Mixing water with either sodium hydroxide or sodium carbonate dilutes the relative strengths of the compounds with a maximum pH comparable to the initial pH of the residue.

When TCA or Hydrogarnet are mixed with water they decompose to a small extent liberating Hydroxide.

The TCA reaction can be summarised as:



This reaction gives pH ~ 10.5 but is very slow to reach equilibrium and the OH<sup>-</sup> concentration is very low. The equilibrium for this reaction is far to the left. i.e. there is only a tiny amount of decomposition of the TCA to give this pH and that the leaching will likely occur for an extended period.

The Hydrogarnet reaction can be summarised as:



This reaction gives a pH ~ 11.2.

Further information on these reactions and the behavior of the residual alkaline materials is contained in Appendix E.

URS conducted column-leaching investigations into the fresh water leaching of red mud and the potential impact on the water quality that will be discharged from the BRDA (URS, 2003). While more detailed experimental review is required the URS data identified over a three-month period:

- After two pore volumes pH reduced from pH 13.0 to pH 12.4;
- After six pore volumes pH reduced from 12.2 to 11.4

These data suggest that most of the soluble alkalinity had been removed from the column and the decomposition of the TCA and Hydrogarnet had commenced. While URS suggested in excess of ten pore volumes of leaching would be required as the experimental leaching period was quite short it is likely the volume required is even greater.

Employing the above limited data and extrapolating ...at an estimated porosity of 63% and permeability that varies between  $4.7 \times 10^{-9} \text{ ms}^{-1}$  and  $5.6 \times 10^{-8} \text{ ms}^{-1}$  (lowest and highest permeability measured by URS and cited Golder (2005c)), suggests that up to 30 pore volumes could be required to achieve the target pH by leaching alone and this would suggest a very long leaching time-frame – three times longer than the 10 pore volume assessment previously arrived at by URS. This conclusion should not be taken out of context as it represents merely a desktop assessment of the chemistry and review of previous data. More importantly, the URS (2003) experiment should be repeated under controlled conditions to confirm the processes at work.

It is reasonable to conclude therefore that meeting the water discharge criteria through long-term leaching alone is unlikely in a short timeframe. Therefore, in order to meet the water quality discharge requirements a significant surface dilution will be required. URS (URS, 2003) suggest that a 400+ fold dilution will occur and result in a reduction



of greater than 2 pH units and therefore meet the desired water quality discharge criteria of pH 9.0 at a much earlier stage.

There are some gaps in the understanding of the surface water quality solution in the closure plan. These are:

- Given the variability in rainfall it is possible that during extended dry periods with minimal dilution the effluent will be >pH 9.0 and during periods of high rainfall <pH 9.0. This issue needs to be quantified and a system that can manage this variability should be developed.
- This variability in water quality of the effluent is also likely to be influenced by the run-off water quality of the vegetated surface and the rate at which organic material or gypsum will need to be added to ensure maintenance of a growth horizon in the residue.
- The available dilution flows will also be significantly influenced by the permeability of the residue and a more definitive assessment of this is required to ensure the modeling precision exists to develop reasonable confidence that the effluent water quality objective will be met.

## Hydrogeological Modeling

During the operation of the BRDA, a perched water table will likely develop within the residue deposit. This water table is retained by the presence of a liner and the low hydraulic conductivity of the basal foundations. The extent of this water table is dependent on the volume of water contributed to the deposit by the residue deposition process, the impact of incident rainfall and seepage from the BRDA.

Post-closure, the entrained water within the residue deposit will lead to ongoing seepage albeit at a diminishing rate as the perched water table within the residue deposit disappears. The capture of rainfall incident on the tailings surface will recharge the tailings leading to further seepage.

While limiting infiltration reduces the seepage and hence leaching of the residue deposit it also increases the period of time required to fully leach the deposit and remove the residual alkalinity present. At best, the rate of seepage can be managed such that there are minimal negative environmental impacts during the leaching period and that the other aspects of the closure process can be sustained at the same time.

To reduce the impact of rainfall on a closed tailings area a surface cover to seal or manage the rainfall is often required. In general, a surface cap is provided in combination with a vegetation or similar solution for aesthetic purposes. This has the added benefit of providing an immediate post closure land use as grassland, limited agriculture or natural vegetation.

At AAL, given the low vertical permeability that will limit infiltration, there is little need for an additional low permeability capping layer. However, the development of a sustainable vegetation layer is essential to prevent dusting and to provide a capture mechanism for infiltrating rainfall.

AAL has presented a method of providing a direct seeded vegetative cover for the residue deposit after suitable amendment. It is suggested that this cover will be self-sustaining within 5 years from closure. AAL proposes to demonstrate in the Closure Demonstration Cells to be commissioned shortly that the 5 year time period for development of a self sustaining direct vegetation cover is realistic.



## Impacts of Seepage

Reference estimates that total seepage from the BRDA at closure is 300 m<sup>3</sup>/day. The components of this seepage are:

- Phase 1 BRDA 145 m<sup>3</sup>/day
- Phase 1 BRDA Extension 60 m<sup>3</sup>/day
- Phase 2 BRDA 90 m<sup>3</sup>/day
- Storm Water Pond 3 m<sup>3</sup>/day
- Perimeter Interceptor Channel 2 m<sup>3</sup>/day

This estimate is based on a probabilistic review of the liner construction and estimated defects. AAL (2005d) states that *"The permeability of the red mud is very low and typically 1E-8m/s. There is likely to be little segregation of the red mud as it is discharged as a paste. Therefore, the vertical permeability will be of similar magnitude to the horizontal permeability and similar to the low permeability of the clayey estuarine subsoil but significantly higher than the composite lining found at the base of the Phase 1 Extension and proposed Phase 2 BRDA. The permeability range for the estuarine soils is between 1E-7mls and 1E-9 m/s. Therefore, where the facility is lined, the majority of flow will be downwards and lateral towards either the perimeter interceptor channel or upper level interceptor channel depending on the stage of the raise."*

A study undertaken in November 1999 (Dames & Moore, 2000) identified that there was no significant seepage from the Phase 1 BRDA extension area to the east to groundwater, signifying that the lining system placed was providing adequate protection of groundwater.

It has been estimated that at the projected rate of seepage from the Phase 2 BRDA it will take 10 – 30 years for seepage to reach the nearest receptor, 50m from the base of the facility (AAL, 2005b). The modeling suggests a maximum impact of pH 9.7 after 100 years at the downstream toe of the embankment of the Phase 2 BRDA (Golders, 2005a). This impact is not significant as it mixes with brackish groundwater and will naturally neutralize.

As is the case with the neutralization of alkaline waters for direct discharge, contaminated alkaline groundwater with a high pH can be buffered by the same precipitation of Ca and Mg carbonates or hydroxides in saline waters. As discussed in Appendix D, the saline water converts soluble hydroxides and carbonates into low solubility mineral precipitates. This procedure transforms most of the soluble alkalinity into solid alkalinity limiting further migration. The hydroxyl ions of the contaminated groundwater are neutralized by reaction with magnesium in the tidal estuary waters to form brucite (Mg(OH)<sub>2</sub>) and hydrotalcite but some are also consumed in the precipitation of additional boehmite and gibbsite, and some reacts with calcium in the tidal estuary water to form hydrocalumite and p-aluminohydrocalcite. Simultaneously, calcium in the seawater reduces the carbonate alkalinity in the contaminated groundwater by forming calcite and/or aragonite. Some carbonate may also be removed in the formation of hydrotalcite and p-aluminohydrocalcite. Some Ca may also be consumed in the formation of others minerals such as whewellite and fluorite (where the concentration in the red mud waste stream is greater than about 4mg/L) and some Mg may be consumed where it isomorphously substitutes for Ca in aragonite.

AAL (2005d) states that the performance criteria for evaluating the limitation of subsurface seepage shall be determined utilizing the existing groundwater monitoring network and program. Groundwater will be monitored in the vicinity of the BRDA. The objective of the monitoring will be to ensure that seepage from the BRDA Area does not influence relevant background water quality parameters by greater than 10% and that the pH should not exceed 9.

Unless the seepage flows were to increase significantly and this would be detectable from the groundwater monitoring network, the impact on groundwater from seepage of contaminated alkaline waters would likely be confined beneath the BRDA with seepage migrating through saline margins and achieving neutralization prior to entering the Shannon Estuary.

### **3. 7 Closure Plan & Relinquishment Criteria**

AAL have defined that at closure, the BRDA will consist of the following components:

- An open domed residue surface approximately 100 ha in area;
- Embankment or containment structure;
- Re-vegetated upstream embankments from Stages 1 to 10;
- Seepage control or mitigation system;
- Water management recycle and/or amelioration and discharge system

As part of the closure process AAL have stated that (AAL, 2005b):

- A self sustaining vegetation cover will be developed within 5 years of closure;
- Surface water quality from the BRDA will be managed using sulphuric acid neutralization of alkaline runoff and this is likely to be required for 5 years until the water quality can achieve a pH < 9.0 and total suspended solids of < 50 ppm (and other elements) without treatment. The associated water treatment system will be decommissioned one year after the attainment of the surface water quality run-off objective. Any associated precipitate and sludges from the plant (categorized as non-hazardous) will be disposed offsite. At this time the Perimeter Interception Channel and the Storm Water Pond will be breached to permit direct discharge to the Shannon Estuary via the Robertstown River.
- Groundwater will be monitored to ensure that appropriate background water quality parameters are not influenced by more than 10%.
- Annual geotechnical monitoring will occur for a period of five years from closure to assess pore pressures and stability of the site.
- Interception and management of contaminated groundwater for amelioration and discharge.
- 25 years of further environmental monitoring

### **3. 8 Landform & Aesthetics**

The landform of a residue disposal facility should mimic the surrounding landforms in geometry, surface cover and stability. To a degree this can be achieved by using vegetation to “smooth-out” the visibility of necessary drainage structures required to manage and “de-energise” water flow from the top of a residue management facility. For a residue facility that will be closed to a vegetation cover this usually means provision of more substantial shrubs and small trees on embankment slopes of the facility and the use of grasses and shrubs on the top of the facility. Visually this results in a smooth sloped landform.

As all landforms will erode in time the nature and issues associated with that erosion should be quantified. For a vegetation cover at closure this maximises the erosion resistance on the top section using vegetation and utilises the armouring present on the embankment slopes to achieve a minimum erodability of the landform.

By matching the erosion resistance of the landform to the degree of leaching of the residue allows the gradual erosion of the landform to occur at a rate that will not create post closure environmental impacts. Erosion is not a uniform process and manifests itself where erosive forces are greatest. This leads to local areas of erosion that require repair and monitoring. Such a monitor and repair process is an essential part of the post-closure management.

AAL (AAL, 2005b) have developed a proposed landform in keeping with this approach where:

- The stepped armoured embankments allow control of high velocity waters with minimal erosion on the steep outer slopes of the BRDA;
- Closed vegetation cover that maximises the erosion resistance at the low final slope; and
- Use of progressive re-vegetation on the lower stages of the BRDA structure.

In tailings storage systems that are required to encapsulate a potentially environmentally hazardous material for an extremely long period, it is appropriate that the rate and impact of erosion on the structural characteristics of the landform be assessed (DITR, 2006).

Given the time required for the residue to achieve an acceptable pH through freshwater leaching and the risk that local erosion can have on both the integrity of the revegetation provided and the effluent water quality, the long-term erosion potential of the closed BRDA should be assessed.

### **3. 9 Surface Cover**

AAL has determined that the restoration of the BRDA surface will support a “nature conservation” end-use (AAL, 2005d). Therefore, a sustainable revegetation of the BRDA will be required to support this goal.

As bauxite residue is essentially nutrient free, to enable vegetation to occur either a suitable cover material is required or the application of sufficient organic materials is required to provide conditions amenable to support vegetation. In addition, the soil structure and nutrient sources required for revegetation are dependent on the initial complexity of vegetation required.

DITR (2006) suggests that there are many possible cover systems for tailings, generally in order of increasing complexity and cost, including:

- direct vegetation of the tailings;
- a thin layer of gravel placed directly over the tailings surface for dust mitigation;
- a vegetated, mono-layer cover, aimed at shedding rainfall runoff in a humid climate;
- a vegetated, non-shedding store/release cover, aimed at minimizing percolation through the cover by the release of seasonal rainfall by evapotranspiration;
- a capillary break layer, overlain by a non-shedding, vegetated growth medium, aimed at controlling the uptake of salts into the growth medium to sustain vegetation, for application in a dry climate; and
- combinations of the above.

## **AAL Research Program**

AAL has conducted research into developing a vegetation cover based on the premise that direct revegetation of the red mud surface is possible using grasses and clover cover if a suitable organic input is made at the commencement of the process. To achieve this, amendment of the residue is required; the basic physical and chemical principles for reclaiming alkaline residues are established. The underlying principles of ameliorating the residue are;

- Creation of drainage if a high water table exists,
- Replacement of entrained sodium with calcium to reduce pH and ESP (exchangeable sodium percentage)
- Addition of the necessary organic matter within the ploughing zone to improve soil structure, add nutrients and stimulate microbial activity;
- Aggregation of particles so as to improve structure and removal of excess salts by leaching.

AAL has developed the methods necessary to establish a revegetation cover on the BRDA. This is evidenced by the AAL sponsored research of the program and the peer reviewed finding presented in Courtney et al. (2003), Courtney & Timpson, (2004) and Courtney & Timpson (2005).

A range of suitable organic matter treatments were investigated. These included spent mushroom compost, thermally dried sewage sludge, dairy biosolid and agricultural manure. The approach to utilize likely recycled materials is commendable and in itself an application of sustainability principles.

The newly created soil (red mud mixed with process sand, gypsum and organic waste) is seeded with a grassland seed mixture and fertilizer applied by broadcast spreader. Typical species include:

- Trifolium pratense Rotra – Rotra Red Clover
- Holcus lanatus – Yorkshire Fog
- Fescue longifolia Dawson – Creeping Fescue

- Lolium perenne Master – Perennial Ryegrass
- Agrostis stolonifera Carmen – Carmen Creeping Bent Grass

At closure the dust suppression system will be utilized to provide irrigation water until surface rehabilitation by a vegetated surface cover is established. AAL propose to achieve a 100% self-sustaining vegetation cover after a period of 5 years. As it is likely to take up to five years to provide such a cover, an interim objective of at least 70% of surface area is targeted for after 3 years.

The water for the vegetation irrigation system will be a combination of recycled rain-water run off and potable water purchased for this purpose (AAL, 2005d).

## Research by Other Alumina Refineries

Research that has been sponsored by Alcan, Alcoa, BHP Billiton, and Rio Tinto has identified similar aspects as identified by AAL. In addition to the references cited in AAL (2005d) there are additional references researching this field identified as Fortin & Karam (1998), Fuller et al. (1982), Gherardi & Rengel (2001), Gherardi & Rengel (2003), Jasper et al. (2000a), Jasper et al (2000b), Meecham & Bell (1977a), Meecham & Bell (1977b), Wong & Ho (1991), Wong & Ho (1992), Wong & Ho (1993), Wong & Ho (1994), Wehr et al. (2005), Wehr et al. (2006) and Eastham & Morald (2006).

On comparison, it is unusual within the alumina industry, to develop a bauxite residue revegetation methodology in an environment where a water surplus exists due to the positive climate balance. Most research is undertaken in areas that experience water deficits for a significant proportion of the year. Hence, a significant focus is placed on providing suitable drainage systems, yet also providing sufficient water storage capacity within the revegetation profile to permit plant growth during periods of extended drought. This drainage system can also function as a pore-breaking layer preventing capillary rise.

This approach has meant that the introduction of a soil profile above the bauxite residue is viewed as an essential part of the revegetation program. However, due to the re-use of process sands in the revegetation, soil horizons have the same nutrient and organic matter deficiencies highlighted in the AAL research. Recent research has highlighted the impact of Manganese deficiency as a critical aspect in sustaining a revegetated community (Wehr et al. 2006).

## Likely Causes of Revegetation Failure

The most likely potential cause of vegetation failure on a revegetated bauxite residue area is due to a failure in the drainage provided within the growth horizon and the impact of capillary rise which brings caustic salts into the growing zone.

There are examples of this in the literature (Wehr et al. 2006) but focus mainly on evaporation concentration of salts within the growing horizon, reaching levels that could not support plant growth. However, in the literature these instances are also based on case study examples of revegetation in low-density wet disposal bauxite residue areas.

Unlike the stacking of high-density bauxite residue at AAL, the wet disposal of bauxite residue is a simple approach to tailings management where high water content (low-density) bauxite residue placed into tailings dams and allowed to dewater through

natural consolidation and solar drying. Due to the fine-grained nature of the residue this process can take many years and still result in only minimal improvements in final density.

Revegetation of these areas effectively commenced prior to the bauxite residue reaching a final density such that further consolidation was unlikely. As a result the topsoil and other soil and drainage structures placed as part of the revegetation program continued to undergo differential settlement as the residue continued to consolidate. This in turn led to the “bowl” surface structure developing as deeper less consolidated residue in the centre of these deposits consolidated to a greater degree than the residue close to the margins of the facility. With little drainage and leaching of the residue the development of large areas of failed vegetation was inevitable (Wehr et al. 2006)

As a general comment the lack of considered post-closure management also prevented the on-going management of these issues and rectification of problems as they occurred. This included allowing erosion to occur exposing less well leached and amended residue magnifying the impact of a bare area, poor security allowing burrowing animals to access the area and the use of the areas as transport corridors.

## Benefits of Dry Stacking

The adoption of high density disposal systems with minimal post-closure consolidation potential means that drainage structures established to manage the rainfall and storm run-off are less likely to experience differential settlement due to post consolidation, residue freezing induced heave or localized desiccation from failure of revegetation systems.

Generally, the higher the final density of a bauxite residue deposit the higher its intrinsic strength allowing ready access to the residue surface or construction of cost effective capacity increasing lifts on the residue surface. This has created other issues associated with the management of large volumes of rainfall run-off from ever increasing elevations from these facilities. This approach has generally been met with increased armouring of perimeter walls and drainage structures to protect against the higher energy water flows that can be generated by these facilities. Placement of bauxite residue at high densities often with purpose built drainage structures now means that the issue of continued residue consolidation is largely avoided.

The final target density of the bauxite residue placed at AAL is 70%. This is approaching the theoretical limit or shrinkage limit of the residue that can be achieved through solar drying processes. By way of comparison, at Australian alumina refineries, the target bauxite residue density target averages 65% before additional residue is placed or revegetation is commenced (Cooling, 1989). While, it is possible to dewater and consolidate bauxite residue above these densities it requires additional energy input and would result in higher costs and greenhouse gas emissions.

In addition, dry stacking systems can be constructed in such a way that they present a landform that can drain naturally. This feature has been adopted by AAL with the final height of the central cone of deposition some 8m above the perimeter drains (32m vs 24m AMSL).

## Key Requirements of Revegetation Success at AAL



The proposed revegetation strategy at AAL addresses many of the causes of revegetation failure identified in the literature. Specifically the strategy has controls to manage:

- Poor drainage control – Managed by developing a self-draining landform and using high-density residue placement methods to minimize differential settlement and poor drainage characteristics over the long-term.
- Insufficient nutrient availability, soil structure and chemical amelioration of the growth horizon – Managed by introduction of organic materials, ameliorants to improve soil structure and allow natural micro-biological processes to develop.
- Unrealistic end-use goals – Managed by setting the final land-use goal to that of “nature conservation” which permits the development of a simple revegetation structure but allows for the development of more complex systems over time with the rate of development determined by the rate of development of the soil structure.

However, there are some issues that will require further field research before the sustainability of this approach can be confirmed. These are:

- Ensuring that there are sufficient nutrients within the soil profile and that the cycling of nutrients develops enabling input of new nutrient sources to be minimized or at least maintained at a manageable rate.
- Ensuring that there is a suitable post-closure management program to address nutrient needs, erosion control, management of burrowing animals and controlled access.
- Ensuring that capillary rise is not a significant influencing issue in a high rainfall/low evaporation environment.

The AAL Closure Demonstration Cells will provide data to enable these issues to be fully assessed.

### **3. 10 Post Closure Management and Acceptance**

The process of tailings storage facility closure, decommissioning and rehabilitation has the broad objective of leaving the facility safe, stable and non-contaminating, with little need for on-going maintenance. The aim is to facilitate relinquishment from the operation. This point will be achieved when the company achieves the agreed completion criteria for the tailings storage facility to the satisfaction of the regulators, and the government is prepared to accept responsibility the land. With this responsibility comes accountability for controlling the future land-use.

The preferred position for Aughinish is that the long-term sustainable land-use for the BRDA is restricted to those activities that do not increase the pollution potential of the rehabilitated facility (AAL, 2005d). As such the preferred land-use option is to develop the area for nature conservation (AAL, 2005d). The definition of “nature conservation” applied from the EPA Landfill Manual is for restoration to incorporate woodlands, wildflower meadows, heathlands and wetlands (AAL, 2005b).

AAL has indicated that the EPA has accepted the suitability of the Closure Plan subject to:

- Demonstration of a sustainable vegetation cover; and
- Demonstration of leachate attenuation to below pH 9.0 within the projected 5 years.

Within the alumina industry there are four commonly applied future land-uses described for residue disposal areas. These are:

- Native Vegetation – At the completion of the residue operation, a sustainable ecosystem of similar vigour and diversity as the surrounding environment will be developed.
- Stable, Non-Productive Vegetation – At the completion of the residue operation, the goal is to create a landform that is self-sustaining, resistant to erosion and that will not create any off-site effects. This goal can be best described as a grassed hill that has no significant purpose other than for aesthetics.
- Agriculture – At the completion of the residue operation, a stable, non-contaminated landform will be created that can support an agricultural purpose in keeping with the surrounding land-uses.
- Light Industry – At the completion of the residue operation, a stable landform will be developed that will have sufficient bearing capacity to support light industrial use applications with sufficient zoning controls to prevent the disturbance of the closed residue facility.

The most common land-use of the land surrounding the BRDA is:

- Nature Conservation
  - The existing Bird & Butterfly sanctuary is adjacent to the north side of the existing BRDA. The bird sanctuary management has been featured and reported on by organizations such as the Irish Wildbird Conservancy since its development in 1981. Accordingly, there is an existing nature conservation focus in the vicinity of the BRDA. The ongoing management, and possible enhancement, of the existing bird sanctuary will be examined in the after use policy for the restored BRDA (AAL, 2005b).
- Amenity Restoration
  - The eastern sides of the BRDA have a network of nature trails starting from the Aughinish Alumina Ltd sports centre complex. Joggers, walkers and sightseers use these amenity features. The ecological features viewed from these trails include some woodland, fernland, and the tidal Poulaweala Creek that includes a bird hide to observe the inter-tidal bird environment.
- Agriculture
  - The principal agricultural activities are meadow growth for hay cropping and grassland pasture for dry stock.

The proposed nature conservation post-closure land use is in keeping with the current land-uses of the surrounding area.



However, there remains a risk to the closed BRDA of disturbance. Provision of a security fence and an appropriate community education program to ensure community understanding and support would be recommended.

The BRDA is located on freehold land owned by AAL. It is likely that at closure the ownership will be transferred to another commercial entity that will ensure the closure and post-closure commitments are completed. As the terms and policy on this issue are still in a formative stage there is no formal AAL position as to how this will occur. However, the structure of this arrangement will likely incorporate some of the following attributes (Thomas Hartney, AAL, Personal Communication):

- The plant infrastructure including storage facilities, the marine terminal and the CHP plant will continue as a viable commercial operation;
- The BRDA itself will be re-vegetated to “Nature Conservation” end use;
- The leachate collection and treatment will continue as necessary as a small component of the overall asset;
- The ongoing IPPC license requirements including monitoring will be transferred to the new commercial entity.

In addition it is likely that the new commercial entity will be vested with the necessary capacity (revenue generation or direct funds) to ensure that the closure objectives are met. In addition, the ultimate ownership of the land will need to be considered and whether it can be sold to private, community organizations, or government agency parties under strict control of future land-use.

One other consideration is how the BRDA could be accessed for recovery of bauxite residue for alternative uses. As will be described in Section 6.0, bauxite residue has many niche re-use applications although the re-use potential of the residue is unlikely to match the production rate of the alumina refinery. However, if access to the BRDA could be managed after closure such that a small scale re-mining activity could be supported, then re-use applications could be considered as a viable means of gradually eliminating the BRDA as a structure.

The timescale of this to occur could be over decades or even longer but the opportunity to support a sequential re-use opportunity should be considered. However, it is unlikely that adopting this approach would then change the nature of the BRDA from a “permanent” change in land use to one of “long-term” land use utilising the definitions described in EPA (2002).

### **3. 11 Operational Residue Management System**

As described in Section 4.8, the adoption of dry stacking by the alumina industry has allowed the creation of naturally draining landforms.

The design of the AAL residue disposal facility incorporates:

- A high density residue deposit with residue placed at near the maximum possible density achievable using solar drying and consolidation techniques;
- A central domed profile with a final slope of 2.5% inducing rainfall runoff to drain naturally via a spiral drain to perimeter drains;
- A series of stepped embankments minimizing the length of slope that rainfall run-off will traverse before the runoff volume induces scouring and erosion of the embankments;

- Armouring of the stepped embankments to prevent localized erosion;
- The incorporation of sand and geotextile filters within the upstream embankments to prevent the movement of sediments into the surface drainage system;
- A simple revegetation blend utilizing robust and locally prevalent grasses and clover to support a sustainable revegetation profile;
- A low technology final land use goal where the adoption of “nature conservation” provides flexibility for AAL in how to meet this goal;
- Provision of “hard access” within the major drainage systems to permit ready access by earthmoving equipment for routine de-silting needs as part of a post-closure maintenance program. The total capacity of the decant structures is considerably in excess of the drainage required from the upper level interceptor channel to the Perimeter Interceptor Drain from a 1 in 10,000 year storm event. This is a precautionary approach to allow for 50% of the decant pipes inoperative and the main discharge outlets on the east ridge road being blocked by sloughing of the red mud during these extreme storm events.
- At closure the surface of the proposed salt cake disposal area will be domed with process sand and capped with 2mm thick textured HDPE overlain by a 1000grm geotextile, 600mm of inert material such as glacial till or estuarine material stockpiled in the unsuitable stockpile and 200mm of topsoil.

AAL propose to continue to operate a high-density residue management system utilising vacuum filtration. This system results in:

- The minimum possible active operational footprint when compared to currently applied technologies in the alumina industry;
- Minimising rainfall run-off volumes in a region with a positive climate balance;
- Ensures a high final density in the BRDA with benefits for stability and optimising the mass of residue that can be accommodated within the BRDA and operating life of the facility.

Further modifications to maximise the density of the bauxite residue are possible in theory but not considered realistic options as they would involve:

- Decommissioning of the existing mud pumping system;
- Development of a direct residue filter cake trucking system with higher operational costs, added risk due to the vehicle exposures and higher stacking angles that would require additional contouring to achieve the same landform.

The residue management system in operation at AAL is considered best practice within alumina industry for a washed alkaline residue management system. A review of the application of neutralization technology is considered in Section 5.

### **3. 12 Operational Controls (Aligned with “Design for Closure”)**

The day-to-day operational activities of the residue disposal area should be aligned with the intentions and goals of the closure plan. This ensures that operations create the deposit structure and landform in accordance with the closure principles and

permit progressive rehabilitation as there is minimal re-contouring and double handling (DITR, 2006). For the BRDA this means:

- Operational residue production, stacking and consolidation are managed to deliver the maximum achievable density in the residue thereby achieving significant strength and reducing the risk of failure of the deposit;
- Monitoring and management of environmental issues is directed to ensure that minimal dust generation occurs, monitoring of all environmental parameters occurs in a timely manner and that anomalies are identified, corrective actions developed and communicated to the necessary stakeholders.

Review of the BRDA Operational Manual, Standard Operating Procedures SWM 2009, 2011, 2012, 2017, 2018, 2021, 2022 suggests that these activities are well considered.

The continued operation of a certified Environmental Management System to ISO 14001:2004 will ensure that issues requiring corrective action will be addressed and the day-to-day operation will remain aligned with the overall design.

### 3. 13 Stakeholder Consultation

Consultation with stakeholders is an essential part of ensuring the sustainable development of a tailings facility. Best practice consultation in this field is demonstrated by diversity in modes of consultation from special consultation events, written correspondence, telephone discussions, one-on-one meetings and active engagement through professional, timely and appropriate feedback. Some organizations also use formal consultative review groups made up of representatives of stakeholder groups with the vested power to approve or reject proposals.

Importantly the consultation process should be integrated with the existing operations community consultation process to present a seamless and consistent information source. Examples of best practice within the alumina industry are the community consultation programs of Queensland Alumina ([www.qal.com.au](http://www.qal.com.au)), Rio Tinto Aluminium Yarwun (Neighbour of Choice Program) and the Residue Planning Liaison Groups developed by Alcoa World Alumina (Kwinana, Pinjarra and Wagerup) (AWA, 2004). The timing and frequency of community consultation programs should reflect the intensity of development and the apparent rate of change of the development. During periods of high activity or change it is not unusual to maintain a monthly formal consultation event.

AAL (2005b) describes the consultation process used to date for the development. Consultation was commenced in 2004 in relation to the proposed Phase 2 extension of the BRDA and raising of the Phase 1 BRDA to ensure that the views of the various stakeholders, the community and individuals are taken into account in the decision making process. Further consultation was carried out in February 2005 concerning the proposed increase in production.

The modes of consultation used by AAL are:

- A “Neighbours Evening” to present the proposals for the Phase 2 extension of the BRDA and raising of Phase 1 BRDA was undertaken on September 1st 2004 at the Training Centre at Aughinish Alumina Ltd. Presentations were

made by AAL on general administration issues relating to the facility over the past year and by RPS Group on the Environmental Assessment process, what had so far been done and what would happen in the coming months. Over 250 “neighbours” were included on the invitation list to the event and 91 actually attended on the evening. Questionnaires were distributed to all attendees to obtain general views on the proposals.

- Letter Correspondence where letters were sent out to a number of stakeholders, asking for their views on the proposed extension and increase in plant production capacity. In each case a map showing the location of the proposed extension and an outline description of the proposals were included with the letter.
- A number of meetings were arranged to discuss details of the project and provide further information. Additional meetings were held with: National Parks and Wildlife with regard to designated areas and protected plant species; Shannon Regional Fisheries Board with reference to the Shannon and its tributaries and their fisheries potential; Limerick County Council with reference to the planning application for the proposed extension; EPA with regard to the Integrated Pollution Prevention and Control License review required as a result of the nature of the proposal.

The community responses presented in the Environmental Impact Statement appear predominantly negative (AAL, 2006). While obtaining 100% support for a development is too optimistic, achieving a balance in responses is realistic and is being achieved elsewhere. In addition this sentiment should be monitored to ensure that the programs and designs being developed are sustainable.

AAL believes that there is no systematic community ill feeling or widespread campaigns (Thomas Hartney, AAL, Personal Communication). Concerns mostly include:

- Visual impact/landscaping measures
  - Addressed by the interim restoration proposals in the project to the exterior of Stages 1 to 6 rockfill lifts.
- Perceived dust impact
  - Addressed though the sprinkler program improvements introduced progressively since 2001 that has eliminated the threat of both internal dusting within the BRDA and fugitive deposition outside the BRDA. Dust deposition monitoring (including independent monitoring) around the BRDA has demonstrated that dust levels outside the BRDA are negligible;
- Odour issues.
  - Linked to disturbances of normally submerged sludges in ponds during the infrequent effluent pond cleanout events

AAL run annual community consultation forums and believe that it provides the necessary feedback to neighbours and community representative groups who are free to ask any questions at such sessions. The records of such meetings are accessible to the EPA who are also informed and invited to the meetings. The last 3 annual presentations from AAL at such meetings dealt with the tangible impacts of the BRDA project (Thomas Hartney, AAL, Personal Communication).

### **3. 14 Operation to certified EMS-ISO14001:2004**

Ensuring that a development operates an Environmental Management System (EMS) is a proven means of enabling the organization to identify and focus on issues that are important to sustaining the organization as well as accommodating the views of groups external to the organization. In essence, it forces an organization to focus on the most important issues and is measured on its effectiveness of implementation.

An organization with an EMS does not mean that there are no significant environmental issues. However, it indicates that there is a recognised system of systematically managing these environmental issues while taking into account the other significant issues an organization may also have to deal with. In this way, environmental issues are aligned with the operational goals of the organization.

The recognised standard of EMS is the International Standards Organization (ISO) Environmental Management System 14001. This standard describes the structure required to integrate all aspects of environmental management. In accordance with this standard to become and remain certified to this standard, an organization must submit to independent third party audit of the effectiveness of the EMS.

AAL is routinely audited by Det Norsk Veritas and achieved certification in 2000 and currently maintains this certification to ISO 14401:2004.

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## 4.0 Alternative Residue Management Practices

The alumina industry has existed commercially since 1893 when the first refinery commenced operation at Gardanne, France. Since that time over 90 alumina refineries have been constructed and some have closed. A large variety of residue management systems have developed in response to occupational hygiene and safety issues, environmental concerns, land availability, cost pressures and closure concerns.

In general the bauxite residue management practices adopted by an alumina operation reflect the necessary compromise between the climatic influences, the protection of local environmental values and the availability of resources. Additional operations modifications usually reflect local technological strengths and regulatory issues.

Although the Bayer Process is commonly used to extract alumina from bauxite the bauxite residue generated at a refinery is highly dependent on the mineralogy of the bauxite ore.

All these factors are variable and site specific, and hence so are the techniques that have developed to manage bauxite residue operations. Therefore, it is rare for the full scope of residue disposal technology that has been developed in one location to be directly transferable to another.

Appendix B has a list of bauxite residue management technologies applied by the alumina industry.

### 4.1 Marine Disposal

Marine disposal of bauxite residue requires the pumping and placement of residue via either purpose-built sub-surface disposal pipes in suitable locations or the disposal using purpose-built shipping that allows dumping from openings in the bottom of the vessel. Disposal is essentially “uncontrolled” as the residue creates a plume of turbid sediment that can spread over many hundreds of kilometres at varying thicknesses.

Dethlefsen (1976) reviewed marine disposal of bauxite residue practices with regard to potential impact on marine organisms and fisheries. The review assessed investigations that included:

- Disposal from the Gardanne refinery at 140,000 tonnes/year (Minimal dispersal);
- An experimental dumping conducted by German authorities in the North Sea from dumping vessels into shallow water (Moderate dispersal);
- A six-year program to dispose 300,000 tonnes of bauxite residue in South Wales into the highly turbulent currents of Newport Deep in the Bristol Channel (High dispersal).

The review concluded that:

- Bauxite residue is slightly toxic to all marine organisms to a greater or less degree. The toxicity is greatly dependent on the bauxite origin;
- Mechanical effects of residue disposal would disturb benthic organisms when complete layers of bauxite residue are formed. This impact was minimised in



the oceanic trench environment but still resulted in the total elimination of the benthic fauna; and

- It is not possible to conclude that bauxite residue can be safely disposed at sea in all cases and that individual site conditions will influence the final outcome and that extreme care should be taken in making this assessment.

Trieff et al. (1995) investigated the toxicity of bauxite residue in a marine environment by relating biological effects to the simultaneous occurrence of aluminium and other toxic contaminants. The study used gametes and embryos from Mediterranean sea urchins as an appropriate biological indicator. This approach has been used widely in multidisciplinary marine studies focused on either the health effects of chemicals or concerning water and sediment quality (Trieff et al. 1995).

The study effluent from a bauxite plant was tested on sea urchin embryos and sperm for the induction of:

- developmental defects in effluent-exposed embryos (retarded, malformed);
- loss of fertilization success (spermotoxicity), and
- transmissible damage to the offspring of pre-treated sperm.

The study identified that a drop in reproductive and developmental success can be anticipated for a bauxite residue concentration at levels as low as 1.5 µg/ml and that toxicity effects were observed from 150 µg/ml. This would suggest that the discharge of bauxite residue would potentially impact on a significantly larger region than the discharge itself involving early life stages and recruitment in aquatic biota. Tellingly, a major conclusion from this study was "Regardless of the mechanisms involved, bauxite effluent (red mud) could represent a significant marine or aquatic ecotoxin and should be regulated accordingly."

His et al. (1996) investigated the toxicity of bauxite residue on oyster embryogenesis (lethal effects) and larval growth (sublethal effects). The study confirmed the toxicity impacts of the Trieff et al. (1995) study and identified that trace metals contents (Hg, Al, Fe and Cr) became bioavailable with enhanced toxicity (3x) of the solid phase as metal species were bound to the sediment particles due to ingestion rather than contact only. This study concluded "benthic systems have an ecological role as a reservoir of contaminants which can impact the marine fauna when re-suspended by natural or artificial changes in hydrodynamic conditions."

Community support for marine disposal (Submarine Tailings Disposal - STD) will be determined on a site-specific basis. However, the application of STD to tailings management in South-East Asia and the Pacific has given rise to the "Manado Declaration on Submarine Tailings". In broad terms this declaration states that dumping mine waste in the ocean is contrary to the principles and hopes of sustainable development (Miningwatch Canada, 2007).

MMSD (2002) states that adoption of marine disposal (STD) occurs where land based disposal options are limited or virtually non-existent. Although the risks associated with land disposal are well known, there is no consensus about the risks associated with marine disposal between the industry, academics and the community. The number of marine disposal case studies is limited and the time frame is such that long-term validation is not yet possible.

Therefore, for marine disposal to be considered as suitable it would have least impact in an oceanic trench preferably located far from communities and fishing activities. Based on the marine disposal systems currently in operation the maximum pumping

distance would limit discharge to less than 50 kilometres. As Ireland is located on a wide continental shelf shared with the United Kingdom and Western Europe, the nearest suitable trench is located approximately 300 kilometres westwards in the North Atlantic. This would represent a significant technical and economic challenge to provide such a system not only for continuous operation but also where it could be safely maintained to ensure availability. In addition, European Union Landfill Directive 1999/EC/31 (26<sup>th</sup> April 1999) requires that Member States apply the proximity principle to future waste infrastructure where waste should be generally managed as near as possible to its place of production. Arguing that such a pipeline and discharge represented “proximity” to the refinery would seem difficult. Given that a viable and successful Bauxite Residue Disposal Area has been in operation for over 20 years an argument based on a “limited” land based disposal option would appear inadequate.

Assuming that a suitable marine disposal system could be constructed, it would not be possible to prevent “uncontrolled” bauxite residue disposal into deep sediments. This deposition would occur over a wide area significantly larger than a land based disposal system. It would be hoped that the residue would remain undisturbed but there remains a risk that residue could be re-suspended into the marine ecosystem at some time in the future. While the likelihood of such an event would seem low it would be reasonable to assume that such an event could occur at anytime and without warning. Monitoring of surrounding waters would be required and may even detect that such an event had occurred. The key issue is if such an event could occur, and result in the residue being transferred into more benthic fauna, how would its impact be managed.

EC (2004) states that BAT for all alumina refineries is to “avoid discharging effluents into surface waters”. While this directive applies to raw alkaline water effluent discharge and encouraging re-use in the refinery, it does not suggest discharging solids as a means to meet this goal as the discharge of solids represents a more significant toxicological threat. Therefore, preventing discharge of bauxite residue solids into surface waters or a marine environment would suggest this is a key requirement of BAT.

An alumina refinery that discharges bauxite residue directly into the marine environment has not been approved for development anywhere in the world in the last 25 years. Existing refineries are under pressure to stop this practice ie. Alumina de Grece by 2011 and Gardanne and Showa Denko by 2015. Adopting such a proposal for the management of bauxite residue at Aughinish cannot be technically, environmentally or economically justified.

## **4. 2 Disposal of Residue via Return Shipment to the Bauxite Mine**

The backfilling of deep hard-rock mines via residue is a standard practice in the mining industry. It usually involves converting the residue to a high-density paste and re-introducing it into deep underground mining voids as a means of closure of these voids, avoiding the construction of tailings dams and improving the geotechnical strength of the underground structures. It is not employed in the alumina industry because

- bauxite for AAL is generally extracted via surface mining as in Guinea and Brazil



- bauxite mines are generally located some distance from the receiving alumina plant (from 20 miles to thousands of miles)
- bauxite mines are generally located in remote areas without the infrastructure suitable for supporting a long-life engineered land-fill
- they are generally remote from the sea and so are overlying freshwater aquifers which is less favourable from a site selection point of view

As such there is no environmental benefit to return residue to the mine site. On the other hand there are significant technical, economic and regulatory obstacles working against such a practice

- the bauxite mining operation does not include infrastructure or know-how suitable for handling the alkaline leachate from bauxite residue – unlike at an alumina refinery where storing and handling alkaline streams is core competence.
- the cost of shipping back to the mine (in most cases but certainly in AAL's case) would be prohibitive. For instance, the incremental costs to do this at AAL would be
  - A port extension and a residue handling and loading system to process approximately 2 million tonnes residue per annum would cost approximately €100 million because the existing jetty at Aughinish already operates at more than 80% berth occupancy
  - Neutralization facilities and associated infrastructure at the mine to handle alkaline leachate (Approximately €10 million)
  - A handling cost of at least €15 per tonne to load, unload and transport the sticky residue at both ports (Approximately €30 million per annum)
  - A shipping cost of €20-€30 per tonne residue to ship the waste in dedicated ships back to Africa or South America (Approximately €40-€60 million per annum).
- The Environmental Impact Assessment of such an operation would likely prevent it receiving approval from one or other of the National Regulatory bodies involved because it would clearly be unsustainable

AAL's cost base would deteriorate by the above incremental amount and this would certainly precipitate closure of the refinery.

### **4. 3 Wet Disposal (Low Density)**

Wet disposal operations normally store a larger proportion of water than a higher density operation. The current residue disposal system at AAL currently releases 0.24 m<sup>3</sup>/tm<sup>3</sup> of residue (SG 3.1 and discharge density of 60% w/w and dewatering to 70% solids w/w). Adopting a wet disposal system would necessitate a bypass of the current filter technology and pumping the residue into the dam at low density (say 30% solids w/w). On deposition the residue would release 0.570 m<sup>3</sup>/m<sup>3</sup> of residue (Discharge density of 30% w/w and dewatering to 55% solids w/w) – currently this entrained liquor is captured and recycled within the refinery)

The additional 0.57m<sup>3</sup>/m<sup>3</sup> or 500,000 m<sup>3</sup> per annum of caustic waters would need to be stored, processed and discharged in a similar manner as current technology. This water is currently captured in the refinery and recycled to the process circuit.

The low viscosity of lower density residue would force a change in residue management practices since the average stacking slope would be less than 1% rather than the 2 – 3 % achieved under the current disposal design. This change would also reduce the overall capacity of the BRDA as the current design depends on the development of a central cone as the final landform structure. Low-density residue with a low viscosity would achieve a near flat final contour. This would also accelerate the rate at which the BRDA fills. Assuming that the upstream embankment lifts could be constructed using additional imported material and geomembranes a change to wet disposal would mean that overall capacity would reduce by approximately 25%. Such a reduction would require access to additional nearby land.

It would be likely that the final landform of the BRDA under a wet disposal system would suffer from many of the same issues as wet disposal systems undergoing closure identified in the literature. Over time the BRDA would continue to consolidate and this process would be at a maximum in the centre of the BRDA. This process would create a “bowl” structure on top of the BRDA, collecting incident rainfall and preventing drainage. Revegetation would be unable to survive in a poorly drained environment and this would lead to the development of seasonally bare areas that would be prone to dust generation during extended dry periods. Finally, maintaining a water dam at elevation would also likely lead to extended saturation of the embankments. This would impact on the overall stability of the structure.

Conversion to a wet disposal system could not be technically, environmentally or economically justified. Wet disposal preceded dry disposal and its attendant environmental management requirements provided the incentive to develop dry disposal as practiced at AAL.

#### **4. 4 Dry Stacking - High Compression Thickeners (Sub-aerial)**

Using high compression thickeners would create a residue of only slightly lower density than is currently achieved using vacuum filters. This would result in a slightly higher volume of liquor reporting to the Storm Water Pond

Adopting a High Compression Thickener disposal system would mean a bypass of the current filter technology and pumping the residue into the dam at lower density (say 45% solids w/w). On deposition the residue would release 0.443 m<sup>3</sup>/m<sup>3</sup> of residue (Discharge density of 45% w/w and dewatering to 65% solids w/w).

The additional 0.13m<sup>3</sup>/m<sup>3</sup> or 100,000 m<sup>3</sup> of caustic waters would need to be stored, processed and discharged in a similar manner as current technology. This water is currently captured in the refinery and recycled to the process circuit.

The final landform and revegetation performance would be similar to that proposed.

While conversion to a high compression thickener system might be justified economically due to lower operating costs, it would generate a slightly larger storage requirement that cannot be justified environmentally.

## 5.0 Residue Neutralization

### 5.1 General

As described in Section 4.11, the residue management system in operation at AAL is considered best practice within alumina industry for a washed alkaline residue management system. Improvements are more likely to be achieved through modifications to the residue chemistry prior to disposal. There are four main options available to AAL to achieve this outcome. These are:

- Seawater (or Estuarine) Neutralization;
- Acid Neutralization;
- Carbonation
- Combined Flue Gas Desulphurisation/Seawater Neutralization

A detailed summary of the underlying chemistry of the neutralization reactions is included in Appendix E.

### 5.2 Seawater Neutralization

As AAL is sited on the shores of the tidal Shannon Estuary the closest and most logical source of seawater would be from this area. However, the Shannon Estuary also captures the freshwater runoff from the entire River Shannon catchment and therefore becomes seasonally diluted when compared to oceanic seawater.

In a seawater neutralization system, residue is mixed with sufficient seawater to neutralize the soluble alkaline components of the residue. Magnesium and Calcium ions in the seawater displace the sodium ions in the residue liquor and held in storage for the reaction to take place. Neutralization using seawater can achieve an initial pH of 8.5 – 9.0. The reaction produces a hydrotalcite gelatinous precipitate that blends with the residue.



The end point for the titration of  $\text{Mg}^{2+}$  with liquor occurs at a pH of approximately 10.5 and further  $\text{Mg}^{2+}$  is required to shift the equilibrium of reaction [2] to the right lowering the pH. A pH below 8.5 is difficult to achieve, requiring a large excess of  $\text{Mg}^{2+}$ .

The residue is then pumped to the disposal area as described previously.

Due to the residual alkalinity held in the residue solids from lime products and desilication products, the pH of the residue will gradually revert to pH 11. Thus leachate run-off from sea-water neutralized residue must still be collected, further neutralized and clarified prior to disposal.

For this technology to be viable, access to seawater, preferably with a low tidal range to minimise pumping capital costs, is required as is a discharge system with sufficient tidal exchange to permit continuous discharge, at elevated temperatures, of a magnesium depleted seawater and low concentrations of trace heavy metals.

As the neutralization reaction is dependent on the concentration of magnesium and calcium ions any dilution of the normal seawater concentrations increases the volume of seawater required to achieve the same level of neutralization. In addition, with greater seawater flow rates the size of the vessels required to perform the neutralization reaction become larger.

A more detailed description of the underlying chemistry is included in Appendix E.

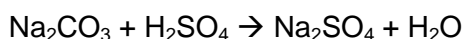
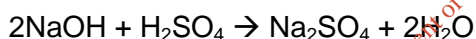
This technology is used by RTAY (Rio Tinto), Queensland Alumina, Australia. Gove (Alcan), Australia has indicated that it will convert to this process after 2015.

## 5. 3 Acid Neutralization

In an acid neutralization system, residue is mixed with either sulphuric or hydrochloric acid to neutralize the alkaline components of the residue. The degree of neutralization is determined by the volume of acid added.

Acid neutralized residue can achieve a neutral pH temporarily by neutralising the soluble alkalinity. The titration curve of the strong acid/strong base reaction is usually extremely steep making process control very difficult. Variation in the reaction can result in changes in pH unless the system is well engineered and well controlled.

Acid neutralization is usually achieved using sulphuric acid rather than hydrochloric acid. This is usually based on the safety concerns and relative cost associated with hydrochloric acid. The reactions are:

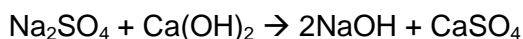


Where NaOH, NaAl(OH)<sub>4</sub> and Na<sub>2</sub>CO<sub>3</sub> are the alkaline species in residue liquor solution.

H<sub>2</sub>SO<sub>4</sub> neutralization can also be applied to neutralize solid phase alkalinity but the time frames are quite much slower (days or weeks). For this reason it is impractical to neutralize solid phase alkalinity prior to residue disposal.

H<sub>2</sub>SO<sub>4</sub> neutralization results in a dilute Na<sub>2</sub>SO<sub>4</sub> solution which must be disposed of (probably by dilution with estuary water) and the residual dry mud will contain solid Na<sub>2</sub>SO<sub>4</sub>·10H<sub>2</sub>O which may also cause difficulties with revegetation. The residue will also contain CaSO<sub>4</sub>·xH<sub>2</sub>O (gypsum) an inert compound.

The liquor can be causticised:



but only with dilute Na<sub>2</sub>SO<sub>4</sub> solutions because of the solubility of CaSO<sub>4</sub>.

An assessment of the sulphate response of local waters is required as there remains the potential for a sulphate response (in areas with a sulphate deficiency) to a sulphate discharge leading to algal blooms and associated issues.

A more detailed description of the underlying chemistry is included in Appendix E.

This technology is used in many alumina refineries as a means of safely disposing of spent sulphuric acid. The neutralising impact is usually minor due to the low strength of the acid relative to the alkalinity in the residue. Disposal is usually achieved by mixing spent acid after the final residue washing stage..

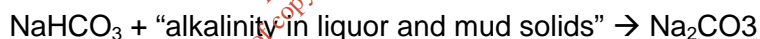
Post neutralization of alkaline process and BRDA run-off waters is quite widespread in the industry with the technology adopted by Aughinish, Ireland (Rusal), Alunorte, Brazil (CVRD/Norsk Hydro), and Vaudreuil, Canada (Alcan).

## 5. 4 Residue Carbonation

Carbonation is the mixing of carbon dioxide with residue to achieve a stable pH level. The neutralization process reduces the pH of the residue from pH 13 to pH 10.5-11.0. Initial developments are based around using a waste carbon dioxide stream but longer term flue gas from refinery boilers will be used.

CO<sub>2</sub> neutralization has been investigated in detail by Alcoa World Alumina. The process consists of reacting NaHCO<sub>3</sub> with the mud slurry and then regenerating Na<sub>2</sub>CO<sub>3</sub> using CO<sub>2</sub> in "flue gas". Alcoa claim that this process:

- Allows flue gas to be used (previously only "pure" CO<sub>2</sub> gas could be used)
- eliminates problems with scale formation that were a serious limitation when using "pure" CO<sub>2</sub>



This process has been patented by Alcoa and a license to operate would be required.

CO<sub>2</sub> neutralization has the advantages over seawater neutralization that it may be possible to produce:

- Relatively concentrated NaHCO<sub>3</sub> solutions compared with seawater where Mg<sup>2+</sup> is present at only about 1.4 g/L (0.12 Molar in "acid" i.e. double the Mg<sup>2+</sup> molarity). A concentrated solution reduces capital cost.
- A higher temperature accelerating the slow reactions (when seawater is used the large volume makes the use of higher temperatures costly)
- A higher delta pH than with seawater to drive the reaction faster

The residue is then pumped to the disposal areas as described previously.

Alcoa has provided some of the reasons for adopting this technology rather than some of the other options available (AAL, 2007). These include:

- Ensuring that even though the residue will be neutralized it will remain "uncontaminated" from the perspective of enabling recycle to the refinery. Operations that experience a water deficit harvest rainfall collected from the residue management areas. By avoiding neutralization technology that is

based on sulphate or chloride materials ensures that the captured runoff can be recycled without impacting on the refinery operation.

- There is evidence that carbonation improves the dewatering rate and hence reduces the drying cycle required to achieve the target final density. By reducing the drying cycle the areas demands are also reduced and hence the rate of expenditure of capital required for facilities to support the operation. Further confirmation of this benefit is required.
- There is evidence that carbonated residue has a lower dusting potential when compared with other neutralized residues and un-neutralized residues. Where un-neutralized residue requires daily irrigation to suppress dusting, the carbonated residue did not require irrigation for four months during the summer period. Further confirmation of this benefit is required..
- There is also evidence of a volume increase in the residue after neutralization with seawater. This is due to the creation of the “hydrotalcite” material created by the reaction of Magnesium and Calcium with Sodium Hydroxide and Sodium Carbonates. The volume change due to this “hydrotalcite” is dependent on the final alkalinity of the partially neutralized residue. As the increased volume increases the area requirements this approach is viewed as being inferior to CO<sub>2</sub> neutralization.

This technology is proposed for use by Kwinana, Pinjarra, Wagerup, (Alcoa), and potentially all Alcoa refineries worldwide. Alcoa has also indicated that it is preparing to commercialise this technology as a means of recovering research and development costs.

## **5.5 Combined Flue Gas Desulphurisation/Seawater Neutralization**

This process is also known as the “Sumitomo Process” a reference to the holders of the patent on the technology. Flue gases are passed through a residue stream to remove sulphur dioxide (creating sulphuric acid) and this blend is then mixed with varying amounts of seawater to achieve a stable pH. The residue is then pumped to the disposal areas as described previously. The technology is used by Eurallumina, Italy (Rusal).

AAL also reviewed the use of the Sumitomo process as a means of managing air emissions. However, an alternative approach using a combination of natural gas fired CHP and adoption of low sulphur fuel oils allowed the air quality goals to be met at high energy conversion efficiencies (AAL, 2005b).

## **5.6 Combination Water Management Systems**

In some situations the full neutralization is not possible but neutralization of the entrained alkaline liquor and rainfall run-off from the residue disposal area is possible. These systems are primarily used where the impacts of climate generate a positive water balance or there is a requirement to reduce the risk and cost exposure of large stored volumes of alkaline contaminated waters. Within the alumina industry there are two types of water management systems:



- Open – A situation where the residue operation discharges excess water to the environment having first neutralized and clarified it.
- Closed – A situation here the residue operation does not discharge any excess waters to the environment. This process requires the establishment of large ponds where the excess water is eliminated by evaporation or is recycled to the refinery.

The open water circuit system technology can incorporate seawater or acid neutralization and is used by Aughinish, Ireland (Rusal), Alunorte (CVRD/Norsk Hydro), Brazil, and Gove, Australia (Alcan).

## 5. 7 Feasibility of Neutralising AAL Bauxite Residue

Aughinish Alumina, along with virtually all other alumina producers, utilise the Bayer Process to refine alumina from bauxite ore. In this process the ground bauxite ore is digested in a hot solution of highly alkaline sodium hydroxide (caustic soda) and the dissolved alumina is removed for precipitation and calcination into alumina powder. The undissolved components of bauxite i.e. bauxite residue are washed to recover residual caustic or alkalinity which is then recycled.

The bauxite residue slurry that exits the final mud vacuum filters contains:

- Diluted liquor that has not been completely washed out.
- The insoluble portion of the bauxite (mostly Iron and Titanium oxides).
- Sodalite (formed by reaction of kaolinite and quartz in the bauxite with liquor).
- Calcium compounds (formed by addition of lime to the process).

Therefore, the sources of alkalinity within the bauxite residue can be defined as:

- The entrained liquor in the residue:
  - NaOH
  - NaAlO<sub>2</sub>
  - Na<sub>2</sub>CO<sub>3</sub>
- Some of the Calcium compounds (formed by addition of lime to the process). When lime, generally in the form of Calcium Hydroxide (Ca(OH)<sub>2</sub>), is added a quite complicated series of reactions occurs depending on the liquor concentration and temperature. The types of calcium compounds found in the Bayer process include:
  - Hydrocalumite
  - TCA (Tri-calcium Aluminate)
  - Hydrogarnet
  - Lime
  - Calcium Oxalate and
  - Perovskite (CaTiO<sub>3</sub>)
- Sodalite ((NaAlSiO<sub>4</sub>)<sub>6</sub>(Na<sub>2</sub>X), where X can be SO<sub>4</sub><sup>2-</sup>, CO<sub>3</sub><sup>2-</sup>, Al(OH)<sub>4</sub><sup>-</sup>, and some minor anions such as Cl<sup>-</sup>.

All of these alkalinity sources need to react with a neutralising agent to achieve full “neutralization” of the residue. A full explanation of the neutralization equations and confirming preliminary experimental investigations is enclosed in Appendix E.



## 5.7.1 Acid Neutralization

Based on the limited experimental data obtained so far the following conclusions can be drawn regarding AAL residue. The Volume of 98% Sulphuric Acid ( $\text{H}_2\text{SO}_4$ ) approximately required:

- To achieve full neutralization of all alkaline products -155 kg per tonne of dry residue
- At 1.95 Mtpa alumina production rates this is equivalent to 193,400 tonnes of sulphuric acid annually at an acid cost of €10 million per annum
- To achieve neutralization of soluble alkaline products - 30 kg per tonne of dry residue
- At 1.95 Mtpa alumina production rates this is equivalent to 37,400 tonnes of sulphuric acid annually at an acid cost of €2 million per annum

These values are based on neutralising the residue to a pH of 9.0. If other mineral acids were used such as Hydrochloric the acid cost would be 3-4 times higher and the safety and maintenance requirements more onerous and costly. Citric acid would be 10 times more expensive.

Additional experimentation is required to more accurately determine the quantities of  $\text{H}_2\text{SO}_4$  required. The quantities required will be affected by the target pH.

However, due to reaction times often measured in weeks, achieving full neutralization is not a realistic option as it would require maintaining close contact between the acid and the residue solids for this period. As the residue management philosophy is based on placement of residue layers to achieve consolidation and dewatering maintaining this contact will not be possible.

Neutralising the soluble alkalinity of the residue is possible. However, as there will still be solid alkalinity still present in the residue (calcium compounds and sodalite), it is anticipated that the pH of the residue will gradually increase over a number of days and stabilise around pH 10.5 -11.0.

Due to the large volume of sulphur compounds being introduced into the residue there is a risk of  $\text{H}_2\text{S}$  generation via anaerobic digestion of sulphates if the final pH remains too low. Thermodynamic calculations of the equilibrium  $\text{H}_2\text{S}$  concentration versus pH and the solution Sulphide concentration show that a pH of 10.3 should be sufficiently high to suppress the  $\text{H}_2\text{S}$  concentration to below the TLV of 10 ppm (there is still a strong odour at 10 ppm) by the following reaction:



At pH 10.3 the reaction is about 99% to the right. Consequently, there is little or no smell because the concentration of  $\text{H}_2\text{S}$  is very low. However, the quantity of  $\text{H}_2\text{S}$  present also depends on the total Sulphide concentration (the higher this is the more  $\text{H}_2\text{S}$  there is at the same pH). Therefore, under a neutralization scheme utilising sulphuric acid to reduce the pH below 10.5, by neutralising all the calcium compounds and sodalite, will lead to a condition of high  $\text{H}_2\text{S}$  generation.

$\text{H}_2\text{S}$  is soluble in water so that dilution can reduce the smell but it can also present a discharge hazard to an aquatic environment. Consideration of an  $\text{H}_2\text{SO}_4$  neutralization

system will need to examine the stability of the final pH and whether additional H<sub>2</sub>S controlling agents are required to ensure control.

A significant safety issue, other than what would normally be associated with the management of concentrated acid, is the potential to induce corrosion or generate high viscosity due to localised low pH (high acid dosage) from incomplete mixing prior to high pressure pumping.

A sustainable sulphuric acid neutralization program would deliver the neutralization of the soluble alkalinity resulting in a final residue pH of approximately 10.5-11.0. Further neutralization would consume increasing quantities of acid and create conditions that would lead to H<sub>2</sub>S generation and odour related issues but with little change in the leachate pH until the bulk of the solid alkalinity had been reacted.

A significant aspect of residue neutralisation is the impact the neutralised run-off will have on the alumina production process. At present a significant fraction of the BRDA run-off is recycled to the plant for use as wash water. Once residue neutralisation is implemented this practice will result in addition of sulphate to the recirculating plant liquor. The alumina process can accept only a limited sulphate input and so this will increase the demand for Council water which is limited. This issue requires detailed evaluation.

## 5.7.2 Seawater Neutralization

Based on the experimental screening data obtained so far the following conclusions can be drawn. The Volume of estuary water approximately required:

- To achieve full neutralization of all alkaline products is up to 100 m<sup>3</sup> per tonne of dry residue
  - At 1.95 Mtpa alumina production rates this is equivalent to 125, million tonnes of Shannon River water annually (this equates to approximately 14,250 m<sup>3</sup>/hr of river water intake and discharge).

This value is based on neutralising the residue to a pH of 9.0 at the point of neutralization

Based on the impracticality of pumping this large volume of water, achieving clarification and safe discharge this option is not considered further.

## 5.7.3 Carbonation

Neutralization of bauxite residue using carbon dioxide has been investigated by Alcoa World Alumina and a patent has been obtained on its application. Limited data is available but the process consists of reacting Sodium bicarbonate (NaHCO<sub>3</sub>) with the residue slurry and then regenerating NaHCO<sub>3</sub> from the Na<sub>2</sub>CO<sub>3</sub> formed using CO<sub>2</sub> in "flue gas". This is significant as the only readily available CO<sub>2</sub> source would be from the AAL flue gases.

The efficiency of the carbonation process at Alcoa will be improved by the removal of the spent filteraid from the residue such that the resulting residue alkalinity will be broadly similar to that existing at Aughinish.

The benefits of using this technology, when compared to application of either acid or seawater neutralization include:

- No contamination of the residue with either potential process contaminants (chloride or sulphate) or potentially H<sub>2</sub>S generating materials (sulphate).
- Additional benefit of capturing carbon dioxide emissions that would otherwise escape (equivalent to approximately 15,000 tonnes or 1.5-2% of the plant's emitted CO<sub>2</sub>);
- Minimal generation of secondary products (hydrotalcite) that increase the residue volume and hence area requirements.
- The possibility to produce relatively concentrated NaHCO<sub>3</sub> solutions compared with seawater where Mg<sup>2+</sup> is present at only about 1.4 g/L (0.47 g/l in the River Shannon) and 0.12 Molar in "acid" i.e. more than double the Mg<sup>2+</sup> molarity. A concentrated solution reduces capital cost and increases the reaction rate.
- The reaction can produce a higher temperature accelerating the slow reactions. When seawater is used the large volume makes the use of higher temperatures costly
- A higher delta pH than with seawater.

Due to the patent application detailed data is not available at present. However, there is evidence that most of the soluble alkalinity and some of the solid alkalinity is neutralized. It is unlikely that all of the alkalinity is neutralized given the slow reaction rates and in view of the publicly stated target for carbonation neutralization to achieve a deposited residue with a pH of less than 10.5.

Although there has been no experimental investigation applying this technology to AAL, the potential advantages and Alcoa's willingness to share this technology mean that further investigation is warranted. In addition, if this technology is successful as well as providing a partially neutralized bauxite residue there will be a measurable reduction in carbon dioxide (greenhouse gas) emission. It must be realised however that the residue represents a sink most likely for only 1.5-2% of the AAL's CO<sub>2</sub> emissions. Its implementation will be capital intensive as it will likely require a CO<sub>2</sub> capture from flue gas followed by cooling and compression. The feasibility of mixing CO<sub>2</sub> efficiently in a thick paste is also questionable and will probably require a dilution of the residue post filtration followed by a re-thickening of the full residue stream. Overall its economic feasibility on an industrial scale requires close examination.

## 6.0 Alternative Use Management Philosophies

While bauxite residue is considered a waste or by-product this is a simplistic view of the issue. Bauxite residue is comprised of a range of potentially useful compounds not only for their intrinsic value but also for the beneficial application of the residue as a whole.

Within the alumina industry there are five main areas of promising alternative use application: These are:

- Metal Recovery – Smelting or refining of metal compounds such as iron oxide for pig iron production, titanium dioxide for pigment usage, and trace metal extraction;
- Soil Amendment – Application of neutralized, partially neutralized or un-neutralized residue to soils for the purpose of nutrient capture, improved water holding capacity, pH adjustment on acid sulphate soils;
- Building Materials – Use of residue in the production of cement, bricks, tiles, clean-fill, plastics, pigments and capping materials. Also the harvesting and re-use of settled residue as a construction material in increasing the capacity of existing residue disposal facilities;
- Effluent Treatment – Application of residue in domestic sewage treatment systems, infiltration basins to manage dairy or piggery wastes, infiltration basins to collect storm, road and urban run-off;
- Carbon Sequestration – Application of residue in the capture of CO<sub>2</sub> from discrete industrial sources or from the capture of CO<sub>2</sub> from flue gases at alumina refineries.

The research available in the literature is extensive and beyond the scope of this report.

Over seventy million tonnes of bauxite residue is produced globally every year. Identifying a suitably commercial application that can encompass this volume is unlikely to be achieved through the development of a single product stream.

It is more likely that a range of niche applications of bauxite residue will be developed that depend on the various regional aspects, competitive advantages or specific bauxite residue properties and applications. In addition, bauxite residue has sequentially available properties. In keeping with a sustainable approach to residue management, it is more likely that multiple alternative use applications will be made.

Examples of this approach could include:

- Carbonation of fine bauxite residue to capture carbon dioxide – Reuse the bauxite residue as a soil amendment material in high phosphorus sources such as dairies or feedlots – When the residue has exhausted its nutrient storage capacity recover and use the nutrient enriched material as a fertiliser supplement for agriculture.
- Harvesting of alkaline bauxite residue for use in treating or creating a buffering filter for the treatment of acid mine drainage – When the residue is neutralized, wash and utilise in the cement or construction industry

There is extensive research with demonstrated benefits and applications. Public funding or industry subsidy supports a large range of bauxite residue applications, however, there are only a small number of commercially successful applications of the approach. Appendix D has a list of commercially successful companies in this field.

## **6. 1 Red Mud Applications**

While the potential remains for bauxite residue to eventually become a resource, the most significant reason it has not already is that bauxite residue is a high volume/low value material. All alternative use applications must carry the high cost of transport and incorporate this into a profitable business model. Therefore, applications that are regionally significant and have demonstrated value within approximately 30 kilometres of a bauxite residue area are more likely to negate the impact of transportation costs and prove successful.

With a regional basis to assess the alternative use opportunities it is worth first examining the high volume applications. These are:

- Soil Amendment;
- Effluent Treatment
- Feedlot Nutrient Filters
- Municipal Effluent Filters

It is highly likely that the nutrient retentive properties found in bauxite residue around the world will occur in AAL residue. While direct application of residue could be possible in controlled circumstances it is likely that further neutralization for re-use purposes is more realistic.

While there remains an acid neutralization and discharge system in operation at the BRDA there is an opportunity to batch treat bauxite residue for alternative use applications. If this approach is successful it could also prove to be a model of a future post-closure application of bauxite residue as a resource.

## **6. 2 Neutralized Process Sand Applications**

Process Sand is coarse-fraction sand (+ 100 micron) and represents approximately 10% of the total bauxite residue stream at AAL. The sand fraction removed via a sand trap before entering the mud circuit in the refinery, washed and trucked to the BRDA.

At an alumina production rate of 1.95 Mtpa approximately 117,000 tonnes of sand will be produced annually. Over the remaining life of the operation (assuming a planned closure date of 2026) this represents a potential resource of 2,300,000 tonnes.

The sand is designated as “non-hazardous” in the EU Waste Catalogue.

At the BRDA the sand is utilized currently as a construction material to separate the bauxite residue activities from the dedicated salt cake disposal area.

### 6.2.1 Alternative Uses of Sand Elsewhere

Before an alternative use program can commence the need for the process sand at the BRDA must be assessed as otherwise the re-use of the sand externally to the BRDA will only force replacement with an externally derived product negating any sustainability benefits. Given that the sand is being used to separate disposal areas, a use that is not dependent to any specific quality of the process sand, it is reasonable to assume that dried mud can be used instead. Rehandling of dewatered bauxite residue for this type of duty can be achieved with low-ground pressure earthmoving equipment and the practice is common in other alumina operations and is not considered a significant issue.

However, the process sand at AAL is currently being consumed also for internal construction purposes at the BRDA. If the process sand were to be diverted elsewhere there remains the requirement for an alternate sand source to be imported for these purposes. This would not be a desirable outcome economically and the net benefit would be marginal or negative.

Other than use as an “internal” construction material at a BRDA, process sand has been used as a:

- Construction material for filling voids and road base;
- Concrete filling material (including a fly ash blend); and
- A high permeability effluent treatment media.

As a potential construction material, Cooling and Jamieson (2004) identified that the most significant limiting factor in achieving sustainable re-use of sand was the potential for leaching of alkaline materials from the sand into the environment. To accommodate this, additional washing, improved size separation and further neutralization (carbonation) of process sand was required to manage the calcium compounds that may be present. Once this was achieved the sand was able to satisfy the requirements of a suitable grade or sub-grade material with a high California Bearing Ratio (CBR) between 12 – 18%. Further research is proposed to fully assess EPA requirements to permit the process sand to be classified as an inert landfill.

As concrete filler, Sri wahyunil et al. (2006) identified that Alcoa process sand:

- Can replace natural sand as fine aggregate in concrete with little impact upon strength;
- Creates a concrete that meets leachate requirements;
- Negatively impacts concrete rheology and hence cold water and chloride diffusion due to the angular nature of the sand. This could be improved through sand modification or additives.

Due to the residual iron-oxides present, process is likely to have excellent nutrient retention properties. Ecomax Waste Management Systems Pty Ltd (Ecomax) currently utilise process sand from Alcoa Kwinana and blend in a small amount of dry gypsum to achieve partial neutralization (Appendix D). The high permeability of the sand combined with the high nutrient retention properties provide the desirable “amended” material necessary for the Ecomax effluent installations to be commercially successful.

Further research by AAL to identify a suitable alternative use is recommended.

## 6.2.2 Need for Sand Neutralization

Bauxite residue data from Aughinish shows that Sand has around 72%  $\text{Fe}_2\text{O}_3$  compared with 43% for Residue. This would suggest that the process sand may contain little Hydrogarnet or Sodalite and therefore it may only need additional washing such that it could be utilised for purposes outside of the BRDA. However, if neutralization was needed it would also suggest that minimal neutralising effort would be required.

Further experimentation is recommended to fully assess the neutralization requirements of process sand as defined in Appendix E. Based on the likely small quantities of acid materials required a neutralising stage using sulphuric acid and then exposure to rainfall to leach any residual contaminants would appear viable

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## 7.0 Conclusions

The EPA outlined three areas where additional technical and economic information was required to enable them examine the Integrated Pollution Control (IPC) Licence Review Application #35-04 fully. These areas were;

- 1 *Undertake a detailed investigation of the sustainability of the current disposal practices for production waste at the plant with particular emphasis on the ultimate, long-term, environmental burden of the land area covered by the red mud stack. In a follow-up clarification the EPA emphasized the need to demonstrate that AAL's proposed landfill technology is sustainable and is the most appropriate for the specific location in view of the proximity to very sensitive receptors with reference to:*
  - *minimum environmental foot-print*
  - *post closure after-care requirements*
  - *post closure potential uses of the land*
  - *on-going land procurement for new storage*
2. *Undertake a detailed feasibility assessment (technical and economic) of the alternatives to the current practice of land disposal of red mud with particular reference to options used in similar plants elsewhere in the world.*
3. *Assess the feasibility of neutralising the red mud and using the neutralized sand as a raw material in construction or other beneficial end-use.*

This review examined the AAL proposal for an extended BRDA under 14 different 'Sustainability Indicators' ranging from site selection through design and operation aspects to final Closure and After-use. It then examined practices for residue disposal employed by the leading Alumina Producers globally. It also examined the key issues regarding residue neutralization and the means by which it could best be implemented at AAL. Finally it examined the state of residue re-use globally and the outlook for greater re-use.

Summarised below are the conclusions reached from this review.

### 7.1 Sustainability Conclusions

1. While the site selection, BRDA design, operational phase and post closure plan are robust, a critical assessment of the sources of alkalinity in bauxite residue identifies the significant degree of residual alkalinity that leaching must overcome in order to produce a leachate that will not require further neutralization. Currently, it is assumed that the leaching of the Phase 2 BRDA will produce a run-off of less than pH 9.0 and enable direct discharge within 5 years of its closure. Based on a review of the chemistry and previous investigations due to the low permeability of the residue it is estimated that up to 30 pore volumes of rain-water washing could be required to achieve complete removal of residual alkalinity. This process could take many years to reduce the pH below 9.0 if no dilution of the leachate occurred and requires confirmation. Of course dilution of the small volumes of expressed leachate by

rainfall run-off will obviously provide benefit but as this is variable and not contained it may have a limited benefit at times. While the absolute time period for the combined leachate/rainwater run-off to reduce below pH 9.0 is subject to conjecture the issue is that it may be longer than 5 years. This suggests that on-going neutralization of leachate may be required for longer than 5 years. AAL has recently completed the construction of two Closure Demonstration Cells to model closure and remediation and pH attenuation of the leachate/run-off. One of the cells has been filled with mud already and the 2<sup>nd</sup> cell will be filled with partially neutralized mud. These cells will provide detailed information on this aspect.

2. The current BRDA has been in place 24 years and the design and operational practices have to-date been demonstrated to be environmentally acceptable. Given the resources currently available and likely to be available during the remaining operational phase of the BRDA this level of performance is likely to be maintained. AAL has previously provided commitments as to the resources necessary to enable managed closure and after-care. The question raised in Point 1 is one of the time required for a leachate treatment system to be maintained. By ensuring that suitable monitoring and water management controls are in place this after-care “burden” can be managed until natural leaching removes the residual alkalinity. This after-care requirement appears to be the key potential future burden for the proposal. It is addressed in detail in the neutralization section.
3. The other long-term issue is the rate of erosion and ensuring that the rate of erosion does not exceed the rate of chemical leaching or rate of growth horizon development. Due to the time-scales involved it is unlikely that these issues can be modelled or trended such that they have meaning in a human context. What is essential is that these aspects remain managed on a day-to-day basis to ensure that issues that arise are effectively addressed in a timely manner and not allowed to grow and create secondary effects that threaten the viability of the system. These aspects will need to be explored in the development of the Closure Demonstration Cells.
4. Importantly, if these after-care aspects remain managed there is limited impact on many alternative land-uses on the BRDA surface. Currently the construction, operation and closure of BRDA’s trigger a change in land-use from original status as agricultural land to post closure status as nature conservation/amenity as described in the AAL proposal. In isolation, this change could be regarded as an un-acceptable outcome if it denies an existing valued land-use and introduces another potentially lower value land-use. While the value of a particular land-use can be a somewhat subjective assessment, the adoption of an amenity land-use designation (as proposed by AAL here) does not specifically exclude the future development of higher value agricultural land-uses. The limiting factor remains the rate of development of a stable and viable growing horizon on the amended residue. This growing horizon is unlikely to support any tree plantation concepts and direct application of grazing animals is not recommended due to the potential for poaching or overgrazing of the surface that could initiate localized dusting. However, the re-use of these areas as a source of fodder cropping or small-scale grass-based carbon capture can be considered. These options should satisfy most of the land use concerns.
5. While it is beyond the scope of this report to address the long-term feasibility of commercial use of a closed and remediated BRDA, it is possible to

anticipate a sustainable commercial entity given the managed land-form and valuable infrastructure that will remain post closure. In this regard, the after-use 'burden' on the land may pose some limitations but these are compensated by the beneficial legacy of a lined and contained land-bank. The potential for a sustainable commercial agricultural facility post closure should be developed through detailed experimentation in the Closure Demonstration Cells and economic benefit analysis.

6. The other potentially significant burden represented by this general proposal is the requirement to remove 80 hectares of land from a low intensity agriculture use to a landfill use. This land will be sterilized for approximately 20 years before being released back to the designated future land use. In the context of the overall utilisation and demand for land in County Limerick for agriculture, this temporary loss of land should not represent a significant burden.
7. Without the BRDA the refinery cannot operate. Therefore, investment in the BRDA with sound design and operational controls provides the opportunity for the sustained operation of the alumina refinery. This BRDA investment comprises 180 hectares of a lined and vegetated land-bank with a lined perimeter channel for water collection and a water treatment plant to render the run-off suitable for discharge. AAL (2003) has provided an assessment of the impact of the alumina refinery on the national and local economy. This impact results in the sustaining of 720 jobs (both permanent and contract) within the local economy and 800 jobs in the regional economy. Post closure of the refinery this investment will provide a sustaining internationally important port and a modern gas fired power generation facility. From a sustainability perspective a managed environmental burden using best practice technology that enables on-going economic development and provides a range of land-uses for affected areas with minimal environmental impact represents a satisfactory and sustainable outcome.
8. Thus, based on review of the AAL proposal, industry standard approaches internationally and AAL acknowledgement of aspects that need to be addressed at a detailed design phase, the proposal presented by AAL for land filling of bauxite residue is in many respects an example of best-practice technology within the alumina industry. A potentially feasible enhancement of residue neutralisation is addressed below.

## **7.2 Alternatives to Land Disposal Conclusions**

9. Bauxite management practices used in the alumina industry were reviewed. The technology used at each alumina refinery is a combination of the site-specific limitations and process related issues at the plant. As such there is no single best practice approach but rather the application of best practices for the site. All operations manage issues similar to that faced by AAL to a greater or lesser degree.
10. Due to the distance from the mine, AAL seeks to minimize bauxite-shipping costs by utilizing the highest quality bauxite ore available and this minimizes the quantity of residue generated per tonne of alumina produced. The residue factor at AAL is ~0.7 tonne /tonne (t/t) alumina and is a global leader when compared to residue factors internationally that range from 0.7 to 2.5 t/t.

11. Dry disposal of partially neutralized bauxite residue adjacent to a saline environment represents the state of the art with respect to site location and choice of technology in the Alumina industry. Such a location can use natural attenuation processes to minimise the potential impact of alkalinity should it escape from a tailings facility.
12. The approach and commitments given by AAL in the proposal for Phase 2 Expansion of the BRDA represent elements of best practice technology and offer the minimal footprint and hazard for the location. With due consideration of the potential to neutralize the residue it is likely that AAL would be considered a world leader in the best practice management of bauxite residue. The EU BREF Document on tailings management references AAL design and practices extensively.
13. The option of disposing of residue via return to the bauxite mine is not feasible on the grounds of:
  - a. Cost – the handling and shipping costs of high-volume zero value waste thousands of miles back to Africa or South America would render the alumina refinery uneconomic.
  - b. Environment – the mines from which the bauxite ore originated are not engineered structures suitable of storing caustic contaminated waste. Furthermore, the transfrontier shipping of large quantities of such waste would breach the EU proximity principle with regard to waste disposal.

We can find no example in the alumina industry where a refinery ships residue back to the mine site. Even in cases where the mine is located close to the refinery the residue is invariably disposed via land filling at an engineered site close to the refinery.

14. Sea disposal of bauxite residue is neither environmentally nor economically feasible for AAL. It would require transport of waste via ship because the likely transport distance of 300 kms to a potentially suitable deep-sea cavern would make pumping non-viable. The cost of installing a ship loading system and a Port extension to handle the huge traffic increase would likely exceed one hundred million euros and would meet with potentially insurmountable regulatory hurdles given the SAC status of the Estuary and the nature of the waste. The on-going costs of operating such a system if implemented would totally undermine the economic viability of the plant.
15. Three Alumina refineries out of about 70 globally are utilizing this method of marine disposal at present – Alumina de Grece, Alcan Gardanne France and Showa Denko Japan. All three of these facilities are planning to cease this practice due to phase out of their permits by their respective regulatory authorities.

## **7. 3 Residue Neutralization Conclusions**

16. The alkalinity of bauxite residue broadly occurs in three different forms:
  - Soluble sodium hydroxide/carbonate alkalinity associated with the entrained liquid in the residue slurry;

- Solid lime-based alkalinity that has formed through the addition of lime to the Bayer Process; and
  - Solid sodium hydroxide alkalinity formed by the reaction of sodium hydroxide and silica compounds within the bauxite ore.
17. Neutralization of these different alkalinity sources using acidic materials occurs at different reaction rates and is independent of the type of acidic materials used. The reaction rate varies from almost instantaneous in the case of soluble alkalinity to days for the solid alkalinity reactions. This has implications as to the effectiveness of neutralization processes at an industrial scale where the size and scale of equipment may limit neutralization periods to an hourly timescale.
18. The practice of de-liquoring the residue solids (dry stacking), the preferred residue management approach to minimise the residue foot-print, further inhibits some of the slower reactions. On this basis, realistically, only the soluble alkalinity can be neutralized (typically 20% of the total alkalinity present) and an initial residue discharge pH of 9.0-10.0 can be achieved exiting the neutralization reactor. Over time the pH of the entrained liquid is expected to rise in pH and stabilise around pH 10.5 – 11.0. Thus, runoff from such a 'partially' neutralized residue disposal area will require further neutralization prior to discharge.
19. Due to some AAL specific process issues, the quantity of slowly reacting solid phase alkalinity that is contained within the residue is lower than at similar alumina operations. This suggests that neutralization of AAL residue would require less acid and so incur less expense compared to other facilities. As the solid alkalinity cannot be neutralized prior to disposal, it follows that the natural leaching of AAL residue towards neutral pH will happen faster than in other alumina operations.
20. A range of potential neutralizing agents was considered in the AAL context. Acidic materials considered include:
- River Shannon Water (Seawater)
  - Carbon Dioxide (Sourced from Power Station stack gases); and
  - Mineral Acids (Hydrochloric/Sulphuric)
21. Neutralization of residue using River Shannon water (source of Magnesium) was identified as being impractical due to the high volumes of water that were required to drive the reaction. This is due to the reduced concentrations of Magnesium of the Shannon estuary and to the fact that salt-water itself is only a weak acid. The study estimated that an intake, reaction system, clarification system and outfall would have to be sized for flows of 14,000 m<sup>3</sup>/hr that is not feasible from economic and environmental perspectives.
22. Neutralization using carbon dioxide offers an effective neutralising agent where soluble alkalinity can be readily neutralized. [The slow reaction rates and unrealistic residence times required render neutralization of the solid phase alkalinity non-feasible]. While carbonation also offers a means of reducing greenhouse gas emissions from plant operations by a few percent its implementation cost is likely to be very high due to the complexity of the gas handling process involved. As this approach is protected under patent at present further research is required to quantify the effectiveness and applicability.



23. Partial neutralization of residue employing sulphuric acid appears the most feasible approach to minimizing the alkalinity of AAL residue prior to disposal. Such a 'partial' neutralization with sulphuric acid would cost approximately €2 million per annum on acid costs alone before considering the other associated Capital and increased Operating costs related to acid handling and pH control.
24. The principal concern related to neutralization employing sulphuric acid is the potential for generating conditions that permit sulphate reduction to odorous H<sub>2</sub>S gas. Such an outcome would be unacceptable to local residents and to staff working in the BRDA and must be avoided. However, ensuring that the final pH of the residue remains above pH10.5 will suppress the formation of hydrogen sulphide. In this way the un-neutralized solid alkalinity can provide a buffer to prevent this occurring.
25. The engineering difficulty of developing a robust system to add acid safely and in a controlled manner to a thick abrasive residue paste to deliver a target pH while avoiding transient localized low pH pockets within the reactor and pumping system should not be under-estimated and requires extensive piloting before full scale implementation.
26. Apart from the neutralisation operation, the recycling of sulphate containing run-off back to the alumina plant is the main process impact.
27. Assuming that a partially neutralized, residue can be produced there needs to be consideration of where this residue can be placed.
  - a. There is only limited long-term benefit to placing neutralized residue on top of the existing alkaline residue deposit within the Phase 1 BRDA. This is due to the existing inventory of alkalinity already present.
  - b. There is clear merit in placing neutralized residue into the future Phase 2 BRDA as the potential for cross contamination will be reduced and the benefits of neutralization maintained. With a reduced alkalinity it is likely that there will be a reduced time required to achieve full leaching of the partially neutralized residue.
28. Even if the entire neutralized residue is placed in the Phase 2 BRDA then the time required to achieve full leaching of the Phase 1 BRDA will remain unchanged. Therefore, it is unlikely that the issues surrounding the extended time required to achieve a leachate pH such that direct discharge will change.
29. Even with a (partially) neutralized residue it is likely that the final pH of the re-vegetation growth horizon will not be able to sustain vegetation. Therefore it is probable that the proposed re-vegetation strategy of introducing amendments and organic material to modify the pH will still be required and will need to be maintained until the re-vegetation is deemed sustainable.

## **7. 4 Residue Re-use Conclusions**

30. Finding beneficial uses of bauxite residue has been an Alumina industry objective for many years. While a number of low-volume niche applications have been found there has not yet been a significant breakthrough to offer an outlet for a meaningful percentage of the 70 million tonnes of residue produced annually.

31. From an industry perspective the areas of construction substitute materials and soil amendments offer the greatest potential for a meaningful scale re-use of this high-volume, low-value material. The industry has been collaborating for more than 5 years to fund research into this area and AAL is an active participant in this collaboration.
32. The final re-use opportunities need to be developed from a market needs basis and in partnership with the EPA as the ultimate leaching, transportation and liability issues will need to be identified before such a program can commence.
33. Specifically for AAL, there is evidence to support the potential re-use of process sand either as a road base material, concrete filler or effluent treatment material. These uses are currently commercially successful or undergoing significant research and development in other parts of the world. Alcoa World Alumina is proactive in the research as approximately 50% of the bauxite residue generated by alumina refineries in Western Australia is a sand fraction (approximately 8,000,000 tonnes per annum).
34. However, the side stream of process sand at AAL (10,000 tonnes per annum) is currently being consumed for internal construction purposes at the BRDA. If the process sand were to be diverted elsewhere there remains the requirement for an alternate sand source to be imported for these purposes. This would not be a desirable outcome economically and the net benefit would be marginal or negative.

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## 8.0 Recommendations

To ensure alignment with the principles of sustainable tailings management it is recommended that AAL address some outstanding issues.

### Residue Neutralization

- While the empirical values for a neutralization process appear valid, analysis of data from the initial experimentation would suggest that further investigation is warranted. In summary the recommendations for further research include:
  - Evaluate “over-acidification”, followed by a pH increase under conditions that are similar to those that could occur in practice. This would examine the fate of silica compounds as well as the mobility of heavy metals. The experimentation should include an exotherm due to dilution of the  $H_2SO_4$  to ensure that high temperatures will not occur. The viscosity aspects of over-acidification also require examination.
  - Evaluate the chemical/physical changes occurring during the residence time in the pipeline from the residue reactors to discharge and the implications for control.
  - Determine the operating conditions required to avoid generation of sulphurous odours.
  - Conduct an engineering assessment of the requirements for a robust acid neutralization system and pilot it.
  - Examine the impact of returning sulphate to the alumina process via the BRDA run-off.
- Engage with Alcoa World Alumina to allow access to their patented residue carbonation process. This will need to allow laboratory scale experimentation and potentially pilot plant scale investigations.

### Closure Planning

- Address some gaps in the understanding of the surface water quality in the closure plan. Improve the long-term predictions of water quality, by a better understanding of residue leachate chemistry and by conducting a more comprehensive assessment of the residue permeability and leaching characteristics. This is not an urgent action; however, it will take a considerable period to determine with precision. It is recommended that:
  - Clear confirmation of the likely starting pH of the residue for all leaching testing. In the documentation reviewed and recent experiments there is over 1 unit difference in pH. While this may appear to be a minor issue it impacts on the predicted alkalinity leaching rate and potential effluent water quality.
  - Make a more thorough assessment of the rainfall variability and impact on surface water quality with emphasis on the likely leachate quality variation and impacts on the proposed management approach.
  - The effluent water quality variability is also likely to be influenced by the run-off water quality of the vegetated surface and the rate at which organic

material or gypsum will need to be added to ensure maintenance of a growth horizon in the residue. A detailed review of the changes in surface water quality in response to the management practices required to sustain the re-vegetation is required.

- A long-term or accelerated freshwater leaching of residue column study is required to confirm the leachate chemistry and provide data to support the theoretical position. This program should include a thorough investigation of the alkalinity leaching chemistry. If possible, the opportunity to conduct a core drill should be considered to examine some of the initial residue placed by the plant before 1985 as this would have had an opportunity to leach for over twenty years.
- An appropriate statistically robust permeability monitoring program followed by a probabilistic approach to the estimation of vertical and horizontal permeability is required to provide confidence limits around the anticipated surface water dilution flows. This information will ensure the modelling precision exists to develop reasonable confidence in predicting when the effluent water quality objective will be met.
- Given the uncertainty in the effluent water quality, specific research is required as part of AAL's ongoing BRDA Closure Plan to address the potential for pH control beyond the budgeted 5 years of operation of the run-off neutralization plant. Pending confirmation of the leachate chemistry over time via the Closure Demonstration Cells it would be prudent to consider development of a wetlands or similar facility to trim the final pH of the run-off prior to final discharge.
- As all land-forms are susceptible to erosion, the potential erosion risk of the post-closure BRDA should be assessed and modelled under a range of potential scenarios.

## Closure - Revegetation

- It is likely that the sustainability of the proposed re-vegetation on a stable, naturally draining residue deposit will be dependent on several key issues. Further experimentation is required to examine the sustainability of the revegetation by:
  - Ensuring that there are sufficient nutrients for the re-vegetation and that the cycling of nutrients develops to a self-sustaining level enabling input of new nutrient sources to be minimized. A review of the cycling demands of these nutrients, amendments and the relationship with the surface water quality is required.
  - Ensuring that there is a suitable post-closure monitoring and control within the overall Closure Plan to address nutrient needs, erosion control, prevention of burrowing animals and controlled human access.
  - Ensuring that capillary rise is not a significant influencing issue in a high rainfall/low evaporation environment. This review should also consider the potential impact of future placement of a neutralized residue layer on a non-neutralized residue layer from a capillary rise perspective.

## Post closure

- The current design does provide some flexibility in the post-closure land-use. It should be emphasised that the proposal of a land-use supporting 'Amenity' is a minimum objective. The potential exists for limited carbon-capture or fodder cropping given sufficient time and organic resources to construct a suitable growing zone on the residue surface. Further investigation into both the carbon capture (Carbon dioxide capture in grasses) and fodder cropping (harvesting of vegetation to supplement off site livestock feed) is recommended.

## Alternative uses of residue

- AAL needs to remain engaged in the industry evaluation and development of alternative use applications of bauxite residue (this progress should also be shared with the community). This should continue to be funded via AMIRA and other alumina focused research groupings. However, it is recommended that AAL consider:
  - Funding of regionally focused research for direct, local applications of bauxite residue alternative uses. This would preferably utilise local research institutions and local businesses. If executed correctly this approach can be used as part of the community engagement program and generate value where currently only a liability is evident.
  - A market research review of the competing products to potential bauxite residue applications and identify potential commercially viable projects or products. A market driven approach allows the identification of opportunities that research efforts can be directed at rather than researching an application that cannot be applied. The essence is to let the market demand for bauxite residue drive the approach.
  - Engaging with EPA to confirm a regulatory pathway for the development of alternative use applications.
  - Utilising product development techniques, develop the "Path to Market" and base the economics of the venture on a "profitless" business concept where the "negative" current value of bauxite residue drives a cost recovery approach thereby maximising profit opportunities for downstream businesses and minimising liability for AAL.
  - Assessing the potential for application of residue in an un-neutralized form to high volume low value applications. If this is not feasible then application with neutralized residue may be the only means. As bauxite residue is a resource of limited but sustaining value consideration should be given as to how the BRDA could be accessed for recovery of bauxite residue for alternative uses. Re-mining for re-use applications could be considered as a viable means of gradually eliminating the BRDA as a structure if a commercially sustainable re-use of the residue is developed.
  - Consider the merits of operating a batch bauxite residue neutralization operation at the BRDA to allow harvesting, treatment and controlled re-use of the current un-neutralized bauxite residue deposit. Should process sand cease to be employed beneficially in the BRDA...adopt the process sand investigation approach of Cooling & Jameson (2004) to define the characteristics needed to develop a sustainable end-use for process sand. These include:

- Full characterisation of process sand – physical, chemical properties;
- Assess the need for neutralization of sand – Confirm the presence of bound soda or whether further washing will be sufficient;
- Conduct parallel tests on sub-grade or filter material – by engaging local civil engineering group/university etc.
- Confirm the total composition/leachate testing of process sand such that leachate quality is fully understood and accepted by EPA; and
- Discuss with EPA what aspects they would need to see in process sand such that they could classify it as an inert material.

## Communications

- Engage the community on the total risk that the BRDA represents in an open and closed condition. The “Probability of Failure” report is of high quality and the results should be communicated clearly and in context to the local community. This is not an urgent action and can proceed when such discussion has merit. Ensuring this occurs will add to the “acceptance” condition for the closure plans.
- AAL, in discussion with the EPA need to fully consider the structure of post-closure management and the expectations of both sides. This should include a full discussion of liability, management of issues after the post-closure requirements have been met and ultimate ownership issues
- Open discussion on the proposed post-closure land-use to community review and comment. While the EPA review and acceptance is important community support will be required for it to be successful.

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## 10.0 Appendices

### 10.1 Appendix A - Residue Management at AAL

The designs and management practices currently in operation at AAL are summarized below.

#### 10.1.1 Residue Production

Bauxite residue is the industry accepted term for the residual material left after dissolution of bauxite in a hot caustic solution at elevated pressure. The dissolution process, termed the Bayer Process, although invented over 100 years ago is the accepted best practice process to refine alumina.

Bauxite residue is itself made up of different size fractions. The fine fraction termed red mud and a coarse fraction termed process sand.

At AAL, approximately 0.7 tonnes of residue is produced for every 1 tonne of alumina.

The bauxite residue is approximately 90% red mud and 10% process sand (+100 microns). The process sand fraction removed via a sand trap before mud circuit in the refinery, washed and trucked to the BRDA

The red mud undergoes 3 stages of counter current washing and thickening followed by one stage of vacuum (drum filtration) where is dewatered to a 65% solids filter cake and then diluted to 60% via the addition of process condensate. The red mud is then mixed and sheared in one of 4 agitated vessels and then pumped via positive displacement pumps to the BRDA.

The red mud contains a residual concentration of sodium ~10-15 gpl  $\text{Na}_2\text{O}$  in liquid phase, with approximate mineral make-up of 45%  $\text{Fe}_2\text{O}_3$ , 20%  $\text{Al}_2\text{O}_3$ , 10%  $\text{TiO}_2$ , 10%  $\text{SiO}_2$ , 7.5%  $\text{CaO}$ , 7.5%  $\text{Na}_2\text{O}$  (including bound sodium hydroxide as descilication product).

On expansion of the AAL refinery to 1.95 Mtpa of alumina total bauxite production will be:

- Red Mud – 1,248,000 tonnes per year
- Process Sand – 117,000 tonnes per year.

In addition to bauxite residue, the alumina refining process will generate other wastes including:

- Salt Cake (containing Sodium Oxalate) – 23,472 tonnes per year
- Lime Slaker Grits (insoluble clinker cores of burnt limestone – 7,464 tonnes per year.
- Other process wastes, sludges, scale etc – 12,552 tonnes per year
- Spent refractory – 372 tonnes per year
- Contaminated sewage and building rubble of varying amounts

The classification of these wastes as defined in the Waste Management Acts 1996 – 2003 is:

- Red Mud – Non-Hazardous
- Process Sand – Non-Hazardous
- Salt Cake - Hazardous
- Lime Slake Grits – Non-Hazardous
- Other process wastes – Non-Hazardous
- Spent refractory – Non-Hazardous
- Contaminated sewage and building rubble of varying amounts – Non-Hazardous

AAL commenced operations in 1983 and has generated as at December 2006 16,700,000 tonnes of residue materials. All materials have been deposited at the BRDA.

### 10.1.2 Design

On Aughinish Island the BRDA site is bounded by Robertstown River and the Poulaweala Creek. Phase 1 is located on Aughinish Island. Phase 2 will encompass parts of Island Mac Teige and Glenbane West. The BRDA has accepted all such process residues generated since the refinery was commissioned.

The BRDA is an engineered structure to accept high-density bauxite residue from the refinery and has been progressively designed and expanded to the best standards of the day. There are three distinct design phases in this structure:

- The Phase 1 BRDA is an unlined facility with in-situ foundations of glacial till and estuarine sediments providing a degree of attenuation both physically and chemically to alkaline leachate generated by the BRDA.
- The Phase 1 BRDA Extension is also provided with a composite lining of High Density Polyethylene (HDPE) and screened glacial till and some occasional Geosynthetic Clay Liner (GCL).
- The proposed Phase 2 BRDA (80ha) will adopt a composite lining of High Density Polyethylene (HDPE) and Geosynthetic Clay Liner (GCL) /Glacial Till depending on materials available.

Seepage limits set by the 1974 planning approval for Phase 1 BRDA, for ponded storage of the wet unfiltered red mud, established an acceptable limit for seepage of 371m<sup>3</sup>/day. The lining of the BRDA is designed to minimise seepage of alkaline leachate into local soils and groundwater. In addition, the adoption of high density filtration to manage residue has reduced the volume of water held in storage above these low permeability sealing subsoils and permitted expansion of the BRDA without exceeding the seepage planning approval.

AAL has adopted the 'Upstream Raising' method of providing incremental residue capacity increases to the BRDA. Upstream raising is a process where the wall lift is constructed 'upstream' or inboard of the centre-line of initial embankment on previously placed residue.

The upstream embankment side slopes are 3H:2V providing a 33° wall slope and approximately 2m high. The overall sequential upstream embankment slope of 6H:1V ensures that sufficient space is left between each lift to permit development of suitable foundation conditions. There is a sequence of 10 contiguous upstream stages, after

linkage and alignment with the Phase 1 BRDA, for a final elevation of 24m AMSL and a central discharge elevation of 32m AMSL. The higher central elevation allows for the angle of repose of 2.5% of the discharged residue.

The upstream lifts are constructed of rockfill placed over either a layer of process sand or a geotextile liner fabric. As part of the Phase2 works, a filtering system will be required upstream of the rockfill embankment walls to prevent the migration of particles of red mud as a result of water erosion

Surrounding the BRDA is a Perimeter Interceptor Drain to collect rainfall run-off from the site and direct it to the Storm Water Pond for neutralization and discharge. The drain is supported by embankments of varying slopes depending on foundation strength. The Perimeter Interceptor Drain and the Storm Water Pond are lined with a composite HDPE/Glacial till or GCL/Glacial Till. The water management facilities are designed to contain and manage rainfall up to a 1 in 200 year storm event.

The base of the perimeter interceptor channel is composite lined with a working top surface. The concrete working surface facilitates machine access to the base of the interceptor channel to clean out any accumulated sediment.

There is an upper level interceptor channel to collect surface runoff from the exposed red mud at higher elevations from Stage 6 to Stage 10, rather than allowing the water to cascade and erode its way down to the perimeter interceptor channel. It will also allow the outer slopes of the first 6 stage raises to be rehabilitated during the life of the facility. The drainage system in the upper channel has been designed to accommodate a 1 in 10,000 year flood will drain into the PIC via decant structures.

Salt cake is currently disposed of in the Phase 1 BRDA. The disposal location will be relocated the Phase 1 BRDA Extension area and the original area capped with process sand and red mud to minimize infiltration and seepage. The new salt cake disposal area will be approximately 1 ha in size and be located on an area with least 10m of red mud over a composite lining.

### 10.1.3 Solids Management

Red mud is pumped to the BRDA via a distribution pipeline and discharge network. The network provides for a number of discharge points that are cycled on a 12 hourly basis. The deposited layer is allowed to dry for a couple days before next layer is placed. After three or four layers of red mud are deposited then they receive several weeks of drying, depending on climatic conditions, before the process recommences.

Salt cake is trucked to the BRDA and placed in a dedicated disposal area. Process sand is trucked to the BRDA and is used to create perimeter embankment walls and isolate the site from red mud disposal activities.

Lime Grits are trucked to the BRDA and are used as landfill road surfacing materials around the salt cake disposal area.

### 10.1.4 Dust Management

AAL (2005a) recognise that fugitive dust generation at the BRDA can occur under the following conditions:

- Wind speeds in excess of 5 m/s;
- Freezing or very warm temperatures;

- Dry air-conditions i.e. low humidity

The primary objective is to prevent the formation of conditions where fugitive dust generation can occur.

AAL (2005a) also describe controls that are applied at the BRDA:

- Minimise mud flat area exposed to dusting risk.
- Keep mud flats in service as long as possible to limit areas of potential dusting.
- Switch points regularly to cover drying mud with wet mud.
- Maximise mud solids to the stack to get best stacking slope.
- Switching mud points regularly to aid stacking angle lift.
- Water spray sprinkler (Dust suppression system) installed to 100% coverage over red mud areas.
- Five bowser units are available to transport and discharge water from the Liquid Waste Pond (LWP).
- AAL Bowsers left at LWP outside of normal business hours and where significant potential for dusting exists. If taken to be used elsewhere on site, must be returned cleaned to LWP and filled with water.
- Open individual valves on sprinklers for approximately five minutes at a time and rotate as required.

The BRDA sprinkler comprises a network of 30 x 30 meter grid of sprinklers with 10 mm apertures. The sprinkler head can rotate through 360 degrees and deliver 160 liters / minute at a design pressure of 4 - bar. During weather periods of relatively risk free dusting conditions, all necessary maintenance work on the sprinkler system is undertaken.

## 10.1.5 Water Management

### Climate

The Shannon Region is characterised by the passage of low pressure cyclonic weather systems and frontal rain bands from the North Atlantic Ocean across Ireland. During winter these systems are quite frequent while during summer they are interspersed with the high pressure anticyclonic weather systems bringing drier air masses and warmer temperatures.

Rainfall and Evaporation data for the BRDA (Adopted Shannon Airport data, 14 kilometres east of the BRDA) are provided as an estimate of the site climate balance.

Month	Rainfall <sup>1</sup>	Evaporation <sup>2</sup>	Balance
January	97.2	7.5	89.7
February	72.1	23.8	48.3
March	71.8	47.5	24.3
April	55.5	76.3	-20.8
May	60.1	105.0	-44.9
June	62.4	116.3	-53.9
July	57.1	106.3	-19.2
August	82.3	87.5	-5.2
September	81.8	60.0	21.8
October	92.4	30.0	62.4
November	94.7	10.0	84.7
December	99.6	3.8	95.8
<b>Total</b>	<b>926.8</b>	<b>673.8</b>	<b>253.0</b>

Sources: 1. Met Éireann ([www.met.ie](http://www.met.ie)) The Irish Meteorological Service Online

2. AAL provided Evapotranspiration data  $ET_o$  derived by the Penman formula and this has been converted to an approximation of a Class 'A' Evaporation pan by dividing by 0.8 for the United Kingdom (as per Doorenbos & Pruitt, 1977). The purpose of this exercise is to highlight the structure of the climate balance not the exact values.

With the site demonstrating a positive climate balance there is a requirement for a net consumption of water from a BRDA, a managed discharge from the site or a combination of both to prevent overflow.

### Refinery / BRDA Water Balance

Nearly all of the water input at the BRDA is due to precipitation. The deposition of red mud contributes a minimal additional amount.



There is no significant water contribution from either process sand or salt cake disposal.

## Neutralization & Discharge

Excess water, with some residual caustic contamination, at the BRDA is managed using a process of neutralization, clarification and cooling prior to discharge into the Shannon Estuary. Excess water is collected in a perimeter interceptor channel that surrounds the BRDA and is directed to a surge pond called the storm water pond.

Water from the storm water pond is directed to a treatment facility consisting of a sequence of ponds and tanks namely the South Pond, the Waste Effluent Disposal Tank (WEDT), the Buffer Tanks, the two Effluent Clarifiers, the Spent Acid Tank, the Fresh Acid Tank, the 'Clean Condensate Make-up Tank (CCMT) and the Pond Water Tank (PWT).

Sulphuric acid is added to the excess water neutralizing and precipitating fine (gelatinous) aluminium hydroxide materials. The particles are removed by flocculent aided sedimentation in a clarifier. Clarified effluent overflows the clarifier via a pipeline to the Liquid Waste Pond (LWP). From the LWP, effluent is discharged under licensed conditions into the River Shannon in accordance with the IPC License.

Discharge to the Shannon is licensed up to a rate of 900 m<sup>3</sup>/hr.

## Storm Water Management

Virtually all water reporting to the BRDA is derived from direct precipitation.

The catchment area for the upper interceptor channel is 130 ha for both Phases 1 and 2. The total storage volume for the upper interceptor channel is 100,000m<sup>3</sup>. The water management facilities are designed to contain and manage rainfall up to a 1 in 200 year storm event up to a total capacity of 375,000 m<sup>3</sup>. This volume includes normal operation water storage and flood storage held within the Perimeter Interceptor Channel and Storm Water Pond.

To contain the effects of wave action, a minimum freeboard is maintained at all times in the:

- Storm Water Pond - 1.0m
- Perimeter Interceptor Channel – 0.5m.

To accommodate “beyond design” scenarios a spillway will be constructed on the Storm Water Pond to discharge excess water to the Perimeter Interceptor Channel.

To accommodate future “beyond design” scenarios on the Perimeter Interceptor a spillway will be constructed to permit discharge into the area bounded by the downstream toe of the outer perimeter embankment wall and the flood tidal defence berm, which has a capacity of approximately 20,000m<sup>3</sup>. The effluent will be contained and temporarily stored prior to pumping back into the perimeter interceptor channel once the storm water level has been lowered.

## Groundwater Contamination

Approximately 70% of the Phase1 BRDA is unlined and relies on the low permeability of estuarine soils and compacted bauxite residue to minimize seepage. AAL (2005d) have identified that seepage is dependent on:

- Defects in the liner after installation;
- The permeability and thickness of the basal clay liner (glacial till/GCL)
- The hydraulic head acting across the composite liner
- The permeability of the red mud

Using mechanical cleaning methods to remove the accumulation of fine residue sediment in the storm water pond has led to some damage of the geomembrane in the past.

Seepage through the Phase 2 PIC will be minimized by installing a composite lining. This will consist of HDPE and glacial till on the channel side slopes and glacial till over a GCL on the base. All surface water leakage from the Phase 1 PIC is recovered by pumping.

The SWP will also be composite lined with a combination of HDPE lining, GCL and processed glacial till. A plan to recover SWP seepages has been submitted to the EPA for approval.

Leakage from the new Phase 2 BRDA will be minimized by a composite lined layer, which will be surrounded by a perimeter interceptor channel that is formed by constructing the outer and inner perimeter embankment walls.

Approximately a third of the Phase 2 BRDA footprint encroaches on the townland of Glenbane West. Of this area, Golder Associates specifically examined approximately 7ha to determine the likelihood that any potential seepage could migrate away from the BRDA and further inland on Glenbane West. The majority of seepage from the Phase 2 BRDA located on Glenbane West will migrate towards the Poulaweala Creek underneath the facility and will be buffered by the saline ground water. In this area, a double composite lining may be installed if required. This is a very conservative approach and during the detailed design phase, additional site work, topographical survey work and detailed contaminant modeling will be undertaken to determine whether the double composite lining system is required and its lateral extent, should it be required. The double composite lining system will consist of two composite linings of HDPE geomembrane underlain by GCL with a drainage blanket in between. Any leakage through the upper collected in the drainage blanket above the lower composite perimeter interceptor channel.

### 10.1.6 Revegetation & Closure

At closure of the Phase 2 BRDA, the surface of the proposed salt cake disposal area will be domed with process sand and capped with 2mm thick textured HDPE overlain by a 1000grm geotextile, 600mm of inert material such as glacial till or estuarine material stockpiled in the unsuitable stockpile and 200mm of topsoil.

Following completion of the upper level interceptor channel, the visual impact of the BRDA will be improved by covering the stack wall with granular material and top soil, which will eventually be re-vegetated.

AAL has conducted research into developing a vegetation cover based on the premise that direct revegetation of the red mud surface is possible using grass and clover cover if a suitable organic input is made at the commencement of the process. To

achieve this, amendment of the residue is required; the basic physical and chemical principles for reclaiming alkaline residues are established. The underlying principles of ameliorating the residue are;

- Creation of drainage if high water table exists,
- Replacement of entrained sodium with calcium to reduce pH and ESP (exchangeable sodium percentage)
- Addition of the necessary organic matter within the ploughing zone to improve soil structure, add nutrients and stimulate microbial activity;
- Aggregation of particles so as to improve structure and removal of excess salts by leaching.

AAL has developed the methods necessary to establish a revegetation cover on the BRDA. A range of suitable organic matter treatments were investigated. These included spent mushroom compost, thermally dried sewage sludge, dairy biosolid and agricultural manure.

The newly created soil (red mud mixed with process sand, gypsum and organic waste) is seeded with a grassland seed mixture and fertiliser applied by broadcast spreader. The species added are:

- Trifolium pratense Rotra – Rotra Red Clover
- Holcus lanatus – Yorkshire Fog
- Fescue longifolia Dawson – Creeping Fescue
- Lolium perenne Master – Perennial Ryegrass
- Agrostis stolonifera Carmen – Carmen Creeping Bent Grass

At closure the dust suppression system will be utilized to provide irrigation water until surface rehabilitation by a vegetated surface cover is established. AAL propose to achieve a 100% self sustaining vegetation cover after a period of 5 years. As it is likely to take up to five years to provide such a cover, an interim objective of at least 70% of surface area is targeted for after 3 years.

The preferred position for Aughinish is that the long-term sustainable land-use for the BRDA is restricted to those activities that do not increase the pollution potential of the rehabilitated facility (AAL, 2005e). As such the preferred land-use option is to develop the area for nature conservation. The definition of “nature conservation” applied from the EPA Landfill Manual is for restoration to incorporate woodlands, wildflower meadows, heathlands and wetlands.

## **10. 2 Appendix B – Industry Residue Disposal Systems**

There are many different designs applied to bauxite residue operations. These include:

- Marine Disposal;
- Wet or Low Density Disposal;
- Dry Stacking – High Compression Thickeners; and
- Dry Stacking – Filter Technology.

Within each disposal system there are variations in the residue chemistry that is applied. The major types are:

- Washed Alkaline Systems;
- Seawater Neutralization;
- Acid Neutralization;
- Carbonation
- Combined Flue Gas Desulphurisation/Seawater; and
- Combination Water Management Systems.

### **Marine Disposal**

In a marine disposal system, low density residue is pumped to or deposited from purpose built ocean dumping vessels to a near shore deep oceanic trench with steeply inclined walls with disposal at depth to minimise turbulence and prevent or minimise surface expression of the residue plume.

Effective neutralization of the residue is achieved by mixing with seawater; however, the dispersion of the residue into a fine plume meant that the resulting deposition area extended over a wide area. The International Maritime Organization (2002) estimates that the oceanic disposal of bauxite residue off the coast of Japan created an area of deposition at the seabed of approximately 50 to 100 km<sup>2</sup> and the average annual deposition thickness of the layer was calculated at less than 1 mm per year.

No new marine disposal systems have been proposed since the 1970's.

This technology is used by Gardanne, France (Alcan), Aluminium de Grece, Greece and Showa Denko Refinery, Japan (Showa Denko).

### **Wet Disposal (Low Density or Sub-Aqueous)**

In a wet disposal system, low density residue (nominally < 30% solids w/w) is pumped to a residue storage facility and deposited in a single, uncontrolled pour. Variations on this system may include placement in several cells to allow partial-consolidation between layers. Collection, recycling or discharge of supernatant liquors is generally used to control the liquor level in the pond. Generally, after placement the residue slowly consolidates to approximately 50% w/w.

As a large proportion of the residue volume is liquor this form of disposal is the most inefficient in terms of mass stored per unit area, water usage and loss and area required to support the operation.

Incremental increases in the capacity of the systems are usually achieved by downstream construction techniques and the residue has minimal bearing capacity. Downstream construction requires the embankment lift to be downstream of the centre-line of the original embankment. These types of construction are used where the bearing capacity of the residue adjacent the walls will not support an embankment lift or the additional capacity required can only be realised by increasing the footprint of the facility.

Until the 1980's this was the most common form of residue disposal practiced by the alumina industry but occupational health, safety and environmental concerns coupled with the high-cost and poor closure management forced innovation.

This technology is used by Queensland Alumina, Australia.

### **Dry Stacking - High Compression Thickeners (Sub-aerial)**

In a dry stacking system utilising high compression thickener technology, high density residue (nominally between 30–60% solids w/w) is produced using self-weight consolidation and the addition of advanced flocculating agents. The added benefit of this approach is an immediate return to the refinery of a water stream that would otherwise be lost to evaporation.

The residue is pumped to a residue disposal facility and placed in either individual layers or cells and allowed to dewater to very high density (65-70% solids w/w).

Due to the high residue density achieved there is usually a high intrinsic strength allowing the development of upstream construction techniques for increases in storage capacity. Upstream construction requires the embankment lift to be in-board or upstream of the centre-line of the original embankment. These types of construction are used where there are limitations on the footprint of the residue facility; the bearing capacity of the residue adjacent the walls are such that they can support the structure. In some cases the residue can be re-handled and used as the construction medium reducing costs and demands for suitable imported borrow materials.

Enhancements to this system are possible through mechanical dewatering (Mud Farming) using earthmoving equipment such as bulldozers and amphibious to achieve higher final densities increasing mass stored per unit area.

This technology is used by Kwinana, Pinjarra, Wagerup, (Alcoa), Worsley (BHPBilliton), Gove (Alcan), RTAY (Rio Tinto) Australia, Alumar (Alcoa/BHPBilliton), Suralco (Alcoa/BHPBilliton), Point Comfort, U.S.A (Alcoa), Vaudreuil, Canada (Alcan).

### **Dry Stacking – Filter Technology (Sub-Aerial)**

In a dry stacking system utilising filter technology residue is thickened using a high pressure or vacuum filtration process to high density (Nominally to above 60% solids w/w) via a filter media that deposits the residue as a semi-liquid cake into trucks or a re-pulping unit for pumping.

On disposal very little water is associated with the residue and minimal further dewatering up to 70% solids w/w can be achieved. As the residue is placed at a density approaching the theoretical maximum the amount of area required to achieve final drying is minimal allowing the smallest possible residue disposal area to be required. As such, it is useful technology in regions where there is an excess of rainfall over evaporation thus necessitating some form of water discharge.

This technology is used by Aughinish, Ireland (Rusal); Alunorte, Brazil (CVRD/Norsk Hydro) and Hindalco, India (Belgaum).

Within each of the disposal systems described there are variations in the residue chemistry depending on the need to achieve a form an acceptable chemistry for process, environmental or strategic reasons.

## Washed Alkaline Systems

In a washed alkaline system residue is washed in the counter-current washing tanks, high compression thickeners or filter stages to achieve the lowest commercially achievable caustic soda concentration in the residue. The residue is then pumped to the disposal area as described previously.

Residue in this form generates an alkaline leachate on contact with water that requires extensive leaching to remove due to the considerable bound caustic soda bound to the desilication product present in all bauxite residues. Residue with residual soda as < 5 grams per litre can have a pH in excess of 12.

Leachate from alkaline residue requires further neutralization prior to discharge. Residue in this state is considered hazardous in Australia but non-hazardous in Europe and North America.

This technology is used by Kwinana, Pinjarra, Wagerup, (Alcoa), Worsley (BHPBilliton), Gove (Alcan), Alumar (Alcoa/BHPBilliton), Suralco (Alcoa/BHPBilliton), Point Comfort, U.S.A (Alcoa), Vaudreuil, Canada (Alcan), Aughinish, Ireland (Rusal) and Alunorte, Brazil (CVRD/Norsk Hydro).

## Dust Management

Due to the need to dewater residue to higher densities, dust management can become a concern. Within the alumina industry, a variety of dust suppression techniques have been successfully applied by industry to control dust generation at bauxite residue disposal areas. These techniques can be used in parallel or individually as required. They include:

- Irrigation of the residue surface with fresh water to dampen the surface dust without impacting on the overall solar drying of the residue;
- Rapid rotation of fresh residue pouring to ensure that no dry residue surfaces are exposed;
- Placement of dust suppressing covers such as vegetative mulch, crushed rock, waste oil and hydro-mulching;
- Reduction of the residual caustic content of the residue, through improved washing, to suppress the surface carbonation and precipitation process;



- Limiting access roads and access to these roads at the BRDA. Use of commercially available dust-binders on access roads to reduce dust generation due to traffic;
- Planting grasses and vegetation in exposed areas;
- Neutralization of the residue using either seawater, acid or carbon dioxide to precipitate out impurities in the residue liquor while it is still within the residue solid thus avoiding the surface precipitation, build-up and desiccation of dusting compounds on the residue surface;
- Ploughing and turning over the residue surface using farming equipment, bulldozers or amphirols (twin archimedes screw tractor) to provide more even residue drying and to ensure that a moist surface is exposed with a high surface roughness and low surface wind speeds to prevent dust lift-off.

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## **10. 3 Appendix C – International Alumina Operations**

### **Introduction**

This document details a selection of alumina operations and associated bauxite residue facilities operating around the world.

The world's alumina refineries produce over 63 million tonnes of alumina and in excess of 70 million tonnes of bauxite residue per year (IAI Website, 2007). Rather than reviewing all operations and creating some duplication in residue management techniques, the operations selected for this review were chosen based on size or technology used thereby ensuring that a reasonable cross-section of residue technologies is captured. Each assessment includes a description of the:

- Operation;
- Local climate;
- Residue Disposal Facility;
- Estimated residue production rates;
- Residue Management Philosophy;
- Residue Design Intent (where available);
- Alternative Uses; and
- Closure Principles.

To a greater or lesser degree for all bauxite residues the main constituents of the residue are Bayer desilication products, haematite (iron oxide) insoluble calcium salts, alumina hydroxides, titanium dioxide and other compounds, including scale, reacted sulphuric acid, calcium carbonate and calcium oxalate.

## Rio Tinto Aluminium - Yarwun

**Alumina Production Capacity:** 1.4 Mtpa with environmental approvals to 4.2 Mtpa.

**Ownership:** 100% Rio Tinto plc

**Location:** Gladstone, Queensland, Australia

Physical Map of the World, April 2006



## Climate

The Gladstone region has a sub-tropical climate with median rainfall of 918 mm mostly received between October to March and pan evaporation of 1,752 mm per year. Average monthly maximum air temperatures range from 22 °C in July to 31 °C in January. Average minimum temperatures range from 13.0 °C in July to 22°C in January. The dominant synoptic winds are southerly and easterly in summer months and southerly in winter. Strong winds occur during thunderstorms and during the cyclone season (November-April) (IAS, 1998).

## Operation

The refinery commenced operations in September 2004. The refinery consumes beneficiated bauxite shipped from the Rio Tinto Aluminium bauxite mine in Weipa. The refinery operates an open seawater circuit with seawater pumped from the wharf to the refinery where it neutralizes the residual caustic in the bauxite residue. Residue is pumped to a disposal facility for thickening and disposal. Rainfall run-off and supernatant waters are returned to the ocean via a clarification pond (IAS, 1998).

## Residue Disposal Facility

The residue disposal facility is located 10 kilometres inland on a 550 ha site owned by Rio Tinto and located in an area that has been set aside by the Queensland Government specifically for the storage of waste from anticipated future industrial projects. There is sufficient area for storage of residue for a project design life of 35 years and beyond (IAS, 1998).

The town of Yarwun is the nearest populated centre (pop 300) and is approximately 3 kilometres from the disposal facility. The property abuts several horticultural properties on one boundary.

The general arrangement and location of the refinery and residue disposal facilities is shown below. Photograph actually taken in 2004 prior to commissioning.



General arrangement of RTAY facilities at Yarwun, Queensland (Google, 2007)

The topography of the Residue Management Area also provides a visual screen and contained surface drainage for the site. It is expected that the facility can be operated for many years before it will become visible to the surrounding community (IAS, 1998).

### Residue Production

Approximately 0.8 tonnes of bauxite residue is produced per tonne of alumina (IAS, 1998). At current (2006) production rates 1,100,000 tonnes (dry) of bauxite residue is produced. Fly ash generated by the refinery steam station is also incorporated into the residue stream.

The residue is neutralized using seawater.

The residue slurry liquor remains alkaline after seawater neutralization with a typical pH of between 8.5 and 9.5. The slurry liquor also has an elevated salinity (total

dissolved salts) of approximately 30,000 mg/L as a result of the addition of seawater. This compares with a salinity of approximately 35,000 mg/L for seawater (IAS, 1998).

The neutralized slurry is pumped at around 20% solids to two high rate deep cone thickeners here it is thickened to 40% solids (w/w) through the addition of flocculants and self eight consolidation. Overflow from these vessels is returned to the ocean via a sediment control dam.

## Residue Management

The thickened residue is typically thixotropic and is pumped, via a single disposal pipeline; to the adjacent drying area here it is directed to purpose built drying bays where it can be placed in a predictable and planned manner at slopes of 1% or less. By containing the residue in this way the area available is used more efficiently than if it was uncontained and allows the design operational area of 42 ha to be maintained.

Mud Farming has been adopted to increase the density of the residue and increase the life of the residue management facility. This process requires placement of residue in shallow layers (< 1m) with periodic ploughing with an Amphirolo to dewater residue to the shrinkage limit. By maintaining a moist surface with high surface roughness maintains an even drying process with minimal dust generation. Ploughing is repeated until dewatering is no longer possible and a swamp dozer is used to trim and re-form the drying bay after which the process is repeated.

The final residue solids approach the shrinkage limit of approximately 70% (w/w).

## Residue Design Intent

The EIS provides some key reasons for the selected disposal facility location and underlying design intent for the residue disposal system (IAS, 1998). These are:

- other potential sites close to the refinery are unsuitable due to potential impacts on wetland areas;
- there is no suitable area of land for residue storage available adjacent to the refinery site;
- the site is located in the upstream area of its sub-catchment, is not subject to flood inundation and will not require major drainage diversion works.
- un-neutralized residue would be highly alkaline and would therefore pose a greater risk to both surface and groundwater resources and be more difficult to rehabilitate;
- neutralization within the residue storage area would result in the discharge of low density residue, reducing the ability for rehabilitation; and
- seawater neutralization at the residue storage area would require the circulation of large volumes of seawater through the storage area and would therefore increase the salinity of any potential release from the storage area which is located in a freshwater drainage environment.

Rio Tinto Aluminium, through its part ownership of the Queensland Alumina operation, is very familiar with the operation of a seawater neutralization process for residue disposal (as are the Queensland Environmental Protection Agency). To eliminate the risk of retaining an inventory of process liquor a process of seawater neutralization is used allowing the discharge of neutralized waters to the ocean. In addition, at the



residue disposal facility, although surface hydrology is fresh the local groundwater is brackish to saline with little downstream usage. As such any seepage from the residue operation would be unlikely to negatively impact on these areas. Therefore, the need for providing a synthetic liner was argued as being unnecessary.

To ensure that the limited disposal space was used as efficiently as possible a dry stacking system, subsequently enhanced using mud farming, as selected to ensure the final residue density was as high as possible.

Therefore, the a residue facility could support a dry stacking, seawater neutralized system as adopted that utilised the existing low permeability clay in the facility foundations and the low permeability of the dewatered residue as the basal liner.

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RTAY Residue Management Area showing Mud Farming drying bays. QEPA (2005)

### Alternative Uses

There are no sanctioned alternative uses for seawater neutralized bauxite residue.

### Closure

The EIS assumes that that rehabilitation and revegetation activities will be carried to render the site self-sustaining as a non-industrial land use (eg, pasture, open grassland) (IAS, 1998). The EIS describes that restoration of the residue disposal area to the original land-use and vegetation will not be possible. One key assumption is that by adopting a high density disposal system the bearing capacity is there could be an opportunity for the residue disposal facility to be utilised as a light industrial area within the Aldoga Industrial Estate.

### References

- Google (2007), Google Earth, Viewed 18/1/2007
- *Impact Assessment Study/Environmental Impact Statement* (1998 – 2000). Comalco Alumina Project, Comalco.
- *Sustainability Strategies at Comalco on a roll*, Compass, Issue 12, Autumn 2005, Sustainable Industries Division, Queensland Environmental Protection Agency

## Queensland Alumina Ltd

**Alumina Production Capacity:** 3.8 Mtpa

**Ownership:** 41.4% Alcan, 38.6% Rio Tinto plc, 20% Rusal

**Location:** Gladstone, Queensland, Australia

Physical Map of the World, April 2006



## Climate

The Gladstone region has a sub-tropical climate with median rainfall of 918 mm mostly received between October to March and pan evaporation of 1,752 mm per year. Average monthly maximum air temperatures range from 22 °C in July to 31 °C in January. Average minimum temperatures range from 13.0 °C in July to 22°C in January. The dominant synoptic winds are southerly and easterly in summer months and southerly in winter. Strong winds occur during thunderstorms and during the cyclone season (November-April) (IAS, 1998).

## Operation

The refinery commenced operations in March 1967 and has been progressively expanded (QAL, 2007a). The refinery consumes beneficiated bauxite shipped from the Rio Tinto Aluminium bauxite mine in Weipa. The refinery operates an open seawater circuit with seawater pumped from the wharf to the refinery where it neutralizes the residual caustic in the bauxite residue. Residue is pumped to a disposal facility for disposal. Rainfall run-off and supernatant waters are returned to a tidal inlet of the Boyne River (Graham & Fawkes, 1992).

## Residue Disposal Facility

The residue disposal facility is located 8 kilometres south on a 900 ha coastal site on Boyne Island. Red Mud Dam #1 (400 ha) was used from 1967 - 1980's. Red Mud Dam #2 (528 ha) was constructed in 1975 and is still in use (Graham & Fakes, 1992). The capacity of both dams has been progressively increased by downstream construction.

Due to limitations in area available to expand further using this technique a process of upstream raising and thickening of residue will be adopted from 2007 (QAL, 2007b). There is sufficient area for storage of residue for a design life of 50 years using this approach (Gladstone Observer, 2007).

The embankments of the residue disposal facility are locally sourced and approach 20m in some areas. Little to no revegetation of the external walls has occurred, primarily due to the regular construction or downstream wall lifts that take place.

The Red Mud Dams are not lined and utilise the in-situ layers of estuarine and mangrove sediments to attenuate both chemically and physically the leachate generated by the neutralized bauxite residue.

The towns of Boyne Island/Tannum Sands are the nearest populated centre (pop 8000) and is approximately 2 kilometres from the disposal facility. The property abuts the Boyne Island Aluminium Smelter.

The topography of the residue disposal facility also provides a visual screen except a high visibility wall adjacent the local community.

The general arrangement and location of the refinery and residue disposal facilities is shown below.



General arrangement of QAL facilities at Gladstone, Queensland (Google, 2007)

## Residue Production

Approximately 0.8 tonnes of bauxite residue is produced per tonne of alumina. At current (2006) production rates 3,000,000 tonnes (dry) of bauxite residue is produced annually.

The residue is neutralized using seawater.

Seawater is added at the refinery and also at the residue discharge point. There are two discharge points with deposition alternated to enable a level disposal area to be maintained. A large inventory of the neutralized water is maintained and continuously discharged via a labyrinth clarification structure to South Trees Inlet (tributary of the Boyne River). Typically the discharge remains alkaline after seawater neutralization with a typical pH of between 8.5 and 9.5.

## Residue Management

The discharged residue has a low angle of repose and settles out over a 1,000m disposal length. Supernatant waters accumulate in the lower sections of the dam prior to discharge via a dedicated settlement channel and submerged discharge point

Periodically the residue point is changed to allow the deposited material to dewater and solar dry.

## Alternative Uses

There are no sanctioned alternative uses for seawater neutralized bauxite residue.

QAL has supported research into alternative uses for neutralized bauxite residue for many years. Most notably there was early support for Virotec International, however it is understood that this has now ceased.

## Closure

The current QAL revegetation strategy (QAL, 2007c) is to:

- Maintain a pasture like cover to control dust and erosion;
- Maintain acceptable water run-off quality; and
- Improve aesthetics.

## References

- Graham G & Fawkes R (1992). Red mud disposal management at QAL. *Proc. International Bauxite Tailings Workshop, Perth*, 1992, 188-195.
- Google (2007), Google Earth, Viewed 18/1/2007
- QAL (2007b) ([www.qal.com.au](http://www.qal.com.au)) Community Forum Update, #28, RMD Long Term Strategy
- QAL (2007c) ([www.qal.com.au](http://www.qal.com.au)) Community Forum Update, #5, Environment Presentation

- “Design changes to red mud dam add years to storage life”, Gladstone Observer, Friday 5/1/2007.
- *Impact Assessment Study/Environmental Impact Statement* (1998 – 2000). Comalco Alumina Project, Comalco.

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## Kwinana Alumina Refinery

**Alumina Production Capacity:** 2.08 Mtpa

**Ownership:** 100% Alcoa World Alumina

**Location:** Kwinana, Western Australia, Australia

Physical Map of the World, April 2006



## Climate

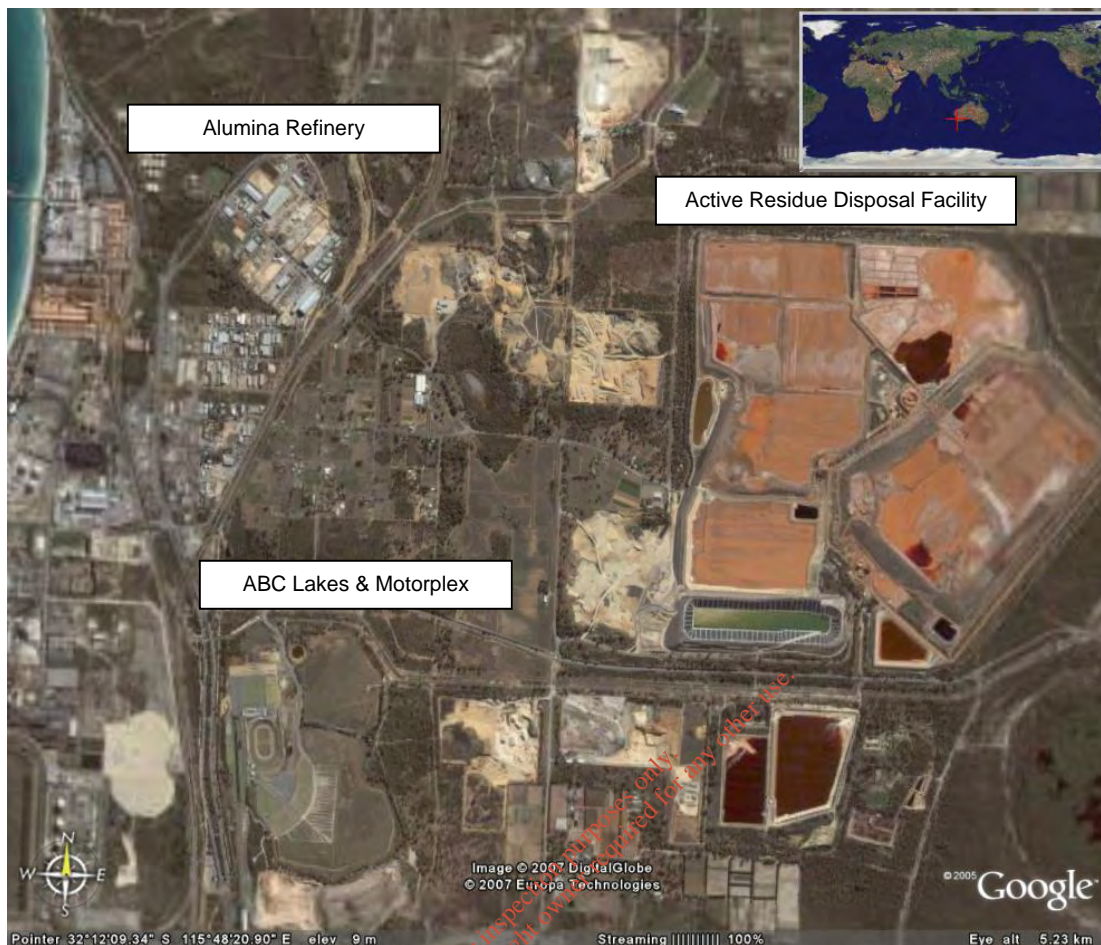
The Kwinana region (20 kilometers south of Perth) has a Mediterranean climate with median rainfall of 793 mm mostly received between May to August and pan evaporation of 1,715 mm per year. Average monthly maximum air temperatures range from 18 °C in July to 30 °C in January. Average minimum temperatures range from 8.0 °C in July to 17°C in February. The dominant synoptic winds are southwest and easterly in summer months and southwest in winter.

## Operation

The refinery commenced operations in March 1963. The refinery consumes bauxite railed from the Alcoa bauxite mines in the Darling Range (Huntly Mine). Bauxite, by world standards, is low grade averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained.

The location of the refinery and residue disposal facilities is shown below.





Overview of Alcoa Kwinana Residue Disposal facilities (Google, 2007)

## Residue Disposal Facility

When operations commenced initial residue disposal facilities (designated A, B, C lakes) were constructed 2 kilometres to the south east of the refinery on an 80 ha site. These areas were constructed on deep sandy soils as a wet disposal operation underlain by an imported clay seal and sand underdrainage blanket. Residue was placed in these areas until 1995.

In 1971 a new residue facility was constructed (designated Areas F, H, I & K) 3 kilometres east of the refinery on a 400 ha site. These areas are constructed on deep sandy soils as a wet disposal operation underlain by an imported clay seal (400 mm of locally extracted Wellard Clay) and sand underdrainage blanket. The more recent construction of Areas H, I & K combine a synthetic liner with the clay seal/underdrainage system.

The capacity of all dams has been progressively increased by upstream construction. There is sufficient area for storage of residue for a design life of 50 years using this approach.

The urbanised community of Kwinana (a suburb of Perth) is the nearest populated centre (pop 20,000) and is approximately 2 kilometres from the disposal facility. The facility is also surrounded by small horticulture properties.

While historically the visibility of the site has been low, the height of the structures now means the active facility is very visible in some sections. Unusually the active facility has a low visibility due to tree screening when in close proximity but when viewed from a distance the size and scale of the operation can be appreciated. This view has been magnified by the construction of a major freeway within 1.5 kilometres. AWA (2006) states that existing residue revegetation on outer batters will have infill planting to improve screening.

## Residue Production

Approximately 2 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 4,000,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of two size fractions at an approximate 50:50 ratio (a fine fraction or red mud and a coarse fraction (+150 micron) or residue sand).

In 1989, the wet disposal operation was converted to dry stacking. This was primarily to reduce the area demands and hence costs but also to reduce the hydraulic head of liquor acting on the clay seals. Identification of seepage of liquor from the facilities into the underlying soils was identified as a critical issue. Recovery of seepage that had entered groundwater has occurred since 1974.

The residue is not currently neutralized.

AWA (2006) states that a bio-removal process has been developed for the destruction of oxalate. Development is subject to obtaining the necessary environmental approvals. The process uses naturally occurring bacteria that can thrive in carbonated residue. The by-products of the process are sodium bicarbonate and biomass. The sodium bicarbonate is then converted to caustic soda on its return to the process.

## Residue Management

Bauxite residue is pumped at low density to the residue disposal facility where it is separated into red mud and residue sand by hydrocyclones.

The residue sand is managed as a separate stream and stockpiled for reuse in upstream construction and underdrainage systems.

The red mud is thickened in a 75m EIMCO Superthickener to approximately 50% solids (w/w) and placed in drying areas in 500 mm layers where it is mud farmed using amphirol equipment to over 65% solids.

A network of sprinklers is used on a pre-emptive basis to minimise the generation of dust from the drying mud surface. There have been some complaints associated with dust generation. AWA (2006) notes that improvements are being made to reduce sprinkler spacing to improve dust suppression operation.

A network of groundwater recovery bores located in the delineated seepage zones capture escaping liquor and return it to the process circuit.

AWA (2007) states that a Long Term Residue Management Plan (LTRMP) is undertaken every five years. This plan is reviewed by the Residue Planning Liaison Group (RPLG). A group that consists of representatives from the Department of Industry and Resources, Department of Environment, Ministry of Planning, Department of Agriculture WA, Peel development Commission, Department of

Conservation and Land Management as well as Alcoa. The RPLG and the Minister for Environment must approve the LTRMP before it can be implemented.

## Alternative Uses

With the adoption of dry stacking in 1987 as the preferred disposal philosophy, it became possible to recover and re-use the residue sand as a construction medium within the confines of the bauxite residue facilities. In doing so, this replaced the need for imported construction materials and increased the operating life of the residue disposal facilities.

The Alcoa World Alumina Research Group, based primarily at the Kwinana Refinery, has developed many uses for bauxite residue and residues from within the Bayer circuit. Since 1978 extensive research has been undertaken with a plethora of scientific papers, studies and funded university investigations. Since 2000 the focus has become more directed to commercial success and linking the development of sustainable residue management practices with alternative use developments.

The development of a carbonation process using waste carbon dioxide from adjacent industry or from flue gas at the refinery allows the bauxite residue to be used to reduce the net carbon intensity of the refinery (Cooling and Jameson. 2002). This research has won several state and national awards. The neutralization process reduces the pH of the residue from pH 13 to pH 10.5. A trial unit is in operation at Kwinana with a full size unit scheduled for commissioning in 2008 (Alcoa, 2006). Recent comments by Alcoa executives suggest that the process will be adopted worldwide (Alcoa, 2007).

Research has focused on developing three commercially viable products: ALKALOAM<sup>®</sup>, REDLIME<sup>™</sup> and Red Sand. Cooling and Jameson (2004) describe the development of these products as:

- ALKALOAM<sup>®</sup> is a fine grained material (red mud) that can increase the pH of acidic soils and provide nutrient capture properties thus reducing the demands for fertiliser application.
- REDLIME<sup>™</sup> is a residual lime product that is a combination of calcium carbonate, hydro-calumite and tri-calcium aluminate. This material is a by-product from a side stream process to the Bayer Circuit that converts sodium carbonate in the liquor stream to sodium hydroxide. Normally this material is recombined with the bauxite residue in the process circuit increasing the residual alkalinity. Research has shown that it is a suitable lime replacement in agriculture.
- Red Sand is the beneficiated coarse fraction of bauxite residue (residue sand). The beneficiation process involves the removal of the lime components, size separation to remove the fine fraction, additional washing to remove soluble soda, carbonation to reduce remaining caustic to carbonates and bicarbonates with a consequent reduction in pH to less than 10. The sand has been promoted as a suitable fill, subgrade and drainage sands.

On the basis that the provision of residue for soil amendment purposes was not a commercial venture, Alcoa sought a government indemnity for protection against "irresponsible or inappropriate" use of the product that was granted in September 1999 (Ryle, 2002). Currently, all of these products are subject to extensive research and their release on hold due to extensive negative media publicity (Cooling and Jamieson, 2002).

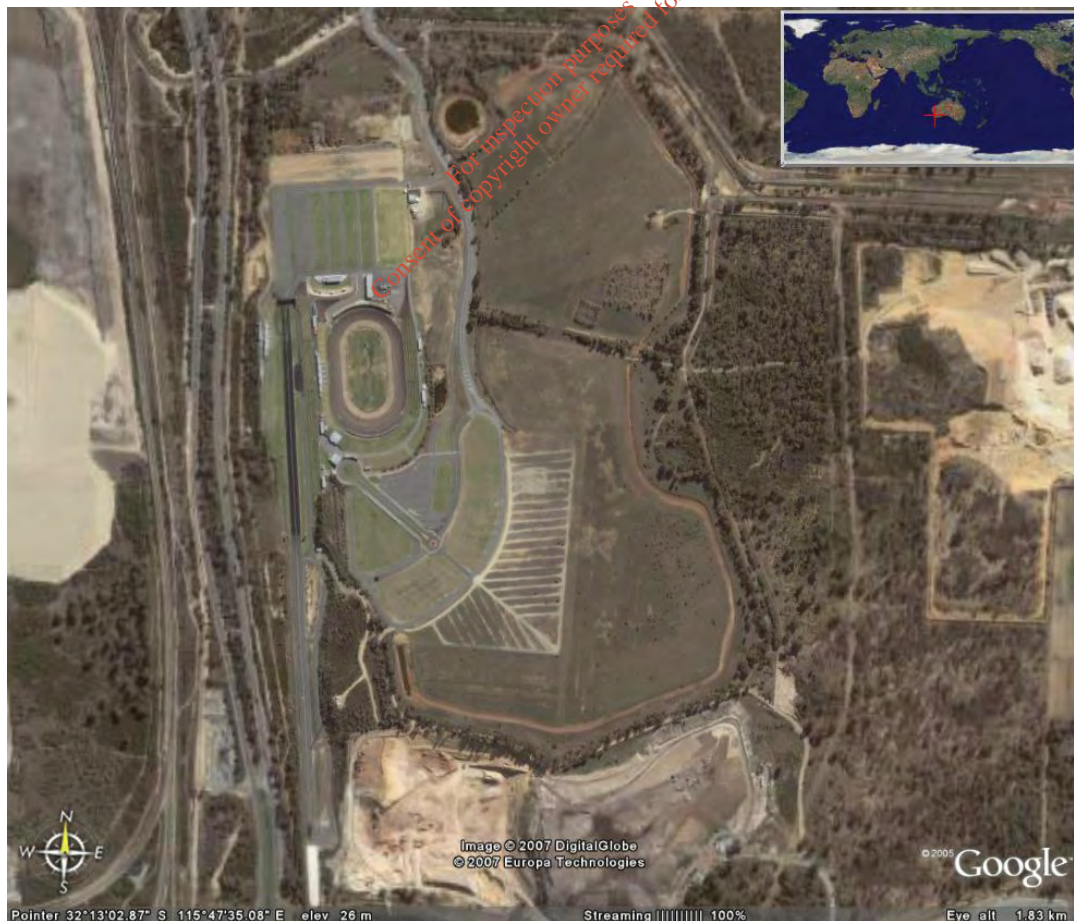


Alcoa has made commitments that there will be a 50% reduction in residue that will be stored in the Residue Disposal Impoundments by 2015. This goal clearly identifies that the process of making residue sand inert and commercially useful will be solved

Kwinana currently supplies Ecomax Waste Management Pty Ltd with gypsum neutralized red mud. Residue has been supplied from Kwinana since 1992 and the units are constructed all over Australia (Ecomax, 2007). Based on designs and estimated sizing approximately 55 m<sup>3</sup> of gypsum neutralized residue is required per installation. Ecomax charges approximately AUD \$1,400 per effluent installation for the gypsum neutralized residue (Shire of Chittering, 2002). Further information on the Ecomax system is detailed in Appendix B.

## Closure

The original A, B, C lakes were leased from the government of Western Australia for the purpose of disposal of bauxite residue. The Alumina Refinery Agreement Act requires Alcoa, on completion of residue disposal operations to rehabilitate the site to a standard able to accommodate light industrial development (TOK, 2003). A decision to construct a motorplex development (combination of public areas for motorsport activities) on some of the A,B,C area as taken by the State Government in 1998 (Hansard, 1998). This area has been returned to the Government for community use in 2000 and the development has been successfully completed. The Motorplex development is shown below.



Overview of the original Alcoa residue Disposal Facility (ABC Lakes) and the post closure land use (Motorplex) (Google, 2007)

AWA (2006) states that current rehabilitation goal, for Area F (the active residue disposal facility) is to use native species to develop a self sustaining ecosystem. AWA (2006) states that plans are in preparation for the early closure of Area F in 2010.

The Kwinana Consultation Community Network was formed in 1996. This group provides a structured consultation for all aspects of the residue operation.

## References

- Alcoa World Alumina, "Kwinana Environmental Improvement Plan – Progress Report", June 2006
- Alcoa (2007), "Alcoa Q4 2006 Earnings Call Transcript", SeekingAlpha Website, 9/1/2007.
- Alcoa (2007), "[www.alcoa.com](http://www.alcoa.com)", Various articles and information (22/1/2007)
- Cooling DJ and Jamieson E (2004) "Bauxite Residues – A High Volume Resource", Green Processing Conference, 10 – 12 May, Fremantle, Western Australia.
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- Google (2007), Google Earth, Viewed 18/1/2007
- Ryle, G, (2002), Sydney Morning Herald, May 7, 2002.
- Shire of Chittering, Western Australia (2002), "Ordinary Council Meeting Minutes", Thursday 15<sup>th</sup> August

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## Pinjarra Alumina Refinery

**Alumina Production Capacity:** 4.2 Mtpa

**Ownership:** 100% Alcoa World Alumina

**Location:** Pinjarra, Western Australia, Australia

Physical Map of the World, April 2006



## Climate

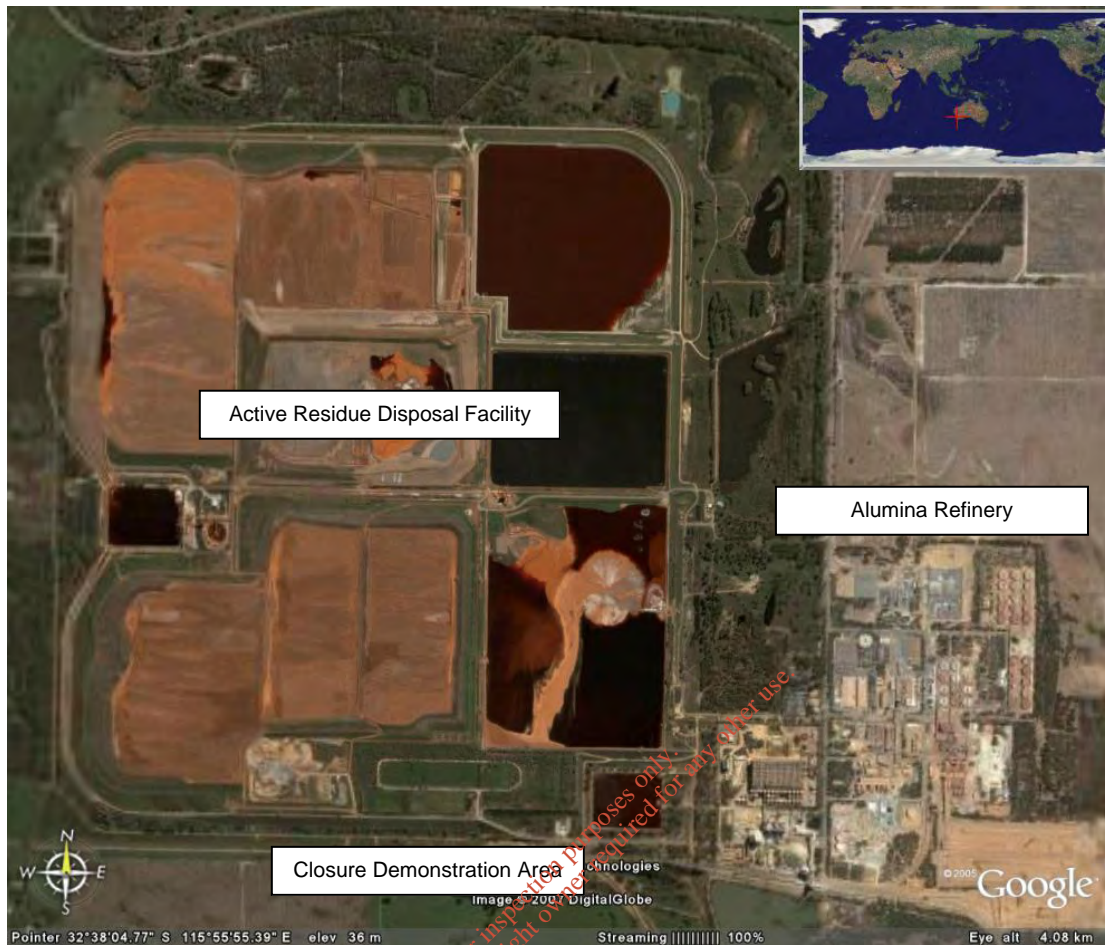
The Pinjarra-Mandurah region (90 kilometers south of Perth) has a Mediterranean climate with median rainfall of 944 mm mostly received between May to August and pan evaporation of 1,788 mm per year. Average monthly maximum air temperatures range from 16 °C in July to 31 °C in January. Average minimum temperatures range from 6.0 °C in July to 16°C in February. The dominant synoptic winds are southwest and easterly in summer months and southwest in winter.

## Operation

The refinery commenced operations in 1972. The refinery consumes bauxite transported by conveyor from the Alcoa Huntly Bauxite Mine. Bauxite, by world standards, is low grade averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained.

The location of the refinery and residue disposal facilities is shown below.





Overview of Alcoa Pinjarra Residue Disposal Facilities (Google, 2007)

## Residue Disposal Facility

A dedicated 600 ha residue disposal facility is constructed adjacent the refinery on Alcoa freehold land. This area is predominately extensive local clay overlain by sandy subsoils. Constructed clay seals have been constructed in all areas. There is no evidence of significant groundwater contamination. The area is underlain by a dedicated underdrainage system.

The capacity of all dams has been progressively increased by upstream construction. There is sufficient area for storage of residue within the refinery buffer for a design life of 45 years using this approach.

The local community of Pinjarra is the nearest populated centre (pop 600) and is approximately 2.5 kilometres from the disposal facility. The facility is also surrounded by extensive Alcoa farmlands (6,000ha).

The visibility of the site is low due to tree screening.

## Residue Production

Approximately 2 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 7,700,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of two size fractions at an

approximate 50:50 ratio (a fine fraction or red mud and a coarse fraction (+150 micron) or residue sand).

In 1987, the wet disposal operation was converted to dry stacking. This was primarily to reduce the area demands and hence costs but also to reduce the hydraulic head of liquor acting on the clay seals.

The residue is not currently neutralized.

## Residue Management

Bauxite residue is pumped at low density to the residue disposal facility where it is separated into red mud and residue sand by hydrocyclones.

The residue sand is managed as a separate stream and stockpiled for reuse in upstream construction and underdrainage systems.

The red mud is thickened in a 90m EIMCO Superthickener to approximately 50% solids (w/w) and placed in drying areas in 500 mm layers where it is mud farmed using amphirolo equipment to over 65% solids.

A network of sprinklers is used on a pre-emptive basis to minimise the generation of dust from the drying mud surface. Dust is recognised as a key sustainability issue with community concerns about caustic and radiation in dust (Martin, 2004).

AWA (2003) states that a Long Term Residue Management Plan (LTRMP) is undertaken every five years. This plan is reviewed by the Residue Planning Liaison Group (RPLG) a group that consists of representatives from the Department of Industry and Resources, Department of Environment, Ministry of Planning, Department of Agriculture WA, Peel development Commission, Department of Conservation and Land Management as well as Alcoa. The RPLG and the Minister for Environment must approve the LTRMP before it can be implemented.

## Re-use Applications

No residue is currently permitted to leave the Pinjarra.

AWA (2006) states that a key target is for all new residue that is generated by the refinery will have a pH less than 10.5 by 2010. This can only realistically occur if the carbonation technology is adopted and modified to utilise the carbon dioxide present in flue gases.

Alternative use underway at Kwinana is likely to be applied at the Pinjarra refinery.

## Closure

AWA (2003) states that the current rehabilitation goal is to return the residue disposal area to the agreed future land use. No final commitment to land use is given due to "...the long operational life of the project and the inevitable changes to statutory requirements and social expectations that will occur over such a long period." However, in 1996 a closure demonstration area was established to assist in developing conceptual closure strategies and used to assist in the community consultation process. This area highlights natural vegetation, grazing and fodder crops as potential closure options. The site incorporates a visitor centre

The trial closure area (showcasing an agricultural or farming closure option) is shown below.



Overview of the closure demonstration area at Pinjarra Residue Disposal Facility (Google, 2007)

The Pinjarra Consultation Community Network was formed in 1994 with a Stakeholder Reference Group dedicated to residue disposal operations. This group provides a structured consultation for all aspects of the residue operation.

## References

- AWA (2003), "Environmental Protection Statement – Pinjarra Refinery Efficiency Upgrade", Report prepared for Alcoa World Alumina Australia by ENVIRON Australia.
- AWA (2006) Alcoa World Alumina, "Pinjarra Environmental Improvement Plan – Progress Report", June 2006
- Alcoa (2007), "[www.alcoa.com](http://www.alcoa.com)", Various articles and information
- Martin K. (2004) "Identification of Issues and Audit of Plans/Strategies", Pinjarra-Brunswick Sustainability Study, Department for Planning and Infrastructure, Prepared for Pinjarra-Brunswick Sustainability Study Steering Committee. January 2004.
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## **Wagerup Alumina Refinery**

**Alumina Production Capacity:** 2.5 Mtpa

**Ownership:** 100% Alcoa World Alumina

**Location:** Wagerup, Western Australia, Australia

Physical Map of the World, April 2006



## **Climate**

The Waroona-Yarloop region (120 kilometers south of Perth) has a Mediterranean climate with median rainfall of 950 mm mostly received between May to August and pan evaporation of 1,788 mm per year. Average monthly maximum air temperatures range from 17 °C in July to 30 °C in January. Average minimum temperatures range from 8.0 °C in July to 16°C in February. The dominant synoptic winds are southwest and easterly in summer months and southwest in winter.

## **Operation**

The refinery commenced operations in 1983 and has been progressively expanded. The refinery currently has a capacity of 2.6 Mtpa of alumina and environmental approvals to produce 3.3 Mtpa although production is currently limited to 2.5 Mtpa by environmental licensing.

The refinery consumes bauxite transported by conveyor from the Alcoa Willowdale Bauxite Mine located 15 kilometres to the east. The bauxite ore, by world standards, is low grade averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained.

The refinery and residue disposal facility is located on Alcoa freehold land and is zoned industrial.

Surrounding the refinery is approximately 6,000 ha of Alcoa freehold property, which is predominately used as a beef farming enterprise. The surrounding land use is predominately rural with most of the region cleared for agriculture.

## Residue Disposal Facility

The existing residue disposal facility covers 546 ha of which 170 ha are currently used for active drying of residue, 12 ha for thickener bypass, 69 ha for alkaline water storage and 32 ha for fresh water storage (AWA, 2005). The layout of the residue disposal facility is shown below.



Wagerup Residue Disposal Facility (Google, 2007)

The residue disposal facilities are underlain by alluvium (clay and sandy clay) of 5 to 15m depth. The early residue disposal facilities were constructed with a 500mm low permeability clay seal but subsequent identification of seepage no mean all residue facilities have a clay/synthetic composite seal.

The local community of Yarloop is the nearest populated centre (pop 640) and is approximately 2.0 kilometres from the disposal facility.

The visibility of the site is low from the main transport corridor due to tree screening but high from surrounding farmlands. The high visibility areas are subject to a Visual Amenity Strategy incorporated into the construction approvals from local council.

## Residue Production

Approximately 2 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 5,000,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of two size fractions at an approximate 50:50 ratio (a fine fraction or red mud and a coarse fraction (+150 micron) or residue sand).

In 1991, the wet disposal operation was converted to dry stacking. This was primarily to reduce the area demands and hence costs but also to reduce the hydraulic head of liquor acting on the clay seals.

The residue is not currently neutralized.

Extensive research has been undertaken examining the carbonation of bauxite residue using either piped waste carbon dioxide from adjacent industry or potentially stack gases from the refinery process. This research has won several state and national awards. The neutralization process reduces the pH of the residue from pH 13 to pH 10.5. Plans are in place for this technology to be in place at Pinjarra and Wagerup. Alcoa (2007) states that residue carbonation will be used in all Alcoa refineries in the near future.

## Residue Management

Red mud is pumped at low density to the residue disposal facility where it is thickened in a 75m EIMCO Superthickener to approximately 50% solids (w/w) and placed in drying areas in 500 mm layers where it is mud farmed using amphirol equipment to over 65% solids.

Residue sand is managed as a separate stream directly from the refinery and stockpiled for reuse in upstream construction and underdrainage systems.

A network of sprinklers is used on a pre-emptive basis to minimise the generation of dust from the drying mud surface. The sprinkler system is undergoing refurbishment to a smaller spacing to improve coverage and effectiveness. Dust is recognised as a key sustainability issue with community concerns about caustic and radiation in dust (Martin, 2004).

To manage the long term development and ultimate closure of the residue area, Alcoa has developed a Long Term Residue Management Strategy (LTRMS) in consultation with government agencies and members of the neighboring community. The LTRMS outlines the strategies to ensure that the residue area at Wagerup will be stable and self-sustaining, and will no longer require further management when refinery operations cease. The LTRMS covers the proposed 30 year plan for residue management at Wagerup and is reviewed and updated on a five yearly basis. The Residue Planning Liaison Group (RPLG) was formed to facilitate the planning, review and endorsement of the LTRMS developed by Alcoa for submission to the Minister for the Environment. The RPLG has membership from the Department of Industry and Resources, Department of Environment (and Water and Rivers Commission), Ministry of Planning, Agriculture Western Australia, the Peel Development Commission, Department of Conservation and Land Management and Alcoa (AWA, 2005). The RPLG and the Minister for Environment must approve the LTRMS before it can be implemented.



## Re-use Applications

No residue is currently permitted to leave the Wagerup Refinery.

Alternative use underway at Kwinana is likely to be applied at the Wagerup Refinery.

## Closure

AWA (2003) states that the current rehabilitation goal is to return the residue disposal area to the agreed future land use. No final commitment to land use is given due to "...the long operational life of the project and the inevitable changes to statutory requirements and social expectations that will occur over such a long period."

The continued management of the bauxite residue facility closure strategy is incorporated into the LTRMS.

## References

- AWA (2005), "Environmental Review and management Programme – Wagerup refinery Unit Three", Report prepared for Alcoa World Alumina Australia by ENVIRON Australia.
- AWA (2006) Alcoa World Alumina, "Pinjarra Environmental Improvement Plan – Progress Report", June 2006
- Alcoa (2007), "Alcoa Q4 2006 Earnings Call Transcript", SeekingAlpha Website, 9/1/2007.
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- Google (2007), Google Earth, Viewed 18/1/2007
- Martin K. (2004) "Identification of Issues and Audit of Plans/Strategies", Pinjarra-Brunswick Sustainability Study, Department for Planning and Infrastructure, Prepared for Pinjarra-Brunswick Sustainability Study Steering Committee. January 2004.

## Alcan Gove

**Alumina Production Capacity:** 3.5 Mtpa

**Ownership:** 100% Alcan

**Location:** Nhulunbuy, Northern Territory, Australia

Physical Map of the World, April 2006



## Climate

The Gove Peninsula (550 kilometers east of Darwin) has a tropical monsoon climate with median rainfall of 1,443 mm mostly received between December to April and pan evaporation of 2,153 mm per year. Average monthly maximum air temperatures range from 28 °C in July to 33 °C in November. Average minimum temperatures range from 19.0 °C in August to 25°C in January. The dominant synoptic winds are northwest summer months and southeast in winter (BOM, 2007).

## Operation

The refinery commenced operations in 1972 and has been progressively expanded. The refinery currently has a capacity of 3.5 Mtpa of alumina having recently (2006) undergone a 2.0 Mtpa expansion. As part of EIS approvals it stated final production capacity as likely to exceed 3.8 Mtpa (Alcan, 2004).

The refinery consumes bauxite transported by conveyor from the Alcan Gove Bauxite Mine located 15 kilometres to the east. The bauxite ore is high grade averaging 51% alumina. The refinery operates an open circuit saltwater cooling system and a seawater neutralization discharge system to manage low concentration caustic affected streams at the residue disposal area (Alcan, 2004).

The refinery and residue disposal facility is located on Alcan special purpose lease land (Alcan, 2004).

The refinery is located on a peninsula with mangrove and native vegetation at the margins.

The location of the refinery and residue disposal facilities are shown below.



Figure 9: Proximity of Alcan Gove Residue Disposal Facility and Gove Alumina Refinery (Google, 2007)

## Residue Disposal Facility

The existing residue disposal facility covers 500 ha of which 180 ha are currently used for active drying of residue, 255 ha for alkaline water storage and 70 ha has been revegetated and returned to traditional landowners (Alcan, 2004). The layout of the residue disposal facility is shown in Figure 10.





Alcan Gove Residue Disposal Facility (Google, 2007)

The residue disposal facilities are underlain by sandy clay and sandy intrusions. All early residue disposal facilities were constructed by reworking the existing clay to a low permeability seal. Subsequent identification of seepage now means all residue facilities have a clay/synthetic composite seal (Alcan, 2004).

The local community of Nhulunbuy is the nearest populated centre (pop 3,500) and is approximately 12.0 kilometres from the disposal facility.

The visibility of the site is low from the main transport corridor due to tree screening but high from surrounding areas including the bay (Alcan, 2004).

## Residue Production

Approximately 0.8 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 2,800,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of a single fine size fraction.

In 1992, the wet disposal operation was converted to dry stacking. This was primarily to reduce the area demands and hence costs (Alcan, 2004).

The residue is not currently neutralized.

Extensive research has been undertaken examining the neutralization of bauxite residue using seawater. Current efforts are directed to eliminating the existing

inventory of alkaline water prior to converting to full neutralization and open circuit operation after 2015 (Alcan, 2004).

## Residue Management

Bauxite residue is thickened to high density (46% solids w/w) and pumped at high pressure and placed in drying areas in 500 mm layers where it is mud farmed using amphirol equipment to over 65% solids.

A long-range residue disposal plan is used to manage residue activities. This is reviewed every three years (Alcan, 2004).

## Closure

Extensive research has been conducted into developing a closure solution to the residue disposal facility. The current requirement is to provide stable, sustainable native vegetation with minimal on-going maintenance. Research in collaboration with the University of Queensland (Centre for Mined Land Rehabilitation) has developed a suitable solution. The existing closed areas of the residue disposal facility are monitored for performance and maintained as required (Alcan, 2004).

Alcan (2004) details four proposed final land uses for the residue disposal facility:

- Stable landform with self-sustaining vegetation;
- Stable vegetated landform suitable for residential or commercial uses;
- Natural vegetation; and
- Retained infrastructure.

Revegetation has been undertaken at the two decommissioned residue disposal facilities (Taylor's Pond and Northern Pond) and the leases relinquished to traditional landholders (Alcan, 2004).

## References

- Alcan (2004) "Draft – Environmental Impact Statement, Alcan Gove Alumina Refinery Expansion Project", URS, February 2004
- BOM (2007) ([www.bom.gov.au](http://www.bom.gov.au)), Bureau of Meteorology, Various information
- Google (2007), Google Earth, Viewed 18/1/2007

## Worsley Alumina

**Alumina Production Capacity:** 3.5 Mtpa

**Ownership:** 86% BHP Billiton, 10% Japan Alumina Associates, 4% Sojitz Alumina

**Location:** Worsley, Western Australia, Australia

Physical Map of the World, April 2006



## Climate

The Worsley region (170 kilometers southeast of Perth) has a Mediterranean climate with median rainfall of 943 mm mostly received between May to August and pan evaporation of 1,840 mm per year. Average monthly maximum air temperatures range from 15 °C in July to 30 °C in January. Average minimum temperatures range from 4.0 °C in July to 13°C in February. The dominant synoptic winds are southwest and easterly in summer months and westerly in winter (BOM, 2007).

## Operation

The refinery is located within the darling escarpment (Elevation 200m) and commenced operations in 1984 and has been progressively expanded. The refinery currently has a capacity of 3.5 Mtpa of alumina and environmental approvals to produce 4.4 Mtpa (EPA, 2005).

The refinery consumes bauxite transported by conveyor from the Mt Saddleback Bauxite Mine located 51 kilometres to the northeast. The bauxite ore, by world standards, is low grade averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained (EPA, 2005).

The refinery and residue disposal facility is located on 2,500 ha of Refinery Lease Area land and adjoining sub-leases for the disposal of bauxite residue (EPA, 1996).

Surrounding the refinery is approximately 10,000 ha of Worsley freehold property, which is predominately used as forested and agricultural purposes (EPA, 1996).



## Residue Disposal Facility

The existing residue disposal facility currently used 420 ha for active drying of residue (Google, 2007). The layout of the residue disposal facility is shown below. The bauxite residue areas show up as a beige colour due to poor photographic resolution.



General arrangement of Worsley Alumina Refinery and adjacent residue disposal facilities (Google, 2007)

The residue disposal facilities are located to the north and south of the refinery and constructed in the natural valley presented by the topography and is underlain by heavy local clay strata; this is reworked to form a low permeability clay seal.

The local community of Collie is the nearest populated centre (pop 9,000) and is approximately 15.0 kilometres from the disposal facility.

The visibility of the site is low from all directions due to natural tree screening.

## Residue Production

Approximately 2.5 tonnes of bauxite residue is produced for every one tonne of alumina (Worsley 2007). Therefore, approximately 8,800,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of a single fine size fraction.

The residue is not currently neutralized.

## Residue Management

Bauxite residue is pumped to the underdrained residue disposal facility where it is placed in drying areas in layers where it is lightly mud farmed using a combination of ploughing, raking and amphirol equipment to high density (Worsley 2006).

Dust from the residue disposal facility is noted as a significant issue. In the most recent EPA approval, the management of dust using the existing dust management plan was deemed acceptable (EPA, 2006).

## Closure

Worsley (2006) states that the long-term plan to rehabilitate the bauxite residue disposal area aims to:

- Re-establish vegetation compatible with the surrounding forest;
- Protect the quality of surface and groundwater flow; and
- Contain and treat any contaminated water held in the residue mass.

## References

- BOM (2007) ([www.bom.gov.au](http://www.bom.gov.au)), Bureau of Meteorology, Various information
- DOIR (2006) "Ministerial Approval – Worsley Expansion", Hon Mark McGowan MLA, 13<sup>th</sup> April 2006.
- EPA (1996) "Expansion of alumina production from 2.0 million tonnes per annum to 3.5 million tonnes per annum at Worsley refinery, and associated bauxite mining activities at Boddington", Report & recommendations of the Environmental Protection Authority, Bulletin 823.
- EPA (2005) "Worsley Alumina – Efficiency & Growth Increase of Existing Operations to 4.4 Mtpa Alumina Production" Report & recommendations of the Environmental Protection Authority, Bulletin 1209.
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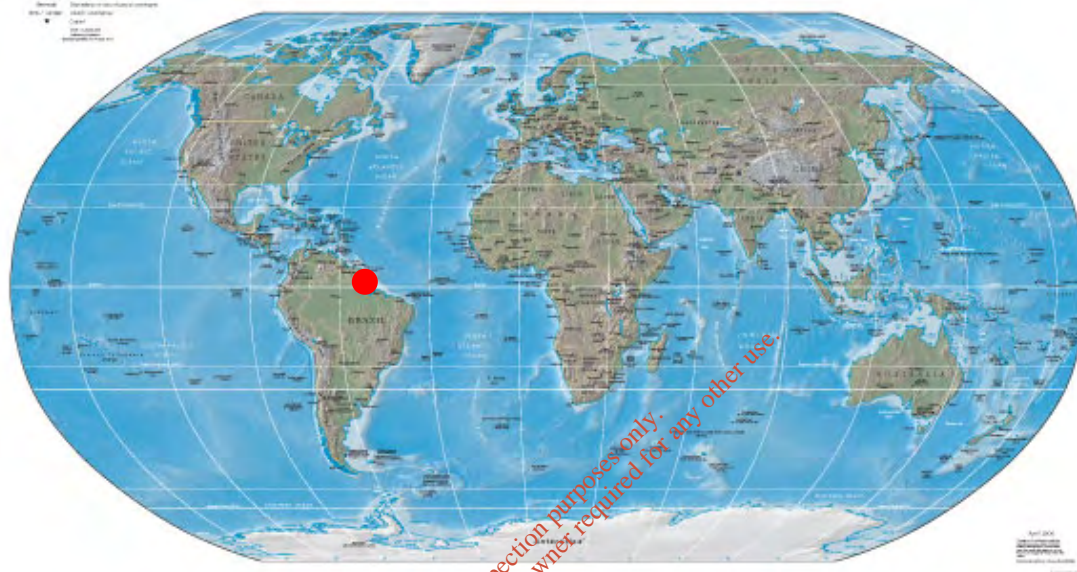
## **Alumina do Norte do Brasil S.A. (Alunorte)**

**Alumina Production Capacity:** 4.4 Mtpa

**Ownership:** CVRD 57.03%/Norsk Hydro 34.03%/NAAC 3.8%/CBA 3.62%/JAIC 1.19%/Mitsui 0.23%/Mitsubishi 0.1%

**Location:** Barcarena, Pará State, Brazil

Physical Map of the World, April 2006



## **Climate**

The Barcarena district (40 kilometers west of Belém) has a wet tropical climate with median rainfall of 2,890 mm mostly received all year round and pan evaporation of 950 mm per year. Average monthly maximum air temperatures range from 30 °C to 22 °C all year. Average minimum temperatures range from 21 °C to 22°C all year (INMET 2007).

## **Operation**

The refinery is located adjacent the Tocantins river (and part of the Amazon River Estuary) and commenced operations in 1995 (although construction started in 1982 and stalled for 9 years while alumina prices were low) and has been progressively expanded. The refinery currently has a capacity of 4.2 Mtpa of alumina with a declared public intention to expand to 6.5 Mtpa. (Alunorte 2007)

The refinery consumes bauxite transported by barge from the Trombetas mine (Mineração Rio do Norte) and Paragominas mine (CVRD) via pipeline. The bauxite ore, by world standards, is high grade averaging 50% alumina. The refinery operates an open circuit freshwater system. All runoff from the residue management areas is neutralized using acid and discharged (Alunorte 2007).

The refinery and residue disposal facility is located within 3,500 ha of buffer land (Alunorte 2007).

## **Residue Disposal Facility**



The existing residue disposal facility currently uses an 80 ha for active drying of residue (Google, 2007). The layout of the residue disposal facility is shown below. The bauxite residue areas (on the right hand side) show up as a beige colour due to poor photographic resolution.



Alunorte Alumina Refinery and Residue Disposal Facility (east of the refinery)

The town of Belém is the nearest populated centre (pop 1,500,000) and is approximately 40.0 kilometres east of the disposal facility.

## Residue Production

Approximately 0.65 tonnes of bauxite residue is produced for every one tonne of alumina (based on 2006 alumina production – 3,850,000 tonnes, Kinch, 2006). Therefore, approximately 2,500,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of a single fine size fraction.

The residue is not currently neutralized.

## Residue Management

Bauxite residue is generated by vacuum filtration and dewatering to approximately 60%. The dewatered residue is then trucked to the residue disposal facility and dumped into a series of 12 dewatering bays (1 per month). Each dewatering bay is allowed to dry for 1 year before the process is repeated

Rainfall run-off from the site is collected and neutralized using acid prior to discharge into the Tocantins River.

## Alternative Uses

The refinery encourages the local ceramic industry to use mud for the fabrication of tiles and bricks and sponsors research at the local university. However, at present, the quantity of mud being used for this purpose is very small being in the order of 300-1000 tonnes per month. The major obstacle for its wide use is cost since Alunorte has to truck the mud to the producers free of charge.

## Closure

Not Available

## References

- Alunorte (2007) ([www.alunorte.net](http://www.alunorte.net))
- Norsk Hydro Website ([www.hydro.com](http://www.hydro.com)), Various information
- Google (2007), Google Earth, Viewed 24/1/2007
- INMET (2007) ([www.inmet.gov.br](http://www.inmet.gov.br)) Instituto Nacional De Meteorologia, Brasil. Viewed 23/1/2007.
- Kinch D. (2006) "Alunorte boosts alumina capacity to 4.4m TPY", Metal Bulletin, no. 8938, pp. 9. 3<sup>rd</sup> April 2006.



## **Jamaica Aluminium Company (Jamaico)**

**Alumina Production Capacity:** 1.4 Mtpa

**Ownership:** Alcoa World Alumina 50%/Clarendon Alumina Production Ltd 50%

**Location:** Clarendon, Jamaica

Physical Map of the World, April 2006



## **Climate**

The Clarendon region (48 kilometers west of Kingston) has a wet/dry tropical climate with median rainfall of 988 mm mostly received between May – June and August - November and pan evaporation of 1,820 mm per year. Average monthly maximum air temperatures range from 31 °C to 34 °C. Average minimum temperatures range from 19 °C to 24°C. The region is subject to the passage of seasonal tropical hurricanes (Jamaico, 2004)

## **Operation**

The refinery commenced operations in 1970. The refinery consumes bauxite transported by rail from the Alcoa Clarendon, South and North Manchester Bauxite Mines. Bauxite, by world standards, is average grade averaging 45% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained and recycled to the operation (Jamaico, 2004).



Overview of Jamalco Residue Disposal Facilities (Google, 2007)

## Residue Disposal Facility

Jamalco presently has four active residue disposal areas (RDA's) covering 314 ha. RDA 1 was commissioned in 1972, RDA 2 in 1980, RDA 3 in 1990, and RDA 4 was commissioned in 1997. RDA's 1 & 2 are constructed as simple clay lined impoundments. The construction of RDA 3 & 4 includes a base drainage system to improve the rate of consolidation of the residue and to reduce the hydrostatic pressure on the clay seal at the base of the deposits (Jamalco, 2004). RDA 5 (100ha), constructed in 2006, is used primarily for storage of thickened residue (Jamalco, 2005).

The RDA is sites over alluvial fan deposits containing a wide range of unconsolidated siliciclastic sediments. These highly permeable materials are used for embankment construction. These sediments overlay a clay layer and limestone bedrock that has high transmissivity and represents a valuable groundwater resource (Jamalco, 2004).

RDA 1, 2, 3 & 4 all have clay seals. There is no evidence of groundwater contamination. RDA 5 is a constructed with a composite liner incorporating a 0.75mm thick PVC geomembrane and a 450mm clay liner. A 750mm thick sand layer is placed over the composite liner and will act as an underdrainage system. The decision to adopt a composite liner is related to the exposure of limestone at the surface under the RDA footprint hence providing a greater risk of potential contamination (Jamalco, 2004).

The capacity of RDA 1 has been progressively increased by upstream construction. There is sufficient area for storage of residue within the refinery buffer for a design life of 45 years using this approach (Jamalco, 2004).

The community of May Pen is the nearest populated centre (pop 45,000) and is approximately 7.5 kilometres from the disposal facility.

The visibility of the site is high due to flat topography and low intermittent vegetation.

## **Residue Production**

Approximately 1.2 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 1,700,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of a single fine size fraction (Jamalco, 2004)

In 2006, the wet disposal operation was converted to dry stacking. This was primarily to reduce the area demands and hence costs but also to reduce the hydraulic head of liquor acting on the clay seal (Jamalco, 2004).

The residue is not currently neutralized.

## **Residue Management**

Bauxite residue is pumped at low density to the thickener here the solids content of the slurry is raised from 10% to between 31 – 34%. Thickened residue is discharged to the drying areas here it forms a self-draining slope of 3 – 5% and consolidates rapidly (Jamalco, 2004).

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## Closure

Jamalco (2005) details the closure process for the Jamalco residue areas. Closure is dependent on the execution of three activities:

- Dewatering,
- Capping, and
- Grading Re-vegetation.

Dewatering commences after the last bauxite residue is deposited in an area. The liquor level in the area is lowered either by surface drains or more extensive dewatering to encourage consolidation, higher settled densities and higher shear strengths.

Once the bearing capacity of the residue has improved to the point where access is possible capping materials including low grade bauxite materials and local native overburden soils. This process provides:

- Load to encourage additional consolidation,
- Reduce or eliminate potential dust emissions, and
- Provide a growing medium for re-vegetation phase.

Jamalco (2005) identifies the areas in proximity to the walls of the RDAs and the lands behind them that extend to the river and support a vegetation type typical of a scrubland/ thorn savannah.

## References

- Alcoa (2007), "[www.alcoa.com](http://www.alcoa.com)", Various articles and information
- Jamalco (2004) "Jamalco 2.8M Metric Tonne per year Efficiency Upgrade, Environmental Impact Assessment", Jamalco, prepared by Conrad Douglas & Associates Ltd.
- Jamalco (2005) "Jamalco RDA 5 Environmental Impact Assessment", Jamalco, prepared by Conrad Douglas & Associates Ltd.
- Google (2007), Google Earth, Viewed 24/1/2007



## **Gardanne Alumina Refinery**

**Alumina Production Capacity:** 0.65 Mtpa

**Ownership:** 100% Alcan

**Location:** Gardanne, France

Physical Map of the World, April 2006



## **Climate**

The Gardanne region (20 kilometers northeast of Marseille) has a Mediterranean climate with median rainfall of 584 mm, mostly received between September to May. Average monthly maximum air temperatures range from 10 °C in January to 28 °C in August. Average minimum temperatures range from 2 °C in January to 18°C in August.

## **Operation**

The refinery commenced operations in March 1893. The refinery consumes bauxite railed from the CBG mine in the Guinea. Bauxite, by world standards, is high grade averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All runoff from the refinery and residue management areas is contained.



An aerial photograph of the refinery is shown below:



## **Residue Disposal Facility**

The refinery does not operate a permanent residue disposal facility. It maintains temporary storage in the event of a pipeline breakdown.

## **Residue Production**

Approximately 0.6 - 0.7 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 300,000 tonnes (dry) of bauxite residue is produced annually (2006). The bauxite residue is made up of a single size fraction.

## **Residue Management**

Residue is pumped 40km and then taken 7km offshore and placed in a trench 340m deep (Peres, 1973).

## **Alternative Uses**

Gardanne have developed "Bauxaline" a residue based construction product (Alcan, 2002). Small scale trials have taken place with some success.

## Closure

Not Available

## References

- Alcan (2002) “ La Bauxaline, A new product for various applications” Aluminium Pechiney, Gardanne.
- Peres J-M, (1973) “Mud as a pollutant of the marine environment”, Evol. Med. Vol. 17, no. 3, pp 223-228.
- Google (2007), Google Earth, Viewed 24/1/2007

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## **10. 4 Appendix D – Commercial Bauxite Residue Re-Use**

### **10.4.1 Virotec International Limited (Virotec)**

Virotec International is an Australian based environmental management company listed on the Alternative Investment Market of the London Stock Exchange.

Virotec has access to patented technology involving the mixing and neutralization of Magnesium and Calcium rich liquors with bauxite residue that provide neutralization such that the material, trademarked Bauxsol™, can be utilised in a range of applications including:

- Industrial Water Treatment;
- Municipal Waste Water;
- Mine Remediation;
- Concrete Production;
- Soil treatments & Fertilisers; and

Bauxsol™, in its various forms utilises the natural affinity of the complex iron-aluminium compounds present in the bauxite residue to absorb nutrients, metals and provide a flocculating agent to suspended colloidal material. Controlling the neutralization process allows the bauxite residue to be tailored to a specific purpose including issues associated with handling, transport and application.

Through a computer model, Basecon™, it is possible to predict the neutralization requirements for a specific bauxite residue. Virotec intends to market this technology, with the assistance of Hatch, to the alumina industry worldwide.

The Bauxsol™ and Basecon™ technologies are licensed to Virotec under an exclusive arrangement by Nouveau Technologies (director associated)

Virotec has successfully applied this technology across the world and has bauxite residue supply agreements in place with Eurallumina (9,000 t/yr) and an un-named alumina operation in North America for 100,000 tonnes.

Derived from information provided at [www.virotec.com](http://www.virotec.com) (23<sup>rd</sup> January 2007)

### **10.4.2 Ecomax Waste Management Systems Pty Ltd (Ecomax)**

Ecomax is a private, Australian based effluent treatment company.

Ecomax has developed and patented the use of amended bauxite residue in purpose-built underground effluent filters that use the complex iron-aluminium compounds present to absorb nutrients, metals and allow bacterial decomposition of liquid effluent overflowing from septic or similar systems.

Ecomax has a bauxite residue supply agreement with Alcoa Kwinana where residue sand, the coarse fraction of bauxite residue, is dry mixed with a small percentage of waste gypsum. This material is provided at cost.

Over 1,000 Ecomax units have been constructed around Australia with an intention to promote the technology around the world. All details derived from information provided at [www.ecomax.com.au](http://www.ecomax.com.au) (accessed on 23<sup>rd</sup> January 2007).

## **10. 5 Appendix E - Neutralization of Bauxite Residue**

Prepared by Dr Angus Hartshorn

### **10.5.1 Executive Summary**

Alumina is extracted from bauxite ore by dissolution in a caustic solution at elevated temperatures and pressures. This process, commonly known as the Bayer Process, was invented by Karl Bayer, an Austrian chemist, in 1888. Around the world, the Bayer Process represents the most commonly applied technology in the alumina refining industry.

After the alumina rich solution is removed, the undissolved components of bauxite, or bauxite residue, are washed to recover any residual caustic or alkalinity which is then recycled.

Bauxite residue as it exits the last washing stage contains three sources of alkalinity:

- Liquor entrained in the bauxite residue
- The Calcium compounds (derived from lime that is also added at various points of the Bayer Process)
- Sodalite (Desilication Product or DSP) formed by the reaction of caustic soda with silica compounds present in bauxite ore.

The residual alkalinity can be neutralized by the addition of neutralising or acidic materials such as carbon dioxide, magnesium (commonly sourced from seawater) or minerals acid (sulphuric or hydrochloric acid).

The proportions of neutralising or acidic materials required to neutralize the solid compounds in the residue and the reactivity of the latter two categories can vary considerably between different refineries. The quantity of neutralising agent required depends on:

- The efficiency of the residue washing process (removing liquor) and the concentration of residual sodium hydroxide and sodium carbonate in the liquor
- The details of the lime usage including:
  - Quantity;
  - Point of addition; and
  - The range of compounds formed
- The quantity of reactive silica in the bauxite (converted to Sodalite)
  - The alkalinity of the Sodalite is also dependent on the liquor impurities, particularly Sulphate.

The rate at which the alkalinity reacts with the "acid" varies greatly. Neutralization of the:

- Liquor - a rapid diffusion controlled process.
- Calcium compounds - varies greatly depending on the compound in question and the temperature at which it is formed. It can occur over a period of minutes to weeks.
- Sodalite - varies from an initial fast to a slow rate because it becomes progressively less alkaline as the most alkaline components are extracted:

- Over dosing with mineral acid can dissolve Sodalite causing changes in residue viscosity when the pH is subsequently increased with potentially serious implications for high pressure pumping applications. Addition of a strong acid to a viscous paste presents a significant engineering challenge.

Consequently the final pH of the "neutralized" residue is highly dependent on the driving force (time/temperature/delta pH [the pH difference between the neutralized solution and solid]) to which the less reactive compounds have been exposed.

Subsequent to any neutralization process being carried out, the final pH of the residue after storage for days to weeks may increase principally due to incomplete reaction of the Calcium compounds. These "slow" reactions make the final pH rather difficult to control and carefully designed laboratory experiments are required to obtain meaningful data.

Due to the inherent variability in bauxite, neutralising agents and mixing conditions, it is necessary for each refinery to investigate the neutralization reactions outlined above for the compounds produced by their version of the Bayer process before arriving at a process that meets their requirements for neutralization of the Bayer residue. "Titration" of the whole residue can be carried out but is less informative than titration of the individual compounds.

Based on the limited experimental data obtained so far the following conclusions can be drawn:

- Volume of acid required to achieve neutralization of the soluble alkalinity is about 30 Kg of 98%  $\text{H}_2\text{SO}_4$  per tonne of dry residue
- Volume of estuary water required to achieve neutralization of the soluble alkalinity is about 100  $\text{m}^3$  per tonne of dry residue

Additional experimentation is required to more accurately determine the quantities of  $\text{H}_2\text{SO}_4$  or estuary water required. The quantities required will be affected by the target pH.



## 10.5.2 Introduction

This report provides some background information into the sources of alkalinity associated with bauxite residue and issues associated with neutralization and leaching of this alkalinity. The report has been produced for Aughinish Alumina Limited and draws on the scientific literature produced by the alumina industry and preliminary experimentation undertaken at Aughinish. Although not all of the sources of the potential sources of alkalinity will apply to the Aughinish Refinery they have been included for completeness and also to highlight differences between the refinery process and other similar operations.

## 10.5.3 Alkaline Compounds in Bauxite Residue

In the Bayer process a hot concentrated Sodium Hydroxide solution (generally known as "caustic" liquor) is used to dissolve Aluminium Hydroxides from the mineral Bauxite. The insoluble fraction of the Bauxite (known as Bauxite residue) is separated and the solution is cooled to re-precipitate Gibbsite. Then the liquor is returned to extract more Aluminium Hydroxides from fresh Bauxite.

After the alumina rich solution is removed, the undissolved components of bauxite, or bauxite residue, are washed to recover any residual caustic or alkalinity which is then recycled.

The Bauxite residue slurry that exits the last washing stage contains:

- Diluted liquor that has not been completely washed out
- the insoluble portion of the bauxite (mostly Iron and Titanium oxides)
- Sodalite (formed by reaction of kaolinite and quartz in the bauxite with liquor)
- Calcium compounds (formed by addition of lime to the process)

Therefore the sources of alkalinity within the bauxite residue can be defined as:

- The entrained liquor
  - Sodium hydroxide (NaOH)
  - Sodium aluminate (NaAlO<sub>2</sub>)
  - Sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>)
- Some of the Calcium compounds (formed by addition of lime to the process) When lime, generally in the form of Calcium Hydroxide (Ca(OH)<sub>2</sub>), is added a quite complicated series of reactions occurs depending on the liquor concentration and temperature. The types of calcium compounds found in the Bayer process include:
  - Hydrocalumite (Not relevant to Aughinish)
  - TCA (Tri-calcium Aluminate)
  - Hydrogarnet
  - Lime
  - Calcium Oxalate and
  - Perovskite (CaTiO<sub>3</sub>)

Smith (2003) is a useful reference to the alkalinity of the Calcium compounds formed in the Bayer process.
- The Sodalite ((NaAlSiO<sub>4</sub>)<sub>6</sub>(Na<sub>2</sub>X), where X can be SO<sub>4</sub><sup>2-</sup>, CO<sub>3</sub><sup>2-</sup>, Al(OH)<sub>4</sub><sup>-</sup>, and some minor anions such as Cl<sup>-</sup>.

All these compounds must be reacted with acid to neutralize the residue. The neutralization reactions of these compounds are discussed in the following sections.

## 10.5.4 Neutralization of Bauxite Residue

In theory any acid can be used to neutralize Bauxite residue, however in practice three acids have been used:

- Mineral acids ( $\text{H}_2\text{SO}_4$  is the preferred mineral acid due to cost and handling issues)
- Carbon Dioxide ( $\text{CO}_2$ ) - Carbon Dioxide is a weak acid capable of neutralising Bauxite residue slurries. It is attractive on environmental grounds because it is converted to Carbonate reducing greenhouse gas emissions, however the process chemistry is quite complex.
- Seawater (the Magnesium ions in seawater precipitate the alkalinity as insoluble Magnesium Hydroxides. It is convenient to regard  $\text{Mg}^{2+}$  as an acid in this context).

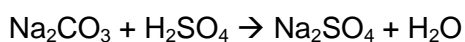
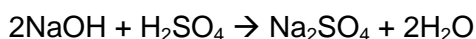
The following sections cover all the known neutralization reactions of Bauxite residue derived from the various versions of the Bayer process practiced around the world. Some of these reactions are not relevant to Aughinish (and where they are not, this is noted).

## 10.5.5 Neutralization of Bauxite Residue with Sulphuric Acid ( $\text{H}_2\text{SO}_4$ )

Sulphuric Acid ( $\text{H}_2\text{SO}_4$ ) will react with each of the alkaline components present in bauxite residue. These reactions are described as:

### 10.5.5.1 Reaction of Alkaline Liquor

The bauxite residue liquor contains the alkaline compounds,  $\text{NaOH}$ ,  $\text{NaAl}(\text{OH})_4$  and  $\text{Na}_2\text{CO}_3$  which react with Sulphuric acid as follows:



These reactions are very fast depending only on the rate of mixing.

### 10.5.5.2 Reaction of Calcium Compounds

The rate at which the Calcium-containing compounds react with acid is related to:

- The alkalinity and surface area of the compound in question.
- The driving force applied:
- The solution pH (the lower the pH the faster the reaction)
- The temperature/time (the higher the temperature the faster the reaction)

The reaction rates are generally slow, varying from minutes to days depending on the compound in question.

- **Hydrocalumite**

Hydrocalumite can have various empirical formulae, the most common are:

$[\text{Ca}_2\text{Al}(\text{OH})_6]_2 \cdot \frac{1}{2}\text{CO}_3 \cdot \text{OH} \cdot 5\frac{1}{2}\text{H}_2\text{O}$  the hemi carbonate

$[\text{Ca}_2\text{Al}(\text{OH})_6]_2 \cdot \text{CO}_3 \cdot 5\text{H}_2\text{O}$  the mono carbonate

The pH of these compounds is approximately 11.0.

Recent work by Rosenberg (2001) has shown that the hemi is always the first compound to form when  $\text{Ca}(\text{OH})_2$  is added to Bayer liquor.

These compounds are formed during the process of carbonate causticisation and oxalate destruction.

### **Carbonate Causticisation (not relevant to Aughinish)**

Carbonate causticisation involves the addition of slaked lime  $\text{Ca}(\text{OH})_2$  to the bauxite residue to recover any residual caustic or alkalinity which can then be recycled. Initially the hemi carbonate is formed. Depending on the caustic concentration and temperature/time, this compound decomposes into:

- Mono carbonate
- Tri-Calcium-Aluminate  $\text{Ca}_3[\text{Al}(\text{OH})_6]_2$  (TCA)
- Hydrogarnet  $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_n(\text{OH})_{12-4n}$
- $\text{CaCO}_3$

If the causticiser is not at a sufficiently high temperature or the residence time is too short significant quantities of hemi and/or mono carbonate remain undecomposed.

### **Oxalate Destruction (not relevant to Aughinish)**

During the precipitation process of alumina, sodium oxalate also precipitates from the liquor. In order to remove this unwanted contaminant the slurry is washed with hot water which dissolves the sodium oxalate.

After the slurry is filtered, the resulting dilute liquor is reacted with  $\text{Ca}(\text{OH})_2$  to precipitate  $\text{Ca}(\text{C}_2\text{O}_4)\text{H}_2\text{O}$  (calcium oxalate). The  $\text{Ca}(\text{OH})_2$  also precipitates the  $\text{NaAl}(\text{OH})_4$  in the liquor as the Hemicarbonate and this forms the major component of the solids from oxalate destruction.

The hemi and mono carbonate react over a period of several minutes with Sulphuric Acid ( $\text{H}_2\text{SO}_4$ ).

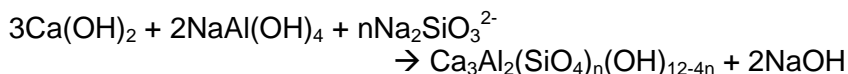
- **Tri-Calcium Aluminate (TCA) and Hydrogarnet:**

These compounds are formed in bauxite residue when Lime is:

- added to Digestion (relevant to Aughinish)

- Used to make Filteraid (not relevant to Aughinish)
- Used for Carbonate Causticisation (not relevant to Aughinish)
- Used for Oxalate Destruction (in minor amounts) (not relevant to Aughinish)

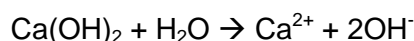
At Aughinish the lime (as slaked lime  $\text{Ca}(\text{OH})_2$ ) is added to digestion. One of the compounds formed is Hydrogarnet it is formed as follows:



The Silica is derived from dissolution of Kaolinite and Quartz in digestion. The quantity of Silica incorporated depends on several factors and “n” will probably be about 0.6 under Aughinish’s digestion conditions.

[Note that when  $n = 0$  the empirical formula collapses to  $\text{Ca}_3[\text{Al}(\text{OH})_6]_2$  (Tri-Calcium Aluminate). These compounds have very similar properties.]

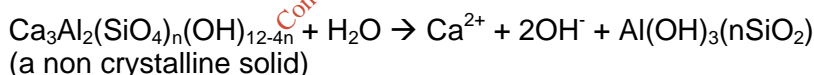
When TCA or Hydrogarnet are mixed with water they decompose to a small extent liberating Hydroxide. The reaction is very similar to the dissolution of  $\text{Ca}(\text{OH})_2$  (Calcium Hydroxide) in water.



As  $\text{Ca}(\text{OH})_2$  is sparingly soluble in water the pH only goes up to about 12.5. Similarly, when Hydrogarnet is mixed with water the pH is about 11.2.

The alkalinity of the Hydrogarnet is one of the major reasons for Aughinish alkaline Bauxite residue solids.

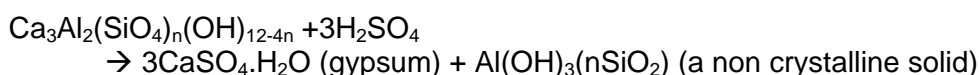
The reaction of Hydrogarnet in water is described below:



This reaction is difficult to describe with a balanced equation because it is a decomposition.

Based on experience Hydrogarnet has a rather lower pH than TCA. These compounds react slowly with  $\text{H}_2\text{SO}_4$ . If these compounds are not reacted with acid for extended periods they can be a major source of residual alkalinity in the residue disposal area. It is likely that, the pH in the residue disposal area will drift up over time.

Hydrogarnet reacts with  $\text{H}_2\text{SO}_4$  as follows. The reaction is slow probably because one quite insoluble solid is being converted into another insoluble solid. In addition, the gypsum  $\text{CaSO}_4 \cdot \text{H}_2\text{O}$  probably forms on the surface of the Hydrogarnet further slowing down the dissolution of this compound.



At this stage the pH would be close to neutral. If excess acid were added or there is not uniform mixing allowing for localised excess acid the  $\text{Al}(\text{OH})_3$  will dissolve:



If insufficient time is given for the first reaction to be complete, the residual Hydrogarnet will cause the pH to drift up by about 2 pH units (causing the residue disposal area to have a high pH).

- **Filteraid (not relevant to Aughinish)**

Some plants clarify their pregnant liquor using TCA as filteraid. The spent filteraid is usually disposed of with the bauxite residue. Filteraid is significantly less reactive than the hemi carbonate and the slow reaction poses a significant problem when attempting to neutralize bauxite residue to a low pH.

- **CaCO<sub>3</sub>, Calcium Oxalate (Ca(C<sub>2</sub>O<sub>4</sub>).H<sub>2</sub>O) and Perovskite (CaTiO<sub>3</sub>)**

These compounds have a neutral pH and do not react with seawater or CO<sub>2</sub>. The first two will decompose if excess H<sub>2</sub>SO<sub>4</sub> is added. CaTiO<sub>3</sub> (Perovskite) is formed at Aughinish. It does not react with any of the acids considered here (It is soluble in Hydrofluoric Acid (HF)).

An indication of the quantity of acid required to neutralize the lime compounds is between 40 and 50 mole % of the Ca(OH)<sub>2</sub> added to the process. Generally this would be a comparable quantity of acid to that required to neutralize the residual liquor. The quantity of acid required to neutralize the lime compounds will depend on the target pH.

### 10.5.5.3 Reaction of Sodalite

Sodalite has the empirical formula (NaAlSiO<sub>4</sub>)<sub>6</sub>(Na<sub>2</sub>X). The so-called "cage" Sodium salts are given as Na<sub>2</sub>X where X can occur as a number of di and mono anions. The remainder, the majority, of the Sodium is known as the "structural" Sodium. X can be SO<sub>4</sub><sup>2-</sup>, CO<sub>3</sub><sup>2-</sup>, Al(OH)<sub>4</sub><sup>-</sup>, and some minor anions such as Cl<sup>-</sup>.

The cage anions can diffuse out of the Sodalite structure and do so for example when the solution pH is lowered. The pH at which the structural Sodium is extracted ranges from approximately 5 to 8.

The cage ions determine the pH of Sodalite. When X =:

- Al(OH)<sub>4</sub><sup>-</sup> the Sodalite is highly alkaline (approximate pH 13) (it appears that X = OH<sup>-</sup> does not occur in Sodalite formed in Bayer liquors)
- CO<sub>3</sub><sup>2-</sup> the Sodalite is moderately alkaline (approximate pH 12)
- SO<sub>4</sub><sup>2-</sup> or Cl<sup>-</sup> the Sodalite is "neutral" (approximate pH 8)

Therefore the alkalinity and the quantity of acid required to neutralize Sodalite is largely dependent on the nature of the cage anions and consequently on the ions present in solution.

The order of adsorption of anions is:

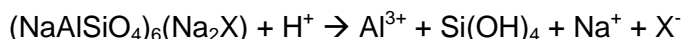
- SO<sub>4</sub><sup>2-</sup> > CO<sub>3</sub><sup>2-</sup> > Al(OH)<sub>4</sub><sup>-</sup> > Cl<sup>-</sup>



Consequently if the liquor contains more than about 10 g/L  $\text{SO}_4^{2-}$  X will largely be  $\text{SO}_4^{2-}$  and the Sodalite will be relatively neutral and will require only a small amount of acid to achieve neutralization. At Aughinish the nature of the cage anions is not known in detail but it is known that some  $\text{CO}_3^{2-}$  is present.

As the solution pH is reduced the alkaline cage anions are extracted. When the pH falls to about 8 the "structural" Sodium begins to be extracted.

Ultimately all the Sodium can be extracted at a pH of about 5. If the pH falls to 3.5 (again if mixing is not uniform) the Sodalite begins to dissolve:



If bauxite residue is over-dosed with a mineral acid (pH < 3.5) the sodalite dissolves and can cause serious process disruption when the pH is subsequently increased due to the precipitation of amorphous  $\text{SiO}_2$  which forms a viscous gel. This aspect presents an engineering challenge when dealing with a filter cake as at AAL.

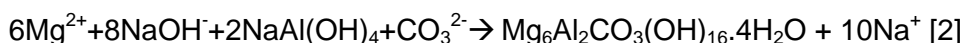
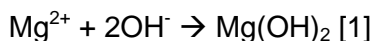
In addition this reaction will consume a large quantity of  $\text{H}_2\text{SO}_4$ . One of the primary issues with the use of  $\text{H}_2\text{SO}_4$  to neutralize Bauxite residue is to design a reactor conformation that prevents excursions to low pH.

## 10.5.6 Neutralization of Bauxite Residue with Seawater

Seawater Neutralization has been practiced by a number of Australian refineries for several years. Residual liquor is returned to the sea and the neutralized solids are stored in dams.

### 10.5.6.1 Reaction of Liquor.

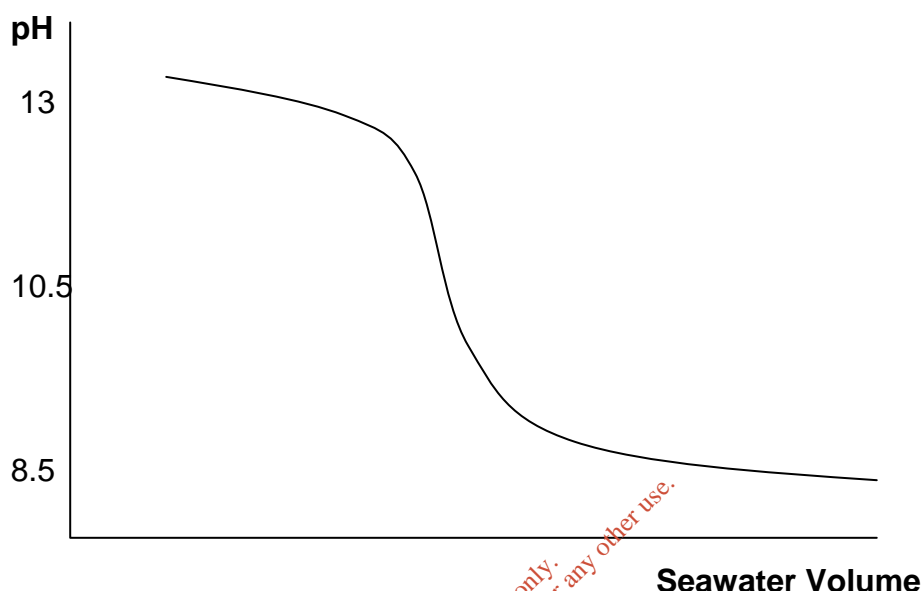
The "active" constituent of seawater is the Magnesium, it precipitates the alkalinity as Hydrotalcite. Although the empirical formula of Hydrotalcite can vary, the neutralization capability of  $\text{Mg}^{2+}$  whether for  $\text{NaOH}$ ,  $\text{NaAl}(\text{OH})_4$  or  $\text{Na}_2\text{CO}_3$  (the alkaline species in the liquor) is relatively simple, two moles of acid ( $\text{H}^+$ ) is equivalent to one mole of  $\text{Mg}^{2+}$ .



The end point for the titration of  $\text{Mg}^{2+}$  with liquor occurs at a pH of approximately 10.5 and further  $\text{Mg}^{2+}$  is required to shift the equilibrium of reaction [2] to the right lowering the pH. A pH below 8.5 is difficult to achieve, requiring quite a large excess of  $\text{Mg}^{2+}$ .

The creation of Hydrotalcite can lead to an increase in the total volume of the residue. Although the change is highly dependent on the initial alkalinity increases up to 30% are possible.

Figure 1 - Titration of seawater and alkaline liquor



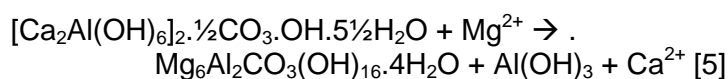
#### 10.5.6.2 Reaction of Calcium Compounds

Starting with the most reactive:

- **Hydrocalumite**

The hemi and mono carbonate react over a period of several minutes with the  $Mg^{2+}$  in seawater to give Hydrotalcite (see reaction [5]) liberating  $Ca^{2+}$  ions. Therefore  $Mg^{2+}$  can be considered an acid in this context.

Hydrotalcite is less alkaline than any of the lime compounds and a portion of the cage ions in Sodalite



- **Tri-Calcium Aluminate (TCA) and Hydrogarnet:**

From experience Hydrogarnet has a rather lower pH than TCA. These compounds are slow to react with the  $Mg^{2+}$  in seawater (and also react slowly with  $CO_2$  and  $H_2SO_4$ ). If these compounds are not reacted with acid for extended periods they can be a major source of residual alkalinity in the residue area because the pH can drift up over time.

- **Filteraid (Not relevant to Aughinish)**

Some plants clarify their pregnant liquor using TCA as filteraid. The spent filteraid is usually disposed of with the bauxite residue. Washed spent filteraid has a pH of about 11. Addition of seawater causes the pH to drop. However after time the pH rises slowly to 10.5 as the Magnesium is consumed.

The conclusion was that filteraid is significantly less reactive than the hemi carbonate and that the slow reaction poses a significant problem when attempting to neutralize residue to a low pH.

### 10.5.6.3 Reaction of Sodalite

Seawater reacts with Sodalite to neutralize the alkaline cage anions (Carbonate and Aluminate)

The  $Mg^{2+}$  in seawater reacts with the cage anions to precipitate Hydrotalcite type compounds. This chemical reaction is difficult to present in a simple form

Cage anions are  $Al(OH)_4^-$  and  $CO_3^{2-}$ .  $+ Mg^{2+} \rightarrow Mg_6Al_2CO_3(OH)_{16} \cdot 4H_2O$

### 10.5.7 Neutralization of Bauxite Residue with $CO_2$

$CO_2$  neutralization is an attractive method on environmental grounds. The cost also appears to be low (although no data is available in the open literature).

$CO_2$  neutralization has been investigated in detail by Alcoa (7th Alumina Quality Workshop (AWQ) p 218). The process consists of reacting Sodium bicarbonate ( $NaHCO_3$ ) with the residue slurry and then regenerating  $NaHCO_3$  from the  $Na_2CO_3$  formed using  $CO_2$  in "flue gas". Conceptually the  $NaHCO_3$  is the acid (it is neutral whereas  $Na_2CO_3$  is alkaline)

$NaHCO_3 + \text{"alkalinity in liquor and residue solids"} \rightarrow Na_2CO_3$

$Na_2CO_3 + CO_2 \rightarrow NaHCO_3$

Alcoa claim that this process:

- Allows flue gas to be used (previously only "pure"  $CO_2$  gas could be used adding to the cost)
- Eliminates problems with scale formation that were a serious limitation when using "pure"  $CO_2$

This process is patented and a license to operate would be required.

It is not clear from the available literature what pH can realistically be achieved using this process. The rate at which the  $NaHCO_3$  can be regenerated from  $Na_2CO_3$  appears to be quite slow. The limited amount of data given in the journal article suggests that a pH less than about 10 will be difficult to achieve.

The efficiency of the carbonation process is improved by the linkages with the alternative use programs for residue currently being researched by Alcoa (Cooling and Jamieson, 2004). As Alcoa uses lime to form TCA for use as a filteraid the overall alkalinity that needs to be neutralized is higher than at Aughinish. However, Alcoa, is actively researching the re-use of spent filteraid as a lime replacement material

(REDLIME®) thereby removing this component of the residue alkalinity prior to the carbonation process.

The advantages of CO<sub>2</sub> neutralization over seawater neutralization include:

- the possibility to produce relatively concentrated NaHCO<sub>3</sub> solutions compared with seawater where Mg<sup>2+</sup> is present at only about 1.4 g/L (0.12 Molar in "acid" i.e. double the Mg<sup>2+</sup> molarity). A concentrated solution reduces capital cost and increases the reaction rate.
- The reaction can produce a higher temperature accelerating the slow reactions. When seawater is used the large volume makes the use of higher temperatures costly
- A higher delta pH than with seawater.

## 10.5.8 Disposal of Liquors after Residue Neutralization

Consideration is required on the environmental effects of these liquors. Of the three acids considered in this document CO<sub>2</sub> is probably preferred because the neutral compound NaHCO<sub>3</sub> is produced.

H<sub>2</sub>SO<sub>4</sub> neutralization produces Na<sub>2</sub>SO<sub>4</sub> and seawater neutralization produces a diluted solution of seawater from which the Mg<sup>2+</sup> has been reduced in concentration. Such solutions require significant dilution with estuary "water" to minimise their environmental impact.

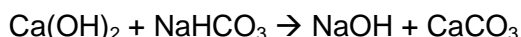
### 10.5.8.1 Seawater Neutralization

Residual liquor from seawater neutralization is effectively seawater with the majority of the Mg<sup>2+</sup> removed. This solution can be returned to the sea if sufficiently mixed with fresh seawater. However, the underflow residue contains the same solution and when stacked and dried will contain solid NaCl or a saturated NaCl solution depending on the conditions. While, revegetation of this material is problematic over time the salinity of the residue will decrease due to leaching by rainfall.

### 10.5.8.2 CO<sub>2</sub> Neutralization

Of all the bauxite residue neutralization methods CO<sub>2</sub> neutralization is probably the method of choice when disposal of the resultant liquor is considered.

Neutralization with CO<sub>2</sub> results in a liquor containing NaHCO<sub>3</sub>. It is possible to causticise this liquor and this appears to be the strategy adopted by Alcoa (7th Alumina Quality Workshop p 218).



This allows the liquor to be recycled as process water. This approach however requires lime and lime is produced by calcining limestone.

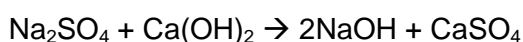


Under these circumstances at least some of the environmental value of using CO<sub>2</sub> is negated.

### 10.5.8.3 H<sub>2</sub>SO<sub>4</sub> Neutralization

H<sub>2</sub>SO<sub>4</sub> neutralization results in a dilute Na<sub>2</sub>SO<sub>4</sub> solution which must be disposed of probably by dilution with estuary water. The residual dry residue will contain solid Na<sub>2</sub>SO<sub>4</sub>·10H<sub>2</sub>O (i.e. it will have a high ionic strength) which may also cause difficulties with revegetation. The residue will also contain a small quantity of CaSO<sub>4</sub>·xH<sub>2</sub>O (gypsum), an inert compound.

The liquor can be causticised:



but only with dilute Na<sub>2</sub>SO<sub>4</sub> solutions because of the moderate solubility of CaSO<sub>4</sub>.

### 10.5.9 Leaching of Bauxite Residue

Leaching occurs when water (e.g. rain) percolates through or runs off deposited residue in a disposal area. If the alkalinity has not been removed the pH of the water will be high.

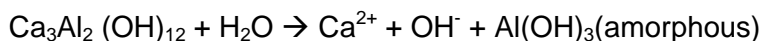
There are two types of leaching:

- Extraction of residual soluble alkalinity from the liquid contained in the pores of the residue
- Decomposition of the alkaline solids present

Mixing water with either sodium hydroxide or sodium carbonate dilutes the relative strengths of the compounds with a maximum pH comparable to the initial pH of the residue. The alkalinity present will be leached at a rate determined by the permeability of the residue.

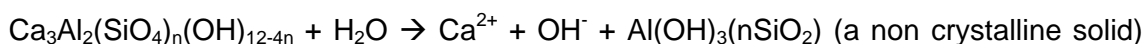
When TCA or Hydrogarnet are mixed with water they decompose to a small extent liberating Hydroxide.

The TCA reaction can be summarised as:



This reaction gives pH ~ 10.5 but is very slow to reach equilibrium and the OH<sup>-</sup> concentration is very low. The equilibrium for this reaction is far to the left.(i.e. There is only a "tiny" amount of decomposition of the TCA to give this pH and that the leaching will likely occur for an extended period).

The Hydrogarnet leaching reaction can be summarised as:



This reaction gives a pH ~ 11.2.

It is not generally understood, even within the alumina industry, that this source of leachable alkalinity is present in bauxite residue. Generally the soluble caustic from the liquor is recognised as being the only source of alkalinity when red mud is leached.



This can lead to erroneous conclusions regarding the length of time required for a bauxite residue to become fully leached and generate a leachate suitable for direct discharge.

The release of this “solid” alkalinity is slow. Slurries can take up to a week to attain their maximum pH. The slow release of alkalinity makes it difficult to predict the leachate pH because it depends on the mud permeability and the amount of rainfall.

The implications for a neutralized residue are that only partial neutralization ie neutralization of the liquid phase is realistic and the pH will drift up towards 10.5 over time as the solid phase alkalinity reacts. In this manner the liquid effluent from the residue disposal area can remain at an approximate pH of 10.5 for many years.

## 10.5.10 Laboratory Investigation of Bauxite Residue Neutralization

Because the alkaline compounds present in Bauxite residue differ for each refinery a fairly extensive laboratory investigation is required to determine appropriate neutralization conditions.

A preferred strategy for such an investigation is to obtain samples of the individual sources of alkalinity and investigate the rate at which they react with the acid whether  $Mg^{2+}$  in seawater,  $CO_2$  or a mineral acid. .

One advantage of investigating the compounds individually is that it allows an algorithm to be constructed to predict the quantity of acid required for the last washer underflow slurry in which the sources and volumetric flows of alkalinity from:

- the liquor
- the different lime compounds
- the Sodalite

can be used as inputs.

### 10.5.10.1 Experiments on Aughinish Bauxite Residue Slurries

As Aughinish use lime only in digestion, producing Hydrogarnet as the primary alkaline Calcium compound, it should be much simpler to obtain the necessary information to construct an algorithm for their version of the Bayer process.

#### 10.5.10.1.1 Reaction of Aughinish Bauxite Residue with Acid

AAL have indicated that Carbonate is present in their Sodalite. Carbonate levels in plant liquor are to some extent being controlled over via carbonate removal through Sodalite formation in digestion. This is due to the increasing reactive Si in bauxite. As Hydrogarnet is also present, the following experiment can quantify the alkalinity present in the residue solids. This information is essential to allow the calculation of the quantity of  $H_2SO_4$  required to fully neutralize the residue. However, Hydrochloric Acid (HCl) is proposed for the investigation rather than Sulphuric Acid ( $H_2SO_4$ ) because  $CaCl_2$  is soluble whereas  $CaSO_4$  is not. This means that a stable pH will be reached more quickly using HCl. The quantity of HCl required will be the same as for  $H_2SO_4$  (in Moles of  $H^+$ )

- **Wash Residue to Remove Liquor**

Liquor can be removed from residue either by:

- Water washing and vacuum filtration
- Centrifuging and resuspending in water several times

The first method is likely to be carried out routinely at Aughinish as the first step in obtaining an XRF assay of the residue and therefore may be preferred.

About 50 grams of should be washed in this way. This may require several smaller amounts of residue to be washed and combined. Residue is difficult to wash because the filtration rates are slow and in my experience when preparing large amounts of well washed residue it is preferred to combine the residue from several standard residue washing operations.

The washed residue should be combined and homogenised in a plastic beaker and a portion oven dried (at 110<sup>0</sup> C) for XRF/LOI and XRD analysis. The mass loss on drying of this portion gives the percentage residue solids in the homogenised residue.

The remainder of the residue should not be oven dried (this can change the reactivity of the components). Water should be added to the residue slurry to give a 10% weight/weight solids slurry (using the mass loss on drying to calculate the quantity of water to add). The slurry should be stored in a closed plastic bottle.

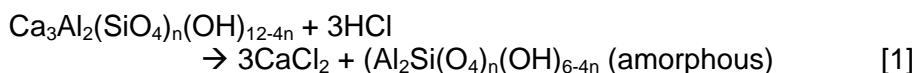
- **Reaction with Hydrochloric Acid**

Portions of the residue slurry and Hydrochloric Acid (1M) should be mixed in a closed plastic bottle until the pH stabilises.

Aughinish data has shown when the pH starts at about 6 this can take at least 1 week when H<sub>2</sub>SO<sub>4</sub> is used. The pH of the initial slurry with no HCl added also should be measured.

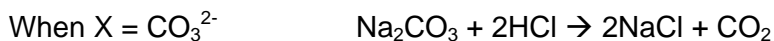
The reactions that will occur with the HCl are:

## Hydrogarnet



The Aluminium will not begin to dissolve until the pH drops to about 5. The quantity of Calcium (Ca) in solution gives the amount of Hydrogarnet and conceivably any other alkaline Calcium compounds present in the residue.

## Sodalite



The acidified solutions must be analysed (ICP is probably preferred) for Ca and Na. The supernatant liquor can be obtained by centrifuging the stabilised slurries. The Na

and Ca concentrations in the initial slurry (with no added acid) should also be measured.

A plot of Moles hydrochloric acid (HCl) added versus the Moles of Calcium (Ca) (reaction [1]) and Moles Sodium (Na) (reaction [2]) in solution at any pH gives a quantification of the alkalinity due to Hydrogarnet and Sodalite. That is, the quantity of acid required to achieve any desired pH due to the alkalinity in the residue solids.

It is also desirable to isolate the residue for XRF/LOI analysis (by filtration and washing with water) but experience has shown that this is difficult to achieve because fine residue can pass through the filter paper giving an unrepresentative sample. Assays of the "acidified residue" can also be used to calculate the quantity of Ca and Na extracted by using the "tie element" method (where the Fe and Ti present do not dissolve).

### 10.5.10.1.2 Measuring the pH of Neutralized Residue Slurries

Measuring the pH of residue slurries is not a simple process because the rates of the neutralization reactions of some of the solids are slow. A simple titration of bauxite residue with seawater for example is likely to underestimate the quantity of acid required to achieve a target pH significantly.

It is recommended that washed residue (and/or sand) is titrated with  $\text{H}_2\text{SO}_4$  (preferably about 10% acid of known molarity) as a guide to the quantity required. Then individual residue slurries can be mixed with appropriate quantities of  $\text{H}_2\text{SO}_4$  and the pH monitored until it stabilises. This may take a few days. These experiments should be carried out in closed plastic containers to prevent atmospheric  $\text{CO}_2$  from reacting and partially neutralising the alkaline slurries.

The pH of "dry" bauxite residue is slow to stabilise when mixed with water. It may take several days for the pH to stabilise (it is likely to increase during this time).

### 10.5.10.1.3 Prediction of Quantity of Acid Required

If the experiment described above is carried out it is possible to set up an algorithm to predict the quantity of acid ( $\text{H}_2\text{SO}_4$ ) required for any desired pH.

Inputs to the algorithm are:

- Residue and Liquor mass flows
- Liquor Total Soda
- The percent Calcium in the residue (the data above will give the proportion of residue Ca that reacts with acid)
- Bauxite reactive silica (this allows the quantity of Sodalite in the residue to be calculated allowing the quantity of alkaline cage Na in the Sodalite to be calculated from the proportion dissolved in the above experiment)

### 10.5.10.1.4 A Lab-Scale Process Simulation

Note that the experiment described above gives the quantity of acid required when equilibrium is reached (i.e. when the pH stabilises).

For a “process simulation” it would be necessary to carry the reactions out for the time/temperature that would occur in practice.

## 10.5.11 Neutralization of Aughinish Sand

Sand is the coarse fraction of the bauxite residue. Aughinish have requested a recommended method for investigating the neutralization of this material as it could be used as a dam wall construction material.

It is expected that sand will contain less solid alkalinity than residue. Data from Aughinish shows that Sand has around 72%  $\text{Fe}_2\text{O}_3$  compared with 43% for Residue. Sand may contain little Hydrogarnet or Sodalite and therefore may only need to be washed.

A sample of sand should be washed and analysed (including XRD to determine the compounds present) and the pH measured. If it is alkaline the  $\text{H}_2\text{SO}_4$  titration (of washed sand) should be carried out in a similar way to that recommended for washed mud.

## 10.5.12 Analysis of Aughinish Bauxite Residue Neutralization Data

### 10.5.12.1 Introduction

The preliminary data provided by Aughinish (undertaken February 2007) provides a good starting point for estimating the cost of  $\text{H}_2\text{SO}_4$  neutralization of their Bauxite residue.

### 10.5.12.2 Analysis of Aughinish Bauxite Residue Neutralization Data

The following is an analysis of the preliminary experimentation undertaken by Aughinish to assess the issues associated with bauxite residue neutralization.

- **Empirical Volume of  $\text{H}_2\text{SO}_4$  Required to Neutralize the Liquor**

The data provided shows that:

- Liquor total soda is 25.3 g/l  $\text{Na}_2\text{O}$  this is  $25.3 \times 2 / 62 = 0.816$  Molar in NaOH plus  $\text{Na}_2\text{CO}_3$ .
- The residue slurry is 58.8% solids
- 0.588 Tonne of residue is associated with  $1 - 0.588 = 0.412$  Tonne of liquor.
- 1 Tonne of residue is associated with  $0.412 / 0.588 = 0.700$  Tonne liquor. Assuming the density of the liquor is 1 this is 700 Litres
- This liquor contains  $700 \times 0.816 = 571$  Moles of Caustic

- 100 grams of 98%  $\text{H}_2\text{SO}_4$  contains  $2 \times 100 \times (98\%) / 98 = 2$  Moles  $\text{H}^+$  (approx) (98 is molecular weight of  $\text{H}_2\text{SO}_4$ ) therefore **50 grams** contains 1 Mole therefore  $50 / 1.84 = 27.17$  ml  $\text{H}_2\text{SO}_4$  per Mole  $\text{H}^+$ .

The 700 Litres of liquor associated with 1 Tonne of residue contains  $700 \times 0.816 = 571$  Moles Caustic. Therefore the:

- Volume  $\text{H}_2\text{SO}_4$**  required to neutralize the liquor is  $27.17 \times 571 / 1000 = 15.5$  Litres
- Mass  $\text{H}_2\text{SO}_4$  required to neutralize the liquor is  $= 15.5 \times 1.84 = 28.5$  Kg of  $\text{H}_2\text{SO}_4$  per tonne of residue

The titration data is plotted in Figure 1.

- 28.5 Kg of  $\text{H}_2\text{SO}_4$  per tonne of residue gives a final pH of about 10.5 and
- A further 9 Kg of  $\text{H}_2\text{SO}_4$  per tonne of residue is needed to neutralize the residue to pH 8.5.

## • Empirical Volume of $\text{H}_2\text{SO}_4$ Required to Neutralize Calcium Compounds and Sodalite

- 1 Tonne of residue contains approximately 58 Kg of Calcium (as  $\text{CaO}$ ).
- Assuming for a moment that all the Ca is alkaline (conceptually  $\text{Ca}(\text{OH})_2$ ) we have  $2 \times 58000 / 56 = 2071$  Moles  $\text{OH}^-$ .
- Therefore (as 27.17 ml  $\text{H}_2\text{SO}_4$  contains 1 Mole  $\text{H}^+$ ) we would require  $2071 \times 27.17 = 56269$  ml  $\text{H}_2\text{SO}_4$ .
- $56269 \times 1.84 / 1000 = 104$  Kg  $\text{H}_2\text{SO}_4$  per Tonne of residue to react with all the **Ca compounds**.
- 1 Tonne of residue contains say 57 Kg of Sodium (as  $\text{Na}_2\text{O}$ ).
- An empirical formula of  $(\text{NaAlSiO}_4)_6(\text{Na}_2\text{X})$  and assuming all the  $\text{Na}_2\text{X}$  is alkaline ( $\text{CO}_3^{2-}$  and  $\text{Al}(\text{OH})_4^-$ ).
- The maximum alkaline Na is  $(2 / [6+2]) \times 57000 / 62 \times 2 = 460$  Moles of " $\text{OH}^-$ ".
- Requiring  $613 \times 27.17 = 12,491$  ml  $\text{H}_2\text{SO}_4$ .  $12491 \times 1.84 / 1000 = 23.0$  Kg  $\text{H}_2\text{SO}_4$  per **Tonne of residue to react with all the alkaline Na**.

Giving a total maximum of 127 Kg per tonne of  $\text{H}_2\text{SO}_4$ .

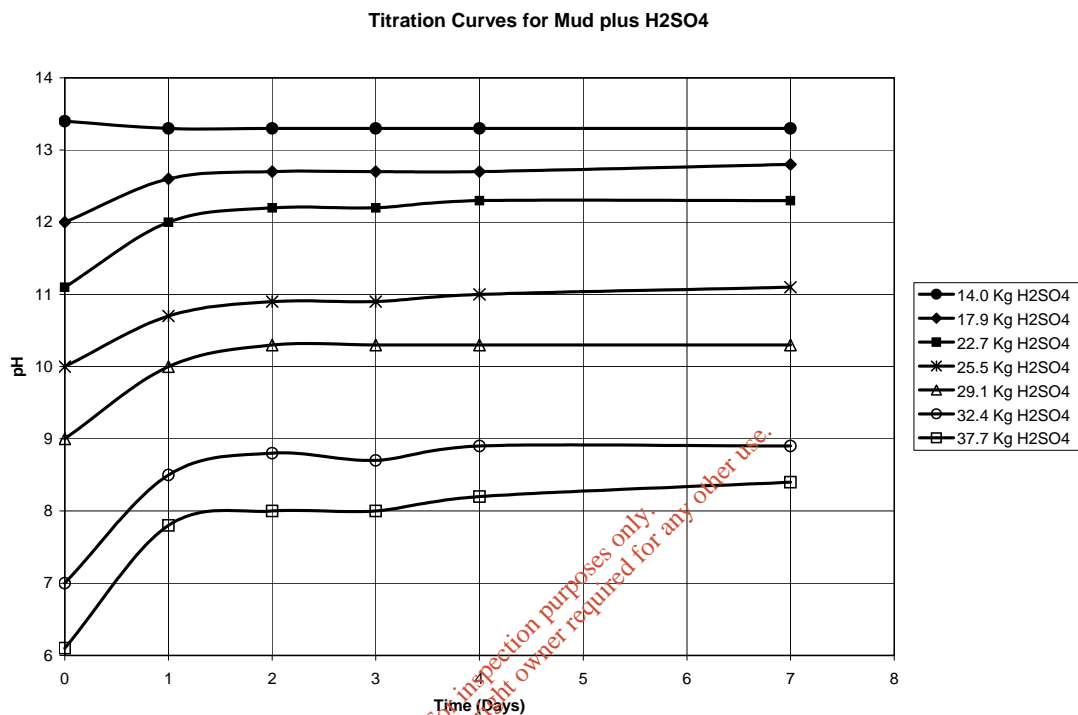
- Assuming that 28.5 Kg per tonne of  $\text{H}_2\text{SO}_4$  is required to neutralize the liquor. Very little of the Calcium compounds or the Sodalite appear to be reacting with the  $\text{H}_2\text{SO}_4$  under the conditions used.
- If 11.2 Kg per tonne (as taken from Aughinish laboratory experiments) of  $\text{H}_2\text{SO}_4$  is required to neutralize the residue solids this amounts to about 10% ( $11.2 / 127$ ) of the potentially alkaline Ca + Na. This suggests that 90% of the alkalinity in the solids remains unneutralized.

In cases where almost all the  $\text{CaO}$  used is added to digestion the portion of the  $\text{CaO}$  converted to Hydrogarnet in digestion gives a very slowly reacting product and that the



pH of this compound depends on the quantity of Silica incorporated into the Hydrogarnet (the more Silica the less alkaline the compound). This seems to agree with the data from the  $\text{H}_2\text{SO}_4$  titration. The only cautionary note is that it may take longer than 1 week for the pH to stabilise.

Figure 2 - Titration Curves for residue +  $\text{H}_2\text{SO}_4$



It has been suggested the reactive  $\text{SiO}_2$  in Aughinish Bauxite is increasing and that adsorption of Carbonate by the Sodalite is occurring.

If the Hydrochloric Acid experiment described is carried out the quantities of alkaline Calcium and Sodalite can be measured. The  $\text{H}_2\text{SO}_4$  consumption can be predicted for future changes in lime addition and Bauxite quality for any residue-liquor Total Soda.

- **Experimental Volume of  $\text{H}_2\text{SO}_4$  Required to Neutralize the Residue Solids**

From Figure 2,  $\text{H}_2\text{SO}_4$  consumption by bauxite residue from which the liquor has been removed. Clearly there is a significant quantity of alkalinity in residue solids.

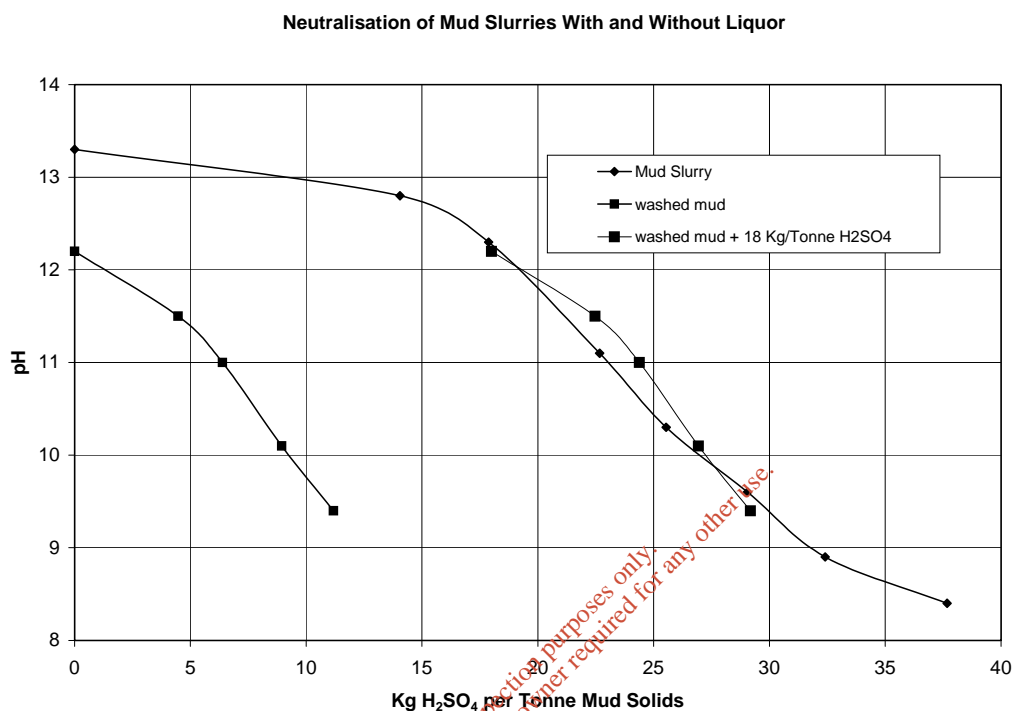
This data does not appear to be in complete agreement with the empirical calculation of the quantity of  $\text{H}_2\text{SO}_4$  required to neutralize the liquor only.

In Figure 2, the data for the residue slurry titration has been included (Day 7 pH) versus quantity of  $\text{H}_2\text{SO}_4$  and a curve for the washed residue slurry plus 18 Kg/tonne  $\text{H}_2\text{SO}_4$ . This data suggests that about 18 Kg/tonne  $\text{H}_2\text{SO}_4$  is required to neutralize the liquor (because the two curves are approximately aligned) not the calculated 28.5 Kg/tonne.

Figure 1 shows that the quantity of  $\text{H}_2\text{SO}_4$  required to reduce the pH from about 10.5 (equivalent to 28.5 Kg per Tonne) to 9.4 (the same final pH in the titration of washed

residue (see Figure 2)) is about (31 – 28.5) 2.5 Kg per Tonne of residue. Far less than the 11.2 Kg per Tonne found in the second experiment.

Figure 3 - Neutralization of Residue Slurries with and without liquor



Such differences can be typical of the first time such experiments are conducted and are likely to improve by further work.

It is recommended that liquor be separated from the residue slurry and titrated with H<sub>2</sub>SO<sub>4</sub>.

It may also be desirable to check the slurry density algorithm that results in a calculated solids content of 58.8% and all other inputs to these calculations.

Clearly it is desirable to obtain more accurate data than that available to date for the purposes of costing the neutralization process.

One can conclude that for the residue slurry in question:

- Between 18 and 28.5 Kg H<sub>2</sub>SO<sub>4</sub> per tonne dry residue is required to neutralize the liquor.
- The residue pH is about 12.2.
- 11.2 Kg H<sub>2</sub>SO<sub>4</sub> per tonne dry residue is required to neutralize the residue solids to pH 9.4.

### 10.5.12.3 The Practicality of Neutralising Bauxite Residue

There is a concern that when adding  $\text{H}_2\text{SO}_4$  during the dilution and redispersion of the residue filtercakes there may be localised corrosion. The agitation must be sufficient to prevent localised regions of low pH. As mentioned previously, if the pH is less than about 4 in any region the Sodalite will begin to dissolve and then as the pH goes up again the  $\text{Al}^{3+}$  and  $\text{Si}(\text{OH})_4$  will reprecipitate and gel respectively causing high viscosity.

Other concerns include the rate of the neutralization reaction with the residue solids. Figure 1 shows that in all cases where some neutralization of the solids has occurred the pH is higher after 1 day (although it probably takes less than 24 hours to reach equilibrium at the higher pH's). The control of the final pH will be difficult under these conditions.

## 10.5.12.4 Management of Hydrogen Sulphide ( $\text{H}_2\text{S}$ )

There is a concern the generation of  $\text{H}_2\text{S}$  will occur in the residue dam if the pH is too low (after neutralization). While, this is an important issue it is difficult to resolve.

Refineries that use seawater can have an issue with  $\text{H}_2\text{S}$ . Clearly this is a sensitive area and specific data would not be easy to obtain.

Sulphate is the source of the Sulphide so that neutralization with  $\text{H}_2\text{SO}_4$  is an unavoidable factor resulting in the presence of this nutrient".

The critical information is:

At what pH can  $\text{H}_2\text{S}$  generating organisms survive?

Seawater neutralization gives a pH of 8.5 to 9 so organisms can survive around this pH range.

Eurallumina (located in Sardinia, Italy) claims their dam pH is about 11 and that they have no  $\text{H}_2\text{S}$  smell.

Thermodynamic calculations of the equilibrium  $\text{H}_2\text{S}$  concentration versus pH and the solution Sulphide concentration show that a pH of 10.3 should be sufficiently high to suppress the  $\text{H}_2\text{S}$  concentration to below the TLV of 10 ppm (there is still a strong odour at 10 ppm) by the following reaction:



At pH 10.3 the reaction is about 99% to the right. Consequently, there is little or no smell because the concentration of  $\text{H}_2\text{S}$  is very low. However, the quantity of  $\text{H}_2\text{S}$  present also depends on the total Sulphide concentration (the higher this is the more  $\text{H}_2\text{S}$  there is at the same pH).  $\text{H}_2\text{S}$  is soluble in water so that dilution can reduce the smell.

So it may be that Eurallumina do have  $\text{H}_2\text{S}$  generating organisms in their dam **but there is no smell** (because it is present as the non-volatile NaHS).

It would be highly desirable to request Eurallumina to analyse their dam water for Sulphide and Sulphate (and to obtain more detailed pH data). If there is no Sulphide

this may be a good indication that a pH of about 11 is “safe” but that a lower pH (not exactly defined) is not.

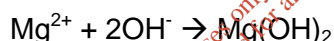
There will be Sulphate in the Eurallumina Bauxite residue dam due to their use of the Sumitomo process for scrubbing SO<sub>2</sub> from their stack gasses. The Na<sub>2</sub>SO<sub>3</sub> formed is oxidised to Na<sub>2</sub>SO<sub>4</sub>.

Perhaps aeration of supernatant liquors can prevent H<sub>2</sub>S formation (and oxidise any H<sub>2</sub>S present). If this path is pursued a microbiologist consultant could be engaged to resolve this issue.

## 10.5.13 Neutralization with Shannon Estuary Water

The following is a discussion of the merits of seawater neutralization.

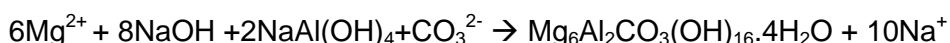
- The Mg concentration of the Shannon Estuary is 0.47 g/l (provided by Aughinish). This concentration is  $0.47/24.3 = 0.019$  Molar. Oceanic seawater is typically 1.4 g/l)
- As discussed previously both the Hydroxide and carbonate react with Mg<sup>2+</sup> (forming Hydrotalcite) so that the simple equation



- This can be used to determine the quantity required ( $2\text{OH}^- = 1\text{CO}_3^{2-}$ ) to neutralize to the pH 10.6 endpoint
- At present we have 2 estimates of the quantity of H<sub>2</sub>SO<sub>4</sub> required to neutralize the liquor in the sample investigated, 28.5 and 18 Kg/tonne dry residue
- It was calculated that 28.5 Kg/tonne H<sub>2</sub>SO<sub>4</sub> is 571 Moles H<sup>+</sup> this is equivalent to  $571/(0.019 \times 2) = 15,000$  Litres of estuary water (the 2 is from Mg<sup>2+</sup>)
- Similarly the largest quantity of H<sub>2</sub>SO<sub>4</sub> used in the first experiment was 37.7 Kg/tonne dry residue that should require about 20000 Litres to give pH 10.6.
- Aughinish data gives 21,258 Litres (21.3 m<sup>3</sup>) to pH 10.03 so the calculations are in reasonable agreement.

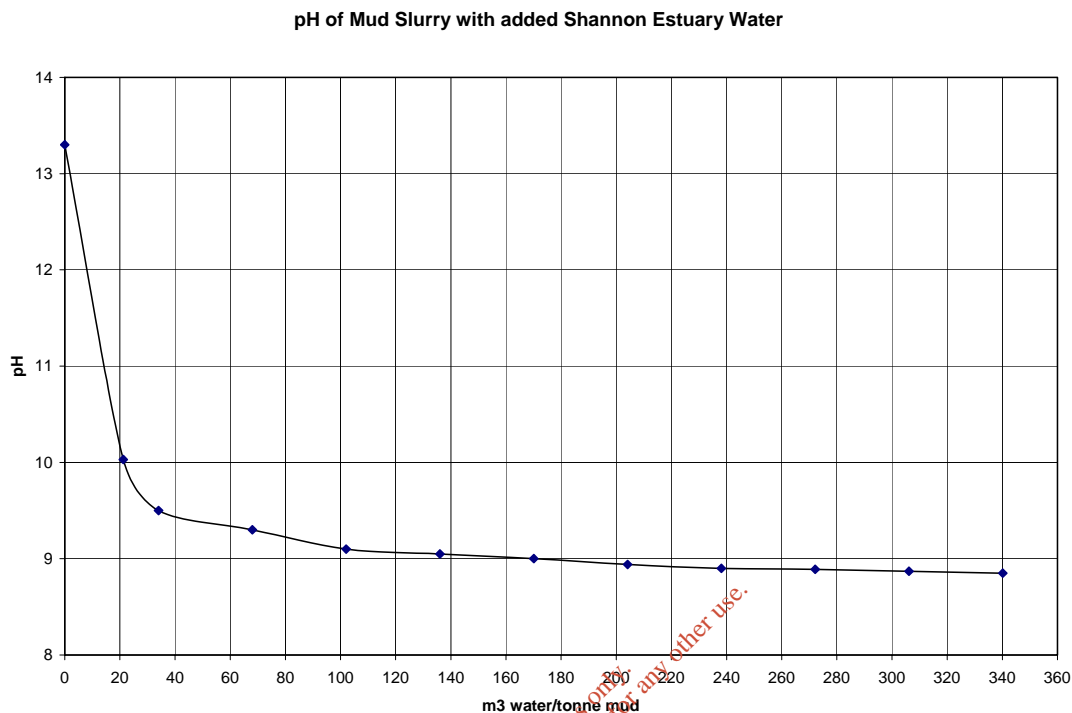
The failure to reach a pH lower than about 8.8 is likely to be due to the low Mg concentration in the estuary water resulting in very large quantities of water being required to drop the pH (but suppressing the solubility of Hydrotalcite).

The pH of Hydrotalcite is about 10.6 and the pH of seawater neutralized residue slurries is suppressed by driving the equilibrium of the following reaction to the right. It is not possible to achieve a pH much below 8.5 with seawater.



Aughinish experimental data confirms what exists in other refineries and the volume of water is similar to that used by other refineries when the more usual 1.4 g/l Mg concentration is taken into consideration.

Figure 4 - pH of Residue Slurry with added Shannon Estuary Water



#### 10.5.14 Cost

Currently, it is not possible to give an accurate cost for  $H_2SO_4$  until the discrepancy between the two methods of estimating the quantity of acid required to neutralize the liquor are resolved and a target pH is decided.

#### 10.5.15 Recommendations

While the empirical values for a neutralization process appear valid, analysis of data from the initial experimentation would suggest that further investigation is warranted. In summary the recommendations for further research include

- It would be desirable for a lab simulation of “over acidification”, followed by a pH increase under conditions that are similar to those that could occur in practice. The experimentation should include an exotherm due to dilution of the  $H_2SO_4$  to ensure that high temperatures will not occur.
- Further experimentation needs to include the residence time in the pipeline from the residue reactors to discharge. If this is a few hours there may be time for the pH to reach equilibrium. This could be investigated in the lab by measuring the pH more frequently after mixing and using the calculated temperature that will exist in the pipe due to the residue temperature plus the increase due to the reaction of the  $H_2SO_4$ .



### 10.5.16 References

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