FULL LIFE CYCLE INTEGRATED AND RISK-BASED APPROACH FOR BAUXITE RESIDUE MANAGEMENT

Li H* and Johnstone P

Rio Tinto Alcan, B&A Engineering, Brisbane, QLD, Australia

Abstract

The life cycle of bauxite residue disposal and management may comprise site selection, storage design and construction, operation, rehabilitation and closure. The processes of residue disposal operations may include neutralisation, thickening, transport, deposition, containment and consolidation.

This paper presents a full life cycle integrated and risk-based approach for bauxite residue management. In this approach, every stage of the life cycle and every operational process are considered together, as a whole, and within a context of sustainability. This multi-dimensional systems approach produces a good stewardship outcome with a solution that is technically sound, sustainable and lowest risk to society and the environment.

The main components of this approach include design for closure, risk management, rheological manipulation, integrated cost analysis and continual improvement. This approach provides a framework for safe, socially acceptable and environmentally responsible disposal and management of bauxite residue. It typically also results in the most cost-effective outcome. Design for closure keeps closure in mind from day one of a storage development. Risk management involves identification of risks for all life cycle phases including post-closure, and managing and mitigating those risks to an acceptably low level throughout. Rheological manipulation requires an understanding of the tailings behaviour, particularly in the paste tailings regime, and how that can be best manipulated to optimise the overall tailings thickening, transport and deposition phases. Integrated cost analysis considers the cost curve for each stage of the life cycle, as well as jointly, so an optimum solution may be achieved. As new technologies emerge, and the social and environmental expectation is increasing, acceptable risk levels are getting lower and lower. Continual improvement is another key component of residue disposal and management and is an essential ingredient to our "social licence to operate" and therefore sustainability of the alumina industry.

1. Introduction

Like other tailings storage facilities, bauxite residue storage facilities are among the largest of manmade structures that, unless designed and managed properly, can pose risks to the safety and health of workers and public as well as the environment. Current risk assessment and management tools and practices are the result of significant efforts and progress by industry, relevant professional groups and government agencies and can be readily applied to the design and management of bauxite residue. Whilst there is very often a residual risk, typically due to economic limits, modern day risk tools facilitate identification and determination of the acceptability of those risks. At times this may drive a re-design, or specification of management controls.

Whilst our dream of full recycle and re-use of bauxite residue slowly materialises we must continue to improve the way in which we deal with the storage of bauxite residue. The typical life cycle of bauxite residue management continues to comprise site selection, storage design and construction, operation, rehabilitation and closure. The operational processes of residue disposal may include neutralisation, thickening, transport, deposition, containment and consolidation. The processes tend to be dealt with separately, being the realm of discipline designers, specialists in one or at most two of the processes, each typically applying their specific design methodologies. Whilst each discipline performs their task very well, an over-arching integrated approach that has considered all the stages and processes, as a whole tends to be lacking, leading to a less than optimal solution in terms of risk and sustainability. In addition, in the design of residue storage facilities, the conventional approach is standards based. Meeting standards does not necessarily result in a zero or "acceptable risk". A risk based approach addresses this issue through design, supported if necessary by control measures.

This paper presents a full life cycle integrated and risk-based approach for bauxite residue management. In this multi-dimensional approach, every stage of the life cycle and every process are considered both individually and together as a whole, to achieve sustainable disposal and closure with an acceptably low risk to society and the environment.

2. Whole spectrum of residue disposal and management

2.1 Spectrum

A life cycle of a residue storage facility consists of (MAC, 1998):

- Site selection and design
- Construction
- Operation
- Rehabilitation and Closure.

In the past, the different stages were typically considered separately. In many instances, the site selection and design phases for Tailings Storage Facilities (TSF) also neglected rehabilitation and closure requirements, often leading to unexpected and very expensive rehabilitation and environmental controls costs. Nowadays, companies and designers are increasingly trying to account for closure at the outset of TSF design, if not at site selection. However, the related processes continue to be dealt with separately. For an optimum outcome, residue disposal and management should not be just restricted to the physical storage facility. Other processes such as neutralisation, thickening and transport also need to be incorporated. The over-arching aspect is rheological manipulation as bauxite residue, and other tailings are typically non-newtonian, and also exhibit shear-thinning properties, which can be used to advantage in holistically designing tailings management systems.

Thus, the whole spectrum of residue disposal and management may comprise the following:

- Neutralisation – with/without seawater, acid, carbon dioxide or other ameliorant
- Thickening – using Deep Thickening technology to produce paste tailings
- Transport – pumping, trucking or conveying.
- Disposal – design of the storage facility, as well as recycling and re-use options
- Operations – efficient, effective, safe and environmentally responsible
- Closure – ensuring no adverse legacy to future generations.

Those processes are interlinked and should not be designed individually. The best solution is to consider them as a whole and undertake design for closure.

2.2 Design for closure

The design for closure keeps closure in mind from day one of a storage development. The first step is to determine what a storage facility will look after closure and rehabilitation and to determine the closure criteria. The engineering design, from conceptual to detailed level, and operations will facilitate environmentally and economically sustainable closure and rehabilitation. Closure plan will be incorporated in designing the layout of a storage facility, especially the location of a decant pond, In selecting a neutralisation method, closure is an important factor. The change away from wet disposal to paste tailings deposition and mud farming was largely driven by closure goals. In wet disposal, bauxite residue remains soft, with a high moisture content and low density. This results in difficult and expensive closure and decommissioning. Weak and soft residue is difficult to traffic and cover. Consolidation of soft residue would take decades, or even hundreds of years to complete, and the consolidation induced settlement is large, adversely impacting post-closure contours and surface drainage and the higher seepage potential could be a significant risk to local groundwater. Paste tailings deposition and mud farming not only overcomes these problems, but also reduces footprint area.

3. Standards based versus Risk based approach

Standards based approach refers to design and evaluation of a storage facility in which a satisfactory safety condition is defined using the current state of the art (or practice) standards or guidelines. Risk based approach refers to design and evaluation of a storage facility in which a satisfactory safety condition is defined using the information from risk assessment.

The standards based approach was developed from many years of good engineering development and has well served the safety objective for tailings and water dams. It is still an essential part of dam safety management. However, our drive to develop standards has led to some deficiencies, including:

- Ambiguity. For example, there are different guidelines for tailings storage facilities in different states in Australia and their design criteria is not the same. In addition, professional opinions and practice can vary over the selection of appropriate design criteria
- Not a zero risk solution. The standards based approach implies that if the standards, such as required factor of safety, are achieved, the risk will be acceptable. However, the approach does not ensure a zero risk solution. A lack of awareness can lead to "blind" risk tradeoffs
- Unjustifiably conservative in some cases. Sole use of a standards based approach without risk assessment could lead to adoption of design criteria that are unjustifiably conservative.
- Limited direction on post-closure aspects, including mitigation of impacts, and planning to prevent loss of potential societal benefits post-closure.

In contrast, risk based approach can overcome the above deficiencies in the standards based approach. The benefits of risk-based approach include:

- Explicit and transparent treatment of uncertainty: A risk-based approach seeks to identify the sources, nature and scale of uncertainties
- A comprehensive risk assessment: A risk-based approach facilitates identification of all hazards and opportunities. Including skilful and knowledgeable participants in the process will facilitate a comprehensive estimation of risks from all failure modes, including those post-closure, as well as opportunities for cost-reduction and more sustainable outcomes
- Defensible decision-making. A risk-based approach can provide a rational and quantitative basis for adopting appropriate design criteria and optimum disposal strategies
- A risk reduction framework. A risk-based approach provides a means of computing the relative cost effectiveness of potential risk reduction measures.

More benefits and challenges are discussed in the ANCOLD guidelines on risk assessment (ANCOLD, 2003). It is important to note that at this stage, risk based approach is not meant to replace the traditional standards based approach, but rather enhance the standards based approach.

4. Risk Analysis

Risk-based design is based on information from risk analysis. It is recommended that risk analysis be carried out for tailings storage facilities that attract a "High" hazard category (ANCOLD, 1999).

There are many types of risk analysis. According to ANCOLD (2003), risk analysis may be classified into two types:

- Qualitative analysis, including semi quantitative analysis, and
- Quantitative analysis.

4.1 Qualitative analysis

The qualitative risk analysis tools generally applied include:

- Hazard and Operability Analysis (HAZOP)
- Preliminary Hazard Analysis (PHA)
- Failure Mode Effects Analysis (FMEA) for the Mud Storage Area.

HAZOP

The HAZOP is carried out for the process, pipe work, pumping, trucking or conveying aspects of the red mud disposal design. The key objectives of the HAZOP analysis are:

- To identify any potentially severe events associated with operation of the process
- To develop an action plan to allow for modifications to the design to incorporate necessary changes that mitigate any significant risk associated with the operation of the process.

A Preliminary HAZOP is recommended for the early design phase, around 30% design development. This facilitates early identification of key risks so they may be more readily and economically addressed during the design phase. It is generally undertaken on a Process Flow Diagram (PFD).

A full HAZOP is targeted toward the latter part of the design phase, around 75% design development, when the Piping and Instrument Diagram (P&ID) has been completed. This is a more extensive analysis that considers each P&ID line in turn, for a range of potential operating conditions, from nil, abnormally low, through normal to abnormally high, in relation to aspects such as flow, pressure and temperature.

PHA

Preliminary Hazard Analysis (PHA) is a risk tool more amenable to the early design phases of the residue storage facility. PHA is a qualitative technique by which future hazards, their probability of occurrence and likely consequences/implications are identified.

The objectives of the PHA are:

- To identify potentially high hazards and rank the risks related to the storage facility operation and closure
- To identify and prioritise the necessary further studies, design development and controls required to be implemented in order to reduce the identified risks to acceptable levels.

A PHA is more suited to the early design development phase and like the Preliminary HAZOP, facilitates early identification of key risks so they may be more readily and economically addressed during the design phase.

FMEA

The Failure Mode Effects Analysis (FMEA) is a qualitative "bottom-up" technique by which the important modes of individual component failures, the factors causing these failures and likely consequences are systematically identified. "FMEA provides a comprehensive approach to dam safety assessment by requiring an exhaustive identification of components and their failure modes. This requirement prompts the analyses to look for potential failure modes, which may not have been considered at the design stage, or that may not be recognised without the systematic steps of FMEA." (ANCOLD, 2003).

The objectives of the FMEA are:

- To identify major risks within the proposed design during operation and post-closure
- To identify acceptable mitigating measures to reduce the risks to acceptable levels
- To identify and prioritise issues that can be incorporated into the current engineering phase, or that need to be considered in the next phase of engineering design.

The main outcomes of the FMEA includes two parts: modification or addition of design of some components in the current engineering phase, and identification of items that require further actions/measures to be taken in the next engineering phase.

Although at times, it may take up to two days to undertake an FMEA, the tool does work well to identify the risk of individual component failure modes. Because it is predominately a "bottom-up" approach we do also try to consider the presence of interactive multi-component, or system failures, that is, using a partial "top-down" approach. In this way, we are perhaps applying a hybrid FMEA.

4.2 Quantitative Analysis

There are a number of risk tools that facilitate qualitative risk analysis, such as Fault-Tree and Event-Tree, amongst others. The analysis typically requires the allocation of probabilities to the event or fault occurring. It is often the case that these probabilities are not available from historical data, in which case it is imperative that experienced personnel are present that can fill that gap from their experience.

Fault-Tree and Event-Tree analyses are "top down" approaches that consider the potential failures and events that may occur in the overall system, and then working down toward sub-systems, or individual components that may cause those to occur. Numerical values of likelihood and consequences are assigned and the resultant risks are compared with acceptable societal, individual and economic risk criteria.

Such analyses can be very time consuming, sometimes taking several days to analyse a tailings storage facility. As a result there is a reluctance to use these tools extensively.

We do, however, often use quantitative techniques for seismic analyses. In this case, the steps for risk assessment may include (ANCOLD, 1998):

- Determine the annual exceedence probability (AEP) of earthquake ground motions over the range of earthquake events
- Determine the conditional probability that for each of the ground motion ranges the dam will breach
- Assess the probability of failure for each range of ground motion
- Sum the probabilities to give the overall annual probability of failure due to earthquake
- Determine the incremental loss of life expected for the dam breach, the population at risk and the risk to the individual
- Assess the acceptability of risk using the tolerable risk criteria.

What is tolerable will depend on many factors including life safety, social, political and economic. ANCOLD (2003) recommended the societal criteria shown in Figure 1, which is expressed as F-N curves of cumulative frequency (F) of life loss exceeding various magnitudes (N). Figure 2 shows another F-N plot for both cost and number of life loss (Christian, 2007).

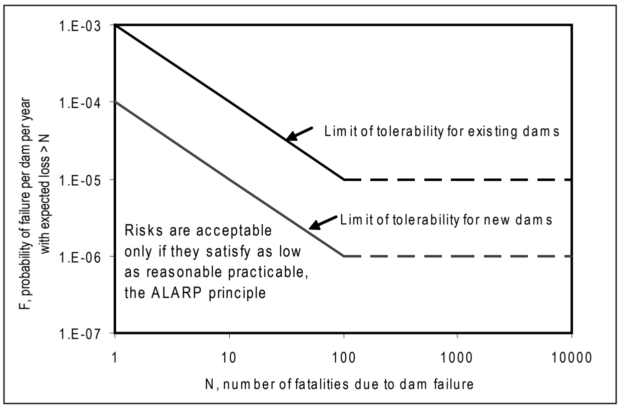

Figure 1. ANCOLD recommended societal risk criteria (ANCOLD, 2003)

5. Integrated cost analysis

Integrated cost analysis considers the cost for each stage of the life cycle and each process jointly so an optimum solution may be achieved. We will use a hypothetical options study as an example to demonstrate the importance of the integrated approach.

In this hypothetical case, the setting is an arid environment, whereby evaporation significantly exceeds rainfall. The integrated approach will consider all the following elements individually and as a whole: neutralisation, thickening, transport, disposal methods and closure. After an initial high level ranking analysis, the following options are selected for further assessment:

- Neutralisation with sea water – neutralised in tanks, pipes and in the proposed storage area
- Pumping – centrifugal, positive displacement pumps
- Thickening – deep thickener

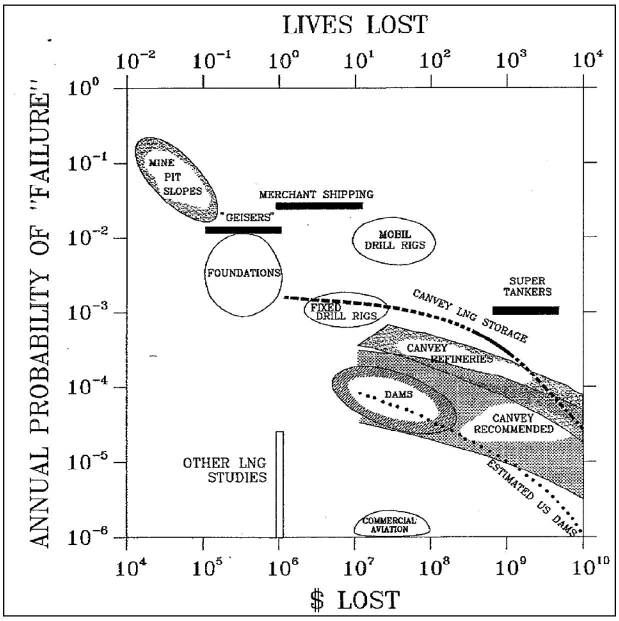

Figure 2. Annual risk versus cost or number of lives. In this plot, both cost and lives are shown; it is customary to use one or the other rather than both on the same plot (Christian, 2007).

- Disposal – dry stacking, sub-aqueous and sub-aerial
- Discharge – paste, slurry, central and spigot discharge
- Mud farming – yes or no, to improve consolidation
- Embankment raising – upstream, centre or downstream
- Dust control – sprinkler system, water cover, and
- Closure – single or double synthetic floor liner for seepage management, or alternatively use of a compacted red mud floor liner system. Long-term post-closure dust management options.

After an integrated cost analysis, the selected system includes:

- Mud is neutralised in pipes and the storage area with seawater and no special tank required
- No need for an additional deep thickener neutralisation facility
- Pumping – using centrifugal pumps
- Disposal – central discharge
- Mud farming – selected
- Embankment raising – upstream
- Dust control – by rotational discharge, with mud farming and a sprinkler back-up system
- Seepage management – Double synthetic floor liner system in decant pond and initial mud deposition areas. New mud deposition areas use compacted red mud
- Post-closure dust management – vegetation growth very poor and sparse, so place 2 metres of local sand overlain by 100 mm of local gravel material.

Savings – significant capital saving on neutralisation tanks, deep thickener; and significant operation cost saving from not using positive displacement pumps.

In this case, the knowledge of permeability characteristics of the red mud as well as the drying properties in the storage area in an arid environment is imperative, and that feeds into the design for neutralisation, thickening, pumping, floor liner, and mud farming operation. This is different from the traditional approach that may only consider just the design of a storage facility, leaving others to design the upstream stages and related processes separately. The latter approach would receive outputs from the upstream stages, which become just inputs to the design of the storage facility, with no feedback loops to optimise the overall system. Often this is a fault of the tender packages, which often, and less than optimally, promote separation of the storage facility design from that of the upstream stages.

Without this integrated approach and cost analysis, significant savings are much less likely to be achieved.

6. Continual improvement

Social and environmental expectations continue to increase and acceptable risk levels continue to reduce. We also see an increase in the number of companies, large and small, supporting and to an extent jumping ahead of the "social licence to operate" paradigm to pro-actively build toward a sustainable future.

There is no doubt that the ongoing emergence of new technologies, improved design methods; more powerful analysis tools and perhaps also larger equipment, all significantly assist our progress toward a sustainable future.

This paper has highlighted the merits of a multi-dimensional systems approach to design and management of bauxite residue operations and post-closure.

A range of key items the authors, and perhaps others in the industry, have on their Continuous Improvement List include:

- Design Performance Reviews – Such reviews are rare for a number of logistical and cost reasons, however, when conducted at intervals of say 1, 2 and 5 years following commissioning of new facilities provide a significant step jump in the learning of both the facility designers and operators
- Research and Development – A broad topic ranging from perhaps technology development through rheological behaviour to onsite consolidation test work, for example. Whilst industry facilitators do a very good job attempting to capture and tailor research programs to satisfy industry needs, there is always an element that must be undertaken in-house for reasons of site specificity, or confidentiality. Whilst we all have a list of items that may not be shared in the public domain, the key point is that such intra-company as well as industry R&D is an essential part of our sustainable future and needs to be allocated due focus and funding
- Sustainability in Design – Although we attempt to capture this aspect during our design risk reviews as discussed within this paper, we recognise a more definitive process is required. To that end we are consolidating our learnings into an in-house guideline/process, primarily to ensure that we are not designing out sustainability opportunities. As a sustainable outcome is often the most economical outcome, this guideline/process should also provide cost-savings
- Knowledge Management – There are perhaps two areas of knowledge management, that which needs to be captured and shared in-house, and that which can be shared externally. We are seeing a number of companies appointing Knowledge Managers to facilitate in-house capture and use as well as adjudicate over what may be shared externally. Whilst we all work within a competitive environment, there is certainly an element of our in-house learning that falls into the collaborative domain for sharing in our drive toward a sustainable business future. Not easy to decide, but certainly a consideration for this and future workshops
- Tender Design Packages – Packaging to promote a multi-dimensional systems approach to design and management of bauxite residue, and other tailings. Whilst there are few companies, or indeed individuals, that can complete designs according to such a multi-dimensional approach, that will change for the better if tender packages are restructured to demand such an approach
- Flocculants and other additives – There is considerable advantage to the inclusion of flocculant and other additive

suppliers in either in-house, or industry R&D programs. Whilst the question of supplier competitiveness is a potential roadblock, there is significant synergy to be gained by a joint approach to at least test work, if not R&D development.

7. Conclusions

A full life cycle integrated and risk-based approach for bauxite residue management is described in the paper. In this approach, every stage of the life cycle and every process are considered together as a whole to achieve economical disposal and rehabilitation with acceptably low risks to society and the environments.

The main components of this approach include design for closure, risk assessment, integrated cost analysis and continual improvement. This provides a framework for safe and socially and environmentally responsible disposal and management of bauxite residue, which is also typically the most cost-effective.

Design for closure keeps closure in mind from day one of a storage facility development. Engineering designs, from conceptual to detailed level, and operations facilitate environmentally and economically sustainable closure and rehabilitation.

Risk management involves identification of risks for all life cycle phases including post-closure, and managing and mitigating those risks to an acceptably low level throughout. The risk based approach for design and evaluation of a storage facility is the key to the risk management. Risk based approach has some benefits over the traditional standards based approach. However, the former is not meant to replace but enhance the latter.

Integrated cost analysis considers the cost for each stage of the life cycle and each process jointly so an optimum solution may be achieved.

As new technologies emerge, and the social and environmental expectation is increasing, acceptable risk levels are getting lower and lower. Continual improvement is an essential ingredient of residue disposal and management and the sustainability of the alumina industry.

References

ANCOLD 1998, *Guidelines for Design of Dams for Earthquake*, Australian National Committee on Large Dams.

ANCOLD 1999, *Guidelines on Tailings Dam Design, Construction and Operation*, Australian National Committee on Large Dams.

ANCOLD 2003, *Guidelines on Risk Assessment*, Australian National Committee on Large Dams.

Mining Association of Canada 1998, *A Guide to the Management of Tailings Facilities,* Ottawa, Canada.

Christian, J.T. (2007). 'The reliability of the geotechnical enterprise', *Proc. 10th Australian New Zealand conference on Geomechanics*, Brisbane, Australia, 21-24 Oct 2007. Vol.1, pp.42-57.