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Improving the Sustainability of Residue Management Practices — Alcoa World Alumina Australia

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ABSTRACT

Alcoa World Alumina Australia is the world's leading producer of aluminium and alumina, with three alumina refineries in Western Australia and a further six refineries located in Europe, the Caribbean, North and South America. During the refining process, an alkaline residue is produced and is deposited in lined storage areas designed to protect ground and surface waters.

As early as 1977, Alcoa recognised the need to investigate alternative residue management strategies. The company made a significant commitment to continuous improvement in tailings management through the establishment of a focussed research and development group charged with the responsibility of "establishing Alcoa's reputation as a leading company in the management of bauxite tailings". Through ongoing research and field trials, a range of significant improvements to residue storage methods have been developed and implemented.

Recent work has focussed on investigating ways to modify the residue, in particular decreasing its alkalinity to further lessen its potential environmental impact. Residue carbonation has been developed and tested at the Kwinana refinery and is currently being expanded to a full scale operation. It is a process which is easily integrated with the current thickening and dry stacking process, offering a range of operational and environmental benefits. The potential to progressively implement the process at Alcoa's other refineries worldwide is currently being evaluated. It is anticipated that residue carbonation will become the alumina industry's best practice benchmark for residue treatment and storage worldwide.

Alcoa has also been focussed on potential re-use opportunities for the residue. A number of potential uses have been progressed through to pilot and demonstration phase, opening the way for the re-use of considerable volumes of residue.

This paper will describe these more recent developments in residue management practices, and outline the sustainability case for progressing their implementation.

1 INTRODUCTION

There are a number of indicators suggesting that industry's traditional waste management practices around the world are coming under increasing scrutiny, and that some of these practices will not be acceptable into the future. In the recently published Mining, Minerals, and Sustainable Development final report, it was noted that:

> *"Mineral products are essential to contemporary societies and economies. Many basic needs cannot be met without them. But simply meeting market demand for mineral commodities falls far short of meeting society's expectations of industry. The process of producing, using, and recycling minerals could help society reach many other goals – providing jobs directly and indirectly, aiding in the development of national economies, and helping to reach energy and resource efficiency targets, among many others. Where industry is falling far short of meeting these objectives, it is seen as failing in its obligations and is increasingly unwelcome" (MMSD, 2002).*

In a truly sustainable global society we will take far fewer minerals from the earth. Instead of requiring ever-growing amounts of minerals and fuels, a sustainable economy will use materials much more efficiently, reduce waste to a minimum, and rely more on recycling, re-use and renewable energy technology.

If resource stewardship is to move toward sustainability, there will need to be an increasing focus on areas such as:

- Maximum incorporation of renewable and recycled materials.
- More benign reagents to replace toxic or non-degradable ones.
- Modification of wastes to a more benign form, lessening the potential for environmental impacts.
- Restricted net volumes of emissions.
- Maximum utilisation of 'waste' streams for products.

The retiring executive secretary of the UN Framework Convention on Climate Change, Michael Zammit Cutajar, told the 2002 Marrakesh conference of parties that the convention and its offspring, the Kyoto Protocol, we're *"not about conservation and pollution abatement"* but about *"the transformations that will bring about greater efficiency in the use of resources and greater equity in access to them"* (Cutajar, 2002).

> *Environmental impacts tend to be closely linked to material and energy intensities. Steel, aluminium and cement represent 73% of total value and 98% of total mass production of the world's mined and chemically transformed minerals. While aluminium is a truly recyclable material, with some 440 million tonnes of the 680 million tonnes ever produced still in use, the production of aluminium via alumina does produce large volumes of residues (red mud). In terms of processing waste and residue production (excluding tailings from mining operations), steel (70%) and aluminium (23%) are the major sources globally (Herbertson, 2001).*

In 1991, the United Nations Industrial Development Organization (UNIDO), commissioned a study into the alumina industry, which was presented and discussed at the UNIDO Conference on Ecologically Sustainable Industrial Development, held in Copenhagen in that same year. The study (Siklosi et al., 1991) concluded that: *"The most important ways of reducing the negative environmental impacts of the alumina industry are;*

- *Reduction of the amount of natural resources (firstly of energy) consumed per unit amount of alumina produced,*
- *Reduction of the residual discharges (effluents, dust, stack gases) per unit amount of alumina manufactured, and*
- *Environmentally sustainable discharge and storage of digestion residue".*

As early as 1977, Alcoa recognised the need to investigate alternative residue management strategies. The company made a significant commitment to continuous improvement in residue management through the establishment of a focussed residue research and development group charged with the responsibility of "*establishing Alcoa's reputation as a leading company in the management of bauxite tailings"* (Cooling, 1997). Through research and field trials, a range of significant improvements to residue storage methods has been developed and implemented over the past two decades. However, through recent long-term planning for residue storage, it has become increasingly apparent that community and government expectations are changing, and that further improvements to the way residue is managed into the future will be needed (Alcoa World Alumina Australia, 2002).

A vision for future residue storage practices can be described pictorially as shown in Figure 1.

Described is an overall transition to a more sustainable method of residue storage, where the potential for environmental impacts is being progressively reduced, with the ultimate aim of reducing the volume of residue being stored through the use of the residue in value adding products. Following is a discussion of the desired overall transition to a more sustainable method of residue storage, where the "area of impact" is being progressively reduced.

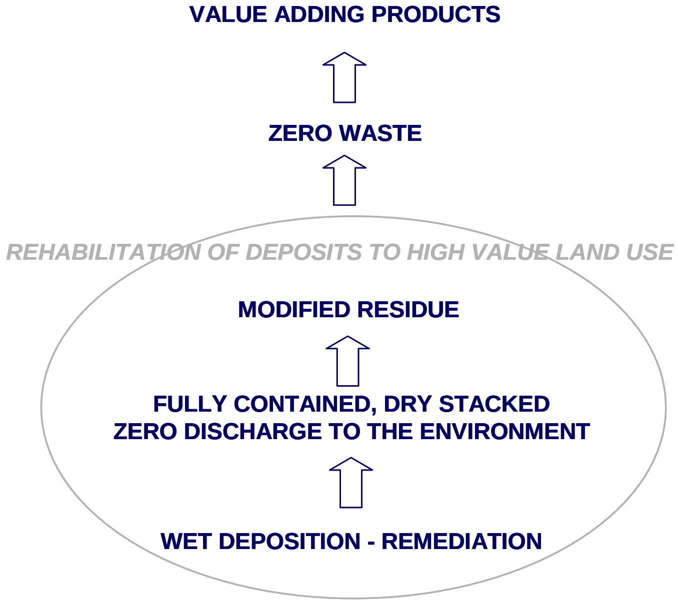

Figure 1 Long-term vision for residue management

2 WET DISPOSAL

Wet deposition is the traditional form of tailings management. Dilute slurry is deposited into an impoundment where it slowly consolidates. The heights of these deposits are generally limited by the economics of impoundment construction; hence large areas are required to continue this type of operation. The potential for environmental releases is relatively high, given the large volumes of liquor associated with the residue, and the large areas exposed to groundwater contamination. The short-term costs are relatively low (depending on the factor of safety built into the base seal of the storage areas), but the longer term costs of closure and remediation of any groundwater contamination can be very high. Community acceptance of this type of storage practice is diminishing, particularly for a residue that can be considered hazardous. This is reflected in recent Western Australian (WA) State Government consultation on waste management. Under a programme initiated by the Waste Management Board of WA, a committee was established to gain critical advice from stakeholders on the development of a strategic framework for a waste-free WA. The committee, referred to as the Core Consultative Committee or 3C, invited public comment on hazardous waste treatment facilities in Western Australia. A strong theme through the feedback was opposition to incineration and land filling of hazardous wastes (Core Consultative Committee, 2004).

3 DRY STACKING

Alcoa has undertaken a number of development projects aimed at lessening both the potential environmental and economic impacts of residue management. This development work commenced in the early 1970s, with the primary focus coming from the discovery of groundwater contamination below the Kwinana storage areas (Cooling, 1997). The original containment areas were constructed on the sandy coastal plain and relied upon a 380 mm thick clay blanket to prevent contamination of the underlying aquifer. While the clay seal prevented general seepage, there were a number of defects in the blanket placed on the embankment. These were thought to be the result of either cracking due to desiccation or erosion caused by rainfall. As a result of the groundwater contamination, the early emphasis of research was placed on improving the design of the base seal.

In 1980, a trial underdrain storage area was constructed to evaluate the concept of base drainage for improved storage of the fine fraction of the residue. The design was identical to the conventional storage area except that a one meter deep sand layer was installed above the base clay seal. A network of perforated pipes was installed in the sand layer and this drained via gravity to a sump.

The incorporation of an underdrainage system offered a number of advantages. Pumping of the sump maintained a low hydrostatic pressure on the base seal reducing the potential for seepage. Base drainage also improved consolidation of the fine grained material and proved an efficient means of recovering alkali for re-use by the refinery. Monitoring of the trial deposit showed an improvement in the density from 55% solids (0.9 t/m^3 dry density) achieved in the conventional storage area to 62% solids (1.08 t/m^3 dry density) thereby providing a 20% improvement in storage efficiency during the operating life of the area (Cooling, 1985).

This improved density increased the strength of the fine grained material providing a more stable deposit which in turn aided surface reclamation. It was thought that long-term rehabilitation would also be enhanced by gradual downward leaching of the deposit. New containment areas at Kwinana were also constructed with a composite clay/synthetic membrane seal which, when installed with a drainage layer placed above this composite seal, provided a very high factor of safety against any seepage.

However, there were a number of environmental and process reasons why the storage of low density "wet" tailings in large impoundments was not the preferred technique for future tailings storage.

Mining companies started investigating sloped deposition of residue many years ago as an alternative to wet disposal. In 1975, Robinsky described what he called “Thickened Tailings Discharge Method” which he helped establish at the Kidd Creek Mine of Texasgulf Canada Limited in Ontario, Canada (Robinsky et al., 1975). In 1987, Chandler outlined the solar drying of red mud residue at Alcan’s alumina refinery at Ewarton, Jamaica (Chandler, 1987).

Alcoa began development work on alternative residue management techniques in the early 1980s and in 1985 "dry stacking" was adopted for Alcoa's Western Australian refineries. Dry stacking utilises a large diameter gravity thickener, called a superthickener, to de-water the fine tailings and produce a thickened slurry. This slurry is then spread in layers over the storage areas to de-water by a combination of drainage and evaporative drying. By utilising the coarse fraction of the tailings for construction of drainage layers and upstream perimeter embankments, the storage area can be constructed as a progressive stack, thus avoiding the need for full height perimeter dykes and allowing continued stockpiling on areas which were previously "wet" impoundments. The following figure describes the overall stacking process.

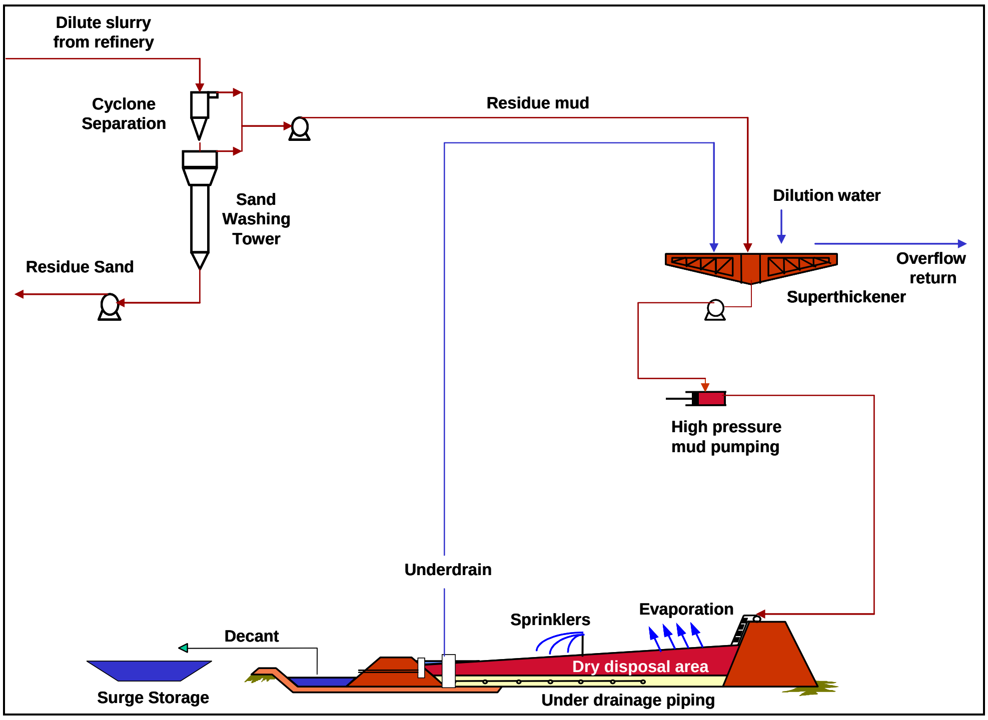

Figure 2 **Schematic of the dry stacking process**

The residue from processed Darling Range bauxite is characterised by a high coarse fraction (nominal particle size > 150 micron). This coarse fraction can be considered as a fine to medium grained sand. The fine fraction of the residue (nominal particle size < 150 micron) is silt to clay sized material and is commonly referred to as 'red mud'. The mud and sand fractions are separated to aid the washing for soda and alumina recovery, and are handled within the residue storage area as separate residue streams. The separation is not complete with around 10-15% of the fine mud remaining with the sand and similarly 10-15% of the coarse sand remaining with the fine fraction. At present, a portion of the sand (around 30%) is used in underdrainage construction and final capping of the storage areas. The balance is placed within the dry stack as either a layer across a drying bed or as a stockpile against an embankment.

The fine tailings are pumped to a thickener vessel where they are flocculated and settled producing high density underflow slurry of around 50% solids (by weight). This slurry is pumped to one of a number of beds where it is placed in layers of up to 0.5 m depth and allowed to dry in the sun. The final dry density of the tailings is around 70% solids. This compares to the final density of 60-65% solids which was being achieved in the wet disposal areas.

Rainfall run-off from the residue storage areas is very dilute alkaline water. It is stored during winter, and then added to the superthickener during summer, along with fresh water, as make-up water to compensate for refinery and residue area evaporative losses. Because this water is dilute, it acts as a final stage of dilution washing of the mud. The overflow from the superthickener is returned to the refinery.

Underdrain from the residue storage areas is a combination of water released from the initial slurry via self weight consolidation and rainfall which infiltrates through the drying beds. Its alkalinity is significantly greater than the decant water. If the alkalinity is lower than that of the total feed to the superthickener (usually as a result of rainfall infiltration through the drying bed), it will be added to the superthickener feed to aid dilution washing. If the alkalinity is greater than that of the feed to the superthickener (which can occur during summer when there is not rainfall dilution occurring in the residue bed and the greatest amount of fresh water is being added to the superthickener to compensate for evaporative losses), the underdrain water will be added to the superthickener overflow being returned to the refinery.

In terms of total soda recovered from the drying beds, a relatively small portion is recovered via the decant system (less than 10%). The majority of the soda recovered is via the underdrain system.

The initial costs of establishing dry stacking at Alcoa's three Western Australian refineries exceeded A$150 million (Cooling, 1997). However there were many benefits, which helped justify the transition to dry stacking including:

- A higher density deposit can be achieved reducing the overall volume of stored tailings.
- The progressive stacking allows the deposit to be taken to a height, which would not be economic with conventional wet impoundments.
- The higher density and increased deposit height means less land is used.
- The exposure of less land area to residue.
- The drained condition of the dry stack and the smaller footprint significantly reduce the risk of groundwater contamination.
- Improved surface stability and drainage mean that completed areas can be reclaimed and re-vegetated quickly.
- Safety hazards to people and wildlife are reduced.

Optimising the coverage on the drying beds has become one of the key operational objectives in recent times. As the height of the stack grows, drying area is lost due to the encroachment of the embankments as they are progressively raised via upstream lifts. This means that additional area needs to be provided and this is at a significant capital cost. If drying of the slurry can be sustained on a smaller area, significant capital for expansion of the drying areas can be deferred. Alcoa measures drying rate in terms of the overall (or average) annual storage rate expressed as the amount of residue that can be stored per unit area each year.

The average pan evaporation rate on the coastal plain south of Perth is around 5.5 mm per day (2000 mm per annum). However this is around 8 mm per day in summer and around 3 mm per day in winter. It is the lower evaporation rate through the winter period which governs the overall drying area needed. To achieve the required moisture loss, through the winter drying cycles, Alcoa routinely ploughs the mud with machinery.

This is generally done using a low ground pressure swamp dozer. An Archimedean screw vehicle, called an Amphirol, is also used at times. This allows a storage rate of between 13000 and 14500 t/yr/Ha to be sustained.

Routine ploughing of the mud with mechanical equipment has been termed "mud farming". Mud farming helps achieve a maximum density which allows the dry stack to be developed with maximum outer slopes (a minimum strength of 25 kPa is achieved allowing an outer slope of 6:1 to be maintained), and maximises the storage efficiency of the stack (Cooling et al., 1994).

Mud farming also minimises the potential for dust generation, which is important given the location of the refineries close to residential areas. Ploughing the surface presents a wet surface, buries carbonate, and provides a surface roughness that prevents dust lift-off once the tailings have dried.

Figure 3 Spreading the slurry, and ploughing using a D6 Swamp Dozer to enhance the drying rate

Dry stacking bauxite residue is now fully operational at all three of Alcoa's Western Australian refineries. A number of operational techniques have been developed to optimise the slurry distribution and drying processes, and these have now become standard practices. The advantages of reduced environmental risks and lower overall storage costs are now being realised. Alcoa is now looking toward treatment of the residue to reduce the pH as the next step in improving the sustainability of residue storage practices. A number of neutralisation options have been investigated over the past two decades.

4 RESIDUE NEUTRALISATION

Residue neutralisation will help reduce the potential for environmental impacts from residue storage activities, and will reduce the need for significant levels of ongoing management of the deposits after closure. Neutralisation will also open opportunities for re-use of the residue which to date have been prevented because of the high pH. The cost of neutralisation will, to some degree at least, be offset by a reduction in the need for long-term management of the residue deposits. Instead of accruing funds to deal with a future liability, the funds can be invested in process improvements, which reduce or remove the liability.

4.1 Sintering

Sintering of residue is one option investigated which resulted in fixation of all leachable alkali, however the cost was found to be very high, primarily due to the high energy consumption, making the process far from economically viable (Clyde-Carruthers, 1981).

4.2 Seawater Neutralisation

Queensland Alumina (QAL) in Queensland and Euralumina in Sardinia dispose of residue by first mixing with seawater and depositing as a dilute slurry (Pasupulatey, 2002). Seawater treatment was first investigated by QAL as a means of conserving fresh water, but it was soon found that the buffering capacity of the seawater was sufficient to partially neutralise the residue. Further optimisation of mixing rates lead to residue mud being deposited at a pH of around 8.6. The large volume of supernatant decanted from the residue deposit is discharge back to a tidal inlet. QAL has completed a detailed survey of trace elements in sediments, water, mangroves and molluscs, and an ecological survey of benthic fauna in the receiving waters of the inlet which showed no significant trends when compared to conditions in a near pristine control site (McConchie et al., 1996). No attempt was made to seal the base of the residue deposits prior to the commencement of filling. Any seepage from the residue storage areas is expected to be of a similar quality to the supernatant. Because the residue deposits are located close to the coast, any seepage will simply mix with the underlying saline groundwater and migrate toward the inlet. QAL has also shown that establishment of salt tolerant grasses is possible on the surface of completed residue deposits, providing a stable cover vegetation. QAL has been able to demonstrate the compatibility of seawater neutralised residue storage with their local environment. They have a storage area that is not going to require high levels of ongoing management beyond the life of the refinery.

However, it has been shown that with the current levels and forms of solid alkalinity associated with the Alcoa residue slurry, seawater neutralisation in conjunction with thickening for dry stacking will be difficult within reasonable dilutions and/or holding times (Fawell et al., 2001). Even if a means of dealing with the slow reaction times could be found, it is still unlikely that seawater neutralisation is a realistic option for Alcoa’s Western Australian locations. Pinjarra and Wagerup are distant from the coast, imposing high costs for circulation of the very large volumes of sea water required, and gaining approval for discharge of the sea water following treatment would be difficult to achieve given the location close to metropolitan Perth.

4.3 Acid Treatment

A number of studies have looked into the feasibility of treating bauxite residue with acid (Colombera, 1981; Colombera et al., 1982; Hughes et al., 1991; and Wong et al., 1994). Large volumes of reagent are required to fully neutralise the residue at a relatively high cost, even if spent (waste) acid could be used. The use of acid will also introduce large volumes of impurities to the process water stream (sulphate in the case of sulphuric acid, chloride in the case of hydrochloric acid). It is therefore likely that the return of any water from the residue deposits will be unacceptable to process without further treatment to remove these added impurities.

4.4 Carbon Dioxide Treatment

Carbon dioxide treatment offers quite a unique process fit solution for Alcoa. Dosing of the residue slurry with the carbon dioxide gas can be accomplished without any significant changes to the current dry stacking process. Sodium carbonate is formed through the addition of CO_2 and this carbonate is an impurity to the Bayer circuit, however processes (known as causticisation) are already in place to convert this sodium carbonate back to sodium hydroxide. There are a number of additional benefits can be derived which are not available via the alternatives described above. While the carbonated residue is not chemically benign, the strong alkalinity will have been reduced, with the pH being reduced by 3 and future residue deposits would be less likely to be regulated as hazardous waste landfills. While the initial cost impact is significant, it can be offset in the long term by reduced construction and operating costs, reduced liabilities for water management and, possibly, carbon credits.

4.5 Future Direction for Alcoa

Sea water neutralisation appears to represent an external benchmark for bauxite residue disposal with minimum environmental impact. However, in Western Australia Alcoa’s refinery locations are such that this option is not considered to be realistically available. The coastal regions in close proximity to the refineries are heavily populated or protected by conservation reserves. There is also a strong and growing local opposition to any form ocean discharge associated with industrial activities.

During 1994, CSIRO prepared an overall summary report into the various residue treatments options they had investigated for Alcoa over several years. The report compared residue treatment using acid, seawater and carbonation (Cardile et al., 1994). Table 1 provides a good overview of the treatment comparison.

Table 1 Comparison of the treatment of last washer underflow with CO_2, seawater, and mineral acid (Cardile et al., 1994)

	CO_2	Mineral Acid (e.g. HNO_3)	Seawater	Deionised Water
Minimum pH value achievable	7	Any value, pH=7 achievable	8.5	11
PH after equilibrium with atmosphere	10.2	Any value, pH=7 achievable	8.5	11
Minimum pH after extended water washing without air equilibrium	9.7	Any value, pH=7 achievable	10.2	11
Minimum pH after extended water washing with air equilibrium	9.8	Any value, pH=7 achievable	8.2	11
Alkaline solution species removable	OH^-, $[Al(OH)^4]^-$	OH^-, $[Al(OH)^4]^-$, CO_3^{2-}	OH^-, $[Al(OH)^4]^-$, CO_3^{2-}	OH^-, $[Al(OH)^4]^-$, CO_3^{2-}
Alkaline solid species removable	TCA, DSP caged OH^-	TCA, DSP, calcite	TCA, DSP caged OH^- CO_3^{2-}	'adsorbed' OH^- and CO_3^{2-} only
Species controlling pH value after treatment	$NaHCO_3/Na_2CO_3$ plus resulting mud solids	Mud solids – alkaline components removed	Solution Mg^{2+} and resulting mud solids	Mud solids containing TCA, DSP
Major species introduced or greatly increased by reagent	HCO_3^-/CO_3^{2-}	Inorganic anion e.g. NO_3^-	Cl^-, Mg, Ca, Na	None
Major species leached from the solids	SO_4^{2-}	Depends on pH. At pH=7: Na, Ca, SO_4^{2-}, Cl^-	Ca	Na
Trace elements leached from the solids	P, Sr, U, Zr	No data	No data	No data
Major solution non-alkaline species reduced by treatment	Al, TOC, Na	Depends on pH. At pH=7: Al	Al	TOC
Trace non-alkaline species removed from solution	Cu, Ga, Pb	No data	No data	No data
Increase in mud volume after treatment without settling	0	Depends on acid concentration	9 times	100 times
Increase in mud volume after settling	0	Depends on pH. At pH = 7: close to zero	1.3 times	Close to zero

The review concludes that carbonation has a number of clear advantages over the other treatment options with respect to minimising the final liquor dissolved solids. Also, carbonation does not introduce contaminants to the Bayer process when compared to acid or seawater treatments.

Residue carbonation, reducing the residue pH to 10.5, is seen as equivalent to seawater neutralisation in rendering the material less hazardous without the negative trade off of increasing the salinity of the leachate or introducing impurities which preclude the return of drainage waters to the refinery (Cooling, 1989). Residue carbonation offers a major improvement opportunity for achieving residue storage with lower environmental risk and reduced implications for long-term management of the storage areas.

4.5.1 Reduced risk to clay and synthetic seals and groundwater

Studies have been carried out by Alcoa World Alumina Australia to investigate the potential impact of residue leachates on clay seal material. This test work indicated that, as the pH (and hence alkalinity) of the leachate in contact with the clay seal increases, the clay itself is increasingly susceptible to dissolution reactions which alter the chemical and mineralogical composition of the clay seal and probably its sealing properties (Thomas et al., 2002).

By reducing the pH of residue leachate, carbonation will significantly reduce the potential risk of long-term degradation to clay or synthetic liners. Also, any leachate which does escape from the impoundment will have a reduced impact on the receiving waters, hence the overall risk of groundwater contamination is reduced significantly.

4.5.2 Quality of runoff and drainage water

The trial work on carbonation has indicated that the quality of drainage water from a carbonated residue deposit will be lower in pH, total dissolved salts and soluble aluminium. There is also likely to be a significant change in the concentrations of some minor elements. While still not suitable for direct discharge, the cost and complexity of treatment of this water for discharge will be greatly reduced. Carbonation can improve the feasibility of implementing a cost effective solution for discharge of the drainage water from carbonated deposits and therefore reduce the costs associated with long-term management of the storage deposits.

4.5.3 Reduced drying area

There are indications that carbonated residue dries more rapidly and develop higher shear strength than non-carbonated residue. This may allow future drying area expansions to be deferred with significant financial savings.

4.5.4 Reduced dust risk

Observations of the carbonated mud suggested that the surface is less prone to dusting than the non-carbonated residue. Also, if the area that is required for drying the residue could be reduced, there will be a smaller active area exposed to dust generation at any one time.

4.5.5 Greenhouse benefit

The carbon dioxide that will be consumed by full scale carbonation across the three WA refineries represents around 5% of the total refinery carbon dioxide output. While this may be seen as a relatively minor offset, other opportunities for reducing aggregate emissions are limited. Also, future carbon credits that this consumption could represent may substantially offset the cost of the carbonation process.

Alcoa conducted comprehensive laboratory and pilot testing of residue carbonation from 1991 to 1996, establishing that it can be accomplished without significantly changing the current dry stacking process. Small scale field trials were conducted at Kwinana in 1996, with promising results. A full scale prototype facility was commissioned in 2000, allowing carbonation of 100% of the residue produced, although it operated only 25% of the time, due to a shortage of available CO_2. The carbonated residue was deposited in a new drying area at Kwinana, allowing a detailed evaluation of a full scale operation over a two year period. As a result of the technology being proved in an industrial setting, the pilot facility is now being recommissioned to treat 100% of Kwinana's residue full time. Full operation started in 2006 using waste CO_2 from another industry in the Kwinana Industrial strip.

The technology is also being further developed, focussing on the direct use of flue gas (high purity CO_2 is currently being used and can either be sourced from other industries or extracted and concentrated from flue gas). If flue gas can be used efficiently, carbonation could be implemented at all of Alcoa's refineries, without relying on synergies with any other industries or having to install additional extraction and concentration technologies This significantly increases the adaptability and generic applicability of the process.

5 USE OF THE RESIDUE AS A PRODUCT

The ultimate aim in terms of sustainability of residue management, and in turn the sustainability of bauxite refining, is to have no residue to store. This might be achieved partly through beneficiation of the ore (leaving part of the ore in the mine rather than taking it through the extraction process to end up with it as residue), interception of value products currently within the processed ore that to date have simply passed through to the residue, or finding alternative uses for the residue produced. The move to dry stacking was a critical step along the pathway toward re-use, as it produced a readily accessible residue (through excavation from the drying beds) at a relatively low cost. Neutralisation of the residue is seen as a similar step along this same pathway, as the more significant hazard associated with the residue (its high pH) has been removed.

Alcoa continues to support a large amount of research into potential beneficial uses of residue. Potential uses that have been identified and continue to be investigated include:

- Use as a soil amendment to help retain nutrients and adjust soil pH.
- Use as a neutralising agent for treatment of acid mine drainage and amendment of acid producing soils.
- Use as a filtration medium to remove phosphorous and nitrogen from sewage effluent in domestic and industrial septic systems.
- Use as an additive to fertiliser to improve phosphorous retention in soils.
- Use as an additive to compost to aid the retention of trace metals.
- Use in brick and tile manufacture, both fired and non-fired.
- Use as a filler for plastics, to impart strength, resistance to UV, heat and chemicals, and colour.
- Use as road base, either using the sand fraction directly, or the mud as a component of a composite with gypsum or fly ash.
- Use as raw materials for the production of cement alternatives, such as mineral polymers and ceramics.
- Use as a pigment for a range of applications in coatings and materials manufacture.

Three of the more promising re-use opportunities that Alcoa believes hold the greatest potential for large volume re-use of the residue include use of the coarse residue fraction (Red Sand) as a general-purpose fill and construction medium, use of the solar dried fine mud fraction (Alkaloam) as a soil amendment, and use of lime residue (Red Lime) as an agricultural liming agent (Cooling et al., 2003).

5.1 Red Sand

The residue from processed Darling Range bauxite is characterised by a high coarse fraction (nominal particle size > 150 μm). This coarse fraction can be considered as a fine to medium grained sand. The fine fraction of the residue (nominal particle size < 150 μm) is silt to clay sized material and is commonly referred to as 'red mud'. The mud and sand fractions are separated to aid the washing for soda and alumina recovery, and are handled within the residue storage area as separate residue streams. The separation is not complete with around 10-15% of the fine mud remaining with the sand and similarly 10-15% of the coarse sand remaining with the fine fraction. At present, a portion of the sand (around 30%) is used in underdrainage construction and final capping of the storage areas. The balance is placed within the dry stack as either a layer across a drying bed or as a stockpile against an embankment. This excess sand consumes considerable volume within the deposit, so finding external re-uses for the sand will be of significant benefit in terms of reducing the ultimate size of the deposit.

Alcoa has conducted a number of standard tests on samples of the Red Sand produced via a wash and carbonation process. The Red Sand satisfies the specifications for fill and sub-grade sands. Although there is an excess of fines (<75 µm) for the drainage sand specification, the fines content is considered to be low and the Red Sand is likely to have good drainage properties. California Bearing Ratio (CBR) values are high (around 50%). These values are significantly higher than typical sands on the Coastal Plain with typical values between 12% and 18%. The high values can be attributed to the angular nature of the sand. It is likely that the final product sand will be suitable for road embankment construction (including sub-grades and foundations). As the Red Sand is likely to have good drainage properties it may also have advantages in some situations over sands that are conventionally used for embankment construction on the coastal plain.

As part of the assessment of the potential for use of the Red Sand in construction, consideration has been given to potential environmental constraints on the use of this material. Total composition and leachate testing has been carried out, with further work planned to ensure the final product sand meets Department of Environment of Western Australia requirements as an inert fill material.

5.2 Alkaloam

The use of red mud to improve the nutrient and water retention of the sandy soils of Western Australia was first reported by Barrow (Barrow, 1982). He suggested that the addition of a blend of waste gypsum and red mud to the relatively infertile, acidic sandy soils of the Swan Coastal Plain could improve the water retention, nutrient leaching and productivity of these soils. In this way two industrial wastes could be combined to produce a valuable product and also reduce the storage and management requirements of both materials. Heightened awareness of the nutrient problems in the Peel-Harvey Estuary resulted in further research and trials on the use of bauxite residue as an aid in catchment management (Summers, 2002; Tacey et al., 1984; and Vlahos et al., 1989).

Red mud has the ability to absorb nutrients such as phosphorous and when added to sandy soil it can substantially decrease the rate at which these nutrients leach to groundwater. Early work involved application rates of up to 2000 tonnes of residue per hectare, which substantially modified the surface soil. However, at these high rates the costs and disruption to normal farming practices were unacceptable. More recent research and trials, conducted by Agriculture WA, indicates that rates from 20 to 80 t/ha can reduce phosphorous leaching by more than 70 percent. Even lower rates of 5 to 20 t/ha can significantly reduce soil acidity and improve crop yields. Pasture improvements of up to 25% have been noted in farm trials.

The use of red mud in broad acre agriculture and horticulture for nutrient control was approved by the Environmental Protection Authority following a Public Environmental Review (Department of Agriculture, 1993). Its use is being controlled and monitored through a comprehensive Code of Practice administered by Agriculture WA. This code has been established through extensive consultation with farmers and all related agencies. Formal application and approval processes have been put in place to ensure that all parties involved in the use of the material are aware of their obligation to ensure that they comply with the Code of Practice at all times. The red mud being used under this programme is being promoted under the Trademark name of Alkaloam.

The EPA approval for the use of Alkaloam limited its use to the Peel-Harvey Catchment, and was conditional on Agriculture WA continuing with detailed catchment monitoring, the results of which are reviewed annually by the Department of Environment and are publicly available through Agriculture WA. However, following negative publicity surrounding the use of Alkaloam in Perth and Sydney based newspapers, Alcoa has decided to place the release of Alkaloam on hold while further research into its use is conducted.

5.3 Red Lime

Lime is used in the Bayer process, primarily to convert sodium carbonate to sodium hydroxide via a process step termed causticisation. The residual lime from this process is a combination of calcium carbonate, mono-carbonate and tri-calcium aluminate. This residual lime is added to the bauxite residue stream as a means of disposal. It is estimated that this lime contributes around 5% of the total residue mass. Work is currently underway looking at the feasibility of producing a Red Lime by-product from this lime residue, with the initial focus on use as an agricultural lime.

Many soils in Western Australia's agricultural areas are naturally acidic. Agriculture also accelerates the acidification through leaching of nitrogen from the root zone. It is estimated that soil acidity affects two-thirds of Western Australia's wheat belt and costs the farming community in excess of A$70 million annually through lost production (Department of Agriculture, 2002). Lime is the simplest and most economical way to increase soil pH and decrease acidity, and the use of lime in agriculture has been steadily increasing over the past decade

It is believed that the rate of acidification of WA farmland requires an ongoing supply of up to 2 Mt of lime per annum, with a “catch-up” requirement of up to 20 Mt of lime. Concern is growing over the availability of lime to meet this demand. Natural sources are limited and many are covered by valuable stands of native vegetation. Increasingly, farmers and researchers are looking for alternative sources of liming materials.

Testing of Red Lime has shown an acid neutralising value of 75-80%. The Acid Neutralising Value (ANV) is expressed as a percentage of calcium carbonate equivalent. Red Lime has an ANV similar to other high-grade agricultural limes. In addition, Red Lime is a fine grained lime, so release of the alkalinity will be relatively fast. It will also have a level of soluble alkalinity that will be flushed into the soil with the first rains, providing an immediate soil pH adjustment. The material will be of a consistent quality, overcoming variability associated with some natural sources of agricultural lime.

As with the Alkaloam, a thorough evaluation of the Red Lime will be carried out to ensure there is a detailed understanding of the potential impacts the use of Red Lime might have on agricultural soils, crops and livestock. Preliminary field trials comparing Red Lime to Alkaloam and a range of conventional liming agents have been commenced by Department of Agriculture WA, under a project supported by the WA Centre for Sustainable Resource processing (Department of Agriculture, 2004).

Separation and use of this lime will also simplify the process of residue carbonation, as it is the TCA6 which is slow to react and it consumes a significant portion of the CO_2 required. Hence removal of the lime will have multiple benefits, these being;

- A reduction in the cost of carbonating the residue mud.
- A reduction of the volume of residue being produced.
- Production of a valuable by product which will help replace a diminishing natural resource.

6 CONCLUSIONS

As early as 1977, Alcoa recognised the need to investigate alternative residue management strategies. The company made a significant commitment to continuous improvement in residue management. Through research and field trials, a range of significant improvements to residue storage methods have been developed and implemented over the past two decades. However, through recent long-term planning for residue storage, it has become increasingly apparent that community and government expectations are changing, and that further improvements to the way residue is managed into the future will need to change.

Alcoa’s vision for residue management is an overall transition to a more sustainable method of residue storage, where the impact on the environment and the surrounding community is being progressively reduced. The move to dry stacking was a significant step toward a more sustainable method of storage, allowing a greater volume of residue to be stored within a given footprint, and providing a stable storage area which could be used for a range of land uses once closed. Neutralisation of the residue is seen as a similar step along this same pathway, as the more significant hazard associated with the residue (its high pH) will be removed.

Work on residue carbonation commenced in the early 1990s with preliminary laboratory testing. This work demonstrated the viability of carbonation and was followed in the mid to late 1990s with small scale pilot testing. Encouraged by the success of these trials, a full scale prototype of residue carbonation was installed and commissioned mid 2000 at the Kwinana refinery. This prototype allowed detailed evaluation of both the initial treatment of a thickened residue slurry with a high concentration CO_2 gas, and the performance of this thickened slurry in a full scale drying bed. This work has shown residue carbonation to be an effective means of treating residue slurry to reduce its pH and hence the hazardous nature of the slurry normally attributed to the causticity of the residue. Full scale implementation of this technology is now underway at Kwinana and further work is in progress investigating efficient ways to use low concentration flue gas at other Alcoa refineries.

However, the ultimate aim in terms of sustainability of residue management is to progressively reduce the volume of residue to be stored. Dry stacking has been an important step toward re-use of the residue, as it has made access and reclamation of the residue more cost effective. Residue neutralisation is similarly a key step toward re-use of the residue, as it will remove the hazardous nature of the residue, removing constraints on its handling and use. With an increased research and development focus over recent years, a number of re-use opportunities are being developed and are progressed toward demonstration stage.

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