Investigation of closure techniques for the Rusal Aughinish Bauxite Residue Disposal Area (B.R.D.A.) and the impact on the surrounding environment post-closure

McGrath, M.

Investigation of closure techniques for the Rusal Aughinish Bauxite Residue Disposal Area (B.R.D.A.) and 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

Michael McGrath, MSc

MIDDLESEX UNIVERSITY

April 2021

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. had requested a Residuals Management Plan which included how the refinery shut down, decommissioned and the site management following its closure. This plan sought to ensure that the closure technique will have no impact on the environment. This plan sought to ensure that the leachate from the BRDA will have a pH lower than 9.0 in 5 years after closure and the residue would be covered with a sustainable vegetation. As such, residue neutralisation methods had to be be researched and investigated, and that all residue pumped to Phase 2 extension would have a pH of 9.0.

Rusal Aughinish has determined that the restoration of the B.R.D.A. surface will support a "nature conservation" end-use (AAL, 2005d). Vegetation trials since the 1990s, the research into neutralization methods of the residue, plot and Demonstration Cell trials guaranteed this commitment.

This theses involves small plot trials (2m x1m) and larger plot trials (10m x 2m) which were established in 2004 and the construction of the two Demonstration Cells which were amended with gypsum, process sand, and spent mushroom compost in 2006/ 2007. This amendment lowered the pH, the exchangeable sodium percentage (ESP) and the availability of Al and Fe in the residue and allowed for grass growing. The 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 to plough in the sand, gypsum, compost and the grass seed.

Two Demonstration Cells were constructed within the confines of the B.R.D.A. (0.6ha) in 2006 and filled in 2007.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 deemed best option, but only partial neutralization can be 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 H_2S odour problems in the BRDA area. Carbonation would also be possible but would require the construction of a plant or the importation of liquid CO_2. Seawater neutralisation using water from the Shannon estuary was prohibited by costs, mainly high-pressure pumps and the treatment of the return liquid to the Shannon River. 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 in 2009 and was evaluated. Modifications have been made to the method of mud farming and results give a partial neutralization with a pH of around 10.0 to 10.5. Trials have been concluded with a pilot Wetlands project.

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 before and after vegetation growth. This monitoring is still on- going with further trials in the second Demonstration Celland monitoring of the vegetation cover. Filling of the cell with residue was determined by the stacking angle of the residue.

Controlling percentage solids of the residue to the BRDA is very important in order to achieve proper stacking of the residue. From the trials and laboratory results 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, wetland trials, and Mud Farming.

The period of this study is from 2003 to 2011.

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.

Table of Contents

List of Tables

List of Figures

List of Appendices

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.

Alumina. 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.

Bauxite. 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.

Bauxite ore ($AL_2 O_3 Xh_2O$). Silica, iron oxide, plus other minor and trace impurities associated with it.

Bauxite Residue Disposal Area (B.R.D.A.). Engineered storage area for residue.

Bayer Process. Predominant method used to extract alumina from bauxite Calcareous substance; Substance containing calcium carbonate.

Calcination. 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 hydrates, carbonate, or other compounds are decomposed, and volatile material is released.

Carbonation of bauxite residue. The process of adding carbon dioxide to bauxite residue with the resultant effect of reducing the pH of the bauxite residue.

Clarification. A process in which suspended material is removed from wastewater. This may be accomplished by sedimentation, with or without chemicals, or filtration.

Digestion. The process of decomposing organic matter by bacteria or chemical action or heat.

Dry stacking. 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.

Electrical conductivity. Routinely used to measure salinity. The types of salts (ions) causing the salinity usually are chlorides, sulphates (ms/cm).

ESP. Exchangeable Sodium Percentage (ESP) reflects the saturation of the exchange complex with Na relative to other cations present in the residue.

Estuarine deposits. 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.

Geo-membrane. A product used in layers along with the geo- synthetic clay liner as part of the disposal facility cover system.

Geo-textile. 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.

Glacial till. A mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited by a glacier.

Groundwater. Water stored in the soil and rock both above and below the water table.

Hydraulic head. 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.

Integrated pollution control (IPC). 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.

kPa. kPa is approximately the pressure exerted by a 10g mass resting on a 1cm ^{2} area.

Leachate. Water containing contaminants that leaks from a disposal site.

Limestone rock. Limestone is a sedimentary rock composed largely of the mineral calcite (calcium)

Maturing. The rate of drying out of the bauxite residue.

Neutralization. The process in which an acid reacts with a base to form a salt and water.

Permeability. The capability of a porous rock or sediment to permit the flow of fluids through its pore spaces.

pH. A logarithmic scale for expressing the acidity or alkalinity of a solution.

Piezometer. An instrument used to measure the level of the water table.

Pollution. 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.

Process sand. Graded medium sand having 90% and 10% of the particles smaller than 500 and 100 microns respectively.

Pulp density. Solids content.

Red mud. A reddish-brown bauxite soil remaining after the extraction process. The red colour is derived from the iron oxide content. It consists of porous agglomerated particles containing some 70% to 80% of amorphous oxides, hydrated oxides and oxy-hydroxides.

Residual dissolved caustic. It is this residual dissolved caustic which gives the red mud its elevated pH characteristics.

Rill volume 'soil loss'. This is a measure of soil detachment, while the erosion pin 'soil loss' indicates the transportation of soil down-slope.

Run-off. The gravity flow of surface water in open channels.

Salt cake. A by-product of the extraction of alumina from bauxite. It is considered a hazardous waste largely due to its constituent of oxalate.

Stoichiometric. 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.

Supernatant. The clear liquid remaining when a precipitate has settled.

Suspended solids. Any particulate matter which is suspended in water.

Sustainable development. 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".

The upstream method. On-going building of embankments upwards to contain the bauxite residue.

Thixotropic. 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.

Viscosity. Is the quantity that describes a fluid's resistance to flow.

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 and would call this Phase 2 of the BRDA.

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) asked the company to prove /demonstrate that the pH will fall to 9.0 or lower 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 Phase 2 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 a decrease 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 was only space at the production rates until 2011, it was 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 were 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 was necessary to demonstrate to the Regulatory Bodies that the pH of the run-off would 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 would 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 would 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 Cells which are lined, and 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 2004 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 in 2005 . 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 rather than manual digging and spreading.

Six one-tonne containers were filled with residue and leachate and run-off 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, 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 during the period that the work was going ahead with the plots and the Demonstration Cell.

Residue management systems and closure techniques of other alumina plants around the world were researched. Finally, a visit and tour were completed of a closed bauxite residue disposal site in Scotland in 2007. The company did recieve planning permission and an extended licence with restrictions around the closure plan in 2011. Residue was pumped into Phase 2 section in 2012 in small quantities while still pumping into Phase 1 section.

1.2 Rusal Aughinish

Figure 1 Rusal Aughinish Plant 2008

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.

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, Plant production started at 800.000 tonnes and has continually increased since start up in 1983 to current production of 1.85 million tonnes of alumina per annum (MTA). The Phase 1 B.R.D.A. was to provide storage to the end of 2011, based on these production levels and the new current planning permission allows 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. By adding these three extra stages it will hold the extra red mud production and have enough space until 2011 and allow commissioned of Phase 2 starting in 2012.

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 if Aughinished used these bauxites.

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 (Al_2 O_3.H $_2$O). The slurry is then filtered and calcined at 1000 ^{0}C to make alumina (Al_2O_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.The extension to the B.R.D.A 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

Two conditions of the licence 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." (Condition 14 IPC Reg No 562)

1.4.1 Residual Management Plan

The on- site residue area shall be operated 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.). Any amendments must be notified and agreed with the EPA.under the Land fill Status Report (Condition 7.4.11)

The Aughinish Residuals Management Plan includes the following:

- A scope of the plan.
- How the BRDA and the plant can be decommissioned with minimum impact to the environment.
- Waste analysis emergency procedures,
- Set up trials and test programmes for the decommissioning plan.
- the plan and a statement as to show how these costs will be covered
- Dust control
- Water management.
- Costing and a bond to cover costs.

A final validation report to include a certificate of completion for the residual's management, shall be submitted to the EPA within three months of execution of the plan. The company will have to prove to the EPA that all research tests / trials will be completed to ensure there is no 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 amend the residue, and sow grass. The results from these trials provided the "recipe" for the vegetation sown on the constructed sites. 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, the outcome of the trials would determine the environmental effects of closing the existing B.R.D.A. on the surrounding areas, namely the visual aspect, run off and its management to the river, control of dusting and safety of the embankment system.

The small trial plots were constructed and sown with grass in 2004, but were completly damaged by a contractor and another section selected and started again. This delayed this part of the research by 12 months. The second small plots were successful. The larger trial plots were constructed at the same time as the 2nd small plots were construcred. These were also amended and sown with grass.

The construction of the Demonstration Cells was initially delayed due to delays in releasing the funding of €250k. Construction went well, but the filling was slower than anticipated due to poor stacking angle of the residue so it had to be done much slower. The filling took 4 months in 2007 whereas it had been anticipated that it would take a few weeks. . Amendment took 6 months and vegetation took a few more months to grow. Under flow sampling of the leachate started as soon as filling was completed and contined for 2 years. Again, disappointment that there was no reduction in pH in that period.

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. Neutralisation systems were researched, and vegetation trials evaluated. The vegetation 'recipe' was decided following what had been successful in the small plots of 2004/205, including information from previous small plot trialls in 1999/ 2000.

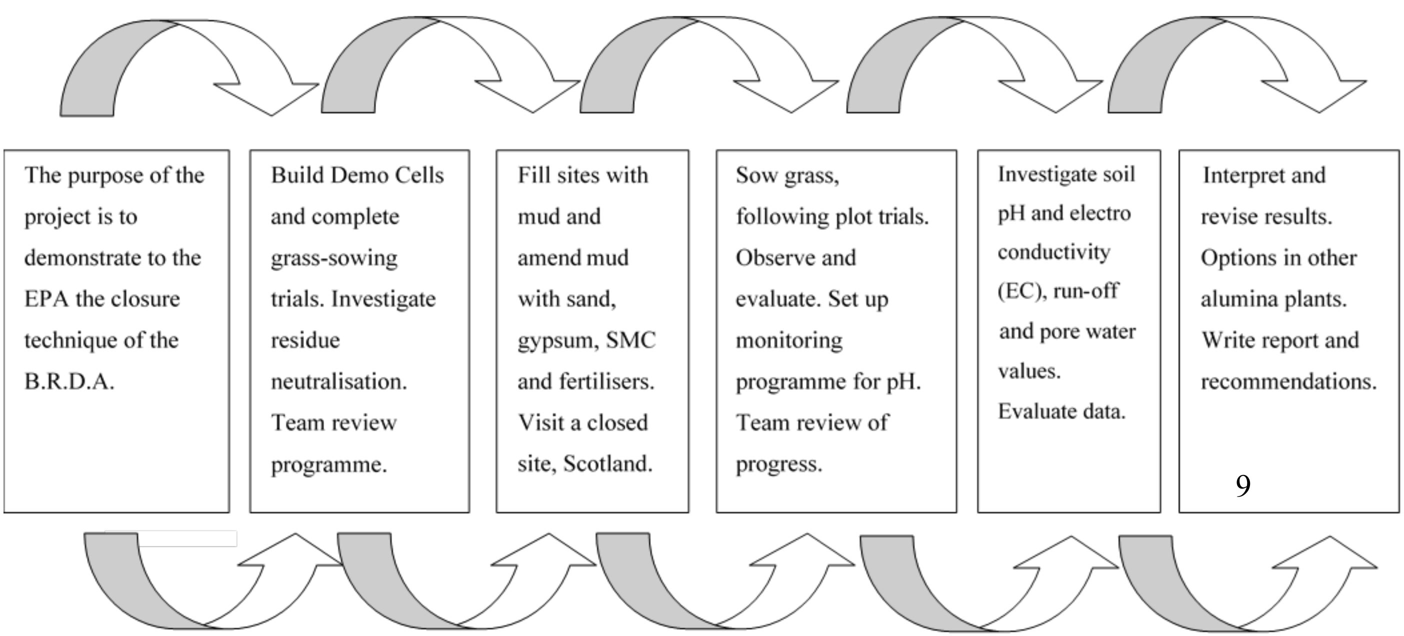


Figure 2 Programme Plan

Timeline: A revised EPA licence was issued in 2004 outlining the above requirements which included the building of the Demonstration Cells and the sowing of vegetation on the residue. Leachate and run off sampling were required to monitor pH trends. The ultimate aim was to get the pH down to 9.0 or below before pumping residue into the new extension of the BRDA Phase 2. (80 hectares). The pH was not at 9.0 by 2011 but the EPA allowed residue into the new section if Mud Farming was commenced immediately which gave partial neutralization of around 10.5 pH. All trials were to continue.

From 2004 to 2007 the construction of the small plots and the larger plots were completed; the residue was amended and grass growing trials commenced. In tandem with these trials, the engineering and construction of the Demonstration Cells were completed. Filling with residue started in May 2007 and completed after four months. Six months later grass was sown, and laboratory analysis commenced.

Monitoring of the vegetation on the trial plots and the cells contined in this period. The company purchased machinery in 2008 and commenced Mud Farming in 2009.

Research of residue treatment in other plants including their closure plans and rehabilitation of the residue continued. Methods of neutralization residue was on going on site and in conjunction with other worldwide plants. Laboratory trials were being conducted on acid and sea water neutralization in Aughinish laboratories.

The construction of the Phase 2 extension commenced in 2006 with the hope it would be ready when required in 2011 if the existing BRDA was at capacity. Some process changes in the plant were made which did help to extend the life of the Phase 1 area. The work on the 80-hectare extension was completed in 2011. The EPA granted planning permission in 2011 for the company to start filling the new area even though the pH of the residue was not at 9.0 provided they started Mud Farming. Also, they insisted that the company would continue to research more nutralisation methods. The author visited the closed refinery in Scotland in 2007 to see and evaluate how their rehabilitation had progressed. This visit again highlighted the slow if any reduction in leachate pH levels even after 3 years. Vegatation sustainability was important, and the trial plots were to be evaluated over the coming years along with the Demonstration Cells. The EPA were agreeable to the closure plan and the end use of the site when they gave the license extension in 2011.

1.5.1 Programme Planning

The expansion of the B.R.D.A. was 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 required the researching of this project to comply with the license. The alumina industry needed this research and further options in rehabilitation methods. The author had the professional expertise and knowledge which helped 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 on the residue. Would the soda levels in the bauxite residue affect amendment rates for vegetation? No plant including Aughinish had ever had a sampling method for leachate from under the mud. All these aspects were studied and evaluated. Knowledge was gained by the author and the company.

The E.P.A. requested the company to neutralize or part neutralize 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. Mud Farming was added to the equation as a means of partial neutralization. It was clear in 2011 that the company could not get the residue to a pH of 9.0 or less but the EPA accepted that it would take a few years to get sufficient analysis from the leachate and run off from the Demonstration Cells and to monitor trends. The Demonstration Cells (0.6 ha in size) were constructed which functioned like 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 were monitored for pH, electrical conductivity, and soda values including quantities. It was intended that the Demonstration Cells would provide an acceptable closure technique to the E.P.A.by sampling run off and leachate and recording pH levels. Also to test grass growing and sample leachate / run off before and after construction.As already stated the pH from under the residue in the Demonstarion Cell did nor reduce after 2 years, the vegetation cover was successful so EPA wanted sampling and monitoring to comtinue. So, in 2011 the research was to continue, and the company were given the licence to pump into Phase 2 of the BRDA as required. So, the plant was safe to continue in production.

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 the size of the BRDA every inch of rainfall that falls 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. The alumina industry worldwide was very interested in this project, and all plants are coming under increasing pressure to rehabilitate their residue areas as well 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 projest to upgrade them, and the management of the B.R.D.A. This led to a Post- Graduate Diploma in Environmental Protection. A year later the author completed an MSc in Environmental Protection. The long-term aim was to improve his knowledge of the B.R.D.A. and become an expert in this field. The company gave the author the time, the money and the authority to progress this project. From researching, visiting other plants and the hands-on work in the BRDA there is not doubt that the author gained good knowledge over the years. The company financed the project and the finance to complete the D Prof. 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. was $40 million and the cost of the Demo Cells was €250k.

The alumina industry worldwide was very interested in this project. 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 in 2003, Canada in 1981, and Brazil in 1995 including the start-up of an alumina refinery plant in Brazil. The author was involved in the engineering, scoping and commissioning of expansion projects associated with the water treatment plants and upgrades to settling and filtration processes prior to 2004 when he started on this project.

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 author the required skills to complete his doctorate. The company is confident of his involvement in the project and is providing the funding required to complete the project, which is a reflection of the author's knowledge and experience. The objects of the project were met, and all parts of the project were completed within budget. The authors knowledge of residue, settling and stacking of the residue also increased.

The people listed below were all involved in the project, and Ronan Courtney had been involved in previous grass growing trials in 1999. All members of the team are skilled, dedicated, very knowledgeable and experienced.

- Dr Ronan Courtney from University of Limerick was involved with earlier trials and completed a PhD in 1999. He is on contract with Aughinish for two years to monitor vegetation sustainability. He is a soil chemist and consultant.
- Mr Tom Hartney, the company Civil Engineering Consultant, has worked for over 20 years with the company and has been directly involved in designing, scoping all upgrades to the B.D.R.A. through the years. He was involved in the planning application to Limerick Co. Council initially.
- Mr Trevor Montgomery, the company Senior Environmental Engineer, and subject matter expert. He has been with the company for 6 years and is involved directly with the E.P.A. on all environmental matters. He has worked closely with Tom Hartney on planning applications and licence applications.
- Maintenance engineers for pipe-work scoping and engineering.
- I.L.A.B-accredited laboratory, two laboratory technologists for all analysis.
- And other personnel within the company. These included process operators to make process changes to divert pumping of residue to the Demonstration Cells as required during the filling process.

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 shutdowns 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.

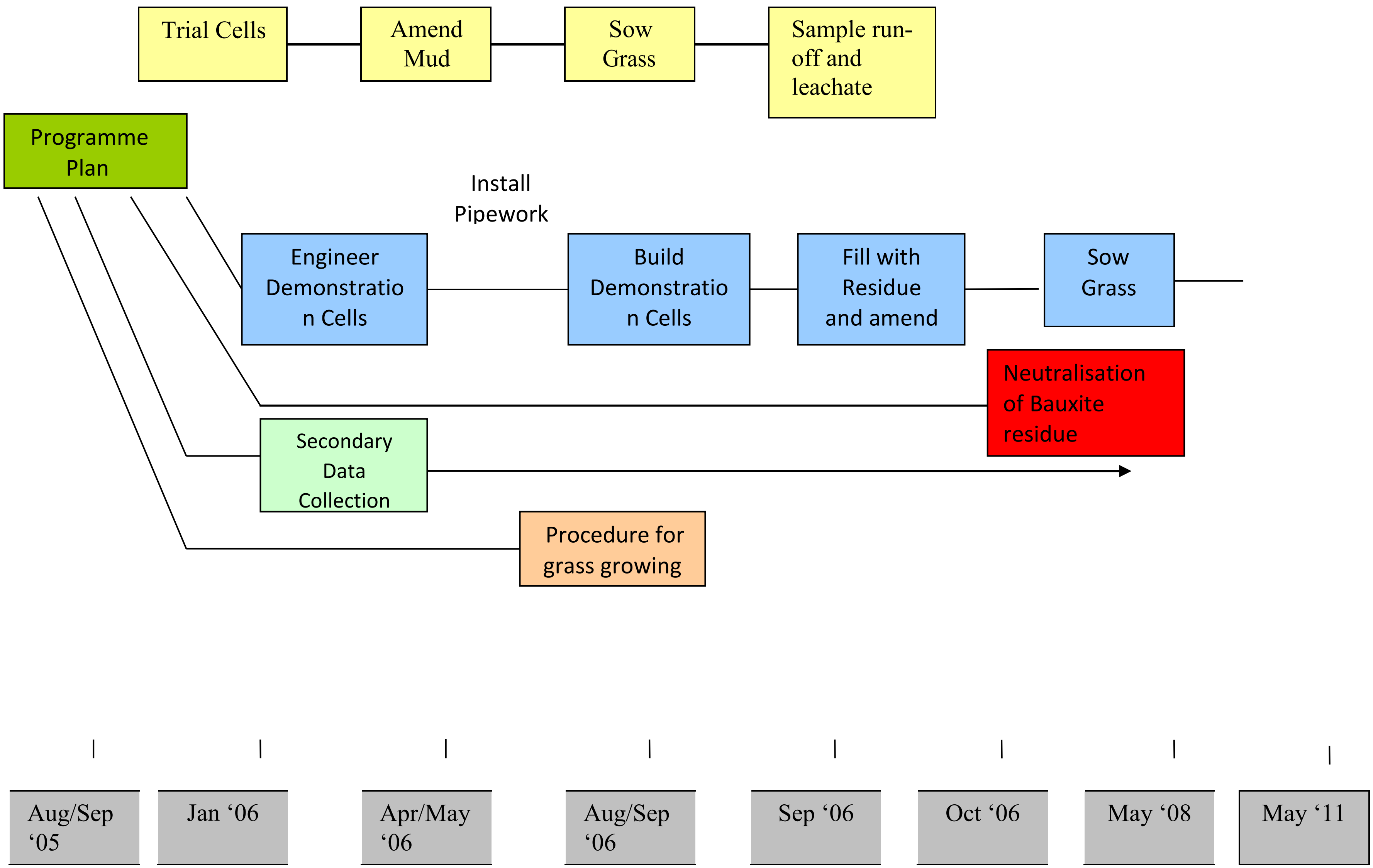


Figure 3 *Programme Timetable*

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.

The time to complete the grass growing trials, the construction of the trial plots, Construction of the Demonstration Cells, amending the mud and sowing grass was deemed achievable. Research into neutralization methods and trials in other alumina plants would continue in tandem.

Planning permission was given, and Phase 2 extensions was commissioned in 2011. Residue was pumped into it and Mud Farming commenced as soon as the residue had settled somewhat. The company continued to deposite mud in Phase 1 section at the same time as there was still some space left. My theseis was submitted to Middlesex University in 2011.

Chapter 2 - Rusal Aughinish Operation and Worldwide Best Practice

2.1 Residue Management at Rusal Aughinish

Management of the residue is a 24-hour requirement. Pumping rates and the control of the solid concentration requires close attention by the Control Room and process operators. If the solids are too low the mud will not stack up and space is lost. This was so important until the Phase 2 extension area was available.

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. There was only storage space in the Phase 1 section until 2011. The extension of 80ha would extend the life of the plant to 2026.

The company agreed with the EPA to carry out research into rehabilitation methods of the residue. 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 Wastewater 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 down into the mud to sample.

The EPA required the company to put a neutralisation system in place for the residue before any residue was stored in the Phase 2 extension. The other method to reduce the pH is by Mud Farming, which is atmospheric carbonation, this involves ploughing up the mud and allowing CO_2 in the atmosphere lower the pH. This process will give partial neutralization. A drop in pH from 13.0 to 10.5 was achieved. The EPA was agreeable to allow residue into Phase 2 in 2011 provided research continued with the Demonstration Cells and full neutralization systems would continue to be investigated.

Therefore, neutralisation options were researched and how the chosen system could be installed in the process to neutralise, or at least partially neutralise continued.

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 had requested that the residue area is capped at closure with sustainable vegetation to prevent dusting and improve visual aspect. 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, required 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 are seen by the company as the way to proceed. Annual "Neighbour Meetings "are held with the local community where future plans are discussed and listen to their concerns.

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 at Rusal Aughinish are as follows.

Bauxite residue is the term for the red mud material which is left after dissolution in Digesters of the bauxite with hot caustic and steam under high pressure. This process is called the Bayer Process, although over 100 years in existence it is the best method to process bauxite into alumina. Given the high-quality bauxite Aughinish processes there is approx. 0.7 tonnes of mud for every 1.0 tonne of alumina produced. Bauxite residue is itself made up of different size fractions. The fine fraction termed red mud and a coarse fraction termed process sand.

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 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 Aughinish bauxite residue is approximately 90% red mud and 10% process sand (+100 microns). The process sand fraction is removed via a sand trap before the mud circuit. The red mud passes through three Washing tanks to remove as much caustic as possible. It is finally washed in drum filters where the soda concentration is down to 8-10 g/l and then pumped to the B.R.D.A. The process sand consists of an agglomerate of particles of less than 1000 microns. Process sand is trucked to the B.R.D.A. and is used to create perimeter embankment walls and roads within the BRDA. And is also used to help amend the residue in preparation for grass sowing. The red mud contains a residual concentration of sodium 8-10 g/p/l Na_2O in liquid phase, with approximate mineral make-up of 45% Fe_2O_3, 20% Al_2O_3, 10% TiO_2, 10% SiO_2, 7.5% CaO, 7.5% Na_2O_3. The mud is analysed daily.

The bauxite residue consists of porous agglomerated particles containing some 70% to 80% of amorphous oxides, hydrated oxides and oxy-hydroxides. This is the Aughish process

Particle size of the bauxite residue indicate that the material is largely silt size with liquid limits between 40% and 50% after deposition and 90% particle size smaller than 35 micron and 35% smaller than 2 micron. 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. The permeability of the mud is low, and the specific gravity of dry mud solids is 3.3.

The process sand has 90% and 10% with particle sizes smaller than 500 and 1000 micron. The permeability of the sand is estimated to be 1000 times greater than the permeability of the red mud.

The dry density of the bauxite residue varies between 1.3t/m_3 and 1.6t/m_3, which increases with depth, and the average dry density beneath the stack walls is 1.41t/m_3. The overall average dry density of the bauxite residue forming the dome area, however, will be less than this and closer to 1.35t/m_3 (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. from the Filtration section via distribution pipelines and discharge network. The network has 13 discharge points that are 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 should be allowed to dry somewhat before the next layer is placed but due to storage constraints that is not possible now. 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 is pumped through three stages of counter-current washing and thickening, followed by vacuum drum filtration, where it exits the filters at 65% solids filter cake and then is diluted to 60% with process condensate in Reactors The red mud is mixed and sheared in these Reactors 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-Hazard.

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 via a number of discharge points in a central area forming a slope of 10 H:1V (6 degrees). With this approach, it was designed for a 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 the initial start-up that the 10H;1V slopes could not be achieved. There are three distinct design phases in this structure:

- Phase 1 B.R.D.A. 90 The B.R.D.A is a structure engineered land fill to store bauxite residue and is not lined. Its foundations of glacial till and estuarine sediments removed from the site initially and it provides attenuation to alkaline leachate generated within the B.R.D.A. All leachate is recovered and returned to the Waste Water Treatment Plant for treatment before pumping to the river Shannon.

- The Phase 1 B.R.D.A. extension 40ha has a foundation of screened glacial till with a composite lining of high-density polyethylene (H.D.P.E) 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 foundation material and synthetic lining of the B.R.D.A. is installed to reduce seepage to a minimum of the alkaline leachate in the surrounding areas and environment. The filtration of high-density residue, up to 60%, reduces the volume of water held in the red mud and storage thus also helping to avoid any excessive seepage into the soil or ground water which could exceed planning permission. 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 the 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 storing waste residue and extends the life of the BRDA. This is a process where the embankment is constructed ‘upstream’ of the initial embankment on previously placed residue. The company had hoped to go to thirteen lifts or stages on its planning application.

The upstream embankment side slopes are 3H:2V, providing a 33o wall slope and approximately 2m high. The sequential upstream embankment slope of 6H:1V give enough space between each embankment lift to provide suitable foundation on the residue. There is a sequence of 13 contiguous upstream stages planned which will give a final. elevation of 24m AMSL and a central discharge elevation of 32m AMSL. The embankment lifts are constructed of rock placed over either a layer of process sand or a geo-textile liner fabric. As part of the planning permission Phase 2 works, a further rock filtering system will be installed to trap any red mud getting through the embankment.

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 where it is sent to the Waste Water Treatment Plants for neutralisation and discharge to the Liquid Waste Pons and then under license to the river Shannon. (Figure 4). The perimeter interceptor channel and the Storm Water Pond are lined with a composite HDPE/Glacial till or GCL/Glacial Till. The available storage facilities can handle 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. 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.

Figure 4 Embankments on east side of the B.R.D.A. and Storm Water Pond. 2006

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. If the pumps trip it shuts down the Filtration building. Maximum condensate wash flows to the vacuum filters are also important to reduce caustic soda levels in the residue going to the BRDA.

2.3 Principles of Sustainable Tailings Management

Red mud (residue) from the process has little or no value and although a few uses have been devised nothing significant has been discovered to date. Some use for red mud includes soil amendment in Australia. Some soils in Western Austrlia are acidic, so residue from refineries around Perth was used to raise the pH of the soil with some success. Plants in Japan and plants in Indai have used it in the manufacture of lime and the manufacture of Portland cement. Construction has used it as a filler in road construction. Some further information later in the thesis on possible uses.

Residue on the BRDA although accepted to a degree by government agencies and the general public it is about tolerated but still causes concern. The Fishery Board is concerned about any environmental pollution in the effluent water going to the river. The licence parameter of the effluent include hourly / daily pumping rates, solids concentration, pH, and heavy metals.The automatic control system can shut the pumping down if the parameters are exceed for 5 mins. Instrumental control on pumping parametes is managed very well. Regular review of community attitudes and operational practices are undertaken by the company with "Neighbour Meetings" which are held annually. Concerns centre around possible failure of the embankments and residue entering the river. Fall out from the boiler's stacks and Calciner stack are monitored in the surrounding countryside in a radius of 10km. These air monitors are sampled monthly, and the results posted on the EPA website

Aughinish must ensure that all stakeholders understand these risks with the BRDA and of future developments, upgrades, and applications for planning permission, etc. Local people have been well-informed with their Annual Meetings with the company, and this increases their knowledge of the process. Bus tours of the site are arranged including the BRDA. One group of farmers in one locality regularly write articles in the local papers claiming there has been fall out from the stacks or there is a risk that the embankments holding the mud will burst and mud will get into the River Shannon.

Aughinish aims to have sustainable development in all its actions and projects and for that reason it has employed a skilled work force, abides by all Irish and European Legislation completes risk assessments, and communicates with all stake holders.

The company has the following systems and procedures in place:

- a good environmental management system (ISO 14001)
- a safe BRDA for residue waste, risk assessments, following world class practices and procedures.
- adheres to appropriate and agreed post-closure operations and land use.
- consultation with interested parties on social, health, safety, environmental and economic impacts associated with these activities.
- informing all parties of significant risks from the operations of the plant and the management of those risks. "Neighbour Meeting" with local residents.

2.4 Elements of Sustainable Tailings Management

The company has in the design of the BRDA what the post-closure land use will be, and the final closure of the plant, it has shown its commitment through regular transparent reporting to the EPA and the community that it will meet these and exceed those commitments. The company aims to achieve a stable and self-sustaining vegetation on the residue by building and commissioning the new Demonstration Cells before closure occurs, so that the closure plan can be finalised and engineered (DITR, 2006).

Following the construction and testing the cells it is then possible to see if the pH will fall to 9.0 and how it will impact on an environment.

A sustainable tailings management principle will provide the required systems to avoid any breaches of the licence in a closure plan. Based on the Strategic Framework for Tailings Management (MCMPR and MC, 2003), the key issues that need to be addressed for closure are:

- prevent any escape of the residue / leachate into the environment.
- limited seepage of contaminated leachate to surface and ground-waters.
- surface cover to prevent erosion from the tailings storage facility.
- aim to minimise post-closure maintenance and cost in manpower, running costs.
- risk and controls to avoid airborne emissions.
- modelling of hydrological/hydro-geological impacts.
- planning to execute the closure requirements.
- continue to consult with stakeholders.
- work to maintain the company's Certified Environmental Management System ISO14001.

The above 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 are carried out for each new lift stage that is constructed and this provides stability of the embankments which reduces the risk of leakage or possible failure.

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/m3 and 1.45t/m3 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 solids' concentration goes down, water and solids separate. If the density goes down further, erosion of already deposited mud will be washed towards and fill up at the embankment. For the above reasons it is important to keep the pulp density up to 56-57% solids.

At a pulp density of about 57%, the moisture content of the bauxite residue is approximately 75%. After the mud is deposited on the previous layer the moisture content decreases and the solids % increases. Typically, the moisture content decreases to about 45% and the solids content increases to about 70%. As the moisture content of the bauxite residue decreases, both shear strength and dry density increases, and its volume decreases. The maturing of the mud is by the following,

- air-drying of the surface of the bauxite residue by evaporation; and

- Consolidation of the bauxite residue under its own weight.

Both wind and sun contribute to evaporation although wind is the main process and therefore occurs throughout the year. 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.2007

Figure 6 North-West Corner of B.R.D.A.2007

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 40m from the discharge outlet, about 4% at a distance of 80m, 3% at 160m, 2.5% at a distance of 200 m and 2% at 300m from the discharge: 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 & Enviroplan Services Ltd,1999).

The height of the B.R.D.A. at its apex is governed by a Limerick County Council (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 stability of the upstream rock embankments and terraces around the mud stack perimeter is checked by the analysis of the un-drained mud. The soda content of the residue is minimised by adequate washing and filtration to optimise soda recovery in the plant.

The integrity of all high-density polyethylene (HDPE) geo-membranes for environmental protection is maintained. No mobile equipment is permitted direct contact with the high- density polyethylene (HDPE) 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 to the River Shannon are maximised to ensure that there is sufficient operational freeboard for major rainfall events. This is achieved by the operation of the Waste Water Treatments plant to max efficiency.

There are 37 areas of bauxite residue covered using sprinklers to prevent dusting. Other techniques, such as mud farming and ploughing, are being tested and developed to replace use of hay and straw deposition to control dusting. 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. There are 40 wells around the BRDA at toe drains, external watercourses and groundwater wells which are sampled every month to monitor for any leakage of liquids from the mud stack. (Aughinish Operational Plan Sept 2004)

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, 2km to the south and the town of Askeaton, 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 building 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 1 Successive strata and thickness (m)

Successive Strata	Thickness (m)
Estuarine Deposits	0 to 20
Glacial Till	4 to 8
Carboniferous Limestone Rock	> 100

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 residue from the plant shows 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 is in the range 1 x 10-8 to 1 x 10- 9m/sec. The permeability of the mud decreases as the mud matures from its initial to final solids content.

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 pumped in the mud stack area are bauxite residue and process sand solids which is trucked and includes liquid trapped within the slurry. The solids are stack up within the area, and part of the liquid is dispersed through evaporation, seepage, leachate and as bleed water to the perimeter channel.

The results of an analysis of bauxite residue are summarised in (Table 2). The principal constituents of the bauxite residue solids are iron oxide (Fe_2O_3), aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2). The liquid trapped within the bauxite residue contains about 8-10g/l soda (sodium hydroxide) and alumina even after four stages of washing. It is this caustic which gives the bauxite residue its high pH.

Table 2 Principal constituents of bauxite residue at Rusal Aughinish

Principal Constituents of Bauxite residue at Aughinish	
Ferric Oxide (Fe_2O_3)	27.5%
Aluminium Oxide	22.0%
(Al_2O_3)	20.0%
Titanium Oxide	7.0%
(TiO_2)	3.5%
Silica (SiO_2)	11.0%

2.6.8 Residue Analysis

The EPA License states that the waste analyses shall be carried out in accordance with Schedule 3(iv). Figure 7 shows the internal analysis and Table 3 shows analysis of bauxite residue, etc.

Waste Class	Frequency	Parameter Note 1
Bauxite residue	Monthly	pH, dry matter, total alkalinity, chloride, fluoride and soda
Sand	Monthly	pH, dry matter, total alkalinity, chloride, fluoride and soda
Salt cake	Monthly	pH, dry matter, total alkalinity, chloride, fluoride and soda
Sludge from the biological Sanitary treatment plant	Annually	pH, dry matter, organic matter, nitrogen phosphorus and heavy metals.
Leachate from the bauxite residue Stack	Monthly	pH, total alkalinity, chloride, fluoride and soda

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

	Bauxite residue	**Process sand**	**Salt cake**
Total Alumina (Extractable & Non-Extractable)	**9.3%**	**9.0%**	**.8%**
Fe_2O_3	**2.4%**	**1.8%**	
TiO_2	**.5%**	**.8%**	
SiO_2	**.0%**	**.1%**	
NA_2O	**.1%**		
CaO	**.6%**		
H_2O			**5.2%**
$Na_2C_2O_4$			**8.6%**
Na_2SO_4			**.8%**
Na_2CO_3 **NaOH expressed as Na_2CO_3**			**0.0%** **2.5%**
Org. Carbon			**.5%**

Table 4 Summary of Eluate Results

Summary of Eluate Results (1 of 1)

EC Draft Directive

			12/2/92		12/7/92	1/14/93		2/17/93		3/15/93		4/9/93	
Hazardous Range mg/l	Insert Range mg/l	Parameter	Eluate Measured (mg/l)	Second Leaching (mg/l)	Eluate Measured (mg/l)	Eluate Measured (mg/l)	Second Leaching (mg/l)	Eluate Measured (mg/l)	Second Leaching (mg/l)	Eluate Measured (mg/l)	Second Leaching (mg/l)	Eluate Measured (mg/l)	Second Leaching (mg/l)
4-13	4-13	pH	11.30	10.20	12.29	12.43	-	12.16	-	11.96	-	11.96	-
0.2-1.0+	< 0.1	Arsenic	0.02	0.03	0.02	< 0.01	-	0.06	-	0.01	-	0.02	-
0.4-2.0	*	Lead	< 0.01	< 0.01	< 0.04	< 0.05	-	< 0.05	-	< 0.05	-	< 0.05	-
0.1-0.5	*	Cadmium	< 0.01	< 0.01	< 0.01	< 0.01	-	< 0.01	-	< 0.01	-	< 0.01	
-	-	Chromium	0.05	0.02	-	0.03	-	0.03	-	0.19	-	0.36	-
0.1-0.5	*	Chromium (Hexavalent	-	-	< 0.01	< 0.01	< 0.01	-	< 0.01	-	< 0.01	-	0.19
2-10	*	Copper	0.01	< 0.01	0.08	0.03	-	0.02	-	0.07	-	< 0.01	-
0.4-2.0	*	Nickel	< 0.01	0.01	0.06	< 0.01	-	< 0.01	-	< 0.01	-	< 0.01	-
0.02-1.0	*	Mercury	< 0.01	< 0.01	< 0.005	< 0.005	-	< 0.005	-	< 0.005	-	< 0.05	-
2-10	*	Zinc	0.02	0.02	0.05	< 0.01	-	< 0.01	-	< 0.01	-	< 0.01	-
10--50	< 5	Fluoride	7.70	1.80	3.05	5.08	1.03	3.99	1.87	0.65	0.63	0.85	0.56
1200-6000	< 500	Chloride	6.30	7.00	6.78	20.92	-	29.46	-	12.59	-	11.96	-
6-30	< 3	Nitrite	< 0.02	< 0.02	< 0.10	< 0.10	-	< 0.03	-	< 0.1	-	< 0.1	-
200-1000	< 1000	Sulphate	23.00	8.00	3.66	85.59	-	71.35	-	63.74	-	58.6	-
0.2-1.0	< 0.1	Cyanide	< 0.02	< 0.02	< 0.01	< 0.01	-	< 0.05	-	< 0.05	-	< 0.05	-
40-200	< 200	TOC	27.30	16.30	75.65	10.74	-	6.24	-	24.32	-	16.48	-
200-1000	< 50	Ammonium	1.44	< 0.02	< 0.01	0.4	-	0.53	-	0.07	-	< 0.1	-
20-100	< 10	Phenols	< 1.0	< 1.0	-	-	-	-	-	-	-	-	-
0.6-3.0	< 0.3	AOX	-	-	-	-	-	-	-	-	-	-	-
0.02-0.1	< 0.01	C1. Solvents	-	-	-	-	-	-	-	-	-	-	-
0.001-0.005	< 0.0005	C1. Pesticides	-	-	-	-	-	-	-	-	-	-	-

0.4-2.0	< 1.0	Lipoph.Sub.	-	-	-	-	-	-	-	-	-	-	-	-
		Electrical Cond	0.93	0.33	-	-	-	-	-	-	-	-	-	-

- * Total of these metals < 5mg/1 and no single result greater than the minimum set for
- * hazardous waste
- * This range refers to limits set for trivalent arsenic
- * Sulphate < 500mg/1 if possible
- * All results for metal anlytes reported as total unless otherwise state
- * Electrical Conductivity in mS/cm
- * Dash (-) in results column indicates

2.7 Bauxite Residue Disposal Area (B.R.D.A.)

Figure 8 East Embankment also showing corner of Storm Water Pond and Shannon River 2008

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.

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 L.W.P. prior to pumping 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. This vegetation has been trialled in the BRDA and will determine the type of grass used in the Demonstration Cells.

Groundwater is monitored in the vicinity of the B.R.D.A., there are 40 observation wells around the site, and the objective of the monitoring is to ensure that seepage from the residue does not raise the back-groundwater concentration 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 Aughinish 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 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 Aughinish 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 ($Al_2O_3xH_2O$) 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.

This is controlled in the Filtration building by the addition of condensate and filtration performance. The yield stress of this material ranges between 25 and 50 Pa (which corresponds to a residual slump height of 15- 25 mm. Daily sampling and analysis of the residue is carried out in the laboratories. 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). The control of % solids is one of the most crucial aspects for mud stacking height and 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.

Control and monitoring by the process operators is key to this parameter. Optimising the coverage on the drying areas has become one of the key operational tasks in recent times and this is helped by regular changing over of the discharge points. This system has been automated in recent years to assist as it was a high labour activity. Significant capital for expansion of the BRDA can be deferred if maximum use is made by controlling the density and stacking angle of the mud. Space in the BRDA will run out by 2011 so the EPA permission to extend to Phase 2 is critical.

Aughinish measures drying rate in terms of the annual storage rate, this capacity is measured monthly.

Figure 9 East embankment 2007

2.8 Residue Handling and Placement

The mud is 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.

Any mud or sand trucked onto the bauxite residue stack is via roads constructed by sand 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. process sand is placed onto bauxite residue surfaces provided the mobile plant is moving on at least 1 metre depth of process sand.

2.8.1 Water Management

The region around the Shannon estuary has low-pressure cyclonic weather systems and frontal rain bands which move in from the North Atlantic Ocean. During winters months there can be frequent spells of rain, during summer they can be periods of high-pressure bringing in drier weather warmer temperatures with good sunshine periods.

See table below of rainfall and evaporation data for the B.R.D.A. (Adopted Shannon Airport data,) are provided as an estimate of the site climate balance (Table 5).

Table 5 Weather Data

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

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

The site has a positive water balance, the excess water must either be recycled to the plant or it is pumped to the River Shannon, which is part of the EPA license.

2.8.1.1 Refinery / B.R.D.A. water balance

Rainfall contributes most of the water input at the BRDA. In order to control dusting the sprinkler system is used which has a large input of water onto the mud. Some water is added from the red mud but this very small. For every 20 mm of rain that falls on the residue it equates to 28,000m^3 of run off. All this runoff water must be processed in the Waste Water Treatment Plants for solids removal and pH adjustment before pumping to the Shannon River under licence.

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 is put through a process of neutralisation, clarification and cooled in the LWP. before pumping to the river Sulphuric acid is added for neutralising and flocculants are added to settle fine particles in a clarifier. Clarified effluent to the Liquid Waste Pond (L.W.P.).and then to the Shannon i. Discharge to the Shannon is licensed up to a rate of 21,000 m^3/day or max 1,700m^3 per hour.

2.8.1.3 Storm Water Management

The upper interceptor channel is 130 ha for both Phases 1 and 2. With a total storage volume of 100,000m^3. To manage rainfall up to a 1 in 200 year storm event the facility has a total capacity of 375,000 m^3. This includes normal storage and storage held within the P.I.C. and S.W.P. A minimum freeboard is maintained at all times.

- S.W.P - 1.0 m
- P.I.C. – 0.5 m.

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 4.2m 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 pumping rate.

The maximum operating volume can increase from 180,000m^3 to 249,000m^3 for the 750m^3/hr pumping rate to the river. 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. depends on the low permeability of the estuarine soils and the residue to reduce seepage of the high pH liquor that seeps through into the perimeter channel. It has been identified that seepage is dependent on:

- Defects in the liner if in place.
- The permeability and thickness of the clay liner.
- The hydraulic head acting across the composite liner where it is installed.
- The permeability of the bauxite residue.

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

Phase 2 B.R.D.A. has a composite lined layer and has a perimeter interceptor channel around it.

A third of the Phase 2 B.R.D.A. footprint encroaches on the townland of Glenbane West. Golder Associates specifically surveyed 7 ha to determine if seepage could migrate away from the B.R.D.A. and further inland. Their survey showed that the majority of seepage will migrate towards the Poulaweala Creek underneath the site and will be buffered by the saline groundwater. The double composite lining system will be installed consisting 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 recorded. 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, salt crystals form on the surface as the caustic soda reacts with the carbon dioxide in the atmosphere. Frost can blister the surface of the mud in the winter. These conditions could cause dusting to happen with the risk of being carried over the perimeter of the plant. The area is monitored by cameras and regular patrols by operations and monitoring of weather conditions. There have been no dusting incidents to date.

Aughinish, has trialled a variety of dust suppression techniques to control dust generation at the BRDA. They include:

- spraying of the residue surface with fresh water to dampen the surface.
- rotation of the discharge points putting wet fresh residue on previous layer.
- mulch, crushed rock, and hydro-mulching
- Hay, straw, animal manure and flocculants.
- improved washing of the mud to reduce the soda content, which in turn will reduce surface carbonation and precipitation process.
- limiting traffic on access road at the B.R.D.A which can generate dusting.
- planting of grasses and vegetation in exposed areas.

Presently 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 piping of the sprinkler system is periodically extended as the red mud is raised.

All trials lasted for a period of time and are neither were 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 amend the bauxite residue to overcome the physio-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 was used and ploughed 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. after plant closure.

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 1m^2 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

	Oats	**Yorkshire Fog**
Bauxite residue	60%	45%
Bauxite residue + 20% process sand	66%	50%
Bauxite residue + 3% Gypsum	80%	70%

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 un-weathered 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) citied ESP of 40%-50% affects nutrient levels in plants.

Table 6 Bauxite amended with sand and gypsum chemical parameters

	Before amendment	**After amendment**
pH	11-12	8.6 – 9.5
EC (ms/cm)	2.6	0.5-0.8
ESP (%)	67-82	12-31
Al (mg/kg)	43	<1 - 1.8

2.9.3 Organic Amendment

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, 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 periods are shown.

Figure 10 The physical and chemical properties of bauxite residue before amendment. (prior to re-vegetation) 1999

Figure 11 The physical and chemical properties of bauxite residue after amendment (prior to re-vegetation) 2000

Figure 12 Effects of different amendments on grass growth (Gypsum, SMC)

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 g1); (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 m1 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 m1, severe between 400–600 ms m1, and very severe with death at >600 ms m1 (Maas, 1990). Untreated bauxite residue is highly saline with EC values in the range of 3000–4000 ms m1 (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 rage of 6.6 to 7.3 (Munshower, 1994). High pH associated with sodium carbonate in alkaline soils may affect anion up take 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 up take 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 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 physio-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 the 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 Demonstration 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 If vegetated successfully it would eliminate the risk of dusting, so an added] benefit. 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 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). Aughinish because it has a surplus water balance it is unusual in the alumina industry to develop a re-vegetation methodology. The B.R.D.A. receives approx. 900 mm of rainfall each year, which equates to $27m/m^3$ of run-off on the residue. The Australian plants have done most research in plants that have a water deficit. In plants like Aughinish the project will focus on providing suitable drainage systems. Sand will help provide this drainage and help reduce the chances of capillary rise to ensure that the vegetation survives (Alcan Gove Bauxite residue re-vegetation research programme May 2005).

This soil profile above the bauxite residue is viewed as an essential part of the re-vegetation program. Process sands in the re-vegetation, soil horizons have the same nutrient and organic matter deficiencies in the 1999 trials along with 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 with residue. The most suitable amendment rates for the residue in the Demonstrations Cells were known from the previous plot trials.

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 Luis in 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 mycorrhyzas 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 Luis, 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 mycorrhyzas 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 valves 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 must 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 2000

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 1996. 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).

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 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 mean 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.

2.16.1.1 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.

Feed	kg CO_2/kL	Reaction
Al_2O_3 (liquor)	5.1	$NaAl(OH)_4 + CO_2$-□ $NaAlCO_3(OH)_2 + H_2O$
TC (liquor)	6.4	$NaOH + CO_2$ □ $NaHCO_3$
TA (liquor)	0.8	$Na_2CO_3 + CO_2 + H_2O$-□ $2NaHCO_3$
TC (adsorbed)	3.4	$NaOH + CO_2$ □ $NaHCO_3$
TA (adsorbed)	0.2	$Na_2CO_3 + CO_2 + H_2O$ □ $2NaHCO_3$
TCA-6	15.8	$3Ca(OH)_2.2Al(OH)_3 + 3CO_2$ -□ $3CaCO_3 + Al_2O_3.3H_2O + 3H_2O$
DSP Na_2O	1.8	$Na_6[AlSiO4]_6$ $2NaOH + 2CO_2$ □ $Na_6[AlSiO4]_6 + 2NaHCO_3$
Total	33.7	

Table 7 Stoichiometric carbon dioxide demand required to treat thickened residue slurry

2.16.2 Mud Farming

The application of ‘mud farming’ to the bauxite residue deposited within the B.R.D.A. commenced at Aughinish in 2009. This system originated in Australia and the machinery purchased by Aughinish came from an Autralian company. It is being widely tested in Australia 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.

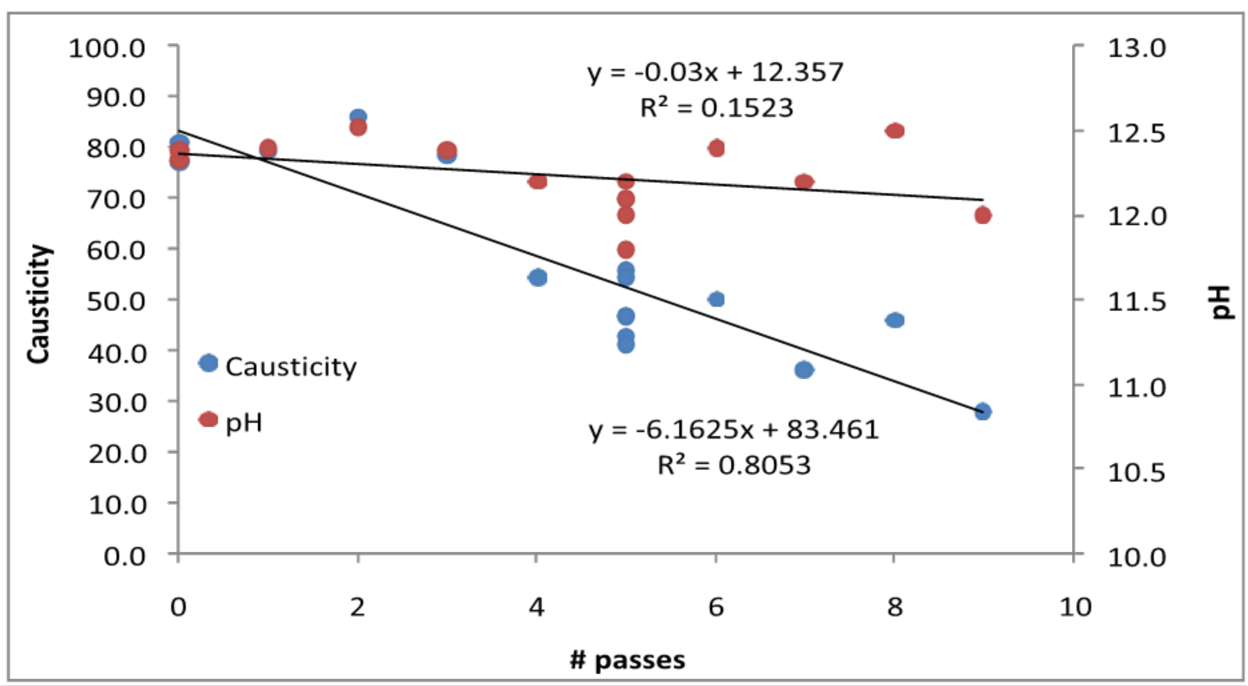


Figure 17 The relationship between the change in causticity and pH as a function of the number of passes with amphirol for samples taken in Cell 3 within the B.R.D.A.

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.

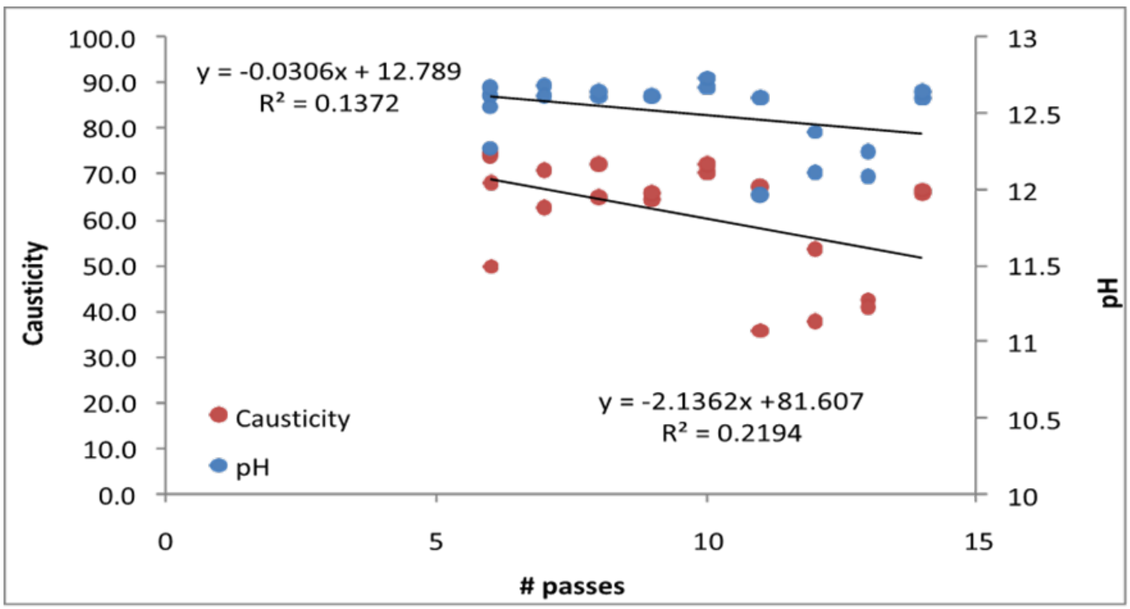


Figure 18 Relationship between the change in causticity and pH as a function of the number of passes with amphirol for samples taken in Cell 6 within the B.R.D.A.

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 60cm.

- 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.

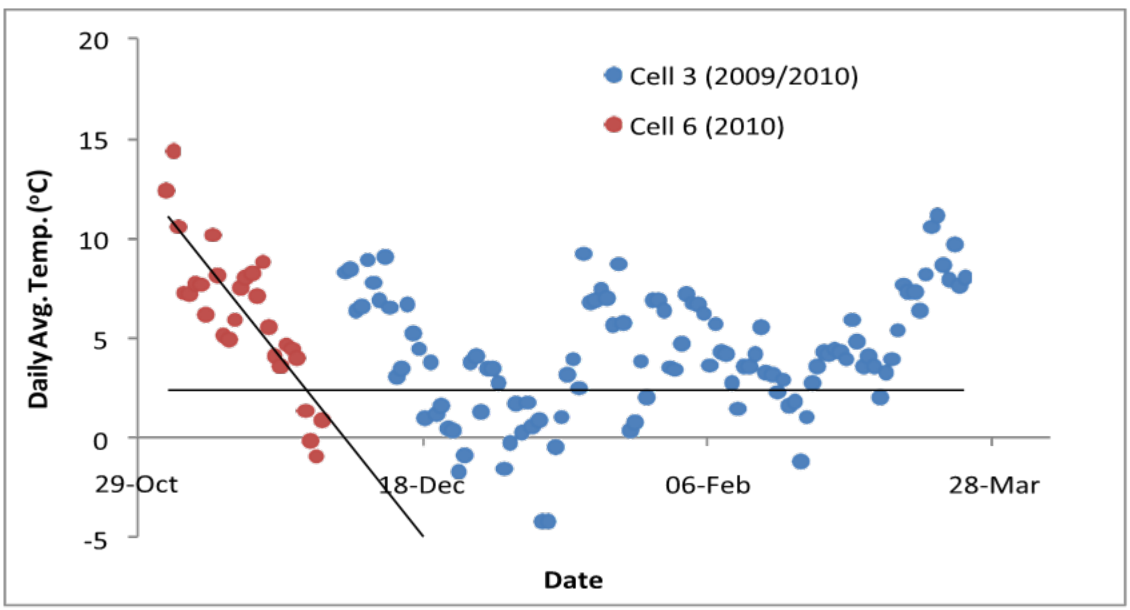


Figure 19 The daily average temperature at the B.R.D.A. during testing periods of Cell 3 and Cell 6.

Figure 20 Residue mud before farming (some sprinklers on)

Figure 21 Residue Mud after Mud Farming

Conclusions

Mud farming is 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 11.0 to 10.5

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.

The company have introduced a second ploughing system with a machine called a “Spader”, this is being trialled since 2018 and involves further ploughing after the Amphirol. It ploughs and breaks up the mud and gives added exposure of he mud to the atmosphere to reduce the alkalinity further.

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 Ca2+ 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 metalliferous 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 de-vegetation 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. 1×10-7 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 d50 = 4 μm from Figure 22 below.

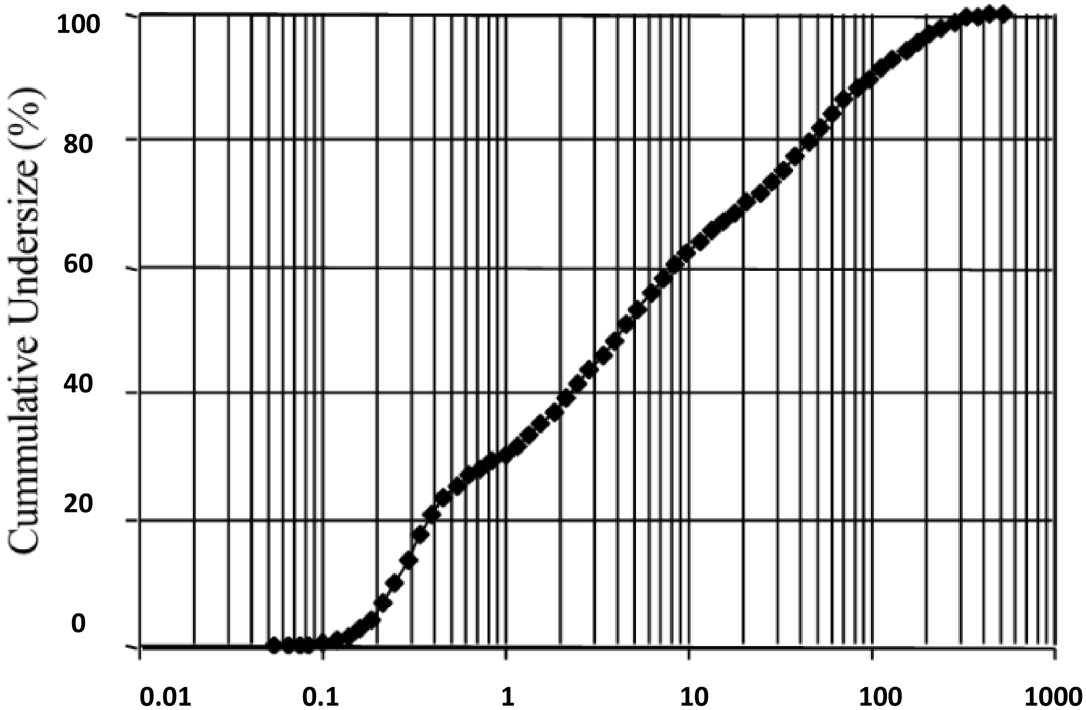
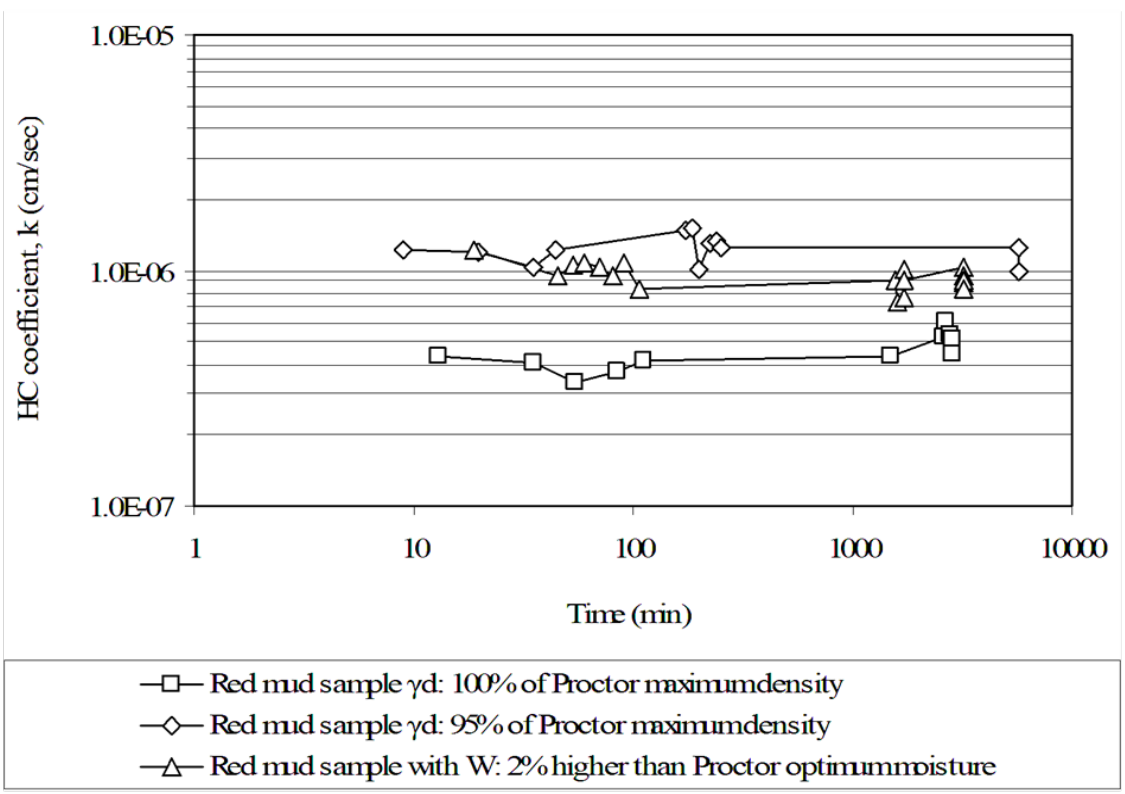


Figure 22 Particle Size distribution of Bauxite Residues

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 3×105 to 4.6×107 cm/sec, depending on the compaction conditions. The lower value of permeability (4.6×107 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., 1×10-7 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□106 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□107 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 Fig 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 1×10-7cm/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 co-efficient. 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 580m^2 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

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.

There were also two Aughinish personnel working in the Gove Plant on two-year assignments. I had discussions with them and gained further information on their operation. 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, $CaSo_4.2H_20$) 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), "Sub- soil" 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.

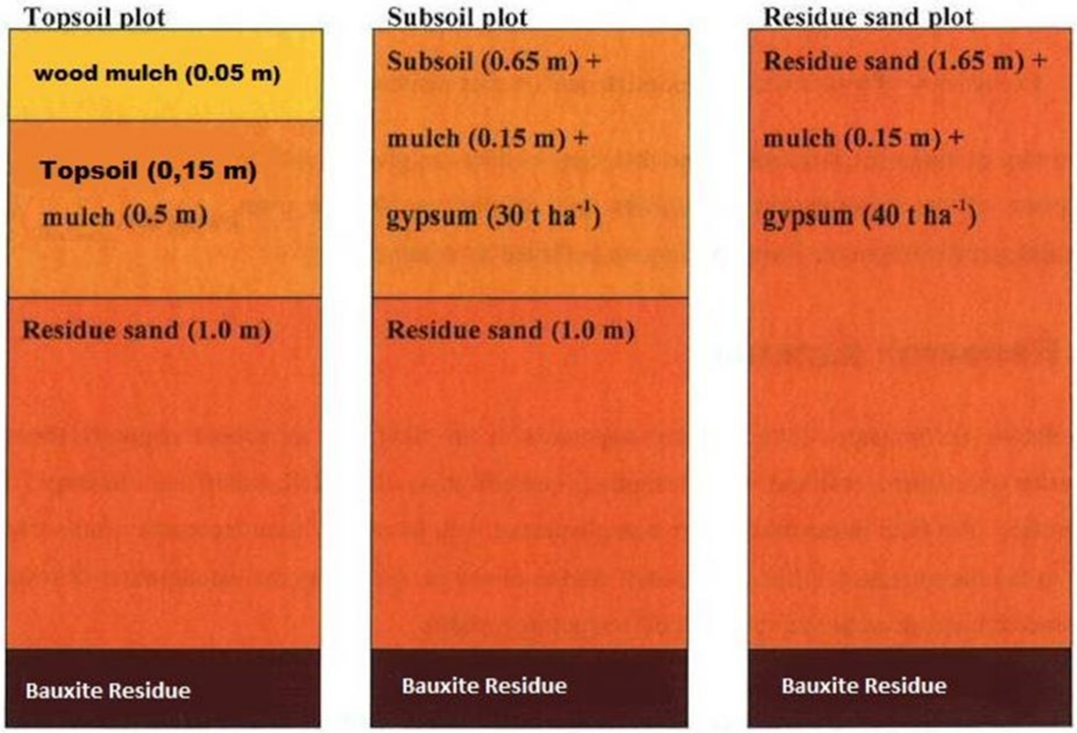


Figure 24 Schematic presentation of the three capping sequences evaluated at the B.R.D.A. in Alcan Gove, Australia

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.

Comments

It would appear that the non-uniform application of seed and the amendments were not good enough, which resulted in bare patches in the larger plots at Aughinish. Generally, spreading by hand had been a reliable method at Aughinish, but some bare patches have occurred which had to be re-treated. Pooling of rainwater on the residue also contributes to lack of growth. Results from other sites mentioned similar problems; in the Brazilian trials it could be assumed that some cappiliary rise caused these bare sections. Non- uniform applications are deemed to be of major concern when amendment is required over a large area. This was more apparent in Aughinish when machinery was used to spread sand, and gypsum because the trial area was exposed, and the wind blew the product away from the spreader. Photos later in thesis show this. 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, they had god drying periods. Similar to the Aughinish trials amendment greater than 40t/ha of gypsum did not have any benefit on vegetation cover. The starting pH was lower in the Jamicia trials which would indicate that it was not capillary rise that caused the bare patches.The main control parameters required for a successful vegetation include the highest possible solids concentration placed in the BRDA and the caustic concentration of the residue.The period of time that the residue is given to weather is important, and the weather itself during that period will determine the amount of drying and compaction of the residue. This will help when vegetation is sown. The correct “reciepe”to amend the residue including sand, gypsum and some organic material has been well tested in Aughinish with the small / large plots. The starting pH is a major factor to speed up the reduction in pH during residue settling and maturing. It is required at around 10.0 before vegetation will grow and be sustainable. The Brazila trials showed that pH could get down to 9.0, Jamacia trials got the pH down to 8.0- 9.0 over a number of years. Carbonation trails in Perth using CO_2 showed the leachate was recorded and maintained at 10 with the residue pH at 9.0. The leachate analysis was from trial plots and not from the BRDA. In Scotland the closed plant was able to sample the leachate from under the BRDA. The author reviewed their analysis after 3 years sampling and there was no reduction in p.H.in that time period.

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

- Aughinish would not dispose of their residue to a mine like the Greek Plant, even if one were available as there is not enough of environmental research information available at present. One Greek and a French plant pumped residue into the sea. Again, this would not happen in Ireland.
- 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 used in the Alcoa plant 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 plant or importing liquid CO_2. The estimated cost of building a plant was $30 million, or liquid carbon dioxide would have to be imported and brought in by road tanker,
- Limitation on the use of boiler bottom ash and fly ash, used in the Brazilian Trial 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 at the Gove Plant 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. This information was very important for the author.
- The French Plant in Gardonne and a Greek plant pumped the residue into the Mediterranean which would be totally unacceptable in Ireland.
- Alcan Plant in Canada pumped mud to a mine 8km away, again not possible in Ireland.
- 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.

- Mud Farming at Aughinish is a similar system to what is used in Australia. In fact, the machinery used in Aughinish was bought and imported from Australia and training was given in Aughinish on its use by the Australian company.

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 in Ireland, so this material is available. 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 before it is returned to the river.

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 than the licence permits. 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 Aughinish, 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).

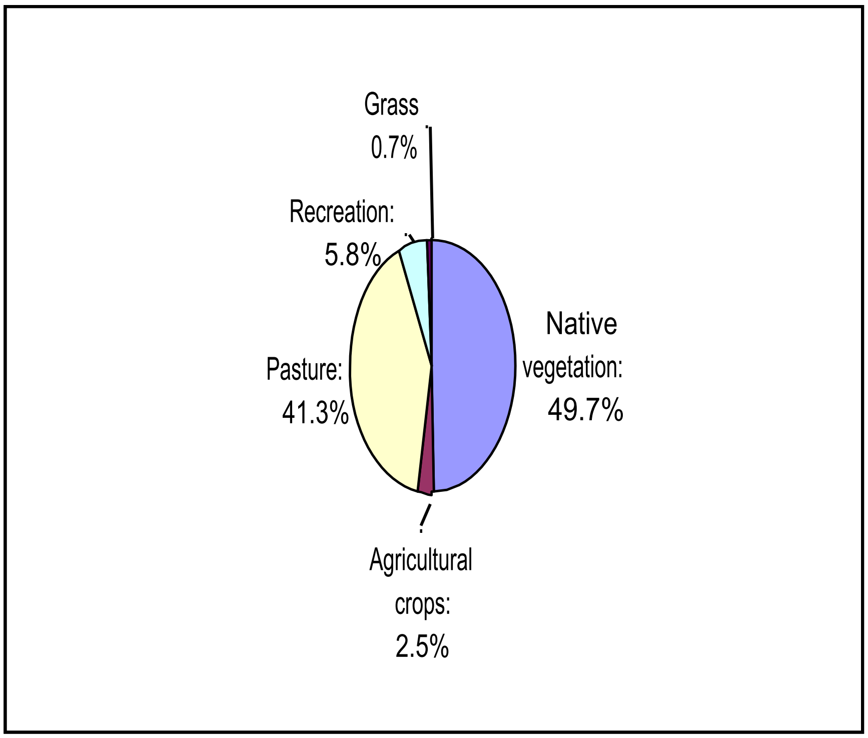


Figure 25 The proportion of area rehabilitated to various land uses

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.

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

Table 8 Materials used to top off residue containment areas before re-vegetation

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 Visit to Burnt island B.R.D.A. Scotland.

2.19.1 Introduction

This Alcan plant closed in 2004 and the author visited the plant in 2007 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.

2.19.2 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

Constituent	**%**
Total $Si0_2$	1 .2
Total Al_20_3	52.9
$Fe20_3$	15.1
$Ti0_2$	1.8
CaD + MgO	0.04
Loss on ignition (LOl)	28.1
Miscellaneous	0.86

Total	100
Free Moisture	8.5

Table 9 Analysis of Burntisland Bauxite

The bauxite residue was transported to the landfill at Whinnyhall, under a Waste Licence WML/9/79 which allowed for the deposition l 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.

Constituent	**%**
Total $Si0_2$	4.7
Total Al_20_3	21.3

Fe_20_3	44.2
$Ti0_2$	7.0
CaO	2.8
Na_20	2.7
Loss on ignition (LOl)	12.9
Miscellaneous	2.4
Total	100
Free Moisture	40%

Table 10 Analysis of bauxite residue

2.19.3 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 was 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.

2.19.4 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_2S 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.

2.19.5 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.

2.19.6 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 120m3 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.

2.19.7 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.

ITEM	**Volume treated 2000m^3**	**Volume Treated less than 2000m^3**
Limit dissolved As (mg/I)	0.5	0.35
Limit dissolved Al (mg/I)	10	7
Limit dissolved V (mg/I)	4	3
Spot Sample Consent Limits		
Suspended Solids ....mg/I		
pH.. 6 to 9		
Discharge Limits		

maximum discharge to sea................ 120 m^3/hr

Table 11 Effluent discharge consent limits

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 120m^3/hr, a pH range of 6.0 to 9.0. Limits in dissolved As, Al and V mg/l were decided in 2000.

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 m^3 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 CO_2 at Alcoa in Australia was a major event. This process had many advantages, including the significant reduction of the environmental impact. They had the CO_2 as a waste gas from an Ammonia plant, which obviously reduces process c 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 H_2S 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, or part neutralization, 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 plant could extend past 2026. 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 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 m/t 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.

In public policy the ‘Outrage Factor’ is public opposition to a policy which is not based on technical details. This terminology was first mentioned by Dr Peter Sandman who has written on Risk and Safety Communications. His writing includes community outrage and the perception of risk. These are the emotional factors that influence people’s perception of risk .This factor was very evident when a small group of local farmers constantly sought publicity and support to have the plant shut down making many false claims of pollution of the river, fallout from the plant and an increase in cancer cases in the locality.Following investigations by the Dept Of Health, and The Irish Farming Organisation nothing was found to implicate the company and the whole publicity died away . That was after €4m was spent on the investigations. The ‘outrage factor’ originated from Peter Sandman’s book, “Responding to Community outrage Strategies for Effective Communications.” See details of ‘Neighbours Meetings’ in other parts of the thesis.

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 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 employer's 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

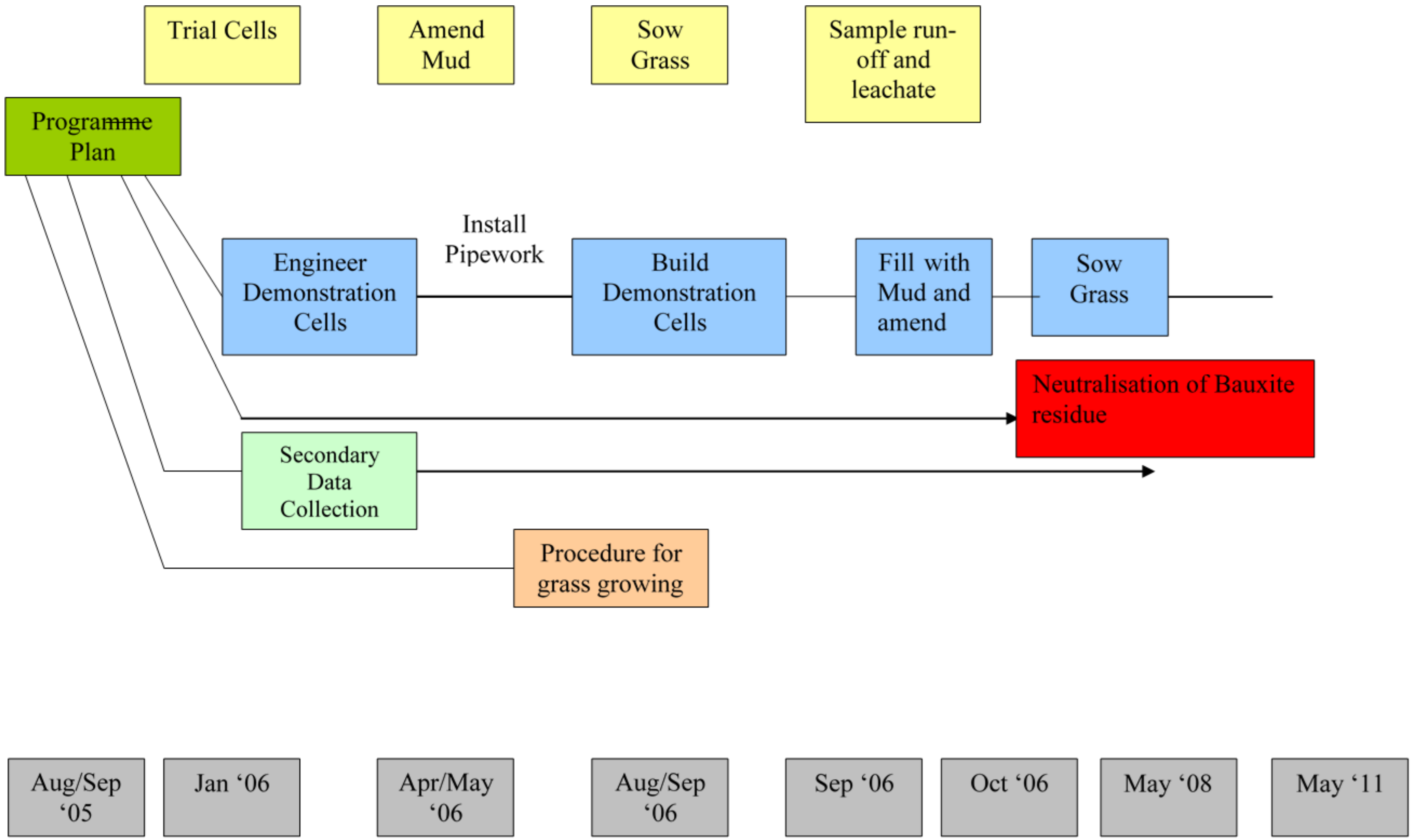


Figure 26 Programme Timetable

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 m^2 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 construction 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.
- Visit a closed B.R.D.A. in Scotland.
- Research residue neutralisation methods and recommend a suitable one for the Aughinish process and plant conditions.
- Wetlands research and trials.
- Mud Farming.

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 license requirements. Trials have been completed on small plots of bauxite residue in 1999/2000, but nothing substantial and nothing tested on fresh residue or no experience in the use of large machinery to plough, add sand , compost etc.

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 updates on progress. Statistical analysis and data collection. Presentation of findings / report and dissertation will follow. 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 explored is that the pH would drop slowly due to rainfall and weathering if left without any fresh covering of grass, even if nothing else was done. Also it needed research into what affect, if any, the grass vegetation on the surface would have on the run-off pH.

The pH, E.C. and soda were measured, and the primary data taken from the collection of leachate from the underground pipework beneath the residue, as well as 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? How long was it necessary to wait before sowing the grass.
- would grass growth change run-off amounts and pH levels?

The specific outcome of the experiment had to be examined. This was 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. As an example, the filling of the Demonstartion Cell was estimated could be filled in a few days. In theory the same residue was pumped to the cellas to the BRDA at the same pressure and % solids but it did work out that way. Because of the samller area and the plastic liner the residue ran from the inlet to the end of the cell instantly and did not stack up . It was required to have the residue placed in layers so pumping about 4 months to fill in the correct manner. The author had to make a decision to slow down the filling and get a 2%- 3% stacking angle of the mud. Doing action research within one's own system can be seen as managing different challenges (Coghlan &Brannick, 2005). Action Researches have to deal with changing and emerging situations. It can involve high hassle and high vulnerability according to Buchanan and Boddy (1992). The times of high hassle and worry for the author were the damaged plots and the above mentioned filling problems with the Demonstration Cell.Action researchers have to deal with emerging and unexpected events, this requires patience, tolerance humility and an ability to learn (Bell 1998)

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. Research wetlands technology install a pilot plant and trial residue leachate through the pilot plant to see if the pH will drop. The company have purchased machinery to farm the mud and monitor the pH when exposed to the atmosphere.

3.3.3 Background

The author had worked for Rusal Aughinish for 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 accepts 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 were 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 author set up his own company in 2008 working in Safety and Environmental training and consultancy. Aughinish had agreed to hired him on a consultancy basis until 2010 to continue on with research in rehabilitation methods of bauxite residue, and as an Environmental Specialist for the completion of the Phase 2 extension until 2011. 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. The author had access to all information, contacts with employees in the company although working as a contractor/ consultant until the planning permission was granted to startt filling residue into Phase 2. in 2011.

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 to be tested, but rather generated and consequently new knowledge propagated. It allowed the project to 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 license 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.

Action Research is a process of inquiry as a permanent member of an organisation and the system in that company (Alder, Shani&Brannick 2004). It usually requires both an academic and organizational perspective. The Insider Action Researcher acts as a facilitator between insiders and outsiders. The author had to attempt making process changes in order to get lower caustic levels and higher solids concentration of the the residue. This might mean a loss of production which would not be acceptable to management. So, it was a discussion between cost and the success of the project. The company had the expectation the project would benefit the company and the organisation in gaining planning permission (Coughlan, Brannick 2002) The author wanted the project to succeed to save the plant but as an Insider Researcher it is necessary to examine my own core values .(Bryclon. Miller 2008). The struggle with the research at times was the delays and the major one was a 12-month delay caused by a contractor who damaged small trials plots which had grass growing for several months. The authors self reflection helped get closer to the cause of the anxiety which was fear of not being successful to save the plant.

Besides doing a normal job doing A.R. meant being engaged in a series of jobs and aseries of activities in scoping, planning, negotiating, communicating, training along with progressing the work. Insider Action Research is an exciting invigorating prospect that contributed to the authors own learning and knowledge along with BRDA project.

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.

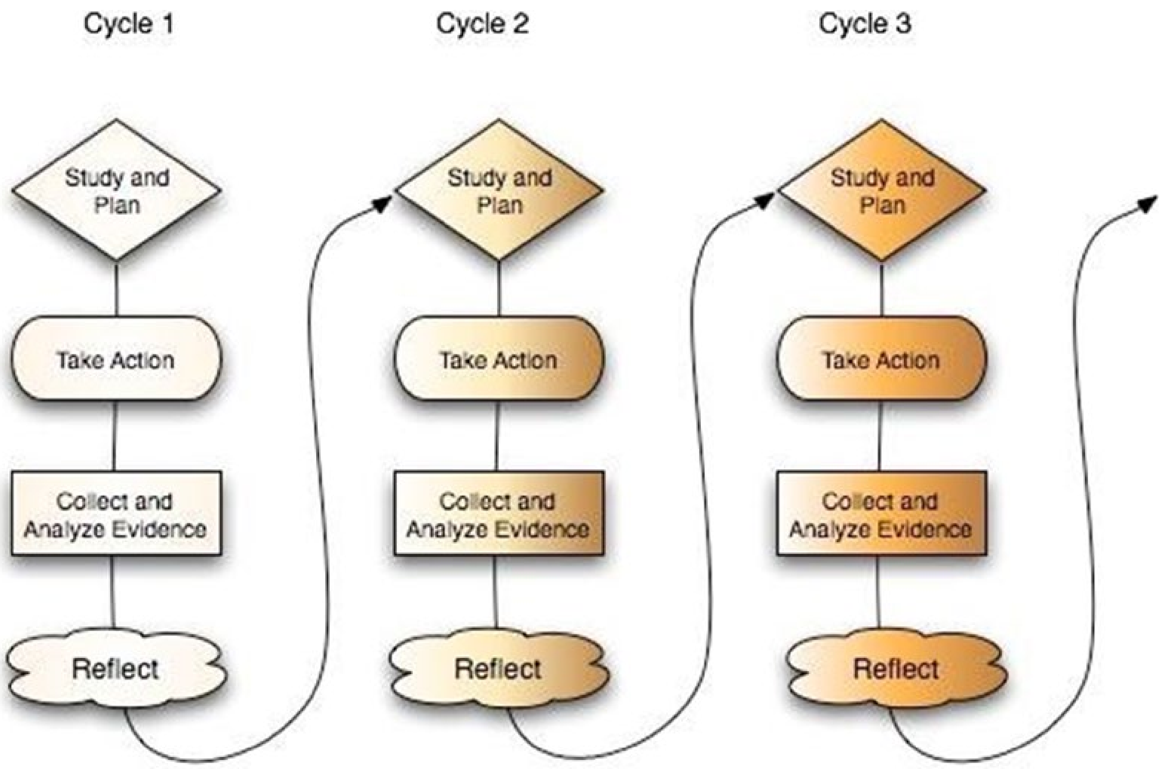


Figure 27 Progressive Problem-Solving with Action Research

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 workload. 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 x1 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 solid's 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).

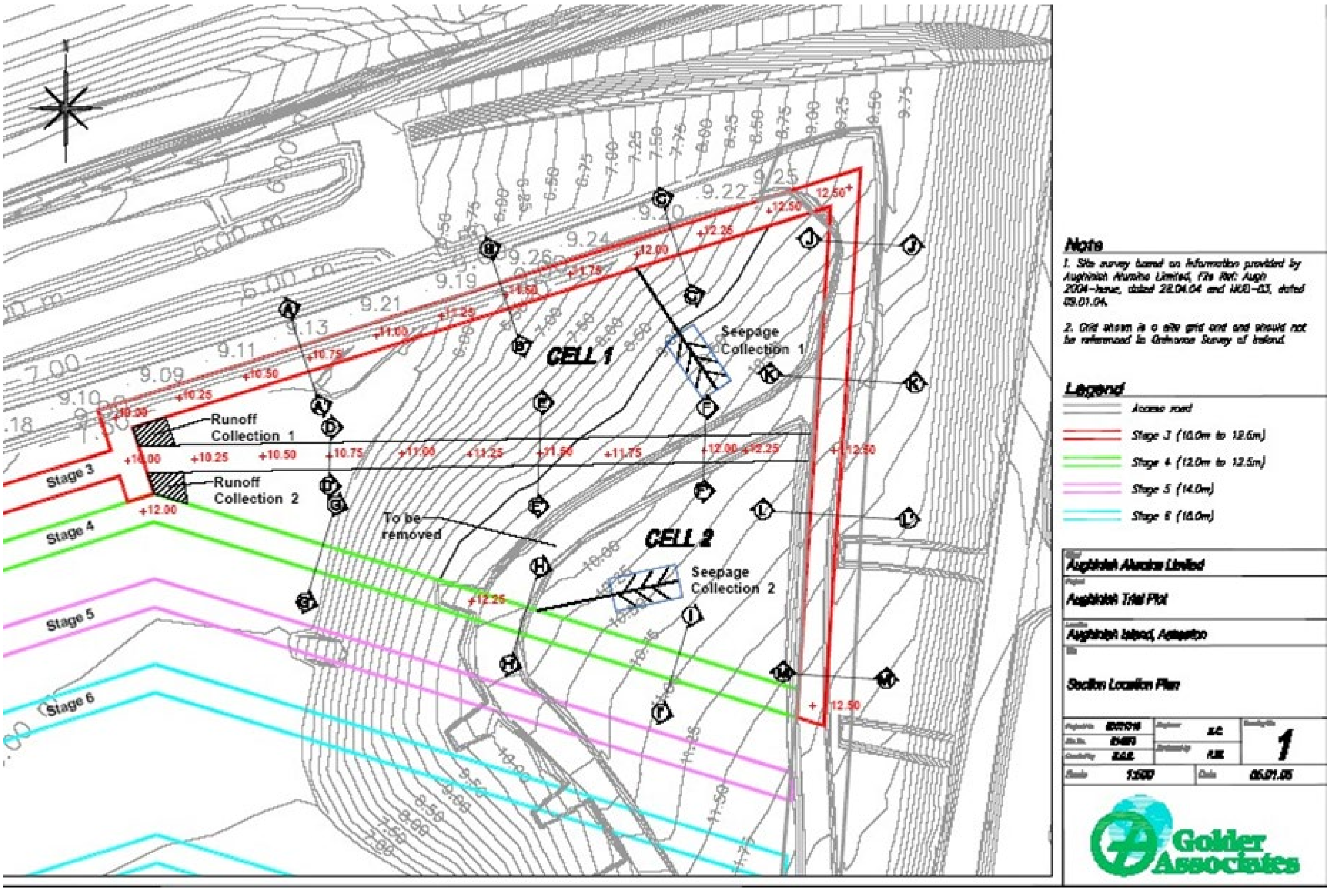


Figure 28 Plan view showing pilot scale B.R.D.A. location

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.
- plough and rotavate residue.
- add sand and plough again, allow further weathering.
- gypsum was now added to lower the pH to 9.0- 9.5 at the correct rate per hectare.
- compost was applied at rates up to 120t/ha.
- 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.

CO_2 could potentially be imported. If not imported, it would require that a plant be built to extract CO_2 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 license 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 making 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 of the mud 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 on-going 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 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.
- trial Wetland pilot plant.
- continue Mud Farming on the residue, analysis the mud following atmospheric carbonation.

Figure 29 View of the B.R.D.A. looking towards the Robertstown and Shannon Rivers 2008

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.

No. of plots	Amendments added
5	0 t/ha Gypsum, 0t/ha SMC
5	40t/ha gypsum, 0t/ha SMC
5	90 t/ha gypsum, 0t/ha SMC
5	0 t/ha gypsum, 60 t/ha SMC
5	40 t/ha gypsum, 60 t/ha SMC
5	90 t/ha gypsum, 60 t/ha SMC
5	0 t/ha gypsum, 80 t/ha SMC
5	40 t/ha gypsum, 80 t/ha SMC
5	90 t/ha gypsum, 80 t/ha SMC
5	0 t/ha gypsum, 120 t/ha SMC
5	40 t/ha gypsum, 120 t/ha SMC
5	90 t/ha gypsum, 120 t/ha SMC

Table 12 Small field trials, amended with different rates of gypsum and SMC

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 had been given a permit to work in this area, who was supervising him, how had the contractor not been given a specific work assignment, was his scope of work, had his work been risk-assessed. The area should have been fenced and sign posted 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 30 Grass in small trial plots (before damage) 2005

Figure 31 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 sign posted. 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 Plots amended of different rates Gypsum & Spent mushroom compost (SMC)

Plot	Quantity of Gypsum	Quantity of SMC
1	0 t/ha gypsum	0t/ha SMC
2	40t/ha gypsum	0t/ha SMC
3	90 t/ha gypsum	0t/ha SMC
4	0 t/ha gypsum	60 t/ha SMC
5	40 t/ha gypsum	60 t/ha SMC
6	90 t/ha gypsum	60 t/ha SMC
7	0 t/ha gypsum,	80 t/ha SMC
8	40 t/ha gypsum	80 t/ha SMC
9	90 t/ha gypsum	80 t/ha SMC
10	0 t/ha gypsum	120 t/ha SMC
11	40 t/ha gypsum	120 t/ha SMC
12	90 t/ha gypsum	120 t/ha SMC

Each application was replicated 5 times.

See results of trials in Appendix 1.

Figure 32 Second set of small plots 2006

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 to 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 33 pH Trends from one-tonne container (No 6*)*

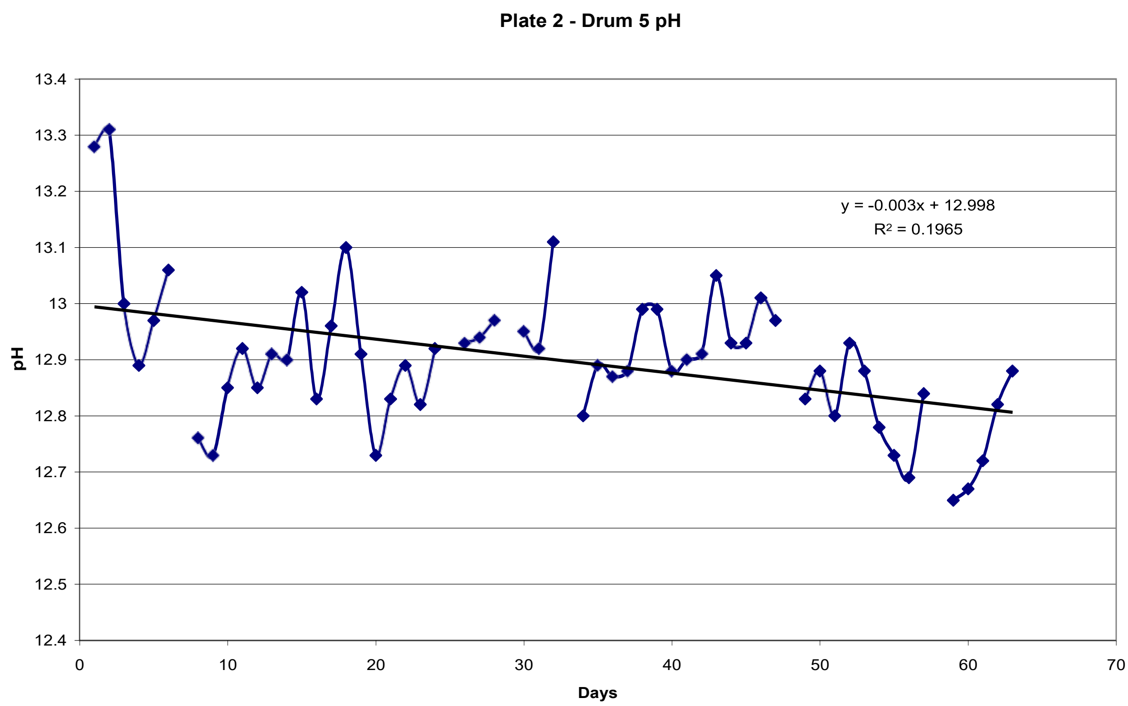


Figure 34 pH Trends from one-tonne container (No. 5)

Figure 35 One-tonne Containers 2005

See all results of one-tonne container data in Appendix 2.

4.2.3 Large Trial Plots – 20 m^2 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, $20m^2$ 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 solid's concentration at deposition and the amount of rainfall.

Study Areas

- Investigate how the residue could be prepared for seed sowing. This area because of its size and location will require access for machinery.

- Gypsum concentrations at 0, 40 and 90 t//ha which was the rates in the small plots was added to lower the pH.
- Again, to lower the pH organic amendment rates of 0, 60, 80 and 120 t/ha was b added, these rates were also added sufficient nutrients to the residue.
- NPK and super-phosphate artificial fertilisers to improve plant growth, was added at 250kg/ha and later reviewed as growth progresses to see if further additions were required.
- This trial area helped to fine tune seed composition and seeding rates.
- 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 of pH change.
- 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.

Plot	Gypsum	Organic
1	90 t/ha	80 t/ha
2	90 t/ha	80 t/ha
3	90 t/ha	160 t/ha
4	90 t/ha	160 t/ha
5	90 t/ha	160 t/ha
6	45 t/ha	80 t/ha
7	45 t/ha	80 t/ha
8	45 t/ha	160 t/ha
9	22 t/ha	160 t/ha
10	45 t/ha	160 t/ha
11	0 t/ha	160 t/ha

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

Figure 36 A, B, C, D. The stages of residue amendment using machinery 2006

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 37 Vegetation in the plots with SMC (160t/ha) and no SMC

4.3 Large Plot Results

One of the purposes of these larger plot was to investigate how this method could be used if and when the plant ceases production and closes down. 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 in Figure 51 show the ploughing, gypsum laying, sand spreading and early grass growth. With these methods it is evident that heavy machinery can travel on the residue after 12 months maturing. Also, that the spreading of gypsum and process sand could be done with the available machinery. Some difficulty did arise depending on the wind strength and direction. A successful seedbed was established in the residue.

Figure 38 Early grass growth on large trial plots 2006

Figure 39 Successful grass growth on large trial areas 2006

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.

The residue was amended at the following rates of Spent Mushroom Compost (0, 60, 80 and 120 t/ha) and gypsum (0, 40 and 90 t/ha) and sown with Holcus Lanatus. After 12 months growing period the residue and vegetation were evaluated.

Treatment	**SMC (t/ha)**	**Gypsum (t/ha)**	**Biomass (kg/m^2)**
1	0	0	0
2	0	40	0
3	0	90	0
4	60	0	1.8
5	60	40	2.6
6	60	90	2.8
7	80	0	3.6
8	80	40	3.7
9	80	90	4.2
10	120	0	3.8
11	120	40	4.9
12	120	90	4.9

Table 15 Various applications of SMC and gypsum results

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 residues 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. If the mud is not amended and grass grown on the residue there is likely to be erosion problems which will result in lack of settling and drying of the mud. The organic material, Spent Mushroom Compost (SMC) helped the physical structure of the residue. Results are summarised as follows:

Figure 40 Bauxite residue before amendment 2004

Figure 41 Bauxite residue after amendment

The bulk density and particle density of the residue was reduced, and the Spent Mushroom Compost improved organic carbon. Gypsum used to get the ph down to around 10.5.SMC on its own showed some lowering of pH with high dosage rates.EC values increased with gypsum due to the formation of salts gypsum was mainly responsible for lowering pH and ESP Gypsum helped flocculation of clay sized particles and so reduced clay dispersion in the mud (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.

Treatment							
SMC t ha -1	Gyp t ha-1	pH	EC	C (%)	ρb	ρp	ESP (%)
0	0	9.6	0.37	0.91	1.64	3.45	31
0	40	8.3	2.28	0.95	1.34	3.47	19
0	90	8.2	2.43	0.98	1.25	3.37	6
80	0	9.3	0.59	1.88	1.17	3.35	25
80	40	8.1	1.51	1.66	1.07	3.30	10
80	90	8.0	2.4	2.09	1.07	3.30	6
120	0	8.4	0.47	2.41	1.10	3.30	19
120	40	8.0	1.9	2.38	1.08	3.26	11
120	90	8.1	2.5	2.18	1.12	3.29	5

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

Nutrient Properties

Poor levels of nutrients are low in Aughinish residue. Nitrogen and carbon levels are also low, and the residue needs high level of organic material to increase these levels. SMC, sewage sludge, farm manure was all used at different times See Figure 54.

Similarly, Mn levels increased with SMC application and provided adequate growth level at higher rate (120 t ha) in Table 0-21. Mg and K were also much increased with SMC. and P levels increased but remained low, (Index 0 in the availability indices.)

SMC improved nutrient and plant performance. Due to lack of organic material resulted in low grass sward, but with organic material it showed good growth rates.

Production of dry mass biomass is affected by 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 * $p < 0.05$). Nutrient will be dependent on application rate and characteristics of the compost (Table 17).

Figure 42 Holcus lanatus (Yorkshire fog) grown in residue with and without SMC (1999)

Treatment		g kg^{-1}	Mg kg^{-1}			C mol kg^{-1}	
SMC (t/ha)	Gypsum (t/ha)	N	Mn	Zn	Cu	K	Mg
0	90	n/a	0.3	0.28	0.24	0.10	0.07
60	90	0.5	1.13	1.24	0.40	0.25	0.15
80	90	0.71	1.46	1.56	0.43	0.28	0.18
120	90	1.10	1.9	2.3	0.60	0.48	0.22

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

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.

Nutrient	**Range**
N (g/ 100g)	1.5 – 3
Ca (g/ 100g)	0.57 – 0.93
P (g/ 100g)	0.27 – 0.40
K (g/ 100g)	2.2 – 4.5
Mg(g/ 100g)	0.13 – 0.19
Zn (mg /kg)	15.6 - 29.2

Table 18 Nutrient range in Holcus lanatus in gypsum and compost-amended residue

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 physio-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. How to get the machinery onto the residue without damaging the liner in the Demonstration Cells.
- 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

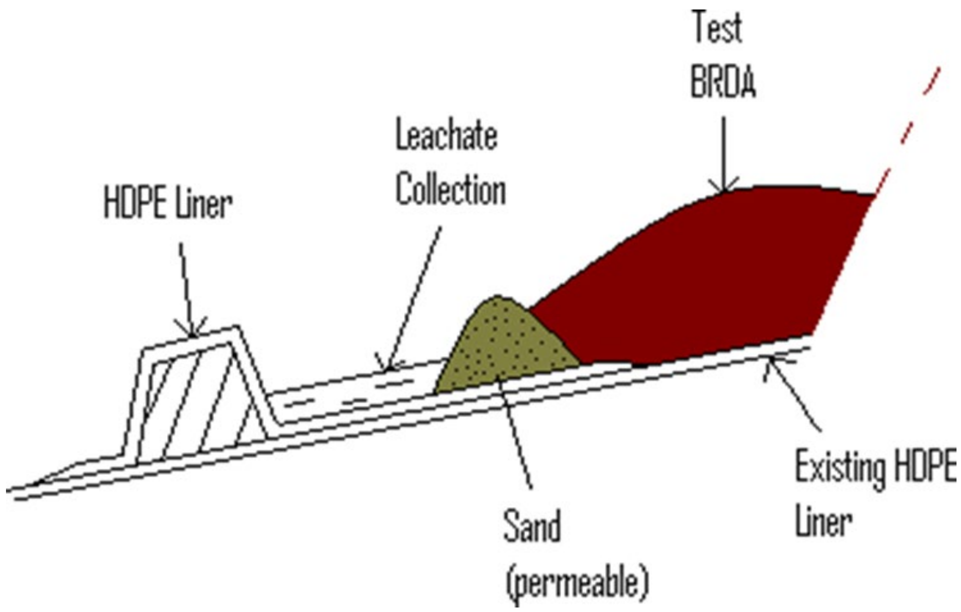


Figure 43 Schematic of pilot scale B.R.D.A.(Demo. Cells)

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 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 several thousand tonnes of sand for embankment building. 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.

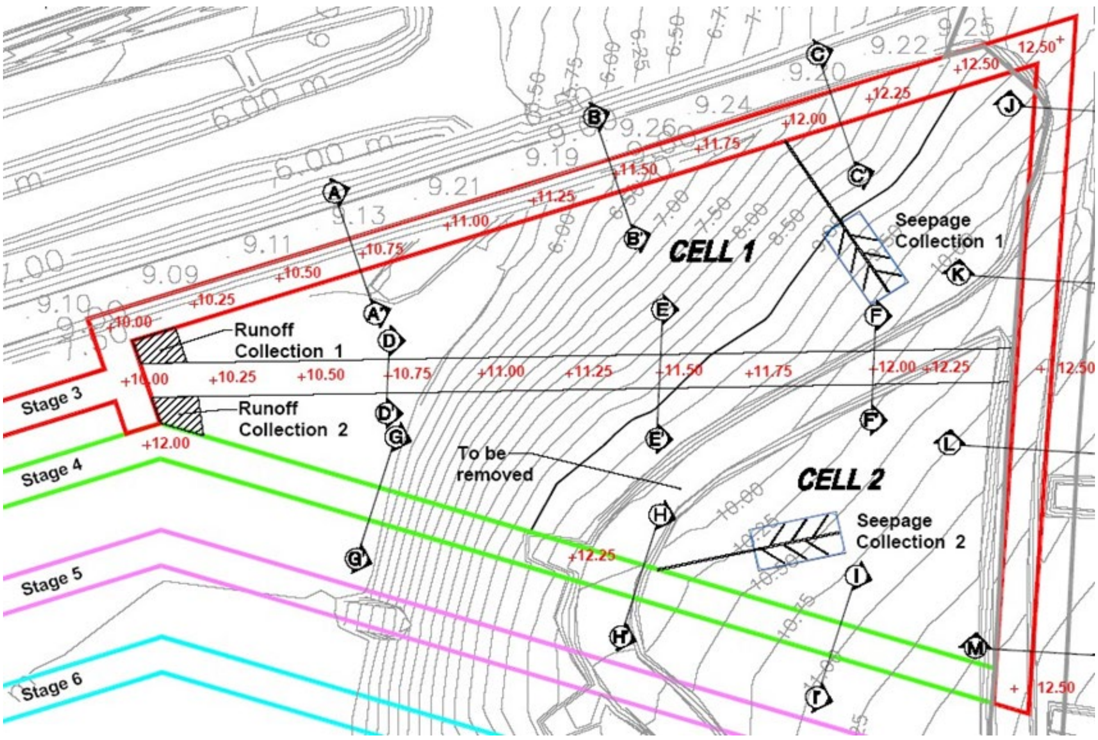


Figure 44 Plan of the Demonstration Cell

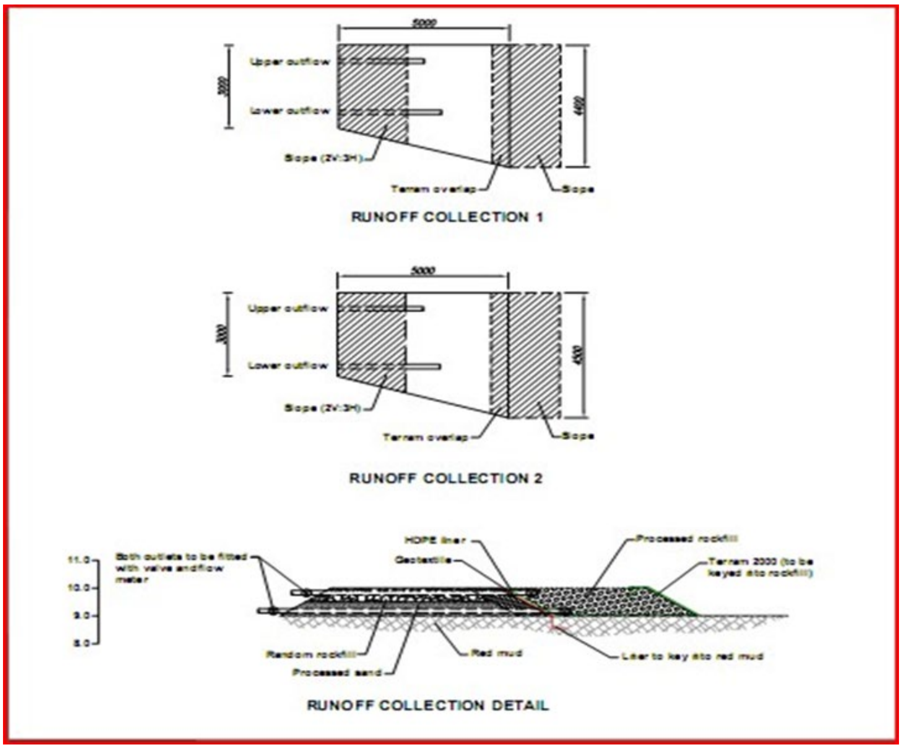


Figure 45 Run-off Collection Details

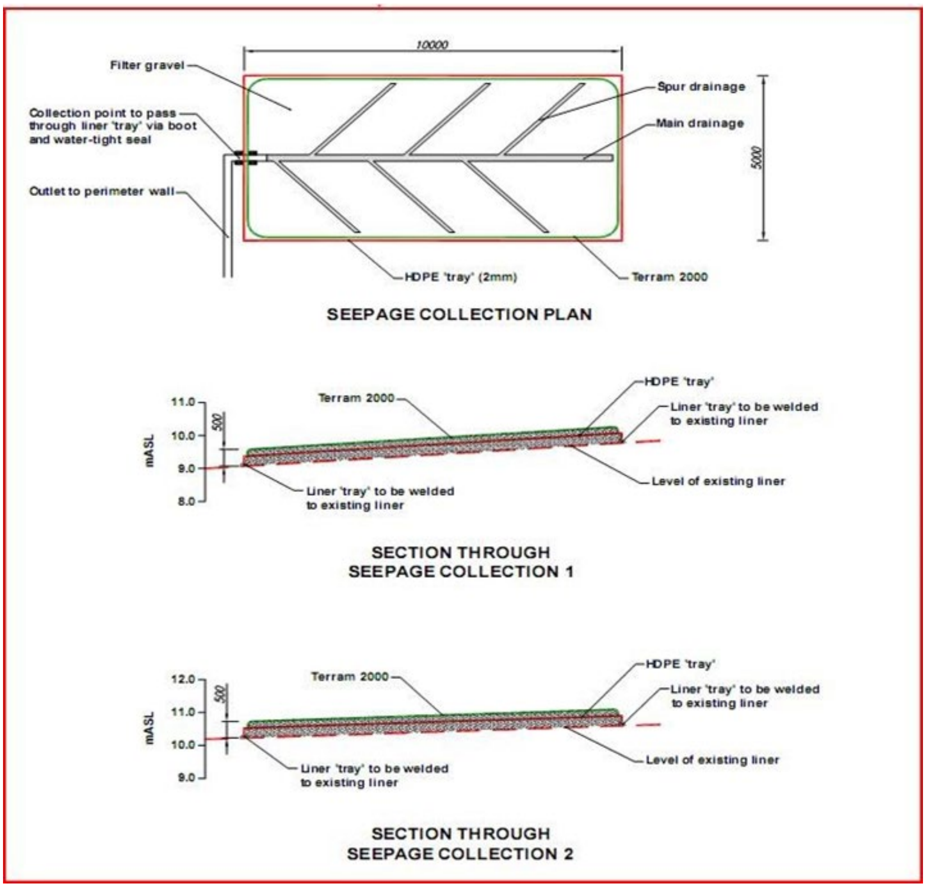


Figure 46 Leachate (seepage) collection system

Figure 47 One Cell before liner was installed, sand and rock only 2006

Figure 48 Seepage collection tray in floor of cell 2006

Figure 49 Inlet filling valve to one Demonstration cell 2007

Figure 50 First fill of bauxite residue pumped into Demonstration cell 2007

Figure 51 Bauxite Residue deposited after first fill 2007

Figure 52 Second fill into Demonstration cell 2007

Figure 53 Level in cell after 3rd fill (white colour is evidence of soda) 2007

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 solid's 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.

Bauxite residue was pumped into the Demonstration Cell in 2007/2008 and amendment started in 2008/2009. Amendment procedures was the same as used on the plot trials. The area was seeded in September 2009 with the same grass species as 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 than the B.R.D.A. itself.

Figure 54 Demonstration Cell filled with red mud 2007

Figure 55 Demonstration Cell before seeding following amendment 2008

Figure 56 Re-vegetated Demonstration Cell (5 months after seeding)2008

Figure 57 Re-vegetated residue in Demonstration Cell (10 months after seeding) 2009

Herbage samples were taken from the re-vegetated trial cell 10 months after seeding (before inflorescence) and nutrient content determined.

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

Table 19 Nutrient Content Range

Nutrient content of herbage growing on trial cell (1st 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

Date	pH	Conductivity ms/cm	Soda mg/l
22/05/2007	12.65	29150	9.59
31/05/2007	12.63	26710	9.57
07/06/2007	12.38	18130	10.51
22/06/2007	12.62	17050	
28/06/2007	12.73	27750	9.03
04/07/2007	12.77	27400	9.23
11/07/2007	12.76	28010	4.04
19/07/2007	12.66	29790	5.32
08/08/2007	12.81	26240	10.24
16/08/2007	12.86	18200	10.31
24/08/2007	12.89	33900	10.51
30/08/2007	12.82	35110	10.58
07/09/2007	12.84	35650	N/A
17/09/2007	12.82	36510	N/A
24/09/2007	13.02	37100	11.32
01/10/2007	12.83	31400	11.86
10/10/2007	12.99	38900	11.53
28/05/2011	13.04	67,905	16.7

Table 20 Analysis of Leachate from Demonstration Cell

	Trial cell	Run-off		
Date	pH	Conductivity mS/cm		Soda mg/l
10/05/2007	12.84	34800		
21/05/2007	12.74	38400		10.45
31/05/2007	12.62	29020		8.69
07/06/2007	12.86	75100		
14/06/2007	12.67	25170		7.41
22/06/2007	12.53	21150		14.96
28/06/2007	12.67	33900		19.48
04/07/2007	12.71	35100		21.27
11/07/2007	12.65	43450		14.22
19/07/2007	12.59	58100		12.77
08/08/2007	12.77	41600		12
16/08/2007	12.55	30300		44.35
24/08/2007	12.65	30300		N/A
30/08/2007	12.95	53570		53.92
07/09/2007	12.41	95800		57.96
17/09/2007	12.92	97200		14.96
24/09/2007	12.63	35100		
01/10/2007	12.48	20160		13.75
10/10/2007	12.54	20140		7.75

Table 21 Analysis of Run-off from Demo Cell

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 l2.8 (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 x 10 -5 m/s. This is similar to the calculated hydraulic permeability of the process sands of between 1 x 10 -4 m/s and 1 x l0 -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 x 10 –8 m/s and 1 x 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 x l0-6 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

Some drilling trials had been carried out in previous years and laboratory sampling to determine the hydraulic permeability of the mud deep in the residue. It was deemed necessary to complete another one following the licence application and the conditions laid down by the E.P.A. so along with checking permeability deep in the residue pH values could be analysised. Pore flushes were carried out to determine from the modelling how many flushes would be required to lower the pH to 9.0 including the time span.

Another company was hired to commence the drilling, and sampling through out the BRDA. The author was part of these discussions along with senior engineers in the company This required the mapping of the areas where drilling and sampling would take place, safety training for the contractors, access permits as to where they could travel on the mud.

The author worked in close contact with the contractors during this work. Following the results one of the recommendations that some means was required to sample the leachate under the residue. There was no such facility in the BRDA,

It was at this stage the the idea for the construction of the Demonstration Cells was recommended. The author was arranging and working on further small plot trials at the time and now became involved with the development of the Cells and organizing the funding, scoping the projct and construction of the cells. So, the concept of trying to prove to the EPA that the pH could be reduced to 9.0 in five years started here.

The first project was the modelling. 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 >1.0m 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 was 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 l00 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 x l0 -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 x l0-6 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 x 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 x l0 -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 I x l0 -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 represents 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 l 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 l0%. 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 m3/d. The model calculated that 2.746 m3/d leaves the B.R.D.A, equivalent to 1,000 m3/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 m3/a being converted to surface run-off.

From the modelling exercise the B.R.D.A. effluent accounts for 1,000 m3/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 l0-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 x l0 -8 m/s to 1 x 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 l x l 0 -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 permeability's.
- 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 built 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.

4.5.6 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 effect 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.

4.5.7 Seepage Summary

The 1974 planning approval for Phase 1 B.R.D.A. for red mud storage was 4.3E-3m3/sec or 371m3/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 m3/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.

4.5.8 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: Extra care required by the contractors installing the liner to avoid any damage which could result in leaks and seepage into the ground. Other factors which will influence seepage rates would include the hydraulic head of the mud on the liner and the depth and quality of the glacial till under the liner.

Finally, the permeability of the red mud could also affect the amount of seepage.
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 author did a visual check of the liner along the full length of the interceptor channel which took a few weeks. Some obvious leaks and damage to the liner were found . These leaks were added to the contact to line Phase 2 section and were repaired.

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 has 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. This did not happen as the EPA did give the company permission to pump residue into Phase 2 in 2011 provided that they carried out partial neutralization by Mud Farming which gets the pH to around 10.5 and continue to monitor leachate / run off results from th Demonstration Cells.

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 acidic materials, CO_2, magnesium = seawater, or sulphuric or hydrochloric acid

Bauxite residue after going through the Decanters, Thickeners, and washing stages has three sources of alkalinity. Liquor in the mud, Calcium which comes from the lime addition in Digestion.and Sodalite (DSP), which comes from the soda and silica reaction. The quantity of neutralising agent required depends on:

- The efficiency of Area 34 Filtering and washing of the red mud and what is the soda concentration in the residue.
- The amount of the lime added in Digestion and at stage of the process it is added. The level of impurities in the bauxite and the final alumina quality required at the end of the process.

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.

The final pH of the residue may increase again after some days due to incomplete reaction of the calcium compounds. The mixing of the acid and mud is difficult, acid can cause corrosion in pipework if complete mixing does not take place adequately resulting in equipment failure. From experimental data carried out by Aughinish Laboratories the following conclusions show what is required for its own bauxite residue.

- To achieve neutralization of the soluble alkalinity 30 Kg of 98% H_2SO4 /t of dry residue
- About 100 m^3/ of Shannon river water / per tonne or residue needed to neutralise the mud.

4.6.1 Alkaline Compounds in Bauxite Residue

When the alumina is removed from the process liquor, the remaining mud is thickened through four stages of thickening and washed in large vessels with a counter flow of washing to remove as much caustic soda as possible This soda is then recycled back to Digestion and added in at the start of the process. This has major cost savings on caustic soda usages in the digestion of the bauxite. The residue slurry at this stage and before it is pumped to the Filtration Building contains about < 30mg/l soda due to incomplete washing. along with insoluble Iron and Titanium oxides, sodalite and calcium due to lime addition in Digestion. All these compounds must be reacted with acid to neutralize the residue.

4.6.2 Neutralization of Bauxite Residue

Any acid can be used to neutralize bauxite residue, however in practice three acids have been used:

- Mineral acids H_2SO4 is the preferred mineral acid due to cost and handling issues.
- CO_2 can neutralising residue slurries. Because it reduces green- house gases it is good for the environmental.
- Magnesium ions in seawater settles out the high alkalinity as insoluble magnesium hydroxides.

4.7 Residue Neutralisation

The management of the residue waste at Aughinish is deemed best practice within the alumina industry. So, the choices open to the company are:

- River Shannon water
- Sulphuric Acid neutralization.

- CO_2
- Boiler stack flue gas desulphurisation / river water neutralization
- Mud Farming

4.7.1. Seawater Neutralisation Results at Aughinish Laboratory

Aughinish is beside of the Shannon River, but the estuary also receives the freshwater run- off from the entire river catchment area which dilutes it and would require extra pumped amounts or bring the sea water into the plant from further out to sea.

Seawater is mixed with sufficient seawater to neutralise the soluble alkaline This would involve pumping large volumes of sea water and mixing it with the residue allowing Magnesium and Calcium ions to displace the sodium ions in the residue. In theory seawater can achieve a pH of 8.5 – 9.0 The large volumes of sea water are required to ensure that the pH can't increase again, about 14,000/m3/hr is estimated amount required. 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.

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 to purchase and also high running costs. The resulting return water would still have to be treated before returning it to the river.

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. Latest information now is that the Gove plant has shut down and is being mot-balled. There is a volume increase using sea water and this has to be managed as part of the plant liquid volume control. RTAY (Rio Tinto), Queensland Alumina, Australia uses this method and also Gove (Alcan).

4.7.2 Acid Neutralisation

Residue is mixed with either hydrochloric or sulphuric acid. The amount the pH falls depends on the amount of acid and where it is added.

Sulphuric acid rather than hydrochloric acid would be used Aughininh because of the cost as it is already used on site. It has the unloading facilities at the terminal plus storage tanks and pumping facilities throughout the plant. Also, the staff are experienced in safety risk associated with handling acids. The reactions are:

$$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$$

$$2NaAl(OH)_4 + H_2SO_4 \rightarrow Na_2SO_4 + Al(OH)_3 + 2H_2O$$

$$Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + H_2O$$

Where acid is used it can hinder revegetation growth and life span of the vegetation on the residue in the BRDA due to the difficulty of controlling addition rates, avoiding pockets of pure acid in the pipework which causes fluctuations in the pH and possible corrosion damage to the pipes and pumps.

Nearly all refineries safely dispose of spent acid, which is acid after acid cleaning digester heaters by adding it directly to the mud and pumping to the BRDA. Aughinish did dispose of spent acid at one time in this manner, but later diverted it to the Waste Effluent Plant for effluent neutralisation. The plant uses all available spent acid in its two Waste Effluent Treatment plants.so fresh acid would be required.

4.7.3 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. Using sulphuric acid (or calcium chloride) to neutralise only the solution alkalinity, will only give a pH of 10.5. This 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.to the equipment. By adding the acid at the individual discharge points of the residue could minimise this risk of corrosion but would prove very costly. This would require individual pipework to each of the 30 mud discharge points on the BRDA.

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.

4.7.4 Reflection on Acid Usage

Initially neutralisation employing sulphuric acid was considered the most feasible for residue neutralisation at Aughinish. Sulphuric acid is stored, used and disposed of 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 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 H2S at the discharge points which could lead to complaints from the outside community 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 this 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.

4.7.5 Carbonation

My contacts with David Cooling in Alcoa in Perth via phone calls and e- mails and documents passed to me includes some of the following into their research.

There is a CO_2 liquid plant close to the refinery in Perth and the CO_2 is pumped directly into the plant. As this is a waste from an Ammonia plant it can be supplied at a low cost.

Carbon dioxide is mixed with residue to lower the pH level. It can reduce t pH 13 to pH 10.5. The local NH_3 plant has waste CO_2 and pumps it to the refinery. But a longer-term plan is to use flue gas from the boilers in their own plant. Alcoa has the patent for this technology which consists of reacting $NaHCO_3$ with the residue and then regenerating $NaCO_3$ using CO_2 in "flue gas" in the boiler stack.

This eliminates taking CO_2 from another plant and also there are no scaling problems in pipework caused by the CO_2. $NaHCO_3$ + "alkalinity in liquor and mud solids" → Na_2CO_3.

$Na_2CO_3 + CO_2 \rightarrow NaHCO_3$

CO_2 neutralisation has the advantages over seawater neutralisation

- CO_2 is a more concentrated solution and therefore reduces cost of pumps and equipment...
- CO_2 has higher delta pH.
- Run off from the residue can be recycled to the plant without the calcium causing any process problems. Carbonation reduces the drying cycle as there is less liquid.
- Less dusting chances.
- Most of the CO_2 stays in the mud so no release of green - house gases. (95%)
- There is a volume increase using sea water and this has to be managed as part of the plant liquid volume control.

The importation of CO_2 would be required as the only waste CO_2 in Ireland is now closed down.

4.7.6 Review at Aughinish Laboratory

For carbonation of only the liquid phase alkalinity, the slow mass transfer of reactants within the bauxite residue slurry is a major problem, especially with the high volumes of mud that require treatment.

This is due to the high viscosity of Aughinish bauxite residue at 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. The use of additional machinery in mud farming will get the pH down to 10.5.

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. This would be a major problem for the Aughinish process. and would have production implications.

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.

4.7.7 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 from the boilers and Calciners could be passed through a residue to take out the sulphur dioxide in the emissions (creating sulphuric acid) and then mixed with seawater to achieve a stable pH. The residue is then pumped as normal onto the BRDA.

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. Following this change over to natural gas the company dropped this idea.

4.7.8 Combination Water Management Systems

Full neutralisation is not always possible, but neutralisation of the entrained alkaline liquor and rainfall run-off from the BRDA can be done especially in areas of high rainfall. The BRDA collects 28,000m3 of rainfall for every 25mm of rain that falls on the site which leads to a positive water balance. This requires large storage ponds, pumping arrangements and large neutralisation plants to treat the run off before pumping to the river, The two types of water management systems are:

- Open – excess water after neutralisation is discharged to the environment (River Shannon)

- Closed – these plants do not have any excess waters They have a closed return system where any excess liquid can evaporate or be returned to the process. Warm countries can have large ponds and tanks and allow for evaporation except during the wet seasons.

4.8 Feasibility of Neutralising Aughinish Bauxite Residue

The only readily available source of soluble Mg2+ is seawater, which will dilute and reduce the % solids of the residue slurry. The amount of sea water required is about 20 times the amount of slurry which requires large pumps and storage plus to get the solids concentration back up again will require further thickening to enable the bauxite residue to be dry stacked in. the B.R.D.A.
While Aughinish refinery is on the Shannon which would allow the brackish water of the estuary to neutralise red mud, the concentration of magnesium and calcium ions required is far lower compared with seawater. Large volumes would be needed for neutralisation.

In the case of sulphuric acid-treated residue, there is a fast initial reaction in a low initial pH. but this is followed by a slower pH reduction to an equilibrium pH that takes longer and is attributed to the solid components of the red mud.

Acid treated bauxite residue, achieves a pH of around 10.5 and that is where there is only soluble alkalinity. An equilibrium pH of around 8.0 can be achieved if the soluble alkalinity is removed If the pH is only reduced to 10.5, it will cause problems with the poor mixing between the acid and the residue.

Concentrated sulphuric acid and concentrated calcium chloride are very corrosive, and would lead to piping leaks and failure. A computational fluid dynamics study of the mixing of concentrated sulphuric acid and Aughinish 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 (Aughinish Laboratory reseach)

The volume of 98% Sulphuric Acid (H_2SO_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.

Due to reaction times, full neutralisation is not a option, good mixing between the acid and the residue solids is necessary for a long period. This would require more storage tanks to give that residence time plus agitation good mixing and monitoring systems.

Due to the large volume of acid required, there is a risk of H2S smells if the final pH remains too low. At pH 10.3 the reaction is about 99% to the right, there is little or no smell because the concentration of H_2S is very low. Acomplaint about smells would be of serious concerns to the company.

4.8.2 Seawater Neutralisation (Aughinish Lab)

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 at Aughinsh plant rates this is equivalent to 124,800,000 tonnes of Shannon River water annually (this equates to approximately 14,250 m^3/hr of river water intake and discharge).

This value is based on neutralising the residue to a pH of 9.0, pumping this large volume of water and the cost involved with extra process equipment required and achieving good effluent water quality to discharge to the Shannon as per EPA license would be far too costly.

4.8.3 Carbonation (Atmospheric, and liquid CO_2)

Atmospheric carbonation takes place in Aughinish residue area by "Mud Farming ". This consists of ploughing up the residue and allowing liquor to drain away and improve / speed up the drying process. It allows more exposure of the mud to carbonation by the atmosphere. This was covered earlier in separate section. The normal operation is to place a layer of mud and after a few days us machinery to plough up the residue, this may take a few passes and some time to see a reduction in the pH.

Care is required not to push rainfall back into the mud with over aggressive farming. Neutralisation of bauxite residue using liquid carbon dioxide has been investigated by Alcoa World Alumina and a patent obtained on its application.

There are benefits compared to either acid or seawater neutralization:

- No H_2S generating materials (sulphate), causing smells in surrounding areas.
- It would capture CO_2 that would otherwise be released in the atmosphere.
- No that increase the residue volume.
- A concentrated solution reduces capital cost and increases the reaction rate.
- Reduce dust generation.
- Produces a more benign waste that might have resale potential.
- Improved long term management.

- Reduces the risk of ground water contamination.

The Australian information from David Cooling Alcoa was via a paper in 2004 Alcoa which he sent to me.

4.8.4 Disposal of Liquors after Residue Neutralization

CO_2 would probably be preferred but is not available in Ireland. H2SO4 neutralization produces Na $_2SO_4$ and seawater neutralization produces a diluted solution of seawater and both these solutions require treatment in the Waste Treatment Plants before discharging into the river. Coupled with the amount of excess condensate from the plant, about $300m^3$ / hr, and the annual rainfall it would increase treatment load on the Effluent plants.

4.8.5 Seawater Neutralization

Reaction of residue with sea water results in the neutralisation of alkalinity through precipitation of Mg -, Ca and carbonate removed. initial reduction is rapid (5mins) and further reduction over several weeks. Reaction produced a residue pH of 8.0.- 8.5. Test were also carried out on residue sand comparable to field conditions. re-vegetation is problematic, but over time the salinity of the residue will decrease due to leaching by rainfall. Below are the results of sampling and analysis by Aughinish laboratories.

Table 22 Residue to B.R.D.A. Acid Neutralisation

Target pH	Vol. of H_2SO_4 mls.	Temp 0.C	pH Day0	pH Day1	pH Day2	pH Day3	pH Day4	pH Day7	Kg/t dry solid
Untreated Mud	0	18.4	13.4	13.3	13.3	13.3	13.3	13.3	
12	8.8	23.5	12.0	12.6	12.7	12.7	12.7	12.8	14.0
11	11.2	23.9	11.1	12	12.2	12.2	12.3	12.3	17.9
10	14.2	25.6	10.0	10.7	10.9	10.9	11.0	11.1	22.7
9	16	26.4	9.0	10.0	10.3	10.3	10.3	10.3	25.5
8	18.2	26.8	8.0	9.3	9.5	9.4	9.5	9.6	29.1
7	20.3	27.7	7.0	8.5	8.8	8.7	8.9	8.9	32.4
6	23.6	27.7	6.1	7.8	8	8	8.2	8.4	37.7

Table 23 Residue with Liquor Removed

Target pH	Vol. of H_2SO_4 mls.	pH Day0	pH Day1	pH Day5	pH Day6	pH Day7	pH Day8	Kg/t dry solid
Start	0	12.2			n/s	n/s	n/s	0.0
10	0.7	10.0	11.3	11.5	n/s	n/s	n/s	4.5
9	1	9.0	11.0	11.0	n/s	n/s	n/s	6.4
8	1.4	8.0	10.1	10.1	n/s	n/s	n/s	8.9
7	1.75	7.0	9.2	9.2	n/s	n/s	n/s	11.2

Table 24 Shannon Estuary Water Neutralisation

200 Grams Mud Slurry	
Volume of Water	**2.5**
pH	**10.04**
Cubic Meters of Water per Tonne of Dry Solids	**3**

50 Grams Mud Slurry											
Volume of Water	**0.625**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
pH	**10.03**	**9.5**	**9.3**	**9.1**	**9.05**	**9**	**8.94**	**8.9**	**8.89**	**8.87**	**8.85**
Cubic Meter of Water per Tonne of Dry Solids	**7.4**	**11.8**	**23.5**	**35.3**	**47.0**	**58.8**	**70.6**	**82.3**	**94.1**	**105.8**	**117.6**

4.8.6 CO_2 Neutralization

Bauxite residue neutralization using CO_2 is probably the method of choice when disposal of the resultant liquor is considered.

Neutralization with CO_2 results in a liquor containing $NaHCO_3$. It is possible to causticise this liquor and this appears to be the strategy adopted by Alcoa (7th Alumina Quality Workshop p 218). $Ca(OH)_2 + NaHCO_3 \rightarrow NaOH + CaCO_3$

This allows the liquor to be recycled as process water. This approach, however, requires lime and lime is produced by calcining limestone.

$CaCO_3 \rightarrow CaO + CO_2$

Under these circumstances at least some of the environmental value of using CO_2 is negated.

4.8.7 H_2SO_4Neutralization

H2SO4 neutralization results in a dilute Na_2SO_4 solution, which must be disposed of probably by dilution with processed water or putting through the Waste Effluent Treatment Plants. Although the acid brings the Ph down it can have grass growing on the residue.

.

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. Approx 28,000 m^3 is collected on the BRDA for every 25 mm of rainfall. If the alkalinity has not been removed, the pH of the run off / seepage water will be high.

If water is added, e.g., rainwater, with either sodium hydroxide or sodium carbonate it will dilute the residue to the initial pH of the residue. How permeable the red mud is determines how much alkalinity will seep through. This is very low around 380m3 per day and the mixes with the runoff caused by the rainfall. The mixing of seepage and run reduces the pH to an acceptable level for the EPA (< 9.0) and that will determine when the Waste Effluent Plants can shut following plant closure. In the license application this is one conditions required to get the extension to extend the BRDA by another 80 hectares

It is understood that the soluble caustic in the liquor is very slow to be leached out. It will come down fairly fast initially but after days it can go back up again... The neutralisation of the liquid phase will achieve a partial neutralisation, maybe to around 10.5. At this level grass growing is difficult and will the addition of gypsum to amend the residue and so have sustainable vegetation.

4.8.9 Neutralization of Aughinish Process Sand

Process sand has to be removed from the process liquor because of it coarse fraction, it will not allow mud to settle in the thickeners and damages rakes and filters. The sand is washed to remove as much caustic as possible and return the caustic to the process. If the washing was better and some neutralisation process method introduced, it would mean lower alkalinity sand going to the BRDA. The method to neutralise sand is to have an adequate washing system. Sand washing is done by using condensate in counter current drum washers. How ever about 10% of the sand deposited on the BRDA is not washed at all. It is dumped out of the process and then trucked to the BRDA. The sand production varies but could be up to 3,000t /week... It is used as dam wall and road construction material in the BRDA.It is trucked to the BRDA. Analysis of the sand shows it is 73%Fe2O3 and the red mud is around 43%. Extra washing stages could reduce the caustic levels in the sand and in turn reduce caustic losses.

It is unlikely that Aughinish would consider selling this sand as they need it for road and embankment construction as the mud levels rise within the BRDA.

4.8.10 Analysis of Aughinish Bauxite Residue Neutralization Data

The preliminary data obtained during experiments at Aughinish (February 2007) in estimating the cost of H_2SO_4 neutralization of their bauxite residue.and process sand. 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 H_2SO_4Required to Neutralize the Liquor

The data provided shows that:

- Liquor total soda is 25.3 g/l Na_2O this is 25.3*2/62 = 0.816 Molar in NaOH plus Na_2CO_3. The residue slurry is 58.8% solids
- 0.588 Tonne of residue is associated with 1-0.588 = 0.412 Tonne of liquor.

- 1 Tonne of residue is associated with 0.412/0.588 = 0.700 Tonne liquor, assuming the density of the liquor is 1, this is 700 Litres
- This liquor contains 700*0.816 = 571 Moles of Caustic
- 100 grams of 98% H_2SO_4 contains 2*100*(98%)/98 = 2 Moles H+ (approx) (98 is molecular weight of H_2SO_4), therefore 50 grams contains 1 Mole, therefore 50/1.84 = 27.17 ml H_2SO_4 per Mole H+.
- The 700 Litres of liquor associated with 1 Tonne of residue contains 700*0.816 = 571 Moles Caustic.

Therefore the:

- Volume H_2SO_4 required to neutralize the liquor is 27.17*571/1000 = 15.5 Litres
- Mass H_2SO_4 required to neutralize the liquor is = 15.5*1.84 = 28.5 Kg of H_2SO_4 per tonne of residue

The titration data is plotted below in Figure 70.

28.5 Kg of H_2SO_4 per tonne of residue gives a final pH of about 10.5 and a further 9 Kg of H_2SO_4 per tonne of residue is needed to neutralize the residue to pH 8.5.

4.8.12 Empirical Volume of H_2SO_4 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*58000/56 = 2071 Moles OH.

Therefore (as 27.17 ml H2SO4 contains 1 Mole H+), we would require 2071*27.17 = 56269 ml H2SO4.

- 56269*1.84/1000 = 104 Kg H_2SO_4 per tonne of residue to react with all the Ca compounds.

One tonne of residue contains say 57 Kg of Sodium (as Na_2O).

An empirical formula of $(NaAlSiO_4)6(Na_2X)$ and assuming all the Na_2X is alkaline (CO_2- and $Al(OH)_4$-). The maximum alkaline Na is (2/[6+2])*57000/62*2 = 460 Moles of OH-

- Requiring 613*27.17 = 12,491 ml H2SO4. 12491*1.84/1000 = 23.0 Kg H_2SO_4 per tonne of residue to react with all the alkaline Na, giving a total maximum of 127 Kg per tonne of H_2SO_4.

Assuming that 28.5 Kg per tonne of H_2SO_4 is required to neutralize the liquor, very little of the Calcium compounds or the Sodalite appear to be reacting with the H_2SO_4 under the conditions used. If 11.2 Kg per tonne (as taken from Aughinish laboratory experiments) of H_2SO_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_2SO_4 titration. The only cautionary note is that it may take longer than one week for the pH to stabilise.

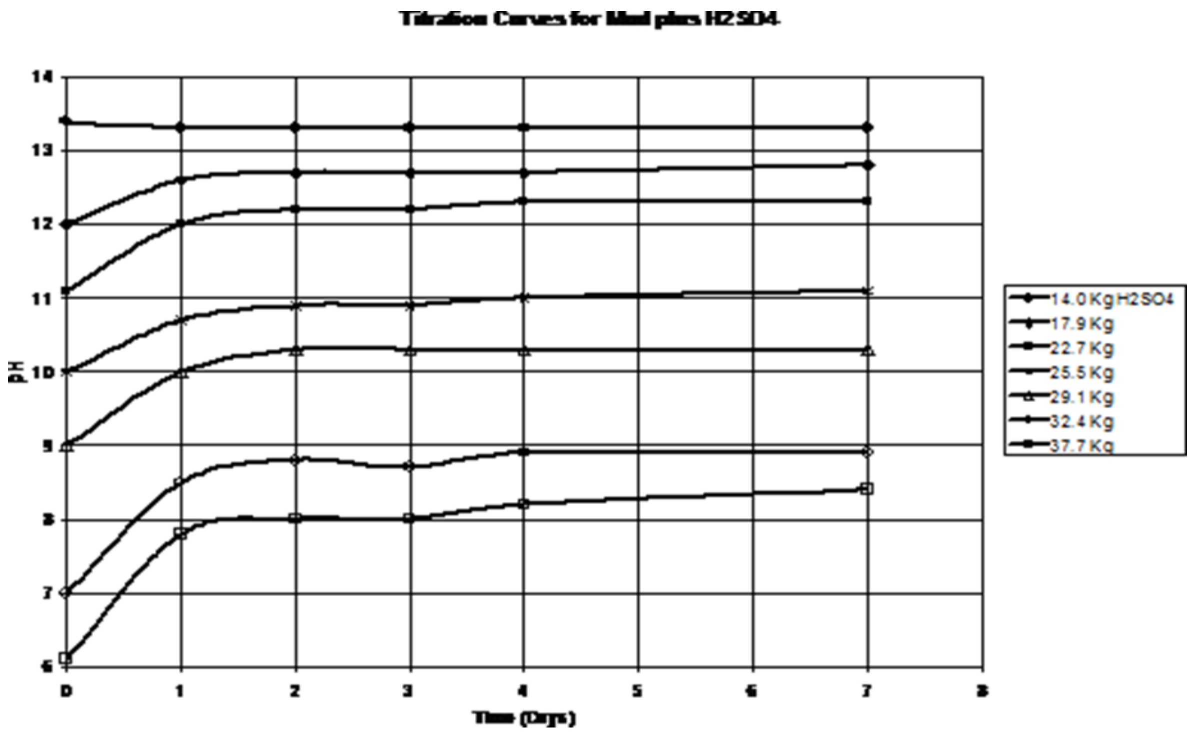


Figure 58 Titration Curves for residue + H_2SO_4

It is thought that the reactive SiO_2 in Aughinish bauxite increases and the sodalite absorbs more carbonate.

If the hydrochloric acid experiment described is carried out, the quantities of alkaline Calcium and Sodalite can be measured. The H_2SO_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 H_2SO_4 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 H_2SO_4 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 H_2SO_4 and a curve for the washed residue slurry plus 18 Kg/tonne H_2SO_4. 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 H_2SO_4 required to reduce the pH from about 10.5 (equivalent to 28.5 Kg per Tonne) to 9.4 (the same final pH in the titration of washed residue is about (31 – 28.5) 2.5 Kg per Tonne of residue), far less than the 11.2 Kg per Tonne found in the second experiment.

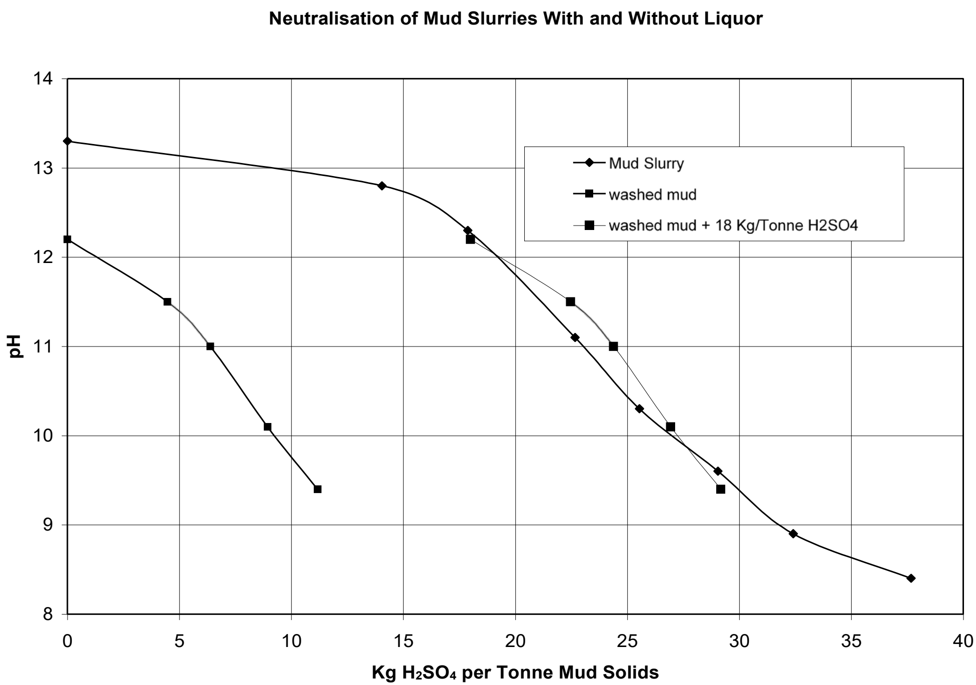


Figure 59 Neutralization of Residue Slurries with and without liquor

These differences may improve with further experiments and work. It is recommended that liquor be separated from the residue slurry and titrated with H_2SO_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_2SO_4 per tonne dry residue is required to neutralize the liquor. The residue pH is about 12.2. 11.2 Kg H_2SO_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_2SO_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. If mixing of the acid and the mud is not sufficient then localised spots can occur resulting in pockets of dangerously low pH. This will cause pipe failure and damage to pumps, and tanks.The risk are that sodalite will dissolve and the pH goes up again or gel can form in the piping causing blockages. It may cause problems in getting vegetation to grow at a later stage.

It is likely from the research that the safest method of acid neutralisation would be to add the acid at the points of discharge in the B.R.D.A. This would mean installation of multi-dosing points and pumping the acid to the distribution points. Handling and pH control could become more difficult. Concerns of possible re-vegetation problems given the formation of gel in the slurry after neutralization.

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. It would also be very difficult to get a licence to return the treated water back into the river again after coming in contact with the residue.

4.8.14.1 Management of Hydrogen Sulphide (H_2S)

There is a concern the generation of H_2S 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. Already there can be odour problems in the Waste Effluent plants where acid is used to manage the pH. Presently a chemical is added to the process (Bio Scent) which kills the smell. This has not been trialled in the residue but has been sprayed over the residue when deposited. Controlling the level of sulphite is the issue to avoid the generation of Hydrogen Sulfite. Refineries that use seawater can have an issue with H_2S. Clearly this is a sensitive area given that the company would not complaints to the EPA or from the local community...

Sulphate is the source of the sulphide, so that neutralization with H_2SO_4 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 CO_2 from the U.K. daily, which is estimated at 4m Euros.

Conclusions

4.8.16 Carbonation

While it would be easier to neutralise low viscosity 40% solids filter feed than the 60% solids (Aughinish slurry) this presents two problems:

1. The vacuum filters recover 85% of the soluble caustic by efficient washing and then de-liquoring of the feed.
2. Caustic losses with the filter cake would increase from 6 kg/tonne alumina to 40 kg/tonne alumina if the residue were neutralised prior to washing and filtration. These losses would add $10 million per annum to the plant operating costs.
3. Vacuum filters cloths must be kept clean and avoid blinding and scaling in order to have a good vacuum. If scaling happened, it would make vacuum filtration post- neutralisation very difficult with increased down time for washing and cloth replacement... Solids % after the filters could not achieve 60% solids required for dry disposal at Aughinish. It would be necessary then to add the acid for neutralisation after filtration and as previously stated would require acid piping to each individual outlet point on the BRDA. if bauxite residue is be neutralised, then the neutralisation stage must be applied after vacuum filtration
4. Problems with CO_2 injection include excessive shear and dilution in the reactors, and the precipitation of solids. Any solids could end up as a sticky gel material which would cause poor filtration and blockages in pipework.

- Having an inconsistent residue concentration to the BRDA would result in poorer stacking and reduce the life space of the area.
- Increase in ground water is also likely.
- It would reduce the ultimate residue storage capacity by an estimated 6%

- C02 would have to be imported into the country.
- Storage and pumping arrangements also required.

4.8.17 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 increase again. 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. 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 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 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.

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.

In-situ atmospheric carbonation via Mud Farming is by far the least invasive method to neutralise bauxite residue; a pH reduction from approximately 12.5 to 11.0. Mud farming effectiveness seems limited by the rate at which the reactant (atmospheric carbon dioxide) can be mixed into the red mud. Further pH reduction is being achieved, which may by ploughing during mud farming to expose a greater surface area of the bauxite residue paste. This is being done by using a plough called a "Spader". This will get the pH down to around 10.5 by multi ploughing sessions.

4.10 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 by which time it has compacted and safe to drive on. 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 is required for the pH to drop to 9.0.

The process of mud farming which commenced at Aughinish in 2009 achieves the two objectives of dewatering via compaction and partial neutralisation via atmospheric carbonation. Using acid for neutralisation will depend on the amount of acid added and the degree of dissolution of solid phase alkalinity to achieve a pH equilibrium.

Using CO_2 has some problems apart from cost and returning liquor to the Shannon River. It can result in an inconsistent residue concentration to the BRDA giving poorer stacking and reduce the life space of the area.

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 CO_2 from the U.K. daily, which is estimated at 4m Euros. There is a concern the generation of H_2S 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. It is likely from the research that the safest method of acid neutralisation would be to add the acid at the points of discharge in the B.R.D.A. This would mean installation of multi-dosing points and pumping the acid to the distribution points. Again, it would increase costs and make control of the dosing rates more difficult.

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 new trials planned for one of The Demonstration Cells with carbonated mud from the BRDA will take a few years to evaluate. This carbonated mud is the mud following Mud Farming with a reduced pH of 10.5. With new vegetation on this section, it is hoped that the pH can be reduced by maybe 2 points. The company have the planning permission now and are filling residue into Phase 2 extension, they have increased the rate of mud farming which will give the partial neutralisation. This is acceptable to the EPA provided the company continue to work at rehabilitation methods, including getting to full residue neutralization, and continue with the provisions for a safe closure in time.

Mud Farming will achieve partial neutralisation which will be accepted by the EPA for Phase 2 BRDA. 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 a great deal 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's closure plan.

Chapter 5 Research Findings

Introduction

This section looked 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.
- Mud Farming.

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. The waste produced from the alumina industry, is considered the world's largest industrial waste. With over 77 million tonnes produced annually and hundreds of millions stored as a regulated waste in tailings dams globally.

The technology re-engineers the residue from alumina refining process into a product called Bauxsol™ enabling it to neutralise acid and reduce the concentration of environmentally hazardous heavy metals by up to 100,000 times.

The technology process transforms the high alkaline (ph13-14) red mud and hazardous alumina refinery waste both physically and chemically into Virotec's Bauxsol™ technology raw material.

This process does not neutralise the red mud, because the alkalinity is uniquely not destroyed, rather it transforms the material into a new product that has particular benefits for the neutralisation of acid and the removal of heavy metals and other compounds.

Virotec International is an Australian-based environmental management company with the technology involving the mixing of magnesium and calcium-rich liquors with bauxite residue that provide neutralization such that the material trademarked BauxsolTM, can be utilised in a range of applications, water treatment, mine remediation, concrete production soil treatments and fertilisers. It can be used in wastewater treatment plants to settle solids, also used for the absorption of heavy metals in contaminated soils.

By modelling BaseconTM, it is possible to predict the neutralization requirements for a specific bauxite residue. 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

Bauxite residue is a high volume/low value material, so any reuse will have a high transport cost. If it could be used in the local region like in Western Australia where it is used for soil amendment in low pH soils then it has some value. Small amounts have been used in waste water treatment plant. The usage has been in the thousands of tonnes whereas the need is for millions of tonnes. Further neutralization for re-use would seem the only way to make acceptable.

Aughinish has an acid system acid neutralization and discharge system in operation for water treatment and a minor facility for spent acid at the B.R.D.A.it require further commissioning and trials.

5.2 Alternate Use Management philosophies

The following are areas where there are possible uses for bauxite residue t.

- metal recovery – using the iron oxide for pig iron production,
- soil amendment – has been used in Perth area to raise soil pH and water retain capabilities, building materials, cement, bricks, tiles. It is used for embankment road building in Aughinish effluent treatment to manage dairy or piggery wastes, and collection of storm water, road and urban run-off;
- carbon filers to clean boiler and calciner stacks and reduce air emissions.

Bauxite residue could be on a regional basis, like Perth in Australia and the Avoca mines.

- 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).

- Treating or creating a buffering filter for the treatment of acid mine drainage before discharge in local river... 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, washed and utilise in the cement or construction industry. (Information from Environmental Section, Wicklow Co. Council.)

5.2.1 Alternative Uses for Neutralised Aughinish Process Sand

The sand is removed via sand traps before entering the mud thickeners and filtration section. Sand size is +100 micron and is 10% of the waste in the process. It is washed with condensate and trucked to the B.R.D.A. At the present production at rate of 1.95 Mtpa approximately 117,000 tonnes of sand will be produced annually. The sand is used to build roads and embankments in the BRDA. The sand is designated as “non-hazardous” under the Waste Management Acts 1996 – 2003.

5.2.1.1 Alternative Uses

If sand was sold or used in another application re-use of the sand externally the company would be forced to use some alternative for road building. Process sand has been used construction material for filling road base, concrete filling material and effluent treatment media.

Cooling and Jamieson (2004) identified that re-use of sand has the potential for leaching of alkaline materials into the ground. Neutralisation and further were required to avoid high pH seepage.

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.

Aughinish needs to identify a suitable alternative use.

5.2.1.2 Neutralisation of Sand

Aughinish analysis shows that sand has around 72% Fe_2O_3 compared with 43% for residue.and may contain little Hydrogarnet or Sodalite and may not need a lot of extra washing. Extra washing has the benefit of recovering more caustic so that has a cost benefit it itself.

5.3 Industry Residue Disposal Systems

Main Findings

These include:

- pump the reside out to sea, two plants in Europe do this.
- dry stacking – high compression thickeners; used in Aughinish
- filter technology - used at Aughinish.
- washed alkaline systems- Aughinish use this method.
- seawater neutralisation.
- acid neutralisation.
- Carbonation presently using atmospheric carbonation.
- combined flue gas desulphurisation/seawater; and
- combination water management systems.

5.3.1 Alternative Residue Management Practices

Many residue management systems have been developed in over 90 alumina refineries around the world since the first plant was started at the end of the 19th century in France. The systems developed had regard mainly for safety issues, and environmental concerns. The process is determined mostly by the quality of the bauxite, how far it has to be shipped, the size of the plant, type of plant and local environmental regulations.

5.3.2 Marine Disposal

The EPA in Ireland would not grant a licence for disposal of the residue at sea. It would require either pumps and pipelines many miles out to sea or barges transporting and dumping it many miles out in the Atlantic Ocean The residue can creates a plume that can spread over many miles. The residue is deemed to be slightly toxic to all marine organisms, the nearest suitable trench is located approximately 160 miles westwards in the North Atlantic.

The European Union Landfill Directive 1999/EC/31 (26th April 1999) states that waste should be managed close to production. Disturbance of the residue could cause an environmental incident and would be like an oil spill. There are no contingency plans in place for such an event. Monitoring of the area would be difficult and expensive.

EC (2004) states that BAT for all alumina refineries is to “avoid discharging effluents into surface waters”. Therefore, preventing discharge of bauxite residue solids into surface waters or a marine environment is a key requirement of BAT.

Existing refineries are under pressure to stop this practice, i.e., Alumina de Greece by 2011 and Gardanne and Showa Denko by 2015. Aughinish could not technically, environmentally or economically justify such a proposal.and would fail to get a licence from the EPA.

5.3.3 Disposal of Residue via Return Shipment to the Bauxite Mine

Pumping residue into old mine shafts has been done in Greece and Canada and is used to back fill these spaces, so returning residue to the bauxite mine is very costly and difficult. Bauxite mines are generally located some distance from the receiving alumina plant (from 20 miles to thousands of miles) Aughinish bauxite comes the Amazon basis and West Africa,

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 residue handling and loading system for 2 million tonnes would cost approximately €100 million. Neutralization facilities a at the mine. a cost of at least €15 per tonne to load, unload and transport, a shipping cost of €20-€30.
- Would the EPA grant a license to ship the residue from the port?

5.3.4 Wet Disposal (Low Density)

The current thickening, washing and filtration systems at Aughinish pumps the residue to the BRDA at a density of 60% solids and dewatering to 70% solids w/w). If the company changed to a wet system disposal it would pump the solids at a lower density (say 30% solids w/w). This extra high pH liquor would have to be stored and pumped back the Waste Effluent Plants. They would reduce the stacking slope of the mud from 2-3% down to 1%., requiring more additional space in the BRDA and extra expenditure.

Low density slurry would lead to pooling of liquor on the residue, extra pressure on the embankments, plus likely to be more seepage. If the residue takes longer to dry and consolidate then getting vegetation established would be difficult or unlikely.

Aughinish started with a Wet System but changed after a few years to a dry system.

Queensland Alumina, Australia uses this technology. The Hungarian plant that had the embankment failure in 2010 also used this system with a large pond and 30-foot-high embankment.

5.3.5 Dry Stacking - High Compression Thickeners (Sub-aerial)

Aughinish high-density residue disposal has good drainage structure and can manage the seepage rates and the yearly rainfall on the residue. Settlement of the mud is good, stacking at 2-3% angle will give increased capacity in the BRDA and extend the life span of the area. The higher the final density of the mud the higher its intrinsic strength and will allow access onto the residue which allows “farming”, ploughing and amendment. It will make for better capacity and embankment construction. 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 and depends on filter performance and the amounts of condensate dilution that is added plus good operator process control. The density of 58% is pumped to the BRDA and then consolidates to 70%.and this is the limit at which solar drying will take place.

Australian alumina refineries have a target bauxite residue density of 65% before a layer of mud is deposited or re-vegetation is commenced (Cooling, 1989.) Aughinish has a final height of the central discharge point (License limit) of 8m above the perimeter drains (32m vs. 24m AMSL).

Aughinish have added one high compressor thickener since 2011 and this allows the company to bypass the filtration building if necessary but reduces the solids and in turn more return liquor for processing. This adds more pressure on storage and treatment of run off and seepage. This by -passing is not being used but it is an option although not a very cost effective one,

5.3.6 Washed Alkaline Systems

At Aughinish the mud is washed and thickened in a series of tanks and then put through vacuum drum filters where it is washed with return process liquor and condensate to recover caustic which reduces the soda concentration of 5-10gm/l and a pH over 13. in the residue going to the BRDA. All leachate and run off from the BRDA is neutralised and solids removed before discharging to the river.

5.3.7 Hydrological Modelling – Surface Run-off Quality

Rainfall on the BRDA amounts for 28,000m^3 per 25mm of rainfall. This water is responsible for leaching of the red mud and this will reduce the pH of the leachate over a long period of time The solid phase alkalinity will be very slow to dissolve due to the low permeability of the mud and Aughinish residue alkalinity is made up of mostly soluble sodium aluminate., hydroxide, carbonate and TCA. Lime addition in the Digestion section contributes to these compounds along with the type of Brazilian bauxite used.

The URS Dames and Moore reports of 2002 and 2003 carried out column leaching investigation of the residue. In the licence request the company had made to the EPA there was a condition that pH should reach 9.0 and would eliminate the running of the Waste Water Treatment plants 5 years after plant closure. This was also a reason for the construction of the Demonstration Cells to test and prove this theory.

The author was involved in these tests as Environmental Facilitator for the plant.

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

URS suggested in excess of ten pore volumes of leaching would be required as the experimental leaching period was quite short. The authors trials in leachate from the Demonstration Cell showed no reduction in 18 months taking weekly samples. So longer time and extra flushing is definitely required or starting at a lower pH.

Using 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 of 9.0 by leaching alone and this would suggest a very long leaching timeframe, three times longer than the 10 pore volume assessment previously arrived at by URS.

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.

The Demonstration Cell leachate sampling over the 18 months was to prove whether periods of high and low falls made any difference to the pH. As can be seen from results in Appenxix no real reduction took place over this time. Also, one theory tested was whether the vegetation could have an influent on leachate and run off. Again, no change.

5.3.8 Reflection on the Run-Off / Leachate

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. These containers were left in the open in the BRDA. They were filled with 58% solids and placed on an embankment in the BRDA. Samples of leachate and run off were taken weekly.

It will be necessary to continue to operate the Waste Effluent Treatment Plants in order to treat the residue run-off and keep to license 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.

5.3.9 Hydro-geological Modelling

A water table will develop within the BRDA, this happens because of the synthetic liner under the mud. The same was true for the Demonstration Cells which had a liner. This water table will be influenced by the refinery process and the type of residue that is deposited on the BRDA, the annual rainfall and whether there a vegetation cover or not. Seepage rates will also be a factor.

There is on- going seepage and this will continue following closure, the water table will reduce once deposition of residue stops. Rain fall will be the only addition and possibility the sprinkler system which will add water if required for control of dusting.

By having a vegetation cover it will slow the rate of pH reduction towards 9.0, but the cover will reduce the rate of seepage. This seepage is mixed with the run off so that pH will be lower and so reduce the pressure on the Waste Effluent Treatment Plants if they are still in operation. It is estimated that 75% - 90% of rainfall will run off the top of the residue (URS 2003), which reduces recharge. A vegetation also has the benefit of stopping dusting on the residue.

5.3.9.1 Impacts of Seepage

Following the modelling by URS (2003) and Golders 2005. The total seepage from the B.R.D.A. was estimated at around 300 m3/day. The components of this seepage are:

- Phase 1 B.R.D.A. 145 m^3/day
- Phase 1 B.R.D.A. Extension 60 m^3/day
- Phase 2 B.R.D.A. 90 m^3/day
- Storm Water Pond 3 m^3/day
- Perimeter Interceptor Channel - 2 m^3/day

How much seepage depends on the permeability of the mud, the soil, or any leaks in the liner. If the mud is discharged at a high solids concentration, it will stack with little segregation.

Pooling will be reduced and in the areas of Phase 1 extension and Phase 2 additional area of 80 hectares the flow will be across the mud with some down wards flow, but the majority will run to the embankment latterly and then to the interceptor channel.

The permeability of the bauxite residue is very low and typically 1E-8m/s. There is no artificial liner in the original Phase1 residue area and has low permeability residue.

Permeability is higher at Phase 1 Extension and proposed Phase 2 B.R.D.A. and both of these areas have a liner. The permeability range for the estuarine soils is between 1E-7m/s and 1E-9 m/s. Where there is a liner under the mud the majority of flow will be downwards and lateral towards the channel depending on how many raised embankment lifts have been constructed, in other words what tonnage of mud is in that location and how deep it is.

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. (Golders 2005a)

The observation wells around the site will sample the seepage rates if any. There are 40 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 background water quality parameters by more than 10% and that the pH should not exceed 9.0.

If the seepage flows were to increase significantly and this would be detectable at the wells, the impact would be under the BRDA and confined in that area. Any leakage would be neutralised by sea water entering the zones.and would be well neutralised before entering the River Shannon.

5.4 Suitable Species for the Re-vegetation of Bauxite Residue at Aughinish

Following the plot trials carried out in 1997 and 1999 by Ronan Courtney the company commissioned him to survey the plots and issue a report annually which the company submitted to EPA in its Annual Environmental Report 2005 / 2006. These are the findings of the survey of the plot trials. The research agreement that the company has with the University of Limerick facilitated all analysis of the samples taken from the plots.

Roan Courtney was a member of the author's team and has been on contract to Aughinish for many years. The following are the results of the report on the earlier trials:

- Due to poor chemical and physical conditions in the residue, there was poor germination and seed growth.
- It is important that good physical and chemical amendment is done before seeding.
- Allowing a period for leaching before amendment is an important period and greatly improves germination and growth.
- Several indigenous species are capable of growing (see below).
- Organic matter alone is not a sufficient amendment if residue exhibits excessive pH, ESP and require amendment with gypsum, 60t/ha process sand 25%w/w, and organic matter at 120t/ha to produces optimum growth.

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 concentration, 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 Aughinish

Avena sativa	O*Agrostis stolonifera* Creeping Bent
Agrostis capillaris	Common bent
Cynosurus cristatus	Crested Dog's Tail
Festuca ovina	Sheep's Fescue
Festuca rubra	Red Fescue
Holcus lanatus	Yorkshire Fog
Hordeum vulgare	Barley
Triticum aestivum	Wheat
Lolium perenne	Perennial Ryegrass
Puccinellia distans	Salt marsh grass
Rumex acetosa	Common Sorrel
Rumex crispus	Curled Dock
Trifolium pratense	Red Clover
Trifolium repens	White Clover

Colonisation by further species and some shrubs occurred on areas once vegetation was established.

5.4.2 Species Diversity Survey

Residue that had previously been re-vegetated in 1997 and 1999, was surveyed in 2005. This survey was requested by Liam Fleming Environmental Manager. Samples were taken by Ronan Courtney and analysed in University of Limerick.in 2005/ 2006...Species diversity was recorded and compared to the initial seed mixture of 6 species. The result of the survey again is required for the Annual Environmental Report for the EPA, and is available in that report.

- 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 60 Selection of Species growing on re-vegetated residue plots 2005

Figure 61 Selection of Species growing on re-vegetated residue plots 2005

Figure 62 Selection of Species growing on re-vegetated residue plots 2005

Figure 63 Vegetation established on residue with invertebrate activity in trial plots 2005

5.4.3 Plant Elemental Content

The trials of 1999 using process sand and gypsum is effective in lowering uptake of Na, Al and Fe in plants These surveys are planned to take place annually and inserted in the A.E.R.

The use and effect of gypsum and process sand on the growth of Trifolium pratense in amended residue are summarized:

- Trifolium pratense grown with gypsum addition had lower aluminium concentration than those in non-gypsum treatments.
- This was also the same in plant iron concentration.
- Using gypsum produced lower Na concentration but if process sand was added Soda levels were reduced even further. concentrations.
- Trifolium grown with gypsum showed higher Mg levels.
- Soda levels did not influence Calcium levels and were adequate for t plant growth.
- Marginal Mg, P and K deficiency were found.
- Mn nutrition may be a limiting factor for long-term growth.
- Nitrogen nutrition is not affected.

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 amendment is required prior to re-vegetation.
- Process sand, gypsum and organic matter are essential components for successful re-vegetation.
- Several indigenous species have grown in the plots.
- Residue results that have been amended hasve lower levels of Na, Fe and Al.

- Nutrient cycling is important to show that the vegetation cover will survive and last.
- 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 years previously) was carried out as part of the survey by Ronan Courtney in 2005/2006.

- 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 appear 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.

Depending on soda level in the residue and these can change dramatically depending how the plant process is operating and the efficiency of the Filtration building, it can lead to excessive levels of Na. Elevated pH may reoccur due to flooding caused by low solids concentration of the mud or sodium release from within desilication products (DSP) in the residue. This can cause established vegetation to regress or die back. Areas of the B.R.D.A. that had vegetation and were re-vegetated in 1997 and 1999 were sampled in 2005/ 2006 to investigate chemical properties of the residue. Properties are summarised below:

pH	**8.02-8.14**
EC (mS/cm)	**0.28-0.52**
Na (mg/kg)	**305-432**
Al (mg/kg)	**<1**

Table 25 Chemical properties of amended residue

Residue in the re-vegetated areas did not exhibit excessive pH, Al or ESP.

5.4.6 Likely Causes of Re-vegetation Failure

Vegetation failure is due to a failure in the drainage provided within the growth horizon. Drainage is best provided with the addition of process sand and residue at high solids level. Capillary rise is the rise of caustic up into the amended area. If drainage is poor and leaching of the residue, large areas of failed vegetation are inevitable (Wehr et al. 2006) Ameliorants are necessary 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. Good management of the BRDA in a post closure scenario is highly essential.

5.4.6.1 Key requirements of re-vegetation success at Aughinish

The following are some controls that will be needed to manage any growth, sustainability problems:

- Poor drainage control – The amended soil needs adequate amounts of process sand, which is a courser fraction than the mud, and deposit the mud at high solids concentration This will give good draining and good settlement.
- Nutrient availability with good soil structure is essential for lasting growth.
- Physical and chemical amendment of the residue requires, organic materials, process sand, and gypsum to lower the pH which will improve the residue structure and allow microbiological processes to take hold in the soil.
- It is hoped the BRDA will eventually develop into a type of nature trail and amenity area., by starting off with few grasses and helped by the natural wild seeding from the surrounding area.

5.4.6.2 Reflection

Summarised below are key defined characteristics and comments on amended Aughinish residue with regards to soil parameters.

- 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.
- Sodium adsorption ratio (SAR) and Exchangeable Sodium Percentage (ESP) Criteria: Sodium adsorption ratio (SAR) of 7 (ESP of 9.5), and 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 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 ≤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.

- Electrical Conductivity Criteria: Electrical Conductivity of < 4 ms/cm.

Un-amended bauxite residue can exhibit EC values of up to 14.1ms 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 Ca_2 in solution and the displacement of Na from the exchange sites by Ca2 and will decrease with leaching due to improved physical properties of the residue.

- 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 company had to submit its closure plan to the EPA and a financial bond that they would not walk away from the facility following closure. This requires all vessels and pipe work in the plant are emptied and cleaned. All hazardous material will be disposed of safely and that the BRDA will be environmental and safely closed. The process will be non-contaminating, with little supervision or maintenance. The company will require agreement with the local authorities, regulators and the local community. The Office of Public Works (the government) will have to accept responsibility for the island and site.

Aughinish must ensure that the future land use of the BRDA is safe, particularly the embankments holding the red mud, that there is no leakage from the residue and that any seepage is collected and disposed of safely into to the surrounding environment. This requires the leachate pH to be at 9.0 or below. If not, all leached must be treated in the Waste Effluent Plants before discharging to the river.

The best option is to develop the BRDA and the plant area for nature conservation. At present a large part of the island has a nature trail with walks and runs over about 6km. "Nature Conservation" applied from the EPA Landfill Manual is woodlands, wildflower meadows, heath lands, wetlands. and walks.

There are four future land uses for residue disposal areas. These are:

- **Native Vegetation** – Vegetation covering the residue area which is sustainable.
- **Stable, Non-Productive Vegetation** – The BRDA will be safe from any dusting, it will be similar to the surrounding landscape, safe from any erosion.
- **Agriculture** – It could be returned to agriculture from whence it came. Aughisish is the Irish for the" island of the horses".
- **Light Industry** – The facilities on the plant site could attract some industry.
- **Nature Conservation**

- There is a Bird & Butterfly sanctuary in a quarry section close to the B.R.D.A. which was established in 1981 It has been published in Irish Wildbird Conservancy. The nature trail already mentioned forms a large part of the island and the roads around the BRDA which extend for about 5km could be incorporated into the scheme.

- **Amenity Restoration**
  - Close to the BRDA there is a sports centre complex. And is the starting point for people to use the trails. It is available to the local community. Joggers, walkers and sightseers use these amenity features. One section at the river's edge at tidal Poulaweala Creek there a bird hide to observe the inter-tidal bird environment.
- **Agriculture**
  - meadow growth for hay cropping and grassland pasture could be used for cattle grazing, silage production. The proposed nature conservation post-closure land use is in keeping with the current land uses of the surrounding area.

The B.R.D.A. and the plant area will be taken over by a government agency and they will require and ensure that the closure plan will be completed.

The plant vessels, tanks and equipment, the marine terminal with its on and off loading facilities and the CHP plant, could continue as commercial operation;

- The B.R.D.A. itself will be re-vegetated and could be an addition to the nature trails.
- The leachate collection and treatment will be required as long as the leachate pH remains above 9.0. This means running the Waste Effluent Plants until that target is reached.
- EPA. monitoring will continue.

B.R.D.A residue could have some alternative uses as discussed earlier. But this maybe limited to thousands of tonnes rather than millions.

The plant has more potential given the CHP could generated electricity as the gas supply is still available, but its present set up would require some usage for the condensate produced or the plant modified to eliminate the excess condensate. The marine terminal and 800-metre jetty arm could be viable.

5.4.8 Operational Residue Management System

The dry stacking of the residue at Aughinish has made the management of the BRDA and eventually its closure much easier in terms of controlling run off, leachate, and dusting.

Aughinish BRDA has:

- Residue deposited at 58% density, which gives a better stacking angle, less liquor in run off and leachate to treat. It will have solar drying and compaction
- The central discharge is doomed at 30m in height with a good stacking angle. A central discharge at 28m height will encourage good run off and avoid pooling on the residue.
- The stepped embankments and their design ensure that the residue is safely contained and there is no risk of bank failure.
- Armouring of the embankments will also ensure reduced leakage,
- The sand and geo-textile filters within the embankments reduces solids seeping through to the perimeter channel.
- A sustainable vegetation cover and the adoption of “nature conservation”

Installing deep thickeners have been added since 2011, which gives extra flexibility to the process of the mud circuit. It will give higher solids concentration and lower caustic in the final residue to the BRDA. Further modifications are being considered in the coming years to improve quality and reduce cost surrounding the management of the residue and BRDA operation.

5.4.9 Operational Controls (Aligned with "Design for Closure")

The running and management of the BRDA is done with available capacity in mind, plus the likely increase in alaumina production depending on world demand and price. At present the space for residue will last until 2026 and the company will have to have another extension constructed by then or the plant will close. The operational activities are carried out with space on the BRDA as top priority and how the area can be safely closed down. For the B.R.D.A. this means:

- High density stacking and to reduce the risk of embankment failure or over spill, and the control of all environmental conditions, to ensure that no dusting occurs, and adhering to all conditions of the EPA License and the Environmental Management System ISO 14001 (2004)

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:

- Because of the type of bauxite used and the Digestion circuit this gives rise to some specific process issues, although the amount of alkalinity in the Aughinish residue is lower than some other Bayer Process Plants it should make neutralisation easier and less costly with better results than some other plants...
- 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. Neutralisation will

only take place with 20% of the soluble alkalinity, this may bring the pH down to 9.0 but will rise again to around 10.5. Rainfall run-off from the BRDA at 10.5 will require collection and return to the Waste Effluent Treatment plants. for neutralisation and solids removal as is the case presently. prior to discharge.

- Using sea water as a source of magnesium to neutralise residue was considered too costly in terms of equipment required to pump large volumes of sea water, low salinity of the diluted river water and the added cost of having to retreat it the before returning the water to the river.
- Carbon dioxide potentially offers a more effective neutralising agent where both soluble and a proportion of the solid alkalinity is neutralised. Availability of CO_2 would require importation from outside the country or using flue gas to extract CO_2 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

River Shannon water (source of magnesium) could be ruled out due the large equipment required to pump large volumes of low salinity water at the Jetty head or take water from further out at sea. These high volumes of water t would be required to drive the reaction. There is a reduced concentration of magnesium in the Shannon estuary due to the freshwater mix. The salt water is only a weak acid, and would require a clarification system, plus a treatment system to return the water to the river. The pumps would be required to pump approx. 14,000m^3/hr. This is not feasible from economic or environmental perspectives.

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 concern is the risk of producing H_2S smell on the plant which could be carried into the surrounding areas. There are periodic incidents happening of these odours at the Waste Effluent Plants where acid is used and disposed of for pH control... This would result in complaints to the EPA.

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 in 2007. 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 with 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 pipework 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 License 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 not 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 pipelines, 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 the highest possible percentage solids, became much more significant in a closure scenario.

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. This meant that production was sacrificed to get higher % solids to the BRDA which gives a better stacking angle and so uses less 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. Mud Farming has reduced the pH to around 10.5 – 11.0. it will take time to evaluate if vegetation will reduce seepage rates enough to effect dilution rates. The Closure Plan is submitted and accepted by the EPA and the partial neutralization of the residue enough to allow Phase 2 section to be operable and so keep the plant in production. So, part of the project aims was achieved, and a lot of knowledge / research completed. 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_2S 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 and can be easily viewed by anyone visting the site. All the analysis will on the Annual Report on the E.P.A web site.

Figure 64 Demonstration Cell filling in 2007

Chapter 6

6.1 Conclusions

As per the licence application Aughinish have committed to have the leachate pH at 9.0 or below 5 years after closure. This would enable direct discharge to the Shannon river without the need of treatment. From the modelling carried out, and research from the trials and due to the low permeability of the mud, it is estimated that over 28 pore volumes will be required to get to a pH of 9.0 or below. The time needed to achieve this outcome may exceed 100 years., The leachate sampling from the Demonstration Cells showed there was no reduction in pH after 18 months which would substantiate that theory. There was no reduction in pH either from the one tonne containers after 18 months sampling. The only real reduction has come from athmospheric carbonation, namely Mud Farming. This showed a reduction of 13.0 to around 11.0- 10.5. From the modelling 400;1 ratio could be achieded which would show that run-off / seepage ratio could get the pH to 9.0. This is from a modelling exercise without any vegetation on the residue. Vegetation will reduce the run off rate so this ratio from the modelling would be reduced. Time and the results from the Cells with Mud Farmed mud will give more information.

Will this outcome be acceptable to the EPA? At present the current practice is acceptable. The EPA requested lower alkalinity mud be placed on top of the residue in Phase 1 but it is difficult to see how this could reduce the alkalinity of the already deposited mud. It would help to sow vegetation but unlikely to reduce the pH of the Phase 1 residue.

Capillary rise from the high pH mud in the area would be the problem. The EPA have requested neutralised red mud or partially neutralised mud only be pumped into Phase 2 BRDA. The partial neutralisation is being achieved by Mud Farming the residue as it is deposited., at best down to around 11.0 – 10.5.

Even with partial neutralised residue in Phase 2 (10.5) the best that can be achieved by the present amount of ploughing and farming, it will take years to achieve a leachate pH of 9.0. This pH of 10.5 leachate and run off will still require treatment in the Effluent plants. Similiarly amendment will still be required to lower the pH of the residue before sowing grassto provide for a sustainable vegetation.

Rusal Aughinish started a process of evaluating methodologies to successfully close the B.R.D.A. in an environmentally 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 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. Results from the closed plant in Scotland would also bear this out. They had no reduction in pH three years after closure and sowing grass on the residue. (See below) The results from the new trials in the Demonstration Cells over a longer period will yield further information in time.

6.2 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.

6.2.1 Vegetation Aughinish Trials

The experience at 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.

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. This did not happen at the time but now the plan is to fill the second cell with partially neutralised mud and then vegetate. The liner will also be removed at the bottom of this cell to avoid a water table building resulting in increased capillary rise.

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 badly 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 now.

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. Overall, the grass growth was very good and lasted. Some small areas had to have additional treatment and reseeding carried out. (See photos back in Large Plot Trials)

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 years or longer 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') is in the semi- tropical coastal regions of Australia. The neutralised residue is deposited as a wet slurry with the run off collected, treated and pumped back to the sea.

Aughinish would need an extension of its licence to return water to the Shannon and unlikely to receive it. Warmer tropical weather conditions help drying and consolidation of the mud much more so than in Ireland which is a big advantage. It also allowable in Australia to allow the run off back into the sea. This system is not suitable for Rusal Aughinish due to high pumping rates and cost of equipment required. The treatment of the return liquor to the sea would also be aa added cost. This would require further expansion of the Waste Effluent Plants.

6.2.3.3 CO_2 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 They use CO_2 which is a waste gas from a nearby Ammonia Plant and is piped into the plant.

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.at Aughinish. The plant 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. Liquid CO_2could be purchased and imported by road tankers, again very costly and would require adequate storage and distribution network installed.

6.3 Closure Plan & Relinquishment Criteria

At closure, the B.R.D.A. which at present production levels will be 2026 unless an extension is added to the existing 180ha, it will be an open domed residue surface. Same as presently the residue will be contained by the embankments. It is planned to revegetate the embankments from Stages 1 to 10. All run off and seepage will be collected and returned to the Waste Effluent plants for treatment.

A full vegetation cover on all of the BRDA will be sown within 5 years. The leachate and run off will be collected and treated until the pH is at 9.0 or below and the solids concentration is less than 50mg/l, these are the present EPA licence parameters. If these conditions can be maintained for 1 year the Waste Effluent plants will be shut down and the interceptor channel will be breached allowing direct flow to the river.

With the introduction of the Wetland pilot plant trial, it is now proposed to complete further trials and eventually be able to release the leachate into the existing wetland on the site if the trials are successful. This would enable the company to shut down the Waste Effluent plant provided the pH is below 9.0. The observation wells around the (40 in total) will be used to sample the groundwater to ensure back groundwater quality is not influenced by more than 10%. Geo-technical checks will be carried out to assess pore pressures of the residue and that the embankments are stable and safe. Contaminated groundwater will be intercepted and managed for amelioration and discharge. There will be twenty-five years of further environmental monitoring as per the EPA licence conditions.

6.3.1 Nature Conservation

The restoration of the B.R.D.A. aims to have a "nature conservation' use, with a lasting vegetation growth. Sufficient organic materials are required as the mud does not have any nutrients. and process sand to provide good drainage. This information regarding the correct amendments has been gathered with the previous trials and the research on the Demonstration Cells. The trials have proven that the revegetation is possible with certain grasses and the correct organic addition, plus good drainage and the avoidance of capillary rise. Important parameters are the caustic concentration and solids % of the residue placed on the BRDA.

The list below is the type of grasses that have been used on site and are successful. Typical types 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. While grass cover is being established it will be necessary to the have the sprinkler system working in case of dusting. This water from the sprinkler system will come from recycled rainwater run-off and potable water which is supplied by the local authority.

6.3.2 Choice of Final Land Use

The long-term sustainable land use of the B.R.D.A. surface must ensure that it is safe, that there are no bank failures or leakage of leachate with high caustic into the surrounding environment. The preferred option is for nature conservation. Aughinish land to the north of the B.R.D.A. has already been developed as a Bird Sanctuary, and a nature trail already exists around the southern and eastern part of the site This option fits in 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'.

Some lands close to the site are subject to EU and National environmental designations 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 trees and shrub species and the spread of scrub woodland to the surface of the B.R.D.A. following closure. Planting of scrubs and trees has already commenced. A naturally evolved woodland such as this would help protect the B.R.D.A. surface from wind erosion and improve stability.

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 has started and will continue. These will be a self-sustaining habitat with 'natural' characteristics, with time, it is hoped that the scrub woodland on the side slopes may spread to the surface of the re-vegetated B.R.D.A.

Due to the amended soil structure of the residue and limited nutrients it may require on going treatment and management 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.

6.3.3 After-care and Demonstration of Performance

By establishing a sustainable growth cover it will avoid the need for the dust suppression system and will reduce seepage through the mud. It will reduce costs in equipment maintenance and possible need to purchase potable water from the local authority. Run off from rain water will be at a lower pH and therefore no need for treatment. How successful the vegetation cover is will be measured for 5 years by vegetation and biological sampling. If the vegetation is not successful Aughinish will have to update the Residuals Management Plan and show how it can meet its requirements.

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.

Dilution of the caustic content and lowering of the pH due to rainfall will provide some benefit but can a pH of 9.0 be reached within 5 years is highly unlikely. The modelling of pore volume flushes and the 18 months sampling of leachate from the Demonstration Cell showed it will be far in excess of 5 years. Neutralisation of leachate will be required for longer than five years and the running of Aughinish Waste Water Treatment Plants will be necessary. Aughinish has committed to the establishment of the Closure Demonstration Cells trials and monitoring so this research will continue. Is such an outcome 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 H_2S 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 effect 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 is being progressed with more machinery and increased ploughing.

CO_2 injection will not happen in the near future given the non-availability of liquid CO_2 in Ireland. The money is not available to build a CO_2 plant or extract CO_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 and vegetation sowing. The knowledge yet to be gained is leachate pH decline over a long period from the Cells. It appears that it will take up to 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.

1. They must continue with Mud Farming which will achieve partial neutralization

2. 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.

3. Continue with Wet Land trials and how this system might influenc pH

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 loosing 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. Some delays were not anticipated, so this again was a learning aspect for a complex project with several smaller projects happening at the same time. The author's delegation of tasks improved over time and 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

In order that all parties, including the community, agree what is a sustainable residue management system and to gain acceptance of the closure plan, the company will have to commit to a number of items and actions:

- Engaging the community on the total risk associated with the B.R.D.A and this can be done at the annual 'Neighbour's Meeting'.
- Continued analysis of the run off and leachate from the Demonstrations Cells. and can an effluent pH <9.0 be achieved. The continued analysis from the Cells for leachate and run off. The modelling of pore volume flushes of the residue will also continue.
- How the vegetation influences the run off and leachate quality will take some years to obtain accurate information. It will require the Waste Effluent Plants to stay running and manned. A monitoring programme will be required to be continued on the vegetation, any changes in the mud permeability, which will affect the run off and leachate pH and the effluent parameter.

The cost estimates to manage five years of operation of the Waste Effluent Plants may need to be reviewed to accommodate a treatment time-frame that may extend out further following results from the Demonstration Cells.

- potential erosion risk has to be assessed.
- On- going monitoring of the vegetation,
- Embankment stability
- Risk of dusting.
- This monitoring will show if sufficient nutrients for the re-vegetation are present and self- sustaining. This is required for costs and manpower. The post-closure management programme should include security of the site, no

unauthorised entry or trespassing and control of wild animals which cause burrowing followed by erosion.

- There is always the risk of capillary rise of high alkalinity residue which would destroy the vegetation. Again, this will be part of the post closure management programme.
- Acceptance by the EPA and the local community are required for any closure plan. In addition, it is recommended that the company: investigates any possible uses for bauxite residue in industry or land use. The company needs to continue to be part of the world
- alumina industry to find alternative uses. This could include working with the EPA and Irish industry.

- Further experimentation is required if acid is used for neutralisation including how long the acid is in the residue pipeline before it is discharge onto the BRDA.as this could lead to" dead legs" and pipe corrosion. If this is a few hours, there may be time for the pH 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.
- Develop a process to neutralise process sand so that it could have a possible end use. These include:

- Further research in re-use of process sand – physical, chemical properties.
- Discuss with E.P.A what parameters are required to classify sand as inert and could be used in construction...
- Major investment is required to engineer, scope and pilot trial acid neutralisation of bauxite residue.
- Wetland evaluation

- Monitoring of nutrient levels in herbage and substrate
- Further evaluation in relation to spreading of sand, gypsum, & organic material on a large scale on the bauxite residue.
- 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, if the acid neutralisation is used in the process

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 EPA require leaching to reduce the pH to 9.0. or below but will depend on how successful the vegetation cover is. 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.
3. The sampling of leachate from the Demonstration Cell did not show any drop in pH. The recommendation here is to continue with the sampling and analysis for soda, conductivity and pH. Is the vegetation making any difference to the pH of the leachate or run-off. Further trials are in progress with the second cell using reduced pH mud following “Mud Farming” from the BRDA. Vegetation will be sown on this and sampled. Research will show if there are differences in the leachate / run off pH between the earlier trails with the first cell.and this new method.
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.
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. Odour could become an issue with acid neutralisation at certain pH values should that happen in the future.
7. The risk of dusting requires the ongoing extension of the sprinkler system into the Phase 2 extension as it is filled with mud. 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.
10. Continue with additional Deep Thickener Projects to increase the residue solids concentration to the BRDA and in turn reducing the caustic levels in the red mud.
11. Mud Farming and ploughing for atmospheric carbonation to continue to reduce the pH in the deposited residue.

List of References

AAL (2005a) Bauxite Residue Disposal Area – Operational Plan (B.R.D.A. OP001), Aughinish Alumina Ltd.

AAL (2005b) Expansion of B.R.D.A. and Increase in Alumina Production Capacity at Aughinish Alumina Ltd, Aughinish Alumina Ltd, Environmental Impact Statement, Volume 2, Prepared by RPS Group.

AAL (2005c), IPC Licence Review # 754, Attachment C.

AAL (2005d), "Expansion of Bauxite Residue Disposal Area and Increase in Alumina Production Capacity – Limerick County Council 05/1836, Further Information Request", Aughinish Alumina Ltd, Volume 1 Response to FI Request, Appendices A to F to O, Prepared by RPS Group, December 2005.

AAL (2005e), Annual Environmental Report (2005), Aughinish Alumina Ltd.

AAL (2006), "Risk Assessment and Break-out Study For the Bauxite Residue Disposal area At Aughinish Alumina", Golders Associates, April 2006.

AAL (2007), "Discussion of Mud Neutralisation at Alcoa", teleconference between David Cooling, Residue Development Manager, Alcoa World Alumina and Mr Liam Fleming and Mr Thomas Hartney, AAL, 23rd February 2007.

Abrahams, A.D., LI, G., Krishnan, C. & Atkinson, J.F. (1998), 'Predicting sediment transport by interill overland flow on rough surfaces'. *Earth Surface Processes and Landforms*, v23 n12 December 1998, pp 1087-1099.

Agriculture Western Australia (2000), 'Copper, zinc and molybdenum fertilizers for new land', Agriculture Western Australia, Farmnote 25/88 (Reviewed 2000).

Alcan (2002), “La Bauxaline, A new product for various applications”, Aluminium Pechiney, Gardanne.

Alcan (2004), “Draft – Environmental Impact Statement, Alcan Gove Alumina Refinery Expansion Project”, URS, February 2004.

Alcan (2004), “Draft – Environmental Impact Statement, Alcan Gove Alumina Refinery Expansion Project”, URS, February 2004.

Alcoa (2007), “Alcoa Q4 2006 Earnings Call Transcript”, Seeking Alpha Website, 9/1/2007.

Alcoa (2007), “www.alcoa.com”, various articles and information (22/1/2007).

Alcoa World Alumina, “Kwinana Environmental Improvement Plan – Progress Report”, June 2006.

Alcoa World Alumina, Australia, Paste 2007.

Alunorte (2007) (www.alunorte.net).

AMIRA INTERNATIONAL (20030, Assess the Impacts of Trace Elements in Bauxite Residues, http://www.amira.com.au.

Argyris, C. & Schön, D. (1978), *Organizational learning: A theory of action perspective,* Reading, Mass: Addison Wesley.

Argyris, C. Putnam, R. & McLain Smith, D. (1985), *Action Science*, *Concepts, methods, and skills for research and intervention*, San Francisco: Jossey-Bass [The entire book is available for download from Action Design].

Argyris, M. and Schön, D. (1974), *Theory in Practice. Increasing professional effectiveness*, San Francisco: Jossey-Bass. Landmark statement of 'double-loop' learning' and distinction between espoused theory and theory-in-action.

Aughinish Residue Carbonation\DSP8092-EZ-PR-001 Revision, A proposal.docx,

AWA (2003), "Environmental Protection Statement – Pinjarra Refinery Efficiency Upgrade", Report prepared for Alcoa World Alumina Australia by ENVIRON Australia.

AWA (2005), "Environmental Review and Management Programme – Wagerup refinery Unit Three", Report prepared for Alcoa World Alumina Australia by ENVIRON Australia.

AWA (2005), "Environmental Review and management Programme – Wagerup refinery Unit Three", Report prepared for Alcoa World Alumina Australia by ENVIRON Australia.

AWA (2006), Alcoa World Alumina, "Pinjarra Environmental Improvement Plan – Progress Report", June 2006.

AWA (2006), Alcoa World Alumina, "Pinjarra Environmental Improvement Plan – Progress Report", June 2006.

Bauxite residue re-vegetation research programme, Final Report to Alcan Pty, Ltd.

Bell, L.C. (1986), Mining. In: Russell, J.S. and Isbell, R.F. (eds.) Australian Soils – The Human Impact. University of Queensland Press, p 445.

Bell, L.C. and J.R. Meecham (1979), Reclamation of alumina refinery wastes at Gladstone, Australia. Reclam. Rev. 1:129–137.

Bell, T.D. Plummer, J.A. and Taylor, S.K. (1993), 'Seed Germination Ecology in South-western Western Australia'. *The Botanical Review*, v59, n1, pp 24-73.

Bell,C.(1998)Self Reflectionand vulnerabilityin action research; *SystemicPracticeand Action Research, 11(2),179-191*

Berstein, L. and Hayward, H.E. (1958), Physiology of salt tolerance, *Ann.Rev.PL.Phy., 9:25-46*.

Blackall, W. E. & Grieve, B. J. (1974), How to Know Western Australian Wild flowers, Parts I, II and III. University of Western Australia Press, Perth, Western Australia.

BOM (2007) (www.bom.gov.au), Bureau of Meteorology, Various information.

Bossuyt, H. Denef, K. Six, J. Frey, S.D. Merckx, R. and Paustian, K. (2001), 'Influence of `microbial populations and residue quality on aggregate stability'. *Applied Soil Ecology*, v16 `n3 pp195-208.

Boufounos, D. Pernientaki, I. Fafoutis, D. Xenidis, A. Harokopou, A.D. and Mylona, E. (2005), Use of bauxite residues for the rehabilitation of abandoned surface mines, Proc. of Int. Conf. Geo environment and Geo-technics (Z. Agioutantis & K. Komnitsas, eds.), Milos, Greece, pp. 183-188.

Bower, C. and Radleigh, C. (1949), Growth and cationic accumulation by four species of plant as influenced by various levels of exchangeable sodium, *Soil Sci. Soc. Amer .Proc*. 13; 218 – 223.

Bower, C. and Turld, L. (1946), Calcium and Magnesium Deficiencies in Alkali Soils. Amer. Soc. Agron. J. 38 ; pp. 723–727.

Bradshaw, A. and Johnson, M. (1992), Re-vegetation of Metalliferous Mine Waste: The Range of Practical Techniques Used in Western Europe. Miner. Metals Environ; pp. 481–491.

Brannick,T.,&Coghlan, D.The case for insider academic research. *Organizational Research Methods, 17(1)*

Buchanan, D., & Boddy, D.(1992) *The expertise of the exchange agent* . London :Prentice - Hall

Bremner, J. M. and Mulvaney, C. S. (1982), Nitrogen – Total. *In*Methods of Soil Analysis, Part 2. Ed. A L Page. pp. 595–624. American Society of Agronomy and Soil Science Society of America, Madison.

Brennan, R. (1998a), 'Copper'. In: Moore, G. (ed.). Soilguide: a handbook for understanding and managing agricultural soils, Bulletin No. 4343.Agriculture Western Australia, Perth, Western Australia; pp 184-188.

Brennan, R. (1998b), 'Zinc'. In: Moore, G. (ed.). Soilguide: a handbook for understanding and managing agricultural soils, Bulletin No. 4343. Agriculture Western Australia, Perth, Western Australia; pp 185-192.

Brofas, G. Varelides, C. (1997), Results of the use of sewage sludge for improvement of calcareous mining spoils. *International Journal of Surface Mining, Reclamation and Environment* 11: 163-167.

Bucher, M.A. (1985), The effects of gypsum and sewage sludge on plant growth and nutrition on alkaline, saline, fine-textured bauxite residue, MSc Thesis, Duke University, Durham, North Carolina.

Cablik, V. (2007), Characterization and applications of red mud from bauxite processing. Gospodarka Surowcami Mineralnymi – Mineral Resources Management, 23, 27–38.

Caines, A.M. and Sherman, C. (1999), Interactive effects of Ca^{2+} and NaCl salinity on the growth of two tomato genotypes differing in CA^{2+} use efficiency plant *Physiol.Biochem., 37:: 569-576*.

Cairns, J. Jr. Integrating top-down/bottom-up sustainability strategies: an ethical challenge. *Ethics Sci Environ Politics* 2003; 1–6. Available from: http://www.intres.com/articles/esep/2003/

Campbell, D.T. & Fiske, D.W. (1959), Convergent and discriminant validation by the multitrait-multimethod matrix. Psychological Bulletin, 56, 81-105.

Campbell, D.T. & Stanley, J.C. (1963, 1966), Experimental and Quasi-Experimental Designs for Research. Rand McNally, Chicago, Illinois.

Charman, P. E. V. & Murphy, B. W. EDS. (2000), Soils - their properties and management, 2nd edition. Oxford University Press, Melbourne, Australia.

Chenu, C. Bissonnais, Y.L. & Arrouays, D. (2000), ‘Organic Matter Influence on Clay Wettability and Soil Aggregate Stability’. *Soil Science Society of America Journal*, v64, pp1479-1486.

Cochrane, T. A. & Flanagan, D. C. (1999), ‘Assessing water erosion in small watersheds using WEPP with GIS and digital elevation models’. *Journal of Soil and Water Conservation*, v54, p678.

Coles, N. & Moore, G. (1998), ‘Run-off and Water Erosion’. In: Moore,G. (ed.). Soilguide: a handbook for understanding and managing agricultural soils, Bulletin No. 4343. Agriculture Western Australia, Perth, Western Australia; pp 223-242.

Commonwealth Environmental Protection Agency (1995), Tailings Containment. Module in the series on Best Practice Environmental Management in Mining.

Cook, T.D. & Campbell, D.T. (1979), Quasi-Experimentation: Design and Analysis for Field Settings. Rand McNally, Chicago, Illinois.

Cooling, D. (1989), Developments in the Disposal of Residue from the Alumina Refining Industry, Light Metals 1989; Las Vegas, Nevada; USA; 27 Feb.-3 Mar. 1989. pp. 49-54. 1989.

Cooling, D. J. (1996), “Long Term Residue Management Planning”, Minerals Council of Australia, Annual Environmental Workshop.

Cooling, D. J., (1997), Tailings Management within Alcoa of Australia - Two Decades of Change. Australian Centre for Geo-mechanics Workshop proceedings, Tailings Management for Decision Makers.

Cooling, D.J. and Jamieson, E. (2004), “Bauxite Residues – A High Volume Resource”, Green Processing Conference, 10-12 May, Fremantle, Western Australia.

Cooling, D. J. (2007), Improving the sustainability of residue management

Practices – Alcoa World Alumina. In A. B. Fourie and R. J. Jewell (Eds.), *Paste 2007—Proceedings of the Tenth International Seminar on Paste and Thickened Tailings* (pp. 3–15). Australian Center for Geo-mechanics, Perth, Australia.

Cooling, D.J. Hay, P.S. Guilfoyle, L. (1991-1996), Carbonation of Bauxite Residue.

Courtney, R. and Hartney, T. (1998), The Development of a Rehabilitation System for Waste Generated at Aughinish Alumina Refinery, *International Workshop on Rehabilitation of Mined Bauxite Lands and Red Mud Disposal Areas*, September 28 – 2 October, Kingston, Jamaica.

Courtney, R. (2002), The development of a rehabilitation system for the red mud residue generated at the Aughinish Alumina Bayer Plant, PhD Thesis, Institute of Technology, Sligo.

Courtney, R.; Timpson, J. & Grennan, E. (2003), Growth of *Trifolium pratense* in Red Mud Amended with Process Sand, Gypsum and Thermally Dried Sewage Sludge, International Journal of Surface Mining, Reclamation and Environment, 17:4: 227-233.

Courtney, R. & Timpson, J. (2004), Nutrient Status of Vegetation Grown in alkaline bauxite processing residue Amended with Gypsum and Thermally Dried Sewage Sludge - A Two Year Field Study, Plant & Soil, 266:1:187-194.

Courtney, R. & Timpson, J. (2005a), Reclamation of Fine Fraction Bauxite Processing Residue (Red Mud) Amended with Coarse Fraction Residue, Gypsum and Thermally Dried Sewage Sludge, Water, Air & Soil Pollution, 164:l- 4:91-102.

Courtney, R. and Timpson, J. (2005b), Nutrient status of vegetation grown in alkaline bauxite processing residue amended with gypsum and thermally dried sewage sludge - A two-year field study. Plant and Soil, 266:1:187-194.

Courtney, R. (2006), Rehabilitation of red mud tailings produced at the Aughinish Alumina Refinery, *9th International Seminar on Paste and Thickened Tailings,* Limerick, Republic of Ireland, 3 – 7 April 2006.

Croker, J. (1999), Response of vegetation to varying irrigation applications on rehabilitated bauxite residue. Dissertation for Graduate Diploma of Science. Faculty of Agriculture. The University of Western Australia, Perth, Australia.

Dan MacIsaac, "An Introduction to Action Research," 1995, http://www.phy.nau.edu/~danmac/actionrsch.html (22/03/1998).

Department of Western Australia (1994), 'Cereal rye – a crop for stabilising erodible soils' Department of Agriculture, Farmnote 91/94.

"Design changes to red mud dam add years to storage life", Gladstone Observer.

DITR (2006), Draft 3 - Leading Practice Tailings Management Handbook, Department of Industry, Tourism and Resources, Leading Practice Sustainable Development Program, Australian Government, 28th September 2006.

DOIR (2006), "Ministerial Approval – Worsley Expansion", Hon Mark McGowan MLA, 13th April 2006.

Doorenbos, J.& Pruit, W.O. (1997), Guidelines for predicting crop water requirements (FAO Irrigation and Drainage Paper 24), Food and Agriculture Organisation of the United Nations (FAO), Rome.

Eastham, J. and Morald, T. (2006), Effective Nutrient Sources for Plant Growth on Bauxite Residue: II. Evaluating the Response to Inorganic Fertilisers, Water, Air and Soil Pollution, 171:315-331.

Eastham, J. and Morald T. (2006), "Effective Nutrient Sources for Plant Growth on Bauxite Residue: II. Evaluating the Response to Inorganic Fertilizers." Water, Air, & Soil Pollution 171(1 - 4): 315-331.

Eastham, J. Rose, C.W. Cameron, D.M. Rance, S.J. & Talsma, T. (1990), Planting density effects on water use efficiency of trees and pasture in an agro forestry experiment. *New Zealand Journal of Forest Science 20*: 39-53.

Ecomax (2007), www.ecomax.com.au, various articles and information (23/1/2007)

Eds, M. Chadwick, & G. T. Goodman, Blackwell, Oxford. Brady, E. (1993), Re-vegetation and Environmental Management of Lead and Zinc Mine Tailings. MpHil Thesis, University of Liverpool.

Emerson, W. W. (1991), 'Structural decline of soils, assessment and prevention'. *Australian Journal of Soil Research*, v29, pp 905-921.159.

Re-vegetation Strategies for Bauxite Refinery Residue (2006), A Case Study of Alcan Gove in Northern Territory Australia Environmental Management Vol.37 No. 3, pp 297-306.

EPA (1996), "Expansion of alumina production from 2.0 million tonnes per annum to 3.5 million tonnes per annum at Worsley refinery, and associated bauxite mining activities at Boddington", Report & recommendations of the Environmental Protection Authority, Bulletin 823.

EPA (2002), Guidelines on the Information to be Contained in Environmental Impact Statements cited in: AAL (2005b) Expansion of B.R.D.A, and Increase in Alumina Production Capacity at Aughinish Alumina Ltd, Aughinish Alumina Ltd, Environmental Impact Statement, Volume 2, Prepared by RPS Group.

EPA (2005), "Worsley Alumina – Efficiency & Growth Increase of Existing Operations to 4.4 Mtpa Alumina Production" Report & recommendations of the Environmental Protection Authority, Bulletin 1209.

EPA (2006), “IPPC Licence Review Application Register P0035-04”, Letter to Mr Liam Fleming, Environmental Coordinator, Aughinish Alumina Limited, 11/12/2006.

Flach, K. W. (1976), Formation, distribution and consequences of alkaline soils in agricultural development. In M. J. Wright (Ed.), *Plant adaptation to mineral stress in problem soils* pp. 25–30. Cornell University, Ithaca, NY.

.Fortin, J. & Karam, A. (1998), Effect of a commercial peat moss-shrimp waste composts on Pucinellia growth in red mud, International Journal of Surface Mining, Reclamation and Environment, 12: 105-109.

Foster, M.B. (1989), ‘Rehabitation After Bauxite Mining at Weipa’. In: Mining and the return of the living environment. Volume 2. Australian Mining Industry Council, 1989, pp. 13-17.

Fuller, R. Nelson, E. & Richardson, C. (1982), Reclamation of red mud (bauxite residues) using alkaline-tolerant grasses with organic amendments, Journal of Environmental Quality, 11(3): pp 533-539.

Gebhardt, M. R. Daniel, T.C., Schweizer, E.E. and Allmaras, R.R. (1985), ‘Conservation tillage’. *Science*, v 230, November 8 1985, pp. 625-630.

Gherardi, M. J. & Rengel, Z. (2001), Deep placement of manganese fertiliser improves sustainability of lucerne growing on bauxite residue: A glasshouse study. Plant Soil 257, pp. 85–95.

Gherardi, M. J. & Rengel, Z., (2003), Bauxite residue sand has the capacity to rapidly decrease availability of added manganese. Plant Soil 234, pp 143–151.

Golder Associates (2005a), The Preliminary Design for the Phase 2 Bauxite Residue Disposal Area, Aughinish Alumina, IPC Application Attachment D2a, Aughinish Alumina, May 2005.

Golder Associates (2005b), The Preliminary Design for the Optimisation Capacity of the Phase 1 Bauxite Residue Disposal Area, Aughinish Alumina, IPC Application Attachment D1a, Aughinish Alumina, May 2005.

Golder Associates (2005c), Geo-technical Investigation for the Optimisation Capacity of the Phase 1 Bauxite Residue Disposal Area at Aughinish Alumina, IPC Application Attachment H2b, Aughinish Alumina, May 2005.

Google (2007), Google Earth, Viewed 18/1/2007.

Google (2007), Google Earth, Viewed 24/1/2007.

Grafe & Klauber (2010), AMIRA P1038: Bauxite residue in situ modification project.

Graham, G. & Fawkes (1992), Red mud disposal management at QAL.Proc. *International Bauxite Tailings Workshop, Perth* 1992, pp. 188-195.

Green Processing Conference, Fremantle, May 2004.

Greenhouse, S.W. & Geisser, S. (1959), On methods in the analysis of profile data. Psychometrika 24:95–112.[ISI]

Group, Doc No 011788-22-RP-001A, undated, Pat Swords.

Gupta, R. & Abrol, I.P. (1985), Dissolution of gypsum in alkali soils Soil Science 140 (5) 382-386

Gupta, R. & Abrol, I.P. (1990), Reclamation and management of alkali soils. Indian J. Agric. Sci. 60, 1–16.

Gupta, R.& Sharma, S.K. (1990), Response of crops to high exchangeable sodium percentage *Irrigation Science*. 11; 173 – 179.

Keren, R. (2000), *Salinity.* In M. E. Sumner (Ed.), *Salinity.* (pp. G3–G25). CRC Press, Boca Raton, FL.

Haby, V. A. Russelle, M. P. & Skogley, E. A. (1990), Testing soils for potassium, calcium, and magnesium. *In*Soil Testing and Plant Analysis 3rd ed. Ed. R. L. Westerman. pp. 229–264. American Society of Agronomy and Soil Science Society of America, Madison.

Hanson, J.B.(1978), Application of the chemiosmotic hypothesis to ion transport across roots *Plant Physiol*., 62. 402 – 405.

Hind, A. R., Bhargava, S. K., and Grocott, S. C. (1999), The surface chemistry of Bayer process solids: A review. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 146, 359–374.

Hossner, L.R. Loeppert, R.H. Woodard, H.J., Moore, T.J. &. Thompson, T.L. (1986), Reclamation and vegetation of bauxite residue. Alcoa Rep. 3. Soil and Crop Science. Dept., Texas A&M Univ., College Station.

http://www.socialresearchmethods.net/kb/intres.php
http://www.refil.gr/Demonstration Test.htm
http://www.refil.grPilot Test.htm

Hudson, L.K. (1987), Alumina production. p. 11–46. *In* A.R. Burkin (ed.), Production of aluminum and alumina. John Wiley & Sons, New York.

Hudson, N. (1995), Soil Conservation: fully revised and updated. 3rd Edition. Batsford Limited. *Impact Assessment Study/Environmental Impact Statement* (1998 -2000) Comalco Alumina Project, Comalco.

Impact Assessment Study / Environmental Impact Statement (1998 -2000).

International Aluminium Institute (2003), Bauxite Residue Management Survey.

INMET (2007) (www.inmet.gov.br) Instituto Nacional De Meteorologia, Brasil. Viewed 23/1/2007.

International Workshop on Rehabilitation of mined bauxite lands and red mud disposal Sept 28- Oct 2 1998.

J. Exp. Agricultural. Animal. Husbandry 17 (1977), pp. 679–688. Growth of *Trifolium Pratense* in Red Mud.

Jamalco (2004), "Jamalco 2.8M Metric Tonne per year Efficiency Upgrade, Environmental Impact Assessment", Jamalco, prepare by Conrad Douglas & Associates Ltd.

Jamalco (2005), "Jamalco RDA 5 Environmental Impact Assessment", Jamalco, prepared by Conrad Douglas & Associates Ltd.

Jarvis, M.S. & Jarvis, P.G. (1972), Stalfelt's Plant Ecology – Plants, the Soil and Man. Longman, London.

Jasper, D. Lockley, I. Ward, S. & White, A. (2000a), Current approaches and future challenges for rehabilitation of bauxite residue, Proceedings of remade lands 2000, International Conference on the Remediation and Management of Degraded Lands, 30 November - 2 December, Fremantle, Western Australia.

Jasper, D. Lockley, I. White, A. & Ward, S. (2000b), Building soil fertility in rehabilitated bauxite residue, Soils 2000, Conference Proceedings, Muresk Institute of Agriculture, Northam, WA, 11-13 July.

Jones, G.E. (1996), 'Vegetation Sampling'. In: Handbook of Western Reclamation Techniques, CD-ROM, University of Wyoming, Office of Research, 1996.

Judd, C.M. & Kenny, D.A. (1981), Estimating the Effects of Social Interventions. Cambridge University Press, Cambridge, MA.

Khan, A.A.H. & Ong, C.K. (1997), 'Design and calibration of tipping bucket system for field run-off and sediment quantification'. *Journal of Soil and Water Conservation*, v52 n6, 437-442.

Khaitan, S., Dzombak, D.A. and Lowry, G.V. (2009a), Chemistry of the acid neutralisation capacity of bauxite residue, *Environmental Engineering Science*, 26 (5), 873-881.

Kinch D. (2006), "Alunorte boosts alumina capacity to 4.4m TPY", Metal Bulletin, no. 8938, pp. 9. 3rd April 2006.

Kinnell, P.I.A. & Risse, L.M. (1998), 'USLE-M: empirical modelling rainfall erosion through -off and sediment concentration'. *Soil Science Society of America Journal*, v62 n6, pp1667-1672.

American Society of Agronomy and Soil Science Society of America, Madison.

Koch, J.M. & Taylor, S.K. (2000), 'Seed Germination Records from Alcoa's Marrinup Nursery'. Alcoa World Alumina Australia, No. 18.

Koch, J.M. Sudmeyer, J.E. & Pickersgill, G.E. (1998), 'Response of seeded eucalypts and under storey to broadcast nitrogen and phosphorus fertiliser on a rehabilitated bauxite mine.' Alcoa of Australia Limited, November 1998.

Kopittke, P.M, Menzies, N.W. So, H.B. Fulton, I. (2004), Effect of Mn Deficiency and Legume Inoculation on Rhizosphere pH in highly alkaline bauxite residue, 13th International Soil Conservation Organisation Conference – Brisbane, July 2004, Conserving Soil and Water for Society; Sharing Solutions.

Kumar, S. Kumar, R. and Bandopadhyay, A. (2006), Innovative methodologies for the utilization of wastes from metallurgical and allied industries. *Resources, Conservation and Recycling* 48, 301–314.

Laflen, J. M. (1997), 'WEPP - erosion prediction for the next millennium (Water Erosion Prediction Project). *Agricultural Research*, v45 n4, p2.

Lamp, C. & Collet, F. (1984), A Field Guide to Weeds in Australia. Inkata Press Pty. Ltd., Melbourne, Australia.

Lawer, A.T. (2000), 'The Effect of Rainfall Intensity and Consolidation on Erosion from Mine Spoil'. Thesis, Natural Resources, Agriculture and Veterinary Science, University of Queensland.

Layman report (EN) Year: 2006 No of pages: 10

Levy, G. J. (2000), Sodicity. In M. E. Sumner (Ed.), *Sodicity.* (pp. G27–G63). CRC Press, Boca Raton, FL.

Lewis, L. J. Shim You, Pedersen, W. & Black, E. (1995), Vegetation of thickened red mud tailings deposits without the use of soil capping techniques. Light Met. (Warrendale, PA) 1995:31–34.

Lin, C.X. Clark, M.W. McConchie, D.M. Lancaster, G. & Ward, N. (2002), Effects of Bauxsol™ on the immobilization of soluble acid and environmentally significant metals in acid sulfate soils. Australian. Journal. Soil Res. 40:805–815.

Lindsay, W. L. & Norvell, W. A. (1978), Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Science. Soc. Am. J. 42, 421–428.

Marschner, B. (1983), The reclamation of fine-textured bauxite residues using alkaline and aluminium tolerant grasses with organic and chemical amendments, MSc Thesis, Dept. of Forestry and Environmental Studies, Duke University, Durham.

Martin, K. (2004), “Identification of Issues and Audit of Plans/Strategies”, Pinjarra-Brunswick Sustainability Study, Department for Planning and Infrastructure, Prepared for Pinjarra-Brunswick Sustainability Study Steering Committee. January 2004.

Maas, E. V. (1990), Crop salt tolerance. In K. K. Tanji (Ed.), *Agricultural salinity assessment and management* (pp. 262–304). ASCE, New York.

McConchie, D. Clark, M. Hanahan, C. & Fawkes, R. (1999.) The use of seawater-neutralized bauxite refinery residues (red mud) in environmental remediation programmes. p. 391–400.

McConchie, D., Saenger, P. & Fawkes, R. (1996), An environmental assessment of the use of seawater to neutralise bauxite refinery waste. p. 407–416.

McConchie, D. Lancaster, G. & Ward, N. (2002), Effects of BauxsolTM on the immobilization of soluble acid.

Mc George, W.T. and Brazeale, J.F. (1938), Studies in soil structure: effect of puddle soils on plant growth; Arz.Agr.Sta.Tech. Bulletin.

Meecham, J. and Bell, L. (1977a), Re-vegetation of alumina refinery wastes. I. Properties and amelioration of the materials, Australian Journal of Experimental Agriculture and Animal Husbandry, 17: 679-688.

Meecham, J. and Bell, L. (1977b), Re-vegetation of alumina refinery wastes. 2. Glasshouse experiments, Australian Journal of Experimental Agriculture and Animal Husbandry, 17: 6879-696.

Mehrotra, N. K., Khana, V. K. & Agarwal, S. C. (1986) Soil sodicity induced zinc deficiency in maize. Plant Soil 92, 63–71.

Menzies, N., Mulligan,D. (1996), Bauxite Residue rehabilitation. Report for Nabalco Pty Ltd. Centre for Mined Land Rehabilitation, The University of Queensland.

Menzies, N., Mulligan, D., and So, B. (1997), Bauxite Residue Rehabilitation Trial Design and Monitoring Programme. Centre For Mined Land, The University of Queensland.

Menzies, N.W., Fulton, I.M. and Morrell, W.J. (2004), Seawater. Neutralisation of Akaline Bauxite Residue and Implications for Re-vegetations. J.Enviro.Quality33: (in press).

Merten, G.H, Nearing, M.A. & Borges, A.L.O. (2001), 'Effect of Sediment Load on Soil Detachment and Deposition in Rills'. *Soil Science Society of America Journal*, v65 n3, pp. 861-868.

Ministerial Council on Mineral & Petroleum Resources and Minerals Council of Australia (MCMPR & MC) (2003), Strategic Framework for Tailings Management, Department of Industry, Tourism and Resources, Australian Government.

Moir, W.H., Ludwig, J.A. & Scholes, R.T. (2000), 'Soil Erosion and Vegetation in Grasslands of the Peloncillo Mountains, New Mexico'. *Soil Science Society of America Journal*, v64 n3, pp 1055-1067.

Morrell, W.J., Menzies, N.M., Mulligan, D.R., and So, H.B., Fulton, I. (2000), Bauxite residue re-vegetation at Nabalco Gove refinery: Addressing the sustainability issue. *In* "Minerals Council of Australia Environmental Workshop" pp. 231- 243.

Munshower, F.F. (1994), Practical Handbook of Disturbed Land Re-vegetation. Lewis Publishers, CRC Press, Florida.

Nelson, E.D.P. (1985), Factors "Influencing Growth On Alkaline Bauxite Residue (red mud)" MSc Thesis, Dept of Forestry and Environmental Studies, Duke University.

Newson, T. Dyer, T. Adam, C. and Sharp, S. (2006), Effect of structure on the

Geotechnical properties of bauxite residue. *Journal of Geotechnical and Geo environmental Engineering* 132, 143–151.

Norsk Hydro Website (www.hydro.com), various information.

O'Callaghan, B. McDaniel, S.C. Richards, D.M. & Reid, R.E. (1998), Development of a topsoil-free vegetative cover on a former red mud disposal site, *International Workshop on Rehabilitation of Mined Bauxite Lands and Red Mud Disposal Areas*, September 28 – 2 October, Kingston, Jamaica.

Oeberg, N. & Steinlechner, E. (1996), Red mud and sands handling—New thoughts on an old problem. Light Met. (Warrendale, PA) 1996: pp 67–73.

Oster, J.D. & Frenkel, H. (1980), The Chemistry of the Reclamation of Sodic Soils with Gypsum and Lime. Soil Soc. Am. Journal 44.

Pate, S. (2000), 'Better Nurseries Mean Better Rehabilitation'. *Groundwork*, v3, pp 4-5.

Paramguru, R. K., Rath, P. C., and Misra, V. N. (2005), Trends in red mud utilization—a review. *Mineral Processing and Extractive Metallurgy Review* 26, 1–29.

Patent WO 1993016003 19930819, "Process for the Treatment of Red Mud".

Peres, J.M. (1973), "Mud as a pollutant of the marine environment", Evol. Med. Vol. 17, no. 3, pp. 223-228.

Polomski, B. (2000), 'Questions and Answers'. *Horticulture, Gardening at its Best*, v97 n3, p14.

Prasad, P.M. Chandwandi, H.K. AND Mahadevan, H. (1996), Disposal practises for Bauxite Tailings at the Alumina Refiniers, Trans. Indian Inst.Met., 49:6: 817- 839.

Prasad, P.M. and Subramanian, S. (1997), Problems and Perspectives of Red Mud Utilisation, Trans.Indian Inst.Met., 50:5:427-442.

Qadir, M., and Schubert, S. (2002), Degradation processes and nutrient constraints in sodic soils. *Land Degradation and Development* 13, 275–294.

QAL(2007b)(www.qal.com.au)Community Forum Update # 28 RMD Long-Term Strategy
QAL(2007c)(www.qal.com.au)Community Forum Update # 5 Environmental Presentation

Radiological Protection Institute of Ireland (RPII), (2005), *"Naturally Occurring Radioactive Materials (NORM) in Bauxite"*, Letter to Mr Thomas Hartney (AAL) from Mr David Fenton (RPII), 10th May 2005.

Ratner, E. (1935), The influence of exchangeable sodium in the soil on its properties as a medium for plant growth. *Soil Science.* 40; 459 – 471.

Rayment, G.E. & Higginson, F.R. (1992), Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.

Ries, F. and McMonagle, J. (2009), A CFD study of the neutralization of Bayer process red mud with sulphuric acid in different mixing systems, *Report prepared by the University of Limerick for Aughinish Alumina Limited (AAL)*.

Renard, K. G. Foster, G. R. Weesies, G.R. McCool, D. K. & Yoder, D. C. (1997), Predict soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agricultural Handbook Number 703, United States Department of Agriculture.

Renard, K. G., Laflen, J.M., Foster, G. R. & McCool, D. K. (1994a), The Revised Universal Soil Loss Equation'. In: Lal, R. (ed.). Soil Erosion Research Methods – 2nd Edition. Soil and Water Conservation Society and St.Lucie Press, U.S.A. pp. 105-125.

Renard, K. G. Foster, G. R. Yoder, D. C. & McCool, D. K. (1994b), RUSLE revisited: status, questions, answers, and the future. (Revised Universal Soil Loss Equation)'. *Journal of Soil and Water Conservation*, v49 n3, pp 213-220.

Reuter, D.J. and Robinson, J.B. (1986), Plant Analysis, an Interpretation Manual. Inkata Press, Melbourne.
Residue Solutions Pty Ltd.

Reuter, D.J. and Walker, J. (1996), Indicators of catchment health: a technical perspective. CSIRO Publishing, Collingwood, Australia. Pp. 112-117.

Reuter, D. J. & Robinson, J. B. (1997), Plant analysis, an Interpretation Manual. 2nd Ed., CSIRO, Australia.

Richard Winter, (1989), Learning From Experience: Principles and Practice in Action-Research (Philadelphia: The Falmer Press, pp, 43-67.

Khaitan, S. Dzombak, D.A. and Lowry, G.V. (2009), Mechanisms of neutralization of bauxite residue by carbon dioxide, *Journal of Environmental Engineering*, 135 (6), 433-438.
Riley, M. (1998) 'Molybdenum'. In: Moore, G. (ed.). Soil guide: a handbook for understanding and managing agricultural soils, Bulletin No. 4343. Agriculture Western Australia, Perth, Western Australia, pp. 193-196.

Roberts, B. R. (1992), Land Care Manual. New South Wales University Press, Australia.

Roberts, E. H. E. (1972), Viability of Seeds. Chapman and Hall, London.

Rogers, P. A. & Murphy, W (2000), Levels of Dry Matter, major elements and trace elements in Irish Grass, Silage and Hay. Teagasc Publications, Wexford.

Rose, C.W. (1985), 'Process-Oriented Research by CSIRO Division of Soils, Canberra, A.C.T.' In: Advances in Soil Science, Volume 2. Springer-Verlag New York, pp. 12-16.

Rowell, D. (1994), Soil Acidity and Alkalinity in Soil Science: Methods and Applications. Prentice Hall.

Ryle, G. (2002), “The great red mud experiment that went radioactive” Sydney Morning Herald, May 7.

Schrader-Frechette, K. (1994), *Ethics of Scientific Research*. Lanham, MD: Ronan and Littlefield.

Schon, Donald. (1987), ‘Educating the Reflective Practitioner’, pg 31 (Jossey –Bass, 1987).

Scholz, G. & Moore, G. (1998), ‘Soil Alkalinity and Soil Sodicity’. In: Moore, G. (ed.). Soilguide: a handbook for understanding and managing agricultural soils, Bulletin No. 4343. Agriculture Western Australia, Perth,Western Australia, pp. 141-145.

Sheridan, G. J. & SO, H. B. (1998), MIN Erosion. School of Land and Food Sciences, The University of Queensland, St Lucia, Queensland.

Shire of Chittering, Western Australia (2002), “Ordinary Council Meeting Minutes”, Thursday 15th August.

Silburn, D.M. & Loch, R.J. (1992), ‘Present Capabilities and Constraints in Modelling Soil Erosion’. In: Proceedings of the 5th Australian Soil Conservation Conference – Volume3: Erosion/Productivity and Erosion Prediction. Department of Agriculture, pp 116-122.

Singer, M.J. Matsuda, Y. & Blackard, J. (1981), ‘Effect of mulch rate on soil loss by raindrop splash’. *Soil Science Society of America Journal*, v45, pp 107-110.

Skinner, B.J. and Porter, S.C. (1995), The Dynamic Earth – 3rd Edition .John Wiley and Sons, Inc., Canada, pp 214-215.

SRK and Enviroplan Services Ltd. The Decommissioning and Closure Plan for the Aughinish Alumina Limited Site, Askeaton, Co. Limerick, 1999.

Sriwahyunil, A, Nikraz, H. Jamieson, E. and Cooling, D. (2006), "Sustainable Use of Bauxite Residue Sand (Red Sand) in Concrete, Green Processing Conference, 5 – 7 June, Newcastle, New South Wales.

Sriboonlue, V. & Treloges, V. (2001), 'Soil Erosion Modelling'. In Regeneration Ecology and Management for Degraded Landscapes and Forest Ecosystems – Working Papers. Chiang Mai University, Murdoch University, Khon Kaen University, pp175-181.

Stephenson, R.E. & Shuster, C.E. (1945), 'Effect of Mulches on Soil Properties'. *Soil Science*, v59, pp219-230.

Stevens, D. P., Cox, J. W. & Chittleborough, D. J. (1999), 'Pathways of phosphorus, nitrogen and carbon movement over and through texturally differentiated soils, South Australia'. *Australian Journal of Soil Research*, v37, 679.

Stocking, M.A. (1994), 'Assessing Vegetative Cover and Management Effects'. In: Lal, R. (ed.). Soil Erosion Research Methods – 2nd Edition. Soil and Water Conservation Society and St. Lucie Press, U.S.A. pp .211-231.

Sumner, M.E., & Miller, W.P. (1996), Cation exchange capacity and exchange coefficients. p. 1201–1229. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Sustainability Strategies at Comalco on a roll, Compass, issue 12, Autumn 2005, Sustainable Division, Queensland Environmental Protection Agency.

Tacey, W.H. Olson, D.P. & Watson, G.H.M. (1977), Rehabilitation of mine wastes in a temperate environment. Annual Australian Mining Industry Council Environmental Workshop. Australian Mining Industry Council, Canberra, Sydney.

Thomas, G. W. (1982), Exchangeable Cations. *In*Methods of Soil Analysis: Part 2, Chemical and Microbiological Properties. Ed. A L Page. pp. 159–165. American Society of Agronomy and Soil Science Society of America, Madison.

Gilmore,T. Krantz, J. & Ramirez, R. (1986), "Action Based Modes of Inquiry and the Host-Researcher Relationship," Consultation 5.3 : 161.

Thomas, G.A. Allen, D.G. Vvyrwoll, K.H. Cooling, D., & Glenister, D. Capacity of clay seals to retain residue leachate. Draft paper submitted for consideration to the International Alumina quality Workshop, 2002.

Thorne, D. (1945), Growth and Nutrition of Tomato Plants as Influenced by Exchangeable Sodium, Calcium and Potassium. *Soil Science. Society. America. Proc*. 9, pp. 185–189.

Tierney, P. (1998), An investigation into the ecological status of metalliferous mine tailings sites in counties Galway, Sligo and Tipperary, MSc Thesis, School of Science, Institute of Technology, Sligo.

Tisdale. S. & Nelson, W. (1975), *Soil fertility and fertilisers*. Macmillan Publishing Co., Inc., New York.

Toy, T.J. Foster, G.R. & Renard, K.G. (1999), 'RUSLE for mining, construction and reclamation lands'. *Journal of Soil and Water Conservation*, v 54 n2, pp. 462-467.

Trochim, W. (1982), Methodologically-based discrepancies in compensatory education evaluations. Evaluation Review, 6, 4, pp. 443-480.

Trochim, W. & Land, D. (1982), Designing Designs for Research, The Researcher, 1.1.1-6.

Troeh, R.T. & Thompson, L. (1992), Soils and Soil Fertility Bradshaw, A. and Johnson, M., Re-vegetation of Metalliferous Mine Waste: The Range of Practical Techniques Used in Western Europe. Miner. Metals Environ., pp. 481–4.

Troug, E.(1947) Soil reaction influence on availability on plant nutrients. *Soil Science .Society.America .Proc*. 11; 305 – 308.

United States Department of Agriculture (1997), 'Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)'. In: Agricultural Handbook. United States Department of Agriculture.

University of New South Wales Press, Sydney. Oeberg, N. & Steinlechner, E. (1996), Red mud and sands handling— New thoughts on an old problem. LightMet. (Warrendale, PA):

URS (2002), Groundwater flow modelling within the mud stack area of Aughinish alumina. In support of the site closure plan.

URS (2003), Mudstack Drilling and Modelling, Aughinish Internal Report, Draft 3, Aughinish Alumina Ltd.

Ward, S. (2000), 'Increasing Botanical Diversity'. *Groundwork*, v3, pp. 36-37.

Ward, S.C., Slessar, G.C., Glenister, D.J. & Coffey, P.S. (1996a), Environmental assessment of the use of seawater to neutralise bauxite refinery waste. p. 407–416. *In* V. Ramachandran and C.C. Nesbitt (ed.) 2nd Environmental resource practices of Alcoa in southwest Western Australia.

Ward, S.C., Slessar, G.C., Glenister, D.J. & Coffey, P.S. (1996.b), Environmental resource practices of Alcoa in southwest Western Australia. *In* D.M. Mulligan (ed.) Environmental management in the Australian minerals and energy industries—Principles and practices. Univ. of New South Wales Press, Sydney.

Wehr, J.B. Fulton, I. Menzies, N.W. (2005), Re-vegetation Strategies for Bauxite Refinery Residue: A Case Study of Alcan Gove in Northern Territory, Australia.

Wehr, J.B. So, H.B. Menzies, N.W. Fulton, I. (2006), Hydraulic Properties of layers soils influence survival of Rhodes Grass during water stress, Plant & Soil, 270, 287-297.

Whitehead, D.C. (2000), Nutrient Elements in Grassland: Soil-Plant-Animal Relationships. CABI Publishing: Wallingford.

Whittington, B. I. (1996), The chemistry of CaO and Ca(OH)2 relating to the Bayer process. *Hydrometallurgy* 43, 13–35.

Woodard, H. J. Hossner, L. & Bush, J. (2008), Ameliorating caustic properties of aluminum extraction residue to establish a vegetative cover. *Journal of Environmental Science and Health, Part A* 43, 1157–1166.

Wong, M.H. and Lai, K.W. (1982), Application of Activated Sludge for Improving Iron-Ore Tailings. Reclamation. Re-vegetation. Res. 1, pp. 83–87.

Wong, J. and Ho, G. (1991a), Effects of Gypsum and Sewage Sludge Amendment on physical Properties of Fine Bauxite Residue. Soil Science. 152 (5) pp. 321–326.

Wong, J. and Ho, G. (1991b), Effects of gypsum and sewage sludge amendment on physical properties of fine bauxite residue, Soil Science, 152: 326-351.

Wong, J. and Ho, G. (1992), Viable techniques for direct re-vegetation of fine bauxite refining residue, Proceedings International Bauxite Tailings Workshop. Perth, Western Australia, 2-6 November 1992. The Australian Bauxite and Alumina Producers. pp. 258-269.

Wong, J. and Ho, G. (1993), Use of waste gypsum in the re-vegetation on red mud deposits: A greenhouse study, Waste Management and Research, 11:249-256.

Wong, J. and Ho, G. (1993), Effectiveness of Acidic Industrial, 5th Edition. Oxford University Press, Oxford.

Wong, J. and Ho, G. (1994a), Sewage sludge as organic ameliorant for re-vegetation of fine bauxite refining residue, Resources, Conservation and Recycling, 77: 7-4: 297.

Wong, J. and Ho, G. (1994b), Effectiveness of acidic industrial wastes for reclaiming fine bauxite refining residue. Soil Sci. 158, 2.

Wong, J. and Ho, G. (1994c), Effectiveness of acidic industrial wastes for reclaiming fine bauxite refining residue. Soil Sci. 158, 2.

Wong, J. and Ho, G. (1994d), Effectiveness of Acidic Industrial Wastes for Reclaiming Fine Bauxite Refining Residue. Soil Sci. 158 (2) , pp. 115–123.

Wong, J.W.C., & Ho. G.E. (1995a), Cation-exchange behaviour of bauxite refining residues from Western Australia. Journal Environmental. Quality. 24: 67–73.

Wong, J.W.C., &. Ho, G.E (1995b), Cation-exchange behaviour of bauxite refining residues from Western Australia. Journal . Environmental Quality. 24:461–466.

Wong, M.H. & Lai, K.W. Application of Activated Sludge for Improving Iron-Ore Tailings. Reclamation. Re-vegetation. Research. 1 (1982), pp. 83–87.

Worsley (2006), "Health, Safety, Environment & Community 2005 Report", Worsley Alumina Ltd.

Worsley (2007) (www.wapl.com.au), Various information.

Worsley Alumina Environmental Report (1997), Development of a bauxite residue disposal area rehabilitation prescription: Residue Preparation Trial 1994 – 1997.

Xenidis, A. Harokopou, A.D. Mylona, E. & Brofas, G. (2004), Modifying Alumina Red Mud to Support a Re-vegetation Cover. *Journal of Metals*, 57(2): 42-46.

Yapp, G. & Gibbons, F. (1988), Water Erosion in the Dryland Cropping Regions of Australia. CSIRO Institute of Natural Resources and Environment, Division of Water Resources, Canberra.

Yu, B. Ciesiolka, C.A.A., Rose, C.W. & Coughlan, K.J. (2000), 'A validation test of WEPP to predict run-off and soil loss from a pineapple farm on a sandy soil in subtropical Queensland, Australia'. *Australian Journal of Soil. Research*, v38 n3, p537.

Zambo, J. (1979.), Red mud: Its properties, handling, storage and utilization. Trav. ICSOBA 15:265–277.Wastes for Reclaiming Fine Bauxite Refining Residue. Soil Science. 158 (2) (1994), pp. 115–123.

Zheng, F. Huang, C. & Norton, L.D. (2000), 'Vertical Hydraulic Gradient and Run-On Water and Sediment Effects on Erosion Processes and Sediment Regimes' *Soil Science Society of America Journal*, v 64 n1 pp 4-11.

Appendix 1

Shoot Height for *Avena sativa* and *Holcus lanatus* after 3 weeks growth

Table No 1

Treatment	Shoot Height (cm)	
	Avena sativa	*Holcus lanatus*
RM	13a	5a
RMO	25b	11b
RMS	10a	5a
RMSO	26b	10b
RMSG	26b	12b
RMSGP	30b	18b

RM = Red Mud; Red Mud + Process Sand RMSG = Red Mud +PS+ 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

Table No 2

	pH	Na (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Al (mg/kg)	Fe (mg/kg)	ESP
Mud	9.7 (0.11)	1120 (176)	3.8 (0.4)	1.4 (0.14)	30 (2.4)	52 (4.7)	62 (5.4)
Sand	10.2 (0.13)	3600 (453)	2.6 (0.5)	0.8 (0.02)	22 (3.1)	1.6 (0.4)	86 (7.4)

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

Table No 3

Treatment	pH	Na (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	ESP
RMS10	9.5	350	148	<1	8.2
RMSG10	7.9	350	1485	2	2
RMSG25	8.0	377	1990	3	2
RMS25	8.9	261	179	<1	5.4

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

Treatment	*A.sativa*	*H.lanatus*
RM	60%a	45%a
RMO	59%a	43%a
RMS	66%a	50%a
RMSO	64%a	48%a
RMSG	80%b	70%b
RMSGO	77%b	72%b

RM = Red Mud

RMS = Red Mud + Process Sand

RMSO = Red Mud + PS + Organic

RMSG = Red Mud +PS+ 3%Gypsum

RMSGO = Red Mud+ps + gypsum +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.

Species	Treatments	
	RMS	RMSG
Avena sativa	13	64
Agrostis stolonifera Carmen	0	27
Agrostis stolonifera Providence	11	45
Agrostis tenuis Barbot	0	41
Festuca litoralis Merlin	0	38
Festuca longifolia Dawson	0	36
Festuca rubra	0	24
Holcus lanatus	0	44
Trifolium pratense Rotra	0	50
Lolium perenne Wendy	0	42
Puccinellia	0	32

RMS = Red Mud +Process Sand

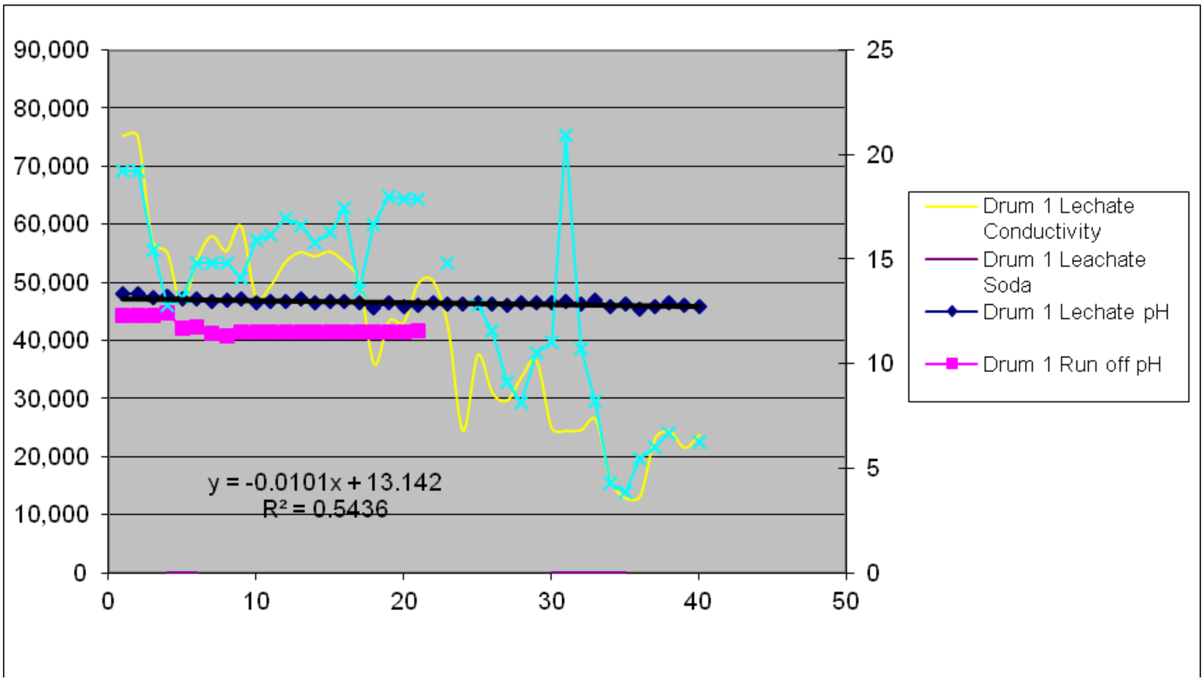
RMSG = Red Mud +PS +3% Gypsum

Appendix 2

Drum 1

			Drum 1					
			Lechate pH	Run-off pH	Lechate Conductivity	Run-off Conductivity	Leachate Soda	Run-off Soda
0.00	38807.00	31-Mar-06	13.33	12.33	75,200	19.21	6.67	17,490
7.00	38814.00	07-Apr-06	13.33	12.33	75,200	19.21		
14.00	38821.00	14-Apr-06	13.16	12.33	57200	15.43		
21.00	38828.00	21-Apr-06	13.22	12.41	55200	12.81	9.17	21,320
28.00	38835.00	28-Apr-06	13.1	11.72	46,200	13.14	5.86	12560
35.00	38842.00	05-May-06	13.12	11.77	53800	14.83	5.46	25,360
42.00	38849.00	12-May-06	12.95	11.48	58000	14.83		13,580
49.00	38856.00	19-May-06	13.02	11.3	55400	14.83		17,180
56.00	38863.00	26-May-06	13.1	11.53	59700	14.09	7.48	13,260
70.00	38877.00	09-Jun-06	12.94	11.53	47500	15.91		
77.00	38884.00	16-Jun-06	12.96	11.53	49400	16.18		
84.00	38891.00	23-Jun-06	12.99	11.53	53500	16.98		
91.00	38898.00	30-Jun-06	13.09	11.53	55200	16.58		
98.00	38905.00	07-Jul-06	12.93	11.53	54500	15.77		
105.00	38912.00	14-Jul-06	12.95	11.53	55300	16.31		
119.00	38926.00	28-Jul-06	12.98	11.53	53500	17.46		
126.00	38933.00	04-Aug-06	12.92	11.53	50200	13.55		
133.00	38940.00	11-Aug-06	12.66	11.53	36000	16.65		
140.00	38947.00	18-Aug-06	12.89	11.53	43400	18		
147.00	38954.00	25-Aug-06	12.74	11.53	43100	17.86		
154.00	38961.00	01-Sep-06	12.8	11.59	49900	17.86		26310
161.00	38968.00	08-Sep-06	12.92		50200			
168.00	38975.00	15-Sep-06	12.86		42300	14.83		
175.00	38982.00	22-Sep-06	12.88		24500			
182.00	38989.00	29-Sep-06	12.91		37500	12.81		
189.00	38996.00	06-Oct-06	12.84		31000	11.59		
196.00	39003.00	13-Oct-06	12.82		29700	9.1		
203.00	39010.00	20-Oct-06	12.9		33900	8.16		
217.00	39024.00	03-Nov-06	12.9		36400	10.51		
224.00	39031.00	10-Nov-06	12.94		25010	11.05	11.05	
231.00	39038.00	17-Nov-06	12.96		24500	20.96	20.96	
245.00	39052.00	01-Dec-06	12.83		24660	10.72	10.72	39083.00

252.00	39059.00	08-Dec-06	13.03	26350	8.22	8.22	39173.00
280.00	39087.00	05-Jan-07	12.75	15950	4.31	3.84	
287.00	39094.00	12-Jan-07	12.87	12,890	3.84	5.46	90.00
		18-Jan-07	12.59	13,360	5.46		22.5
		05-Feb-07	12.76	23180	6		
		14-Feb-07	12.9	24380	6.67		
8.91	Ph	20/02/2007	12.79	21580			
9.58904	year	28=02-07	12.76	23860	6.27		
		07/03/2007	12.79	24920	6.67		
			no				
		no sample	rain		4.92		
		11/04/2007	No sample				

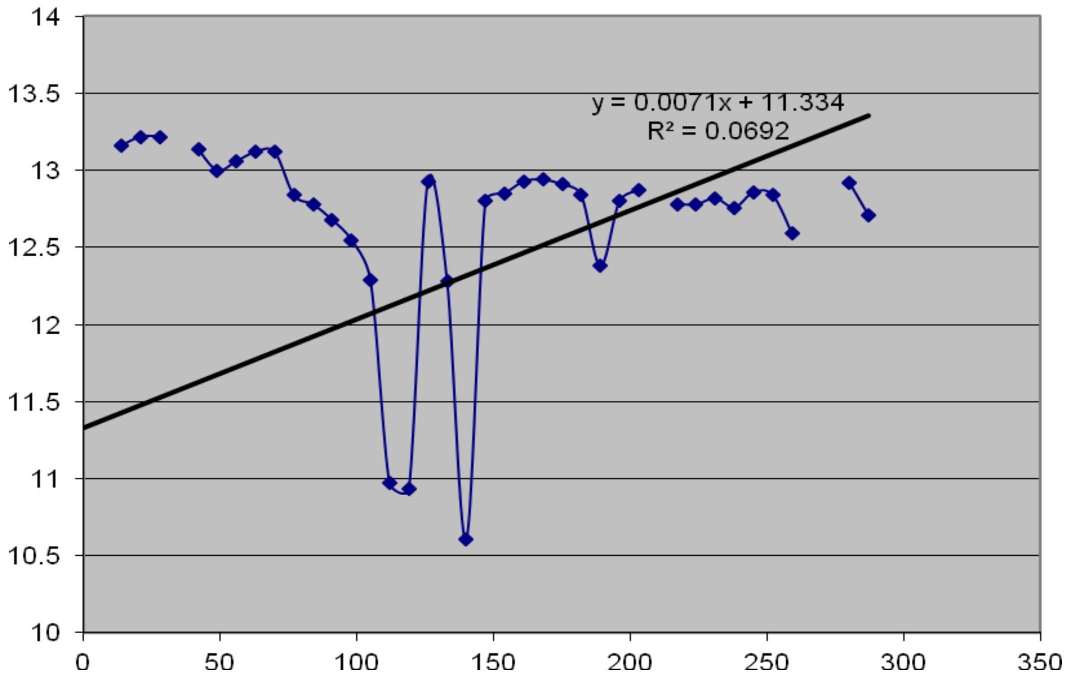

90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
25
20
15
10
5
0
0
10
20
30
40
50
y = -0.0101x + 13.142
R² = 0.5436
Drum 1 Lechate Conductivity
Drum 1 Leachate Soda
Drum 1 Lechate pH
Drum 1 Run off pH

Drum1; Graph

Drum 2

			Drum 2				
0	38807	31-Mar-06	Lechate pH	Run-off pH	Lechate Conductivity	Run-off Conductivity	Leachate Soda
7	38814	07-Apr-06					
14	38821	14-Apr-06	13.16		57200		15.43
21	38828	21-Apr-06	13.22	12.08	55200	23460	12.81
28	38835	28-Apr-06	13.22		64,400		13.14
35	38842	05-May-06					
42	38849	12-May-06	13.14		58900		14.42
49	38856	19-May-06	13		58700		13.68
56	38863	26-May-06	13.06		57900		
63	38870	02-Jun-06	13.12	11.74	58100	17850	14.09
70	38877	09-Jun-06	13.12		57900		14.63
77	38884	16-Jun-06	12.84		28470		8.43
84	38891	23-Jun-06	12.78		25970		8.56
91	38898	30-Jun-06	12.68		26150		9.1
98	38905	07-Jul-06	12.55		25090		8.69
105	38912	14-Jul-06	12.29		25940		10.65
112	38919	21-Jul-06	10.97		23490		11.05
119	38926	28-Jul-06	10.93		23500		10.78
126	38933	04-Aug-06	12.93		62800		9.03
133	38940	11-Aug-06	12.28		19660		9.57
140	38947	18-Aug-06	10.61		20990		13.14
147	38954	25-Aug-06	12.8		38000		15.84
154	38961	01-Sep-06	12.85		47200		
161	38968	08-Sep-06	12.93		49500		16.51
168	38975	15-Sep-06	12.94		42500		13.68
175	38982	22-Sep-06	12.91		24300		
182	38989	29-Sep-06	12.84		34700		7.08
189	38996	06-Oct-06	12.38		20600		8.96
196	39003	13-Oct-06	12.8		25540		5.93
203	39010	20-Oct-06	12.87		28200		7.28
210	39017	27-Oct-06					
217	39024	03-Nov-06	12.78		23070		8.16
224	39031	10-Nov-06	12.78		24790		6.94
231	39038	17-Nov-06	12.82		23910		7.14

238	39045	24-Nov-06	12.76	20340	14.56
245	39052	01-Dec-06	12.86	10700	10.04
252	39059	08-Dec-06	12.84	22400	5.06
259	39066	15-Dec-06	12.59	20400	
266	39073	22-Dec-06			
273	39080	29-Dec-06			
280	39087	05-Jan-07	12.92	17980	
287	39094	12-Jan-07	12.71	11,670	4.65
		18-Jan-07	12.77	18,020	4.65
		05-Feb-07	12.77	26340	7.89
8.923		14/02/2007	12.88	27650	8.09
15.06849		20/02/2007	12.7	14350	13.68
		27-Feb-07	12.72	21270	6.74
		07-Mar-07	12.76	25070	6.81
		21-Mar-07	12.91	26450	7.62
		02-Apr-07	12.81	26400	8.22
		11-Apr-07	12.79	17600	
		17-Apr-07	no sample		
		14-Apr-07	12.15	16200	
		22-Apr	12.3	15100	4.72
			n/s		4.18
		31-May-07	12.51	17600	4.65
		07-Jun-07	12.58	17760	6.47
		14/06/2007	12.54	19990	6.07
		22/06/2007	12.69	18480	6.81
		04/0707	12.65	21240	6.87
		11/07/2007	12.58	21850	4.58
		19/07/2007	11.27	22050	7.41
		08/08/2007	12.52	20480	7.28
		10/08/2007	12.52	21560	7.14
		30/08/2007	12.58	22620	7.01
		07/09/2007	12.47	21550	7.01
		17/09/2007	12.43	20150	6.74
		24/09/2007	12.42	17200	5.8
		01/10/2007	12.49	15780	5.53
		09/10/2007	12.56	16160	5.26


y = 0.0071x + 11.334
R² = 0.0692
14
13.5
13
12.5
12
11.5
11
10.5
10
0
50
100
150
200
250
300
350

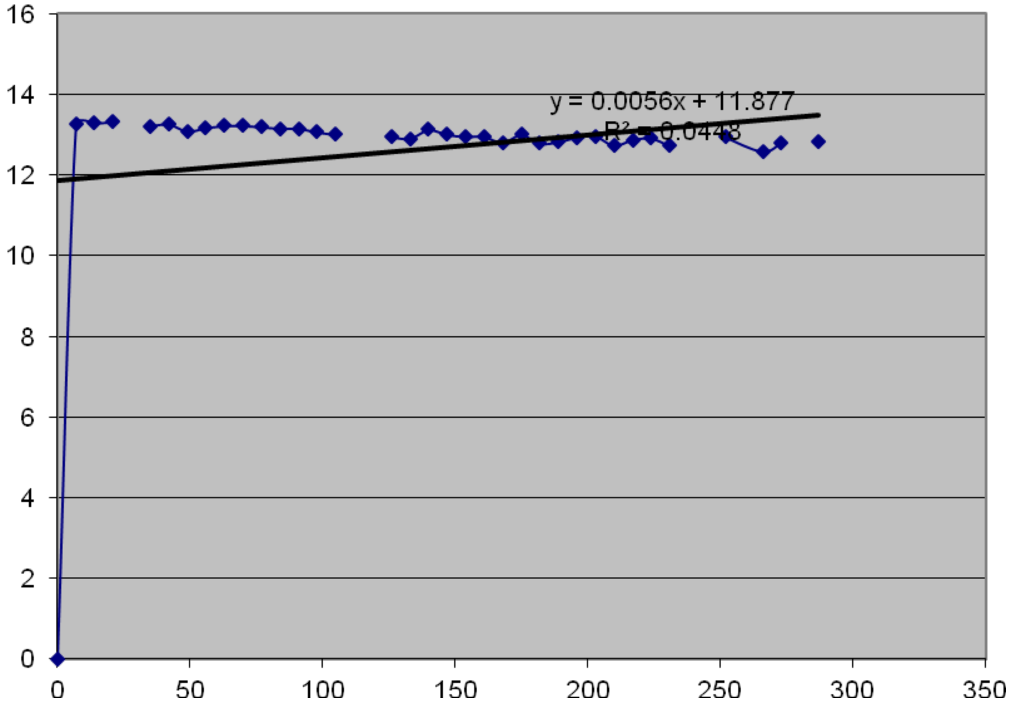
Drum 2 graph

Drum 3

DRUM 3

0	38807	31-Mar-06	Lechate ph	Run-off pH	Lechate Conductivity	Run-off Conductivity	Leachate Soda	Run-off Soda
7	38814	07-Apr-06	13.27	12.97	83000	30400	34.3	11.86
14	38821	14-Apr-06	13.29	12.37	84900	36500	22.92	18.74
21	38828	21-Apr-06	13.33	12.24	88900	36300	23.12	18.67
28	38835	28-Apr-06						
35	38842	05-May-06	13.22	12.12	89600	43500	23.59	24.6
42	38849	12-May-06	13.27	11.9	85400	54800	23.86	34.51
49	38856	19-May-06	13.09	11.63	86100	28270	22.85	13.28
56	38863	26-May-06	13.18	11.49	85900	35300		
63	38870	02-Jun-06	13.23	11.63	88400	25310	24.06	18.06
70	38877	09-Jun-06	13.23	n/s			23.79	
77	38884	16-Jun-06	13.2		78100		22.71	
84	38891	23-Jun-06	13.16		78800		21.7	
91	38898	30-Jun-06	13.16		75300		22.44	
98	38905	07-Jul-06	13.07		74700		24.2	
105	38912	14-Jul-06	13.01		75600		17.25	
112	38919	21-Jul-06						
119	38926	28-Jul-06						
126	38933	04-Aug-06	12.96		62800		20.15	
133	38940	11-Aug-06	12.91		57600		22.92	
140	38947	18-Aug-06	13.13		67100		22.38	
147	38954	25-Aug-06	13.01		66200		21.64	
154	38961	01-Sep-06	12.96	11.63	65500	27490		
161	38968	08-Sep-06	12.96	11.62	49500	26510	21.7	12.94
168	38975	15-Sep-06	12.81		43600		17.32	
175	38982	22-Sep-06	13.01		46500		17.32	
182	38989	29-Sep-06	12.79	11.17	36200	10100	12.6	3.91
189	38996	06-Oct-06	12.83		38900		12.94	3.75
196	39003	13-Oct-06	12.94	10.99	38700	9410	12.81	3.84
203	39010	20-Oct-06	12.97	11.09	41100	10700	13.28	4.25
210	39017	27-Oct-06	12.74		28690		10.11	

217	39024	03-Nov-06	12.88		22160		7.14	
224	39031	10-Nov-06	12.92	11.19	20750	6300	18.8	2.83
231	39038	17-Nov-06	12.73		20340		8.29	
238	39045	24-Nov-06						
245	39052	01-Dec-06						
252	39059	08-Dec-06	12.95		14320		7.01	
266	39073	22-Dec-06	12.59		11800			
273	39080	29-Dec-06	12.81	10.6	19200	3170		
280	39087	05-Jan-07						
287	39094	12-Jan-07	12.82	11.12	15,500	22,405	6.13	
		18-Jan-07	12.82	10.75	7,610			
8.91		05-Feb-07					n/s	
5.48		14-Feb-07						
		28-Feb-07	12.77		20400			


y = 0.0056x + 11.877
R² = 0.0448
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250
300
350

Appendix No 3

Review International Alumina Plant Case Studies

Introduction

The author in the previous sections has looked at research in some Alumina plant around the world. This section will examine a selection of alumina operators and bauxite residue facilities carried out by **Residue Solutions Pty Ltd**. This company was hired by Rusal Aughinish to complete a "**Residue Management Sustainability Review** "of the plant in 2007.

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

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

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 22ºC in July to 31ºC in January. Average minimum temperatures range from 13.0ºC in July to 22ºC 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).

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.

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.

Figure 1 General arrangement of RTAY facilities at Yarwun, Queensland (Google, 2007).

The topography of the residue management area also provides a visual screen and contained surface drainage for the site. It is expected that the facility can be operated for many years before it will become visible to the surrounding community.

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.

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).

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.

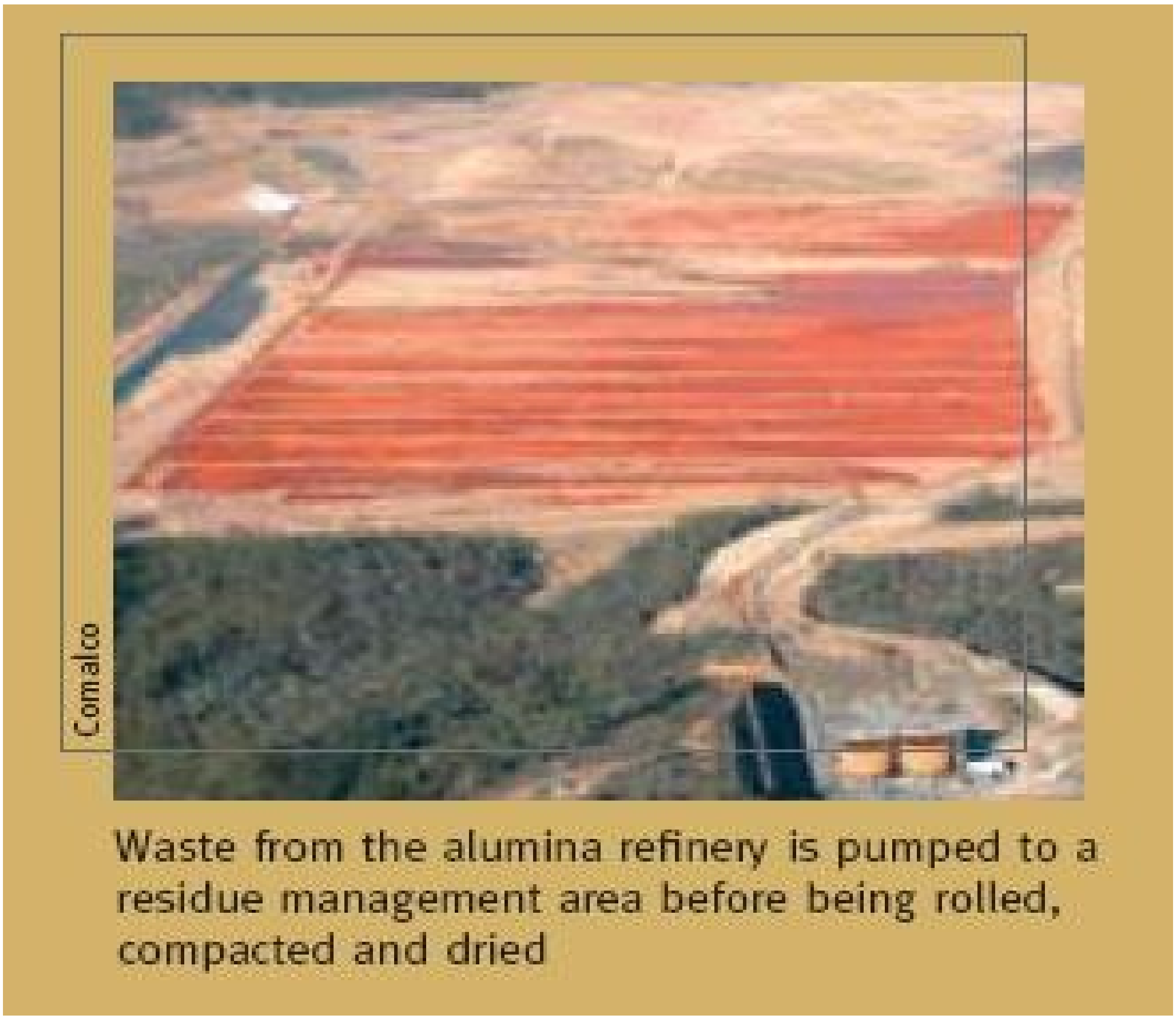


Figure 2 RTAY Residue Management Area showing Mud Farming drying bays. QEPA (2005)

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.

Queensland Alumina Ltd

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

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).

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).

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

Residue Production

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

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.

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.

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.

Kwinana Alumina Refinery

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

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 º C in July to 30 º C in January. Average minimum temperatures range from 8.0 ºC in July to 17º C in February. The dominant synoptic winds are south-west and easterly in summer months and south-west in winter.

Operation

The refinery commenced operations in March 1963. The refinery consumes bauxite railed from the Alcoa bauxite mines in the Darling Range (Huntly Mine) 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.

Figure 4 Overview of Alcoa Kwinana residue disposal facilities (Google, 2007).

Residue Disposal Facility

When operations commenced, initial residue disposal facilities (designated A, B, C lakes) were constructed 2 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.

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.

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.

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 amphirol equipment to over 65% solids.

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

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 Jameison, 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).

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.

Figure 5 Overview of the original Alcoa residue Disposal Facility (ABC Lakes) and the post-closure land use (Motorplex) (Google, 2007).

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

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

Pinjarra Alumina Refinery

Alumina Production Capacity: 4.2 mtpa
Ownership: 100% Alcoa World Alumina
Location: Pinjarra, Western Australia, Australia

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 º C in July to 31 º C in January. Average minimum temperatures range from 6.0 º C in July to 16º C in February. The dominant synoptic winds are south-west and easterly in summer months and south-west in winter.

Operation

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

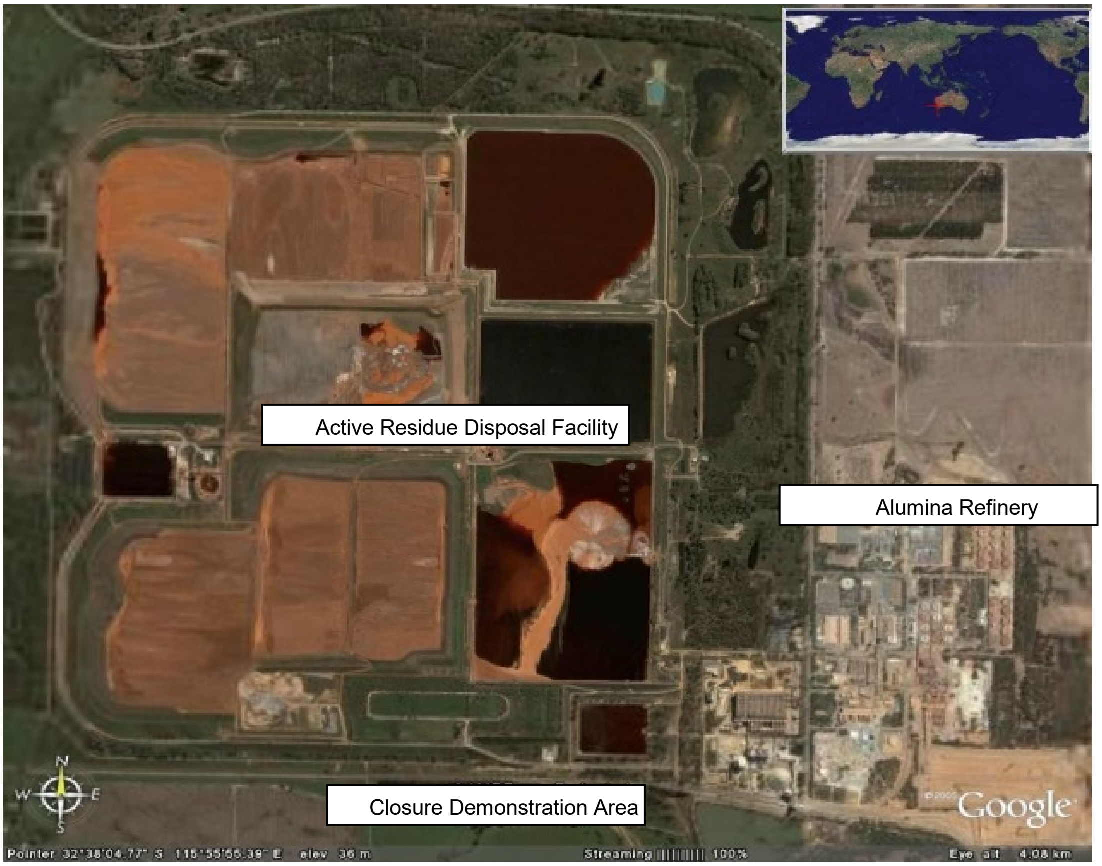


Figure 6 Overview of Alcoa Pinjarra Residue Disposal Facilities (Google, 2007).

Residue Disposal Facility

A dedicated 600-ha residue disposal facility is constructed adjacent the refinery on Alcoa freehold land. This area is predominately extensive local clay overlain by sandy 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.

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.

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 amphirol equipment to over 65% solids. A network of sprinklers is used on a pre-emptive basis to minimise the generation of dust from the drying mud surface. 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.

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.

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).

Figure 7 Overview of the closure demonstration area at Pinjarra Residue Disposal Facility (Google, 2007).

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

Wagerup Alumina Refinery

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

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 º C in July to 16º C in February. The dominant synoptic winds are south-west and easterly in summer months and south-west in winter.

Operation

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

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

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 8 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.

Residue Production

Approximately 2 tonnes of bauxite residue is produced for every one tonne of alumina. Therefore, approximately 5,000,000 tonnes (dry) of bauxite residue is produced annually

(2006). The bauxite residue is made up of two size fractions at an approximate 50:50 ratio (a fine fraction or 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.

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.

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.

Alcan Gove

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

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 º C in July to 33 º C in November. Average minimum temperatures range from 19.0 º C in August to 25º C in January. The dominant synoptic winds are north-west summer months and south-east in winter (BOM, 2007).

Operation

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

The refinery consumes bauxite transported by conveyor from the Alcan Gove Bauxite Mine located 15 kilometres to the east. The bauxite ore is high-grade, averaging 51% alumina. The refinery operates an open-circuit saltwater cooling system and a seawater 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.

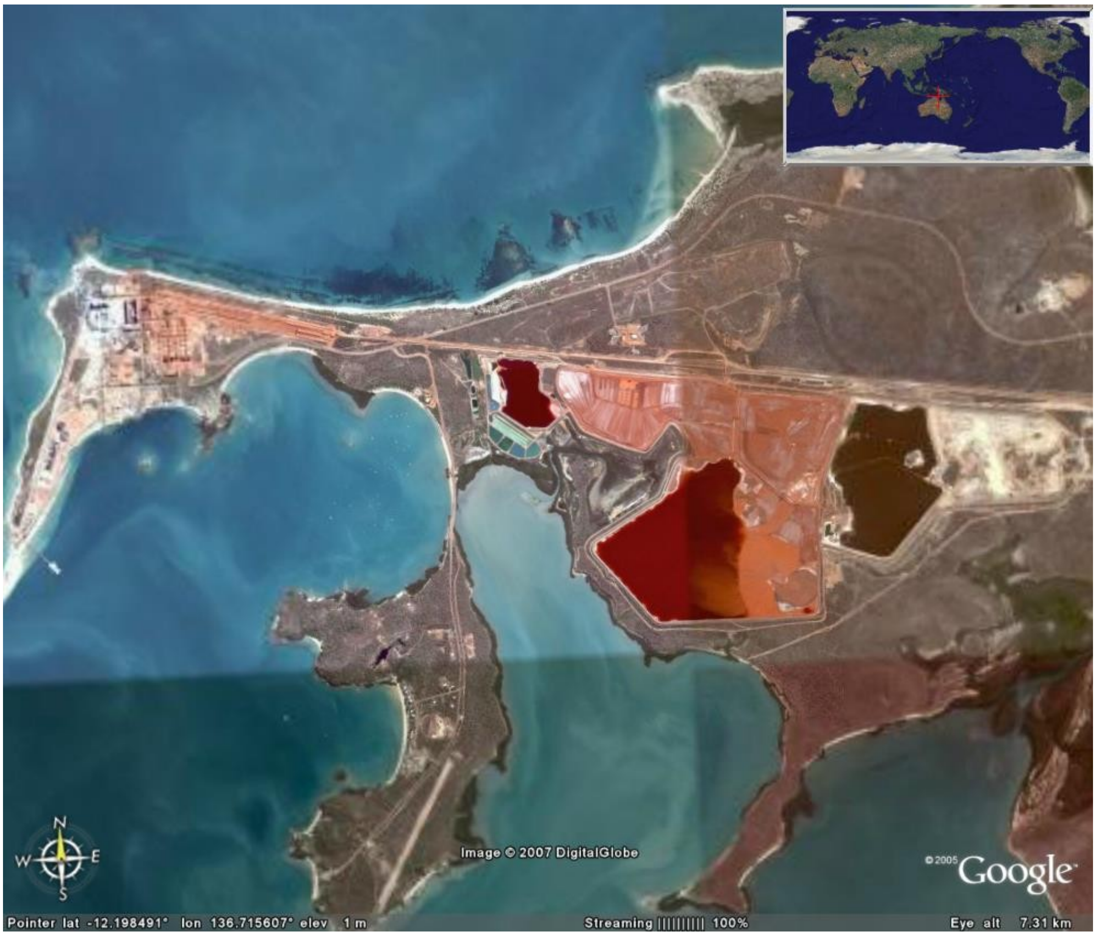


Figure 9 Proximity of Alcan Gove Residue Disposal Facility and Gove Alumina Refinery (Google, 2007).

Residue Disposal Facility

The existing residue disposal facility covers 500 ha, of which 180 ha are currently used for active drying of residue, 255 ha for alkaline water storage and 70 ha has been re-vegetated and returned to traditional landowners (Alcan, 2004).

Figure 10 Alcan Gove Residue Disposal Facility (Google, 2007).

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

The local community of Nhulunbuy is the nearest populated centre (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).

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).

Residue Management

Bauxite residue is thickened to high density (46% solids w/w) and pumped at high pressure and placed in drying areas in 500 mm layers where it is mud farmed using amphirol equipment to over 65% solids. A long-range residue disposal plan is used to manage residue activities. This is reviewed every three years (Alcan, 2004).

Closure

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

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

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

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).

Worsley Alumina

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

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 º C in July to 30 º C in January. Average minimum temperatures range from 4.0 º C in July to 13º C in February. The dominant synoptic winds are south-west and easterly in summer months and westerly in winter (BOM, 2007).

Operation

The refinery is located within the Darling escarpment (elevation 200m) and commenced operations in 1984 and has 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).

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 11 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.

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.

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).

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.

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

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 30º C to 22º C all year. Average minimum temperatures range from 21º C to 22º C all year (INMET 2007).

Operation

The refinery is located adjacent to 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).

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.

Figure 12 Alunorte Alumina Refinery and Residue Disposal Facility (east of the refinery)

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

Residue Production

Approximately 0.65 tonnes of bauxite residue is produced for everyone 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.

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.

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.

Closure

Not Available

Jamaica Aluminium Company (Jamalco)

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

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).

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).

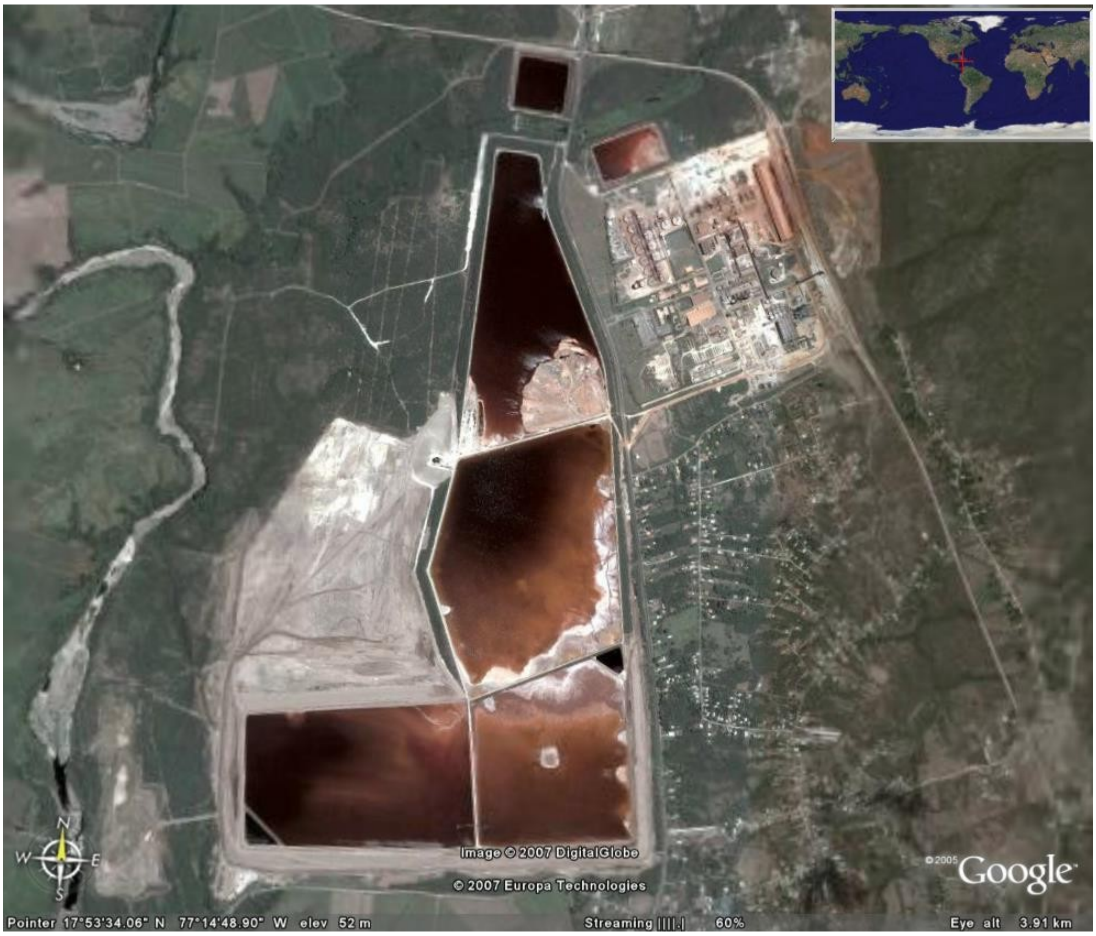


Figure 13 Overview of Jamalco Residue Disposal Facilities (Google, 2007).

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 geo-membrane 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.

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.

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).

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.

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 º C in January to 28 º C in August. Average minimum temperatures range from 2 º C in January to 18º 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

Figure 14 Gardanne Complex

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.

Appendix No 4

Development Projects / Trials

This information is from Aughinish Alumina Annual Environmental Reports 2018./ 2019.and from discussions with a company consultant associated with these projects. Some information is from papers issued by the International Alumina Institute (IAI) . Aughinish has a representative on the committee.

New Methods of Bauxite Residue Rehababilitaion.in 2020.

Aughinish Alumina have some new practices and projects in operation and in the pipe line to assist in their Closure Plan. The licence and the plan stipulate that the leachate from the BRDA will be below pH 9.0 5 years after closure. During those 5 years it is planned to run the Waste Effluent Treatment plant to neutralise and clarify the leachate from the residue before pumping to the River Shannon. If this time frame could be shortened it would significantly reduce the cost of closing the plant... Manpower would be reduced along with running cost of equipment, energy, maintenance of equipment, and chemical dosing costs.

The following are the projects presently in progress in Aughinish,

Mud Farming and Ploughing.

Mud Farming has been covered earlier in my thesis and the results from the process. An Archimedes Screw Tractor called Amphiroll is used to plough and densify the mud. It compresses the mud layers and also improves atmospheric drying. Some additional work on the residue includes ploughing. The new machine called a Spader follows the “Amphiroll” which is an amphibian machine which turns over the mud and exposes it to the atmosphere for drying and carbonation. By exposing more mud to atmospheric CO_2, it reduces the alkalinity and pH. The moisture is reduced by approx. 10%. The strength, density and stability of the mud is increased. (David Cooling Alcoa Australia)

The new “Spader” machine ploughs the mud and reduces the size of the lumps, drying is improved by increasing the surface area. It is basically a commercial rotavater. If the pH is not below 11.5 then the process is repeated. Putting down thinner layers of residue also helps in this process.as it speeds the drying process.

The new licence condition IE 8.4.20 confirms that neutralisation will be by Mud Farming. The residue is pumped into cells which are numbered. Three samples are taken from each cell, dated and location. The farming continues until the pH is lowed to 11.0.

This process is very equipment driven plus constant changing of the pumping destinations within the BRDA. (See page73)

Deep Thickeners

The red mud in thickened and some caustic is washed out in a series of Decanters and Thickeners. This gives a solids concentration of about 40% before filtration and final caustic washing. The mud is now at 58% solids going to the BRDA. By installing extra Deep Thickener vessels the solids concentration can be increased to 70%. This will extend the life of the BRDA with less moisture in the mud, higher solids and better stacking, it also reduces the soda levels in the mud and maybe eliminate the requirement for the final Filtration section.

Demonstration Cells.

Two demonstration lined cells wells were constructed at a cost of €250,000. Pipework was constructed to pump mud into the cells and the mud in one cell was amended with sand, compost, gypsum and grass sown. The cells had sampling arrangements both from underneath and run off installed as part of the project. I monitored the leachate from the cell for 18 months for pH, soda, and

E.C. Grass was grown successfully but some problems developed with bare sections and die back over the years. Some sections were amended again and re seeded.

Now it has been decided to fill the second cell with Carbonated mud from the BRDA and run some more trials using only compost in one section and compost and gypsum in another part. Residue will be amended to a depth of 300m with a selection of a specialised blend of sodium tolerant grasses at a rate of 100kg / hectare.

A company called EINRICH have been contracted to carry out this trial which includes sampling and analysis of the soil and vegetation.

Wetlands

The Closure Plan addresses the time frame it will take to get the pH of the leachate to 9.0 or below which would allow it to be discharged into the local environment without any treatment. A lot of studies around the world have looked at ways of neutralisation the residue which in turn would make it easier to cover / cap it and vegetate the residue... Wetlands have been used for years to treat commercial and waste water. It appears that wetlands have some capacity to improve waste water quality either industrial or community systems but the EPA in many countries are concerned about the potential to alter the biotic communities of natural wetlands. These constructed systems are designed to mimic natural wetland plants, soils and their associated microorganisms to remove contaminants or in Aughinish's case reduce the pH and the alkalinity of the leachate.

In 2012 Rusal the plant owners and the International Aluminium Institute (IAA) decided to fund a project to pilot a wetland system. In 2013 the unit was set up and a trial commenced. Over a 12-month period the unit successfully treated BRDA leachate and lowered the pH from typically 13.0 to less than 9.0

In 2015 a second trial started to check the treatment of the leachate. One difference in this second trial was the mixing system had an addition of di- ionised water. It proved that the system could buffer low Ca leachate to 6.8- 8.2 pH range. All soil and vegetation components were regularly sampled during this trial period.

There were some variations in sampling results between summer and winter in the Phase 1 trial but none in Phase 2. This was attributed to inconsistency in the leachate feed mix and the discharge outlet to the wetland.

A new multi-cell wetland system is being developed and it is hoped to start the trial in 2020.... It is eventually hoped that all leachate can be discharged to the area of wetlands on the site which is on the N.W. side of the BRDA. following closure.

Bauxite Residue Potential Uses.

Since the very first Bayer Process plant was built in France back in 1887 Karl Bayer had the idea that the iron content in the residue could be extracted and used in iron production. Land space is in short supply to store millions of tonnes of residue, rehabilitation is difficult, neutralisation requires chemicals, or sea water to reduce the alkalinity so companies are making great efforts to find uses for the residue in all alumina refineries around the world. It is also difficult for communities to accept these plants on their doorstep. Hundreds of patents have been given to companies and many trials undertaken. There has been some success but the usage in these products does not go anywhere near matching the total residue production world- wide on an annual basis. There is approx. 2 million tonnes of residue used for every tonne of alumina produced. Although the application maybe successful the cost and risk may not be justifiable in the reuse of bauxite residue.

Applications

Some alumina plants in China are using significant amounts of residue to recover iron in their recovery schemes. Their target for 2020 was 20% recovery of the 40m tonnes produced in their refiners. But it appears that only achieved 4% recovery. By extracting iron or other metals they use them in cement production.

Another application is the use of the colour as a construction material like bricks, tiles. or aggregate blocks. The residue has been used as an impermeable material to cover land- fills. Parameters that affect the use in various applications include whether the residue is classified as hazardous or nonhazardous in any particular country. Also the residual sodium, particle size and moisture concentration can affect its utilisation.

Potential Applications.

In the production of Portland cement the iron content and alumina provides strength, improves setting characteristics in the product. A plant in India is using up to 50% residue in its cement plant along with bauxite and gypsum.... The AdG plant in Greece which originally pumped the residue to the sea now uses it in the local cement factory.

Bricks have been made with 90% bauxite residue when dried at a temperature of 1000 degrees C. In Western Australia residue has been used to treat acidic

and sandy soils. This treatment improved water and nutrient retention as well as raising the pH. Treatment rate was 250 t/ha of residue on the soil.

It is not known exactly how much residue is reused world-wide, the estimate is approx 2mt/year, of that about 400,000 tonnes are used in cement production mainly in Greece and China, capping landfill in France uses 100,000t/y and

55.000 t/y for refractory production in Romania....

So, at the moment the main potential uses are soil amelioration, cement production, iron recovery, road construction and landfill capping Rehabilitation....

Continuing research on residue pH reduction/ remediation is being funded by the International Aluminium Institute. Their research and the work by individual companies seems to be concentrating on treating the surface layers of the disposal areas followed by sustainable vegetation. They are looking at some form of neutralisation and concretion. Aughinish are using both these systems. They installed Deep Thickeners in the washing and thickening process to raise the solids % going to the BRDA and further compaction by Mud Farming and ploughing. This will also drain more moisture from the residue and reduce the amount of leachate that requires treatment. By doing this it is exposing the mud to atmosphere carbonation and getting the pH down below 11.0 which will allow vegetation to survive. The EPA have accepted this method and practice as part of the licence but want the company to continue with further trials in the existing Demonstration Cell using mud that has been farmed and carbonated. This will involve trucking residue from one part of the BRDA into the Demonstration Cell.

The Wetlands project which is due to start in 2020 is a very interesting one and could be the means of getting the residue pH lower after mud farming, down from 11.0 to 9.0. The Demonstration Cell trial will give further information that could allow the leachate to be released into the BRDA wetland following closure.