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Investigate closure techniques for the Rusal Aughinish Bauxite Residue Disposal Area (B.R.D.A.) & show the impact on the surrounding environment post-closure.

A project submitted to Middlesex University in partial fulfilment of the requirements for the degree of Doctor of Professional Studies

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October 2011
Abstract

Rusal Aughinish operates an alumina refinery situated on Aughinish Island on the south side of the Shannon estuary. The company submitted an application to extend the Bauxite Residue Disposal Area (B.R.D.A.) by another 80 hectares in 2006. Space to store residue was estimated to run out in 2011, thus requiring the construction of the extra 80 hectares which needed planning permission and an extension of the licence. It was vital to get planning permission and licence extension. There is a large volume of residual alkalinity, held in a soluble and solid phase, retained in the bauxite. The E.P.A. has requested a Residuals Management Plan which included, as a minimum, a scope statement for the plan. The criteria, which defines the successful decommissioning of the activity or part thereof, ensures minimum impact to the environment. However, this is subject to: the provision of a sustainable vegetation cover; and demonstration of leachate attenuation to below pH 9.0 within 5 years. Residue neutralisation methods were also investigated.

Rusal Aughinish has determined that the restoration of the B.R.D.A. surface will support a “nature conservation” end-use (AAL, 2005d). Therefore, sustainable re-vegetation of the B.R.D.A. was required to support this goal. Small plot trials (2m x 1m) and larger plot trials (10m x 2m) were established, which were amended with gypsum, process sand, and spent mushroom compost which lowered the pH, exchangeable sodium percentage (ESP) and the availability of Al and Fe in the residue. The newly created soil (bauxite residue mixed with process sand, gypsum and organic waste) was seeded. Results show that the establishment of vegetation was achievable. Additionally, investigations were carried out into the use of machinery on the residue.

Two Demonstration Cells were constructed within the confines of the B.R.D.A. (0.6ha). The sides and floor of the cells were lined and a leachate collection system was installed on the floor of the cells. Monitoring of pH, electrical conductivity, and soda was conducted in run-off and leachate before and after vegetation growth on the residue in the cell. No reduction was noted in leachate or run-off pH since monitoring commenced in 2007.

Following research into neutralization methods the use of sulphuric acid was the best option, but only partial neutralization was achieved, due to the large volume of acid required for full neutralization. There was also the likelihood of creating pH conditions that would lead to H₂S odour problems. Carbonation would also be possible, but would require the construction of a plant or the importation of liquid CO₂. Seawater neutralisation using water from the Shannon estuary is prohibited by costs. An initial modelling project looked
at groundwater flow within the B.R.D.A. in two dimensions and assumptions were made as to the physical stratification and structure of the B.R.D.A. Mud-farming commenced and was evaluated.

In conclusion, direct vegetation was found to be feasible, and so avoiding the high cost of topsoil. Soil construction and plant establishment was demonstrated. Demonstration Cells were constructed as per design and monitoring for pH, conductivity and soda of the leachate and run-off was conducted before and after vegetation growth. This monitoring is still ongoing. Filling of the cell with residue was determined by the stacking angle of the residue. Controlling percentage solids of the residue is very important in order to achieve proper stacking of the residue, Leachate pH may take years to drop from 13 to 9.0 or below. Recommendations to the company include further monitoring of Demonstration Cell leachate, run-off, and the vegetation cover on the residue. Finally, it is recommended to continue investigation into residue neutralisation methods.

Acknowledgements

I would like to thank my wife Ita, my children Jack, Kevin, and Hilary for their support and tolerating my absence for many hours throughout my Doctor of Professional Studies. Also I would like to thank RUSAL Aughinish Management for sponsoring me and giving me the encouragement to take up these studies.

Special thanks must go to Trevor Montgomery and Helen Carey for their knowledge, time, help and guidance they gave me during the programme.

Finally I extend my thanks to Andrew Hodgers and Nick Hodgers for steering me in the right direction along the way.
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**Glossary of Terms and Abbreviations**

Below is a partial glossary of terms used in this report. The definitions herein are not to be taken as comprehensive, but solely as an aid to the non-technical reader.

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<th>Term</th>
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<tr>
<td>Alumina</td>
<td>A compound of two parts aluminium and three parts oxygen which occurs naturally as corundum. Alumina is the base of aluminous salts, a constituent of feldspars, micas, etc., and the characterising ingredient of common clay, in which it exists as an impure silicate with water, resulting from the erosion of other aluminous minerals. In a hydrated form it is bauxite. Alumina is used in aluminium production and in abrasives, refractories, ceramics, and electrical insulation.</td>
</tr>
<tr>
<td>Bauxite</td>
<td>A whitish, greyish, brown, yellow or reddish-brown rock composed of hydrous aluminium oxides and aluminium hydroxides and containing impurities such as free silica, silt, iron hydroxides, and clay minerals; the principle commercial source of aluminium.</td>
</tr>
<tr>
<td>Bauxite ore (AL₂O₃xH₂O)</td>
<td>Silica, iron oxide, plus other minor and trace impurities associated with it.</td>
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<tr>
<td>Bauxite Residue Disposal Area (B.R.D.A.)</td>
<td>Engineered storage area for residue.</td>
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<tr>
<td>Bayer Process</td>
<td>Predominant method used to extract alumina from bauxite Calcareous substance; Substance containing calcium carbonate</td>
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<tr>
<td>Calcination</td>
<td>A process by which a material is heated to a high temperature using heated unformed ceramic materials in a kiln or heating ores, precipitates, concentrates or residues; so that</td>
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<tr>
<td>Carbonation of bauxite residue</td>
<td>The process of adding carbon dioxide to bauxite residue with the resultant effect of reducing the pH of the bauxite residue.</td>
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<tr>
<td>Clarification</td>
<td>A process in which suspended material is removed from wastewater. This may be accomplished by sedimentation, with or without chemicals, or filtration.</td>
</tr>
<tr>
<td>Digestion</td>
<td>The process of decomposing organic matter by bacteria or chemical action or heat.</td>
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<tr>
<td>Dry stacking</td>
<td>Utilises a large diameter Super thickener to de-water the fine tailings, which is then spread in layers over the storage areas to de-water by a combination of drainage and evaporative drying.</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>Routinely used to measure salinity. The types of salts (ions) causing the salinity usually are chlorides, sulphates (ms/cm).</td>
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<tr>
<td>ESP</td>
<td>Exchangeable Sodium Percentage (ESP) reflects the saturation of the exchange complex with Na relative to other cations present in the residue.</td>
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<tr>
<td>Estuarine deposits</td>
<td>Consists of thick deposits of soft, unconsolidated silty clay, which is saturated with water; these soil layers are situated at the bottom of certain estuaries, which are normally in temperate regions that have experienced cyclical glacial cycles.</td>
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<td>Geo-membrane</td>
<td>A product used in layers along with the geo-synthetic clay liner as part of the disposal facility cover system.</td>
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<tr>
<td>Geo-textile</td>
<td>A product used as a soil reinforcement agent and as a filter medium. It is made of synthetic fibres manufactured in a woven or loose non-woven manner to form a blanket-like product.</td>
</tr>
<tr>
<td>Glacial till</td>
<td>A mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited by a glacier.</td>
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<tr>
<td>Groundwater</td>
<td>Water stored in the soil and rock both above and below the water table.</td>
</tr>
<tr>
<td>Hydraulic head</td>
<td>The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. Fluids flow down a hydraulic gradient, from points of higher to lower hydraulic head.</td>
</tr>
<tr>
<td>Integrated pollution control (IPC)</td>
<td>A system of licensing which covers all emissions to air, water and land, including noise and is intended to minimise the impact on the environment by taking account of pollution that may be transferred from one environmental medium to another.</td>
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<tr>
<td>kPa</td>
<td>kPa is approximately the pressure exerted by a 10g mass resting on a 1cm$^2$ area.</td>
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<tr>
<td>Leachate</td>
<td>Water containing contaminants that leaks from a disposal site.</td>
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<tr>
<td>Limestone rock</td>
<td>Limestone is a sedimentary rock composed largely of the mineral calcite (calcium)</td>
</tr>
<tr>
<td>Maturing</td>
<td>The rate of drying out of the bauxite residue</td>
</tr>
<tr>
<td>Neutralization</td>
<td>The process in which an acid reacts with a base to form a salt and water.</td>
</tr>
<tr>
<td>Permeability</td>
<td>The capability of a porous rock or sediment to permit the flow of fluids through its pore spaces.</td>
</tr>
<tr>
<td>pH</td>
<td>A logarithmic scale for expressing the acidity or alkalinity of a solution.</td>
</tr>
<tr>
<td>Piezometer</td>
<td>An instrument used to measure the level of the water table.</td>
</tr>
<tr>
<td>Pollution</td>
<td>The direct or indirect alteration of the physical, chemical, thermal biological, or radioactive properties of any part of the environment in such a way as to create a hazard or potential hazard to the health, safety or welfare of living species.</td>
</tr>
<tr>
<td>Process sand</td>
<td>Graded medium sand having 90% and 10% of the particles smaller than 500 and 100 microns respectively.</td>
</tr>
<tr>
<td>Pulp density</td>
<td>Solids content.</td>
</tr>
<tr>
<td>Red mud</td>
<td>A reddish-brown bauxite soil remaining after the extraction process. The red colour is derived from the iron oxide content. It consists</td>
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of porous agglomerated particles containing some 70% to 80% of amorphous oxides, hydrated oxides and oxy-hydroxides.

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<td>Residual dissolved caustic</td>
<td>It is this residual dissolved caustic which gives the red mud its elevated pH characteristics.</td>
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<tr>
<td>Rill volume ‘soil loss’</td>
<td>This is a measure of soil detachment, while the erosion pin ‘soil loss’ indicates the transportation of soil down-slope.</td>
</tr>
<tr>
<td>Run-off</td>
<td>The gravity flow of surface water in open channels.</td>
</tr>
<tr>
<td>Salt cake</td>
<td>A by-product of the extraction of alumina from bauxite. It is considered a hazardous waste largely due to its constituent of oxalate.</td>
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<tr>
<td>Stoichiometric</td>
<td>In general, chemical reactions combine in definite ratios of chemicals. Since chemical reactions can neither create nor destroy matter, nor transmute one element into another, the amount of each element must be the same throughout the overall reaction.</td>
</tr>
<tr>
<td>Supernatant</td>
<td>The clear liquid remaining when a precipitate has settled.</td>
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<tr>
<td>Suspended solids</td>
<td>Any particulate matter which is suspended in water.</td>
</tr>
<tr>
<td>Sustainable development</td>
<td>Defined by the Burntisland Commission (1987) as “development that meets the needs of the present without compromising the ability of the future generations to meet their own needs”.</td>
</tr>
<tr>
<td>The upstream method</td>
<td>On-going building of embankments upwards to contain the bauxite residue.</td>
</tr>
<tr>
<td>Thixotropic</td>
<td>This describes a material which undergoes a reduction in viscosity when shaken, stirred or otherwise mechanically disturbed and which readily recovers to dry and stack.</td>
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<tr>
<td>Viscosity</td>
<td>Is the quantity that describes a fluid's resistance to flow.</td>
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Chapter 1 – Introduction
1.1 Introduction

RUSAL Aughinish operates the alumina refinery situated on Aughinish Island on the south side of the Shannon estuary. The island is located between Askeaton and Foynes and is some 30 km west of Limerick City. The Island is approximately 400 hectares in area and is bound by the River Shannon to the north, the Robertstown River to the west and south-west and the Poulaweala creek to the east and south-east. The existing Phase 1 Bauxite Residue Disposal Area (B.R.D.A.) is located south-west of the existing process plant. The proposed Phase 2 B.R.D.A. is located immediately to the south of the existing Phase 1 B.R.D.A.

Rusal Aughinish submitted an application for an Integrated Pollution Control License (I.P.C.L.) in 1995, under the terms of the Environmental Protection Agency Act 1992. The license was granted in May 1998 and a revised license was issued in January 2004. In 2006 the company submitted an application to extend the B.R.D.A. by another 80 hectares.

In the case of the B.R.D.A. run-off, which is returned to the plant for treatment, the Environmental Protection Agency (E.P.A) has asked the company to prove /demonstrate that the pH will be 9.0 in five years following closure, with minimum impact to the environment. They also added a condition to neutralise or partly neutralise the residue prior to depositing it in the extended area of the B.R.D.A. by 2012.

Residue stability will be provided for by the installation of a robust and self-sustaining surface vegetation cover, which sheds the maximum amount of runoff and utilises significant amounts of soil moisture in evapotranspiration. There is an expectation that a surface cover will provide for decreases in sub-surface run-off, which will in turn lower the pH of the combination of run-off / leachate mixture. Neutralisation or partial neutralisation of the residue will also need to be evaluated and a pilot scheme put in place prior to full neutralisation in the coming years.

The future of the company and the length of time it stays in production depend on the space in the B.R.D.A. available for bauxite residue. As there is only space at present production rates until 2011, it is vital for the company to receive planning permission and a licence from the EPA to extend the existing B.R.D.A. by 80 hectares.

The company are prepared to spend €40 million on the Phase 2 extension to extend the life of the plant to 2026. They need planning permission and the licence extension from the E.P.A. before work can start. The jobs of 450 employees, plus up to 150 contractors, depend on Aughinish staying in production.
It is necessary to demonstrate to the Regulatory Bodies that the pH of the run-off will drop over time and that by sowing grass on the residue it will enhance the appearance of the area and avoid any potential for dusting when the residue dries out. The establishment of vegetation on the residue will improve its physical stability, reduce erosion, and also the dispersion of dust on the surrounding environment. It could reduce run-off and also reduce the high pH (13.0) leachate from the residue. In addition, it mitigates the visual impact and will facilitate a beneficial post-closure after use of the B.R.D.A.

A pilot scale version of the existing B.R.D.A. has been constructed and divided into two demonstration lined cells, 0.6 hectares in size in total. This area was constructed in the north-eastern section of the B.R.D.A. at a cost of €250,000.

The result of run-off and leachate plus the effects of grass growing on the residue would determine the environmental effects of closing the existing B.R.D.A. The following research work was carried out:

- Sixty small plots (2m x 1m) were constructed in order to obtain the correct “recipe” for vegetation growth on the residue in the Demonstration Cells. An area of 0.4 hectares in size and divided in to eleven plots 10m x 2m. All these trial areas were amended and vegetation established and monitored for 18 months. The main purpose of the larger area was to gain experience of using large machinery on the residue. Six one-tonne containers were filled with residue and leachate and run-off and were monitored for 18 months for pH, soda and electrical conductivity and rate of compaction recorded.
- These Demonstration Cells were filled with residue, amended with sand, spent mushroom compost, and gypsum and vegetation established.
- Herbage analysis was conducted and a plant diversity survey conducted in the plots sown in 1997 and 1999.
- Groundwater flow modelling and hydrological / hydro-geological modelling within the B.R.D.A. was carried out to obtain more information on the residue, including seepage and pH results.
- Residue neutralisation techniques were investigated.
- Residue management systems and closure techniques of other alumina plants around the world were researched.
- Finally, a visit and tour was completed of a closed bauxite residue disposal site in Scotland.
1.2 Rusal Aughinish.

Figure 1  Rusal Aughinish Plant

Rusal Aughinish Ltd, as part of Rusal, a Russian company which is the largest producer of aluminium and alumina in the world, operates an alumina refinery situated on Aughinish Island, Co Limerick, Ireland. The plant employs 450 permanent employees and 150 contract personnel. The operation contributes more than 40 million Euros per annum to the local economy in terms of wages and services.
1.3 Description of the Operation

The plant and ancillary structures were constructed between 1978 and 1983 representing an investment of some €0.8 billion, which is the largest single private investment in the Irish economy. Plant production has continually increased since the commissioning of the plant in 1983 and current production is approximately 1.85 million tonnes of alumina per annum (MTA). The Phase 1 B.R.D.A. will provide storage to the end of 2011, based on the company’s current planning permission conditions which allow RUSAL Aughinish to raise the facility to Stage 7 (elevation 18m AMSL), which equates to a central elevation of 27.5m AMSL, or 26m above original ground level. It is now proposed that three more stages be added (Stage 8 elevation 20m AMSL, Stage 9 elevation 22m AMSL and Stage 10 elevation 24m AMSL), resulting in a maximum central elevation of 32m AMSL.

The basis of the operation is a Bayer plant which extracts and refines alumina from bauxite which is imported from Guinea in West Africa, and the Amazon Basin in Brazil. All the alumina is exported, some 97% destined for aluminium smelters where it is converted to aluminium with the balance sold as hydrate of alumina for use in water treatment plants and other chemical applications. The reason the bauxite is bought in these countries is due to its higher percentage of alumina. Some of the Australian bauxites have lower concentrations of alumina and higher mud percentage. This means higher transport cost plus higher production costs.

The plant is a high-temperature digestion process treating bauxite ore to make metallurgical grade alumina, a fine white crystalline powder. The Bayer Process is well established worldwide and the principles have changed little since its invention in the late 19th century. At present there over 50 similar alumina plants throughout the world and the Bayer Process is the predominant method used to extract alumina from bauxite. At Aughinish the imported bauxite is stored temporally, then crusted and ground prior to treatment with hot caustic soda solution to dissolve and extract the alumina. The insoluble constituents of the bauxite; mainly sand (5%) and the finer bauxite residue (20%) are separated from the pregnant solution by filtration before the alumina is precipitated as slurry of white aluminium hydrate \((\text{Al}_2\text{O}_3.3\text{H}_2\text{O})\). The slurry is then filtered and calcined at 1000°C to make alumina \((\text{Al}_2\text{O}_3)\), which is stored in silos prior to export through the company’s marine terminal. The sand and bauxite residue are stored along with some other process...
residues in a permanent storage area adjacent to the refinery on the western side of the island, this area is named the B.R.D.A.

Currently, an accumulated 16 million m$^3$ of residue (bauxite residue and sand) are stored in the B.R.D.A that covers 103 hectares. A planned extension to the B.R.D.A for 2011 will result in a final closure area of 182 ha with a capacity for 21.5 million m$^3$ of residue. Besides Rusal Aughinish, the other stakeholders in the project include the Environmental Protection Agency (EPA), Limerick County Council, Shannon Regional Fisheries, the local community and other Alumina plants worldwide.

The life of the plant can be extended indefinitely as long as there is a demand for alumina, and suitable bauxite can be purchased and processed economically. In contrast, the life of the B.R.D.A. is finite, governed by the permitted volumes of material that can be deposited and the production rates from the plant.

1.4 Closure Requirement for Rusal Aughinish

In June 1995 Rusal Aughinish Limited submitted an application for an Integrated Pollution Control License (IPCL) under the terms of the Environmental Protection Agency Act 1992. The license was granted in May 1998 and a revised License was issued in January 2004. Two conditions of the license concerned the eventual closure of the site. Condition 14 deals with site closure and decommissioning, while Condition 15 is concerned with the financial provisions Rusal Aughinish Ltd should make for closure. The most pertinent extracts from Condition 14 in respect of preparation of a closure plan include the following:

“Following termination or planned cessation for a period greater than six months, of use or involvement of all or part of the site in the licensed activity, the licensee shall, to the satisfaction of the Agency, decommission, render safe or remove for disposal/recovery, any soil, sub-soils, buildings, plant or equipment, or any waste, materials or substances or other matter contained therein or thereon, that may result in environmental pollution.”
1.4.1 Residuals Management Plan

The Residuals Management Plan as agreed with the EPA and is reviewed annually and proposed amendments there to be communicated to the Agency for agreement as part of the Annual Environmental Report (A.E.R.). No amendments may be implemented without the written agreement of the EPA.

The Residuals Management Plan shall include as a minimum, the following:

- A scope statement for the plan.
- The criteria that define the successful decommissioning of the activity or part thereof, which ensures minimum impact to the environment.
- A programme to achieve the stated criteria.
- Where relevant, test programmes to demonstrate the successful implementation of the decommissioning plan.
- Details of costing for the plan and a statement as to how these costs will be underwritten.

A final validation report to include a certificate of completion for the residuals management plan, for all or part of the site as necessary, shall be submitted to the EPA within three months of execution of the plan. The licensee shall carry out such tests, investigations or submit certification, as requested by the Agency, to confirm that there is no continuing risk to the environment.

In the case of the B.R.D.A. run-off which is returned to the plant for treatment, the E.P.A. has asked the company to prove / demonstrate that the pH will drop to 9.0 or below in five years following closure, with minimum impact to the environment.

1.5 Aims and Objectives

The aim of this research project was to determine feasible options for achievement of the licence requirements, to demonstrate a closure technique of the Bauxite Residue Disposal Area (B.R.D.A) at Rusal Aughinish and show the impact with the surrounding environment post closure. Concurrently knowledge of bauxite residue settling would be improved and management would gain expertise in bauxite residue rehabilitation methods.

The objectives of the project were achieved by constructing trial plots initially, to ameliorate the residue, and sow grass. The results from these trials provided the “recipe” for
the vegetation sown on the constructed site. The specific objective was to build the
Demonstration Cells, 100m x 90 m (0.6 ha) within the Bauxite Residue Disposal Area
(B.R.D.A) stack embankment. This was filled with bauxite residue over a period of a few
months by installing high-pressure pipe work 0.5km in length from the main distribution
system into the Demonstration Cells. Finally, it is intended to predetermine the environmental
effects of closing the existing B.R.D.A. on the surrounding areas.

Demonstration Cells
These were mini versions of the B.R.D.A. Research carried out on the Demonstration Cells
included sampling the leachate from under the residue. A collection system built during
construction under the residue allowed for this facility. Neutralisations systems were
researched and vegetation trials evaluated. This included a visit a closed alumina refinery and
its rehabilitated residue area in Scotland.

Figure 2 Program Plan

1.5.1 Programme Planning

The expansion of the B.R.D.A. is vital for the long-term life of the plant and meeting the
conditions of the Integrated Pollution Control Licence (I.P.C.L.). The company requires the
researching of this project to comply with the licence. The alumina industry needs this
research and further options in rehabilitation methods. The author has the professional expertise and knowledge which will help to achieve this.

There were some gaps in rehabilitation knowledge from the Aughinish perspective, namely:

- did the residue percentage solids affect duration of residue drying time?
- would artificial fertilisers enhance vegetation growth on the residue?
- there was no experience in the use of machinery to spread sand, compost or gypsum.
- did the soda levels in the bauxite residue affect amendment rates for vegetation?

The E.P.A. has also requested the company to neutralise the residue placed in the Phase 2 expansion of the B.R.D.A. by 2012. The best option to neutralise or part neutralisation Aughinish residue was needed. This will mean researching neutralisation methods, complete the costing of implementation, set-up and pilot a system and then construct / install a facility to neutralise the residue before pumping to the Phase 2 extension.

In order to prove that the pH will drop to 9.0, the Demonstration Cells (0.6 ha in size) were constructed which function as a miniature version of the B.R.D.A. Bauxite residue (red mud) was pumped into the Demonstration Cells from the plant, it was allowed to mature, the residue was amended and sown with grass. The run-off and leachate was monitored for pH, electrical conductivity, and soda values including quantities. It is intended that the Demonstration Cells would provide an acceptable closure technique to the E.P.A.

The management of water is an aspect of the process and includes the disposal of water into the river Shannon under licence. All run-off from the B.R.D.A. must be returned to the plant for treatment prior to discharging it into the river. Due to its size every inch of rainfall on the B.R.D.A. means the treatment of 28,000m$^3$ of high pH water in the Waste Water Treatment Plants, plus the water that has leached out of the mud.

### 1.6 Team Members

To expand the B.R.D.A. in the next two years will cost €40 million to extend the life of the plant to 2026, and the author was part of the team to complete this project, along with the trials needed for the licence. If the project does not go ahead, the plant will close after 2011. The alumina industry worldwide are very interested in this project, as very little is known or
done with bauxite residue and all plants are coming under increasing pressure to rehabilitate their residue areas as way as pay greater attention to the environment.

The author’s interest in the environment came about through involvement in the Waste Effluent Treatment Plants and the management of the B.R.D.A. This led to a Post-Graduate Diploma in Environmental Protection, which consisted of 8 modules over two years. A year later the author completed an MSc in Environmental Protection. The long-term aim is to improve his knowledge of the B.R.D.A. and become an expert in this field. The company have financed the project and to complete the DProf. A team was assembled to engineer and construct the Demonstration Cells and complete the grass-growing trials. The author was Project Manager for the project and was given the opportunity to research this project and gain more knowledge of bauxite residue and acceptable closure techniques; it also helped the company to acquire greater expertise within the industry. The cost of extending the B.R.D.A. is $40 million, to which the company is committed.

The alumina industry worldwide is very interested in this project, as very little is known about rehabilitation methods on amended bauxite residue or residue neutralisation. Mostly topsoil has been used to cover the bauxite residue and then grass is usually sown. In case studies at other alumina plants, the emphasis has been on vegetation growth to cover the residue, very little information is available in terms of run-off or leachate. Nor has there been much research of environmental impacts around these residue disposal areas.

The author’s process knowledge gained over the past 27 years in Aughinish started with training in Canada in an Alcan refinery and assisting with the start up teams to draw up pre-commissioning and commissioning plans for the Aughinish plant. The author has also worked in several areas of the plant in various roles including all our expansions projects, the mud filtering and Bauxite Residue Disposal Area (B.R.D.A.) and the wastewater treatment plants.

The author also gained experience in plants in Spain, Canada, and Brazil, including the start-up of an alumina refinery plant in Brazil, and was involved in the engineering, scoping and commissioning of expansion projects associated with the water treatment plants and upgrades to settling and filtration processes.

As part of the process, the author has worked in the settling, thickening of the bauxite residue and the storing, plus management of the disposal area (B.R.D.A.). In the projects to expand the B.R.D.A., the author gained skills and experience in planning applications for the expansion of the disposal area. Process knowledge of the bauxite residue circuit and the wastewater treatment plants and the management of the B.R.D.A. gave the
The author was given the authority and the responsibility to make changes to the process in the Filtration Building during the periods of pumping residue to the Demonstration Cells. These adjustments were required to lower caustic levels in the residue and to pump at higher densities, which was important for residue settling and distribution. The switch over from normal pumping to pumping to the Demonstration Cells had to be completed without any trip outs or shut downs of the plant.

The caustic concentrations determine the amendment rates. Two process operators were made available to the author to make the pipe work switches and process adjustments. In conjunction with the Engineering Department, the author decided on the routing of the piping to pump residue to the Demonstration Cells plus the valve arrangements.
Programme Plan

Trial Cells

Amend Mud

Sow Grass

Sample runoff and leachate

Install Pipework

Engineer Demonstration Cells

Build Demonstration Cells

Fill with Residue and amend

Sow Grass

Secondary Data Collection

Procedure for grass growing

Neutralisation of Bauxite residue

Aug/Sep ’05 Jan ’06 Apr/May ’06 Aug/Sep ’06 Sep ’06 Oct ’06 May ’08 May ’11

Figure 3 Programme Time table
1.7 Reflections

The author’s concern was for the company’s future. If planning and the E.P.A. licence extension for the B.R.D.A. were not forthcoming, then the plant would close with a devastating loss to the area. There was some local resistance by farming communities to the plant and to the company’s application to extend the life of the plant. A few local farmers had complained about fallout from the stacks, as well as animal deaths during the 1980s. The E.P.A. and the Department of Agriculture investigated these complaints, but nothing was found that related to the refinery operation. Concerns would centre around the bauxite residue with possible dusting in case it would carry beyond the site boundary, and also the visual aspects of the B.R.D.A. itself.
Chapter 2 - Rusal Aughinish operation and worldwide best practice
2.1 Residue Management at Rusal Aughinish

2.1.1 Terms of Reference

The Stakeholders in the Project include Rusal Aughinish, EPA, Local Authority, Shannon Fisheries Board, Local Community, other alumina plants and the author.

2.1.2 Rusal Aughinish

Bauxite residue disposal is a major issue for the company into the future. At present there is only storage space in the Phase 1 section until 2011. The extension of 80ha will extend the life of the plant to 2026. Planning permission is required, as well as an extension of the licence from the EPA to put residue into this area once constructed.

The company agreed to carry out research into rehabilitation methods of the residue to meet the demands of the E.P.A. From the trials conducted in this project, the company will be in a position to provide sustainable vegetation on the residue that will be self-managing and robust for the site conditions.

Monitoring the pH values, electrical conductivity, and soda values from the Demonstration Cells run-off and leachate will determine the length of time required to lower the pH from 13.0 to 9.0 at which time the Waste Water Effluent Plant could be closed down and run-off allowed exit directly into the Shannon River. The facilities installed at the bottom of the Demonstration Cells will allow sampling to be done. Prior to this, there was no means of sampling under the residue in the B.R.D.A. unless by drilling to sample the mud.

The EPA requires the company to put a neutralisation system in place for the residue before any residue is stored in the Phase 2 extension. The Phase 2 section will be required in 2012.

Therefore neutralisation options were researched and how the chosen system could be installed in the process to neutralise, or at least partially neutralise, the residue before it is deposited in the Phase 2 disposal area.
2.1.3 Environmental Protection Agency

The EPA must ensure that the company has an adequate closure plan in place and be confident that the company does not walk away and leave 30 million tonnes of residue in the disposal area with a high pH. The EPA has requested that the residue area is capped at closure with sustainable vegetation to prevent dusting. Rusal Aughinish must ensure that dusting does not occur which could be carried over the site boundary, also that untreated run-off or seepage is not allowed into the Shannon River. The closure technique and the final landscape must include long-term plans for the site and its contents.

2.1.4 Local Authority

The Local Authority, Limerick Co. Council, requires that the construction of the 80-hectare extension is properly constructed to international standards, that all visual aspects are acceptable, and that dusting cannot occur which could carry to the surrounding countryside. Mature trees are required on all sides, except the riverside.

2.1.5 Local Community

Visually the site is of concern to locals; they meet with the company each year and are updated on progress and plans. The main concerns are the possibility of dusting in dry or frosty weather but the company has installed an automated sprinkler system across the whole residue area, which is more than adequate to prevent any such thing from happening. Meaningful communications with the local residents is seen by the company as the way to proceed.

2.1.6 Shannon Regional Fisheries Board

To protect aquatic life in the Shannon River, the board is concerned about waste effluent parameters and quantity. The company is governed by their E.P.A. licence and has an automatic control system in place to prevent any contamination or out-of-specification
pumping to the Shannon River. Some of the parameters include solids concentrations, pH, temperature, and hourly / daily flow rates.

2.2 Scope of Rusal Aughinish Operation.

This scope includes
- residue production
- design
- residue management
- principles of sustainable management
- elements of sustainable management
- bauxite residue management
- organisational principals
- chemical properties
- general
- bauxite residue (red mud)
- water management
- review previous trials in Rusal Aughinish.

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

Bauxite residue is the industry-accepted term for the residual material remaining 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 Aughinish approximately 0.7 tonnes of residue is generated for every 1 tonne of alumina produced.

The amount of residue produced depends on the quality of the bauxite and where it comes from. Different bauxite mines have different levels of alumina, iron, sand, etc. The Australian plants have lower quality bauxite, but the bauxite is closer to the refinery and the process is low temperature process. These plants have very high production rates. Analyses of Australian bauxite from the WEIPA and Darling Mines show gibbsite $\text{Al(OH)}_3$, 58% and 51%
and boehmite Al(OH) of 12.5%, 0.4%. The Guinea mine in West Africa, which supplies Rusal Aughinish, has gibbsite of 71.9% and boehmite of 14.4% (Whittington 1996).

Rusal Aughinish ship the highest quality bauxite over a much greater distance as it is more beneficial production-wise to do so. When looking at requirements for the B.R.D.A. at Aughinish it is necessary to examine other plants and what they have and what they do. All bauxite at Aughinish comes from the Amazon basin and West Africa. Other bauxites have been tested through the years but only in times of low stocks and carrying out trials. These trials generally resulted in process problems in mud settling / separation resulting in a poorer product quality and lost production.

The bauxite residue is approximately 90% red mud and 10% process sand (+100 microns). The process sand fraction is removed via a sand trap before mud circuit in the refinery; it is washed in drum filters and then trucked to the B.R.D.A. The process sand consists of an agglomerate of particles of less than 1000 microns. The agglomerates comprise clusters of mineral grains which are generally less than 4 microns. The mineral grains are amorphous or very poorly crystalline. Process sand is trucked to the B.R.D.A. and is used to create perimeter embankment walls and isolate the site from red mud disposal activities. The red mud contains a residual concentration of sodium 10-15 g/p/l Na₂O in liquid phase, with approximate mineral make-up of 45% Fe₂O₃, 20% Al₂O₃, 10% TiO₂, 10% SiO₂, 7.5% CaO, 7.5% Na₂O (including bound sodium hydroxide as descilication product). The bauxite residue consists of porous agglomerated particles containing some 70% to 80% of amorphous oxides, hydrated oxides and oxy-hydroxides. The bauxite residue particles are sub-rounded, friable with a very low crushing strength.

The bauxite residue is a silt of intermediate plasticity with a general range of liquid limits between 40% and 50% and plastic limits between 30% and 45%. Sedimentation tests indicate the clay size particles make up between 33% and 44% of the bauxite residue and silt size particles between 44% and 53% of the bauxite residue. Therefore the moisture content ranges generally between 37% and 47% for mature bauxite residue. There are difficulties in measuring the moisture content of the bauxite residue because of its amorphous mineral composition and high caustic nature.

The dry density of the bauxite residue varies between 1.3t/m³ and 1.6t/m³, which increases with depth, and the average dry density beneath the stack walls is 1.41t/m³. The overall average dry density of the bauxite residue forming the dome area, however, will be less than this and closer to 1.35t/m³ (URS, 2002). The average specific gravity ranges between 3.05 and 3.10.
2.2.1 **Residue Production**

Red mud is pumped with high-pressure pumps to the B.R.D.A. Filtration section via distribution pipelines and discharge network. The network provides for a number of discharge points that were cycled on a 12 hourly basis, but due to the present limitation on space, the rotation of the discharge points takes place every few hours during the day shift and one to two times during the night shift. The deposited layer is allowed to dry somewhat before next layer is placed. Originally after three or four layers of red mud were deposited, the residue received several weeks of drying, depending on climatic conditions, before the process recommenced, but in later years it has been necessary to save space until the extension is constructed by more frequent rotation of the points. This is the critical control of solids management at present. The residue must be pumped at maximum solids concentration, to a distribution point that changes over every few hours. This greatly increases the manpower requirement to change valve arrangement regularly. If the residue is pumped at low density it will flow across the residue to the embankment and will not stack up. This limits the storage capacity and also increases drying time.

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

On expansion of the Aughinish refinery to 1.85 Million tonnes per annum of alumina, total bauxite production will be:

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

The classification of both of these wastes as defined in the Waste Management Acts 1996 – 2003 is: Non-Hazardous.
2.2.2 Design of B.R.D.A.

The initial design concept for the B.R.D.A. was based on a water-retaining structure to store wet bauxite residue. This design required the removal of the estuarine soils to the glacial till beneath the dam foundations, which was a significant undertaking. This original design was never implemented and was subsequently revised in 1974. The disposal of bauxite residue was changed from wet bauxite residue disposal to the Giulini System, in which the bauxite residue is discharged as a paste from a central discharge area forming a slope of 10 H:1 V (6 degrees). With this approach, it was designed for a 1m high perimeter bund, which would be adequate to retain the bauxite residue for the life of the facility. The base was formed by the in-situ low permeability natural estuarine soils or, where they were of insufficient depth, by imported compacted estuarine fill. The footprint of the B.R.D.A. was located on the estuarine soils. It was envisaged that the central discharge point would attain a height of 30m and give a 25-year life for the plant. This was estimated at the original production rate of 0.8 million tonnes per year and not 1.8 million tonnes at present. It was apparent from that the initial start-up that the 10H;1V slopes could not be achieved.

The B.R.D.A is a structure engineered 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:

- Phase 1 B.R.D.A. 90 ha 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 B.R.D.A.

- The Phase 1 B.R.D.A. extension 40ha is also provided with a composite lining of high-density polyethylene (H.D.P.E) and screened glacial till and some occasional geo-synthetic clay liner (GCL).

- The proposed Phase 2 B.R.D.A. (80ha) will adopt a composite lining of High density polyethylene (H.D.P.E) and geo-synthetic clay liner (GCL) /glacial till depending on materials available.

Seepage limits set by the 1974 planning approval for Phase 1 B.R.D.A. for ponded storage of the wet unfiltered red mud, established an acceptable limit for seepage of 371m$^3$/day. The lining of the B.R.D.A. 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 sub-soils and permitted expansion of the B.R.D.A. without exceeding the seepage planning approval.

These design parameters have implications for the rate of seepage to groundwater, also the rate of seepage to the interceptor channel and this in turn affects the quantity of Storm Water / run-off that is returned to Waste Effluent Plant for treatment. If there are excessive volumes of seepage, it will be collected in the observation wells that are located around the B.R.D.A. (40 wells in total). Clearly all this has implications for the final pH.

Aughinish has adopted the ‘Upstream raising’ method of providing incremental residue capacity increases to the B.R.D.A. 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 33⁰ 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 B.R.D.A., 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 rock-fill placed over either a layer of process sand or a geo-textile liner fabric. As part of the Phase 2 works, a filtering system will be required upstream of the rock-fill embankment walls to prevent the migration of particles of red mud as a result of water erosion.

Surrounding the B.R.D.A. is a perimeter interceptor drain to collect rainfall run-off from the site and direct it to the Storm Water Pond for neutralisation and discharge (Figure 4). 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 run-off 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, designed to accommodate a 1 in 10,000 year flood, will drain into the PIC via decant structures.

From Aughinish’s experience and the different types of storage handling of residue around the world the company have scoped Phase 1 and 2 extensions in such a manner to handle excessive rainfalls, with increased storage capacity for run-off and the collection systems around the channels. The limitation with periods of high run-off and high returns to the Waste Water Treatment plants is not the treatment but the limitation the E.P.A. have put on the pumping rates to the river Shannon (21,000m$^3$ per day). The company are at present negotiating with the agency to have this rate increased given the extra collection area for rainwater on the Phase 2 extension.

![Embankments on east side of the B.R.D.A. and Storm Water Pond.](image)

**Figure 4** Embankments on east side of the B.R.D.A. and Storm Water Pond.
2.2.3 Solids Management

Good solids management is critical due to space limitations. This is managed by process operators, who must target the highest possible percentage soils that the pumps can pump without causing the pumps to trip out which shuts down the Filtration building. Maximum condensate wash flows to the vacuum filters are also important to reduce caustic soda levels in the residue.

2.3 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” for 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 reflect 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. For this reason Rusal Aughinish have consulted and informed the local residents by means of an annual “Neighbours Meeting” on site of future plans, upgrades, applications for planning permission, etc. This system has worked well to keep people well-informed, and increases their knowledge of the process. The company have brought about some changes as a result of feedback from those meetings. 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 can only be achieved through a systematic approach to the design, operation and closure of a tailings facility and that this process includes 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). This states that when applied to tailings management, “Enduring Value” requires operators to undertake a broad range of initiatives, including:

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

2.4 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 lead
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 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 (MCMPR and MC, 2003), the key issues that need to be addressed for closure are:

- Containing/encapsulating the residue to prevent its escape into the environment;
- Minimizing seepage of contaminated water from the residue 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 minimise post-closure maintenance; and
- Ensuring adequate sequential land use controls.

Therefore, the key elements of a sustainable residue management system are systems and designs that at closure can demonstrate appropriate

- 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;
- modelling of hydrological/hydro-geological impacts;
- planning to execute the closure requirements;
- relinquishment criteria;
- landform & aesthetics;
- post-closure management and acceptance;
- operational residue system;
• operational Controls to ensure alignment of operations with “Design Closure”;
• consultation with stakeholders;
• site operation using a Certified Environmental Management System ISO14001;

The above key elements show that the company has a sustainable management system in place as they follow those elements to the letter of the law. From research of other plants and their evaluation, it is evident that Rusal Aughinish has a good sustainable management system. The residue management system at Aluesa in the north of Spain has ponds; the Gardonne plant and Greek plants pump to the sea. The Brazilian Plant in the Amazon Basin store residue in single ponds and when full, construct another one. The Canadian plant where the author worked had ponds and later pumped to an old mine.

Looking at worldwide systems for residue storage, it is the author’s opinion upon reflection that the Aughinish plant will never experience a disaster similar to the Hungarian B.R.D.A. spillage of 2010. In this case the Hungarian plant had a pond with a single embankment 30 feet high with low concentrated slurry stored behind the embankment that failed and millions of tonnes of slurry flowed into the nearby town. The author has noted that the B.R.D.A. management at Aughinish has worked well since start-up, with no licence breach, no spills and no dusting. Dry stacking methods present in Aughinish are now becoming more of the norm around the world, rather than ponds. It is the author’s opinion that the design and the overall management of the B.R.D.A. at Aughinish is world-class. Risk assessments carried out for each new lift stage that is constructed.

2.5 Residue Management

Generally, 1–2 tons of bauxite residue are generated for every ton of alumina produced (Hind et al., 1999; Kumar et al., 2006). Residue generation may be as little as 0.3 tons per ton of alumina, or as much as 2.5 tons for low grade ore (Cablik, 2007; Paramguru et al., 2005). In 2006, it was estimated that nearly 90 Mt of bauxite residue was produced worldwide (Kumar, 2006).

The volume of residue produced is also dependent on the dry density of the bauxite residue and sand and a conservative value of 1.35t/m$^3$ and 1.45t/m$^3$ have been used respectively in
determining these volumes. The bauxite residue is dewatered in the plant using vacuum drum filters. The dewater bauxite residue slurry or filter cake has a pulp density of 65% and is scraped from the drum filters. Water is added to reduce the pulp density (solids content) to 57% and by shear thinning; the bauxite residue is pumped to the B.R.D.A. by positive displacement pumps. The mud is discharged into the facilities as a paste from fixed spigot points. The process sand is trucked out from the plant and is used to construct ramps and access roads in the facility.

Pumping is the best way to discharge the slurry, but the most expensive way initially due to miles of pipe work, very expensive high-pressure pumps and associated equipment. Some plants pump to the sea, which will have to stop in the next few years. Other plants like Brazil (Alunorth plant) transport the residue over two miles to its B.R.D.A. Trucking is slow and such methods can cause spills along the way and are very labour-intensive. A big advantage with trucking is that it can be transported at higher % solids than pumping, which will reduce space requirements and give better drying / stacking. The Brazilian has ample space to store residue, so their reason for not pumping was initial cost outlay. The author worked in the Filtration / B.R.D.A. section in this plant for three months during commissioning in 1995.

Pumping at low solids concentration and storing in ponds runs the risk of embankment failure like the Hungarian disaster in 2010.

At a pulp density of 57% the bauxite residue flows down the slope with the appearance of lava at an average slope of 2.5%. Reductions in the pulp density results in a reduction in viscosity, which in turn reduces the slope angle. At the target pulp density, no bleeding of water should occur and no segregation of the solids is likely to occur either. As the pulp density decreases, bleeding will occur and some segregation of the bauxite residue particles will also occur. As the pulp density decreases further, erosion of existing deposited bauxite residue will become an issue and therefore it is important to consistently maintain the design pulp density of 57%.

At a pulp density of about 57%, the moisture content of the bauxite residue is approximately 75%. After deposition, the moisture content decreases and the in-situ density increases. Typically the moisture content decreases to about 45% and the in-situ solids content increases to about 70%. As the moisture content of the bauxite residue decreases, both its un-drained shear strength and dry density increases, while its volume decreases. The maturing of the bauxite residue is achieved by the following principal methods:

- air-drying of the surface of the bauxite residue by evaporation; and
• Consolidation of the bauxite residue under its own weight.

Air-drying by evaporation is the most important process in dewatering the bauxite residue and improving un-drained shear strength. Both wind and sun contribute to evaporation although wind is the main process and therefore occurs throughout the year. Air-drying results in the formation of a desiccated crust that is typical of wet fine-grained materials. The desiccated cracks extend to maximum depths of between 200 mm and 250 mm. The desiccated cracks fill with water during rain periods, although the water tends to be displaced once the bauxite residue is deposited.

With the drying comes the risk of dusting and Aughinish have had to install a vast water sprinkler system to cover the complete B.R.D.A. This system uses treated water that would otherwise have been pumped to the river Shannon. Unfortunately it results in extra run-off from the residue as this water flows back to the plant for recycling.

It is important to prevent pooling of water on the bauxite residue surface in order to promote the maturing of the bauxite residue. It is also important to place the mud in relatively thin layers, typically less than 300 mm in thickness and allow it to be exposed to the atmosphere for as long as possible. Such is the concern about the lack of space that Rusal Aughinish now are changing the distribution points 3 times per day. This will allow for thinner layers of mud and faster drying and consequently better stacking.

The mud can be directed into selected areas by hydraulically actuated rotating pipes at the end of the discharge points. The placement and direction of movement of the bauxite residue is also strongly influenced by the level and distribution of the previously deposited material. Also, bunds can be constructed from the bauxite residue to direct mudflows to specific areas.
2.6 Bauxite Residue Disposal Area

**Figure 5** South-west corner of B.R.D.A. and Robertstown River.

**Figure 6** North-west Corner of B.R.D.A.
2.6.1 General

The original design for the B.R.D.A. (Figure 5) was a thickened mud disposal system with a main central discharge to form a central cone. The expected slope of the cone was anticipated to be about 6 degrees (10H: 1V), but during the early stages of operation this was measured at 1.4 degrees or 2.5% (40 H: 1V). Subsequently several discharge points were developed within the B.R.D.A. Recent measurements based on the 2002 survey indicated that the beach slope varies considerably between the various discharge points and with the distance from the discharge point. There are a range of slopes typically about 6% at a distance of 40m from the discharge point, about 4% at a distance of 80m, 3% at 160m, 2.5% at a distance of 200 m and 2% at a distance of 300m from the discharge point; generally, from the central discharge area to the edge of the stack wall. The overall slope is about 2.5% and this has been used as the final profile of the facility. To optimise the storage capacity of the facility, it was necessary to have the discharge points with a maximum distance of 200m from any area of bauxite residue within the facility to ensure the beach slope does not in general fall below 2.5%.

Other factors also influence the beach slope, such as the pulp density of the paste, and obstructions to flow such as other discharge points, the effluent sludge pond, salt cake disposal area and the internal access roads. The current locations of the discharge points are within 200 m of one another.

As a result of the shallower slopes, the bauxite residue is retained by a perimeter stack wall, constructed of rock-fill and normally placed over a layer of process sand, which in turn is placed on the bauxite residue. This method of construction is termed upstream raising, although unlike other tailings disposal facilities this does not retain any water behind the stack walls and is therefore significantly safer to operate (SRK & Enviropian Services Ltd, 1999).

The capacity of the Phase 1 B.R.D.A was planned to be up to Stage 7 with the perimeter embankment at an elevation of 18.0 m AMSL and centre point elevation of 27.5 m AMSL.

The height of the B.R.D.A. at its apex is governed by a Limerick County Council (LCC) planning permission condition and is fixed at a height of 26 metres above ground level (27.5m).
2.6.2 Organisational Principles

The following summarises the operating principles for the B.R.D.A.

The overall stability of the upstream rock fill core mud retention terraces around the mud stack perimeter is determined by routine monitoring and assessment of the un-drained mud. The soda content of the drained shear strength of the bauxite residue and underlying estuarine soil bauxite residue and other residues being deposited is minimised to optimise soda recovery in the plant and to minimise environmental liabilities within the mud stack.

The integrity of all high-density polyethylene (HDPE) geo-membranes for environmental protection is maintained. No mobile equipment is permitted direct contact with the geo-membrane. The runoff and leachate from the mud is collected in the perimeter drain and pumped back to the plant. This lined perimeter drain runs around the entire B.R.D.A. and all run-off / leachate collected is pumped to the Storm Water Pond and is then returned to the Waste Water Treatment Plants for treatment prior to discharging to the Shannon under licence.

The surface water inventories in the perimeter drain and adjacent storm water pond are minimised and pumping capacities are maximised as practicably as possible, to ensure that there is sufficient operational freeboard for major rainfall events.

The optimum areas of bauxite residue are covered using sprinklers to prevent dusting. Other techniques, such as radial and contour ploughing, are being tested and developed to replace and/or augment hay and straw deposition as dusting prevention measures. The spreading of straw was tested and used in Aughinish for a few years but the life span of the straw was short. It was also highly labour-intensive. The downstream toe drains, external watercourses and groundwater observation wells are routinely inspected to monitor for any migration of liquids from the mud stack.
2.6.3 Boundaries and Topography

The mainland to the east and south of the island and the plant is mainly agricultural. The nearest residential settlement of any size is Foynes, some 2km to the west of the island. Considerable industrial activity also takes place in Foynes, which is an active deep-water port. Other settlements of note in the vicinity of the island are Borrigone, some 2km to the south and the town of Askeaton, some 6km to the east.

The B.R.D.A. area comprises the original B.R.D.A., the extension to the B.R.D.A., and the Storm Water Pond area. The B.R.D.A. lies to the south-west of the alumina extraction plant. The site extends eastwards to a limestone ridge (termed hereafter as the east ridge), which rises to the plant area and is bordered to the south by open grassland. The watershed catchment area of the B.R.D.A. area is defined by a ring road comprising of the perimeter embankment crest Road and the east ridge road.

2.6.4 Geology and Hydrology

The B.R.D.A. area occupies a low-lying area that has previously been reclaimed from tidal flats, through the construction of an earth dike seawall and a ditch drainage system. See Table 1 below.

Detailed site investigations have been undertaken in and around the B.R.D.A. during the course of the design of both the existing B.R.D.A and the proposed recent extension.

<table>
<thead>
<tr>
<th>Successive Strata</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuarine Deposits</td>
<td>0 to 20</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>4 to 8</td>
</tr>
<tr>
<td>Carboniferous Limestone Rock</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>

There is no substantial aquifer under the B.R.D.A. and its quality is generally classified as brackish. There is no connection between the aquifer and the mainland. All watercourses around the B.R.D.A. area are just local surface water collection ditches with no upstream
catchment outside the island or indeed outside the immediate mud stack area itself. These watercourses all flow into the tidal Robertstown River through a sluice gate system.

2.6.5 Local Meteorology

There is a fully automated weather recording station located between the B.R.D.A. and the alumina plant and all its information is downloaded to the process information system. Historical data can be retrieved to investigate incidents brought to the attention of Rusal Aughinish.

2.6.6 Residue Properties

Particle size analyses of bauxite residue indicate that the material is largely silt size, with 90% of the particles smaller than 35 microns and 35% finer than 2 microns. The permeability of the mud is correspondingly very low and has been assessed to be in the range $1 \times 10^{-8}$ to $1 \times 10^{-9}$ m/sec. The permeability of the mud decreases as the mud matures from its initial to final solids content. The average specific gravity of the dry mud solids is 3.3.S.G.

The process sand is poorly graded medium sand with 90% and 10% of the particles smaller than 500 and 100 microns respectively. The permeability of the process sand is estimated to be about 1000 times greater than the permeability of the bauxite residue.

2.6.7 Chemical Properties

The residues deposited in the mud stack area comprise principally of bauxite residue and process sand solids and an aqueous solution entrained within the bauxite residue slurry. The solids are retained within the storage area, whereas part of the aqueous solution is dispersed through evaporation, seepage, leachate and as bleed water to the perimeter drain of the stack.

The results of an analysis of bauxite residue discharged to the storage area are summarised in (Table 2). The principal constituents of the bauxite residue solids (expressed as the oxides) are iron oxide ($\text{Fe}_2\text{O}_3$), aluminium oxide ($\text{Al}_2\text{O}_3$) and titanium dioxide ($\text{TiO}_2$).

The aqueous solution entrained within the bauxite residue contains a small amount of residual dissolved caustic (sodium hydroxide) and alumina in spite of the repeated washing in
the plant. It is this residual dissolved caustic which gives the bauxite residue its elevated pH characteristics. Most of the caustic converts to sodium carbonate and sodium bicarbonate on the B.R.D.A.

Table 2 Principal constituents of bauxite residue at Rusal Aughinish

<table>
<thead>
<tr>
<th>Principal Constituents of Bauxite residue at Aughinish</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferric Oxide (Fe₂O₃)</td>
<td>27.5%</td>
</tr>
<tr>
<td>Aluminium Oxide (Al₂O₃)</td>
<td>22.0%</td>
</tr>
<tr>
<td>Titanium Oxide (TiO₂)</td>
<td>20.0%</td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>7.0%</td>
</tr>
<tr>
<td></td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td>11.0%</td>
</tr>
</tbody>
</table>

2.6.8 Residue Analysis

Condition 7.5 of the Licence indicates that the waste analyses shall be undertaken in accordance with Schedule 3(iv) of the same. Figure 7 shows the internal analysis and Table 3 shows analysis of bauxite residue, etc.
<table>
<thead>
<tr>
<th>Waste Class</th>
<th>Frequency</th>
<th>Parameter Note 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite residue</td>
<td>Monthly</td>
<td>pH, dry matter, total alkalinity, chloride, fluoride and soda</td>
</tr>
<tr>
<td>Sand</td>
<td>Monthly</td>
<td>pH, dry matter, total alkalinity, chloride, fluoride and soda</td>
</tr>
<tr>
<td>Salt cake</td>
<td>Monthly</td>
<td>pH, dry matter, total alkalinity, chloride, fluoride and soda</td>
</tr>
<tr>
<td>Sludge from the biological Sanitary treatment plant</td>
<td>Annually</td>
<td>pH, dry matter, organic matter, nitrogen phosphorus and heavy metals.</td>
</tr>
<tr>
<td>Leachate from the bauxite residue stack</td>
<td>Monthly</td>
<td>pH, total alkalinity, chloride, fluoride and soda</td>
</tr>
</tbody>
</table>

Figure 7 Schedule of residue analysis from the IPPC Licence, Reg No. P0035-02

Table 3 Internal laboratory analyses of bauxite residue, process sand and salt cake

<table>
<thead>
<tr>
<th></th>
<th>Bauxite residue</th>
<th>Process sand</th>
<th>Salt cake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Alumina (Extractable &amp; Non-Extractable)</td>
<td>9.3%</td>
<td>9.0%</td>
<td>.8%</td>
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<tr>
<td>Fe₂O₃</td>
<td>2.4%</td>
<td>1.8%</td>
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<tr>
<td>TiO₂</td>
<td>.5%</td>
<td>.8%</td>
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</tr>
<tr>
<td>SiO₂</td>
<td>.0%</td>
<td>.1%</td>
<td></td>
</tr>
<tr>
<td>NA₂O</td>
<td>.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td></td>
<td>5.2%</td>
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<tr>
<td>Na₂C₂O₄</td>
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<td>8.6%</td>
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<tr>
<td>Na₂SO₄</td>
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<tr>
<td>Na₂CO₃</td>
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<tr>
<td>NaOH expressed as Na₂CO₃</td>
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<td>2.5%</td>
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<tr>
<td>Org. Carbon</td>
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<td>.5%</td>
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## Table 4: Summary of Eluate Results

### Summary of Eluate Results (1 of 1)

#### EC Draft Directive

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<tr>
<th>Hazardous Range mg/l</th>
<th>Insert Range mg/l</th>
<th>Parameter</th>
<th>12/2/92 Eluate Measured (mg/l)</th>
<th>12/7/92 Eluate Measured (mg/l)</th>
<th>Second Leaching</th>
<th>1/14/93 Eluate Measured (mg/l)</th>
<th>Second Leaching</th>
<th>2/17/93 Eluate Measured (mg/l)</th>
<th>Second Leaching</th>
<th>3/15/93 Eluate Measured (mg/l)</th>
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<th>4/9/93 Eluate Measured (mg/l)</th>
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<td>4-13</td>
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<td>0.2-1.0+</td>
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<td>Chromium</td>
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<td>&lt; 0.01</td>
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<td>2-10</td>
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</tr>
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<td>&lt; 0.03</td>
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</tbody>
</table>

* Total of these metals < 5mg/l and no single result greater than the minimum set for hazardous waste
* This range refers to limits set for trivalent arsenic

All results for metal analytes reported as total unless otherwise state

<table>
<thead>
<tr>
<th>Phenols</th>
<th>Electrical Conductivity in mS/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.0</td>
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<tr>
<td>&lt; 1.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical Cond</th>
<th>-</th>
</tr>
</thead>
</table>

| Sulphate | < 500mg/l if possible |

- Insert (*) in results column indicates not tested
2.7 Bauxite Residue Disposal Area (B.R.D.A.)

This area is composed of two functional units:

- the area that contains the residues from the process circuit,
- the water management system for the B.R.D.A., which includes the peripheral drains, monitoring wells, the Storm Water Pond, the Liquid Waste Pond, and the Waste Water Treatment Plant (Figure 8).

The B.R.D.A. is an engineered repository that has been designed to ensure the long-term stability of the residues of processing bauxite. It has been designed and operated to ensure that run-off from the facility is collected and treated before discharge to the river Shannon and that sub-surface seepage is minimized. The water management system provides for collection and treatment of the storm water off the B.R.D.A. (Figure 8). The storm water pond collects B.R.D.A. run-off, which is pumped back to the industrial effluent treatment plant where it is neutralized and solids removed in two clarifiers. The treated effluent flows to the liquid waste pond prior to discharge under license to the river Shannon.
The B.R.D.A. has been designed to ensure that it is structurally stable under operational and expected closure conditions. Nonetheless, the Residuals Management Plan must provide for the on-going stability of the structure by limiting increases in pore pressure within the B.R.D.A. embankment walls and minimising erosion. This will involve measures to limit infiltration and encourage surface run-off, while promoting evapotranspiration of a healthy vegetation cover and positive drainage system.

The major requirement to minimise water infiltration and prevent erosion in order to maintain B.R.D.A. stability will be provided for by the installation of a robust and self-sustaining surface vegetation cover, which sheds the maximum amount of runoff and utilises significant amounts of soil moisture in evapotranspiration. Surface cover will provide for decreases in sub-surface run-off into the future.

Groundwater is monitored in the vicinity of the B.R.D.A. and the objective of the monitoring is to ensure that seepage from the area does not influence relevant back groundwater quality parameters by greater than 10%.

It will be necessary to treat the run-off from the B.R.D.A. following closure as long as the pH remains over 9.0. This is expensive in terms of running equipment in the Waste Water Treatment Plants, with chemical dosing, equipment up keep and manpower. Use of indigenous species of grass on the mud is desirable in the Aughnish scenario.

Hence knowledge on long-term growth of native vegetation is necessary. There is a general consensus that data for more than one growing season is needed to evaluate the long-term vegetative growth in the residue. So what is important for the company is to demonstrate to the regulatory bodies is that the run-off pH will drop over time. The establishment of vegetation on the residue will improve its physical stability, reduce erosion, and also the possible dispersion of dust on the surrounding environment. In addition, it mitigates the visual impact and will facilitate a beneficial post-closure after-use of the B.R.D.A.

Currently there is limited information on rehabilitation of bauxite residue and there was a need for further studies into pore water and runoff water quality, also the establishment of native vegetation The Demonstration Cells will provide this information and sampling will continue over several years. Previous trials with native vegetation have been successful but unlike other areas of research this work is confined and limited. Some unknowns in the Aughnish case included how soon could access be gained onto the residue, how long does it take to weather enough before amendments commence. There is a need for further information on the long-term impact of growth on the residue to allow the company plan for closure of the plant and have the necessary financial resources in place. To do this, it is
necessary to construct pilot scale versions of the existing B.R.D.A. and monitor the environmental effects. The results of this investigation can determine the environmental impacts of closing of the existing Bauxite Residue Disposal Area (B.R.D.A.).

2.7.1 Bauxite Residue (Red Mud)

Bauxite ore \((\text{Al}_2\text{O}_3\times\text{H}_2\text{O})\) has silica, iron oxide, plus other minor and trace impurities associated with it. Bauxite residue (bauxite residue and process sand) are insoluble impurities formed during the Bayer Process and are removed in the clarification section.

The B.R.D.A. typically receives slurry at a density of between 54 - 58% solids by weight. The yield stress of this material ranges between 25 and 50 Pa (which corresponds to a residual slump height of 15-25 mm, measured in 100 mm diameter by 100 mm height cylinder). The slurry with these properties will spread across the drying area at a layer depth of around 0.3 m on a bed slope of 1-1.2 % (1:100 to 1:80 slopes).

It has been found that slurry with a slump of less than 15 mm will flow to the bottom of the slope in a very thin layer and without spreading laterally. If the slurry has a slump above 25 mm, the layer will build up in thickness at the dropper before flowing down the slope. Through improved control of the yield stress of the slurry, and constraining the lateral flow of the slurry, a very even distribution of the slurry is achieved. Optimising the coverage on the drying areas has become one of the key operational objectives in recent times. As the height of the stacks grows, drying area is lost due to the encroachment of the embankments as they are progressively raised via upstream lifts. This means that additional area needs to be provided and this is at a significant capital cost. If drying of the slurry can be sustained on a smaller area, significant capital for expansion of the drying areas can be deferred.

Aughinish measures drying rate in terms of the overall (or average) annual storage rate (expressed as the amount of residue, which can be stored per unit area each year). There is a reduction in soluble caustic losses as the caustic is returned to the plant for treatment. The reduction in volume by water loss and recovery of caustic also lessens pollution by hydraulic seepage. Consolidation of the residue can also allow for trafficking of the surface to enable implementation of dust control measures and rehabilitation. So far there are no appropriate technologies for the bulk utilization of these bauxite tailings and the disposal of the wastes adds up to 2-5% of the production costs.
2.8 Residue Handling and Placement

All residues are either pumped or trucked in skips or dumpers to the B.R.D.A. Only pumped residues are permitted to be deposited directly onto high-density polyethylene-lined landfill storage surfaces.

All trucked residues are transported onto the bauxite residue stack area on internal access roads constructed to engineering standards directly on the HDPE liner or on internal roads constructed by the landfill operations contractor on bauxite residue surfaces with at least 2 metres cover to the HDPE liner. No mobile equipment is allowed to drive directly on the HDPE lined bauxite residue surfaces.

Trucked residues are deposited on at least 1 metre in depth of matured bauxite residue. However, process sand may be deposited directly onto bauxite residue surfaces provided mechanical plant is confined to adjacent engineered designed and supervised access roads or the mobile plant is moving on at least 1 metre depth of process sand.
2.8.1 Water Management

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 winters these systems are quite frequent, while during summer they are interspersed with the high-pressure anti-cyclonic weather systems bringing drier air masses and warmer temperatures.

Rainfall and evaporation data for the B.R.D.A. (Adopted Shannon Airport data, 14 kilometres east of the B.R.D.A.) are provided as an estimate of the site climate balance (Table 5).
### Table 5: Weather Data

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall(^{1\text{mm}})</th>
<th>Evaporation(^{2})</th>
<th>Balance</th>
</tr>
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<tbody>
<tr>
<td>January</td>
<td>97.2</td>
<td>7.5</td>
<td>89.7</td>
</tr>
<tr>
<td>February</td>
<td>72.1</td>
<td>23.8</td>
<td>48.3</td>
</tr>
<tr>
<td>March</td>
<td>71.8</td>
<td>47.5</td>
<td>24.3</td>
</tr>
<tr>
<td>April</td>
<td>55.5</td>
<td>76.3</td>
<td>-20.8</td>
</tr>
<tr>
<td>May</td>
<td>60.1</td>
<td>105.0</td>
<td>-44.9</td>
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<tr>
<td>June</td>
<td>62.4</td>
<td>116.3</td>
<td>-53.9</td>
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<tr>
<td>July</td>
<td>57.1</td>
<td>106.3</td>
<td>-19.2</td>
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<tr>
<td>August</td>
<td>82.3</td>
<td>87.5</td>
<td>-5.2</td>
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<tr>
<td>September</td>
<td>81.8</td>
<td>60.0</td>
<td>21.8</td>
</tr>
<tr>
<td>October</td>
<td>92.4</td>
<td>30.0</td>
<td>62.4</td>
</tr>
<tr>
<td>November</td>
<td>94.7</td>
<td>10.0</td>
<td>84.7</td>
</tr>
<tr>
<td>December</td>
<td>99.6</td>
<td>3.8</td>
<td>95.8</td>
</tr>
<tr>
<td>Total</td>
<td>926.8</td>
<td>673.8</td>
<td>253.0</td>
</tr>
</tbody>
</table>

Sources:
1. Met Éireann ([www.met.ie](http://www.met.ie)) The Irish Meteorological Service Online
2. 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 B.R.D.A., a managed discharge from the site or a combination of both to prevent overflow.
2.8.1.1 Refinery / B.R.D.A. water balance

Nearly all of the water input at the B.R.D.A. is due to precipitation. The deposition of red mud contributes a minimal additional amount. Water is added to the residue during the operation of the sprinkler system, which is in periods of very dry or frosty weather. There is no significant water contribution from either process sand or salt cake disposal.

2.8.1.2 Neutralisation & discharge

Excess water, and run-off is collected in the perimeter channel around the B.R.D.A. and the Storm Water Pond. This is pumped to the Waste Treatment Plants for neutralization prior to discharge into the river Shannon. This liquor contains some residual caustic contamination, and is managed using a process of neutralisation, clarification and cooling prior to discharge into the Shannon Estuary.

Sulphuric acid is added to the excess water, thus neutralising 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 (L.W.P.). From the L.W.P, effluent is discharged under licensed conditions into the River Shannon in accordance with the I.P.C. Licence. Discharge to the Shannon is licensed up to a rate of 21,000 m$^3$/day.

2.8.1.3 Storm Water Management

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$^3$. 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$^3$. 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.

- Storm Water Pond - 1.0 m
- Perimeter Interceptor Channel – 0.5 m.
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 20,000 m$^3$. 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.

The total storage volume capacity of the Storm Water Pond at a top water elevation of 5 m AMSL and the perimeter interceptor channel at a top water elevation of 4.2 m AMSL is approximately 375,000 m$^3$. This is sufficient to accommodate 1 in 200 year storm and allow the maximum operating volume to increase from 180,000m$^3$ to 243,000m$^3$ for the 500m$^3$/hr pump rate.

The maximum operating volume can increase from 180,000m$^3$ to 249,000m$^3$ for the 750m$^3$/hr pump rate. From the current data, the water level in the Storm Water Pond and the PIC should not exceed about 4.0 m AMSL. However, the S.W.P. can operate at a different level to that of the PIC and therefore a combination of levels in the two structures could provide the maximum operating level. After the raising of the SWP and construction of the Phase 2 PIC, the total volume of the structures was determined. ‘Plimsoll’ lines indicating the elevation were painted on the HDPE lining of the SWP and PIC. The maximum operating level should not be exceeded and a trigger level system was installed to inform the operators if this level is approached. Aughinish operates a set of emergency procedures if the SWP exceeds its current design capacity. These procedures were revised when the SWP was raised and will be again when the Phase 2 B.R.D.A. is in operation.

It was essential to install a spillway on the SWP and PIC to protect the walls from severe erosion if the facility is ever over-filled. It is designed to accommodate the 1 in 200 year event. Downstream of the SWP is the bird sanctuary and this is a protected area. It was therefore decided that the spillway should discharge effluent from the SWP back into the perimeter interceptor channel. This can be best managed by controlling the discharge into the SWP from the pumps in the PIC.
The overall control will mean keeping the pond level below 50% during normal operation. This will give some storage capacity in the event of very heavy rainfall that could exceed the pumping transfer rate out of the pond.

### 2.8.2 Groundwater Contamination

Approximately 70% of the Phase 1 B.R.D.A. is unlined and relies on the low permeability of estuarine soils and compacted bauxite residue to minimize seepage. It has been 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.

The Storm Water Pond is composite lined with a combination of HDPE lining, GCL and processed glacial till.

Leakage from the new Phase 2 B.R.D.A. 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 B.R.D.A. footprint encroaches on the townland of Glenbane West. Of this area, Golder Associates specifically examined approximately 7 ha to determine the likelihood that any potential seepage could migrate away from the B.R.D.A. and further inland on Glenbane West. The majority of seepage from the Phase 2 B.R.D.A. located on Glenbane West will migrate towards the Poulaweala Creek underneath the facility and will be buffered by the saline groundwater. 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 modelling were 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 geo-membrane underlain by GCL with a drainage blanket in between.

Aughinish have gone for best international practice on the Phase 2 extension, thereby providing the best possible storage facility for the residue taking into consideration the
environment and all interested parties. The design of the storage, the collection, and treatment of all run-off is leading edge practice.

A leak detection survey will be carried out after the geo-membrane is installed using direct (DC) electric current. The technique used is closely related to the electrical resistivity method. Electric current is passed between two electrodes, one placed in the water inside the cell and the other in the peat outside the cell. With the geo-membrane intact, the water in the cell will be electrically isolated from the external environment. The resulting potential field, measured as a potential difference between two non-polarising electrodes, is small but uniformly distributed over the geo-membrane. If the geo-membrane is defective, current will flow through the point of leakage and the measured potential will peak around the position of the defect. All defects will be recorded, repaired and retested.

Modelling and testing seepage rates are important in determining run-off / leachate for treatment requirements plus potential leaks to the environment. The E.P.A. requires residue sampling and seepage rate calculations and the Storm Water Pond water management system. Pumping rates to the river are limited by the E.P.A. licence, these are hourly and daily rates. Storage capacity is crucial and level management must balance the pumping capacity with the treatment capacity.

2.8.3 Dust Management

Although the red mud is very fine and forms a relatively stable crust, it is prone to dusting, firstly, by the formation of salt crystals on the surface as the caustic soda reacts with the carbon dioxide in the atmosphere which blister the red mud, and secondly in wintertime, a sharp frost can blister the surface. In both cases the agglomerated red mud particles can be picked up in a strong wind.

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 B.R.D.A. Use of commercially available dust-binders on access roads to reduce dust generation due to traffic;
• planting of grasses and vegetation in exposed areas.

At Aughinish, dusting is proactively managed on the Phase 1 B.R.D.A. by a system of sprinklers that cover the entire exposed mud surface on approximately a 30 m grid. The fixings of the sprinkler system are periodically extended as the red mud is raised.

Aughinish have tried several methods to prevent dusting. Hay, straw, animal slurry and flocculants have been tested. They all last for a period of time and are neither 100% effective nor easy to use. Although the initial capital cost of a water sprinkler system is high and adds to extra run-off, it is the most effective means of preventing dusting and the sprinklers can be set to work automatically from the control room.

The current system used for the Phase 1 B.R.D.A. will be adopted for Phase 2. Initially the base of the sprinkler points will be fixed to a steel plate on top of a minimum thickness of 0.6m of red mud that protects the HDPE geo-membrane. The size and weight of the steel plate and the initial vertical height of sprinkler pipe will be finalised after field trials on Phase 1.

The process sand, which forms many of the access roads on the B.R.D.A., is prone to dusting during trafficking in dry conditions and during strong winds at any period of the year. During dry conditions the haul roads are systematically wetted with road tankers.

2.9 Previous Trials at Aughinish

2.9.1 Trials in 1998-1999

These trials were conducted at the request of the Limerick Co. Council and the trials were conducted on a section of the west embankment.
The author was process co-ordinator for the B.R.D.A. at the time of these trials and was completely aware of and involved in the planning of the project. As Process Co-ordinator for the B.R.D.A., an integral part of the job was to give clear and concise information to all interested parties. All updates and information passed to the section staff on the project was carried out by the process co-ordinator.

Trials of grass establishment on the bauxite residue surface began in 1998 on the perimeter rock-fill embankment. The trial plots were located on terrace bench between two rock fill embankments, outside of the active storage area, but with run-off and leachate flow occurring through the bench.

The aim of the trial was to create a living soil from the bauxite residue which would sustain a long-term vegetation cover on the mud. It was necessary to ameliorate the bauxite residue to overcome the physico-chemical problems inhibiting vegetation establishment.

The following process was undertaken at the site of the selected trial plots:

- the mud was left to weather under a cereal straw cover for 12 months
- surface drains were installed to divert surface run-off. The importance of this was to ensure that high caustic run-off could not reach the trial plots
- process sand was rotavated into the top 15 cm of bauxite residue, resulting in a circa 4: 1 mixture of sand and residue
- the area was left to weather for 4 months
- various mixtures of organic matter, spent mushroom compost, cattle slurry were used and rotavated into the surface prior to seeding

The result of the weathering, cultivation, and amelioration with sand, compost and organic matter gave a soil with structure, organic content and tilth. From initial laboratory pot trials it was demonstrated that oats and rye grass grew successfully in bauxite residue amended with spent mushroom compost and process sand. Field trials followed in September 1998/ 1999 with 48 plots of 4m x 4m in size.

The following ameliorants were arranged:

- 200t/ha   Spent mushroom compost
- 100t/ha   Spent mushroom compost
- 100t/ha   Spent mushroom compost + 40,000 litre/ha cattle slurry
• 100t/ha Spent mushroom compost + NPK 250kg/ha fertiliser
• 100t/ha agricultural topsoil.

Grass mixtures at 220 kg/ha of the following, rye grass, oats, common bent, creeping bent
sweet vernal grass, false oat grass, cocksfoot, red fescue, Yorkshire fog, meadow grass,
oxeye daisy, poppy, buttercup and common sorrel. Each was divided into two and gypsum at
117 kg/ha was added to one half of each plot plus NPK at grass sowing.

The highest biomass production occurred in rye grass and in oats under-sown with
rye grass. High biomass also occurred in the grass/herb mixture, but few of the planted
species established well.

No run-off or leachate sampling was carried out during any of these trials due to
lack of facilitates to do so. The importance and priority of pH came at a later stage following
requests from the E.P.A. and its concerns about the time span to get the pH down below 9.0.
The vegetation that survived was left without any aftercare for a few years. No further
analysis is available for any of this project.

2.9.2 Trials 1999

In 1999 the company decided to restart the project. Ronan Courtney, a soil chemist /
consultant, was hired to head the project. This work consisted of three separate but related
trials.

2.9.2.1 Small pot trials

These trials consisted of screening 20 potential species to assess germination success and
growth rates of bauxite residue amended with different rates of process sand with and without
gypsum. The five most successful species were carried on to the next stage. Pots were seeded
at a rate of 15 per pot of oats and 100 per pot of Yorkshire Fog.
2.9.2.2 Large Pot Trials

These trials were carried out in sheltered bench conditions using five species and these were assessed using a range of criteria including germination rate, biomass yield, root/shoot ratio and uptake of metals. The residue was amended in-situ in the B.R.D.A. and transported to Sligo Institute of technology to carry out the pot trials. The species of grass used were *Fresue longifolia*, *Lolium perenne*, *Trifolium pratense*, *Holcus lanatus*, and *Agrostis stolonifera*.

2.9.2.3 Field Trials

These trials were to assess performance under open climatic conditions in the B.R.D.A. residues investigated included agricultural, slurry, spent mushroom compost and industrial sludge. It was considered important to predict the availability of these wastes in the future as agricultural and industrial practices could change. Four plots were constructed with the following amendments.

The four plots each approx 25m x 3m had the following mixtures:

1. Residue + 10% process sand
2. Residue +10% process sand + 2% w/w gypsum
3. Residue +25% process sand + 2% gypsum
4. Residue +25% process sand

These blocks were then sub-divided into 1m² and organic material added the rates listed below.

Organic application rates were as follows, which were worked in manually to a depth of 0.2 m (Courtney, 2002).

- Spent Mushroom Compost: 75t/ha
- Thermally Dried Sewage Sludge: 35t/ha
- Dairy Industry Bio-soils: 100t/ha
- Agricultural Manure: 90t/ha
- Grass seeding varied between 100- 200 kg/ha.
Preliminary Findings

Oats and Yorkshire Fog were selected for investigation as they had varying degrees of germination success on bauxite residue samples. Replicate mud treatments consisted of non-amended mud, mud with 20% process sand and mud amended with 3% gypsum. Sodium and pH values were taken.

- Bauxite residue = pH 9.8 and Na 100 ppm
- Bauxite residue +20% sand = pH 10.1 and Na 110 ppm
- Bauxite residue +3% gypsum = pH 8.1 and Na 30 ppm.

### Germination Rates after 3 weeks

<table>
<thead>
<tr>
<th></th>
<th>Oats</th>
<th>Yorkshire Fog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite residue</td>
<td>60%</td>
<td>45%</td>
</tr>
<tr>
<td>Bauxite residue + 20% process sand</td>
<td>66%</td>
<td>50%</td>
</tr>
<tr>
<td>Bauxite residue +3% gypsum</td>
<td>80%</td>
<td>70%</td>
</tr>
</tbody>
</table>

**Oats**

Oats sown in un-amended bauxite residue and mud-amended with process sand had a lower percentage germination rate than residue amended with gypsum (see results above). After 3 weeks, shoots in mud treatments and mud amended with sand began to show signs of toxicity and yellowing, death occurred after 5 weeks. These treatments also produced shoots (14-18 cm) than mud amended with gypsum (27 cm). See Appendix 1 for results.

Addition of organic matter did not significantly enhance germination rates, residue and residue / sand treatments yielded 60% and 69% respectively. Bauxite residue amended with 3% gypsum had a slightly lower germination rate when organic matter was added (75%). Nevertheless, growth rates were significantly improved upon addition of organic matter.

**Yorkshire fog**

Yorkshire fog had higher germination rates on residue with gypsum, 70% than the ones without gypsum. For residue treatment, 45% of seeds germinated and 50% germinated on the mud /sand results in germination rates up to 80% and shoot lengths. Further trials
investigated used different organic matter at different application rates to determine the most cost-effective rehabilitation methods.

After 4 weeks, shoot length in mud and mud/sand reached an average 5 cm but began to die off. Shoots in residue amended with gypsum and in treatments receiving organic matter grew to 10-13 cm.

After 6 weeks, shoots in the relatively unweathered bauxite residue treatment amended with organic matter began to show signs of toxicity and died off.

**Effects of Gypsum and Process Sand**

- *Trifolium pratense* grown in gypsum-amended treatments had significantly lower aluminium concentration than those in non-gypsum treatments and levels are not considered excessive. This trend was also found for plant iron concentration.

- Gypsum amendment produced lower Na concentration in herbage, concentrations were markedly decreased with greater process sand addition.

- Higher manganese concentrations were observed for *Trifolium* grown in treatments with gypsum addition.

- Sodium levels in the substrate were not high enough to affect calcium in the plant cells. Calcium levels were in the range deemed adequate for the growth.

- Marginal Mg, P and K deficiency was found.

- Mn nutrition may be a limiting factor in achieving long-term growth (Courtney, 2002)

Gypsum addition lowered pH and sodium levels in the bauxite residue, whereas additions of process sand raised pH and sodium levels in residue treatments. This was due to the process not being sufficiently weathered. By this is meant that if the residue is left for as long as possible, rainfall and atmospheric conditions will leach the residue and lower the pH somewhat. Gypsum addition also improved germination percentage rates and shoot height for each species.

Typical improvements that have been achieved in residue at RUSAL Aughinish are listed in Table 6 below.

Exchangeable Sodium Percentage (ESP) reflects the saturation of the exchange complex with Na relative to other cations present in the residue. Ratner (1935) and Thorn (1945) cited ESP of 40%-50% affects nutrient levels in plants.
Lack of organic matter and nutrient deficiency is recognised as a limiting factor in establishing vegetation on the residue (Williamson *et al.*, 1982). Incorporation of organic matter into the rooting medium is a critical component of the re-vegetation prescription. Organic matter is high in nitrogen 2.5% and low in potassium 1%, it also increases water-holding capabilities and reduces pH (Munshower, 1994). Several organic amendments have been investigated in greenhouse and field trials.

- Spent Mushroom Compost, Aughinish Trials
- Thermally Dried Sewage Sludge (*Wang & Lei*, 1982)
- Topsoil (Alcan Gove Australia & Alumar Brazil)
- Farmyard Manure (*Williamson et al.*, 1982; Munshower, 1994)
- Agro-industrial Sludge Jamaica plants, and Aughinish.

From Figure 10 and Figure 11 Figure 12 below, the changes and improvements that take place with the residue following the addition of process sand, organic material, gypsum and some leaching / weathering period are shown.
**Figure 10** The physical and chemical properties of bauxite residue before amendment. (prior to re-vegetation)

**Figure 11** The physical and chemical properties of bauxite residue after amendment (prior to re-vegetation).
**2.10 General Constraints**

The reclamation method investigated was based on ameliorating the substrate by improving the physical and chemical nature of the residue and selecting plants most suited to meet the rigorous conditions. The predominance of the fine fraction in bauxite residue, and the physical and chemical properties are the main constraints limiting the efforts to reclaim the residue (Wong & Ho, 1994). The high pH values of 12 to 13, plus the toxic levels of sodium remaining after the final mud washing stage, make re-vegetation difficult.

Sodium levels are determined by the effectiveness of the mud wash circuit. The aim for the new trials was to improve this aspect of the residue. The author was given the authority to make process changes to soda washing and solids concentration of the bauxite residue. Reductions in soda levels in residue can be achieved but sometimes the penalty is a reduction in alumina production. Residue removal from the process stream affects production. If the caustic soda washing is reduced, it allows the removal of more residue from the process. This caustic exiting with the residue is a loss, but production losses are a higher penalty to pay. The higher caustic soda levels in the residue also increase difficulty with vegetation growth.
Lack of organic matter, plus low nitrogen and low plant nutrients, along with the poor drainage caused by the fine material and high pH, are all limiting factors. Bauxite residue holds numerous chemical and physical limitations to plant growth. The major chemical limitations include a high pH, high levels of soluble salts, toxic levels of some elements (e.g., Al), and nutrient deficiencies (e.g., N, P, K, Mn, Zn). Physical restrictions to growth in residue mud include low hydraulic conductivity, poor drainage, and restricted root growth (Meecham & Bell 1977b; Fuller et al., 1982).

Physical properties of bauxite after crushing during processing, results in bauxite residue which is extremely fine-grained and has an average particle size of 0.01 mm dia. (Paramguru et al., 2005). Usually the material is separated into two streams: a course residue sand fraction (e.g., >90% particle diameter 0.02–2.00 mm) and a residue mud fraction (90% particle diameter <0.02 mm; Cooling, 2007). Although large differences exist between refineries, typically, 10–20% of residue exists as sand and the remainder is mud. Separation is not complete and there are usually significant amounts of sand in the mud fraction and vice versa. Often, the mud fraction consists of 20–30% clay-sized (<0.002 mm dia.) particles with the majority being in the silt-sized range (0.02–0.002 mm dia.) (Newson et al., 2006). However, great variations exist in particle size distribution, due to differences in processing techniques and the nature of the bauxite ore deposit.

Some mud has >50% of particles in the clay-sized range (Wehr et al., 2006). The small particle size of residue mud gives the material a relatively high surface area (13–22 m$^2$ g$^{-1}$); (Hind et al., 1999; Paramguru et al., 2007). The material tends to have a relatively high specific gravity (Gs = 2.8–3.3) (Newson et al., 2006). Because of its small particle size, when deposited in disposal impoundments residue mud can consolidate to form a solid mass.

The process sand is a coarser fraction and therefore increases leaching and consequently reduces salinity and causticity due to higher hydraulic conductivity (Meecham & Bell, 1977a). Rainfall and CO$_2$ exposure in the atmosphere will reduce pH and sodium over time but because of the very low permeability of the mud leaching rates are slow (Williamson et al 1982). Depositing the bauxite residue at higher % solids helps stacking and drying and in turn cracking occurs in the residue, which helps the leaching process.

Salinity is measured as the electrical conductivity (EC) in soil solution, saturation paste extracts, or soil and water extracts. Soils are generally classified as saline when they have an EC of 400 ms m$^{-1}$ or more in saturation paste extracts. Although great differences in tolerance to salinity can occur between plant species, it is generally considered that effects on plant growth are slight at EC values of 200–400 ms m$^{-1}$, severe between 400–600 ms m$^{-1}$, and very
severe with death at >600 ms m\(^1\) (Maas, 1990). Untreated bauxite residue is highly saline with EC values in the range of 3000–4000 ms m\(^1\) (Meecham and Bell, 1977a; Woodward et al., 2008). These soluble salts therefore need to be leached out prior to re-vegetation. The main negative effects with salinity are plant water stress and poor root and shoot development. Salinity results in a more negative water potential in soil solution and this impairs the ability of plants to absorb water (Flach, 1976; Keren, 2000).

2.10.1 Substrate pH

Due to entrained residual caustic, the bauxite residue has high pH and can be in the 11 to 13 range (Prasad et al. 1996). This high pH affects plant growth, which normally is achieved with a pH in the range of 6.6 to 7.3 (Munshower, 1994). High pH associated with sodium carbonate in alkaline soils may affect anion uptake and prevent the establishment of a pH gradient across the root membrane (Hanson, 1978) through its effect on reducing the solubility of essential nutrients such as magnesium, iron, manganese, zinc, and copper (Truog, 1947).

Phosphorous nutrients of plants can be restricted at high pH and at high pH ammonium nitrogen is converted to ammonia, which is toxic and volatile (Tisdale and Nelson, 1975).

2.10.2 Sodium and salt-affected soils

Plant growth in salt-affected soils can be limited by three processes; (a) the restriction of water uptake, (b) direct ion toxicity (mainly Na and Cl) and (c) competitive inhibition of nutrient uptake. If the plant is salt-stressed, there is a decrease in potassium uptake and an increase in Na influx (Caines and Sherman, 1999).

The capacity of a soil to absorb and exchange positive ions (cations) is called Cation Exchange Capacity (CEC). Some cations, e.g. calcium and manganese in exchangeable forms are good sources to promote good soil structure and soil cultivation.

Soil sodicity is characterised by the presence of excessive amounts of sodium (greater than 15\%) on the exchange complex and is detrimental to both soil and plants (Gupta and Sharma, 1990). These levels cause the soil to disperse with the result that the soil
structure and pore spaces are destroyed. A dispersed soil is sticky and plastic, especially when wet. When dry it is massive and hard and therefore is impermeable to water and air. High concentrations of sodium and \( \text{HCO}_3^- \) can be toxic and can inhibit the uptake of calcium and various micro-nutrients by repressing their solubility.

Elevated concentrations of sodium can be expressed by the exchangeable sodium percentage (ESP), which reflects the saturation of the exchange complex with Na relative to other cations present. Ratner (1935) and Thorne (1945) cited an ESP of 40% - 50% as levels above which nutritional disturbance in plants occur from excess sodium. Various authors have recorded high levels of ESP ranging from 70% to 90.9%. These levels reported for bauxite residue are above the levels cited as critical for plant growth. Bower and Radleigh (1949) generally found that increasing the ESP of the substrate resulted in a decrease accumulation of calcium, magnesium, and potassium in plants. Experiments have shown that that addition of calcium and magnesium to alkali soils can improve plant growth with an associated increase in the up-take of these added elements by the plants (Bower and Turld, 1946). Sodium in soil may exert important secondary effects and make some modifications to the structure, which may lead to poor aeration and low water availability, especially if the soil is fine textured (McGeorge and Brazeale, 1938).

### 2.11 Conclusions from trials

Ecological surveys indicate that succession is taking place on the rehabilitated areas on the B.R.D.A. Although 6 species were initially seeded, a total of 47 species were recorded on the re-vegetated B.R.D.A. (Samples taken on site and analysis carried out at Limerick University 2007.) Encouragingly, woody shrub species *Betula* and *Salix* were recorded growing on the B.R.D.A. As there was limited variation in physico-chemical conditions of the substrate, the increased diversity of species on the older B.R.D.A. vegetated area is attributed to age and succession.

Satisfactory levels of substrate N and K with only slightly deficient levels of P were recorded. Improved levels are attributed to application of inorganic fertilizer. However, deficiency in Mn and Mg were evident in the substrate. Encouragingly, levels of exchangeable Na and Al in the substrate were low and analysis showed promising signs of organic matter and nutrient build-up (Courtney & Timpson, 2005).
Similarly, plant analysis showed sufficient quantities of most nutrients but with deficiencies in Mg and Mn. Sodium levels were not considered to be excessive and gypsum-amended treatments displayed lower Na and significantly lower Mg concentrations. Due to high adsorption capacity P nutrition may be a long-term issue. See Appendix 1 for further results.

Although initially beneficial in rehabilitating alkaline and sodic residues, there may be a long-term issue with Mg and other cations imbalance induced by Ca supply in gypsum. Application of fertilizer appears to provide sufficient K, and N is not limiting. The impact of fertilizer application on nutrient content and cation behaviour needs to be further monitored (Courtney, R., 2002). See Appendix 1 for tables of results.

2.11.1 Review by Team

The conclusions from the trials stated that further trials were necessary and monitoring required, especially with the use of fertiliser. Process changes in the filtration section were made to lower the caustic soda levels in the residue. This was done by increasing the primary and secondary wash flows to the vacuum drum filters and increasing the net wash to the mud circuit. The author was given the authority by management to make the necessary changes to the process to improve soda levels and percentage solids. Higher percentage soils in the residue could be achieved by reducing dilution and pumping with a higher pressure in the transfer lines to the B.R.D.A. and the Demonstration Cells. On average he soda levels were reduced from 40-50 mg/l to levels of 15-20 mg/l (Laboratory Analysis Aughinish May 2007). This was done at times of pumping to the Cells to give the best stacking angle of the residue. The residue had already been deposited where the plot trials would take place, so nothing could be changed with the residue in the trial plot location. Nothing could be changed regarding the particle size of the residue as this was determined by process conditions in the digestion section and the type of bauxite purchased by the company. The time allowed for the weathering of the residue was another issue that the team and the company looked at and the areas selected for the small and large plots were areas with the oldest residue available.

High concentrations of soil solution Na reduce Ca uptake by plants and as a result Ca deficiency is common (Kopittke and Menzies, 2004; Qadir and Schubert, 2002). The
decreased Ca uptake affects the permeability of plant membranes, which in turn decreases the uptake and transport of other essential nutrients. Indeed, high Na uptake can lead to deficiencies of K, Zn, Cu, and Mn (Levy, 2000). It can be seen from other research (Bernstein and Hayward 1958) and Aughinish experience that getting the soda levels down as low as possible in the residue plays an important part in success or failure of vegetation.

The team decided that further small plots 2 m x 1m should be constructed using the optimal mixtures of sand, gypsum and spent mushroom compost to start another set of trial plots using the information learned from the previous trials. Where possible, adjustments were made to the process in the Filtration section to give lower soda and higher solid concentrations. This was done, and in conjunction with these small plots, it was decided to take a section of embankment and construct eleven larger plots 20m x 10m in size.

Sixty small plots were selected, that is 12 treatments replicated 5 times. This was done to determine optimum application rates of amendments with a difference in residue quality. Plot sizes were always determined by the need to balance space available on the embankments, treatment under investigation and the need to be representative. The changes to the process in the Filtration building would reduce caustic soda levels and increase percentage solids. All these could be monitored for any improvements in amendment rates, and reduction in drying periods of the residue on the B.R.D.A. drying period. It was planned to use some fertilisers on the vegetation in the trial plots and the Demonstration Cells.

It was decided to set up a second set of larger trial plots 20 m x 10m in size. It was deemed necessary to test machinery on the residue, which would be more like a closure scenario.

In the case of the larger plots it was determined by available space on the embankment how they could be constructed. This section of the B.R.D.A. between embankment lifts 6 and 7 was wider than other embankments. There was access for machinery on the terrace to plough, and spread the sand, gypsum and spent mushroom compost. The knowledge gained from the case studies was of help in deciding on efforts to:

- prevent capillary rise
- Reduce the sodium levels to as low as possible in the residue.
- Aughinish had advantages in some ways over the other companies in that the company had sufficient process sand to improve drainage, and sufficient spent mushroom compost was available at a cheap rate.
It was acknowledged that as all work on amending the residue in the smaller plots had been done by manual work, larger plots would highlight any potential problems using machinery. This would involve using mechanical spreaders for sand, gypsum, and SMC. How the machinery would travel on the residue and the amount of time required for the residue to mature were questions that needed to be answered.

The area selected by the team was deemed the most suitable due to age of residue and location, it was situated at Level 6 embankment and was facing the port of Foynes. There was a risk of dusting due to the location of the nearest sprinklers and its elevated height. For these reasons it was decided to use this area as the large plot test area. Amendments and types were based on review of literature, availability and residue properties and target values. The author kept up-to-date with similar work at other alumina refineries. It was necessary to be site-specific regards to climate, vegetation that could be used, residue properties and amendments available. The author had contacts in other plants and shared information with these plants. Aughinish also had a technical agreement with Alcan who have plants and shares in plants around the world and information was received from contacts at these plants.

2.12 Research by other Alumina Refineries

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

By comparison, it is unusual within the alumina industry to develop a bauxite residue re-vegetation methodology in an environment where a water surplus exists due to the positive climate balance, which is the case at Aughinish. Aughinish B.R.D.A. receives approx. 900mm of rainfall each year, which equates to 27m/m³ of run-off on the residue. Most research is undertaken in areas that experience water deficits for a significant proportion of the year, for example some of Australian plants. Hence, for the research project a significant
focus is placed on providing suitable drainage systems. The addition of sand will help provide this drainage while also providing sufficient water storage capacity within the re-vegetation 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 is critical to ensure that the vegetation survives (Alcan Gove Bauxite residue re-vegetation research programme May 2005).

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

The “recipe” could be narrowed down to getting the solids concentration and the soda levels as low as possible in the residue pumped from the Filtration building and the amendment rates in line with those in the previous trials. The targets were set to get solids concentration to 58% solids and soda concentrations to less than 10mg/l. The percentage solids were known in some of the case studies around the world, but no information on caustic concentrations in residue was available. The process and the washing arrangements in the Aughinish Filtration section of the plant aimed to achieve low caustic and high solids in the residue parameters at all times.

Reflecting on the previous trials and the decisions with regard to amendment rates centred on the limitations of the size of the plots compared to the size of the Demonstration Cells and the final vegetation cover required for the whole of the B.R.D.A., there are some questions regarding the use of machinery to spread the amendments, how soon could the machinery travel on the residue, and given the different concentrations of sodium in the residue in different locations, would the “one mix fix all” approach be successful.

There was concern about the possibility of capillary rise in dry weather if drainage was poor or the sodium levels varied in the residue going to the B.R.D.A. The Alcoa Plant had some problems with capillary rise during their dry season. Some of these parameters depended on how the Filtration Building was washing caustic from the residue. All the plot trials would take place while the Demonstration Cells were being constructed. This included the pipe work installation to pump residue to the Cells. The piping was a branch off from the main residue line to the B.R.D.A. and would consist of a 10-inch high-pressure line approx. 400 m in length with isolation valves to manage flows.
The selection of suitable terraces, with residue that had matured and leached was limited. The analysis of all the residue was known from laboratory analysis, and the length of time the residue took to mature.

Filling the one-tonne containers was a means of getting more information. The modification made to the containers allowed the sampling of the leachate, which could not be done with the plots.

The programme was set out and by the time the Demonstrations Cells were constructed and filled the most suitable amendment rate for the residue in the Demonstrations Cells were known.

2.13 Research by other alumina refineries

Alumina plants around the world have tried and introduced different rehabilitation methods to make the residue storage of bauxite residue more acceptable from an environmental perspective, or they require more storage for the residue, or for aesthetic reasons. The following companies have conducted trials and are reviewed in this section.
2.14 Case Study – Consórcio de Alumínio do Maranhão, Alumar

Information of this case study was available from Rusal Aughinish Research and Development Department. The company are members of the International Aluminium Institute and the author’s manager is a committee member. This was one of the Institute’s case studies in their Residue Management Survey 2003.

The Alumar plant at Sao Luisin Brazil had stored bauxite residue in a sealed and undrained impoundment from 1984 to 1991. Around 2.6 million cubic metres of settled residue were stored and major concerns to the public were mostly over environmental issues such as groundwater contamination, surface rehabilitation, and future use.

In Alumar, some “prescribed” materials used for rehabilitation of bauxite residue, such as gypsum, are difficult to find and very expensive. The use of a local soil layer of up to 2 m thick was considered unacceptable. Experiments investigated the suitability of topsoil, sub topsoil, boiler ash (both fly and bottom ash) obtained from the boiler house, and a combination of these materials to cover the residue. The acid boiler ash was disposed of in landfill. From the trials, this material was deemed to give the best results in terms of plant growth and it was applied at a depth of 20 cm to 60 cm, capping the residue surface.

After 2 years, pH values were taken 20 cm to 40 cm deep into the residue and pH values had reduced from 12.0 -13.0 down to 7.0. After 2 years, root penetration was observed in the residue below the ash capping. Alumar carried out trials using organic and inorganic fertilisers. They used sludge from breweries, chicken manure, and cafeteria compost. The results showed that the utilization of organic amendment was essential to promote plant establishment and development. Among the organic amendments used was brewery biological sludge, clearly this also provided an outlet for this sludge and solved the brewery problem of sludge disposal. The Alumar rehabilitation system of recycling waste material such as boiler ash and organic sludge, and the application of biotechnology using soil micro-organisms such as nitrogen-fixing bacteria and mycorrhizas fungi, provided them with a successful rehabilitation system. The vegetation grew, tress and scrubs were planted. The area was completely covered in vegetation by 2000. No information was available on leachate or run-off results from this period (see Figures 0-13, 14, 15).

Similar to all Bauxite Residue Disposal Areas major public concerns with the Alumar project in São Luís, were mostly over environmental issues such as groundwater contamination, surface rehabilitation and future use.
The topsoil, subsoil and combination treatments were significantly better, as growth mediums, than the bauxite residue, but not as good as the ash capping. Analysis of pH values, taken 20 and 40 cm deep into the profiles, after two years, showed that the ash leachate reduce the pH value of residue around 7.0 (seven) - the lowest pH value in the residue is 9.0.

Research was also carried out by Alumar and Scientific Research Centres comparing the use of organic versus inorganic fertilizers for residue rehabilitation. Several organic amendments were tested such as sludge from brewery, chicken manure, cafeteria compost, etc. The results showed that the utilization of an organic amendment was essential to promote plant establishment and development. In all cover materials, including the residue surface, the vegetation had better results when compared with inorganic fertilizers.

Searching for alternatives for rehabilitation, the agreements with Scientific Research Centres and private companies such as Equatorial Brewery created a rehabilitation system, based on the recycling of waste materials such as boiler ash and biological sludge, and by the application of biotechnology using soil microorganisms such as nitrogen-fixing bacteria and mycorrhizas fungi.

Comments
No run-off or leachate results were available from these trials. The analysis in the report showed pH values of the residue itself following the amendment of the mud with ash, compost and gypsum. The results for pH values were achieved from residue slurry and not leachate. They achieved great vegetation cover within a one-year period. The vegetation cover will prevent dusting on the residue, which is an important aspect.

Brewery sludge in combination with both bottom ash and fly ash was used as compost addition. In Ireland, bottom ash goes to land fill and fly ash has to be exported out of the country and treated as hazardous waste. Therefore this is a non-viable option for Aughinish. Analysis of the leachate / run-off will determine the water management structure. It is possible that there will be no need to recycle water or to store large quantities during the wet season. If the quality is good enough, they could release it directly to the environment. In all trials around the world the leachate and run-off pH values seem to be of secondary importance. Most effort goes into the vegetation capping for aesthetics reasons. Treatment of the effluent does not become an issue unless there is the prospect of plant closure. Figure 13 and Figure 14 show vegetation trial plots.
Figure 13 Aerial view of the Alumar residue areas in 1993. In the left corner, field vegetation trials on RDA #1.

Figure 14 Alumar residue disposal area #1 surface in September 1998. Note that area is almost blended with surrounding vegetation.
Figure 15: Alumar rehabilitated area in August 2000, four years of seeding

Figure 16: Visitor Centre in Alumar
2.15 Jamaica Plant Trials

Information on the Jamaican trials was available from Rusal Aughinish Public Affairs Manager sent by Dr Karl Wellington in July 1995, West Indian Alumina Company. Information was also received from Sylvan C. Mc Daniel, Manager Land & Agricultural Department, Windalco; and information on trials was gathered from the International Aluminium Institute Residue Survey 2003 International Workshop on Rehabilitation of Mined Bauxite Lands and Red Mud Disposal Ponds, 1998.

Trials in Jamaica were conducted to reduce erosion, increase evapotranspiration during the wet season, reduce wind-blown dust in dry periods, to improve the aesthetics and visual impact of the site and to gradually restore the site to a productive function.

Trials in 1973 had been encouraging, with an observed pH reduction brought about by adding gypsum to the residue, however flooding on the plots and the unacceptable high cost of gypsum resulted in the abandonment of the trials. Nevertheless, the trials showed that if the pH was lowered and if nutrients such as N, P, Mn were added, plant growth could be achieved.

In 1996, the Kirkvine plant in Jamaica began trials on a small former bauxite residue area known as Pond 6 in order to develop necessary procedures for the future closing of full scale mud disposal sites. The site was 4.0 ha and was divided into 4 plots, each measuring 30 m x 18 m, and in addition there were 16 plots 2m x 2m in size. Fourteen sampling points were selected throughout the test areas. Laboratory tests were carried out to find what was the optional gypsum application to bring about a reduction in pH and ameliorate soil characteristics by exchanging Ca for Na in the bauxite residue. Prior to sowing a variety of seeds, poultry litter and inorganic fertilizer were applied.

Based on the laboratory tests, gypsum dosage rates of 10, 20, 40, 60 t/ha were chosen for the four plots and in the 16 smaller plots 40, 60, 80, 100 t/ha were used with each sequence repeated 4 times.
2.15.1 Chemical Changes

The average pH declined from 9.0 in March 1997 to 8.0 in July 1998. The plots that had the 20t/ha or 40t/ha gypsum had a lower reduction than the 10t/ha dosage. No significant benefit was obtained from increasing the application of gypsum to 60t/ha. The sodium concentration showed a decline from 580 ppm to 410 ppm Na for gypsum of 60t/ha in the time frame. The electrical conductivity reduced from 2,660 ms/cm to 2,300 ms/cm in July 1998. At some higher application rates of gypsum, it would seem that higher electrical conductivity results were recorded.

In the smaller drained plots, the pH reduced from 9.7 to 7.4 between February and December 1997. No significant effect of gypsum rates above 40t/ha was observed. There was a reduction in Na concentration between February to December 1997 in the first four plots in the area known as Pond 6 from 370 to 280 ppm and an increase in the remaining 10 plots. There was a convincing increase in electrical conductivity from February 1997 to December 1997, from 2000 to 3,100 ms/cm.

In February 1998 poultry litter was spread at application rates of 4 t/ha on the larger plots and 4.5 t/ha on the smaller plots. At the same time ammonium sulphate was spread at application rates of 0.62 t/ha on the larger blocks and 0.55 t/ha on the smaller plots in an effort to obtain improvement in vegetation growth, in May 1998 five varieties of grass seeds were sown, these were native seeds, including Bermuda grass, castor bean and logwood, on both the larger and smaller plots. By July, some growth was evident but some areas were bare, this was thought to have been caused by not applying the seed uniformly when done by hand. The bare patches were re-seeded in late July and at the same time N-P-K fertilizer was spread over the vegetated area at a rate of 4.5t/ha. Some artificial irrigation was also necessary. Additional sewage sludge was also added later in the year. The areas with sewage sludge appeared to grow best for a while, but later the original applications became degraded. Some success was achieved on coarser textured bauxite residue (Nelson, 1985). Intensive irrigation was later applied to the 2 m x 2 m plots in an attempt to lower the sodium concentrations (Bucher, 1985).
Comments
It would appear that the non-uniform application of seed and the amendments were not good enough, which resulted in bare patches. Generally, spreading by hand has been a reliable method at Aughinish, but some bare patches have occurred which had to be re-treated. Non-uniform applications are deemed to be of major concern when amendment is required over a large area. It was also noted that gypsum above 40 t/ha did not yield a greater degree of vegetation spread. The extra irrigation would indicate perhaps an insufficient period of residue weathering, or perhaps the trials were conducted during a very dry period.
It was noted that the plots in Aughinish with bare patches, mostly the large plots from 2006, developed usually as a result of flooding or pooling problems on the residue caused by very compacted residue. This was possibly due to insufficient digging or ploughing, not enough sand or residue or following insufficient weathering. While Jamaican trials did not use any sand, this could have helped with drainage of the residue. Similar to the Aughinish trials amendment greater than 40t/ha of gypsum did not have any benefit on vegetation cover.

2.16 Carbonation of Bauxite Residue (Alcoa)

This information was received from David Cooling Alcoa World Alumina Western Australia following a telephone conversation.

Alcoa World Alumina Australia (Alcoa) investigated residue carbonation as a potential major improvement opportunity for achieving residue storage with lower environmental risk and reduced potential for long-term management requirements. Comprehensive laboratory and pilot scale testing of residue carbonation were conducted during the period 1991 to 1996. Results from these pilot scale trials were promising with carbonated mud pH of 9 being achieved and leachate quality from the drying beds being maintained at around pH 10.

2.16.1.1 Alcoa Plant

Alcoa World Alumina produces 16 million tonnes of alumina annually at its refineries located in Australia, the United States of America, South America and the Caribbean. This represents 22% of the world production of alumina. These refineries also produce over 20
million tonnes of an alkaline residue annually. Storage of this residue poses some major environmental challenges.

From an environmental viewpoint, it is mainly the alkalinity of the bauxite residue which is of concern. Alcoa has undertaken a number of development projects aimed at improving the methods of residue storage. This development work commenced in the early 1970s, with the primary focus coming from the discovery of groundwater contamination below the Kwinana plant in Western Australia storage areas. The original containment areas had been constructed on the sandy coastal plain and relied upon a single 380 mm thick clay layer to prevent contamination of the underlying aquifer. While the clay seal had been effective in preventing general seepage, there were a number of places where the clay was damaged during the operation life of the storage area. The damaged areas were possibly the result of cracking of the clay due to desiccation or erosion caused by rainfall.

As a result of the groundwater contamination, improved methods of sealing the storage areas were adopted. New containment areas at Kwinana were constructed with a composite clay/synthetic membrane seal, and a drainage layer placed above this composite seal to reduce the hydrostatic head at the base of the residue, further reducing the potential for seepage. The drainage layer had the added advantage of increasing the consolidation of the residue, improving the storage efficiency of the area, and recovering alkaline drainage water for return to the refinery.

The initial cost of establishing dry stacking at Alcoa's three Western Australian refineries exceeded $150 million. The change here meant that Alcoa could with the installation of deep thickeners get the solids concentration of the residue to a higher level (48%) This would still be a lot lower than Aughinish, which pumps to the B.R.D.A. at 55% - 58% solids.

Solar drying of the residue produces a much higher density than can be achieved with wet disposal, reducing the overall volume of stored tailings. Progressive stacking allows the deposit to be taken to a height, which would not be economical with conventional wet impoundments. Higher density and increased deposit height means less land is used. This is similar to Rusal Aughinish system.

Exposure of less land area to residue and the drained condition of the dry stack significantly reduced the risk of groundwater contamination. Aughinish does not have a problem with groundwater contamination and with the liner in place contamination is unlikely to happen in the future. Improved surface stability and drainage mean that
completed areas can be reclaimed and re-vegetated quickly. Safety hazards to people and wildlife were reduced.

**Residue Carbonation**

Residue carbonation is the addition of gaseous CO$_2$ to the thickened residue slurry, prior to the deposition of this slurry onto the residue drying areas. The CO$_2$ reacts with the alkaline components within the liquor, and if held in contact with the slurry for long enough, the adsorbed and solid forms of alkalinity also react. Table 07 below lists the stoichiometric carbon dioxide demand requirement to attain a pH of approximately 8.3 for entrained liquid in a typical Kwinana plant super thickener underflow (slurry density of 48% solids wt/wt).

Alcoa have cheap CO$_2$ gas available from a nearby ammonia plant that is piped into the refinery. With regards to the plant at Aughinish, it would need to import CO$_2$ gas as it is not available in Ireland in sufficient quantities. Another option would be to build a CO$_2$ plant, the initial cost of which has been estimated at €30m, or use gas from the boiler stacks to extract CO$_2$. Neither of these options is likely to happen in the near future at Aughinish due to the cost involved. There is, however, merit in mud farming, which is the ploughing-up of the residue and exposure of the residue to the atmosphere, leading to atmospheric carbonation.
Table 7 Stoichiometric carbon dioxide demand required to treat thickened residue slurry

<table>
<thead>
<tr>
<th>Feed</th>
<th>kg CO₂/kL</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃ (liquor)</td>
<td>5.1</td>
<td>NaAl(OH)₃ + CO₂ → NaAlCO₃(OH)₂ + H₂O</td>
</tr>
<tr>
<td>TC (liquor)</td>
<td>6.4</td>
<td>NaOH + CO₂ → NaHCO₃</td>
</tr>
<tr>
<td>TA (liquor)</td>
<td>0.8</td>
<td>Na₂CO₃ + CO₂ + H₂O → 2NaHCO₃</td>
</tr>
<tr>
<td>TC (adsorbed)</td>
<td>3.4</td>
<td>NaOH + CO₂ → NaHCO₃</td>
</tr>
<tr>
<td>TA (adsorbed)</td>
<td>0.2</td>
<td>Na₂CO₃ + CO₂ + H₂O → 2NaHCO₃</td>
</tr>
<tr>
<td>TCA-6</td>
<td>15.8</td>
<td>3Ca(OH)₂·2Al(OH)₃ +3CO₂ → 3CaCO₃ + Al₂O₃·3H₂O + 3H₂O</td>
</tr>
<tr>
<td>DSP Na₂O</td>
<td>1.8</td>
<td>Na₆[AlSiO₄]₆ 2NaOH + 2CO₂ → Na₆[AlSiO₄]₆ + 2NaHCO₃</td>
</tr>
<tr>
<td>Total</td>
<td>33.7</td>
<td></td>
</tr>
</tbody>
</table>

2.16.1.2 Mud Farming

The application of ‘mud farming’ to the bauxite residue deposited within the B.R.D.A. commenced at Aughinish in 2009. Mud farming is typically achieved using an Archimedean screw vehicle, called an Amphirol. Mud farming leads to rapid and greater residue dewatering and material consolidation, ensuring the residue material is deposited at maximum density, with maximum storage rates and capacities realised (Cooling, 2007).

An analysis of atmospheric carbonation of bauxite residue within the B.R.D.A. was carried by Dr Luke Kirwan, a member of the Aughinish Research and Development Department. The rate at which mud farming can accelerate bauxite residue carbonation by atmospheric carbon dioxide was initially examined in Cell 3 within the B.R.D.A. Fresh bauxite residue was deposited in the cell and the change in bauxite residue compaction and pH was measured as a function of the number of passes with the Amphirol. This was carried out over a 112-day period. The results are presented in Table 8 and show that there is significant carbonation of the bauxite residue, with a strong correlation between decreasing causticity with increasing amphirol passes. However, there is only a very weak correlation between number of amphirol passes and pH reduction. As the causticity did not reach below 30, it is
not expected that the pH would reduce below 12, as evident from the laboratory results. This also suggests that the liquid phase alkalinity had reacted and the system is now buffered by solid phase alkalinity.

![Diagram showing the relationship between pH and causticity](image)

**Figure 17** The relationship between the change in causticity and pH as a function of the number of passes with amphirol for samples taken in Cell 3 within the B.R.D.A.

A protocol of more intense mud farming was introduced to Cell 6 to see if the causticity and the pH could be driven to lower values, it was anticipated that approximately 15 passes may achieve a pH of around 11.5.

The results of the Cell 6 analysis are given in Figure 18. The results were not very encouraging and show only a very weak correlation between number of amphirol passes and decreasing pH and causticity. Given the strong correlation between causticity and amphirol passes as shown in Cell 3, this is somewhat disappointing.
Figure 18 Relationship between the change in causticity and pH as a function of the number of passes with amphirol for samples taken in Cell 6 within the B.R.D.A.

The main differences between the two tests that may go towards explaining the observed differences include:

- Cell 3 was sampled to only a depth of 30 cm, whereas Cell 6 was sampled to a depth of 60 cm;
- Both tests were carried out a similar time of the year, and in fact Cell 3 had the lower average daily temperature (4.2°C compared to 6.3°C for Cell 6), suggesting that kinetics are not a factor. However, Figure 18 shows that there is a lot more variation in the temperature for the Cell 3 data, while for the Cell 6 data there is little scatter and the temperature dropped rapidly over the duration of the test. A greater understanding of ambient conditions on the progress of carbonation by mud farming is warranted;
- The absolute time taken to do the tests, as can be seen in Figure 19, Cell 6 test was carried out within a month, where amphirol passes were done every few days, whereas for Cell 3, the test was carried out over 112 days, with each amphirol pass in excess of a week apart.
Figure 19: The daily average temperature at the B.R.D.A. during testing periods of Cell 3 and Cell 6.

Figure 20: Residue mud before farming.
Conclusions

Mud farming is already incorporated into the B.R.D.A. management process at Aughinish, having commenced in 2009 (see Figures 0-20 & 21). Mud farming minimises the potential for dust generation as the ploughing motion maintains a wet surface, buries carbonates, and provides a rough surface that prevents dusting once the residue area has dried. The mechanism of mud farming, in particular the burying of surface carbonates and exposure of a fresh liquid surface, is thought to have potential to perform in-situ or atmospheric carbonation of the bauxite residue within the B.R.D.A., giving the equivalent to neutralisation achieved with carbon dioxide neutralisation, resulting in neutralisation to a stable pH around 11.

When isolated from the bauxite residue solid phase, the atmospheric carbonation of the liquid phase within the bauxite residue occurs relatively quickly with an initial sharp decrease in pH down to approximately pH 11.5, associated with the consumption of free hydroxide. Beyond this, the decrease in pH is more gradual due to the buffering action of aluminium hydroxide and dawsonite precipitation and the solution buffering of the carbonate/bicarbonate system, which buffers most strongly at around pH 10.2.
In the presence of bauxite residue solid, and with the action of atmospheric carbonation, the liquid phase will carbonate down to around pH 12. Beyond this pH the solid phase alkalinity will buffer the system such that a minimum pH of approximately 11 is achieved. To reduce the pH beyond 11 relies on an accumulation of common ions such as Ca\(^{2+}\) to suppress the solubility of the alkaline solid material, whereby a pH of around 10.5 may be achieved. A reduction below pH 10.5 requires the complete dissolution/transformation of the solid phase alkalinity.

The rate at which mud farming can accelerate bauxite residue carbonation by atmospheric carbon dioxide within the B.R.D.A. was examined. Initial results showed that there was significant carbonation of the bauxite residue. The causticity reduced from around 85 to 30, and was strongly correlated with increasing amphirol passes. However, there was only a very weak correlation between number of amphirol passes and pH reduction, with the pH reducing from around 12.5 to 12.0. A causticity of around 30 suggests that the liquid phase alkalinity has reacted and that the system is buffered by solid phase alkalinity, with buffering of the solid phase alkalinity contributing to a pH as high as 12.

A more intense mud farming protocol was implemented to see if the Causticity and the pH could be further reduced. However, the results were not very encouraging and only showed a very weak correlation between number of amphirol passes and decreasing pH and Causticity.

The main differences of sampling of sampling protocol could be ambient conditions, or the time span between the two tests may go towards explaining the observed differences, while the results for the atmospheric carbonation of bauxite residue within the B.R.D.A. by mud farming were not very convincing, there appears great potential and it is likely achievable through optimisation of the process.

Areas of optimisation may include:

- Establish a robust sampling procedure that is reproducible and representative;
- Establish the effect of ambient conditions such as temperature, rainfall, humidity, and evaporation;
- Establish if there is a time component associated with the frequency of amphirol passes required to achieve sufficient carbonation;
- Establish the effect of different mechanical manipulation of the bauxite residue, for example, plough as opposed to amphirol.
2.17 Greece Case Study

This project was financed by the European Union LIFE–ENVIRONMENT Demonstration Project; Rehabilitation of abandoned bauxite surface mines using alumina red mud as filler (REFILL, 2006).

The Greek plant Aluminium of Greece was used as the case study. The company had been pumping their bauxite residue into the sea and so were under pressure to find an alternative storage area for the bauxite residue. On the other hand, most of the open pits of surface exploitation of metalliferrous ores were left abandoned after ore extraction was completed.

The company examined the development and field application of an innovative and cost-effective method for restoring abandoned surface mines using mainly bauxite residues as a filling material. The methodology investigated included dewatering of bauxite residues, controlled disposal of dried bauxite residues, capping with waste rock or treated bauxite residues and, finally, development of a vegetation cover. This scheme was investigated at laboratory and pilot field scale. The results obtained from laboratory tests, field pilot tests, and simulation confirmed the hypothesis that the amount of water infiltrating through bauxite residues being released to the environment was minimal, i.e. approximately 3% of the annual precipitation. Thus, the risk of groundwater contamination due to bauxite residue disposal in abandoned mines was low.

The large open pit areas of surface mining, as well as the huge amount of wastes produced from mining and metallurgical activities, are considered as the two most important environmental problems associated with the mining and metallurgical industry. While many mine operators have taken precautions to fill in and restore surface mine sites, most were left abandoned after ore extraction was completed. Furthermore, a common practice of mine operators was the stockpiling of waste rock around the mining open pit sites, resulting in the devegetation of the surrounding surface.
The main objective of this study was to develop and demonstrate an innovative, cost-effective and generic methodology for restoring abandoned surface mines by disposing of mining and metallurgical wastes in an environmentally safe matter. By doing so, both environmental problems associated with the mining industry, i.e. the abandoned open pits and the disposal of mining and metallurgical wastes would be eliminated.

The project objectives would be achieved by

- implementing environmental characterisation of materials, bauxite residue, waste rock at the mine, sewage sludge for vegetation growth,
- using filter presses to de-water the residue
- setting up vegetation cover on the test area, using gypsum, sewage sludge
- setting up pilot tests and field demonstrations.

Bauxite residue was proposed as a filling material for the remediation of abandoned surface mines. The amount of bauxite residues in the Greece plant was significant and dependant on the quality of the bauxite mineral used. Aluminium of Greece is the only aluminium refinery in Greece. It produces almost 680,000 tonnes of bauxite residues annually. This residue is pumped through pipes from the refinery to the seabed of Gulf of Corinth. The disposal of bauxite residues in the sea currently applied by Aluminium of Greece is not a method widely applied. In order to avoid any kind of environmental problems related with this method, it is necessary to find alternative, environmentally-friendly, technologically feasible and cost-effective land disposal methods.

Although bauxite residue is an alkaline waste, the potential environmental risk associated with the containing alkalinity from such a disposal option is low. This low risk is due to the very low hydraulic conductivity coefficient of bauxite residues, which is slightly higher than the limit posed for low permeability layers in the Landfill Directive by the European Commission, i.e. \(1 \times 10^{-7}\) cm/sec. However, in order to act as a low permeability layer, prior moisture reduction of bauxite residues to their optimum value is required. By acting as a low permeability layer and taking into account the low precipitation and high evapotranspiration rates at the sites, it is estimated that water percolation through bauxite residue layers would be minimal. In order to prove this statement pilot field tests were carried out and simulation of both the pilot tests and an abandoned mine that has been designed to be restored were executed.
2.17.1 Remediation Scheme

The methodology investigated for the rehabilitation of abandoned surface mines includes
dewatering of bauxite residues to certain moisture content, transportation and controlled
disposal of the dried material, and finally capping with gravel and treated bauxite residues or
waste rock and the development of a vegetation cover.

2.17.2 Bauxite residues

Bauxite residue is the main material that will be used for the restoration of abandoned surface
mines. It is a very fine material with $d_{50} = 4 \mu m$ from Figure 22 below.

![Particle Size distribution of Bauxite Residues](image)

The optimum moisture content (OPC) resulting in maximum dry bulk density was determined
according to the standard Proctor method by varying the density vs. moisture content. As
shown in Figure 22, the optimum moisture content corresponding to maximum bulk density
(1.506 t/m$^3$) was 28.38% wt. dry basis. The optimum moisture content is approximately 2%
less than the plasticity index, which is common for all fine materials.
Permeability measurements indicated that bauxite residues present low hydraulic conductivity values ranging from $3 \times 10^5$ to $4.6 \times 10^7$ cm/sec, depending on the compaction conditions. The lower value of permeability ($4.6 \times 10^7$ cm/sec) was obtained when bauxite residue had optimum moisture content and was compacted at maximum dry bulk density according to the standard Proctor test method (Figure 20). This value indicates that properly compacted bauxite residues present low hydraulic conductivity values, slightly higher than the limit posed in the landfill directive by the European Commission for low permeability layers, i.e. $1 \times 10^{-7}$ cm/sec (1999/31/EK 26-04-1999). By acting as a low permeability layer and taking into account the low precipitation rates at the sites into consideration, it is estimated that water percolation through bauxite residue layers will be minimal. When bauxite residues are compacted at 95% of the maximum dry bulk density, the hydraulic conductivity coefficient was found $1.3 \times 10^6$ cm/sec, whereas when the material is compacted at the moisture content of 30.4% wt. db (2% higher than the optimum value), the permeability coefficient was $9.1 \times 10^7$ cm/sec, i.e. twice the value obtained when compaction was performed at optimum conditions. Variation of hydraulic conductivity coefficient with time, compaction and moisture contents is given in Figure 23.

Figure 23: Dry density vs. moisture content according to standard Proctor method
The low hydraulic conductivity coefficient values may become even lower, when pressure is applied on bauxite residues. Permeability measurements conducted under various loading rates indicated that the hydraulic conductivity coefficient values could be as low as $1 \times 10^{-7}$ cm/sec.

In this study, the bauxite residues layer was expected to act as a low permeability layer. Therefore this layer has to be compacted to the maximum dry density at the optimum moisture content in order to obtain the lowest possible hydraulic conductivity coefficient. Therefore, the moisture content of bauxite residues, combined with the proper material compaction, is crucial to obtain low permeability values. For this reason the dried bauxite residues have to be compacted in successive layers of only 30 cm (Layman Report 2006).

2.17.3 Gravel

On top of the bauxite residues layer, gravel was also placed to a depth of 50 cm. This layer acted as a drainage layer. Considering that the gravel layer overlies a low permeability layer, this layer was necessary to remove the water that penetrates the upper layer. It also reduced pore water pressure in the overlying layers improved slope stability, and impeded upward capillary movement of any waters from the underlying bauxite residues (Zheng et al. 2000).

2.17.4 Vegetation Layer

It is necessary to encourage the formation of a vegetation layer as it will prevent wind and water erosion, enhance evapotranspiration and improve aesthetics. Due to the absence of topsoil in most of the bauxite mining open pit areas, two alternatives were examined for the formation of protective and topsoil layers: (a) the use of waste rock, and (b) the use of bauxite residues. Both materials need to be properly modified in order to act as a substrate for the development for a vegetation cover. Sewage sludge and organic material were found to be efficient ameliorants of waste rock (Brofas & Varelidis, 1997), whereas a mixture of gypsum, sewage sludge and calcium oxy-phosphate was needed to ameliorate bauxite residues so that it can support vegetation (Xenidis et al., 2004).
2.17.5 Pilot Tests

Pilot tests covering an area of approximately 580m² were performed in an abandoned surface mine in order to investigate the behaviour of bauxite residues as a low permeability cover under site-prevailing conditions and to obtain the design parameters for the restoration of abandoned bauxite mines. The entire pilot testing area was divided with geo-membrane into two equal sections test pads (test pad 1 and test pad 2). Although total precipitation in the area during the first year was 570 mm, only 15 and 17 mm of water percolated through the material in test pads 1 and 2 respectively, and this was collected in the drainage collection vessels in early April 2005. This quantity of drainage water corresponded to less than 3% (2.7 and 2.9 % for test pads 1 and 2 respectively) of the annual precipitation on the test pads. The quantity of drainage water collected during the second year of monitoring was higher than this value.

According to the data from two years monitoring, the average annual percolation rates for the test pads 1 and 2 were 23 and 30 mm respectively, which correspond to only 4 and 5.3% of total precipitation.

The initial design also involved the installation of lysimeters beneath bauxite residues to collect and monitor any leachate that may have infiltrated through the bauxite residues mass. However, based on the meteorological conditions at the field site and the geo-technical properties of the bauxite residues (low hydraulic conductivity), it was believed that the drainage water was minimal. No figures given to show what was collected by the collection system / lysimeters.

Based on laboratory and field pilot test results, it is estimated that the annual infiltration rate of water was minimal, approximately 3% of the annual precipitation. For the Kleisoura mine, the reference scenario resulted in total annual percolation rate corresponding to 3.1% of the annual precipitation. The respective value for all the other scenarios was between 2.3 - 4.6 %. Even at the worst-case scenario, in which the values resulting in high infiltration rates were given to all the parameters simultaneously, the infiltration through the dump remains low still (29.96 mm or 6.3% of the annual precipitation) (Layman Report 2006).

Concerning the simulation of the pilot tests, the water infiltration result determined was approximately 4.4%, which was close to the infiltration values (less than 3% of the total
annual precipitation) measured in the corresponding field tests implemented and monitored for the same period.

2.17.6 Conclusions / Review

A cost-effective method for restoring abandoned surface mines using mainly dried bauxite residues as a filling material was investigated. The results of field tests monitoring, simulation of the Kleisoura mine planned for restoration and pilot tests using Visual Mod Flow and Visual HELP, confirmed the hypothesis that the amount of water infiltrating through bauxite residues and released to the environment was minimal, i.e. approximately 3% of the annual precipitation. Therefore, the authors reported the risk of groundwater contamination due to bauxite residues disposal in abandoned mines was low.

They are very optimistic about the infiltration rates, but it is still a significant release into the environment. No figures were given for leachate either flows/quantity or pH values. No information on how the leachate samples were extracted was given. Clearly it would require further monitoring of leachate quantities and values over a longer period to be sure that no groundwater contamination can happen.

On reflection of these case studies, there is relatively no chance that Aughinish could dispose of its bauxite residue in a mine, even if one were available. Disposal in a mine has been done in Canada. It was for a period while their plant was constructing a B.R.D.A. similar to Aughinish to change from a mud pond system. It required high-pressure pumps to pump the slurry over several miles. Environmental regulations in Ireland would require all tailing to be lined, which would not be feasible in a mine.

From these case studies there was information that helped in determining amendment rates particularly of gypsum. The use of boiler bottom ash and fly ash, which is available in Ireland from power stations, is not allowed due to environmental regulations. The authors / researchers seem very optimistic about the percentage of leachate that would infiltrate the groundwater. Although they consider this level to be low and acceptable it would not be accepted in Ireland. Certainly Aughinish would not consider seepage rates of this level and would deem them unethical, environmentally unsafe and therefore not to be considered.
2.18 Alcan Gove Bauxite Residue vegetation Research Programme

Australia (Case Study)

2.18.1 Introduction

This is a review of the method used by Alcoa and the trials they conducted in conjunction with The University of Queensland, Australia. People involved in this research were J. Bernhard Wehr, School of Land and Food Science, Neal W. Menzies, School of Land and Food Science, University of Queensland and Ian Fulton, Alcan Gove. The information on trials at Gove was received from Alcan Head Office in Montreal from Jacque Lareieux, Alcan Technical committee consultant who attends quarterly meetings in Aughinish. There is a technical agreement between Alcan and Aughinish since the days when Alcan owned Aughinish.

The Gove plant is in the north-west corner of Australia in the tropical region where land access is very difficult during the wet season. Bauxite refinery residue at Alcan Gove consists of 13% sand-sized, 40% silt-sized and 47% clay-sized particles. The residue is separated prior to disposal into a coarse-sized fraction (residue sand) and a fine fraction termed bauxite residue, which contributes approximately 86% of the total waste material. Disposal of residue in engineered dams requires re-vegetation prior to mine closure to minimise negative environmental impacts such as seepage, water and wind erosion and to improve visual amenity of the disposal site.

The refinery residue is much the same as other refineries is characterised by high alkalinity (pH > 10), high sodium (Na) concentration (> 10 g/l), high salinity (EC, >5 mS/cm) and low concentrations of nitrogen, phosphate and organic carbon, which prevents growth of vegetation on the residues. The growth constraints of the material can be partially overcome by mixing large quantities of organic material (compost, manure, sewage sludge, paper pulp) and inorganic materials (gypsum, CaSO4.2H2O) with the top layer of residue. This approach achieves short-term results, but the pH and salinity of the residue is too extreme to sustain long-term vegetation growth (Gupta et al., 1985).

Past re-vegetation attempts at Alcan Gove utilised thin capping layers of soil over bauxite residue and while this allowed vegetation to establish in the short-term, long-term success was not consistently achieved, presumably due to:

• lack of sufficient water reserves in the capping layer during the dry season;
Inadequate drainage; rise of alkalinity from the residue into the soil capping, and; plant nutrient imbalances (Morrell et al., 2000).

In 1998, a 1.25 ha field trial was set up by Alcan Gove in collaboration with the University of Queensland, using three possible capping sequences, viz. "Topsoil" plot (5 cm wood-mulch and 15 cm topsoil over 50 cm subsoil over 100 cm residue sand over bauxite residue), "Subsoil" plot (15 cm wood mulch and 65 cm subsoil over 100 cm residue sand over bauxite residue) and "Residue sand" plot: (15 cm wood mulch and 165 cm residue sand over bauxite residue). Figure 25 shows the layer of residue sand between bauxite residue and the soil capping was thought to act as a capillary break layer, improve drainage and serve as a rooting medium.
Alcan Gove contracted the University of Queensland to monitor the field trial and to conduct research into the re-vegetation of disposal areas under the Bauxite Residue Re-vegetation Research Programme.

2.18.2 Research summary

The relative performance of the capping sequences in the field was monitored regularly through vegetation assessment, soil and water sampling, quantification of rainfall, run-off and drainage, and root growth. The field observations were complemented with laboratory-based research results which aided in the interpretation of the data. Initial studies aimed at optimising the amelioration of residue sand, since it is intended to form the bulk of the rooting medium.

The outcome of the completed research programme allowed formulation of possible re-vegetation strategies for residue disposal areas in the monsoonal climate of Gove. The principle behind the recommended strategies was to cap the bauxite residue with a capillary break layer and a soil layer. The vegetation would derive its nutrients from the soil capping, while available water would be provided from the soil capping and the capillary break layer. It was intended that the surface soil layer would have high rainfall infiltration which allowed good seedling establishment, while the subsurface soil layer would have a high water holding capacity. A capillary break between the soil cover and the bauxite residue limits rise of alkalinity into the soil capping, aids drainage and provides significant supply of water to the vegetation. This project focused on the use of seawater neutralised residue sand as capillary break layer and subsoil or topsoil plus subsoil as soil capping (Menzies et al., 2004).

Based on the assumption that materials used in the future are similar in chemical and physical characteristics to those used in the various glasshouse and field studies, in particular at their Northern Ponds in relation to the hydraulic properties, the following capping sequences would be suitable. These were identified by (Menzies et al., 1997):

- 10 cm surface-suitable soil over 50 cm subsoil over 110 cm residue sand
- 10 cm surface-suitable soil over 150 cm residue sand
- 50 cm subsoil over 120 cm residue sand

These capping options supply between 250 and 260 mm plant available water, which is the minimum needed to support a vegetation cover consisting of grass and a few trees, similar to
that on the subsoil and topsoil plots. The plant available water content (PAWC) influences ecological, hydrological and vegetation distribution and is very significant (refer to Annual Report 2002/2003) (Menzies et al., 1997).

2.18.3 Future Direction

Subsequently residue sand was no longer available as a separate waste stream following the refinery expansion, which was completed in 2007. Therefore, the drainage/break layer needed to be added to by either low grade bauxite or crushed laterite (LGB) or a substrate of cloddy seawater neutralised bauxite residue which Alcoa Gove has available.

Low-grade bauxite, due to the large proportion of gravel-sized particles (60% >2 mm), has a very high hydraulic conductivity (>2000 mm) but a low water-holding capacity (approx. 5 mm per 10 cm). The coarse texture of low-grade bauxite makes it ideal as a drainage layer. The low water holding capacity of LGB would necessitate the use of a very thick capping layer if vegetation has to rely on water stored in this material. If it were intended that LGB be used only as a capillary break layer and drainage layer, a thin layer (50 cm) would be sufficient. While the fertility of the material is unknown, it can be assumed to be low, especially in phosphorus.

Other options, such as combining low-grade bauxite in a matrix of cloddy seawater-neutralised bauxite residue to form the substrate (capillary break/drainage layer) of the capping profile, will be investigated.

2.18.4 Comparisons with Aughinish and Case Studies Review (Team Review)

- Aughinish would not dispose of their residue to a mine even if one were available as there is not enough of environmental research information available at present.
- From these case studies there was information which helped in determining suitable application rates particularly of gypsum at Aughinish. The sodium concentration showed a decline. The electrical conductivities also showed reductions from 2,660 ms/cm to 2,300 ms/cm in the Jamaican trials.
The CO$_2$ neutralisation was the one preferred by the E.P.A. in their discussions on the licence extension for Phase 2. Aughinish could install it by building a CO$_2$ or importing liquid CO$_2$.

Limitation on the use of boiler bottom ash and fly ash, which is available in Ireland from power stations, prevents Aughinish taking that option, due to environmental regulations. Fly ash is classed as hazardous waste and must be exported out of the country for treatment.

The Australian trials showed the importance of the break layer between the residue and the ameliorants to prevent capillary rise from the higher pH residue. This is probably more relevant in tropical regions given the very wet and then very dry seasons.

Use of low-grade bauxite would require high shipping costs plus added storage space. Aughinish only import high-grade bauxite. Low-grade bauxite would have to be stored in the open as there is no covered storage available.

Use of topsoil or subsoil is expensive and usually not readily available, either in Ireland or most countries.

Seawater neutralisation at Aughinish would be very expensive due to high pumping costs and the run-off would still require treatment prior to discharging back into the Shannon River. This is the same process as is presently used to treat the B.R.D.A. run-off return from the Storm Water Pond.

Major differences in climate, residue sand production and availability of composting and top soil materials made the Alcan Gove plant look for alternatives in capping layers. Aughinish has sufficient quantities of residue sand, up to 2,000 tonnes per week is removed from the process. Composting materials are obtained free of charge from a waste disposal company. Rainfall in Ireland is more moderate and evenly spaced throughout the year, which does not cause swings in water table or risk of capillary rise to the same degree.

The option of sea water neutralisation of either / both residue sand or bauxite residue Aughinish deems this process too costly and not practicable due to the amount of fresh water in the river Shannon which gives it a lower salinity. Large pumps are required to pump seawater into the residue slurry pipe work, and the supernatant would require treatment.

The high rainfall which causes erosion and gives high run-off levels would be acceptable in Aughinish, as the higher flows would have a dilution in the leachate / run-off
mix, resulting in lower pH values. The pH values do not seem to be of any concern to Alcoa given they use sea water neutralisation for part-neutralisation of the residue sand and there is no mention of environmental considerations on effluent discharges. If low-grade bauxites were used in Aughnish, it would mean importing this lower grade and using this solely in residue disposal.

2.18.5 Rehabilitation Procedures

According to results of the International Aluminium Institute Survey 2003, eleven operations stated they have carried out some rehabilitation of residue containment areas (39.4% of reported production). Four of the operations started rehabilitating containment areas in the 1970s, two in the 1980s, four in the 1990s and one operation commenced rehabilitation in 2003. These eleven operations have rehabilitated a total of 671 ha, mostly to native vegetation and pasture (see Figure 26).

Figure 26 The proportion of area rehabilitated to various land uses
Operators consider that the major soil factors restricting plant growth on the rehabilitated containment areas are alkalinity (10 operations) and nutrient deficiency (9 operations). Six operations nominated salinity, sodicity and soil compaction and two operations nominated chemical toxicity, water-logging or low water holding ability as potential factors restricting plant growth on rehabilitated residue containment areas. One operator considered that the main factor limiting vegetation growth at their operation, in an area with monsoonal rainfall, is the water availability at the end of the dry season.

Containment areas are topped off with top-off containing coarse residue or other capping material before rehabilitation at all but one operation. The materials used and the depths of materials applied are given below in Table 8.

<table>
<thead>
<tr>
<th>Capping material</th>
<th>No. of operation</th>
<th>Depth of application (mm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse residue</td>
<td>3</td>
<td>600-3000</td>
<td>one site also applies 300 mm of imported soil</td>
</tr>
<tr>
<td>Soil removed before construction</td>
<td>1</td>
<td>100</td>
<td>plus 50 mm of imported soil</td>
</tr>
<tr>
<td>Imported soil</td>
<td>4</td>
<td>300-2000</td>
<td></td>
</tr>
<tr>
<td>Industrial residues</td>
<td>1</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Unspecified</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A number of different soil amendments are used by various operations as part of their rehabilitation process. About 50 tonnes per hectare of gypsum was incorporated into the surface to a depth of 200-300 mm to reduce the pH at three operations. Surface ripping, to an average depth of 725 mm, was carried out by four operations. Six operations incorporated surface drains in their rehabilitated containment areas. Six operations applied organic and inorganic fertilisers, two used only organic fertilisers and three did not apply either organic or inorganic fertilisers.

The costs of rehabilitating areas of residue are very high for all types of final land use; the average cost reported was US $53,214 per hectare with a maximum of US $100,000.
per hectare. A monitoring and reporting programme to formally assess the strength and weaknesses of the rehabilitation programme is in place at seven operations.
2.19 Review International Alumina Plant Case Studies

Introduction
This activity examines a selection of alumina operators and bauxite residue facilities around the world. World refineries produce over 60 million tonnes of alumina and more than 70 million tonnes of residue per year (IAI Website, 2003). The operations selected here are based on size and technology.

Each Assessment includes a description of the
- Operation
- Local climate
- Residue disposal facility
- Residue management philosophy
- Residue design intent
- Alternative uses
- Closure principles

2.19.1 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

2.19.1.1 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) (I.A.S.1998).
2.19.1.2 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 neutralises 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.

2.19.1.3 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 (I.A.S., 1998).

The town of Yarwun is the nearest populated centre (population: 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. Figure graph actually taken in 2004 prior to commissioning.
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.

### 2.19.1.4 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 neutralised using seawater. The residue slurry liquor remains alkaline after seawater neutralisation 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.
The neutralised slurry is pumped at around 20% solids to two high-rate deep-cone thickeners, where it is thickened to 40% solids (w/w) through the addition of flocculants and self aid consolidation. Overflow from these vessels is returned to the ocean via a sediment control dam.

2.19.1.5 Residue Management

The thickened residue is typically thixotropic and is pumped, via a single disposal pipeline to the adjacent drying area, where 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 Amphirol machine to dewater residue to the shrinkage limit. By maintaining a moist surface with high surface roughness, it 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).

2.19.1.6 Residue Design Intent

The Environmental Impact Statement (EIS) provides some key reasons as to the selected disposal facility location and underlying design intent for the residue disposal system (IAS, 1998). These include:

- other potential sites close to the refinery are unsuitable due to potential impacts on wetland areas;
- there was no suitable area of land for residue storage available adjacent to the refinery site;
- The site was located in the upstream area of its sub-catchment, is not subject to flood inundation and would not require major drainage diversion works;
• un-neutralised residue would be highly alkaline and would therefore pose a greater risk to both surface and groundwater resources and be more difficult to rehabilitate;
• neutralisation within the residue storage area would result in the discharge of low density residue, reducing the ability for rehabilitation; and
• seawater neutralisation 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 neutralisation 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 neutralisation is used to allow the discharge of neutralised 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, was selected to ensure the final residue density was as high as possible.

Therefore, a residue facility could support a dry stacking, seawater neutralised 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.
The EIS assumes that rehabilitation and re-vegetation activities will be carried out to render the site self-sustaining as a non-industrial land use (e.g., pasture, open grassland) (IAS, 1998). The EIS notes that restoration of the residue disposal area to the original land use and vegetation will not be possible. By adopting a high-density disposal system the bearing capacity would be there and could be an opportunity for the residue disposal facility to be utilised as a light industrial area within the Aldoga Industrial Estate.

2.19.1.7 Closure

The EIS assumes that rehabilitation and re-vegetation activities will be carried out to render the site self-sustaining as a non-industrial land use (e.g., pasture, open grassland) (IAS, 1998). The EIS notes that restoration of the residue disposal area to the original land use and vegetation will not be possible. By adopting a high-density disposal system the bearing capacity would be there and could be an opportunity for the residue disposal facility to be utilised as a light industrial area within the Aldoga Industrial Estate.
2.19.2 Queensland Alumina Ltd

Alumina Production Capacity: 3.8 mtpa
Ownership: 41.4% Alcan, 38.6% Rio Tinto plc, 20% Rusal
Location: Gladstone, Queensland, Australia

2.19.2.1 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 (IAS, 1998).

2.19.2.2 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 neutralises 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).

2.19.2.3 Residue Disposal Facility

The residue disposal facility is located 8 kilometres south on a 900 ha coastal site on Boyne Island Bauxite residue. Dam #1 (400 ha) was used from 1967 - 1980’s and Dam #2 (528 ha) was constructed in 1975 and is still in use today (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 was 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 20 m in height in some areas. Little to no re-vegetation of the external walls has occurred, primarily due to the regular construction or downstream wall lifts that take place.

The Bauxite residue 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 neutralised bauxite residue.

The towns of Boyne Island/Tannum Sands are the nearest populated centre (population 8000) and are 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 for a high-visibility wall adjacent the local community. The general arrangement and location of the refinery and residue disposal facilities is shown below (Figure 29).

*Figure 29* General arrangement of QAL facilities at Gladstone, Queensland (Google, 2007).
2.19.2.4 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 neutralised 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 neutralised 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 neutralisation with a typical pH of between 8.5 and 9.5.

2.19.2.5 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. The residue point is periodically changed to allow the deposited material to dewater and solar dry.

2.19.2.6 Alternative Uses

There are no sanctioned alternative uses for seawater neutralised bauxite residue. QAL has supported research into alternative uses for neutralised bauxite residue for many years. Most notably there was early support for Virotec International, however it is understood that this has now ceased.

2.19.2.7 Closure

The current QAL re-vegetation strategy (QAL, 2007c) is to:
• maintain a pasture-like cover to control dust and erosion;
• maintain acceptable water run-off quality; and
• improve aesthetics.
2.19.3  Kwinana Alumina Refinery

Alumina Production Capacity: 2.08 mtpa
Ownership: 100% Alcoa World Alumina
Location: Kwinana, Western Australia, Australia

2.19.3.1  Climate

The Kwinana region (20 km 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 south-west and easterly in summer months and south-west in winter.

2.19.3.2  Operation

The refinery commenced operations in March 1963. The refinery consumes bauxite railed from the Alcoa bauxite mines in the Darling Range (Huntly Mine) and by world standards, is low grade, averaging 32 - 33% alumina. The refinery operates a closed circuit freshwater system. All run-off from the refinery and residue management areas is contained. The location of the refinery and residue disposal facilities is shown below.
2.19.3.3 Residue Disposal Facility

When operations commenced, initial residue disposal facilities (designated A, B, C lakes) were constructed 2 km 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 under-drainage blanket. Residue was placed in these areas until 1995.

In 1971 a new residue facility was constructed. The facility was divided into areas and given numbers, which is usual in alumina refineries (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 under-drainage blanket. The more recent construction of Areas H, I & K combine a synthetic liner with the clay seal/under-drainage system.

Figure 30 Overview of Alcoa Kwinana residue disposal facilities (Google, 2007).
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 horticultural 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 re-vegetation on outer batters will have infill planting to improve screening.

2.19.3.4 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 bauxite residue 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 in 1974 continues. The residue is not currently neutralised.

AWA (2006) stated 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.
2.19.3.5 Residue Management

Bauxite residue is pumped at low density to the residue disposal facility where it is separated into bauxite residue and residue sand by hydro-cyclones. The residue sand is managed as a separate stream and stockpiled for reuse in upstream construction and under-drainage systems.

The bauxite residue is thickened in a 75m EIMCO Super-thickener to approximately 50% solids (w/w) and placed in drying areas in 500 mm layers, where it is mud farmed using amphiroil 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 have been 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.

2.19.3.6 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, the need for imported construction materials was replaced and the operating life of the residue disposal facilities increased.

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, 2004). This research has won several state and national awards. The neutralisation process reduces the pH of the residue from pH 13 to pH 10.5. A trial unit was in operation at Kwinana with a full size unit commissioned 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®, REDLIME™ and Red Sand. Cooling and Jameson (2004) described the development of these products as:

- ALKALOAM® is a fine-grained material (bauxite residue) that can increase the pH of acidic soils and provide nutrient capture properties, thus reducing the demands for fertiliser application.

- REDLIME™ 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, thus 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, sub-grade 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 as 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.
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 resolved.

Kwinana currently supplies Ecomax Waste Management Pty Ltd with gypsum neutralised bauxite residue. 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$^3$ of gypsum neutralised residue is required per installation. Ecomax charges approximately AUD $1,400 per installation for the gypsum neutralised residue (Shire of Chittering, 2002).

2.19.3.7 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 capable of accommodating light industrial development. A decision to construct a motorplex development (combination of public areas for motor sport activities) on some of the A,B,C area as taken by the State Government in 1998. This area was returned to the Government for community use in 2000 and the development has since been successfully completed. The Motorplex development is shown below.
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.

2.19.4 Pinjarra Alumina Refinery

**Alumina Production Capacity:** 4.2 mtpa

**Ownership:** 100% Alcoa World Alumina

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

2.19.4.1 Climate

The Pinjarra-Mandurah region (90 km 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 south-west and easterly in summer months and south-west in winter.

2.19.4.2 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 run-off from the refinery and residue management areas is contained. The location of the refinery and residue disposal facilities is shown below.
Figure 32 Overview of Alcoa Pinjarra Residue Disposal Facilities (Google, 2007).

### 2.19.4.3 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 sub-soils. Constructed clay seals have been constructed in all areas. There is no evidence of significant groundwater contamination. The area is underlain by a dedicated under-drainage system. The capacity of all dams (Residue disposal areas) 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 (population 600) and is approximately 2.5 kilometres from the disposal facility. The facility is also surrounded by extensive Alcoa farmlands (6,000 ha). The visibility of the site is low, due to tree screening.
2.19.4.4 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 bauxite residue and a coarse fraction (+150 micron) or residue sand). In 1987, the wet disposal operation was converted to dry stacking. Primarily this was done 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 neutralised.

2.19.4.5 Residue Management

Bauxite residue is pumped at low density to the residue disposal facility where it is separated into bauxite residue and residue sand by hydro-cyclones. The residue sand is managed as a separate stream and stockpiled for reuse in upstream construction and under drainage systems.

The bauxite residue is thickened in a 90m EIMCO Super-thickener to approximately 50% solids (w/w) and placed in drying areas in 500 mm layers, where it is mud farmed using amphiroil 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).

Similar to the Kwinana plant, a Long-Term Residue Management Plan (LTRMP) is undertaken every five years, which must be approved by the Residue Planning Liaison Group (RPLG) and the Minister for the Environment.
2.19.4.6 Re-use Applications

No residue is currently permitted to leave the Pinjarra.

AWA (2006) states that a key target for all new residue 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.

2.19.4.7 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 aid in developing conceptual closure strategies and 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 (Figure 33).
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.

### 2.19.5 Wagerup Alumina Refinery

**Alumina Production Capacity:** 2.5 mtpa  
**Ownership:** 100% Alcoa World Alumina  
**Location:** Wagerup, Western Australia, Australia

#### 2.19.5.1 Climate

The Waroona-Yarloop region (120 km 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 south-west and easterly in summer months and south-west in winter.

### 2.19.5.2 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 run-off 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.

### 2.19.5.3 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 (Figure 34).
Figure 34 Wagerup Residue Disposal Facility (Google, 2007)

The residue disposal facilities are underlain by alluvium (clay and sandy clay) of 5 to 15m in depth. The early residue disposal facilities were constructed with a 500 mm low permeability clay seal, but subsequent identification of seepage into the groundwater now means all residue facilities have a clay/synthetic composite seal.

The local community of Yarloop is the nearest populated centre (population 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.

2.19.5.4 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
The bauxite residue is made up of two size fractions at an approximate 50:50 ratio (a fine fraction or bauxite residue and a coarse fraction (+150 micron) or residue sand). In 1991, the wet disposal operation was converted to dry stacking. The residue is not currently neutralised.

Extensive research has been undertaken to examine 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 neutralisation 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.

### 2.19.5.5 Residue Management

Bauxite residue is pumped at low density to the residue disposal facility where it is thickened in a 75m EIMCO Super-thickener 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 under-drainage 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).

Similar to some other Australian plants, there is a Long-Term Residue Management Strategy (LTRMS) in consultation with government agencies and members of the neighbouring community. No residue is currently permitted to leave the Wagerup Refinery.

### 2.19.5.6 Closure

AWA (2003) stated 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 continued
management of the bauxite residue facility closure strategy having been incorporated into the LTRMS.

2.19.6 Alcan Gove

Alumina Production Capacity: 3.5 mtpa  
Ownership: 100% Alcan  
Location: Nhulunbuy, Northern Territory, Australia

2.19.6.1 Climate

The Gove Peninsula (550 km 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 north-west summer months and south-east in winter (BOM, 2007).

2.19.6.2 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 neutralisation discharge system in order to manage the 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 in Figure 32 below.

**Figure 35** Proximity of Alcan Gove Residue Disposal Facility and Gove Alumina Refinery (Google, 2007).

### 2.19.6.3 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 re-vegetated and returned to traditional landowners (Alcan, 2004).
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 (population 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).

### 2.19.6.4 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 as primarily to reduce the area demands and hence costs (Alcan, 2004). The residue is not currently neutralised. Extensive research has been undertaken to examine the neutralisation of bauxite residue using seawater. Current efforts are directed at eliminating the existing inventory of alkaline water prior to converting to full neutralisation and open circuit operation after 2015 (Alcan, 2004).

2.19.6.5 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).

2.19.6.6 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.

Re-vegetation 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).
2.19.7  Worsley Alumina

**Alumina Production Capacity:** 3.5 mtpa  
**Ownership:** 86% BHP Billiton, 10% Japan Alumina Associates, 4% Sojitz Alumina  
**Location:** Worsley, Western Australia, Australia

2.19.7.1  Climate

The Worsley region (170 km 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 south-west and easterly in summer months and westerly in winter (BOM, 2007).

2.19.7.2  Operation

The refinery is located within the Darling escarpment (elevation 200m) and commenced operations in 1984 and has since 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 north-east. The bauxite ore, by world standards, is low-grade, averaging 32 - 33% alumina. The refinery operates a closed-circuit freshwater system. All run-off 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 for forestry and agricultural purposes (EPA, 1996).
2.19.7.3 Residue Disposal Facility

The existing residue disposal facility currently uses 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 Figure graphic resolution.

![Figure 37](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 (population: 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.
2.19.7.4 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 neutralised.

2.19.7.5 Residue Management

Bauxite residue is pumped to the under-drained 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).

2.19.7.6 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.

2.19.8 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
2.19.8.1 Climate

The Barcarena district (40 km 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).

2.19.8.2 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 had a capacity of 4.2 mtpa of alumina (Alunorte 2007) and expanded to 6.5 mtpa in 2009.

The refinery consumes bauxite transported by barge from the Trombetas mine (Mineração Rio do Norte) and Paragominas mine (CVRD) via a pipeline. The bauxite ore, by world standards, is high-grade, averaging 50% alumina. The refinery operates an open-circuit freshwater system. All run-off from the residue management areas is neutralised using acid and discharged (Alunorte 2007). The refinery and residue disposal facility is located within 3,500 ha of buffer land (Alunorte 2007).

2.19.8.3 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 show up as a beige colour due to poor Figure-graphic resolution.
The town of Belém is the nearest populated centre (population: 1,500,000) and is approximately 40.0 kilometres east of the disposal facility.

2.19.8.4 Residue Production

Approximately 0.65 tonnes of bauxite residue is produced for every one tonne of alumina (Kinch, 2006). Therefore, approximately 3,500,000 tonnes (dry) of bauxite residue is produced annually (2009). The bauxite residue is made up of a single fine size fraction. The residue is not currently neutralised.

2.19.8.5 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 neutralised using acid prior to discharge into the Tocantins River.

2.19.8.6 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 Alunorté has to truck the mud to the producers free of charge.

2.19.8.7 Closure

Not Available

2.19.9 Jamaica Aluminium Company (Jamalco)

Alumina Production Capacity: 1.4 mtpa
Ownership: Alcoa World Alumina 50%/Clarendon Alumina Production Ltd 50%
Location: Clarendon, Jamaica

2.19.9.1 Climate

The Clarendon region (48 km 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 (Jamalco, 2004).
2.19.9.2 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 run-off from the refinery and residue management areas is contained and recycled to the operation (Jamalco, 2004).

![Overview of Jamalco Residue Disposal Facilities (Google, 2007).](image)

Figure 39 Overview of Jamalco Residue Disposal Facilities (Google, 2007).

2.19.9.3 Residue Disposal Facility

Jamalco presently has four active residue disposal areas (RDAs) covering 314 ha. RDA 1 was commissioned in 1972, RDA 2 in 1980, RDA 3 in 1990, and RDA 4 was commissioned in 1997. RDAs 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 0.75- mm thick PVC geomembrane and a 450-mm clay liner. A 750 mm-thick sand layer is placed over the composite liner and acts as an under-drainage 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 (population: 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.

### 2.19.9.4 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 as 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 neutralised.
2.19.9.5 Residue Management

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

2.19.9.6 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, are introduced. 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.

2.19.10 Gardanne Alumina Refinery

Alumina Production Capacity: 0.65 mtpa
Ownership: 100% Alcan
Location: Gardanne, France
Climate

The Gardanne region (20 km 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 run-off from the refinery and residue management areas is contained. An aerial graph of the refinery is shown below: Figure 40
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 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 40 km and then taken 7 km offshore and placed in a trench 340m deep (Peres, 1973).

Alternative Uses

Gardanne have developed “Bauxaline” and residue-based construction product. Small-scale trials have taken place with some success.

Closure

Not Available.

2.19.11 Visit to Burntisland B.R.D.A. Scotland.

2.19.11.1 Introduction

This Alcan plant closed in 2004 and the author visited the plant in 2006 to review their closure technique and monitor progress. The B.R.D.A is in Whinnyhall, a few miles away from the alumina refinery at Burntisland. The bauxite residue was transported to the landfill at Whinnyhall, some 2 km to the north-east of the plant site. Bauxite residue had been trucked from the plant to the B.R.D.A for over 40 years. As the plant was old and production levels small, it was not viable to continue production.

This Closure, Restoration and Aftercare Plan was prepared for Whinnyhall Landfill in response to the request of the Scottish Environmental Protection Agency (SEPA) to Alcan Aluminium (UK) Ltd. in July 2003.

The plan had been prepared in accordance with the SEPA guidelines titled ‘SEPA Technical Guidance Note, Closure, Restoration and Aftercare Plan for submission to SEPA giving due consideration to the following documents:

- Waste Licence No. WML/9/79 for Whinnyhall Landfill;
• The Working Plan for Whinnyhall Landfill (February 1999);
• The Landfill (Scotland) Regulations 2003.

The objective of the plan was to provide a safe environmentally acceptable and cost-effective closure strategy for the landfill that would support the proposed end use.

Consultation was undertaken with SEPA during the preparation of the plan to clarify their objectives for the closure, restoration and aftercare of Whinnyhall Landfill, and SEPA requirements for the plan.

2.19.11.2 Description of Material Deposited

Bauxite processing at the Burntisland site involved the production of aluminium hydroxide and oxide from the raw material bauxite, which was primarily mined in Ghana. Bauxite is a particular type of laterite, which forms as a result of intense chemical weathering of silicate rock. When this weathered rock is enriched with aluminium hydroxides it is called bauxite. An average chemical analysis of the Ghana Bauxite is detailed in Table 9.

Table 9 Analysis of Burntisland Bauxite

<table>
<thead>
<tr>
<th>Constituent</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total SiO₂</td>
<td>1.2</td>
</tr>
<tr>
<td>Total Al₂O₃</td>
<td>52.9</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>15.1</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.8</td>
</tr>
<tr>
<td>CaO + MgO</td>
<td>0.04</td>
</tr>
<tr>
<td>Loss on ignition (LOI)</td>
<td>28.1</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
</tr>
<tr>
<td>Free Moisture</td>
<td>8.5</td>
</tr>
</tbody>
</table>

The bauxite residue was transported to the landfill at Whinnyhall, under a Waste Licence WML/9/79 which allowed for the deposition of a maximum 800 tonnes/day or 150,000 tonnes/annum of inert and industrial waste. The bauxite residue deposited at Whinnyhall can be divided into two types, fine composition are as follows:
• Bauxite Residue —Fine (Bauxite residue)

Bauxite residue comes into the category of clayey silt. It is disposed containing 40% free moisture. A typical analysis is in Table 10.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total SiO₂</td>
<td>4.7</td>
</tr>
<tr>
<td>Total Al₂O₃</td>
<td>21.3</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>44.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>7.0</td>
</tr>
<tr>
<td>CaO</td>
<td>2.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.7</td>
</tr>
<tr>
<td>Loss on ignition (LOI)</td>
<td>12.9</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
</tr>
<tr>
<td>Free Moisture</td>
<td>40%</td>
</tr>
</tbody>
</table>

**Table 10: Analysis of bauxite residue**

2.19.11.3 Landfill Closure, Restoration and After-care Plan

Surface water channels designed to collect water from above the capping layer will have increased run-off characteristics associated with the capping layer and steep gradients to reduce water ingress. They therefore will be required to be attenuated before discharge to the receiving water. Attenuation characteristics can be designed to ensure that discharge from this system is limited to flow rates well below the natural run-off characteristics for the landfill site. Therefore no adverse impacts will be associated with the capping of the landfill in terms of the hydrological characteristics. The natural surface water system surrounding the landfill site should remain in its existing state as far as practical. There are also two ponds in the catchment areas that have been identified for attenuation. In this way natural variations in the hydrological surface water regime of the Kirkton Burn and Kinghorn Loch would be maintained.

All zones were graded to allow for suitable run-off conditions of rainwater. The surface drainage were rationalized with contour drains connecting to collector drains, and
appropriate attenuation and testing before discharge to the Kirkton Burn or Kinghorn Loch or where necessary for treatment at the Leachate Treatment Plant.

2.19.11.4 Landfill Gas Management System

Due to the inert nature of the deposited material, landfill gases are not expected to be generated at the site. At the time of the visit, it was planned to conduct a gas survey in all of the recently installed boreholes within the landfill area and analysis carried out on the percentage of CO$_2$, CH$_4$ and H$_2$S to confirm this understanding. No information is available regarding whether this took place or not. To provide medium-term gas monitoring data, 2 boreholes per zone will be selected for monthly analysis and a decision will then be made as to the requirement to keep monitoring for gas once the capping layer has been placed. This decision will be made on the results taken during the gas survey and monthly monitoring.

2.19.11.5 Landfill Stability

A full stability analysis was undertaken to assess the stability of the land filled areas and its embankments and also included the long-term stability post-capping. This analysis assessed existing steep side slopes, the increased water levels within the site, the underlying fault and the material used in the construction of embankments.

It was envisaged that a combination of measures including reducing the heights of certain embankments, re-grading the slopes and controlling hydraulic gradients within the slopes would increase the stability to appropriate levels. It was also envisaged that the height of the Shale Zone embankments would be reduced to ensure their long-term stability and reduce the visual impact. A number of standpipes have been installed across the site to enable on-going monitoring of groundwater levels which will assist in the design of the stability works.

Following completion of the restoration and slope stability works annual topographical surveys will be conducted in the short term to monitor for any settlement or movement of the landfilled material. Regular stability inspections would also be conducted
annually in the short term by a suitably qualified engineer to verify the stability of the embankments.

2.19.11.6 Leachate Management System

The leachate management system was designed to collect leachate generated at the site, treat it to an acceptable level and discharge the clean effluent to sea. The system consisted of collection pipework within the landfill, a Leachate Treatment Plant (LTP) at the base of the landfill and a discharge pipeline and sea outfall.

As the Alcan processing site at Burntisland was being decommissioned, a decision was taken to relocate the leachate treatment plant to the Whinnyhall landfill. The relocated LTP, consisting of acid neutralisation and settlement, with a capacity to treat 120m$^3$ of leachate per hour while meeting current SEPA standards for discharge to the sea (see Table 0-12). The LTP at Whinnyhall was contained within a secure compound. It was envisaged at that stage that the LTP would be in operation as long as required after the capping works were complete and would ensure that any issues regarding security and operations would be quickly detected. The operation of the LTP would be kept under constant review.

Leachate from Whinnyhall is treated by acid stabilisation to neutralise the alkaline water to a more neutral pH at a range between 6 and 9 pH as prescribed in the SEPA Discharge Licence, followed by the removal of suspended solids using a hydro-cyclone type settling mechanism. The treatment plant process has consistently met SEPA effluent standards since its commissioning in the early 1990s.

2.19.11.7 SEPA Licensing Requirements

Leachate originating within the bauxite residue is directed to the treatment stream via filter drains. Additional interceptor subsurface drains would be provided during the restoration works to intercept groundwater flows at the base of embankments. Subsurface drains were also provided at the East Zone to prevent leachate flows to the Kinghorn Loch. This would ensure that impacted surface or groundwater is adequately collected and treated before discharge to the receiving water.
Depending on detailed requirements for surface water attenuation the pond at the eastern edge of the landfilled area, which collects run-off from the eastern zone, would be fully lined as part of the restoration plan and act as an attenuation pond for surface water run-off.

**Table 11** Effluent discharge consent limits

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Volume treated 2000m³</th>
<th>Volume Treated less than 2000m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit dissolved As (mg/l)</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Limit dissolved Al (mg/l)</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Limit dissolved V (mg/l)</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

**Spot Sample Consent Limits**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended Solids</td>
<td>…………………60 mg/l</td>
</tr>
<tr>
<td>pH</td>
<td>…………………6 to 9</td>
</tr>
</tbody>
</table>

**Discharge Limits**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum discharge to sea…</td>
<td>…………………120 m³/hr</td>
</tr>
</tbody>
</table>

The Scottish Environmental Protection Agency (S.E.P.A.) agreed the limits in Table 0-12 with the company. Discharge maximum flow to sea of 120m³/hr, a pH range of 6.0 to 9.0. Limits in dissolved As, Al and V mg/l were decided in 2000m³.

The capping of the landfill and rationalisation of the surface water network would reduce the amount of rainwater contained in the leachate flows. The new LTP, at the Whinnyhall, was designed specifically to deal with landfill leachate. The plant was successfully commissioned and tested to meet the stringent operational requirements. It was envisaged that with this level of standby equipment, alongside the comprehensive alarm systems, manual fall-back procedures and the upgrading of the west pond, a need for the additional capacity within the clay zone was removed. A review of the above against the backdrop of reduced leachate flows would be undertaken to establish when the clay zone cell could be re-graded. This cell would be eliminated by the removal of the supporting bunds and re-graded to allow for suitable surface water flows in the area.

The leachate seepages south east of the landfill, at present managed through collection and returned to the leachate treatment plant, is currently being investigated and the
results of this investigation will determine the most appropriate long-term management measures for this area.

Modifications may be made to rationalize the existing pumping arrangements and storage system to allow the leachate flow to the sea via a gravity system. It was envisaged that this could happen if the capping / vegetation caused a reduction in the leachate / run-off rates.

Untreated Leachate analysis October 2007 to December 2007 showed that

- pH in the range 11.51 to 12.61.
- suspended solids 68 to 268 (mg/l)
- sodium 841 to 2246 (mg/l)
- volumes ranged between 29,700 to 39,900 m³ monthly

The variance in results and fluctuations in total flows was possibly due to rainfall amounts. Leachate pH remains high even three years after the plant had been shut down, requiring the Waste Effluent Plant to continue treatment of the run-off and leachate. It is not known for how long the treatment will continue, or at what cost. The treatment is run automatically with an alarm system to alert on-call personnel.

2.20 Reflection

When examining rehabilitation methods of other plants around the world, the author questioned what they had achieved, compared to Aughinish. The carbonation of the residue with CO₂ at Alcoa in Australia was a major event. This process had many advantages, including the significant reduction of the environmental impact. They had the CO₂ as a waste gas from an Ammonia plant, which obviously reduces process costs. The test cases researched gave some valuable information on amendment rates and vegetation successes. However, there was little information on leachate production or pH values. They had carried out numerous trials but still did not know what the pH of the leachate was, or at what rate if any the pH it was reducing. There did not seem to be any concern about the leachate / run-off pH. If they were protecting the environment, then as much information as possible must be collected. Nevertheless, would the caustic stay locked in the residue for years? Residue neutralisation is potentially the way forward to achieve the pH drop. With the dilution
effect the pH could drop to below 10.0. That would eliminate the need for the Waste Effluent Treatment Plants.

The plants that use seawater to either neutralise residue or process sand are reducing the pH to around 10-10.5. However, these plants have high pumping costs and some plants must treat the run-off before discharging back into the sea. Some Australian plants, depending on their location, can allow the run-off decant back into the sea. However, main concerns are the control of dusting and the two plants in western Australia have some groundwater contamination and they are still trying to recover back to the plant for treatment even after nearly thirty years. This contamination forced the plants to change to dry stacking like Aughinish, instead of wet stacking, and install liners under the residue.

As can be seen from the Burntisland leachate results, there was no reduction after three years with the Effluent plant still in operation. It must be noted that unfortunately there were some leachate analyses that were not available to the author.

The use of vegetation seemed initially to be the complete solution but now a better long-term solution is necessary. Neutralisation or part neutralisation of the residue in Phase 2 extension will solve a long-term problem by getting to the source of the problem.

Although neutralisation or part neutralisation reduces one problem it may cause other problems, like gel in the residue or H₂S smells when the residue is discharged onto the B.R.D.A. This will require further testing and research.

Clearly nothing can be done with the present residue on the B.R.D.A. except cover it with vegetation and improve the visual aspects of it. The residue going to the Phase 2 extension may have the pH lowered by neutralisation, and mud farming which will be a long-term solution to the problem, which is also acceptable to E.P.A. Phase 1 of the B.R.D.A. will require closure, depending on production levels. If the residue solids concentrations are maintained on target and the intensity of mud farming is high, then the life of Phase 1 could be in operation for another 1-2 years. Neutralising the last 1.0.m of residue deposited in the Phase 1 would help to achieve sustainable growth by avoiding capillary rise to the growth medium.

From a personal perspective, the author had numerous activities taking place. Construction of the Demonstration Cells, preparation of the trial plots, amendment and re-vegetation, which required arranging contractors for ploughing the residue, transporting compost, sand and gypsum, marking out the plots, the addition of amendments, and regular monitoring. Communicating progress to the process teams in the section and discussing performance with management to keep them up-to-date was an on-going task.
Running in parallel with this work was the scoping and engineering of the Demonstration Cells, which took up a considerable amount of time. Decisions had to be made concerning the route of the pipework, valves for isolation of the pipework and an agreed procedure with process personnel to pump from the plant to the Demonstration Cells. The construction of the Demonstration Cells was under the control of the civil engineer. The author’s knowledge was increasing. The building of the Demonstration Cells was a totally new experience for team members. Much thought went into the selection of the area, its size, the height of the embankments, and the required pipework. The routing of the extra pipe work caused plant personnel some concerns as the filling of the Demonstration Cells with residue was a stop / go pumping arrangement. The problem did not materialise, much to the relief of all concerned.

2.21 Ethical Issues

To help anticipate the impact of an Alumina Refinery, it is important to provide a framework for the ethical and scientific issues involved with building a refinery close to a estuary, near farming areas or populated regions and the implications of storing millions of tonnes of bauxite residue.

Ethical analysis may assure society that the promise of building such an industry does not conceal hazards and risks for workers, the local population or the environment. The company and the industry authorities will look to the prospect of added employment for the region, the money for the local authority and all the benefits that they entail. An emerging belief is that science and technology cannot be based on past practices in which ethical and social reflection is a second step to using newly developed science; rather, ethical reflections must accompany research every step of the way.

On reflection, it has to be stated that the building of another 80 ha providing storage for another 20 mt of residue will impact on the visual aspects of the area, increase the risk of potential dusting given the larger area of residue, and increase extra pumping rates of effluent to the river. All of these potential risks have been assessed and controls are in place. While the current research on the Demonstration Cells including vegetation, plus neutralisation, will help, it does not distract from the fact that millions of tonnes of residue with a high pH are deposited on the island of Aughinish.
The local community and farming population need to have regular information and communication meetings with the company as a means to receive updates. The company must be honest with all the stakeholders when presenting the results of this research and indeed with the information from other plants around the world.

The Annual Environmental Report (A.E.R.) can form the basis for these information meetings.

It is important that all team workers can provide input and influence the project. The research leader must accept responsibility for maintaining confidentiality and there is equal access to information generated by the process for all participants.

The ethical decisions are the way in which bauxite residue and alumina refining is depicted, the potential benefits, and the associated hazards and risks. When information about the hazards of bauxite residue is in doubt, the critical question is where to draw the line about the necessary level of protection. The ethical issues with extending the B.R.D.A. or managing the existing area centre around the risk analysis carried out concerning embankment building, how scientific it is, what is the impact is on the environment, if any, is there any risk of a repeat of the Hungarian incident in 2010, will there will be dust carried from the site, and that the company can and will keep to the licence parameters in pumping effluent to the Shannon river.

The ethical issues that mostly affect workers working in the plant and the B.R.D.A. involve the use of chemicals and these are linked to identification and communication of hazards and risks by management, and employers; acceptance of risk by workers; implementation of controls; choice of participation in medical screening; and adequate investment in toxicology and exposure control research. The ethical issues involve the identification and assessment of hazards and risks, that they are doing no harm, justice (fairness in distribution of risks), privacy, and respect for persons health and safety, and respect for the environment.

Factual scientific knowledge, which is the basis for ethical decisions about occupational safety and health, may be influenced by biases and values. Scientific knowledge is unavoidably value-laden. No scientific theory can be considered to be wholly objective, but one theory maybe more objective than another. Underlying and the residual risk are at a given level of protection. Risk assessments are partly subjective and likely to be highly politicised, thus all risk projections are value-laden. The ethical issues will be specific only for the knowledge base at a given time and for a specified production and use scenario. Assessments
were needed to capture the ethical and political values that inform policies such as locating an alumina refinery close to a major river or town.

The way in which bauxite residue and alumina refining is depicted may influence society’s reactions to research, and development, the prevention and control of potential hazards to workers, the local community and the environment. It is important to the author to be true to all values, the company has not tried to influence the author in lowering the risk or hazards associated with the project findings or research. It will of course try to get best value for money and the objective is to extend the life of a plant, provide an acceptable and safe closure technique for the B.R.D.A., the environment and all stakeholders. This can provide profits for the company and maintain employment in the region.

2.22 Identifying and communicating hazards and risks

The “hazard identification” stage of risk analysis is the basis for risk management decision-making. Interpreting scientific information about the hazards of the alumina industry is basic to communicating the hazards and risks posed to workers, the community and the environment. Interpreting and communicating hazard and risk information is an integral part of risk management by employers. The employers’ decision-making will focus on deciding which preventive controls should be used to assure a safe and healthy workplace and without any impact on the surrounding region, its population, flora and fauna. Employers, workers and the community look to scientists, engineers and authoritative organizations to help interpret hazard and risk information and to put it into context. This expectation may pressure scientists to go beyond the mere conduct of research. The interface between science and morality is exceedingly complex, but scientists, and engineers, are generally considered to have ethical obligations to society at large(Schrader-Frechette 1994). However, no consensus has been reached about the nature of those ethical obligations beyond fulfilling the professional responsibilities internal to scientific research. Framing a clear and coherent approach to the ethical responsibilities of scientists in industry is a difficult task. At the very least, such an approach requires scientists to use appropriate qualifiers in published papers and to be cautious in generalizing their results. More broadly, it means not shrinking from considering the implications of their work, even if all the scientific details are not known. Decision-makers may have inadequate scientific information to help them decide
how precautionary their approach should be to determine whether a decision conforms with the principle of doing good (Cairns, 2003).

With regard to the alumina industry, the contextual pressures on practitioners and authorities arise from a company’s or society’s needs and desires for the alumina industry to grow and develop.

Conflicting demands on research practitioners, from being both an agent of a company like the author, and an autonomous professional, constitute a social and structural problem rather than a problem of individual ethics.

Clearly, society accepts that some plants are inherently riskier than others. However, in most countries the societal goal is to provide a safe and healthy workplace for all workers and a safe environment outside of the plant.

The critical ethical question related to the control of the B.R.D.A. is whether sufficient controls are being implemented to prevent harm to the environment by seepage of high pH leachate to groundwater, dust nuisance and fallout on the surrounding countryside or contaminated effluent to the estuary. Are there critical ethical questions regarding the management of the B.R.D.A. and an adequate closure plan in place? From this project management have examined the closure options, the re-vegetation of the residue, if this vegetation can be sustained, and finally it is necessary for the pH to drop to 9.0 or lower over time.
Chapter 3 Research methodology
3.1 The overall aim of the project

Figure 41 Programme Time Table
3.2 Introduction

RUSAL Aughinish requires planning permission and an extension to its Integrated Pollution Control Licence from the E.P.A. in order to construct an 80-hectare extension to the B.R.D.A. The definition of research is a systematic way of asking questions, gathering data, and drawing conclusions. The researcher begins with a problem that needs answering or needs a solution, then this must be narrowed down to a problem or a question that needs answering to one that can be reasonably studied in a research project. The author’s research problem is to demonstrate closure technique to the E.P.A whenever the plant should close and if the pH will drop and at what rate when bauxite residue is left undisturbed and amended for vegetation.

The overall aim of this research was to determine feasible options for achievement of the licence requirements, namely to prove a closure technique acceptable to the E.P.A. for the closure of Phase 1 and 2 of the B.R.D.A. The following are the activities to achieve the aim:

- Construction of 60 small plots (2m x 1m) in size and conduct trials with different mixtures of process sand, gypsum, fertilisers and grass seeds to determine the most cost-effective, productive and sustainable grass for Aughinish residue.
- Construction of 11 x 20 m² trial plots on the residue aged 12 months. (0.4 ha in size) within the B.R.D.A. area. These trials will test the use of large machinery. On all previous trials plots amendments such as sand, gypsum, and fertiliser could only be spread by hand due to their size, but in the closure scenario large machinery would be required. In order to test machinery these larger plots were constructed and sown with grass.
- Construction of two lined Demonstration Cells (0.6ha in size) filled with residue and monitored pH, for conductivity, soda in run-off and leachate. It was envisaged that these will be mini versions of the B.R.D.A. and conditions would be identical in both cells. Sampling of leachate was conducted from underneath the residue. The cells have collection trays constructed on the floors of the cells to collect leachate, which seeps down through the residue and this was drawn up by means of a vacuum pump. No other research has constructed similar cells with this facility to sample seepage down through the residue. Quantities of the leachate were also measured which would give new information regarding seepage rates through the bauxite residue. The
author’s involvement started with the scoping team to design the cells, then the
collection and the engineering of the pipe work route from the plant to the cells. It
was the author’s decision to determine the route of the pipework.

Therefore data was collected from:

- Grass-growing trials on the trial plots and the Demonstration Cells.
- One tonne containers filled with bauxite residue.
- Pore flushing analysis
- Eco-toxicity sampling and analysis.
- Groundwater modelling.
- Research rehabilitation methods in other alumina plants.
- Research residue neutralisation methods and recommend a suitable one for the Aughinish
  process and plant conditions.

3.3 Research Structure

The research problem is to demonstrate closure technique to the E.P.A. whenever the plant
should close. This was to ensure that the company could not walk away and leave the
B.R.D.A. without a proper closure to satisfy all licence requirements. Trials have been
completed on small plots of bauxite residue, but nothing substantial and nothing tested on
fresh residue or no experience in the use of large machinery.

The detail is the precise figure the E.P.A. has given the company on pH values and the
closure method:

- Flexibility was required with the author’s time during the trial and also with the project if
  things do not go according to plan, e.g. extra flushing water to lower the pH, delays in
  construction, or weather hold-ups.
- Theory will be generated.
- Reviews will be regular on progress and up dates on progress.
- Statistical analysis and data collection.
- Presentation of findings / report and dissertation.
• The final report will then be reviewed by the company and then with the E.P.A.

3.3.1 Theory, Practice, Transformation

For example, one theory is that the pH will drop slowly due to rainfall and weathering if let without any fresh covering of grass, even if nothing else is done. Also what affect, if any, the grass will have on the run-off pH.

This how it was done: pH, E.C. and soda was measured and the primary data taken from the collection of leachate from the underground pipework beneath the residue, and the run-off from across the top of the residue. The questions that needed to be answered were:

• how would the different sections of the trial site be influenced by rainfall or by water flushing?
• what changes could occur with the maturing of the residue?
• Will grass growth change run-off amounts and pH levels?

The specific outcome of the experiment had to be examined. This was be how much the pH dropped and over what length of time, and any likely problems to the local environment. Where necessary, the theory needed to be modified in light of the findings.

For action researchers, theory informs practice, practice refines theory, in a continuous transformation. In any setting, people’s actions are based on implicitly held assumptions, theories and hypotheses, and with every observed result, theoretical knowledge is enhanced. The two are intertwined aspects of a single change process. It is up to the researchers to make explicit theoretical justifications for the actions, and to question the bases of those justifications, thus ensuing practical applications that follow are subjected to further analysis in a transformative cycle that continuously alternates emphasis between theory and practice.

Action research is used in real situations, rather than in contrived, experimental studies, since its primary focus is on solving real problems. The Aughinish refinery and its B.R.D.A. is a real-life project and problem, with is 30 million tonnes of residue with a high pH of 13.0. Mostly, though, in accordance with its principles, action research is chosen when circumstances require flexibility, the involvement of people, or change must take place quickly or holistically. Time is very important in this project, for the company and the workforce, and indeed the local community.
3.3.2 Main Research Objective

The main objectives are to complete the vegetation trials, construct the Demonstration Cells, test and investigate if the pH of the run-off / leachate will drop to pH 9.0, within five years of closure of the company. Research residue bauxite neutralisation options for the company. All run-off from the B.R.D.A. is at present collected and returned to the Waste Effluent Treatment Plants for treatment before discharge to the Shannon River. Following plant closure this treatment would have to continue until the pH dropped to 9.0. If and when the pH reaches 9.0, the effluent treatment plants could be closed down, resulting in major cost savings. From computer modelling it was estimated that would take five years for the pH to drop to 9.0. This would be achieved by the reduction in leachate quantity when vegetation was established because rainfall would be taken up by the vegetation and not leached down through the residue. The run-off flow from the top of the residue would be in excess of 400;1 ratio with the leachate which would dilute the pH to 9.0 or below. The information from the Demonstration Cells would give more information on run-off /leachate quantities and pH values.

3.3.3 Background

The author had worked for Rusal Aughinish for the past twenty-seven years in a variety of roles. The author joined the company before start-up and went to work in other alumina refineries in Canada and Spain and spent time in Brazil on the start-up and commissioning of a new alumina plant in the Amazon basin. The role had also involved the management of the B.R.D.A, scoping, engineering and monitoring of earlier trial areas within the B.R.D.A., including compliance with the company’s Integrated Pollution Control Licence. Given the author’s process and environmental experience, including the management of the B.R.D.A., and knowledge gained academically in environmental matters provided the author with a solid basis for further development and the capabilities to research this project. As the author proceeded through the research asking questions, his perception changed and outlook changed, he no longer accept fixed ideas, or truths and was more open to various and alternative interpretations.
It was very important to involve the team, use their knowledge and experience to help and guide the project. Changes were made along the way, compromises were made, and priorities were changed. Constant review of progress was carried out. Post-modern practitioner research methodologies seem to reflect this position by continuing to question and interpret all processes, rather than having a fixed closure on research questions and conclusions at the beginning and end of a single research cycle.

The author was trying to be aware of the tried and tested models available, but also to be aware of his own strengths and dispositions and knowledge and use these as best he could. Also, he came to this research with a lot of experience, skill and knowledge, which formed the bedrock of the expertise required for good worker research.

All the author’s attributes as a competent professional fitted well and with the attributes of a good practitioner researcher. The author hopes that in the end he created his own type of individual enquiry and put his increased knowledge to good practical use to help the company and the alumina industry with a sound closure technique for the B.R.D.A., as well as meet the licence requirements for the E.P.A. The team members were experienced and knew the importance for the company and all its employees, including their own jobs.

The author feels that his direct contact with the project and the team was most important if he was to develop new insights about bauxite residue rehabilitation. His background did influence what he saw in the research and experience acted as a sensitizer and filter for him. As regards his fieldwork, experience helped to gain assistance from other people in the organisation. He was involved in the planning, in the scoping, installing and reviewing on many projects and job assignments down through the years.

The author was given the time, the team and the finances to complete this project. The overall cost of these trials was in the region of 250,000 Euros, not including salaries for staff or contractor hire.

His role as the Action Researcher was primarily to complete the trials, do the research, advise the company on closure techniques and whether it was necessary for the company to continue with further trials. The author had the time required to be actively involved with the project, following his retirement in 2008, the company hired him on a consultancy basis for a further two years at least, to continue on with research in rehabilitation methods of bauxite residue. The author was also the Environmental Specialist for the construction of the Phase 2 extension. He was actively involved in the research into implementation of acid neutralisation process. He was able to make changes as was
necessary, most importantly had the expertise of the process to suggest changes and modifications to the process that would help the research work.

3.4 Researcher Role

As a worker researcher with a dual role, it was necessary to be reflexive in the research. It was also important to consider the implications of the dual role and the worker researcher (insider) when planning the project.

The research approach was action research. Theory was not be tested, but rather generated and consequently new knowledge propagated. It allowed the project be carried out in its own setting, it involved manipulating one variable. It was not possible to have complete control over the research, as it was a real life situation/problem. This project had an outcome, that is, it demonstrated to the E.P.A. an acceptable closure technique for the B.R.D.A., including the impact on the surrounding environment post-closure.

As an insider, the author’s knowledge of the plant process and knowledge gained from previous environmental studies was an advantage and he also had excellent relations with the team involved in the project. The main advantages for the author as a worker researcher included insider knowledge, process experience, access to other alumina plant information worldwide, support of the company and the support structure that goes with it. The company and the alumina industry in general required the information from this project.

3.5 Research Structure

The research problem was to demonstrate closure technique to the E.P.A., for if the plant were to close. This was to ensure that the company cannot walk away and leave the B.R.D.A. without a proper closure to satisfy all licence requirements. Computer modelling and trials have been completed on small plots of bauxite residue, but nothing substantial and nothing tested on fresh residue.

The detail is the precise figure the E.P.A. has given the company on pH values and the closure requirements. Flexibility was required during the trial with the author’s time and also with the project if things did not go according to plan, e.g. extra flushing water to lower the pH, delays in construction, or weather hold-ups.
Reviews were regular on progress and updates on progress, statistical analysis and data collection, presentation of findings/report and dissertation. The final report will then be reviewed by the company and then with the E.P.A.

3.6 Rationale

There are two realms that are involved in a research: theory, what goes on in the researcher’s head; and observations, which is translating ideas setting up programmes to action something and then measuring it. In the author’s case, the E.P.A. presented the company with a problem. The company came up with a proposal to provide a solution by building the Demonstration Cells, the programme was set in place to build the sites. The Demonstration Cells was constructed, then filled with bauxite residue, amended the residue, vegetation sown, and the leachate monitored/analysed. This is how his research question was investigated. Other activities in conjunction with the construction of the Demonstration Cells included the correct amended mixture to obtain sustainable vegetation. Neutralisation options for the residue at Aughinish were also investigated.

A closure technique was recommended that would not have any adverse impact on the environment and was acceptable to all stakeholders.

3.7 Research Approach

The chosen approach was action research.

Kurt Lewin is generally accredited as the person who coined the term ‘action research’. Action research is a process of deep inquiry into one's practices in service of moving towards an envisioned future aligned with values. Action Research is the systematic, reflective study of one's actions and the effects of these actions in a workplace context. As such, it involves deep inquiry into one's professional action.

The researchers examine their work and look for opportunities to improve. As designers and stakeholders, they work with others to propose a new course of action to help their company improve its work practices. As researchers, they seek evidence from multiple sources to help them analyse reactions to the action taken. They recognize their own view as subjective and seek to develop their understanding of the events from multiple perspectives. The researcher uses data collected to characterize the forces in ways that can be shared with
practitioners. This leads to a reflective phase in which the designer formulates new plans for action during the next cycle.

Researchers both act and seek to learn from the actions taken. The subject of action research is the actions taken, the change, and the theory of change that is held by the persons enacting the change. While the design of action research can originate with an individual, actions taken without the collaborative participation of others are often less effective. To be successful, the action researchers have to plan in such a way as to draw an ever-widening group of stakeholders into the arena of action. The goal is to work towards a better understanding of their situation in order to affect a positive change.

This form of research is therefore an iterative, cyclical process of reflecting on practice, taking an action, reflecting, and taking further action. Therefore, the research takes shape as it is being executed. Better understanding from each cycle points the way to improved actions.

The team was involved at every step of the way and all decisions were agreed within the team and then agreed by the company. The goals of action research include:

- The improvement of practice through continual learning and progressive problem-solving;
• A deep understanding of practice and the development of a well specified theory of action;
• An improvement in the process in which your practice is embedded through participatory research.

Action research as a method is scientific in that it changes something and observes the effects through a systematic process of examining the evidence. The results of this type of research are practical, relevant, and can inform theory.

Action Research is different from other forms of research as there is less concern for universality of the findings and more value is placed on the relevance of the findings to the researcher and the local collaborators. It can be the process through which an organization learns. Aughinish and other alumina plants will learn from this research, the team members will learn and other stakeholders should have more information and be more assured about the future of the company, including any concerns about the B.R.D.A.

### 3.8 Role of the Action Researcher

Upon invitation into a domain, the outside researcher’s role is to implement the Action Research method in such a manner as to produce a mutually agreeable outcome for all participants and stakeholders, with the process being maintained by them afterwards. To accomplish this, it necessitated the adoption of many different roles at various stages of the process, including those of listed here:

- planner
- leader
- catalyser
- facilitator
- teacher
- designer
- listener
- observer
- synthesizer
- reporter

The author’s role included the above, initially planning the lay-out of the project that had to be agreed by everyone. It also included the finances, which had to be approved by the company. The project was scoped, safety and environmentally assessed, it was installed and finally commissioned and brought into service.
The role included facilitating other team members in their roles, and acting as leader when decisions were required, communicating constantly with management on progress, and in times of production problems negotiating windows of opportunity for extra personnel to make process switches to suit the work load. All stakeholder concerns were taken into consideration when it came to the final solution / outcome when reaching an acceptable solution for all.

3.9 Primary Collection Techniques

3.9.1 Task No 1 = Grass sowing trials (Small and Large Plots)

These trials came under the “Act” part of the cycle

The first data collection involved construction of small trial plots and the sowing of grass in the small plots and deciding the most suitable amended rates and type for the bauxite residue.

Small plots (2 m x 1 m) were set up on terraces in the B.R.D.A., and were seeded with *Holcus Lanatus* (Yorkshire Fog). Each plot was amended using gypsum, sand, and spent mushroom compost (SMC). Information on gypsum seed sand SMC was gathered following these applications. By the time the Demonstration Cells were built, the best amendment rates / prescription were known for grass establishment to be used in the larger plots and Demonstration Cells.

Work on these small 2m x 1m plots was completed and grass was sown, but there was damage caused by a contractor working on nearby embankments. The damage meant the loss of 12 months of work. This was the first major problem for the team and the company, as it entailed selecting another area, constructing other 2 m x 1m plots, amending the residue and starting again. This extra cost had not been budgeted for in the plan. Part of the Team Review following this incident was to cordon off the second area, signpost it stating it was an area under research and keep away.
3.9.2 Large Plots

This area which was 200 m x 20 m and divided into eleven plots 20 m² in size each, gave valuable practical information into the use of large machinery if and when any sections of the B.R.D.A. were closed and rehabilitation was required. It also gave information with regard to working with mud of different ages. Experience was required in the use of machinery on residue, such as, what were the limitations regarding type and size of the equipment that could travel on mud that had not matured for a long period of time. The residue generally required up to 12 months maturing and consolidation in order to be able to travel on it, depending on the solids concentration at deposition and the amount of rainfall during the maturing time.

3.9.3 Task No 2 = Demonstration Cells construction Plan

Plan view of Demonstration Cell below

This part also came under the “Act” section of action research:

- Research and construction of the Demonstration Cells and trial sites was a large undertaking (see Figure 40). Tom Hartney, team member and civil engineer, was the main player in the construction of the embankments for the cells and the lined membrane. The author’s part concerned the scoping of the pipework, what route the pipework would take and the tie-ins with process lines. Some problems arose concerning safety while constructing the embankments and installing fall protection. This did not result in any delays, but this safety point was not foreseen and only arose during windy weather.

- Fresh mud was deposited in the cell to the top of the embankment. It was allowed to dry and mature enough to allow access onto it after 6 months. Sand, gypsum, and fertiliser were applied and leaching rates monitored. Sustained period of enforced leaching was introduced to reduce pH, alkalinity, electrical conductivity (EC), and high exchangeable sodium percentage (ESP). Sampling of the amended residue was carried out to determine efficiency of the weathering, namely if the mud was hard enough to allow traffic onto it to commence amendment techniques. It is envisaged that this period would be up to 3 months, but in fact it took more than six months due to very wet weather during the summer months. When the mud was mature enough to
allow traffic the sand, gypsum and fertiliser were added and grass sown on it. Once
the mud was filled into the cell sampling commenced for pH, soda and electrical
conductivity in the run-off and leachate.

3.9.4 Task No. 3 – Demonstration Cell

This was the observation section of the action research diagram. Weekly analysis of pH,
conductivity, and soda commenced for run-off and leachate commenced immediately after
residue was pumped into the cell. Other sampling commenced when the vegetation cover had
grown such as quantification of vegetation yields.

The following parameters were investigated:

- pH and EC
- alkalinity
- conductivity
- soluble aluminium levels
- extraction of leachate from under the residue in the cell using a vacuum pump and
  complete drop tests on the quantity
- run-off water (initial tests for pH, conductivity, soda, during weathering) and
- pore water quality (initial tests during weathering).
3.9.5 Task No 4 - Eco-toxicity sampling / analysis

The analysis was completed by Ronan Courtney in the University of Limerick on the residue in the Demonstration Cells in the summer of 2010.

In addition to chemical analysis of the amended substrate bauxite residue, samples were taken to determine eco-toxicity levels in the residue and the effects on plant seeding growth. In order to develop a monitoring system for accessing sustainable indicators, key soil parameters were determined.

Soil organic matter and organic carbon nutrient levels (nitrogen, phosphorous, potassium) electrical conductivity were examined.

3.9.6 Task No 5 - Procedure for grass establishment

The agreed procedure for grass establishment was:

- allow the residue to mature after it was deposited, if possible for up to twelve months. Some leaching would take place during this period and time also allowed consolidation of the residue to allow small machinery travel on it.
o plough and rotavate residue.
o add sand and plough again, allow further weathering.
o gypsum was now added to lower the pH to 9.0-9.5 at the correct rate per
hectare.
o compost was applied at rates up to 120t/ha.
o sow selected grass seed.

Care was taken to avoid holes or hollows where pooling of rainwater could occur. If changes
were necessary to the procedure for grass growing, it would come in the section on “Reflect”
on the action research cycle diagram.

- Set up procedure to establish grassland on the residue.
- Monitor run-off water from the Demonstration Cells. By controlling the run-off rate
it will avoid ponding or flooding on the residue.
- Monitor pore water.
- Monitor leachate.

Some problems reviewed by the team centred around flooding and drainage in some areas on
the residue. Also reviewed and “actioned” were difficulties with use of machinery on the
larger plots and the Demonstration Cells. There was no problem with “the mixture”, some
problems were experienced with spreading of the sand and gypsum over large areas. This
would require further study and scoping if and when the B.R.D.A. is in a closure situation.

3.9.7 Task No 6 Residue Neutralisation

Methods to neutralise bauxite residue were investigated and reviewed. The research of
neutralisation involved scoping and costing the installation of a pilot scheme for acid
neutralisation, and the cost of importing CO$_2$ to inject into the slurry to lower the pH.

Some advantages Aughinish had in reviewing acid neutralisation included:

1. The company have acid storage on site, and can import large shiploads in through
their jetty.
2. Sulphuric acid is already used for acid cleaning of heat exchanges and for
neutralisation in the Waste Effluent Treatment Plants.
3. People are experienced in its use and safety risks.
CO₂ could potentially be imported. If not imported, it would require that a plant be built to extract CO₂ gas from flue gas stacks on site. It would take an estimated cost of €30 million to install such a plant.

3.9.8 Data results

All the results were collected and presented to the company. These results can be compared where appropriate with any analysis from other alumina plants around the world. Most plants have only been concerned with closure and have not carried out sampling on the seepage from the residue.
3.9.9 Observations

All these observations were assessed and subsequently the company was advised on the most suitable closure technique for Aughinish. Observations are objective, with all data collected and reported as it comes. Observation included the gathered facts from other plants, and following consideration the company was on the best closure technique.

There are certain advantages and disadvantages in this position; these include years of process experience, having worked with all the team members for some years. Crucially, the company are prepared to spend a lot of money to come up with an acceptable closure method that will satisfy the E.P.A. This in turn will secure the extension to the licence and enable the plant to stay in production until 2026. The disadvantages are the company’s expectations, the restrictions and conditions the E.P.A. put on the company in granting the licence.

The main role, however, is to nurture other team members and for company management to understand the methods and will be able to carry on when the author leaves.

The author’s role as the Action Researcher was primarily to complete the trials, do the research, advise the company on closure techniques and if necessary advise the company how to continue with further trials. The author had the time required to be actively involved with the project, following his retirement in 2008, the company hired him on a consultancy basis for a further 2 years to continue with research into rehabilitation methods of bauxite residue.

The author was also the Environmental Specialist for the construction of the Phase 2 extension and actively involved in the implementation of acid neutralisation process. He was able to make changes as necessary; most importantly he had the expertise of the process to suggest change and modifications to the process that would help the research work.

3.10 Review Of Rehabilitation Programmes in other plants

Having looked at different rehabilitation methods around the world, the team reviewed the rehabilitation programme that was introduced in Gove Northern Australia, Jamaica, Greece Aluminium, Alumar plant in Brazil and the closed refinery in Scotland.

Some techniques can be used to gather information / data in either a quantitative or qualitative way. In publications some companies put considerable amounts of information
into the domain. Their data collection methods in these reports are by testing and observations. They have condensed a good deal of information into a format that is easily understood by the readers and it is also convincing. Clearly they have also put a lot of money into their rehabilitation programmes.

At Alcoa, researchers placed considerable emphasis on the data collection. The report has given percentage solids, densities and rainfall, etc. The researcher appears to want to give a more positivist approach and is make a distinction between data and the process descriptions.

There is a feeling of confidence about most reports, in other words any information that could hurt the company on a local level is not there, which is understandable from a business point of view. The technology is well known throughout the alumina industry. We accept that the information is fair and accurate. And although ‘proof’ does not exist in action research, the companies have produced enough evidence to convince us that their systems work well for them.

3.11 Review of the Scotland B.R.D.A.

The visit to the plant in Scotland would not have been any good as a learning exercise without the help of the Scottish E.P.A. Alcan although allowing the visit onto the site would not supply any information on leachate sampling, treatment or quantity. All information on analysis came from the Scottish E.P.A.

Looking at the analysis the author would agree that the data provided would support existing knowledge, but is not sure if it challenges any existing knowledge, as there nothing different. Neither does it answer any previously unanswered questions. Given that there has been no drop in leachate pH over a three-year period since closure, it would appear that it would be many years before they can shut down their treatment plants.
3.12 Reflection.

Reflection is an exhibition of tacit knowledge that derives from time, experience and knowledge of how to do a task. The difference from reflecting-on-action (hindsight or linear process) is that reflection-in-action (simultaneous or cyclical process) ‘can shape our future action’. This enables the researcher to become better at their skill set, resulting ‘in the acquisition of artistry’ in their practice (Schon, 2002).

As the action researcher, the author has gained professional insight into the project by utilising the tools of action research and reflective practice. His knowledge in critically researching data has improved, he was surprised by some results, particularly the changes in pH of the run-off following any rainfall. The rainfall has a significant dilution affect thereby lowering the pH.

The researcher needs to be aware of factors that may be beyond their control but they can still influence the outcome, due to their reflecting in action. To have this ability of recovering a potentially costly mistake is of great business value. Looking back on the damaged plots, the situation was retrieved following the re-scoping of the task and consultation with the company.

The action research cycles are designed to encourage reflective thought; the timing of reflection can be critical in a project’s life cycle. The more that is reflected, tacitly or explicitly, and recorded and shared amongst a team, the better for the project. There is no doubt that all the reviews between the team and the company were a significant factor in getting through all the complex activities in a time of demands for increased production and limits on manpower availability.

Empowerment of the author throughout the project resulted in new ways of thinking with inevitable impact on the team and ultimately on the company’s business reputation. The influence the author had on the immediate environment was positive, resulting in his personal key skills being recognised and utilised in a number of ways. For example some of the changes made to the process resulted in a better stacking angle of the residue on the B.R.D.A. when the percentage solids were increased. These changes in the Filtration Building were very significant, it made drying and maturing much faster, which in turn helped in the vegetation trials. It was possible to access the residue at an earlier stage and improved drainage.
The author’s working relationship, not just with the team members, but with staff in the plant, was very important for the completion of tasks. It was necessary to ask people to carry out extra tasks and facilitate the project work outside of their normal work and responsibilities. This required negotiating skills and using the proper approach. Although contractors were paid for their work, again it required the correct approach to achieve results.

The author’s knowledge improved greatly on an ongoing basis, sometimes the information came very quickly, other times it seemed as if the plan was going nowhere and the next hurdle was insurmountable. Patience was required, not alone with people, but in the pace of the project. The author’s wife constantly recognised that sometimes my thoughts were on the project and not at home. Being mindful of this was important for my family.
Chapter 4 - Activities
4.1 Introduction

By completing all the activities to their conclusion, an acceptable closure technique that the company could implement was anticipated and also acceptable to the E.P.A. with regard to granting the licence and the Local Authority to give planning permission for the 80-ha extension to the B.R.D.A. (see general view of the B.R.D.A. Figure 41).

The purpose of growing grass in the small plots was to obtain the most suitable and cost-effective amendment rates (“recipe”), which would then be used on the residue in the Demonstration Cells. The investigation into neutralisation was a condition in the I.P.P.C licence.

Other activities on the larger plots were to gain experience with machinery so information would be available if and when sections or all of the B.R.D.A. were closed due to rehabilitation. The sampling of pH over the period gave information on the likely time frame for the pH of the run-off/leachate to drop to 9.0. All information gathering from other plants, the visit to Scotland, and a rehabilitated B.R.D.A. were used to make final recommendations to the company on the best closure technique.

The following activities were carried out:

- small plots (60 in total) established and were used to assess vegetation growth on amended residue. These plots provided the best possible mixture of mud, sand, gypsum and fertilizer and helped to identify the best type of grass which would establish and grow on the residue in the Demonstration Cells.
- An area of 0.4 h in size (200m x 20m) with eleven plots, in an area of older mud deposits, again amended with sand, gypsum, and compost, were established. These large plots were established to gain experience in the use of large machinery on bauxite residue and the likely problems associated with spreading large quantities of process sand, gypsum, and compost. Leachate sampling was conducted in this area during preparation and following grass sowing.
- Demonstration Cells were constructed within the B.R.D.A., a miniature version of the residue area. Suitable high-pressure pipe work was installed to pump residue slurry into the cells. When residue was matured sufficiently it was amended it and grass sown on it.
Demonstration Cells will be used as the company’s “Showpiece” for the E.P.A., Local Authorities, and the local community

- to demonstrate a sustainable vegetation can be grown on the residue
- to show results of run-off and leachate including quantities, and chemical characteristics.
- to show that no leakage/seepage will take place due to the complete lining of the cells.
- Finally, the cells are easily accessible and can be viewed from a raised perimeter road close to the Butterfly Sanctuary and nature trails. When they come on-site, the local community can view these cells during the annual “neighbours meeting”.

Other on-going trials included six (6) one-tonne containers filled with bauxite residue. They were let in the open to monitor the leachate and run-off on a weekly basis for pH, conductivity and soda. Rate of compaction by the residue was also noted.

Groundwater flow model was used to confirm characteristics of the residue and hydrological/hydro-geological modelling deep in the residue of the B.R.D.A.

An investigation into neutralisation of the bauxite residue was completed. This has come about as a result of new conditions required by the E.P.A. to grant an extension to the license for the 80 hectares in Phase 2.

A closed alumina refinery and rehabilitated residue area was visited in Scotland.
4.2 Trial Plots (2m x 1m) - 2005 - 2006

The results from these trials were used to determine the mix of amendments and the most suitable type of grass for the Demonstration Cells. The two sets of trials were established in 2005. One set of plots was damaged by a contractor covering them over with gravel, and the second set of plots was then constructed. Twelve months later this second set of plots provided the information of the best mixes of sand, compost and gypsum, i.e. correct tonnages per hectare, and the most suitable species of grass to suit the Aughinish residue.

Establishment of grass-growing plots (2m x 1m)

- sixty small plots were installed on a west terrace, they were sown with grass with the following mixes
- gypsum at 0, 40 and 90 t/ha
- SMC at 0, 60, 80 and 120 t/ha. Table 12 gives the amended rates.
Table 12: Small field trials, amended with different rates of gypsum and SMC

<table>
<thead>
<tr>
<th>No. of plots</th>
<th>Amendments added</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0 t/ha Gypsum, 0t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>40t/ha gypsum, 0t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>90 t/ha gypsum, 0t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>0 t/ha gypsum, 60 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>40 t/ha gypsum, 60 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>90 t/ha gypsum, 60 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>0 t/ha gypsum, 80 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>40 t/ha gypsum, 80 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>90 t/ha gypsum, 80 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>0 t/ha gypsum, 120 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>40 t/ha gypsum, 120 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>90 t/ha gypsum, 120 t/ha SMC</td>
</tr>
</tbody>
</table>

After 12 months these plots were damaged by a contractor who was spreading gravel on the terracing above the plots. The plots were covered with stone and gravel, rendering them unless (Figure 46). This meant setting up another 60 small plots in another area of the B.R.D.A. and restarting the trial.

The first set of plots had been progressing well, as can be seen from Fig 42. This was a major set-back for the team and the company. There was no way the situation could have been retrieved as the plots were covered in stone and gravel.

It was decided in the review that project sites like this needed better management and control. The company viewed this incident as a failure on the part of the team and in particular the author. Questions included how a contractor been given a permit to work in this area, who was supervising him, how the contractor not been given a specific work assignment, what was his scope of work, had his work been risk-assessed. The area should have been fenced off, and signposted by contractors working on the B.D.R.A. to prevent any unlawful entry.

Following the review, the author selected another area north of the damaged plots and set about repeating the same trials. The money was approved and the process was repeated. There had been delays at several stages along the way with funding, hold-ups with
contractors, process changes required in the plant, but this was the most disappointing event for the author during the entire project.

Figure 45 Grass in small trial plots (before damage).

Figure 46 Small trial plots (These ones were damaged after 12 months).
4.2.1 Second Set of Small Field Plots

The small field trial plots, 60 in total same as the previous ones. These plots were constructed to take the place of the ones damaged by the contractor (Figure 47).

A further 60 small plots 2m x 1m in size were constructed and sown with grass (amended rates in Table 13 below). To ensure that these plots remained untouched during the trial, the access road at either end of the terracing was fenced off to block any entry, and signposted. The work permit system for contractors working on the B.R.D.A. was updated with added controls. All these efforts were an attempt to prevent any future damage to the new plots and to have better control over contractor activities in the B.R.D.A.

Table 13 Plot amended of different rates Gypsum & Spent mushroom compost (SMC).

<table>
<thead>
<tr>
<th>Plot</th>
<th>Quantity of Gypsum</th>
<th>Quantity of SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 t/ha gypsum</td>
<td>0 t/ha SMC</td>
</tr>
<tr>
<td>2</td>
<td>40 t/ha gypsum</td>
<td>0 t/ha SMC</td>
</tr>
<tr>
<td>3</td>
<td>90 t/ha gypsum</td>
<td>0 t/ha SMC</td>
</tr>
<tr>
<td>4</td>
<td>0 t/ha gypsum</td>
<td>60 t/ha SMC</td>
</tr>
<tr>
<td>5</td>
<td>40 t/ha gypsum</td>
<td>60 t/ha SMC</td>
</tr>
<tr>
<td>6</td>
<td>90 t/ha gypsum</td>
<td>60 t/ha SMC</td>
</tr>
<tr>
<td>7</td>
<td>0 t/ha gypsum, 80 t/ha SMC</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>40 t/ha gypsum</td>
<td>80 t/ha SMC</td>
</tr>
<tr>
<td>9</td>
<td>90 t/ha gypsum</td>
<td>80 t/ha SMC</td>
</tr>
<tr>
<td>10</td>
<td>0 t/ha gypsum</td>
<td>120 t/ha SMC</td>
</tr>
<tr>
<td>11</td>
<td>40 t/ha gypsum</td>
<td>120 t/ha SMC</td>
</tr>
<tr>
<td>12</td>
<td>90 t/ha gypsum</td>
<td>120 t/ha SMC</td>
</tr>
</tbody>
</table>

Each application was replicated 5 times

See results of trials in Appendix 1.
4.2.2 One-Tonne Container Trials (March 2005 - 2007)

The purpose of this trial was to have the containers left in the open (Figure 47) fitted with valves to sample run-off on top and a drain valve underneath to sample the leachate. Initially it was intended to use small drums filled with residue. A modification was subsequently installed in the Filtration Building, which allowed these one-tonne drums be filled with residue from the outlet of the mud reactors. Following a safety and risk assessment, the drums were filled, having already installed a layer of stone in the bottom of the drums and filter medium on the sides.

The idea behind the plastic containers was to try to have a large volume of residue in a sealed container like the sealed embankments and floor of the Demonstration Cells and with the facility to sample run-off from the top and leachate underneath.

Compaction of the residue was also noted over an 18-month period in the containers. This gave some information on compaction rates of the B.R.D.A. itself. Four one-tonne containers were filled with bauxite residue directly from a mud reactor in the Area 34 Filter Building. It is from here that the bauxite residue is pumped to the B.R.D.A.
Drum No. 1 and Drum No 2 had 2 inches of small stone placed in the bottom, the stone was 1” diameter in size. This was to give good drainage and prevent blockages in the bottom drain valve. The stone and the sides of the containers were lined with plastic, the type used for weed suppressant in flowerbeds. The purpose of the stone and plastic was to aid drainage and enable leachate flow to the drain valve at the bottom of the drum. It was hoped by using the plastic, that short circuiting would be avoided and thus get a proper leachate sample through the red mud.

Drums No 3 & 4 had 3 inches of stones of similar size to drums 1&2 placed in the bottom but without plastic. Two other drums were filled with mud in April 2006.

Drum No 5 and Drum No 6 had stone and plastic similar to drums 1 and 2 placed inside before they were filled with bauxite residue. The underflow stopped on drum No 4 after a few days and did not restart. The reason for this was not known. One possibility could have been the failure of the drain itself in jamming and failing to open. It was thought that the plastic and the stones in the bottom the container prevent this from happening.

The drums were placed on a terrace in the B.R.D.A. and sampling commenced on a weekly basis for pH, electrical conductivity and soda. The leachate was taken from a drain valve in the bottom of the drum and run-off was taken from the liquid on top of the bauxite residue.

First Results:  Leachate pH varied between 13.34 –13.27
Conductivity ranged between 79,800--- 63,700 ms/cm
Run-off pH varied between 13.11 to 13.16 and
Electrical conductivity was between 57,300 and 54,100 ms/cm

Generally, during the springtime there was run-off on top of the mud to sample, but during the dry weather of the summer months there was very little, if any, liquid on top. Quantity of leachate varied, but enough was available for a sample each week. Some samples of mud were taken at different depths in the mud but the pH was more or less the same as the leachate. All drums were drained out completely on three occasions and allowed to leach through to the drain again. This was done to offset the chance that liquid was bypassing and getting down the sided of the drum to the drain, not percolating through the mud and check ph changes, if any. The residue compacted by approx 30% in the drums over the 18-month period. This compaction rate is surprising, one possible explanation is the number of times
the drums were completely drained of liquid. This was done on three occasions during the 18-month period.

The information gained from this research was the close-up observation on the residue and the compaction rate, it afforded the opportunity to completely drain the drums and then flush the residue through (pore flushing) with clean water. Flushing the residue completely three times did not make any difference to the pH. From previous research ten pore flushes were required to get the pH to 9.0. The leachate results showed that it would take up to seventeen years for the pH to drop to 9.0.

![Figure 48](image)

**Figure 48** pH Trends from one-tonne container (No 6).
Figure 49 pH Trends from one-tonne container (No. 5).

Figure 50 One-tonne Containers.

See all results of one-tonne container data in Appendix 2
4.2.3 Large Trial Plots – 20 m² Plots

Area of 4,500 m² (2006 – 2008)

This trial was deemed necessary in order to gain experience in the use of machinery on the residue. This area of (0.4 ha) bauxite residue would allow experience to be gained in the practical aspects of driving equipment on the mud, and how the different amended materials can be applied over large areas.

This area was selected for this trial because of its location, which was high up at Stage 6 embankment. As it was a very open area exposed to north-west winds and was facing the Shannon river, it was a possible location that dusting could occur. Vegetating this embankment would eliminate the possibility of dusting. Access for machinery, although a bit restricted, would be a good test. This area would only be available for another three years and then would be converted into a collection channel for run-off from the higher stages in the B.R.D.A. This period would be sufficient to gain some further information on amendment application with machinery.

The bauxite residue was amended with similar concentrations of process sand, gypsum and compost similar to the small plots and then grass was sown (see Table 0-18). Information was collected on rehabilitation of this recently deposited bauxite residue, which did not have sufficient time for weathering or caustic leaching of the residue.

This area was 200 m x 20 m and divided into eleven plots, 20m² in size each. The aim was to use large machinery to plough the mud, spread large tonnages of gypsum, fertiliser and compost. It would also give information working with mud of different maturity. Experience is required in the use of machinery on residue; for example, what are the limitations regarding type and size of the equipment that can travel on mud that has not matured for a long period of time. The residue generally requires up to 12 months maturing and consolidating enough to travel on it, depending on the solids concentration at deposition and the amount of rainfall.

Study Areas

- Investigated variations of the procedure to optimise conditions for preparing residue prior to seeding
- Use of gypsum at 0, 40 and 90 t/ha will lower the pH
- Use of organic amendment at 0, 60, 80 and 120 t/ha, will add nutrients, and lower the pH
- Use of inorganic fertiliser (NPK and super-phosphate) on plant growth, this was added at 250kg/ha and later reviewed as growth progresses to see if further additions are required
- Seeding regime (seed composition and seeding rate)
- Monitor pH of run-off and leachate. Run-off pH was monitored from a trench constructed at the side of the plots, a general leachate sample was taken from a piezometer close by. This would not be sampling the trial plots solely more the general area, but was deemed to give some indication
- Use of large plant machinery for the first time to amend the residue

Prior to this, only plots of 2m x 1m in size had been tested. This area had recently deposited mud, (July 2005) which would not have had much time (12 months) to weather and leach, and would provide further information regarding time required before vegetation should commence.

This method needed testing to know at what stage entry could be gained onto the residue and what size / weight of machine could be used. Also, by covering this area with vegetation, it would eliminate the risks of dusting during dry weather.

- This area was 200 m x 20 m in size and was divided into 11 different sections. The mud had been deposited in this section in July 2005 and had matured somewhat in 12 months.
- It was allowed to dry and mature enough to allow access onto it.
- Sand, gypsum, and fertiliser were applied and leaching rates monitored commencing in March 2006. The bauxite residue, run-off when available, and leachate were monitored on a weekly basis for
  - pH
  - Electrical conductivity
  - Soda.

Some problems were experienced with the spreading of sand and compost. It was necessary to spread the gypsum by hand in places and the distribution of both the sand and compost was not completely even throughout the eleven plots. This was evident in the plots when
vegetation commenced, as some plots were patchy and did not develop. On the day of the compost spreading, the wind became a factor and tended to blow the sand and compost away.

The mechanical spreader was limited in the distance it could “throw” the material, so it was necessary to spread from both sides of the plots, this resulted in the wind making it difficult to get a good distribution. An attempt to offset this by some manual spreading was partially successful. From Figure 51D sand can be seen blowing in the breeze.

Table 14 Plot amended with rates of different Gypsum & SMC in the large plots.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Gypsum</th>
<th>Organic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90 t/ha</td>
<td>80 t/ha</td>
</tr>
<tr>
<td>2</td>
<td>90 t/ha</td>
<td>80 t/ha</td>
</tr>
<tr>
<td>3</td>
<td>90 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>4</td>
<td>90 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>5</td>
<td>90 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>6</td>
<td>45 t/ha</td>
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</tr>
<tr>
<td>7</td>
<td>45 t/ha</td>
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</tr>
<tr>
<td>8</td>
<td>45 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>9</td>
<td>22 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>10</td>
<td>45 t/ha</td>
<td>160 t/ha</td>
</tr>
<tr>
<td>11</td>
<td>0 t/ha</td>
<td>160 t/ha</td>
</tr>
</tbody>
</table>
The above photos show: (A) the ploughing by tractor of the total 0.4 ha plot, (B) shows the white colour of the gypsum spread over the plot, (C) Figure shows the beginning of grass growth, and (D) the sand spray from the spreader.

Both run-off and leachate samples were taken weekly. During dry weather there was only a leachate sample from the adjacent piezometer. Residue samples were taken also to monitor pH values. The run-off and leachate samples were analysed for pH, soda and electrical conductivity.

The plots with the higher levels of gypsum and compost performed the best, see Figure 19 below. Although plots 8-11 had lower levels of gypsum, they also tended to collect more rainwater and were inclined to flood. The reason for pooling of water was attributed to less sand in this section and in turn poorer drainage. When pooling occurred, some of the gypsum and compost were diluted and washed away.

Because of the low infiltration rate, low hydraulic conductivity and relatively high water holding capacity (Menzies et al., 2004; Wehr et al., 2006), water tends to pond on the surface and the surface layers can remain waterlogged during the wet parts of the year. The lack of structure of the pasty fine material does not represent a favourable environment for
root growth (Wehr et al., 2006) and periods of waterlogging further limit potential plant establishment. Installation of a drainage system below the surface layers is essential. Even so, the low hydraulic conductivity tends to inhibit drainage and favour waterlogging.

Figure 52 Vegetation in amended bauxite residue with SMC (160t/ha) (right) and without (left).

4.3 Large Plot Results

Transfer of this methodology to a closure scenario will necessitate adaptation in areas such as amendment spreading and incorporation. The use of large machinery required at least a 12-month maturing period prior to allowing heavy machinery to travel over the residue from the experience gained from these trials (Figure 48A).

Photos indicate some of the stages in residue amendment for seedbed preparation (Figure 48 A,B,C,D.). Findings from this work shows that the key stages in the re-vegetation programme can be achieved at a large-scale level. These include the ability for the residue to support movement of traffic. Methodologies have been developed for spreading large volumes of amendment (chemical, physical and organic) with some difficulty depending on the wind strength and direction. A successful seedbed was established in the residue.
Figure 53 Early grass growth on large trial plots

Figure 54 Successful amendment and vegetation establishment in large plots
The team spent a good deal of time reviewing the machinery problems. Following lengthy discussions with contractors and team members it was decided that the residue should be allowed maturing time. It was estimated to take at least 12 months, depending of course on the amount of rainfall during that period, and the solids concentration of the residue. As sections of the B.R.D.A. are filled to capacity and ready for rehabilitation in the coming years, the B.R.D.A. management of deposition locations must take this time span into consideration.

“Mud Farming”, which is the ploughing up of the residue with amphibian machinery to enhance drying, draining, and carbonation, could reduce this 12-month time frame in the future.

### 4.3.1 Evaluation of the Vegetation Trial 1999

The bio-mass results from various applications of SMC and gypsum results are given in Table 0-19 below.

To evaluate the use of organic matter [spent mushroom compost (SMC)] with gypsum as amendments for promoting vegetation cover, residue was amended at varying rates of SMC (0, 60, 80 and 120 t/ha) and gypsum (0, 40 and 90 t/ha) and sown with *Holcus Lanatus*. Following a one-year growing period, residue properties and plant performance were evaluated.
Table 15 Various applications of SMC and gypsum results.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SMC (t/ha)</th>
<th>Gypsum (t/ha)</th>
<th>Biomass (kg/m²)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>0</td>
</tr>
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<td>4</td>
<td>60</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>40</td>
<td>2.6</td>
</tr>
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<td>80</td>
<td>40</td>
<td>3.7</td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>90</td>
<td>4.2</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td>0</td>
<td>3.8</td>
</tr>
<tr>
<td>11</td>
<td>120</td>
<td>40</td>
<td>4.9</td>
</tr>
<tr>
<td>12</td>
<td>120</td>
<td>90</td>
<td>4.9</td>
</tr>
</tbody>
</table>

4.3.2 Physical Properties of Residue

Although large differences exist between refineries, typically 10–20% of residue exists as sand and the remainder is mud. Separation is not complete and there are usually significant amounts of sand in the mud fraction and vice versa. Often, the mud fraction consists of 20–30% clay-sized (<0.002 mm dia.) particles, with the majority being in the silt-sized range (0.02–0.002 mm dia.) (Newson et al., 2006). However, great variations exist in particle size distribution, due to differences in processing techniques and the nature of the bauxite ore deposit. Some residue have >50% of particles in the clay-sized range (Wehr et al., 2006). The small particle size of residue mud gives the material a relatively high surface area (13–22 m² g/1) (Paramguru et al., 2007). The material tends to have a relatively high specific gravity (Gs = 2.8–3.3) (Newson et al., 2006). Because of its small particle size, when deposited in disposal impoundments, residue mud can consolidate to form a solid mass.
Unless amended and vegetation established, the massive structure and lack of aggregation of the residue is likely to pose erosion problems. Physical properties of the substrate were significantly affected by organic (SMC) application rate to the residue. Results are summarised as follows:

- SMC significantly reduced the bulk density and particle density of the residue
• Organic carbon content increased with SMC application rates, with significant increases for each application rate
• pH was significantly reduced when amended with gypsum
• SMC amendment without gypsum was also effective in lowering pH of residue but only significantly at higher rates
• EC values significantly increased with increasing gypsum application rates due to the formation of salts
• Application of gypsum was the principal mechanism in reducing residue pH and ESP
• Gypsum application promoted flocculation of clay sized particles thereby reducing clay dispersion in the residue (Wong and Ho, 1994a).

Because of the low infiltration rate, low hydraulic conductivity and relatively high water-holding capacity (Menzies et al., 2004; Wehr et al., 2006; Zhang et al., 2001), water tends to pond on the surface and the surface layers can remain waterlogged during the wet parts of the year. The structure-less, pasty fine material does not represent a favourable environment for root growth (Wehr et al., 2006) and periods of waterlogging further limit potential plant establishment. Installation of a drainage system below the surface layers is essential. Even so, the low hydraulic conductivity tends to inhibit drainage and favour waterlogging. See Appendix 1 for Tables 2 & 3

Table 16 Selected properties of bauxite residue as affected by gypsum and SMC application

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SMC t ha⁻¹</th>
<th>Gyp t ha⁻¹</th>
<th>pH</th>
<th>EC</th>
<th>C (%)</th>
<th>pb</th>
<th>pp</th>
<th>ESP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>9.6</td>
<td>0.37</td>
<td>0.91</td>
<td>1.64</td>
<td>3.45</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>40</td>
<td>8.3</td>
<td>2.28</td>
<td>0.95</td>
<td>1.34</td>
<td>3.47</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>90</td>
<td>8.2</td>
<td>2.43</td>
<td>0.98</td>
<td>1.25</td>
<td>3.37</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0</td>
<td>9.3</td>
<td>0.59</td>
<td>1.88</td>
<td>1.17</td>
<td>3.35</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>40</td>
<td>8.1</td>
<td>1.51</td>
<td>1.66</td>
<td>1.07</td>
<td>3.30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>90</td>
<td>8.0</td>
<td>2.4</td>
<td>2.09</td>
<td>1.07</td>
<td>3.30</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>0</td>
<td>8.4</td>
<td>0.47</td>
<td>2.41</td>
<td>1.10</td>
<td>3.30</td>
<td>19</td>
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<tr>
<td></td>
<td>120</td>
<td>40</td>
<td>8.0</td>
<td>1.9</td>
<td>2.38</td>
<td>1.08</td>
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<td>90</td>
<td>8.1</td>
<td>2.5</td>
<td>2.18</td>
<td>1.12</td>
<td>3.29</td>
<td>5</td>
</tr>
</tbody>
</table>
Nutrient Properties
Nutritional status of un-amended bauxite residue is poor. Limited nitrogen is available in un-amended bauxite residue at Aughinish, while carbon levels were also very low. Residue without organic amendment exhibited poor levels of nutrients.

Application of SMC at all rates significantly raised levels of nutrients in the bauxite residue substrate (Figure 54). Mn levels were significantly increased with SMC application and at highest rate (120 t ha) are within range indicated in Table 0-21 for optimal growth. Levels of Mg and K were also much increased with SMC application to levels above those cited as deficient. Residue P levels were also increased but levels remain low, corresponding with Index 0 in the availability indices.

Overall, application of SMC to amended bauxite residue was effective in improving nutrient content and plant performance. No grass sward persisted in treatments without SMC application, reflecting the lack of organic matter and nutrients in these treatments. The significant increases in biomass with each application rate of SMC are attributed to the improvement in nutrient content of the substrate and the provision of a favourable growth medium.

Dry weight biomass production was positively affected by substrate nutrient concentration with greatest correlations in the order of K > C > Mn > Zn > Mg > Cu > N (r = 0.835 **, 0.821 **, 0.767**, 0.715 **, 0.632**, 0.573**, 0.445*; ** p < 0.01 and * p < 0.05)

Changes in bauxite residue nutrient content following application of composts will be dependent on application rate and characteristics of the compost (Table 17).
Figure 57 *Holcus lanatus* (Yorkshire fog) grown in bauxite residue without SMC organic application (left) and with application (right) (1999)

Table 17 Effect of spent mushroom compost (SMC) application on bauxite residue nutrient content

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Gypsum (t/ha)</th>
<th>N</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>K</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC (t/ha)</td>
<td>n/a</td>
<td>0.3</td>
<td>0.28</td>
<td>0.24</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>90</td>
<td>0.3</td>
<td>0.28</td>
<td>0.24</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>90</td>
<td>1.13</td>
<td>1.24</td>
<td>0.40</td>
<td>0.25</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>90</td>
<td>1.46</td>
<td>1.56</td>
<td>0.43</td>
<td>0.28</td>
<td>0.18</td>
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<tr>
<td>120</td>
<td>90</td>
<td>1.90</td>
<td>2.30</td>
<td>0.60</td>
<td>0.48</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

**Plant Content**

Application of spent mushroom compost at rates of ≥80 t ha was effective in grasses with sufficient content of nutrients P, K, Mg for grass growth with ≥120 t/ha effective for N content. With gypsum and compost addition, Na content was within background levels and Ca levels were adequate.

Nutrients Zn, Mn and Cu were not limiting in compost and gypsum-amended treatments.
Table 18 Nutrient range in *Holcus lanatus* in gypsum and compost-amended residue

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (g/ 100g)</td>
<td>1.5 – 3</td>
</tr>
<tr>
<td>Ca (g/ 100g)</td>
<td>0.57 – 0.93</td>
</tr>
<tr>
<td>P (g/ 100g)</td>
<td>0.27 – 0.40</td>
</tr>
<tr>
<td>K (g/ 100g)</td>
<td>2.2 – 4.5</td>
</tr>
<tr>
<td>Mg (g/ 100g)</td>
<td>0.13 – 0.19</td>
</tr>
<tr>
<td>Zn (mg /kg)</td>
<td>15.6 - 29.2</td>
</tr>
</tbody>
</table>

### 4.4 Demonstration Cell

At each stage along the way the author would talk to the team members, maybe together or individually, depending on the work coming up, e.g. if the work entailed civil work on the construction of the Demonstration Cell, the author talked to the civil engineer. When the plan and scope of work was decided the author would first consult with the manager and would arrange to attend the weekly managers’ meeting to update them on progress and developments. Sometimes at this meeting the author looked for the release of funding, or purchase order approval for contractors, etc. In this way, the line of communication was always open to top management and they were updated on progress.

With regard to the personnel in the process area, which includes the B.R.D.A., they were updated by the author at their monthly information meetings. There was some concern throughout the plant that space was running out in the B.R.D.A. and the personnel in the Filtration Building were being requested to keep closer control over the caustic in residue and percentage solids to save on space. This meant extra work for those staff members.

Construction of the Demonstration Cells consisted of the building of a 0.6 ha mini B.R.D.A. within the confines of the existing B.R.D.A. The large-scale (0.6 ha) dedicated research Demonstration Cell and other trial plots within the B.R.D.A. Leachate and run-off monitoring commenced after bauxite residue started filling into the Demonstration Cell. Monitoring of pH, soda concentration, and electrical conductivity of the run-off and leachate started, and continued weekly for 18 months. These samples were also taken following grass sowing, so comparisons could be made of results before and after vegetation growth. It was not known how vegetation can /would influence infiltration or run-off.
Following the construction of the Cells the liner was installed and quality control leak tests were carried out. The team civil engineer verified these results.

Flow meters were installed in pipe work sampling on the run-off and leachate. The author engineered the installation of these flow meters with the Instrument Engineer. The leachate was drawn from beneath the residue by a vacuum pump.

Some key areas investigated included:
- pH of run-off /
- pH of leachate
- soda
- electrical conductivity and if vegetation influences the pH levels and quantity will
- residue physico-chemical conditions
- leachate pH generation
- run ph flow rates
- compaction rates
- using large machinery on the residue for applying amendment

4.4.1 Study Areas

- Gain experience using large machinery on larger areas of residue. The added problem in the Demonstration Cells was the liner on the edge of the embankments, how to get the machinery onto the residue without damaging the liner. This was achieved by building a ramp of process sand.
- Re-vegetated area will be sustainable.
- Will the vegetation influence pH quality and quantity? We have the results for 18 months before the grass was sown and now the same samples are being monitored with the vegetation.
- pH, conductivity and soda monitoring. The monitoring started after the first fill of residue was pumped into the Cell
- Quantities of run-off and leachate. This was measured by the flow meters installed on the run-off and leachate lines
The new Demonstration Cells were built in the eastern section of the B.R.D.A. The containment area was constructed by building two embankments around the perimeter of the new development area. These embankments and trench area were covered with impervious high-density polyethylene (HDPE) geo-membrane to prevent loss through leaching of the run-off-stream (Figure 55). A series of perforated piping was laid on the membrane and routed to the outside of the embankment to collect the leachate that filtered down through the mud and collected for analysis. These pipes were be set in a trough to aid collection (Figures 58, & 60). The sampling from this collection area under the mud requires a pump to lift the leachate up approximately 20 feet from the bottom of the cell. The laboratory jeep has an inbuilt generator and pump that will be used to take these samples.

As action researcher the author was integrally involved in the construction, including the engineering and civil work for the construction of the Demonstration Cells. It was necessary to arrange truckloads of sand, several thousand tonnes for embankment building, with the plant. Contractor safety and risk assessment were completed. The author was the co-ordinator for all this work. When the cells were constructed, another contractor was employed to complete the lining. This required strict adherence to quality control regarding the welding of the liner and leak testing procedures.

The first aim was to test and evaluate the new pumping and pipe work layout. This was agreed by the author as project leader with Projects Department and Process
Departments to change over from the normal pumping route to the new route to the Demonstration Cells. This worked out well and there were no problems in changing back and forth between the Cells and the B.R.D.A. during filling. Concerns about isolation and drain down / depressurisation of the new pipe work did not materialise.

As project leader, the contractor’s safety was paramount. This was standard procedure within the company that the project leader monitored the safety of the contractors and was responsible for the scope of work.

The embankments were typically constructed of process sand. This sand is removed from the plant process on a continuous basis and amounts to about 2000 tonnes per week. It is generally used to construct roads in the residue area and is trucked by an outside contractor on a daily basis.

A spur was taken from the pipeline to the B.R.D.A. and used to fill the compartments of the Demonstration Cells. The author had the authority to decide on the routing of this pipeline and valve arrangement. This high-pressure piping was engineered and installed in such a way as to provide isolation and drainage facility when not in use. It was safety-assessed with the engineering and contractor teams.

The route of the pipe was agreed with plant process personnel. Initially it was planned to fill the cell for a few hours every day but the residue would not stack up in such a short length of time. It was found that the residue ran to the bottom the cell and would have overflowed the embankment. Therefore it was necessary to fill for a few hours at a time and then allow it to dry / mature for seven days at a time. This allowed the mud to stack higher and thus fill the complete cell. This was something that had not been envisaged and set the programme back a few months. The author’s concern at this point was the possibility that the stacking up would not happen, or it would take a long time.

The filling took about three months, with weekly filling to allow the mud to dry and therefore give a better stacking angle. When the mud was sufficiently dry enough to walk and travel on and had weathered sufficiently, it was possible to add sand, gypsum and fertiliser and sow grass.

Procedure for pumping residue to the Demonstration Cell

- Set-up procedure to fill the Demonstration Cell with the new pipe work arrangement and evaluate this system
• Commission new pipework
• Make process changes to the Filtration Building to transfer at high percentage solids and reduced soda levels in the residue without upsetting plant production. The necessary changes were to the residue in the Filtration Building prior to pumping to the Cells.

Sampling and amendments
• Further investigation into the use of machinery to work on the residue..
• Set up procedures to establish grassland, including the amendment rates, the ploughing, the spreading of compost, and gypsum.
• Sampling of the amended residue prior to amendment is necessary to determine efficiency of weathering. Some carbonation and leaching will take place, even without any amendment of the residue. The aim is to have the ph below 10.0 before sowing grass.

![Figure 59 Plan of the Demonstration Cell](image)
Figure 60 Run-off Collection Details
Figure 61 Leachate (seepage) collection system

Figure 62 One Cell before liner was installed, sand and rock only
Figure 63 Seepage collection tray in floor of cell

Figure 64 Inlet filling valve to one Demonstration cell
Figure 65 First fill of bauxite residue pumped into Demonstration cell

Figure 66 Bauxite Residue deposited after first fill
Figure 67 Second fill into Demonstration cell

Figure 68 Level in cell after 3rd fill (white colour is evidence of soda)
Once full, the Demonstration Cell (Figure 69) remained undisturbed by refinery activities. Following 12 months of weathering, the amending process commenced (Figure 70). Amendment procedures to establish native grassland on the residue were as follows:

- Process sand mixed and rotavated into the mud.
- Gypsum addition for alkaline amelioration.
- Nutrient addition, compost 120t/ha (was being delivered almost daily to the plant).
- Fertilization of bauxite residue.
- Sow selected grass species in the amended residue selected following the other small trials.

The first filling commenced on 17th May 2007 by switching the bauxite residue from the normal line to the B.R.D.A. into the cell. The density of the residue was less than 55% solids, as there was washing of filters taking place in the filter building. The result of this was the residue ran to the bottom of the cell without filling the top sections and stacking did not occur. This was an oversight that resulted in having to leave the deposited bauxite residue for a week to allow some drying before depositing the next layer of mud.

On reflection, it would have been better not to have pumped to the Cell with the conditions in the Filtration Building on that particular day. It was felt it was necessary to start filling to test the pipework and the system. Pressure testing of the pipework in a controlled manner was necessary.

From the experience gained from the first fill it was necessary to have all conditions in the Filtration Building perfectly correct before pumping commenced. These included maximising the washing of the residue, and reducing dilution to pump at highest percentage soils as possible.

It was decided to delay the second filling one week and only pump after all washing was completed in the filter building and this gave residue at 60.8% solids. The mud began to build and stack at the inlet section and did not run to the bottom of the cell. Had stacking not taken place, it would have been impossible to fill the complete cell to near the top of the embankments. This was a good learning point for the author.

Although our original plan was to put 2.0 m depth of residue in the cell, the author decided to attempt a fill to maximum depth of the embankment, this would be more
representative of the actual B.R.D.A. The target solids concentration for each fill was to be higher than 60% solids by arranging the process conditions in the plant to match this target, and pumping did not take place until these conditions were achieved. One lesson learned from these filling exercises was how important it was pump at the highest solids concentration in order to achieve maximum stacking and take up minimum space in the B.R.D.A.

The filling programme was for five hours on one day per week until full. In total it took fourteen sessions to completely fill the cell. This took some organisation with the plant to set up the filter building to reduce dilution of the mud and pump at the highest density mud as possible.

Caustic analysis at the time was recorded along with the solids concentrations of the residue. Sampling of the run-off and seepage from the collection tray underneath the residue and the soda analysis commenced at the first fill.

The Demonstration Cell received fresh bauxite residue in 2007/2008 and amelioration commenced in 2008/2009. Amendment procedures used are those previously described.

The amended area was seeded in September 2009 with species that had previously been sown in the small and large plots.

Leachate samples taken in May 2011, four years following the filling showed no reduction in pH, conductivity or soda levels from the first sample of May 2007.

May 2007 pH = 12.65 Conductivity 29,150ms/cm, soda = 9.59 g.p.l
May 2011 pH = 13.0 Conductivity 67,106, soda = 16 g.p.l.

As the cell is completely lined, there is no possibility of recharge other than by pumping. This is different that the B.R.D.A. itself.
**Figure 69** Demonstration Cell filled with fresh bauxite residue before commencing amendment procedures

**Figure 70** Amended bauxite residue in Demonstration cell before seeding
Figure 71 Re-vegetated residue in Demonstration Cell (5 months after seeding).

Figure 72 Re-vegetated residue in Demonstration Cell (10 months after seeding)
Herbage samples were taken from the re-vegetated trial cell 10 months after seeding (before inflorescence) and nutrient content determined.

Table 19 Nutrient Content Range

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Range</th>
<th>Typical range(^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (g/100g)</td>
<td>1.9 – 2.6</td>
<td>1 – 5</td>
</tr>
<tr>
<td>Ca</td>
<td>0.6 – 0.86</td>
<td>0.33 – 0.73</td>
</tr>
<tr>
<td>P</td>
<td>0.3 – 0.46</td>
<td>0.1 – 0.6</td>
</tr>
<tr>
<td>K</td>
<td>1.7 – 3.43</td>
<td>2.16 – 4.01</td>
</tr>
<tr>
<td>Mg</td>
<td>0.1 – 0.14</td>
<td>0.08 – 0.26</td>
</tr>
<tr>
<td>S</td>
<td>0.3 – 0.5</td>
<td>0.15 – 0.6</td>
</tr>
<tr>
<td>Zn (mg/kg)</td>
<td>22 – 34</td>
<td>10-60</td>
</tr>
<tr>
<td>Mn</td>
<td>50 – 130</td>
<td>30-100</td>
</tr>
<tr>
<td>Cu</td>
<td>8 – 14</td>
<td>5-30</td>
</tr>
</tbody>
</table>


Nutrient content of herbage growing on trial cell (1\(^{st}\) years growth) Nutrient content is typical for normal ranges in grassland herbage (Whitehead, 2000) and similar to that previously reported for re-vegetated bauxite residue.
Table 20 Analysis of Leachate from Demonstration Cell

Trial Cell Leachate

<table>
<thead>
<tr>
<th>Date</th>
<th>pH</th>
<th>Conductivity ms/cm</th>
<th>Soda mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/05/2007</td>
<td>12.65</td>
<td>29150</td>
<td>9.59</td>
</tr>
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<td>31/05/2007</td>
<td>12.63</td>
<td>26710</td>
<td>9.57</td>
</tr>
<tr>
<td>07/06/2007</td>
<td>12.38</td>
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<td>28/06/2007</td>
<td>12.73</td>
<td>27750</td>
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<td>04/07/2007</td>
<td>12.77</td>
<td>27400</td>
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<td>11/07/2007</td>
<td>12.76</td>
<td>28010</td>
<td>4.04</td>
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<td>19/07/2007</td>
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<td>16/08/2007</td>
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<td>10/10/2007</td>
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<td>28/05/2011</td>
<td>13.04</td>
<td>67,905</td>
<td>16.7</td>
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Table 21 Analysis of Run-off from Demo Cell

<table>
<thead>
<tr>
<th>Date</th>
<th>pH</th>
<th>Conductivity mS/cm</th>
<th>Soda mg/l</th>
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</thead>
<tbody>
<tr>
<td>10/05/2007</td>
<td>12.84</td>
<td>34800</td>
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<td>21/05/2007</td>
<td>12.74</td>
<td>38400</td>
<td>10.45</td>
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<td>31/05/2007</td>
<td>12.62</td>
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<td>7.41</td>
</tr>
<tr>
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No sample available on 28/05/2011

4.4.2 Sampling & Field Results from B.R.D.A.

The objective in doing this sampling and fieldwork across the B.R.D.A. was to include coring or continuous sampling of the residue. This was to facilitate a better assessment of the number, extent, thickness, and spacing of horizontal higher permeability layers as well as
carry out a chemical analysis of the residue from different depths which would allow the evolution of pH of the interstitial fluids to be assessed. Permanent monitoring wells were installed at different depths for sampling throughout the B.D.R.A. Laboratory pore volume flushing of residue samples was also carried out to determine how much water is needed to reduce the pH of the effluent to 9.0 or below.

This information was required by the E.P.A. for the application for planning permission and the subsequent closure plan. As Process Co-ordinator for the B.R.D.A., the author was involved in the scoping of the work with the civil engineer and environmental department. Any work on the B.R.D.A. by contractors had to be safety-assessed and supervised to ensure personnel safety on the B.R.D.A. This was part of the author’s job at the time. The author also had to ensure the contractors complied with the scope of the work. The Process Co-ordinator would communicate all project work to Section staff and was the channel for the flow of information between projects and line staff. The scope of work was agreed with the contractor, including the time span and daily permits to work and in what location were issued by the author.

The company Golders Associates was hired to take samples from the residue, following the installation of bore holes/wells throughout the B.R.D.A. Analysis of Pore water, Run-off & leachate were conducted for the following parameters:

- soil pH and EC
- alkalinity
- ESP
- soluble aluminium levels

### 4.4.3 Pore Volume Flushing & Effluent pH Evolution

Three U-100 undisturbed samples were taken for pore volume flushing experiments. One sample was taken from BH-D (between 2.8 m and 3.3m) and two were taken from BH02-01 (between 6.2 m and 6.7 m, and between 9.5 m and 10.00 m). These samples were sent to a URS geo-technical laboratory in New Jersey, USA.
4.4.3.1 Soil Chemistry

Five samples were taken for chemical analysis. Two samples were taken from BH-A, one each at 4.5 m and 14.0 m, of sand and mud respectively. One mud sample was taken from BH-B, at 4.0 m, and two mud samples were taken from BH-C, at depths of 3.5 m and 8.5 m. Each of these samples were analysed for aluminium content, sodium content, acid soluble carbonate and soil pH.

4.4.3.2 Groundwater Sampling

Groundwater samples were taken from all nine piezometers and three monitoring wells for field determination of pH using a calibrated field meter. Groundwater pH ranged from 12.8 (PZ5) to 13.4 (BH-D).

PZ5 is screened within the estuarine silt below the B.R.D.A.; it is considered that the high pH reading represents groundwater which was introduced into the borehole during drilling from the B.R.D.A. above, rather than groundwater within the estuarine silt.

4.4.4 Laboratory Tests

The rate of water injection was low due to the low permeability of the mud. Higher injection pressures were not used, as it was desirable to avoid too high a pressure differential across the mud samples which could cause physical changes (such as fractures) in the mud, samples and possibly resulting in the creation of preferential flow paths.

Initial pH readings of approximately 12.4 were recorded for each of the three samples. As water was flushed through the samples, the pH initially rose; this is thought to represent the replacement of pore water by influent tap water. The pH rose up to a maximum of 12.94 (sample between 2.8 m and 3.2 m in depth within B.R.D.A.). The pH of the effluent then steadily decreased in all three samples to between 12.04 and 12.20, after each sample was flushed with between 2.5 and 3.0 pore volumes.

Following this initial reading, and relatively rapid drop in pH, the rate of decline in pH decreased.
After the three samples were flushed with between 4.67 and 5.84 pore volumes, the pH had further declined only to between 11.67 and 11.93. It was predicted that it would require in excess of ten volumes of water to reduce effluent pH below 9.

### 4.4.5 Soil Chemistry

Chemical laboratory results for the five soil samples analysed are summarized below:

- **Aluminium content**: The aluminium content of the process sand was 25 g/kg. For the process mud, the aluminium content was between 25 g/kg and 30 g/kg in three of the samples and 1g/kg in one sample. The aluminium content, as expected, was high in all samples.

- **Sodium content**: For the process sand sample, the sodium content was 9 g/kg. In the four samples of process mud, the sodium content ranged between 19 g/kg and 28 g/kg.

- **Acid soluble carbonate**: Acid soluble carbonate was 15% in the sand samples, and ranged between 9% and 40% in the four mud samples.

- **Soil pH**: The pH for the sand and mud samples was consistently between 12.3 and 12.5

### 4.4.5.1 Hydraulic Testing

Falling head hydraulic tests were conducted in all of the monitoring wells and piezometers installed. Pressure-sensitive data loggers were installed in each monitoring well/piezometer and the depth to groundwater was measured manually and recorded. A known volume of water was then added to the monitoring well/piezometer; the data-logger recorded the resulting rise in water level and the rate of water level decline against time. The water level was allowed to decline until it had reached its original revel. The rate of water level decline is used to calculate the hydraulic permeability of the aquifer in the vicinity of the monitoring well/piezometer.
The hydraulic permeability of the process sands was not measured directly, but can be said to be greater than, or equal to, $5 \times 10^{-5}$ m/s. This is similar to the calculated hydraulic permeability of the process sands of between $1 \times 10^{-4}$ m/s and $1 \times 10^{-5}$ m/s (URS Dames & Moore, 2002).

Previous studies of the red process mud had calculated the hydraulic permeability from laboratory tests. It had been estimated that the bauxite residue would have a hydraulic permeability of between $1 \times 10^{-8}$ m/s and $1 \times 10^{-9}$ m/s. The field hydraulic testing has confirmed these values as being at the lower end of the range, i.e. the hydraulic permeability within the deeper, older bauxite residue (URS Dames & Moore 2002).

The shallower, younger, bauxite residue has a higher field hydraulic permeability, approximately $4 \times 10^{-6}$ m/s. From the data, this higher permeability appears to apply to bauxite residue to a depth of 3.0 m below surface.

Given the very slow response from the estuarine silts, it is considered valid to model the base of the mud sack as a no-flow boundary.

**4.5 Conceptual Site Model**

In an initial modelling project, which considered groundwater flow within the B.R.D.A. in two dimensions only, many assumptions were made as to the physical stratification and structure of the B.R.D.A. These included:

- the presence of many very high permeability layers. These represented the sand and straw layers which were thought to exist;
- the terraced sides of the B.R.D.A. were assumed to have a higher permeability and be interconnecting from one terrace to the next;
- only the main process roadway which ran through the whole depth of the B.R.D.A. was included. No buried roads were included.

After the drilling investigation it is now known that there are no extensive thin layers of sand or straw within the mud. This straw and hay had been used as a dust suppressant. It had been partially successful but did not last very long. It either rotted down into the residue or was blown away. The straw present is well rotted and embedded within the mud matrix; it does not form distinct layers which would affect the permeability of the mud.
The CPT drilling through the lower terraces indicated that each terrace was separated by bauxite residue. Thus they were not interconnected as had been previously considered to be the case. The drilling has indicated the presence of several buried roads of > 1.0 m in thickness, but of limited area extent.

The B.R.D.A. can be described as a relatively uniform mound of fine silty clay. The perimeter was comprised of seven terraces, with the thickness of mud at each terrace averaging:

- Terrace 1 - 5.0m
- Terrace 2 - 7.5 m
- Terrace 3 - 9.5 m
- Terrace 4 - 11.5m

The terraces are composed of limestone blocks and fill material on a bed of process sand but are separated from each other by the process mud.

As there are no higher permeability sand layers, it is considered that the groundwater flow within the B.R.D.A. will be via slow seepage through the mud. The presence of higher permeability sand roads, buried sand wedges associated with roads and buried small roads act as longitudinal drains with localized effects on water levels within the stack.

Evaluation

Based on the mud permeability the residue cannot allow the transmission of much water. Much of the rainfall on the residue, which would be available for recharge, exits as run-off to the perimeter channel. This will lead to a reduction of the pH in the channel. Higher permeability layers increase the recharge that the residue can take. The roadway changes the flow patterns within the mound because of the layers of rock and sand used to construct the roadway down through the years. Generally there is little groundwater movement deep in the residue stack.

The majority of rainfall will not infiltrate the residue and only the higher permeability layers close to the surface, i.e. within the top few metres, will allow any recharge. The growing of grass on the residue will further reduce infiltration down into the residue and in turn reduce leachate seepage.
4.5.1  B.R.D.A. Groundwater Flow Model

The purpose of the flow model was to get a representation of the B.R.D.A. and attempt to predict the final pH value and the time span in reaching 9.0.

Numerical modelling of the groundwater system within the mud stack area was undertaken in order to assess whether the proposed five-year period is sufficient to reduce the pH of the outflows from the mud stack area below pH 9.0. The groundwater flow modelling objectives were:

- to investigate the depth of circulation of groundwater within the mound;
- to assess the groundwater flux via the mud to the perimeter drain;
- investigate the influence of layering and heterogeneity on groundwater flows within the mud stack;
- assess the likely impact of reduced infiltration over time (due to proposed vegetation of the stack area when surface pH decreases) on groundwater flux to perimeter drain.

4.5.1.1  Model Limitations

The model developed is based on the available data from extensive field and laboratory testing. The model has incorporated all available data and professional judgment has been made as to the suitability and representative nature of the available data.

Numerous different simulations of the B.R.D.A. were performed, incorporating different degrees of complexity. The model developed is just one of many possible models, given the available data. It is not definitive but is considered to be a reasonable representation of the B.R.D.A. The model, which was completed to bear the greatest similarity to the observed hydro-geological conditions on the B.R.D.A., is described below.
4.5.1.2 Model Domain

A map of the B.R.D.A. was used as a scale base for the B.R.D.A. model. The dimensions of
the B.R.D.A. map were the equivalent of 1300m x 1050 m. At its highest point, the total
thickness of the modelled B.R.D.A. was assigned at 20.0 m.

The plan area of the B.R.D.A. was divided into a grid of 100 columns and 100 rows,
this is a reasonably fine grid the equivalent of approximately 13 m x 10.5 m on the ground.
In the vertical plane, the modelled B.R.D.A. ranged from 3.0 m to 20.0 m in thickness, the
lower height representing the perimeter drain with successively higher elevations assigned for
the terraces. The model was divided into six layers.

While the shape and topography of the B.R.D.A. terraces were defined within the
model domain the topography of the gently sloping B.R.D.A. surface was not. The model
only considers cells that are saturated to be part of the model, if, on completion of a model
simulation, a cell is dry it is automatically inactivated. Therefore, there was no need to define
the unsaturated surface of the model; upon completion of the model simulation the
piezometric surface would define the top of the model and the water table within the mud
mound.

4.5.2 Model Properties Hydraulic Permeability

The main body of the B.R.D.A was assigned a hydraulic permeability of $1 \times 10^{-8}$ m/s, this is
at the higher end of the observed range of hydraulic permeability of mature residue from field
and laboratory tests (URS Dames & Moore, 2002).

The topmost layers of residue and those at the surface along the terraced sides were
assigned a higher hydraulic permeability of $1 \times 10^{-6}$ m/s. This is in accordance with the
observed field hydraulic test results.

In the middle of the model the two lowest layers of residue were assigned a lower
permeability of $1 \times 10^{-9}$ m/s. This is in line with hydraulic testing results from some of the
deeper piezometers such as BH-C (URS Dames & Moore, 2002).

No layers of thin high permeability sand have been included as the field
investigation showed.
4.5.2.1 Terraced Sides

The terraced sides and perimeter drain were assigned a higher permeability than the main body of residue, in line with both earlier calculations and actual field observations. The permeability assigned was $1 \times 10^{-5}$ m/s. The terraced sides and perimeter drain run along the southern, western, northern and north-eastern B.R.D.A. boundaries.

4.5.2.2 Roadways

The main roadway, the northern access ramp, the road around the sludge pond and the buried perimeter road from the original footprint of the B.R.D.A. (i.e. prior to the extension) were also assigned the higher permeability value of $1 \times 10^{-5}$ m/s.

The main roadway extends through to the base of the B.R.D.A. The northern access ramp and the road around the sludge-pond extend partially through the mud mound from the surface. The original perimeter roadway is buried beneath layers of mud. Other smaller roadways and tracks of limited areal extent and thickness have not been included.

4.5.2.3 Storage

The residue, whether at the surface or deeper within the B.R.D.A., was assigned a total porosity of 0.7 (70% of the total volume) and an effective porosity of 0.5, as had been used in previous 2D simulations and determined from laboratory tests.

The roads and terraces were assigned a total porosity of 0.25 and an effective porosity of 0.2, which are in line with literature values of these parameters for the sand and fill material of which these features are made. Similar values had been used in the 2D simulations.
4.5.2.4 Model Boundaries

4.5.2.4.1 Recharge

As is common in groundwater modelling scenarios the chosen value of recharge was assigned through a trial and error process. Many different simulations were run and, as with the 2D modelling, it was found that the B.R.D.A, could not process large amounts of recharge. In the end the assigned recharge value was 1 mm/a. Recharge was the only source of water in the model.

4.5.2.4.2 Constant Head

The perimeter drain was set up in the model as a constant head boundary, set at 3.0 m. The perimeter drain runs along the southern, western, northern and north-eastern boundaries. At the north-eastern corner the perimeter drain discharges to the storm water storage pond. The position of the constant head cells, represent the perimeter drain and act as a mechanism for water to exit.

4.5.2.4.3 Drains

Drain cells were assigned along the terraced sides, just at the top of each terrace. This was to simulate the seepage of water from the B.R.D.A. that has been observed to occur along the tops of the terraces. Drain cells allow water to exit the model.

4.5.3 Water Balance

As noted, recharge was assigned through a ‘trial and error’ iterative process. As in the 2-D modelling exercise, the B.R.D.A. was found to be able to process very little water. A recharge of 1 mm/y was assigned to the model, which represents less than 1 % of the available recharge. The mass balance of the calibrated model had an error of -8.86, which is within the acceptable error of 10%. The model calculated that slightly more water leaves the B.R.D.A. than is added through recharge.
Recharge through rainfall of 1 mm/a is the only input of water to the model. The rate of recharge applied corresponds to an input of 2,513 m$^3$/d. The model calculated that 2.746 m$^3$/d leaves the B.R.D.A, equivalent to 1,000 m$^3$/d. All of the discharge from the B.R.D.A. is via the perimeter drain, no water was calculated to leave the B.R.D.A. through the terrace drains.

### 4.5.3.1 Implications for Final Effluent pH.

The laboratory results found that the rate of decrease in pH of effluent from bauxite residue declined with time. The laboratory experiments were allowed to run for a period of three months. During the first two pore volume flushing, the pH fell by between 0.4 to 0.5 to give pH readings of around 12.2 to 12.4.

Following this initial phase, the pH decline became less rapid, and after flushing by a total of six pore volumes at the end of the three-month period, the pH had fallen to between 11.2 to 11.4. Under the laboratory conditions, it was not practical to continue the experiment further. In order to reduce the pH of the effluent, further flushing by in excess of ten pore volumes would be required.

The 3-D modelling results have confirmed that the B.R.D.A. can process only negligible amounts of recharge, as indicated in the 2-D modelling exercise. Average annual rainfall for Shannon Airport is given as 927 mm/a. With 1 mm/a of this becoming recharge to the B.R.D.A., and assuming as much as 40% evaporates, then 556 mm/a would be available for surface run-off from the B.R.D.A. directly into the perimeter drain. As the area of the B.R.D.A. is 80 ha, this equates to a discharge of 444,800 m$^3$/a being converted to surface run-off.

From the modelling exercise the B.R.D.A. effluent accounts for 1,000 m$^3$/a. Thus, the B.R.D.A. effluent is greatly diluted by direct surface run-off to the drain, diluted by approximately 445 times. A 10-fold dilution would result in a pH reduction of 1, therefore the dilution effects of direct surface run-off would result in a pH reduction greater than 2 for the effluent from the perimeter drain.
4.5.4 Outcomes

The fieldwork completed confirmed and quantified many characteristics of the bauxite residue and B.R.D.A. that had previously been assumed or estimated from laboratory tests.

- The field scale permeability of the majority of the bauxite residue is within the previously determined range from laboratory scale experiments, $1 \times 10^{-8}$ m/s to $1 \times 10^{-9}$ m/s. It was found that the deeper bauxite residue had lower hydraulic permeability than the shallower (more recently deposited) bauxite residue. In fact the hydraulic permeability of the topmost layers of bauxite residue (to about 3.0 m below the top of the B.R.D.A) had a hydraulic permeability of $1 \times 10^{-6}$ m/s.

- It was found from the drilling returns that extensive thin layers of process sand or straw were absent. Therefore, there were no thin layers within the B.R.D.A. that would affect the groundwater flow pattern. This was a surprising result due to the fact that both hay and straw had been widely used in the early years of plant production as a dust suppressant. Process sand was used for road building and there was a network of roadways throughout the B.R.D.A., so again it would be expected to have differences in the hydraulic permeabilities.

- The bauxite residue itself was found to be quite consistent throughout the depth of the B.R.D.A., which was found to be over 20.0 m at the centre of the stack. Variations in consistency from stiff, to firm to soft were noted. The thin stiff layers of mud were interpreted to be old, desiccated mud surfaces that had been buried by subsequent mud deposition, and indicate that once the mud has dried it does not readily re-hydrate to the same extent.

- The pH of the mud was found to be quite consistent from different depths and different locations across the B.R.D.A. and ranged between 12.3 and 12.5. A similar factor was noted in the results from the one-tonne drums and the Demonstration Cells.

- Groundwater levels within the B.R.D.A. were high, generally about 1.0 m below the surface of the B.R.D.A. At one drilling location, BH-D, which was located at some distance from the roadways and terraces, the groundwater level was found to be artesian, and over-pressurized due to rapid deposition.
• The main roadway was found to exert quite a strong influence on the groundwater flow pattern, the groundwater level measured at BH-A, within the sands of the main road, was found to be much lower than at other locations within the mud. The main roadway through the centre of the B.R.D.A. has been there since plant start up in 1983. It has been raised stage by stage as more residue was deposited. It was build with rock, limestone grit, process sand and solid scale lumps cleaned from tanks and vessel on site, so this would have substantial influence on groundwater flows.

• One monitoring well was installed into the estuarine silts below the B.R.D.A, PZ-5, It was found that the groundwater head at this location was below that of groundwater within the B.R.D.A., implying a downward hydraulic gradient from the B.R.D.A. into the estuarine deposits. The estuarine silt had an extremely low hydraulic permeability, even lower than that of the bauxite residue. In the original B.R.D.A. the prevention of seepage is reliant on the estuarine soil (there is no lining). There are over forty observation wells around the B.R.D.A. so any seepage to groundwater is detected.

4.5.5 Laboratory Soil flushing tests

• These tests reconfirmed the low permeability of the mud at between 1 x 10\(^{-8}\) m/s.

• The pore volume flushing was slow, given the low hydraulic permeability and the low hydraulic head driving water through the sample. It was feared that an excessive hydraulic head would alter the structure of the mud samples and result in preferential pathways.

• The pore volume flushing experiment succeeded in lowering the pH of the effluent from the sample from around 13.0 to around 11.2 after six pore volumes had been passed through the sample.

• A decline in the rate of pH reduction was noted during the course of the experiments.

• In order to reduce the pH of the effluent to less than 9.0, it would be necessary to flush the samples by in excess of ten pore volumes.

The three pore flushes given to the residue in the one tonne containers did not show any changes in pH.
**Review/ Discussion**

The numerical modelling states that the pH will drop to 9.0 in 5 years, but the rate of capillary rise of soda through the residue, which would have an adverse affect on vegetation, is an unknown. (Capillary rise is the movement of water upwards, which is influenced by the layers of contrasting textures.) The building of a field scale model of the B.R.D.A. and hence the construction of the Demonstration Cells was a recommendation of the modelling investigation. The E.P.A. then requested the company to prove that the pH would drop to 9.0 in 5 years, by constructing the Demonstration Cells and monitor pH in leachate plus run-off. The author’s role following on from requests from the E.P.A. was to evaluate these results and set up the plots trials and get the Demonstration Cells constructed to monitor the run-off and leachate ph. Investigate how vegetation could influence seepage rates and in turn lower the combination pH of run-off and leachate.

**Seepage Summary**

The 1974 planning approval for Phase 1 B.R.D.A. for ponded storage of the wet unfiltered red mud was 4.3E-3m$^3$/sec or 371m$^3$/day seepage rate from the residue on the B.R.D.A. The total projected seepage emanating from the Phase 2 B.R.D.A. at Stage 10 and including the S.W.P. and perimeter interceptor channel= 236 m$^3$/day. This is within expectations and with the run-off / leachate at 400:1 this would lower the ph to 9.0, given the reduction shown in the pore flush modelling.

**B.R.D.A.**

With the composite lining, seepage from the base of the Phase 2 B.R.D.A. would be minimised and is dependent on the following key factors:

- number of 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.

Even with the most thorough quality control and quality assurance procedures carried out during the installation of the geo-membrane, some defects will occur. There is a considerable amount of data on the potential number and size of holes that can be expected for a competently supervised and quality assured geo-membrane installation. This is part of the
scope of work for the contractors. The number of defects was further reduced by undertaking a geo-physical leak detection survey after the geo-membrane had been installed.

The combination of slow pH reduction by pore flushing of the mud and dilution of the B.R.D.A effluent by direct surface run-off from the surface of the stack will result in the final pH of the effluent reducing to 9.0 or below within a period of five years, following closure of the B.R.D.A., in the absence of capillary effects. However, it should be noted that capillary rise effects could be significant in the fine-grained bauxite residue.

From the results generated from the trial plots the way to avoid capillary rise is the correct management of soda in residue, maximum soils concentration, adequate drainage by the addition of process sand, gypsum, and compost amelioration. All of these factors need to be right for the mixture of run-off (rainwater) and leachate to have a pH of 9.0 or less in 5 years.
4.6 Neutralisation of Bauxite Residue

Following the application by the company for an extension of 80 ha to the B.R.D.A. in 2007, the agency have requested the final 1.0 m layer of mud in the existing residue area be capped with neutralised or partially neutralised bauxite residue, that is residue with a pH of 9.0, or if partially neutralised a pH of 10.5 – 11.0. All final residue routed to Phase 2 extension is to be neutralised to pH of 9.0. The E.P.A. gave the company until 2012 to have a neutralisation system in place or before any residue is routed to Phase 2 extension section.

The action plan was to come up with the best option for the company regarding neutralisation considering the time factor, the Aughinish process, and cost. There was a facility in the process to dispose of spent acid to the B.R.D.A., but it had not been used for years. The writer set about the researching in conjunction with the University of Limerick into neutralisation methods.

Initial scope of the Aughinish plant highlighted the fact that Aughinish has facilities on-site and imports shiploads of sulphuric acid for heater cleaning, and use in the Waste Effluent Treatment Plants, so storage or pumping systems are items that would not be required should the company opt for acid neutralisation.

The residual alkalinity of the residue 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).

Bauxite residue as it exits the last washing stage in the process 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 proportions of neutralising or acidic materials required to neutralise 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 – the rate 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 - this rate 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.

Aughinish had disposed of “spent acid “, after heater cleaning, by pumping it to the B.R.D.A. with the residue but it was in small quantities and low flows. Aughinish Research and Engineering Department came up with a proposed injection system of acid into the slurry. The proposed method of injecting acid into the mud circuit system was reviewed by the team and highlighted some problems. Localised pockets of acid in the pipe work and pumps were a possibility and the acid would cause severe corrosion in the pipework, resulting in its failure. Pipework failure would be a safety issue and would possibly shut the plant down. To avoid corrosion, acid injection lines to each of the residue discharge points in the B.R.D.A. will be required. Extra controls and extra pipework will add significantly to costs.
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 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% H₂SO₄ per tonne of dry residue
- Volume of estuary water required to achieve neutralization of the soluble alkalinity is about 100 m³ per tonne of dry residue

The quantities required will be affected by the target pH. This section provides some background information on the sources of alkalinity associated with bauxite residue and issues associated with neutralization and leaching of this alkalinity. This 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.
4.6.1 Alkaline Compounds in Bauxite Residue

After the alumina-rich solution is removed, the un-dissolved 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) and
- 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$_2$)
  - Sodium carbonate (Na$_2$CO$_3$)
- calcium compounds (formed by addition of lime to the process). When lime, generally in the form of Calcium Hydroxide (Ca(OH)$_2$), 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 Aughnish)
  - TCA (Tri-calcium Aluminate)
  - Hydrogarnet
  - Lime
  - Calcium Oxalate and
  - Perovskite (CaTiO$_3$)

- Sodalite ((NaAlSiO$_4$)$_6$(Na$_2$X), where X can be SO$_4^{2-}$, CO$_3^{2-}$, Al(OH)$_4^-$, and some minor anions such as Cl$^-$).
All these compounds must be reacted with acid to neutralize the residue. The neutralization reactions of these compounds are discussed in the following sections.

### 4.6.2 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).

### 4.7 Residue Neutralisation

The residue management system in operation at Aughinish 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 Aughinish to achieve this outcome. These are:

- Seawater (or estuarine) neutralisation;
- Acid neutralisation;
- Carbonation
- Combined flue gas desulphurisation/seawater neutralisation
4.7.1 Seawater Neutralisation

As Aughinish 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 run-off from the entire River Shannon catchment and therefore could become seasonally diluted when compared to oceanic seawater.

In a seawater neutralisation system, residue is mixed with sufficient seawater to neutralise 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. Neutralisation using seawater can achieve a pH of 8.5 – 9.0. The reaction produces a hydrotalcite gelatinous precipitate that blends with the residue.

\[
\begin{align*}
\text{Mg}^{2+} + 2\text{OH}^- & \rightarrow \text{Mg(OH)}_2 \\
6\text{Mg}^{2+} + 8\text{NaOH} + 2\text{NaAl(OH)}_4 + \text{CO}_3^{2-} & \rightarrow \text{Mg}_6\text{Al}_2\text{CO}_3(\text{OH})_{16} \cdot 4\text{H}_2\text{O} + 10\text{Na}^+
\end{align*}
\]

The end point for the titration of Mg\(^{2+}\) with liquor occurs at a pH of approximately 10.5 and further 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 Mg\(^{2+}\).

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

Residue in this form can be discharged to the residue area and the neutralised liquor collected, clarified and discharged to a marine environment. Due to the residual alkalinity held in the residue solids from lime products and descilication products, unless sufficient magnesium and calcium are added, the pH of the residue can revert to pH 11.

This neutralisation and precipitation is effective at capturing some insoluble trace metals that are present in the Bayer circuit. The gelatinous precipitate can be easily remobilised and care must be exercised to ensure that sufficient time is provided to clarify the neutralised water prior to discharge.

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

Seawater Neutralisation Results at Aughinish

This research was carried in the Aughinish Laboratory. It was used as part of the information gathering required for the E.P.A.

Both the CaCl$_2$ and MgSO$_4$ were very soluble and they precipitated alkalinity from bauxite residue immediately and the pH remained stable. MgSO$_4$ was more effective than CaCl$_2$ with a pH reduction to approximately pH 8.5, compared with a pH reduction to approximately 10.5 using CaCl$_2$.

Due to the highly soluble nature of both CaCl$_2$ and MgSO$_4$, they were easily removed with washing and once they are no longer present in excess, they no longer suppress the solubility of the alkaline solid phases within the bauxite matrix and the pH of the system trends upwards.

Therefore, the sustainable pH achievable through addition of a soluble Ca$^{2+}$ or Mg$^{2+}$ source is likely to be approximately 10.5 at best. The only readily available source of soluble Mg$^{2+}$ is seawater; however, availability and the massive dilution associated with its application are factors against seawater neutralisation implementation at Aughinish. Pumping capacity is in the region of 14,200m$^3$/hr, which would require very large pumps and motors at very high cost.

Seawater neutralisation is considered Best Available Technology for some coastal Alumina refineries in Australia. In the past year the Gove Refinery in the Northern Territories has consolidated its seawater neutralisation system by addition of a clarifier on the return seawater to maintain a low suspended solids discharge.

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.
4.7.2 Acid Neutralisation

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

Acid neutralised residue can achieve a neutral pH, however, 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 well outside the range of acceptable environmental discharge criteria unless a large diluting flow is available to stabilise the process, acid neutralisation of residue solids is usually avoided.

Acid neutralisation is usually achieved using sulphuric acid rather than hydrochloric acid. This is usually entirely based on relative cost. The reactions are:

\[
\begin{align*}
2\text{NaOH} + \text{H}_2\text{SO}_4 & \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O} \\
2\text{NaAl(OH)}_4 + \text{H}_2\text{SO}_4 & \rightarrow \text{Na}_2\text{SO}_4 + \text{Al(OH)}_3 + 2\text{H}_2\text{O} \\
\text{Na}_2\text{CO}_3 + \text{H}_2\text{SO}_4 & \rightarrow \text{Na}_2\text{SO}_4 + \text{H}_2\text{O}
\end{align*}
\]

Where NaOH, NaAl(OH)$_4$ and Na$_2$CO$_3$ are the alkaline species in residue liquor solution, H$_2$SO$_4$ neutralisation results in a dilute Na$_2$SO$_4$ solution, which must be disposed of (probably by dilution with estuary water), and the residual dry mud will contain solid Na$_2$SO$_4$.10H$_2$O, which may also cause difficulties with re-vegetation. The residue will also contain CaSO$_4$.xH$_2$O (gypsum) an inert compound.

The liquor can be causticised

\[
\text{Na}_2\text{SO}_4 + \text{Ca(OH)}_2 \rightarrow 2\text{NaOH} + \text{CaSO}_4
\]

but only with dilute Na$_2$SO$_4$ solutions because of the solubility of CaSO$_4$.

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.
This technology is used by nearly all refineries as a means of safely disposing of spent acid, which is acid after acid cleaning digester heaters. The neutralising impact is usually minor due to the low strength of the acid and the alkalinity in the residue. Disposal is achieved by mixing spent acid in the final washer underflow. Aughinish did dispose of spent acid at one time in this manner, but later changed to the Waste Effluent Plant for effluent neutralisation.

Review following tests in Aughinish Laboratory

The pH of bauxite residue can potentially be reduced to any value through the application of a mineral acid such as sulphuric acid. However, the reaction of sulphuric acid (or calcium chloride) to neutralise only the solution alkalinity, resulting in a pH of approximately 10.5, poses a significant problem because of the ineffective mixing of neutralising reagent into the thick bauxite residue paste. Rapid intimate mixing is imperative as both concentrated sulphuric acid and concentrated calcium chloride are very corrosive.

As mineral acids are strong acids, in theory any equilibrium pH can be achieved, depending on the amount of acid added and the degree of solid phase dissolution. However, only neutralisation of soluble alkalinity is feasible kinetically, so an equilibrium pH of 11.0 dictated by TCA dissolution can be achieved.

Reflection on Acid Usage

Initially neutralisation employing sulphuric acid was considered the most feasible retrofit for residue neutralisation at Aughinish. Sulphuric acid is stored, used and disposed at the plant so the required infrastructure, storage and handling procedures are in place. However, the design of a suitable acid injection system to neutralise bauxite residue presented insurmountable engineering problems. This was discussed earlier in the author's investigation of the likely corrosion problems with the mud pumps and reactor systems. Another possible problem is the likelihood of the generation of H\textsubscript{2}S, which could lead to complaints, should the smell carry over the site boundary.

Prior to the start of the author’s research, the most ideal method of neutralisation would have been acid, but as difficulties and problems arose his option changed. The best method and possibly the only suitable neutralisation injection system into the residue slurry is for the injection to be added after the high-pressure pumps at each discharge point at the
B.R.D.A. This will add considerably to the cost and the pH control, but it would avoid causing any corrosion damage to equipment.

Final neutralisation of alkaline process waters is more widespread with the technology adopted by Aughinish, Ireland (Rusal), Alunorte, Brazil (CVRD/Norsk Hydro), and Vaudreuil, Canada (Alcan).

4.7.3 Carbonation

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

\[ \text{CO}_2 \text{ neutralisation has been investigated in detail by Alcoa World Alumina. The process consists of reacting NaHCO}_3 \text{ with the mud slurry and then regenerating Na}_2\text{CO}_3 \text{ using CO}_2 \text{ in “flue gas”}. \]

Alcoa claims that this process:

- allows flue gas to be used (previously only “pure” CO\(_2\) gas could be used)
- eliminates problems with scale formation that were a serious limitation when using “pure” CO\(_2\)

\[ \text{NaHCO}_3 + \text{“alkalinity in liquor and mud solids”} \rightarrow \text{Na}_2\text{CO}_3 \]

\[ \text{Na}_2\text{CO}_3 + \text{CO}_2 \rightarrow \text{NaHCO}_3 \]

This process is patented and a license to operate would be required. CO\(_2\) neutralisation has the advantages over seawater neutralisation, in that it may be possible to produce:

- relatively concentrated NaHCO\(_3\) solutions compared with seawater where Mg\(^{2+}\) is present at only about 1.4 g/L (0.12 Molar in “acid” i.e. double the Mg\(^{2+}\) 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.
Alcoa has provided some of the reasons for adopting this technology rather than some of the other options available. These include:

- ensuring that even though the residue is neutralised, it will remain “uncontaminated” from the perspective of enabling recycling to the refinery. Operations that experience a water deficit harvest rainfall collected from the residue management areas. By avoiding a neutralisation technology that is not based on sulphate or chloride materials ensures that the captured run-off 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.

- there is evidence that carbonated residue has a lower dusting potential when compared with other neutralised residues and un-neutralised residues. Where un-neutralised residue requires daily irrigation to suppress dusting, the carbonated residue did not require irrigation for four months during the summer period.

- discharge of water streams into the local marine environment has been avoided due to political and environmental concerns of discharge into Cockburn Sound (less than 25 kilometres from Perth, pop. 1,100,000). Carbonation avoids these issues and also provides a means of capturing carbon dioxide discharges that would otherwise escape into the atmosphere. Early research indicates that up to 95% of the injected carbon dioxide remains with the residue.

- there is evidence of a volume increase in the residue after neutralisation 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 un-neutralised residue. As the increased volume increases, the area requirements this approach is not viewed as being the best available.

Review at Aughinish Laboratory
For carbonation of only the liquid phase alkalinity within the bauxite residue, the slow mass transfer of reactants within the bauxite residue slurry presents a major obstacle, such that it is not likely that the volume of bauxite residue produced could be treated within a reasonable operating time.

This appears to be due primarily to the inherently high viscosity of Aughinish bauxite residue, which is on average 60 wt% solids. The solids concentration at Alcoa Kwinana, where bauxite residue carbonation is carried out, is significantly lower at an average value of 48 wt%.

In-situ atmospheric carbonation via mud farming is by far the least invasive method to neutralise bauxite residue; however, the pH reduction measured thus far has been less than desirable, reflecting a pH reduction from approximately 12.5 to 12.0.

Mud farming is also limited by mass transfer, where the effectiveness seems limited by the rate at which the reactant (atmospheric carbon dioxide) can be incorporated into the bauxite residue material.

While carbonation does not add an ion impurity to the process, any liquor return would be too high in carbonate to be incorporated into the process liquor.

Further pH reduction may potentially be achieved through optimisation of the mud farming operation, which may include ploughing during mud farming to expose a greater surface area of the bauxite residue paste.

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 and not to gain commercial advantage.

4.7.4 Combined Flue Gas Desulphurisation/Seawater Neutralisation

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.

Aughinish reviewed the use of the Sumitomo process as a means of managing air emissions; however, an alternate 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.

This technology is used by Eurallumina, Italy (Rusal).

### 4.7.5 Combination Water Management Systems

In some situations the full neutralisation is not possible, but neutralisation 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 to the environment excess water from the process. Invariably, discharge can only occur after the excess waters have been neutralised.

- **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 a seawater or acid neutralisation and is used by Aughinish, Ireland (Rusal), Alunorte (CVRD/Norsk Hydro), Brazil, and Gove, Australia (Alcan).

### 4.8 Feasibility of Neutralising Aughinish Bauxite Residue

The only readily available source of soluble Mg$^{2+}$ is seawater, which adds significant dilution of the bauxite residue slurry on treatment. For example, the volume of seawater added during bauxite residue neutralisation is up to 20 times the volume of the bauxite residue. Following this, significant capital expenditure would be required for an additional bauxite residue thickening process, assuming that the treated bauxite residue is amenable to re-thickening, to enable the bauxite residue to be dry stacked to the B.R.D.A.
Other than the costs implications, there are others factors against seawater neutralisation implementation at Aughinish. While the location of Aughinish on the Shannon estuary lends itself to the possibility of using the brackish water of the estuary to neutralise red mud, the concentration of magnesium and calcium ions required for neutralisation in the estuarine water is far lower compared with seawater. This would mean that excessive volumes would need to be extracted from the Shannon for neutralisation.

For the sulphuric acid-treated bauxite residue, there is a fast initial reaction between acid and solution alkalinity resulting in a low initial pH. However, this is followed by a slower pH rebound behaviour to an equilibrium pH that takes several days to achieve and is attributed to the more sluggish reactivity of the acid with the solid components of the bauxite residue.

At up to 2 wt% dosage of sulphuric acid, only solution species react within the treated bauxite residue (equilibrium pH around 10.5). The buffering from 2 to 3 wt% dose (pH 10 to 9) and from 4 and 5 wt% dose (pH 8 - 7) is attributed to calcium mineral dissolution and sodalite dissolution, respectively. With calcium mineral (solid alkalinity) dissolution, there is additional solution carbonate removal by precipitation, suggesting that the acid facilitates the dissolution of calcium mineral, such as TCA, and the subsequent transformation to calcite and aluminium hydroxide.

Therefore, for acid treated bauxite residue, the equilibrium pH is around 10.5 when there is solution alkalinity removal only. When the solid phase alkalinity is removed an equilibrium pH around 8 is achieved. If the solid phase alkalinity is removed (i.e. equilibrium pH ~ 8), there is little change is the leachate quality with successive leaching, and presents a method to potentially achieve a sustainable low pH. However, the kinetics of the reaction of acid with the solid phase alkalinity is very slow and at present does not seems achievable within a reasonable time scale of bauxite residue treatment within the refinery.

In fact, the reaction of sulphuric acid (or calcium chloride) to neutralise only the solution alkalinity, resulting in a pH of approximately 10.5, poses a significant problem because of the ineffective mixing of neutralising reagent into the thick bauxite residue paste. Specifically, both concentrated sulphuric acid and concentrated calcium chloride are very corrosive, hence rapid intimate mixing is imperative. A computational fluid dynamics study of the mixing of concentrated sulphuric acid and AAL bauxite residue within reactors that could be integrated into a pipe system was investigated at the University of Limerick. Numerous geometries were examined, however, none were able to effectively mix the acid and bauxite residue slurry (Ries and McMonagle, 2009).
4.8.1 Acid Neutralisation

Based on the limited experimental data obtained so far, the following conclusions can be drawn. The volume of 98% Sulphuric Acid (H\textsubscript{2}SO\textsubscript{4}) approximately required:

- to achieve full neutralisation 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
- to achieve neutralisation 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
- these values are based on neutralising the residue to a pH of 9.0.

However, due to reaction times often measured in weeks, achieving full neutralisation 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, and 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.

Due to the large volume of sulphur compounds being introduced into the residue, there remains a risk of H\textsubscript{2}S if the final pH remains too low. Thermodynamic calculations of the equilibrium H\textsubscript{2}S concentration versus pH and the solution sulphide concentration show that a pH of 10.3 should be sufficiently high to suppress the H\textsubscript{2}S concentration to below the Threshold Limit Value (TLV) of 10 ppm (there is still a strong odour at 10 ppm) by the following reaction:

H\textsubscript{2}S + NaOH \rightarrow NaHS

At pH 10.3 the reaction is about 99% to the right. Consequently, there is little or no smell because the concentration of H\textsubscript{2}S is very low. However, the quantity of H\textsubscript{2}S present also
depends on the total Sulphide concentration (the higher this is the more H₂S there is at the same pH). Therefore, under a neutralisation 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 H₂S generation.

H₂S 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 H₂SO₄ neutralisation system will need to include the stability of the final pH and whether additional H₂S controlling agents are included to ensure control.

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

A sustainable sulphuric acid neutralisation program would require the neutralisation of the soluble alkalinity resulting in a final residue pH of approximately 10.5. Further neutralisation will consume very large quantities of acid at high cost and create conditions that would lead to H₂S generation and odour-related issues.

### 4.8.2 Seawater Neutralisation

The volume of estuary water approximately required:

- To achieve full neutralisation of all alkaline products is up to 100 m³ per tonne of dry residue.
- At 1.95 Mtpa alumina production rates this is equivalent to 124,800,000 tonnes of Shannon River water annually (this equates to approximately 14,250 m³/hr of river water intake and discharge).

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

Purely based on the practicality of pumping this large volume of water, achieving clarification and safe discharge this option is unlikely to be considered further.
4.8.3 Carbonation

Neutralisation of bauxite residue using carbon dioxide has been investigated by Alcoa World Alumina and a patent obtained on its application. The process consists of reacting Sodium bicarbonate \((\text{NaHCO}_3)\) with the residue slurry and then regenerating \text{NaHCO}_3 from the \text{Na}_2\text{CO}_3 formed using \text{CO}_2 in "flue gas". This is significant as the only readily available \text{CO}_2 source would be from the Aughinish boiler flue gases.

Benefits of using this technology, when compared to application of either acid or seawater neutralisation includes:

- No contamination of the residue with either potential process contaminates (chloride or sulphate) or potentially \text{H}_2\text{S} generating materials (sulphate);
- Additional benefit of capturing carbon dioxide emissions that would otherwise escape;
- Minimal generation of secondary products (hydrotalcite) that increase the residue volume and hence area requirements;
- The possibility to produce relatively concentrated \text{NaHCO}_3 solutions compared with seawater where \text{Mg}^{2+} 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 \text{Mg}^{2+} 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 \text{pH} than with seawater.

Due to the patent application, detailed data is not available; however, there is evidence that all of the soluble alkalinity and at least some of the solid alkalinity is neutralised. It is unlikely that all of the alkalinity is neutralised since the publicly stated target for carbonation neutralisation is to achieve a residue with a \text{pH} of less than 10.5.
4.8.4 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$_2$ is probably preferred because the neutral compound NaHCO$_3$ is produced.

H$_2$SO$_4$ neutralization produces Na$_2$SO$_4$ and seawater neutralization produces a diluted solution of seawater from which the Mg$^{2+}$ has been reduced in concentration. Such solutions require significant dilution with estuary “water” to minimise their environmental impact.

4.8.5 Seawater Neutralization

Residual liquor from seawater neutralization is effectively seawater with the majority of the Mg$^{2+}$ 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 re-vegetation of this material is problematic, over time the salinity of the residue will decrease due to leaching by rainfall.

Table 22 Residue to B.R.D.A. Acid Neutralisation

<table>
<thead>
<tr>
<th>Target pH</th>
<th>Vol. of H$_2$SO$_4$ mls.</th>
<th>Temp 0.C</th>
<th>pH Day0</th>
<th>pH Day1</th>
<th>pH Day2</th>
<th>pH Day3</th>
<th>pH Day4</th>
<th>pH Day7</th>
<th>Kg/t dry solid</th>
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<tr>
<td>Untreated Mud</td>
<td>0</td>
<td>18.4</td>
<td>13.4</td>
<td>13.3</td>
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</tr>
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<td>25.6</td>
<td>10.0</td>
<td>10.7</td>
<td>10.9</td>
<td>10.9</td>
<td>11.0</td>
<td>11.1</td>
<td>22.7</td>
</tr>
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<td>16</td>
<td>26.4</td>
<td>9.0</td>
<td>10.0</td>
<td>10.3</td>
<td>10.3</td>
<td>10.3</td>
<td>10.3</td>
<td>25.5</td>
</tr>
<tr>
<td>8</td>
<td>18.2</td>
<td>26.8</td>
<td>8.0</td>
<td>9.3</td>
<td>9.5</td>
<td>9.4</td>
<td>9.5</td>
<td>9.6</td>
<td>29.1</td>
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<tr>
<td>7</td>
<td>20.3</td>
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<td>7.0</td>
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<td>8.7</td>
<td>8.9</td>
<td>8.9</td>
<td>32.4</td>
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<tr>
<td>6</td>
<td>23.6</td>
<td>27.7</td>
<td>6.1</td>
<td>7.8</td>
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<td>8</td>
<td>8.2</td>
<td>8.4</td>
<td>37.7</td>
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Table 23 Residue with Liquor Removed

<table>
<thead>
<tr>
<th>Target pH</th>
<th>Vol. of H$_2$SO$_4$ mls.</th>
<th>pH Day0</th>
<th>pH Day1</th>
<th>pH Day5</th>
<th>pH Day6</th>
<th>pH Day7</th>
<th>pH Day8</th>
<th>Kg/t dry solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>0</td>
<td>12.2</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>10.0</td>
<td>11.3</td>
<td>11.5</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
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<tr>
<td>9</td>
<td>1</td>
<td>9.0</td>
<td>11.0</td>
<td>11.0</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>6.4</td>
</tr>
<tr>
<td>8</td>
<td>1.4</td>
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<td>10.1</td>
<td>10.1</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
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<td>7</td>
<td>1.75</td>
<td>7.0</td>
<td>9.2</td>
<td>9.2</td>
<td>n/s</td>
<td>n/s</td>
<td>n/s</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Table 24 Shannon Estuary Water Neutralisation

<table>
<thead>
<tr>
<th>Estuary Water Neutralisation</th>
<th>cubic meters of water per tonne of dry solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>200grams mud slurry</td>
<td></td>
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<tr>
<td>Volume of water pH</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>10.04</td>
</tr>
<tr>
<td>50 grams mud slurry</td>
<td></td>
</tr>
<tr>
<td>Volume of water L pH</td>
<td></td>
</tr>
<tr>
<td>0.625</td>
<td>10.03</td>
</tr>
<tr>
<td>1</td>
<td>9.5</td>
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<tr>
<td>2</td>
<td>9.3</td>
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<td>3</td>
<td>9.1</td>
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<td>4</td>
<td>9.05</td>
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<td>9</td>
<td>8.87</td>
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<tr>
<td>10</td>
<td>8.85</td>
</tr>
<tr>
<td></td>
<td>117.6</td>
</tr>
</tbody>
</table>
4.8.6 **CO₂ Neutralization (Resultant Liquor)**

Bauxite residue neutralization using CO₂ is probably the method of choice when disposal of the resultant liquor is considered.

Neutralization with CO₂ results in a liquor containing NaHCO₃. It is possible to causticise this liquor and this appears to be the strategy adopted by Alcoa (7th Alumina Quality Workshop p 218).

\[
\text{Ca(OH)}_2 + \text{NaHCO}_3 \rightarrow \text{NaOH} + \text{CaCO}_3
\]

This allows the liquor to be recycled as process water. This approach, however, requires lime and lime is produced by calcining limestone.

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

Under these circumstances at least some of the environmental value of using CO₂ is negated.

4.8.7 **H₂SO₄ Neutralization (Liquor)**

H₂SO₄ neutralization results in a dilute Na₂SO₄ solution, which must be disposed of probably by dilution with estuary water. The residual dry residue will contain solid Na₂SO₄.10H₂O (i.e. it will have a high ionic strength), which may also cause difficulties with re-vegetation. The residue will also contain a small quantity of CaSO₄.2H₂O (gypsum), an inert compound.

4.8.8 **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 of the residue: extraction of residual soluble alkalinity from the liquid contained in the pores of the residue, and 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, thus liberating hydroxide.

The TCA reaction can be summarised as:

\[
Ca_3Al_2(OH)_{12} + H_2O \rightarrow Ca^{2+} + OH^- + Al(OH)_3(\text{amorphous})
\]

This reaction gives pH ~ 10.5, but is very slow to reach equilibrium and the OH\(^-\) 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:

\[
Ca_3Al_2(SiO_4)_n(OH)_{12-4n} + H_2O \rightarrow Ca^{2+} + OH^- + Al(OH)_3(nSiO_2) \text{ (a non-crystalline solid)}
\]

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 bauxite residue 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, i.e. neutralization of the liquid phase, is realistic and the pH will drift up towards 10.5 over time as the solid phase alkalinity reacts. 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).
4.8.9 Neutralization of Aughinish Process Sand

Sand is the coarse fraction of the bauxite residue. The recommended method for the neutralization of this material is process washing more than it gets at present. It is used as dam wall construction material.

It is expected that sand will contain less solid alkalinity than residue. Data shows that sand has around 72% Fe₂O₃ compared with 43% for residue. Sand may contain little Hydrogarnet or Sodalite and therefore only needs to be washed. Although some washing does take place, it could reduce caustic losses by increasing the washing stages.

4.8.10 Analysis of Aughinish Bauxite Residue Neutralization Data

The preliminary data obtained during experiments at Aughinish (undertaken in February 2007) provides a good starting point for estimating the cost of H₂SO₄ neutralization of their bauxite residue.

The following is an analysis of the preliminary experimentation undertaken at Aughinish to assess the issues associated with bauxite residue neutralization.

4.8.11 Empirical Volume of H₂SO₄ Required to Neutralize the Liquor

The data provided shows that:

Liquor total soda is 25.3 g/l Na₂O this is 25.3*2/62 = 0.816 Molar in NaOH plus Na₂CO₃.

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*0.816 = 571 Moles of Caustic

100 grams of 98% H₂SO₄ contains 2*100*(98%)/98 = 2 Moles H⁺ (approx) (98 is molecular weight of H₂SO₄), therefore 50 grams contains 1 Mole, therefore 50/1.84 = 27.17 ml H₂SO₄ per Mole H⁺.

The 700 Litres of liquor associated with 1 Tonne of residue contains 700*0.816 = 571 Moles Caustic. Therefore the:
• **Volume H₂SO₄** required to neutralize the liquor is \(27.17 \times 571/1000 = 15.5 \text{ Litres}\)

• Mass H₂SO₄ required to neutralize the liquor is = 15.5\(\times 1.84 = 28.5\) Kg of H₂SO₄ per tonne of residue

The titration data is plotted below in Figure 70.

28.5 Kg of H₂SO₄ per tonne of residue gives a final pH of about 10.5 and a further 9 Kg of H₂SO₄ per tonne of residue is needed to neutralize the residue to pH 8.5.

### 4.8.12 Empirical Volume of H₂SO₄ Required to Neutralize Calcium Compounds and Sodalite

1 tonne of residue contains approximately 58 Kg of Calcium (as CaO), assuming that all the Ca is alkaline (conceptually Ca(OH)₂) we have \(2 \times 58000/56 = 2071\) Moles OH.

Therefore (as 27.17 ml H₂SO₄ contains 1 Mole H⁺), we would require \(2071 \times 27.17 = 56269\) ml H₂SO₄.

• \(56269 \times 1.84/1000 = 104\) Kg H₂SO₄ per Tonne of residue to react with all the Ca compounds.

One Tonne of residue contains say 57 Kg of Sodium (as Na₂O).

An empirical formula of \((\text{NaAlSiO}_4)_{6}(\text{Na}_2\text{X})\) and assuming all the Na₂X is alkaline \((\text{CO}_3^{2-}\) and Al(OH)₄⁻).

The maximum alkaline Na is \((2/[(6+2)]\times 57000/62\times 2 = 460\) Moles of OH⁻

• Requiring \(613 \times 27.17 = 12491\) ml H₂SO₄. \(12491 \times 1.84/1000 = 23.0\) Kg H₂SO₄ per Tonne of residue to react with all the alkaline Na, giving a total maximum of 127 Kg per tonne of H₂SO₄.

Assuming that 28.5 Kg per tonne of H₂SO₄ is required to neutralize the liquor, very little of the Calcium compounds or the Sodalite appear to be reacting with the H₂SO₄ under the conditions used.
If 11.2 Kg per tonne (as taken from Aughinish laboratory experiments) of H$_2$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 un-neutralized.

In cases where almost all the CaO used is added to digestion, the portion of the CaO converted to Hydrogarnet in digestion gives a very slow-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 H$_2$SO$_4$ titration. The only cautionary note is that it may take longer than one week for the pH to stabilise.

![Titration Curves for residue + H$_2$SO$_4$.](image)

Figure 73 Titration Curves for residue + H$_2$SO$_4$

It is thought that the reactive 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 H$_2$SO$_4$ consumption can be predicted for future changes in lime addition and bauxite quality for any residue-liquor total soda.
4.8.13 Experimental Volume of H₂SO₄ Required to Neutralize the Residue Solids

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 H₂SO₄ required to neutralize the liquor only.

In Figure 70 the data for the residue slurry titration has been included (Day 7 pH) versus quantity of H₂SO₄ and a curve for the washed residue slurry plus 18 Kg/tonne H₂SO₄. This data suggests that about 18 Kg/tonne H₂SO₄ is required to neutralize the liquor (because the two curves are approximately aligned), not the calculated 28.5 Kg/tonne.

Figure 71 shows that the quantity of H₂SO₄ 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 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.

Such differences can be typical of the first time such experiments are conducted and are likely to improve through further work.

Figure 74 Neutralization of Residue Slurries with and without liquor
It is recommended that liquor be separated from the residue slurry and titrated with \( \text{H}_2\text{SO}_4 \). 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.

Between 18 and 28.5 Kg H\(_2\)SO\(_4\) per tonne dry residue is required to neutralize the liquor. The residue pH is about 12.2. 11.2 Kg H\(_2\)SO\(_4\) per tonne dry residue is required to neutralize the residue solids to pH 9.4.

### 4.8.14 Reflection on Neutralising Bauxite Residue

There is a concern that when adding H\(_2\)SO\(_4\) during the dilution and re-dispersion of the residue filter-cakes, there may be localised corrosion. This could cause equipment failure and shutdown of the plant. The agitation must be sufficient to prevent localised regions of low pH.

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 Al\(^{3+}\) and Si(OH)\(_4\) will re-precipitate and gel respectively, causing high viscosity residue. This will cause pumping problems to the B.R.D.A. and possible vegetation growth problems on the residue.

It is likely from the research that the safety method of acid neutralisation would be to add the acid at the points of discharge in the B.R.D.A. This will mean installation of multi-dosing points and pumping the acid to the distribution points. Handling and pH control could become more difficult.

Other concerns include the rate of the neutralization reaction with the residue solids. In all cases where some neutralization of the solids has occurred, the pH is higher after one day (although it probably takes less than 24 hours to reach equilibrium at the higher pHs). The control of the final pH will be difficult under these conditions.

Concerns of possible re-vegetation problems given the formation of gel in the slurry.

Carbonation would require Aughinish to operate the final residue slurry density lower and closer to Alcoa. This would be against best practice and would take up extra space in the B.R.D.A., thereby reducing its life span.

Seawater is far too costly and not energy-efficient.
4.8.14.1 Management of Hydrogen Sulphide (H₂S)

There is a concern the generation of H₂S will occur in the residue area if the pH is too low (after neutralization). Odour problems would lead to complaints to the company and to the E.P.A. from local residents. While this is an important issue, it is difficult to resolve. Refineries that use seawater can have an issue with H₂S. 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 H₂SO₄ is an unavoidable factor resulting in the presence of this “nutrient”.

4.8.15 Cost

Currently, it is estimated that acid would cost in the region of 4m Euros per annum to purchase. Aughinish have the storage facilities but do not have the dosing arrangement Carbonation would cost 26m Euros to build storage and reactors, plus the cost of trucking liquid CO₂ from the U.K. daily, which is estimated at 4m Euros.

Conclusions

Carbonation

While it would be easier to neutralise low viscosity 40% solids filter feed than the highly viscous 60% solids (Aughinish slurry) filter cake discharge, this is not feasible for two reasons:

1. The vacuum drum filters are very efficient caustic recovery units. They recover typically 85% of the soluble caustic in the filter feed through a combination of efficient washing of the thin filter cake followed by efficient de-liquoring of the thoroughly washed cake. Caustic losses with the filter cake would increase dramatically from 6 kg/tonne alumina to almost 40 kg/tonne alumina if the caustic associated with the residue were neutralised prior to vacuum filtration. The extra 34 kg/tonne caustic losses would add $10 million per annum operating costs.

2. Vacuum filters require the residue being filtered not to scale or blind the fine mesh filter cloth. The scaling reactions accompanying neutralisation would make vacuum
filtration post-neutralisation unworkable. Re-thickening would thus be limited to
gravity thickeners and would not deliver the 60% solids condition required for dry
disposal at Aughinish.

For these reasons if bauxite residue is be neutralised, then the neutralisation stage must be
applied after vacuum filtration. Furthermore, the neutralisation process must not compromise
disposal of high yield stress residue at typically 60% solids.

Even if the CO$_2$ injection system could be designed to avoid excessive shear and
dilution in the reactors, there are other serious concerns. CO$_2$ neutralisation reactions result in
the precipitation of aluminates as solid aluminium hydroxide and dawsonite. Calcium that is
solubilised during the neutralisation will also re-precipitate as solid calcium carbonate. Any
DSP solubilised would re-precipitate as a sticky silica gel.

• It would reduce the consistency of bauxite residue being deposited, which would
undermine the B.R.D.A. structural integrity and increase the potential for seepage
to groundwater. This is the key consideration.

• It would reduce the ultimate residue storage capacity by an estimated 6% by
reducing the terminal in-situ density by 2% according to Alcoa.

• It would undermine the operability of the alumina plant through scaling and
blockage of the 3.5 km-long high-pressure residue transfer pipeline.

• It would cost €25.9 million to install and €4 million per year to operate for very
little pH benefit, despite undermining B.R.D.A. dry disposal integrity.

For the above reasons it cannot be classified as BAT for the Aughinish B.R.D.A.

Acid Neutralisation
It has been found that the alkalinity within the solution phase reacts relatively quickly in
comparison to the solid phase alkalinity, such that a relatively low pH may be recorded
immediately after acid addition. However, the subsequent reactions with the solid phase
alkalinity results in a slow pH rebound behaviour. The time taken to achieve a pH
equilibrium value will depend on the amount of acid added and the degree of dissolution of
solid phase alkalinity. For example, Khaitan et al. (2009) found that the equilibrium reaction
of bauxite residue with acid to a pH of 8 took approximately 50 days.
Therefore the stability of the pH measured from mineral acid addition to bauxite residue slurry is a complex interplay between the reaction of solution and solid species, with the kinetic effect being strongly dependent on the identity and reactivity of the solid phases present in the bauxite residue. Hence, as mineral acids are strong acids, in theory any equilibrium pH can be achieved depending on the amount of acid added and the degree of solid phase dissolution. However, only neutralisation of soluble alkalinity is feasible kinetically, so an equilibrium pH of 11.0 dictated by TCA dissolution can be achieved. Initially neutralisation that employs sulphuric acid was considered the most feasible retrofit for residue neutralisation at Aughinish. Sulphuric acid is stored, used and disposed at the plant so the required infrastructure, storage and handling procedures are in place. However the design of a suitable acid injection system to neutralise bauxite residue presented insurmountable engineering problems.

Another important factor to take into account with pH reduction, is the quality of the leachate and the implication this has to the refinery and ultimately to the environment. For the neutralisation of bauxite residue using sulphuric acid, a calcium or a magnesium source, all their leachates give the same relationship between \([\text{OH}^-]\) and alkalinity. In the context of the refinery, using one of these treatments to neutralise bauxite residue to pH 10, gives a leachate solution alkalinity reduction to < 1 % of the alkalinity in the untreated bauxite residue sample. For the expressed leachate collected from the B.R.D.A. this represents a significant reduction in the load on the effluent system, in comparison to bauxite residue that has not been treated at all.

In contrast, for CO\(_2\) treated bauxite residue to pH 10, the alkalinity of the final carbonated solution is equivalent to more than half (~ 57 %) the alkalinity of the liquid phase of the untreated bauxite residue sample, offering a significantly smaller benefit to the load on the effluent system.

For the neutralisation of bauxite residue using sulphuric acid, a calcium or a magnesium source, the relationship between pH and the solution aluminium concentration demonstrates two clear trends. One trend includes samples treated with calcium or magnesium sources, while the other trend is for samples treated with sulphuric acid. The acid-treated samples give a higher solution aluminium concentration as a function of pH than the calcium or magnesium-treated samples.

For all of the neutralisation methods, an aspect of the pH reduction is the formation of a precipitate. For ‘in-process’ methods, this presents a very real and potentially significant
scaling issue. If the scaling cannot be contained within a specific reaction vessel, or delayed until out in the B.R.D.A., then there is potential that the pipeline carrying the bauxite residue to the B.R.D.A. may become blocked.

Generally, the precipitates formed during neutralisation reactions are thought to be relatively gelatinous and cause cementation. This will likely present an issue to bauxite residue dewatering and compaction.

4.9 Bauxite residue farming using multiple Amphirols

The process of mud farming which recently commenced at Aughinish achieves the two objectives of dewatering via compaction and neutralisation via carbonation. The faster the residue is dewatered, the greater the impact of atmospheric CO$_2$ on residual caustic. The company proposes to invest in additional Amphirols and evaluate mud farming performance that employs these Amphirols in the extended B.R.D.A. The indications are that it will be necessary to plough each layer of residue up to 15 times to achieve a pH consistently below 12 and with the potential to achieve 11.5. This rate of ploughing will present a logistical challenge and significant resources will be allocated to this aspect.

Both the CaCl$_2$ and MgSO$_4$ were very soluble and they precipitate alkalinity from bauxite residue immediately and the pH remained stable. MgSO$_4$ was more effective than CaCl$_2$ with a pH reduction to approximately pH 8.5, compared with a pH reduction to approximately 10.5 using CaCl$_2$. Due to the highly soluble nature of both CaCl$_2$ and MgSO$_4$, they are easily removed with washing and once they are no longer present in excess, they no longer suppress the solubility of the alkaline solid phases within the bauxite matrix and the pH of the system trends upwards. Therefore, the sustainable pH achievable through addition of a soluble Ca$^{2+}$ or Mg$^{2+}$ source is likely to be approximately 10.5 at best. The only readily available source of soluble Mg$^{2+}$ is seawater; however, availability and the massive dilution associated with it application are factors against seawater neutralisation implementation at Aughinish.

The pH of bauxite residue can potentially be reduced to any value through the application of a mineral acid such as sulphuric acid. However, the reaction of sulphuric acid (or calcium chloride) to neutralise only the solution alkalinity, which results in a pH of
approximately 10.5, poses a significant problem because of the ineffective mixing of neutralising reagent into the thick bauxite residue paste. Rapid intimate mixing is imperative, as both concentrated sulphuric acid and concentrated calcium chloride are very corrosive and could cause corrosion damage to pipework and the high-pressure pumping systems.

Similarly, for carbonation of only the liquid phase alkalinity within the bauxite residue, the slow mass transfer of reactants within the bauxite residue slurry presents a major obstacle, such that it is not likely that the volume of bauxite residue produced could be treated within a reasonable operating time. This appears to be due primarily to the inherently high viscosity of the AAL bauxite residue, which is on average 60 wt% solids. The solids concentration at Alcoa Kwinana, where bauxite residue carbonation is carried out, is significantly lower at an average value of 48 wt%.

In-situ atmospheric carbonation via mud farming is by far the least invasive method to neutralise bauxite residue; however, the pH reduction measured thus far has been less than desirable, reflecting a pH reduction from approximately 12.5 to 12.0. Mud farming is also limited by mass transfer, where the effectiveness seems limited by the rate at which the reactant (atmospheric carbon dioxide) can be incorporated into the bauxite residue material. Further pH reduction may potentially be achieved through optimisation of the mud farming operation, which may include ploughing during mud farming to expose a greater surface area of the bauxite residue paste.

If the mass transfer limitation for acid and carbon dioxide treated bauxite residue can be overcome, then an equilibrium pH around 10.5 will be achieved. However, further pH reduction is unlikely as this requires removal of the solid phase alkalinity, and the kinetics of the reaction with the solid phase alkalinity is so slow that it does not seem that it could be achieved within a reasonable time scale of bauxite residue treatment within the refinery.

General Reflection on all activities
The small and large plot trials culminated in excellent results in terms of deciding the ideal “recipe” for vegetation and this could be used in a closure scenario immediately. Large machinery can be used about twelve months after deposition of the residue. The groundwater flow modelling and seepage rates surveys gave the projected ratio of 400:1 for run-off / leachate in order to achieve a pH of 9.0. However, the eighteen months sampling from the one-tonne containers, the experience of the Burntisland plant in Scotland and the leachate
sampling from under the Demonstration Cell would indicate a much longer period would be required for the pH to drop to 9.0.

The author’s knowledge and skill improved such that, should the necessity arise for a section of the B.R.D.A. to be closed, the competence and skills have been achieved to complete the task to the satisfaction of the company, the E.P.A. and the local authorities.

The Demonstration Cells were constructed within the B.R.D.A. They are safe and accessible. The residue has vegetation sown and the sampling is in progress of run-off and leachate.

The author’s communication and organisational skills have shown that it was possible to complete all tasks and pull all the strings with this project with many different people involved. There was the team, the company management team, the process staff on the plant, and the laboratory staff who have all learned along the way.

The author has learned from tests carried out in Aughinish laboratories and researched the problems with neutralisation methods. It is now known what is suitable or not suitable for Aughinish.
Chapter 5 Research Findings
Introduction

This section looks at the following findings from this research:

- what re-uses are available for bauxite residue and thus reduce/eliminate the need to store the residue, as well as the trial work carried out in Aughinish over the past number of years on residue rehabilitation;
- review other alumina plant rehabilitation methods;
- bauxite residue disposal options;
- re-vegetation of the residue;
- Demonstration Cells construction and the monitoring of pH values of run-off and leachate;
- options for neutralisation or part neutralisation;
- the predictions for pH reductions over what periods;
- trial plots review;
- visit to a closed alumina refinery in Scotland;
- devise and recommend a closure technique for the B.R.D.A.

5.1 Commercial Bauxite Residue Re-Use

5.1.1 Virotec International Limited (Virotec)

This section looked at possible re-uses for Aughinish residue and companies who are researching such uses.

Virotec International is an Australian-based environmental management company with 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.
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 provides a flocculating agent to suspended colloidal material. It can be used in wastewater treatment plants to settle solids, also used for the absorption of heavy metals in contaminated soils. 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.

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 unnamed alumina operation in North America for 100,000 tonnes.

Information is provided at www.virotec.com

5.1.2 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 and metals, and allow bacterial decomposition of liquid effluent overflowing from septic tanks 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. Over 1,000 Ecomax units have been constructed around Australia with an intention to promote the technology around the world.

Information from www.ecomax.com.au

5.1.3 Bauxite Residue 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 RUSAL Aughnish 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 B.R.D.A. 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.

### 5.2 Alternate 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 neutralised, partially neutralised or un-neutralised 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$_2$ from discrete industrial sources or from the capture of CO$_2$ from flue gases at alumina refineries.

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 vast 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 – re-use 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 (Cooling, et al., 2004).

• Harvesting of alkaline bauxite residue for use in treating or creating a buffering filter for the treatment of acid mine drainage. One closed copper mine on the east coast of Ireland is presently conducting trials to increase pH levels of seepage into the Avoca River. When the residue is neutralised, wash and utilise in the cement or construction industry. Information from Environmental Section, Wicklow Co. Council.
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.

### 5.2.1 Alternative Uses for Neutralised Aughinish Process Sand

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

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” under the Waste Management Acts 1996 – 2003.

At the B.R.D.A. the sand is utilized as a construction material to separate the bauxite residue activities from the dedicated salt cake disposal area.

#### 5.2.1.1 Alternative Uses

Before any modification of the process sand occurs, it is important to consider the intended end-use opportunities. Before an alternative use programme can commence the need for the process sand at the B.R.D.A. needs to be assessed, otherwise the re-use of the sand externally to the B.R.D.A. will only force replacement with an externally derived product, thus negating any sustainability benefits. Given that the sand is being used to separate disposal areas, a use that is not dependent on any specific quality of the process sand, it is reasonable to assume that fine bauxite residue can be used instead. Re-handling of dewatered bauxite residue for this type of duty can be achieved with low-ground pressure earth-moving equipment and the practice is common in other alumina operations and is not considered a significant issue.

Other than use as an “internal” construction material at a B.R.D.A., 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 neutralisation 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 E.P.A requirements to permit the process sand to be classified as an inert landfill.

• It could replace natural sand as fine aggregate in concrete with little impact upon strength.
• It creates a concrete that meets leachate requirements.
• It 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 sand 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 neutralisation. 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 Aughinish to identify a suitable alternative use could be undertaken.

5.2.1.2 Neutralisation of Sand

Bauxite residue data from Aughinish shows that sand has around 72% Fe₂O₃ 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 B.R.D.A. Extra washing would also recover more caustic from the sand and would provide extra savings. However, if neutralisation were needed, it would also be suggested that minimal neutralising effort would be required.

5.3 Industry Residue Disposal Systems

5.3.1 Main Findings

There are many different designs applied to bauxite residue operations and the findings to follow look at suitable options for Aughinish. These include:

- marine disposal;
- wet or low-density disposal;
- dry stacking – high compression thickeners; and
- dry stacking – filter technology.

Within each disposal system, variations in the residue chemistry apply. The major types are:

- washed alkaline systems;
- seawater neutralisation;
- acid neutralisation;
- carbonation;
- combined flue gas desulphurisation/seawater; and
- combination water management systems.

5.3.2 Alternative Residue Management Practices

The alumina industry has existed commercially since 1893 when the first refiner 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 the techniques that have been 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.

### 5.3.3 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. Bauxite residue is slightly toxic to all marine organisms to a greater or less degree. The toxicity is greatly dependent on the bauxite origin.

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 (26th 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 meeting 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, i.e. Alumina de Greece 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.

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

### 5.3.4 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 geo-technical strength of the underground structures. It is not employed in the alumina industry because

- Bauxite for RUSAL Aughinish 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 landfill
- 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 RUSAL Aughinish ’s case) would be prohibitive. For instance, the incremental costs to do this at RUSAL Aughinish would be:

- A port extension and a residue handling and loading system to process approximately 2 million tonnes of 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.

RUSAL Aughinish’s cost base would deteriorate by the above incremental amount and this would certainly precipitate closure of the refinery.

The previous case study of the Greek plant researched this system. Low production levels might allow trucking over short distances, pumping would require expensive equipment with high running and maintenance costs.

5.3.5 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 RUSAL Aughinish currently releases 0.24 m$^3$/tm$^3$ 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$^3$/m$^3$ 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$^3$/m$^3$ or 500,000 m$^3$ 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 B.R.D.A. 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 B.R.D.A. fills.

Assuming that the upstream embankment lifts could be constructed using additional imported material and geo-membranes, 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 B.R.D.A. 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 B.R.D.A. would continue to consolidate and this process would be at a maximum in the centre of the B.R.D.A. This process would create a “bowl” structure on top of the B.R.D.A., collecting incident rainfall and preventing drainage. Re-vegetation 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 RUSAL Aughinish.

This technology is used by Queensland Alumina, Australia. The Hungarian plant that had the embankment failure in 2010 also used this system.

5.3.6 Dry Stacking - High Compression Thickeners (Sub-aerial)

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 re-vegetation 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. Solids concentrations of Aughinish residue are generally in the 55% - 58% region exiting the process. The residue will consolidate more after deposition in the B.R.D.A. The control of the solids concentration is managed by the operation in the Filtration Building in Aughinish and depends on filter performance and the amounts of condensate dilution that is added.
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 RUSAL Aughinish 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 re-vegetation is commenced (Cooling, 1989). While it is possible to dewater and consolidate bauxite residue above these densities additional energy input is required and this 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 RUSAL Aughinish with the final height of the central cone of deposition some 8m above the perimeter drains (32m vs. 24m AMSL).

Using high compression thickeners this 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$^3$/m$^3$ of residue (discharge density of 45% w/w and dewatering to 65% solids w/w). The additional 0.13m$^3$/m$^3$ or 100,000 m$^3$ of caustic waters would need to be stored, processed and discharged in a similar manner as with current technology. This water is currently captured in the refinery and recycled to the process circuit. The final landform and re-vegetation 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.
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).

5.3.7 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.

Residue in this form generates an alkaline leachate on contact with water that requires extensive leaching to remove due to the considerable 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 neutralisation 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).

5.3.8 Hydrological Modelling – 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.

RUSAL Aughinish 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 mostly due to the addition of lime within the bauxite digestion process where:

- sodium aluminate is expressed as NaAlO₂
• sodium hydroxide is expressed as NaOH
• sodium carbonate is expressed as NaCO₃
• TCA is expressed as Ca₃Al₂(OH)₁₂
• hydrogarnet is expressed as Ca₃Al₂(SiO₄)ₙ(OH)₁₂⁻₄n

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:
Ca₃Al₂(OH)₁₂ + H₂O → Ca⁴⁺ + OH⁻ + Al(OH)₃ (amorphous)

This reaction gives pH ~ 10.5 but is very slow to reach equilibrium and the OH 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:
Ca₃Al₂(SiO₄)ₙ(OH)₁₂⁻₄n + H₂O → Ca²⁺ + OH⁻ + Al(OH)₃(nSiO₂) (an amorphous solid)
This reaction gives a pH ~ 11.2.

URS Dames & Moore (2002) conducted column-leaching investigations into the fresh water leaching of bauxite residue and the potential impact on the water quality that will be discharged from the B.R.D.A. (URS, 2003). Over a three-month period the URS data identified:
• 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 data and extrapolating at an estimated porosity of 63% and permeability that varies between $4.7 \times 10^9$ ms$^{-1}$ and $5.6 \times 10^8$ ms$^{-1}$ (lowest and highest permeability measured by URS and cited by Golders (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.

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 modelling precision exists to develop reasonable confidence that the effluent water quality objective will be met.
5.3.9 Reflection on the Run-Off / Leachate

Although the URS modelling suggested that ten pore flushes and a ratio of 400:1 between run-off / leachate were required to lower the pH to 9.0. there are some factors that need consideration:

- Variations in rainfall;
- The influence of vegetation uptake;
- Solid concentration of the residue deposited.

From the pH sampling from the one tonne containers and run-off / leachate analysis it would appear that it will take many years for the pH to come to 9.0. The leachate results did not change during the eighteen months sampling with three pore flushes on the residue in the one-tonne drums.

It will be necessary to continue to operate the Waste Effluent Treatment Plants in order to treat the residue run-off and keep to licence parameters of pH 6.0 - 9.0. If the leachate seepage rate is low and reduces, while on the other hand the run-off is 400:1 ratio or greater, then the pH will come down to 9.0.

The on-going results from the Demonstration Cells will be the source of this information over the coming years.

5.3.10 Hydro-geological Modelling

During the operation of the B.R.D.A., 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 B.R.D.A.

Post-closure, the entrained water within the residue deposit will lead to on-going 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, the surface cover of vegetation will seal or manage the rainfall. It is estimated that 75% - 90% of rainfall will run off the top of the residue (URS 2003), which reduces recharge.

At Aughinish, 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.

5.3.10.1 Impacts of Seepage

The total seepage from the B.R.D.A. at closure is 300 m³/day. The components of this seepage are:

- Phase 1 B.R.D.A. 145 m³/day
- Phase 1 B.R.D.A. Extension 60 m³/day
- Phase 2 B.R.D.A. 90 m³/day
- Storm Water Pond 3 m³/day
- Perimeter Interceptor Channel 2 m³/day

This estimate is based on a probabilistic review of the liner construction and estimated defects. The permeability of the bauxite residue is very low and typically 1E-8 m/s. There is likely to be little segregation of the bauxite residue 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 B.R.D.A. The permeability range for the estuarine soils is between 1E-7 m/s 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.

It has been estimated that, at the projected rate of seepage from the phase 2 B.R.D.A., it will take 10 – 30 years for seepage to reach the nearest receptor, 50m from the base of the facility. The modelling suggests a maximum impact of pH 9.7 after 100 years at the downstream toe of the embankment of the phase 2 B.R.D.A. (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. 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)$_2$) and hydrotalcite, but some are also consumed in the precipitation of additional boehmite and gibbsite, and some react 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 bauxite residue waste stream is greater than about 4mg/L) and some Mg may be consumed where it isomorphously substituted for Ca in aragonite.

The performance criteria for evaluating the limitation of subsurface seepage shall be determined utilizing the existing groundwater monitoring network and program. There are forty observation wells around the B.R.D.A. and groundwater analysis is carried out monthly. The objective of the monitoring will be to ensure that seepage from the B.R.D.A. does not influence relevant back groundwater quality parameters by more than 10% and that the pH should not exceed 9.0.

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 B.R.D.A. with seepage migrating through saline margins and achieving neutralization prior to entering the Shannon Estuary.
5.4 Suitable Species for the Re-vegetation of Bauxite Residue at Aughinish

Findings of the plot trials on residue and residue amended with gypsum and organic matter are summarised.

- There was poor germination and initial seedling growth limited by both poor chemical conditions and physical conditions in the residue.
- Physical and chemical amendment of residue is necessary before seeding.
- Amending with process sand and gypsum followed by a period of leaching greatly improved germination and growth of tested species.
- Several indigenous species are capable of growing amended bauxite residue at RUSAL Aughinish (see below).
- Organic matter alone is not a sufficient amendment if residue exhibits excessive pH, ESP.
- Amendment with gypsum, 60t/ha process sand 25%w/w and organic matter 120t/ha produces optimum growth in residue.

The above conditions necessary for vegetation growth are similar to the previous trials and knowledge and experience gained from around the world but the importance of weathering, the caustic and the solids concentration also had serious impact on success or failure.

This manifested itself more in the filling and treatment of the Demonstration Cell. The residue would not stack up if the solids concentration was below 55%, and the high caustics were visible in dry weather on top of the residue. In normal operations in the B.R.D.A. high soda on any particular day(s) is covered over with fresh residue and would not be visible. Prior to this study, little would have been thought about the caustic levels in the residue other than the loss of caustic. Consideration would not have been given to the weathering time, the stacking space or leachate pH. Greater consideration was given in later years to soda losses in residue because of the cost factor to production and space availability.
5.4.1 Species capable of growing in amended bauxite residue at RUSAL Aughinish

<table>
<thead>
<tr>
<th>Species</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avena sativa</td>
<td>Oats</td>
</tr>
<tr>
<td>Agrostis stolonifera</td>
<td>Creeping Bent</td>
</tr>
<tr>
<td>Agrostis capillaris</td>
<td>Common bent</td>
</tr>
<tr>
<td>Cynosurus cristatus</td>
<td>Crested Dog’s Tail</td>
</tr>
<tr>
<td>Festuca ovina</td>
<td>Sheep’s Fescue</td>
</tr>
<tr>
<td>Festuca rubra</td>
<td>Red Fescue</td>
</tr>
<tr>
<td>Holcus lanatus</td>
<td>Yorkshire Fog</td>
</tr>
<tr>
<td>Hordeum vulgare</td>
<td>Barley</td>
</tr>
<tr>
<td>Triticum aestivum</td>
<td>Wheat</td>
</tr>
<tr>
<td>Lolium perenne</td>
<td>Perennial Ryegrass</td>
</tr>
<tr>
<td>Puccinellia distans</td>
<td>Salt marsh grass</td>
</tr>
<tr>
<td>Rumex acetosa</td>
<td>Common Sorrel</td>
</tr>
<tr>
<td>Rumex crispus</td>
<td>Curled Dock</td>
</tr>
<tr>
<td>Trifolium pratense</td>
<td>Red Clover</td>
</tr>
<tr>
<td>Trifolium repens</td>
<td>White Clover</td>
</tr>
</tbody>
</table>

Composition of seed mixture were be affected by what was commercially available at time of seeding. Colonisation by further species occurred on areas once vegetation was established.

5.4.2 Species Diversity Survey

Residue that had previously been re-vegetated, 1997 and 1999, was surveyed in 2005. Species diversity was recorded and compared to the initial seed mixture of 6 species.

- There were 50 species belonging to 40 genera and 16 families.
- Asteraceae and Poaceae were the dominant families.
- Seven leguminous species were recorded growing.
- Dominant grass species were Holcus lanatus with Festuca rubra and Agrostis stolonifera.
• Although useful as a nurse crop, *Lolium perenne* may not persist long-term.
• Woody species *Betula, Salix* and *Alnus* have established on the re-vegetated areas.
• Patches of hay, previously used to suppress dust, acted as a seed source.

*Figure 75* Selection of Species growing on re-vegetated residue
Figure 76 Selection of Species growing on re-vegetated residue

Figure 77 Selection of Species growing on re-vegetated residue
5.4.3 Plant Elemental Content

Trials have demonstrated that the addition of process sand and gypsum is effective in lowering uptake of Na, Al and Fe in plants. Findings at RUSAL Aughinish are in keeping with those reported at other refineries. Long-term monitoring is necessary to evaluate effect of low P and Mn in vegetation growing on amended bauxite residue.

The effects of gypsum and process sand on the growth of *Trifolium pratense* in amended residue at RUSAL Aughinish are summarized:

- *Trifolium pratense* grown in gypsum-amended treatments had significantly lower aluminium concentration than those in non-gypsum treatments and levels are not considered excessive.
- This trend was also found for plant iron concentration.
- Gypsum amendment produced lower Na concentration in herbage, concentrations were markedly decreased with greater process sand addition.
- Higher manganese concentrations were observed for *Trifolium* grown in treatments amended with gypsum.
• Sodium levels in the substrate were not high enough to affect calcium in the plant cells. Calcium levels were in the range deemed adequate for the plant growth.
• Marginal Mg, P and K deficiency were found.
• Mn nutrition may be a limiting factor in achieving long-term growth.
• Nitrogen nutrition is not adversely affected in organically amended residue.

5.4.4 Findings of Residue - Re-vegetated

These were surveyed in 2006. Species diversity was recorded and compared to the initial seed mixture of 6 species.
Findings to date:
• Chemical and physical limitations of the refinery residues must be addressed prior to re-vegetation.
• Process sand, gypsum and organic matter are essential components of the re-vegetation prescription.
• Several indigenous species are capable of growing in amended bauxite residue.
• Effective amendment of the residue results in lower plant content of Na, Fe and Al.
• Nutrient cycling in the residue is seen as a critical parameter to demonstrate that the vegetation cover is self-sustaining cover.
• Leachate pH will remain high for a number of years following closure and will require treatment.

5.4.5 Results of Different Amendments.

Nutrient status of re-vegetated residue (c. 5 yrs previously) was investigated.
• Organic matter content strongly influenced organic carbon, total kjeldahl nitrogen (TKN) and available phosphorous.
• Nitrogen and organic carbon values had increased significantly compared to values for un-amended residue.
• Much of the P remains locked up in the residue matrix with low levels of plant-available phosphorous.
• Calcium does not appeared to be deficient but excess-exchangeable Ca may limit Mg availability.
• Application of fertiliser appears to have influenced K nutrition. Long-term effect of fertiliser management needs to be assessed.
• Mn nutrition remains deficient.

A concern with vegetation growing on bauxite residue is that excessive levels of Na or elevated pH may reoccur due to flooding with process water or sodium release from within desilication products (DSP) in the residue. Such conditions may cause established vegetation to regress or die back. Areas of the B.R.D.A. that had vegetation were re-vegetated in 1997 and 1999 were sampled in 2005 to investigate chemical properties of the residue. Properties are summarised below.

Table 25 Chemical properties of amended residue

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.02 – 8.14</td>
</tr>
<tr>
<td>EC (mS/cm)</td>
<td>0.28 – 0.52</td>
</tr>
<tr>
<td>Na (mg/kg)</td>
<td>305 – 432</td>
</tr>
<tr>
<td>Al (mg/kg)</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Residue in the re-vegetated areas did not exhibit excessive pH, Al or ESP.

5.4.6 Likely Causes of Re-vegetation Failure

The most likely potential cause of vegetation failure on a re-vegetated 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. With little drainage and leaching of the residue, large areas of failed vegetation are inevitable (Wehr et al. 2006). Lack of ameliorants for good soil structure. Even distribution of ameliorants is vital to avoid bare patches. It is likely that this will happen in places and so will require separate patch planting. This came to light the first time that machinery was used on the large plots.
The wind blew the discharge from the spreader to outside of the intended area. This resulted in some small area not receiving the correct amount of ameliorant.

All on-going management issues and rectification of problems as they occur is necessary in a post-closure scenario. This could mean reseeding some bare areas or adding fertilisers. This includes not 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.

### 5.4.6.1 Key Requirements of Re-vegetation Success at RUSAL Aughinish

The re-vegetation strategy addresses many of the causes of re-vegetation problems. 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.
- **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 microbiological 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 re-vegetation 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.

### 5.4.6.2 Reflection

Summarized below are key defined characteristics and comments on amended Aughinish residue with regards to soil parameters.

1. **pH**
   - Criteria: Stable residue solution pH below 9.0 and above 5.5
   - Comment: Amendment with gypsum at rates of 45 and 90 t/ha- reduces residue pH to ≤ 8.5. This is necessary for the vegetation to establish and survive.

2. Sodium adsorption ratio (SAR) and Exchangeable Sodium Percentage (ESP)
Criteria: Sodium adsorption ratio (SAR) of 7 or less (ESP of 9.5 or less), and a residual sodium carbonate (RSC) value of 1.25 or less.

ESP values in un-amended residue were high (62 – 92%) and typical for the range reported for other bauxite residues.

Preparation of the residue surface for re-vegetation reduces to values to approximately 30-40% and high application rates (120t/ha) of organic matter alone or with low application rates of gypsum reduce this further (11-30%) but do not achieve the target level of \( \leq 9.5 \). Consequently, co-application with gypsum is needed to reach target ESP values. Application of gypsum at 90 t/ha is effective in achieving ESP values of <6.

1. Electrical Conductivity Criteria: Electrical Conductivity of < 4 ms/cm.

Un-amended bauxite residue can exhibit EC values of up to 14.1 ms cm\(^{-1}\). Typically, weathering and leaching will reduce these values over time.

Values typical of areas prepared for re-vegetation (physical improvement with organic matter and gypsum application) range from 0.37 to 2.4 ms/cm. Application of gypsum can cause elevated levels of EC in the residue and was attributed to an excess of \( \text{Ca}_2 \) in solution and the displacement of Na from the exchange sites by \( \text{Ca}_2 \) and will decrease with leaching due to improved physical properties of the residue.

2. Bulk Density Criteria: Bulk density of less than or equal to 1.6 g cm\(^3\).

Un-amended residue bulk density values range from 1.3 – 1.9 g cm\(^3\).

Organic matter addition significantly reduces the bulk density of the residue with values decreased from un-amended residue to 1.02 g cm\(^3\) with compost at 120 t/ha. Decreases in bulk density as a result of the compost (organic matter) additions are due to a dilution effect caused by mixing the less dense organic material with the denser mineral fraction of the residue.

Application rates of organic matter and amendment/incorporation into the substrate achieve the desired bulk density values.
5.4.7 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 for 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 B.R.D.A. is restricted to those activities that do not increase the pollution potential of the rehabilitated facility. 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, heath lands and wetlands.

There are four future land uses 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 B.R.D.A. is:
• **Nature Conservation**
  
  o The existing Bird & Butterfly sanctuary is adjacent to the north side of the existing B.R.D.A. 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 B.R.D.A. The on-going management, and possible enhancement, of the existing bird sanctuary will be examined in the after-use policy for the restored B.R.D.A.

• **Amenity Restoration**
  
  o The eastern sides of the B.R.D.A. have a network of nature trails starting from the Rusal Aughinish Ltd sports centre complex. Joggers, walkers and sightseers use these amenity features. The ecological features viewed from these trails include some woodland, fern-land, and the tidal Poulaweala Creek that includes a bird hide to observe the inter-tidal bird environment.

• **Agriculture**
  
  o 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 of disturbance to the closed B.R.D.A. Provision of a security fence and an appropriate community education programme to ensure community understanding and support would be recommended.

The B.R.D.A. is located on freehold land owned by RUSAL Aughinish. 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 RUSAL Aughinish position as to how this will occur. However, the structure of this arrangement will likely incorporate some of the following attributes:

• The plant infrastructure, including storage facilities, the marine terminal and the CHP plant, will continue as a viable commercial operation;
• The B.R.D.A. 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 on-going IPPC license requirements including monitoring will continue.
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. As well as this, 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 B.R.D.A. could be accessed for recovery of bauxite residue for alternative uses. 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 B.R.D.A. 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 B.R.D.A. 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 B.R.D.A. from a “permanent” change in land use to one of “long-term” land use utilising the definitions described in EPA (2002).

5.4.8 Operational Residue Management System

The adoption of dry stacking by Rusal Aughinish has allowed the creation of naturally draining landforms.

The design of the RUSAL Aughinish 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 run-off 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 run-off volume induces scouring and erosion of the embankments;
- Armouring of the stepped embankments to prevent localized erosion;
- The incorporation of sand and geo-textile filters within the upstream embankments to prevent the movement of sediments into the surface drainage system;
• A simple re-vegetation blend utilizing robust and locally prevalent grasses and clover to support a sustainable re-vegetation profile;
• A low technology final land use goal where the adoption of “nature conservation” provides flexibility for RUSAL Aughinish in meeting this goal;
• Provision of “hard access” within the major drainage systems to permit ready access by earth-moving equipment for routine de-silting needs as part of a post-closure maintenance programme.
• 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 an 1000grm geotextile, 600mm of inert material such as glacial till or estuarine material stockpiled in the unsuitable stockpile and 200mm of topsoil.

RUSAL Aughinish will 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 B.R.D.A. with benefits for stability and optimising the mass of residue that can be accommodated within the B.R.D.A. and operational 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, with 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 RUSAL Aughinish is considered best practice within alumina industry for a washed alkaline residue management system.
5.4.9 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. For the B.R.D.A. 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.

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.

5.4.9.1 Findings of Residue Neutralization

The potential to neutralise the bauxite residue was undertaken with some confirmation of issues by experimentation. Some key findings are:

- Due to some specific process issues, the amount of alkalinity that is contained within the residue is lower than similar alumina operations. This would suggest that neutralisation would incur less expense and result in a better outcome than similar alumina operations.
- Full neutralisation of residue using sulphuric acid (or hydrochloric) cannot neutralise all of the alkaline compounds present in residue due to the slow rates of reaction required to achieve neutralisation. The practice of separating the residue solids (dry stacking) prevents some of the slower reactions from occurring. At best, the soluble alkalinity can be neutralised (approximately 20% of the total alkalinity present) and an immediate residue discharge pH of 9.0 achieved. However, over time the pH is expected to rise and
stabilise around pH 10.5. Rainfall run-off from such an area will likely require further neutralisation prior to discharge.

- Full neutralisation 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 and also needed to be discharged.

- Neutralisation using carbon dioxide potentially offers a more effective neutralising agent where both soluble and a proportion of the solid alkalinity is neutralised. However, as this approach is protected under patent further research is required to quantify the effectiveness. Availability of CO₂ would require importation from outside the country, or using flue gas to extract CO₂ which would require equipment/plant to be constructed on site at an estimated cost of 29 million Euros. Importantly, carbonation does offer a sustainable means of reducing greenhouse gas emissions during operations. Due to the limited data available it is not possible to confirm whether rainfall run-off from a carbonated residue will require further neutralisation prior to discharge.

### 5.4.9.2 Seawater Neutralization

Neutralisation of residue using river Shannon water (source of magnesium) was deemed impractical, due to the high volumes of water that would be required to drive the reaction. There is a reduced concentration of magnesium in the Shannon estuary due to the fresh water mix. The salt water is only a weak acid. It is estimated that an intake system with pumps and piping, a clarification system, and an outfall system which would have to handle flows of approx. 14,000m³/hr. This is not feasible from economic or environmental perspectives.

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.

### 5.4.9.3 Acid Neutralization

Acid neutralisation offers a solution at Aughinish for the following reasons:

- It is the most effective means of reducing the pH of red mud residue.
- The acid used will be sulphuric acid. The sulphates resulting from the neutralisation are acceptable in the long-term storage of the residue.
• Rainfall run-off from the B.R.D.A. will be neutralised, and so part of the acid added to residue neutralisation will replace acid currently added to neutralise rainfall run-off. This is fine while the Waste Effluent Plants are in operation, but the pH would have to be below 9.0 before the effluent plants could be shut down.

• Sulphuric acid is already used for descaling and water neutralisation at Aughinish. There is adequate storage and it is imported via the Aughinish Jetty. It is available from a number of sources, so there will be no problems with continuity of supply.

• The acid can be added with negligible effect on the solids content of the residue going to the B.R.D.A. but localised corrosion is likely if mixing is not complete.

• The acid will be injected into a static mixer at the disposal point in the B.R.D.A. This needs to be a robust system and careful engineering is necessary to avoid localised low pH pockets.

• The principal concerns related to neutralisation employing sulphuric acid is the potential for generation conditions that permit sulphate reduction to odorous H₂S. Such an outcome would be unacceptable to local residents and staff working in the B.R.D.A.

Post-neutralization of alkaline process and B.R.D.A. 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).
5.4.10 Field Data Findings

5.4.10.1 One-tonne Containers.

The findings from the one-tonne containers after 1.5 years analysis showed a drop in pH from 13.25 to 12.85 in drum No 6, which would be comparable to the other 4 drums. Results from these trials would indicate that up to 17 years were required to reach a pH of 9.0 or below in residue run-off. This is accounting for a drop in leachate only, but if both run-off and leachate were mixed, the drop in pH could be faster. On reflection this trial worked out very well in allowing close-up monitoring of compaction of the residue, the chance to complete pore flushes and the facility to sample both run-off and leachate.

5.5 Findings from Grass-Growing Trails

- Direct vegetation was found to be feasible, and so avoiding the high cost of topsoil.
- Soil construction and plant establishment was demonstrated.
- Bauxite residue showed improved results when amended with gypsum but this is costly.

There were still unanswered questions at this stage of the research, namely:

- Could the vegetation survive long periods of drought;
- Could an adequate soil biological community be developed to facilitate nutrient recycling and could the vegetation be self-sustaining;
- Whether a cost-effective supply of organic matter is available.

5.5.1 Demonstration Cells

The large-scale (0.6 ha) dedicated research Demonstration Cells created within the B.R.D.A. received residues typical of a closure scenario. Behaviour of the residue as it underwent consolidation and drying was monitored prior to employing the re-vegetation prescription.
Drying was slow, due to very wet weather during the summer months after the Cell was filled. It was impossible to access the residue for several months during this period.

This larger area provided the experience of using large machinery on the residue and problems associated with spreading large quantities of sand, gypsum, fertiliser and composts. The quantity and quality of run-off and leachate were monitored weekly for pH, soda, and conductivity. Run-off flows were recorded by flow meter and leachate flows were calculated by drop testing flows from the vacuum pump, which vacuumed the sample from collection area under the residue. Work will continue on these cells over the next five years or more.

Filling of the cell commenced in May 2007 and initially it was planned to fill the two cells but only sow grass on one and leave the other without grass. This was to compare the impact of grass on pH in run-off and leachate. Due to a request from the E.P.A to commence trials on neutralised residue, it was decided to leave one and use that cell for the neutralisation trials at a later stage following investigation into methods, feasibility, costs, etc.

It was possible to walk on the mud by end of 2007, and by late spring 2009 machinery commenced the amendment process in preparation for grass-growing in September 2009. It had been anticipated that after six months of maturing, work could have started on the amelioration of the residue and grass sowing, but drying was not good enough.

In the meantime analysis of the leachate and run-off continued weekly. The major finding from leachate and run-off analysis showed little or no drop in pH measurements after eighteen months. This would indicate that it would take far longer than five years for the pH to drop to 9.0 or lower. The leachate analysis did not change during the eighteen months but the run-off pH varied according to the amount of rain that fell. The fluctuations in pH matched the flows (quantity) of run-off, indicating the dilution effect of the higher rainfall.

Access onto the residue again was determined by the speed of drying, i.e. again governed by rainfall. Some flooding took place on the north side of the cell, restricting access for machinery and in turn amendment of the residue. The amendment process was delayed over the summer months because of the very wet weather at a time when the best drying should have taken place. During any period of dry weather, the run-off would virtually disappear and it was necessary to close the valve on the take-off pipe to allow the level to build up again. There was always sufficient liquor to obtain a leachate sample.
It will be necessary to continue running the Waste Effluent Treatment plants long after plant closure to lower the pH prior to discharging to the river Shannon, given there was no change in leachate pH analysis. If both samples are combined it is possible that the average of the two samples could get closer to 9.0 in times of high run-off flows, which would cause a dilution of the higher leachate pH.

**General Comments on Findings**

1. Direct vegetation on the residue was possible

2. Vegetation is sustainable. Plant and soil construction established

3. Demonstration Cells were constructed as per design, filling via new pipe-work worked well. There were no leaks when the pipe work was commissioned. Rate of filling was determined by the stacking angle of the residue.

4. Controlling percentage solids of the residue very important to achieve proper “stacking “of the residue in the Cells.

5. Leachate pH may take years to drop from 13 to 9.0 or below.

6. Acid neutralisation is the best option; CO$_2$ requires building a plant, seawater not feasible, due to dilution of seawater by the river Shannon and the cost of equipment.

7. No adverse impact on the environment with any technique. It is likely that the Waste Water Treatment Plants will have to operate far longer than five years in order to keep run-off pH within Licence parameters of 6.0 to 9.0. Monitoring to continue for 25 years at minimum.

8. Following closure, the vegetation cover can be in place in five years.

**5.6 Reflection**

The original programme of getting the project approved by the company, getting the time available, becoming an action research worker on the project was a steep learning curve. It was great to be involved from the start. Along the way difficulties arose, there were delays, not everything went to plan (the damaged plots for example). There were delays in getting monies approved, budgets were tight for a period, people were not always available when required. The weather was bad when good drying was required. Having said all that, the team had the expertise, the company wanted the projects to proceed.
Apart from the damaged plots the grass growing trials went well, the information gained copper-fastened information from previous trials. The construction of the Demonstration Cells was delayed for some time due to funding. The filling programme did go to plan due to residue stacking angles. The prolonged wet summer caused delayed the drying process of the residue and prevent access onto the residue.

The communications with the process people to keep them up-to-date was done on a monthly basis and managers were updated on all progress or if a problem arose which required input, e.g. funding.

Acid neutralisation seemed more straightforward at the start and the opinion was that it could be installed and tested very quickly.

However, it was not as straightforward when it was researched fully. There could be possible problems with corrosion in the pumping equipment, gel material forming in the pipe lines, which could cause possible vegetation problems and costs of the separate injection points in the B.R.D.A., rather than one single injection system into the mud reactors and pumps.

The main intention of the project was to help secure the future of the company by getting planning permission and the E.P.A. licence extension to keep in operation with all jobs secured. The author wished to improve his knowledge of bauxite residue and its disposal, and become an expert in this field.

The author realised that the project would take up family time. Researching, working on the plant and in the B.R.D.A. was the best part of the project. Organisation of workload, getting contractors to complete tasks, the release of people and the process changes required a lot of co-ordination with the different groups. Any problem that arose was accepted, studied, discussed with the team, the company and action taken to resolve it. There was no such thing as “that cannot be done”. Once a review had taken place the author would take on board all suggestions, but at the end of the day the final decision was with the author.

Acid neutralisation methods appeared the best choice at the beginning, given the experience of using acid on the plant, but this raised some unexpected problems. The importance of weathering, and the better stacking achieved by pumping the residue at highest possible percentage solids, became much more significant and important researching a closure scenario. Transporting the residue to the B.R.D.A. was the most important aspect for Aughnish up to recent times when space in the B.R.D.A. became a priority. The percentage
solids and soda levels were primary issues with the B.R.D.A. filling up and space limited. The priority changed in the operating of the Filtration Building because of the risk that the plant could be shut down due to lack of space.

The plot trials showed the importance of the above parameters, how important it was to lower the pH and the other sustainable conditions before sowing grass. The author feels very confident that given the plot trials and the knowledge gained from the Demonstration Cell that vegetation could be sown and would be sustainable within five years. Some doubts remain over the leachate / run-off pH reaching 9.0 in the required time frame. Numerous process factors will need to be adhered to if the reduction in pH is to be achieved.

Looking at other neutralisation systems around the world, seawater is not suitable for Aughinish, CO$_2$ is suitable if the company could build a new plant or extract CO$_2$ from the stack gases. Acid neutralisation, although it can cause problems with corrosion in the pipework and gel in the slurry and possible H$_2$S smells on the B.R.D.A. still appears the best option for the company.

The Demonstration Cells are the showpiece for the company and can be available for community visitors, the results will be given to the E.P.A annually.
**Figure 79** Demonstration Cell filling with bauxite residue
Chapter 6 Conclusions
Assessing the sustainability of bauxite residue management practices presents a wide range of issues that often compete for limited capital resources and place judgements on the relative importance of issues.

However, a critical assessment of the sources of alkalinity in bauxite residue has identified the significant residual alkalinity that leaching must be overcome in order to produce a leachate that will not require further neutralisation. Currently, it is assumed that the leaching of the Phase 2 B.R.D.A. will produce a leachate of less than pH 9.0 and enable direct discharge within five years of closure. Due to the low permeability of the residue, it is estimated that over 28 pore volumes will be required to achieve this requirement and the time needed to achieve this outcome (influenced by the permeability) may exceed 100 years.

Dilution due to rainfall will provide some benefit, but as this is highly variable and not contained it will have a limited impact. While the absolute time period is subject to conjecture the issue is that this is significantly longer than five years. This would suggest that neutralisation of leachate will be required for longer than five years. Aughinish has committed to the establishment of the Closure Demonstration Cells and these will provide detailed information on this aspect.

The key issue with this finding is whether this represents an unsustainable outcome. Presumably, the current practice is acceptable and given the resources currently available, it is also sustainable. While sustainable, this approach may not be appropriate. More importantly, the question that needs to be assessed is whether such an outcome is acceptable to EPA.

There is limited long-term benefit to placing neutralised residue on top of the existing alkaline residue deposit within the Phase 1 B.R.D.A. This is due to the existing inventory of alkalinity present and the potential for capillary rise to lead to contamination of the neutralised residue. However, there is considerable merit in placing neutralised residue into the future Phase 2 B.R.D.A., as the potential for cross-contamination will be reduced and the benefits of neutralisation maintained.

With a reduced alkalinity, it is likely that there will be a reduced time required to achieve full leaching of the neutralised residue. However, even if the entire neutralised residue is placed in the Phase 2 B.R.D.A., then the time required to achieve full leaching of the Phase 1 B.R.D.A. 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.

Even with a neutralised residue, it is likely that the final pH of the re-vegetation growth horizon will not be able to sustain vegetation. Without amendment, it is likely 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.

Finally, 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. The final re-use opportunity needs 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 programme can commence.

Rusal Aughinish started a process of evaluating methodologies to successfully close the B.R.D.A. in an environmental sustainable manner. In this time areas of the B.R.D.A. have been rehabilitated to grow grass using a variety of methods. There are many different experiences worldwide in rehabilitation, but Rusal Aughinish trials have amended the bauxite residue itself without any additions of topsoil.

The diversity analysis completed in 2006 of the 1998 and 1999 trials plots showed that the number of grass species had increased from five to forty during that period.

Analysis of leachate from the one-tonne containers over a two-year period and from the Demonstration Cells over an eighteen month period showed the reduction in pH will take far longer than the modelling exercise carried out. The time span would appear to be in the region of 10-15 years or even up to 100 years. The results from the Cells over a longer period will yield further information in time.

**6.1 Visit to Burntisland, Scotland.**

The visit to the closed plant in Burntisland, Scotland in 2004 and the rehabilitated residue area showed that they had installed an elaborate run-off collection system to separate the run-off from the leachate. This reduced the volume of liquor for processing, but eliminated the dilution effect the run-off would have on the leachate. The residue was capped with topsoil
and grass sown on the residue. From the flow sheet of the leachate collection system and pumping of the treated effluent to sea, there was very little reduction in either flow rates or pH levels following closure.

Three years later, they continue to run the treatment plant and treat the leachate prior to pumping to the sea under licence. Figures supplied by the Scottish E.P.A show virtually no reduction in pH levels over this period.

6.2 Aughinish Trials

6.2.1 Vegetation Trials

The experience at Rusal Aughinish is that a mixture of process sand on the top 300 mm of the bauxite residue, followed by a prolonged weathering, will help to reduce the caustic levels in the bauxite residue. When sufficient reduction of the caustic in the bauxite residue is achieved, then gypsum and organic material are mixed into the bauxite residue. Following this amendment, grass seed can be applied to the bauxite residue soil and grass growth is successful. This procedure has been refined and the application rates of the following:

- Sand range from 80 to 120 ton per hectare,
- Gypsum from 0 to 90 ton per hectare, and
- Organic material 80 to 180 ton per hectare.

The main control on the application of gypsum and organic amendments is the caustic level in the mud. This can be controlled to acceptable levels by the washing arrangement in the Filtration Building, sometimes at the expense of production. High gypsum can overcome this but is not the ultimate solution; if possible the caustic level should be reduced back to the original lower levels, but this has production implications, so it is cheaper to use more gypsum than cut production.

A longer period of weathering is necessary for the bauxite residue after sand is mixed in. At current caustic levels six to twelve months of weathering is required before gypsum and organic material should be applied in the residue. With lower caustics, three months of weathering would be sufficient.
6.2.2 Demonstration Cells

Filling of the Demonstration Cell took longer than anticipated, due to the lack of the stacking angle; if filling was done too quickly, the residue was inclined to run to the bottom of the cell and not stack up. By filling for a few hours at a time and allowing the residue to dry out for a few days it was possible to get the residue to build and stack. When the E.P.A. requested residue neutralisation to the Phase 2 extension, the decision was made to use the second cell for the acid neutralisation.

Over the period of 18 months monitoring the leachate pH did not drop, indicating that it will take many years for a pH of 9.0 to be achieved without neutralisation. Due to the liner, it appeared that the top section of the residue remained very waterlogged for longer periods than normal, which restricted access onto the residue for amendment purposes. Good access has been provided around the perimeter of the cells for machinery.

6.2.3 Experience on the test plots

In the larger test plots (20 metres square) technologies were utilised which would be required for the final B.R.D.A. closure. In these cells (11 in total) different concentrations of sand, gypsum and organic material similar to the rates applied to the smaller plots were applied. There were a number of problems in achieving consistent coverage of the amended bauxite residue. The spreader used for sand and compost spreading could not travel on the residue because of its weight and the bauxite residue had not matured enough. This required the spreading to be done from the embankments, which resulted in sections in the middle not receiving the correct dosage.

Spreading of the gypsum was done by hand and again, it was not uniformly done. Wind conditions are also important, as the area is exposed and high up, resulting in materials blowing from either the spreaders or hand applications.

The plots with lower gypsum and sand applications had reduced drainage, and as a consequence flooded and vegetation failed.
6.2.3.1 One-Tonne Container Trials

The conducted trials (mini test cells) in 1 tonne plastic containers (6 in total) lasted for 18 months, to determine the leachate and run-off quality of the mud within these units. The results would not support the claim that the pH of the combined leachate and run-off from the B.R.D.A. would be below 9 in five years. The results from the trials would show that 10-15 year are required to reach a pH of less than 9.

6.2.3.2 Seawater neutralisation

At present, the only bauxite residue neutralisation technology operated commercially (‘seawater mixing’) in the semi-tropical coastal regions of Australia. In all such cases, the resultant neutralised residue is disposed as a wet slurry with decantation of the supernatant back to the sea. High drying rates under the tropical weather conditions permit adequate additional drying and consolidation of this wet residue slurry, such that it shrinks to occupy the volume similar to what it would have occupied had it been pre-filtered. It appears that the system is acceptable in Australia to allow the supernatant run back into the sea without any further treatment. This system is not suitable for Rusal Aughinish due to high pumping rates required and treatment of the return liquor to the sea would be required as per Aughinish E.P.A. licence.

6.2.3.3 CO₂ Neutralisation

Only one Alumina refinery in the world, Alcoa’s Kwinana Refinery in Western Australia, has tested carbonation of bauxite residue on an industrial scale.

This system would require plant and equipment installed at a high cost up to 30m Euros, even if they could purchase the technology from Alcoa. It would require a different operating process to the present one. Aughinish could use flue gases from the boiler stacks, but again this would require large investment in plant even if the patent were obtained from Alcoa.
6.3 Closure Plan & Relinquishment Criteria

At closure, the B.R.D.A. will consist of the following components:

- An open domed residue surface approximately 180 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, a self-sustaining vegetation cover will be developed within 5 years of closure. Surface water quality from the B.R.D.A. will be managed using sulphuric acid neutralization of alkaline run-off and this is likely to be required for 5 years or 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 sludge from the plant (categorized as non-hazardous) will be disposed of off-site. 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 back groundwater quality parameters are not influenced by more than 10%. Annual geo-technical monitoring will occur for a period of five years from closure to assess pore pressures and stability of the site. Contaminated groundwater will be intercepted and managed for amelioration and discharge. There will be twenty-five years of further environmental monitoring.

6.3.1 Nature Conservation

The restoration of the B.R.D.A. surface will support a “nature conservation” end-use. Therefore, sustainable re-vegetation of the B.R.D.A. 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 re-vegetation are dependent on the initial complexity of vegetation required.

Direct re-vegetation of the bauxite residue 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 in order to improve structure and removal of excess salts by leaching.

The methods necessary to establish a re-vegetation cover on the B.R.D.A. have been established. The newly created soil (bauxite residue 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. It is possible 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 rainwater run-off and potable water purchased for this purpose.
6.3.2 Choice of Final Land Use

The long-term sustainable land use of the B.R.D.A. surface will be restricted to those activities that do not increase the pollution potential of the rehabilitated facility. In deciding the most suitable end use for the B.R.D.A., it has been determined that activities which may lead to over-grazing, poaching, cultivation, uprooting of trees by wind-blow and other surface disturbance, will be avoided.

The preferred land use option, based on current knowledge of the chemistry and biology of the sown grassland cover, is to develop the area for nature conservation. A section of RUSAL Aughinish land to the north of the B.R.D.A. has already been developed as a Bird Sanctuary, so the development of a nature conservation area is in keeping with RUSAL Aughinish procedure in the past. The choice of after use is also in line with procedures in the E.P.A Landfill Manual where it states that ‘the restoration of landfill sites must take account of any existing or proposed environmental designations in and/or adjacent to the landfill’.

Lands adjacent to the Aughinish facility are subject to EU and National environmental designations and the sensitivity of these environmental receptors, particularly in the key areas of surface and groundwater quality, have been taken into account in the design of the restoration process and after-care of the B.R.D.A.

The EPA Landfill Manual points out that ‘the establishment of areas of nature conservation can be a highly effective after use for restored landfill sites and … can lead to the creation of new habitats’. Restoration for nature conservation can incorporate woodlands, wildflower meadows, heath lands and wetlands. Proposed landscaping of the B.R.D.A. incorporates the planting of tree and shrub species and the spread of scrub woodland to the surface of the B.R.D.A. following closure will be encouraged. A naturally-evolved woodland such as this is desirable, as it would protect the B.R.D.A. surface from wind erosion and improve stability.

Proposals for the interim re-vegetation of the B.R.D.A. side slopes allow for the planting of appropriate herbaceous and shrub species on the treated side slopes. These should be capable of developing into a broadly self-sustaining habitat with ‘natural’ characteristics, which, if not subject to human intervention, could develop into scrub or woodland. Given time, there is a possibility that any scrub woodland that develops on the side slopes may spread to the surface dome of the decommissioned and re-vegetated B.R.D.A. So far, no
trials have been carried out to determine whether any scrub species can grow in the amended bauxite residue.

There is a possibility that the artificial soil structure and limited nutrient sources that will be present in the B.R.D.A. may not be conducive to the natural development of woodland. Wind exposure and post re-vegetation application of nutrients may also impede the growth of scrub vegetation. In order to encourage the spread of scrub woodland, species tolerant of exposed and coastal sites will be incorporated into landscaping of areas of the B.R.D.A. Suitable species include blackthorn (*Prunus spinosa*), sea buckthorn, (*Hippophae rhamnoides*) and whitebeam (*Sorbus aria*). Other scrub species such as hazel (*Corylus avellana*) and hawthorn (*Crataegus monogyna*) may also prove viable. Where scrubland species are dominant in the vegetation cover, annual monitoring and sampling procedures will be adapted to accommodate their presence.

### 6.3.3 After-care and Demonstration of Performance

Success of surface re-vegetation (which will be critical in meeting requirements for control of fugitive dust and valuable in the limitation of subsurface seepage and the maintenance of geotechnical stability) will be measured on the basis of vegetation and soil biological surveys. These surveys will be conducted annually for five years, upon which time it is anticipated that the re-vegetation programme will be deemed successful. Should the five-year objective not be met, RUSAL Aughinish should update the Residuals Management Plan to identify the measures that it will undertake to improve the performance of the cover.

Monitoring of nutrient levels in herbage and substrate will continue post-closure as deficiencies in some essential elements were highlighted in the second year of trials carried out in 1999/2000. Nutrient deficiencies could impact on overall plant performance and its role in the restoration of the B.R.D.A. Annual herbage and substrate sampling will also determine levels of aluminium, sodium and iron. In collaboration with other B.R.D.A. research bodies, a review of other potential eco-toxic elements will be undertaken and, where necessary, their monitoring incorporated into the annual analysis. The re-vegetated B.R.D.A will continue to receive aftercare management via amendment with nutrients, trace elements and organic ameliorants, where necessary.

Monitoring the volume and quality of surface run-off and seepage from the residue in the Demonstration Cell will indicate over time if the vegetation is reducing infiltration.
through the residue. Vegetated areas will be compared with control areas to determine the effect of grassland cover on generation and quality of seepage from the B.R.D.A. Surface run-off and leachate from the trial area will be monitored on a continual basis for critical parameters including pH, soda content and aluminium.

Assessing the sustainability of bauxite residue management practices presents a wide range of issues that often compete for limited capital resources and place judgements on the relative importance of issues.

Based on a review of the design, industry standard approaches and Rusal Aughinish acknowledgement of issues that need to be addressed at a detailed design phase, the design presented is in many respects an example of best-practice technology within the alumina industry. A series of recommendations has been developed to address some of these issues.

Dilution due to rainfall will provide some benefit but as this is highly variable and if not contained, will have a limited impact. While the absolute time period is subject to conjecture, the issue is that this is significantly longer than five years. This would suggest that neutralisation of leachate will be required for longer than five years and the running of Rusal Aughinish Waste Water Treatment Plant. Rusal Aughinish has committed to the establishment of the Closure Demonstration Cells and these will provide detailed information on this aspect in the coming years.

The key issue here is whether this represents an unsustainable outcome. Presumably, the current practice is acceptable and given the resources currently available, it is also sustainable. The change is one of the times required for the leachate neutralisation system to be maintained. While sustainable, this approach may not be appropriate. More importantly, the question that needs to be assessed is whether such an outcome is acceptable to EPA.

### 6.4 Reflection

Vegetation will grow and is sustainable given that the caustic in the residue has been reduced, the % solids of the residue are maintained high, the, correct amendments are added and enough weathering time has been allowed. This would appear to be guaranteed. The options for neutralisation are not so clear-cut. In the early stages it appeared to the writer that acid was the most appropriate method and may still be but there are problems with $\text{H}_2\text{S}$
smells, acid corrosion in the vessels and the pipe work. Along with these there is a likely problem of gel forming in the slurry, which would have a have an adverse affect on vegetation.

Sea water neutralisation is not feasible, due to high cost and diluted sea water in the Shannon river, plus having to treat the return water, this is no different than treating the run-off from the B.R.D.A. which is happening at present in the Waste Effluent Plants.

The neutralisation of leachate down to 9.0 is unlikely in five years, the combined leachate / run-off could come down following vegetation in five years depending on rainfall. Mud farming will help with atmospheric carbonation and reduced drying time of the residue. This procedure could be progressed more with more machinery.

CO\textsubscript{2} injection will not happen in the near future given the non-availability of liquid CO\textsubscript{2} in Ireland. The money is not available to build a CO\textsubscript{2} plant or extract CO\textsubscript{2} from the flue gas stacks at Aughinish.

The author’s knowledge has improved over the years working on this project, particularly in neutralisation methods. The knowledge yet to be gained is leachate pH decline over a long period from the Cells. It will take up five years before this information will show any significant changes. The vegetation on the Cell is good and its influence on the leachate will now be monitored to see what changes in pH come about.

The author’s skills in co-ordinating so many different strands of the project improved in dealing with so many individuals, contractors, Aughinish management and staff. The staff included supervisors, engineers, process operators, laboratory chemists, technicians and maintenance personnel. The author also developed insight into how the process was controlled to give the most suitable residue, even making judgements on the weather to commence certain actions on the B.R.D.A.

The company have secured planning permission and their E.P.A. licence extension, but with limitations. They can use the Phase 2 extension and they must continue to monitor the Demonstration Cells with progress reported in their Annual Environmental Report. So performance-wise that aim and objective have been achieved.

The company gave the author the time, the finances plus the people to take on this project. The author was responsible for making changes to the process to suit the filling of the Cells and plots and this could have had implications for production if not handled correctly. The author’s experience of the plant and process was the difference here in
achieving this without cutting or losing production. The author was given the responsibility to select trial areas, select the routing of the pipeline to the Demonstration Cells and arrange with contractors to complete the building of the embankments and construct the Cells. All of this was achieved, although some target dates were behind at times for a few reasons.

Approval of funding was sometimes delayed, the availability of people and the weather delayed progress, due to extending the drying time of the residue in the Demonstration Cell. It was frustrating, plus massively disappointing at times when progress was delayed. These delays were not anticipated or built into the Programme Plan, so this again was a learning aspect for a complex project with several smaller projects happening at the same. The author’s delegation of tasks improved over time and the he realised that he could not do everything himself, even if he felt it could happen faster.

By constant communication with the staff of the Process Section, they were kept up-to-date with progress on the project, tours were arranged to bring people onto the B.R.D.A. to show and explain how we were proceeding. This alleviated people’s fears that there was a plan to satisfy the planning authorities and the E.P.A. and by doing so, the future of the plant could be secured. The worry of staff was that the planning permission and licence from the E.P.A. would not be given and the plant would close.

Communication with the team and top management was weekly / monthly and this was necessary for long-term planning and funding arrangements. Looking back the area of funding did cause some concern, and the author would suggest that if in a similar situation again, to make sure approval was guaranteed as early as possible to avoid delays.

The author would have liked to visit a plant that used seawater for neutralisation of the residue, but this did not happen due to funding.
Chapter 7 – Recommendations
To ensure alignment with the principles of sustainable residue management and to gain acceptance of the closure plan, it is recommended that Rusal Aughinish address some outstanding issues. The company should consider:

- Engaging the community on the total risk that the B.R.D.A. 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.

- Closing some gaps in the understanding of the surface water quality solution in the closure plan. Due to the difficulties in providing long-term predictions of water quality, understanding residue leachate chemistry and small sample measurements of permeability some of the assumptions made regarding the likely achievement of a B.R.D.A effluent pH <9.0 needs on-going research and verification. Initial review of the likely chemistry of the leaching process does not support this assumption. This is not an urgent action; however, this will take a considerable period to determine with precision. It is recommended that there is clear confirmation of the likely start pH of the residue for all leaching testing.

A more thorough assessment of the rainfall variability and impact on surface water quality should be made with emphasis on 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.

An appropriate statistically robust permeability monitoring programme, followed by a probabilistic approach to the estimation vertical 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 that the effluent water quality objective will be met and when.

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
programme should include a thorough investigation of the alkalinity leaching chemistry. If possible, there exists an opportunity to conduct a core drill should be considered to examine some of the initial residue placed by the plant <1985, as this would have had an opportunity to leach for over twenty years.

Given the uncertainty in the effluent water quality the cost estimates presented to manage five years of operation may need to be reviewed to accommodate a treatment timeframe that may extend for over 100 years, pending confirmation of the leachate chemistry.

- As the time required for the residue to achieve an acceptable pH is extremely long, it is highly likely that the residue will remain alkaline longer than the time required for serious erosion issues to develop if the site was left unmanaged. The potential erosion risk of the post-closure B.R.D.A. should be assessed and modelled under a range of potential scenarios.

- 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 re-vegetation 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 management programme to address nutrient needs, erosion control, prevention of burrowing animals and controlled human access.
  - Ensuring that capillary rise is not a significantly influential issue in a high rainfall/low evaporation environment. Importantly, this review should also consider the impact of placement of a neutralized residue layer on a non-neutralized residue layer from a capillary rise perspective.

Opening discussion on the proposed post-closure land use to community review and comment. While E.P.A. review and acceptance is important, community support will be required for it to be successful. In addition, it is recommended that:
• Rusal Aughinish in discussion with E.P.A need to fully consider the structure of post-closure management and the expectations of both sides.

• As bauxite residue is a resource of limited but sustaining value, consideration should be given as to how the B.R.D.A. could be accessed for recovery of bauxite residue for alternative uses.

• Rusal Aughinish needs to remain engaged in the industry evaluation and development of alternative use research and applications of bauxite residue. This should continue to be funded via AMIRA and other alumina focused research groupings.

A market research review of the competing products to potential bauxite residue applications and identify direct and potentially commercially viable projects or products.

Engaging with EPA to confirm a regulatory pathway for the development of alternative use applications.

Assessing the potential for application of residue in an un-neutralised form to high volume low value applications. If this is not feasible then application with neutralised residue may be the only means.

While the empirical values for a neutralisation 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:

• 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 p to reach equilibrium. Whatever the situation, the control pH should be the pH at the discharge points at the B.R.D.A. and not that in the Filter Building.

• Define the characteristics needed to develop a sustainable end-use for process sand. These include:
  o Full characterisation of process sand – physical, chemical properties.
  o Discuss with E.P.A what aspects they would need to see in process sand such that they could classify it as an inert material.
  o Major investment is required to engineer, scope and pilot trial acid neutralisation of bauxite residue.
• Monitoring of nutrient levels in herbage and substrate to continue post closure. Further evaluation in relation to spreading of sand, gypsum, & organic material on a large scale on the bauxite residue.
• Further investigation on the leaching time period for bauxite residue with high caustic content and sustainability of vegetation.
• Continue to monitor the Demonstration Cells for ph, soda and conductivity of leachate and run-off.
• Fill the second cell with neutralized bauxite residue and amend to sow grass. This could the first part of the pilot trial using acid.
• Evaluate the effects of residue neutralisation on the rheology (yield stress) of the mud.
• Annual herbage and substrate sampling will also determine levels of aluminium, sodium and iron.
• Monitor odour potential, during the acid neutralisation process
• Determine the ultimate drying, consolidation and stability properties of neutralised bauxite residue.
• Put in place a management plan to coordinate the monitoring and maintenance of the demonstration cells over the next five years.

The re-vegetated B.R.D.A. will continue to receive after-care management via amendment with nutrients, trace elements and organic ameliorants, where necessary.

Critical Discussion
From all the suggested recommendations there are some crucial ones if the E.P.A, the local community and the Local Authorities are to accept the closure plan.

1. The critical assessment of the sources of alkalinity in residue has highlighted the residual alkalinity, which is significant. This will require leaching to reduce to 9.0 or below but will be difficult given the variations in rainfall over a given year. The 400:1 ratio between run-off and leachate would not be achieved in periods of low rainfall. If the dilution is not taking place it will be necessary to run the Waste Effluents Plants for longer than five years. The present system is acceptable to the E.P.A. but it has added costs for the company.
2. The vegetation trials highlighted the necessity for a longer weathering period before amendment. The importance here is to ensure that as much leaching has taken place as possible and so reduce the risk of capillary rise which would destroy the vegetation. This could delay vegetation growing on the residue if certain sections of the B.R.D.A. were closed and then required grass.

3. The sampling of leachate from the Demonstration Cell did not show any drop in pH, which does not bode well for the five-year time frame. The recommendation here is to continue with the sampling and analysis for soda, conductivity and pH. What needs to be known here is the vegetation making any difference to the pH of the leachate or run-off.

4. The sustainability of the vegetation will require yearly analysis for nutrients, that the cycle of nutrients has developed, and if the vegetation had had any impact on the leachate pH. Some years of monitoring are required to collect adequate information. Did the vegetation have any impact on leachate pH.

5. The meetings with local communities are important to gain acceptance for all work around the B.R.D.A. There has always been concern about the visual aspects, the fallout from the stacks, dusting from the B.R.D.A. and the tonnes of residue left behind. The money into the local economy will sway public opinion to keep the plant in operation under stringent environmental controls.

6. In case neutralisation has any affect on the rheology (yield stress) of the mud, this aspect needs further monitoring. This is an unknown at present. However, if neutralisation could get the pH down to 9.0 vegetation would be less of an issue. Odour could become an issue with acid neutralisation at certain pH values.

7. The risk of dusting when the residue dries out is always a risk, this requires the extension of the sprinkler system into the Phase 2 extension. The automation of this system will reduce the dusting risk as it can be activated from the control room instantly.

8. Continuous monitoring of grounds water from the forty observation wells will pick up any seepage from the liner under the residue.
9. Engaging with E.P.A. looking at alternative uses for the residue and process sand, along with industry in general should continue.
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### Appendix 1

**Shoot Height for *Avena sativa* and *Holcus lanatus* after 3 weeks growth**

**Table No 1**

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<th>Treatment</th>
<th>Shoot Height (cm)</th>
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<th><em>Holcus lanatus</em></th>
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RM = Red Mud; Red Mud + Process Sand
RMSG = Red Mud + 3% Gypsum.
O = Organic Amendment

Means within a treatment followed by the same letters are not significantly different at p <= 0.05.
### Water Soluble Elements and ESP for Field Trials Prior to amendment

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<th>Ca (mg/kg)</th>
<th>Mg (mg/kg)</th>
<th>Al (mg/kg)</th>
<th>Fe (mg/kg)</th>
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<td><strong>Sand</strong></td>
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<td>2.6 (0.5)</td>
<td>0.8 (0.02)</td>
<td>22 (3.1)</td>
<td>1.6 (0.4)</td>
<td>86 (7.4)</td>
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Values in parentheses are standard deviation of 8 samples.

### Water Soluble Cations and pH levels in trial Plots following substrate amendment and prior to seeding

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RMS10 = Red Mud & 10% Process Sand
RMSG10 = Red Mud & 10% Process Sand & Gypsum
RMSG25 = Red Mud & 25% Process Sand & Gypsum
RMS25 = Red Mud & 25% Process Sand
## Percentage Germination after 3 weeks

Table No 4.

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<td>RMSGO</td>
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RM = Red Mud  
RMSG = Red Mud +PS+ 3%Gypsum  
RMS = Red Mud + Process Sand  
RMSGO = Red Mud+ps + gypsum +organic  
RMSO = Red Mud + PS + Organic  
RMO = Red Mud + Organic  

O = Organic Amendment  
Means within a treatment followed by the same letters are not significantly different at p <= 0.05.
Percentage Germination after 8 weeks.

Table No 5.

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RMS = Red Mud + Process Sand
RMSG = Red Mud + PS + 3% Gypsum
### Appendix 2

#### Drum 1

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