# LEADING PRACTICE SOLUTIONS FOR ACID ROCK DRAINAGE PREVENTION AND CONTROL: A KEY TO ACHIEVING A SUSTAINABLE FUTURE FOR MINERAL RESOURCE DEVELOPMENT

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## ABSTRACT

*The mineral resources industry has a poor record with a legacy of mines that continue to leach acid and contaminants making water unfit for human consumption and ecosystem health. As clean water is a human right and fundamental to sustainable development, the mining industries social licence to develop resources will depend on ensuring that ARD does not impact people's access to safe water.*

*An acid generating mine has the potential for long-term impacts on surface and ground water and aquatic life. In some cases the problems may be evident from the outset and steadily increase during the life of the mine. In others, ARD may appear later in the mine life or only after the mine has closed and the company has left the area. Once started, however, the process can endure for centuries.*

*It is apparent that ARD management strategies are not being effectively implemented at many new and operating mines and the ARD liability is likely to grow over the next decades. This is simply because the industry as a whole has not adequately adopted and implemented the knowledge and technologies that have been developed and proven over the past 30 years. As a result opportunities to incorporate effective ARD management into mine planning and day-to-day operations have been missed, and once ARD has started it is almost impossible to stop.*

*This paper presents the fundamentals of ARD prediction, prevention and control with site-specific experience from mine sites in the Asia Pacific region. These case studies demonstrate strategies for oxidation control, water flux control and acid-base management for ARD prevention and control.*

## 1.0 INTRODUCTION

The performance by the minerals industry in ARD management is variable. Some companies are well advanced and continually improving, but the practices of others are out-dated and some are flawed. Action by companies individually and collectively is clearly required. In many areas, small companies are crucial to the standards of large ones. For example, projects near closure can be sold by multi-nationals to small companies that are not aware of a pending ARD liability thus opening up ways to avoid obligations and damage the industry as a whole. Multi-nationals and funding agencies can also fail in due diligence by not adequately accounting for ARD risks and liability in acquisitions. Collective action

must include companies of all sizes in order to produce positive results. INAP is one such industry organisation with a charter to facilitate this cooperation.

An acid generating mine has the potential for long-term impacts on surface and ground water and aquatic life. In some cases the problems may be evident from the outset and steadily increase during the life of the mine. In others, ARD may appear later in the mine life or only after the mine has closed and the company has left the area. Once started, however, the process can endure for centuries.

The financial liability of ARD is almost impossible to quantify but is currently likely to be many billions of dollars. It is also apparent that ARD management strategies are not being effectively implemented at many new and operating mines and the ARD liability is likely to grow over the next decades.

The reason for this is simply because the industry as a whole has not adequately adopted and implemented the knowledge and technologies that have been developed and proven over the past 30 years. As a result opportunities to incorporate effective ARD management into mine planning and day-to-day operations have been missed, and once ARD has started it is almost impossible to stop.

In addition to loss of productivity, sulphidic wastes can have a profound effect on the surrounding ecosystems. Where they are not physically stable, erosion or catastrophic failure may result in severe or long-term impacts. Where they are not chemically stable, they can serve as a permanent source of pollutants to natural water systems. These impacts have lasting environmental and socio-economic consequences and are extremely difficult and costly to address through remedial measures.

Historically the industry has a very poor record with a long legacy of mines that continue to leach acid and contaminated water. The combination of acidity and dissolved contaminants is toxic to most forms of aquatic life, and make water unfit for human consumption. As clean water is a human right and fundamental to sustainable development, the mining industries social licence to develop resources will depend on ensuring that ARD does not impact people's access to safe water.

## 2.0 ACID GENERATION IN SULPHIDIC MINE WASTE

ARD problems are established at the time of deposition or placement of sulphidic waste rock and tailings.

Typically when sulphidic mine materials are first exposed to atmospheric condition there is a lag before low pH conditions develop. This lag can vary from days to many years depending on the inherent geochemical lag (due to neutralising minerals such as a calcite that provide short term buffering), as well as construction and hydrological delaying mechanisms.

Figure 1 is a schematic of the time evolution of ARD generation and release from a waste storage facility. After the lag period, the pH drops and the acid load increases to a peak rate at some time later in the mine life or even post-closure. The acid generation rate (AGR) typically exceeds the acid release rate (ARR) due to the accumulation or storage of a significant amount of acid and oxidation products within the waste facility. The ARR can vary from less than 10% to more than 90% of the AGR depending on the climate and physical characteristics of the waste. The stored oxidation products include acid in minerals such as jarosite and melanterite and metal precipitates as sulphates and oxyhydroxides. The stored oxidation products are a concern for closure and post-closure as they can continue to

release acid salts and metals to the environment into the long term, even if oxygen and water influx to the waste has been reduce through placement of covers or other ARD mitigation strategies.

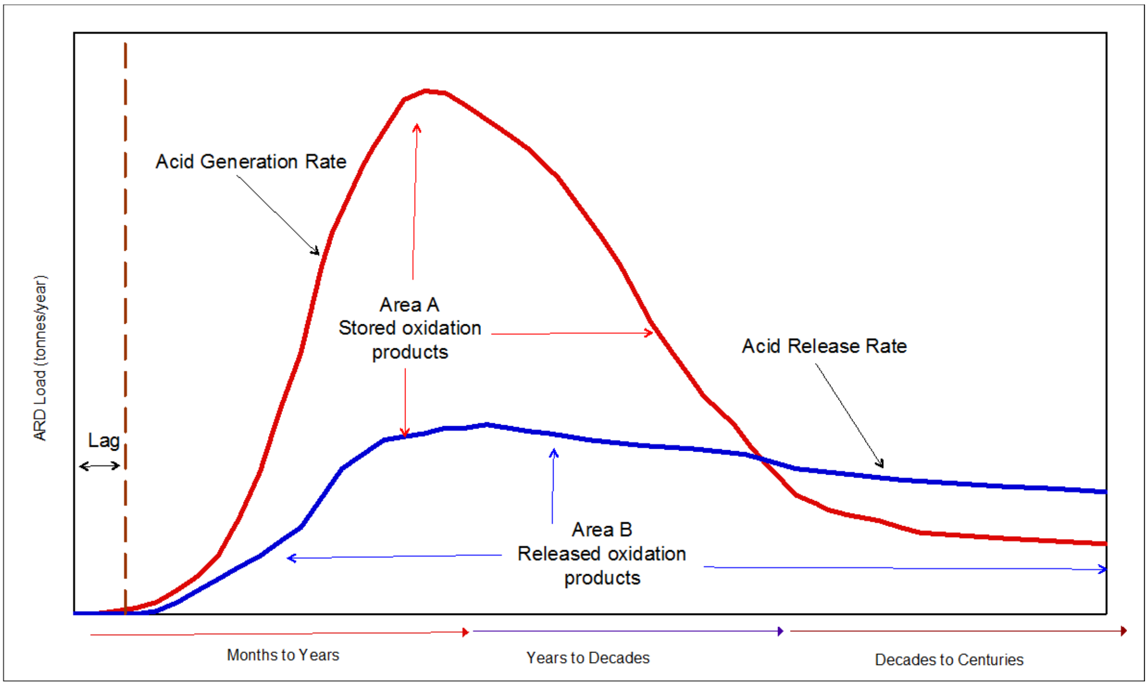


**Fig. 1. Schematic of the time evolution of ARD generation and release from a waste storage facility**

ARD is not a problem at every mine, even in sulphide-rich deposits. In some circumstances the inherent buffering capacity may be adequate to neutralise the acid and maintain near neutral pH conditions. But in these cases sulphates and elements such as Cu, As, Mn and Zn may still follow a similar evolution curve as shown in Figure 1 even though acid (low pH) conditions do not develop. Drainage with near neutral pH, which contains elevated concentrations of elements or sulphate is Neutral Mine Drainage (NMD) and can pose similar risks and liabilities as ARD. The term AMD (Acid and Metalliferous Drainage) can be used to cover both ARD and NMD.

Atmospheric oxygen is the main driver of oxidation and ARD generation and Figures 2 and 3 show how a dump built by the common practice of end tipping waste rock from a high tip head can promote the transfer of oxygen into the dump and vastly increase the mass of material exposed to oxygen.

Figure 2 shows how coarse and fine material segregates when dumped over an advancing face, creating a coarse base layer, chimney structures where the face angel changes and interbedded coarse and fine layers throughout.

Figure 3 is a section through this dump after 10 years and clearly shows the interbedded coarse and fine layers with extensive oxidation along the coarse layers extending out into the finer grey layers with stored oxidation products (mainly yellow jarosite). Oxygen movement

occurs by advection/convection along coarse layers driven by heat generated from the exothermic oxidation reaction with pyrite and by diffusion into the fine layers.

These Figures clearly show how the internal structure influences ARD generation and that alternative designs, such as bottom up construction in small compacted lifts, are necessary to prevent advective airflow when dealing with reactive mine waste.

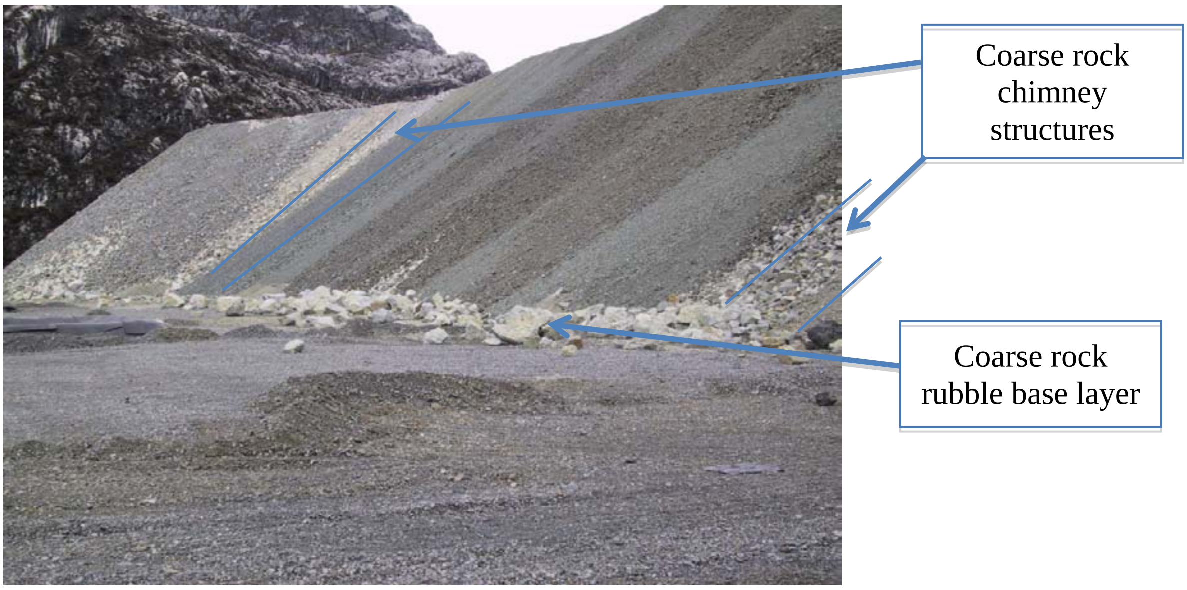


**Fig. 2. Construction of a waste rock reactor**

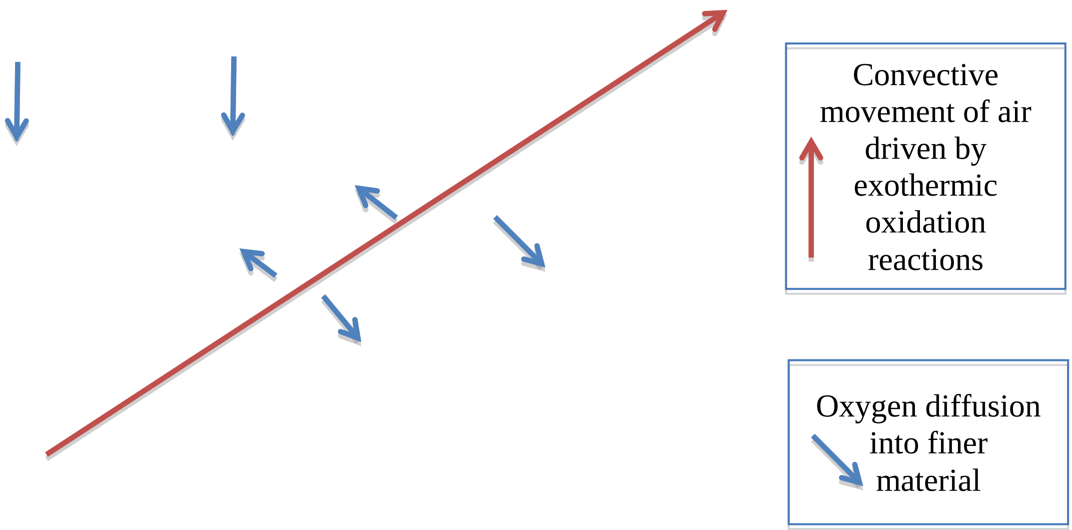


**Fig. 3. Uncontrolled oxidation within waste rock reactor**

## 3.0 PREDICTION AND GEOCHEMICAL CLASSIFICATION

The science for prediction of an ARD risk prior to mining is well advanced. Many management options can be considered with early identification and quantification of an ARD risk whereas option will be limited and costs highest if ARD is not addressed until later in the mine life.

Characterisation and identification of the ARD risk is the first step in developing an ARD management plan. Key to this is a comprehensive sulphur and geological database with associated ARD parameters such as carbonate, acid neutralising capacity (ANC), net acid generation (NAG) and associated mineralogical and elemental assays and kinetic test work programs such as leach columns or similar.

Compiling these data should commence as early as possible in the mine life cycle with adequate data available for consideration of ARD implications and costs at the feasibility stage. Once properly characterised and quantified, site-specific options can be fully evaluated and costed. There are many publications that can assist practitioners in this area including the GARD Guide (INAP), the ARD Test Handbook (AMIRA), MEND publications, the Leading Practice Handbooks on ARD (Australian Government) and numerous papers in proceedings of ARD specific conferences and workshops.

## 4.0 PREVENTION AND CONTROL

ARD prevention must be truly integrated with technical planning, design and operation. It must begin at exploration and be part of the process through to closure and beyond. If ARD is effectively managed, then closure costs and the risk of a long-term liability will be minimised, and access to future resources will not be compromised by poor performance.

Leading practice should not be defined by parameters that are set by regulation or read out of a manual, but there are specific task that are essential components of leading practice. These include:

- Geochemical classification;
- Quantification and production schedules by geochemical waste types;
- Selective mining, segregation and controlled placement; and
- Performance evaluation and monitoring

Leading practice at one site may not be appropriate at another and this is particularly evident across different climate and hydrological regimes. Water covers and oxygen barrier layers that prevent oxygen access to reactive sulphide mineral surfaces are best suited to climate regimes where precipitation exceeds the potential evapotranspiration. It is difficult to maintain saturation or near saturation in climates where the potential evapotranspiration exceeds precipitation and options must aim to minimise the generation (through oxygen flux control) and leaching (through water flux control) of oxidation products by segregation and selective placement of NAF and PAF materials, control of the internal structure of dumps to prevent advective/convective transfer of oxygen, infiltration control, water shedding, diversion and store and release mechanisms. In addition, blending of acid consuming (AC) and PAF rock to mitigate the ARD risk may be feasible where material geochemical properties and production schedules are favourable.

The following summarises some lessons from experience that are relevant to the development of leading practice solutions to ARD:

- Geochemical classification, quantification and production of waste types (e.g. potentially acid forming, non-acid forming, acid consuming) are critical for effective ARD management.
- ARD problems are established at the time of deposition and planning for closure in parallel with project feasibility and mine planning is fundament to leading practice. Control options are fewer and costs higher the later ARD management is addressed in the project cycle (most options at feasibility stage; least options and highest cost at closure).
- Delayed implementation of controls results in the accumulation of oxidation products within the disposal facility and major issues for closure and long term liability.
- The internal structure, composition and properties of waste storage facilities must be designed and constructed to control gas and water fluxes for ARD control.
- Engineered soil covers:
    - Well demonstrated to be effective for ARD control on tailings storage facilities
    - Much less successful and difficult to manage on waste rock piles due to positive topography, unnatural geological structures, erosion, natural systems.

  Soil covers have received significant attention and are a perceived low cost option at the feasibility stage of a project (due to NPV budgeting methods). However, covers are not necessarily the solution to long term ARD, especially when delayed until later in the mine life after oxidation has commenced and secondary products are being stored within the waste pile. Although the cover may limit water and oxygen entry, it may not prevent ongoing dissolution and leaching of secondary products and may not stop oxygen transfer sufficiently to meet environmental needs. Experience at sites such as Rum Jungle in Australia and the Equity Silver mine in Canada demonstrate the potential inadequacy of covers placed late in mine life or post-closure. As shown previously on Figure 2, there can be a significant store of soluble oxidation products that will continue to leach from the pile long after oxidation has slowed. This is particularly relevant to wetter environments where there will always be some percolation through a low permeability cover system.

- Water or elevated water table covers have been well demonstrated and are the best solution for geochemical control provided potential stability issues are addressed.
- Mitigation of an ARD risk through blending potentially acid forming and acid consuming material needs to have a substantial excess of the neutralising component. For ROM waste rock blends the NAPP needs to be less than minus 150 kg$H_2SO_4$/t; crusher/stacker built waste rock dumps require the reactive size fraction (<5mm) to have an ANC/MPA greater than 2; for tailings an ANC/MPA greater than 1.5 has been demonstrated.
- The climate and/or water balance influences control strategies, such as:
    - Focus on oxidation flux control where precipitation exceeds evaporation
    - Focus on water flux control where evaporation exceeds precipitation
- A comprehensive monitoring program including material geochemistry, oxygen concentrations and temperature within waste piles, drainage water quality and flow, as well as geotechnical and physical parameters associated with control structures

including encapsulating, containment or sealing layers is essential. This information is required to continually evaluate the performance of the ARD management plan and to refine designs and specifications as needed.

- Documented ARD Management Plans with clearly defined operating procedures, responsibilities and key performance indicators is required. Diligent supervision and quality control are critical to the effective implementation of an ARD management plan.

## 5.0 APPLICATION OF LEADING PRACTICE IN THE ASIA PACIFIC REGION

There are encouraging signs in the industry, including the Asia Pacific region, where leading practice ARD mitigation measures as well as leading practice for ARD control at the whole mine site level are being demonstrated. These practices include:

- ARD control through exclusion of atmospheric oxygen by design (water and engineered covers)
- Acid base balance control through use of high carbonate mine waste (blending/covers)
- Acid base balance control through sulphide recovery
- Segregation and selective placement

ARD control through exclusion of atmospheric oxygen by design has been demonstrated at the following sites:

- Martha Mine, New Zealand
- Golden Cross Mine, New Zealand
- Phu Kham, Lao PDR
- Ban Houayxai, Lao PDR
- Kelian, Indonesia

At the Martha Mine, PAF cells were constructed and encapsulated by compacted NAF waste. Tight engineering controls are in place and a comprehensive monitoring program including in-dump oxygen and temperature confirm the performance of this design. Figure 4 shows a PAF cell during construction and Figure 5 shows the placement and compaction of the sealing layers. Crushed limestone is broadcast on exposed PAF material prior to covering to control Mn solubility in runoff from active areas.

**Fig. 4. PAF cell construction at Martha Mine, New Zealand**

**Fig. 5. Construction of encapsulation layers**

The Phu Kham Copper Gold mine in Lao PDR incorporates many aspects of leading practice for ARD control in a wet environment. The Phu Kham site presents significant challenges for managing potentially acid forming mine waste in steep topography and a high rainfall environment. Early identification of the ARD risks prior to mining and integration of the geochemical requirements with the mine plan has enabled the company to managed ARD without any significant events.

The plan is based on the fundamental strategy of isolating sulphidic mine waste from atmospheric oxygen. This is achieved through placement of the higher sulphidic acid generating waste rock (Red Waste) within the tailings impoundment where it is progressively inundated by the supernatant pond. The lower sulphidic acid generating waste rock (Orange Waste) is isolated in cells within the downstream portion of the tailings storage facility embankment. Fine grained non-acid forming waste (Green Waste) and borrow material is used for encapsulation layers around PAF cells. Figure 6 is an overview of the TSF showing

the construction of PAF cells within the downstream zone of the embankment and placement of reactive PAF material within the TSF.

Performance monitoring of the geochemical and geotechnical characteristics of placed waste rock; oxygen and temperature monitoring within the PAF cells: and water quality data confirm that although there are significant environmental risks the results to date have clearly demonstrated that with good design, monitoring and management that ARD can be managed in a cost effective manner.

Key to the success of ARD management plan has been company wide awareness of the ARD risks and diligent operational management with regular technical review and evaluation of performance.


**Fig. 6. Waste Rock Management for ARD Control at the Phu Kham Mine in PDR Lao**

Pan Aust have applied the strategies developed at Phu Kham to their recently commissioned Ban Houayxai mine in Lao. This site is a lower risk ARD site, but segregation and selective placement of PAF and NAF material types is integrated with mine operations. The dumps are constructed from bottom up in small lifts to avoid segregation of fine and coarse materials and minimise the risk of developing advective/convective gas transfer between the atmosphere and interior of the dump.

The now closed Golden Cross mine utilised similar practices to Martha Mine with the segregation and compaction of PAF waste and compaction of NAF encapsulation layers to achieve a high degree of saturation for oxidation control. Golden Cross also closed the pit by partial backfilling with inert waste to create a free draining pit. Figure 7 is an aerial view of the mine post closure.

**Fig. 7. Aerial view of Gold Cross Mine Post-Closure**

The Kelian Equatorial Mine (KEM) in Kalimantan, Indonesia planned for water covers for waste rock, tailings and the final pit from early in the mine life. Waste rock was placed in a purpose built dam that was flooded at closure. Geochemical testing indicated that tailings were likely to have a lag period of at least a few years before low pH conditions would develop and hence the tailings were placed sub-aerially forming large beaches during operations. At closure the water level was raised to cover all tailings. The pit was filled with water to cover most of the PAF and problematic material types, however there is sufficient PAF above the final water level to result in dissolved Mn concentrations that exceeding guidelines for direct discharge. A constructed wetland system is used to remove the Mn and meet water quality standards for discharge.

Figures 8, 9 and 10 show the TSF and pit with final water level RL and waste rock dam prior to the final water level raise, respectively.

**Fig. 8. Kelian TSF at closure**

**Fig. 9. Kelian Pit at closure**

**Fig. 8. Kelian Waste Rock Dam at closure**

Acid base management for ARD control through use of high carbonate mine waste (blending/covers) is used at:

- Ok Tedi, Papua New Guinea
- Grasberg Mine, Indonesia
- Savage River Mine, Australia
- Beenup, Australia

In addition, acid base management by sulphide removal from tailings has been demonstrated at Ok Tedi and is proposed for Grasberg when the GRS block cave operation commences.

Experience at Ok Tedi and Grasberg demonstrate the need for a substantial excess of ANC to produce an effective blend for long term ARD control at the run-of-mine scale. At Ok Tedi, mine planning schedules mine production to deliver waste rock to the tip head at a NAPP of not less than minus 150 kg $H_2SO_4$/t on a quarterly basis (known as the NAPP minus 150 plan). Annual sampling of the waste rock in the Harvey Creek and Ok Mani dumps is carried out to confirm that the material is NAF with a high factor of safety (ANC/MPA>2 in the fine fraction).

Experience at Grasberg demonstrated that PAF rock and limestone could not be effectively blended using ROM size material with truck dumping from high tip heads due to segregation of the coarser limestone and finer PAF rock down the face. However, utilising a crusher and stacker method, effective blending was demonstrated and has been utilised for construction of the Lower Wanagon dump. The key operational target is to ensure that the reactive fraction in the blend (less that 5mm size) has an ANC/MPA of greater than 2. This requires a

substantial excess of ANC in the blend which is of similar magnitude to the NAPP minus 150 plan applied at Ok Tedi.

Figure 9 shows the scale of the Lower Wanagon dump with low tip faces (up to 600m). Figure 10 shows the average and median ANC/MPA for the bulk and fine fraction based on samples collected from down the face of the dump on a 6 monthly basis.

**Fig. 9. Lower Wanagon stacker built dump at Grasberg Mine**

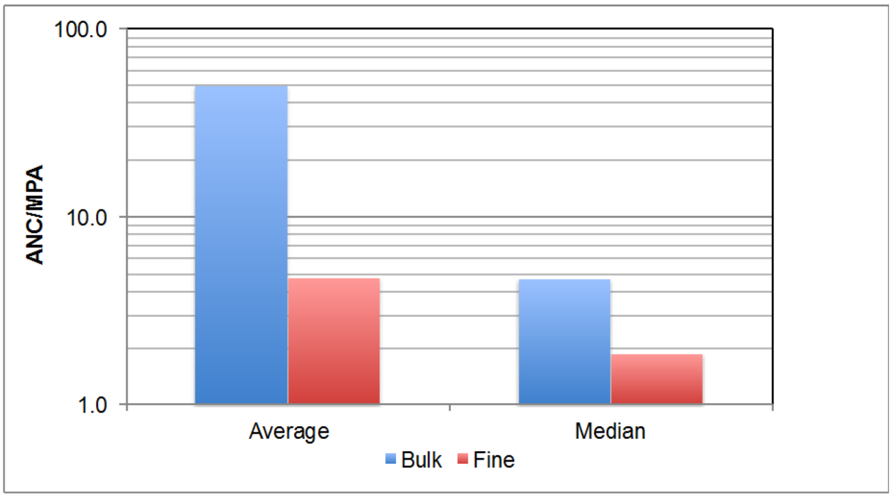


**Fig. 10. ANC/MPA of Bulk and Fine (minus 5mm) material place in the Lower Wanagon Dump**

At Ok Tedi, sulphur recovery from the tailings is carried out to ensure that mine derived sediments that are being dredge and stacked adjacent to the river at Bige will not be a long term ARD concern. The Pyrite concentrate is piped to the Bige area from the recovery plant and deposited below the water table with dredged sands stacked over the disposal cells to ensure permanent isolation from atmospheric oxygen.

Figure 11 shows the actual (sampled daily) and predicted (modelled) ANC/MPA of dredge sands. The sulphur recovery plant was commissioned in Q4 2008 resulting in an immediate increased in the ANC/MPA which is now generally greater than 1.5 and predicted to further increase as mining continues.

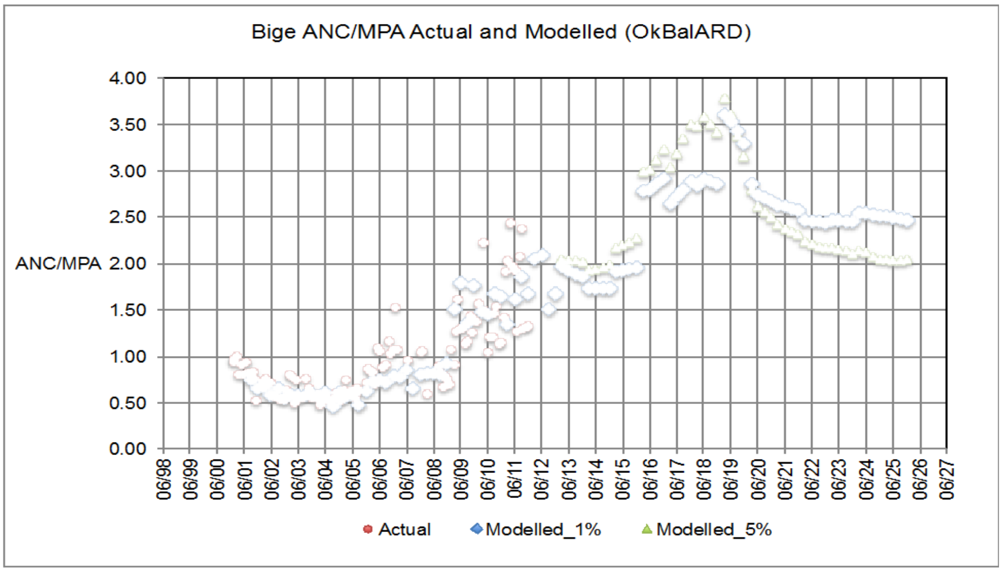


**Fig. 11.** **ANC/MPA of Bige dredge sands (actual and modelled values shown). The 1% and 5% model runs reflect the expected range in annual erosion rates from the Harvey Creek waste rock dump.**

Figure 12 shows the west back dredge sand stockpile and active PCon disposal cell in the background and dredge channel to the Ok Tedi. The dredge to access the PCon disposal area for cell construction uses the dredge channel. As each PCon cell is filled, they are covered progressively with dredge sands from the river. The PCon remains under the water table and is covered with at least 15 m of dredge sand.

**Fig. 12. Bige Dredge sand stockpile showing a PCon disposal cell in the background (water filled pond).**

## 5.0 CONCLUSION

The common thread at successfully managed ARD sites is early identification of the risk and incorporation of appropriate ARD control strategies throughout the project cycle from pre-feasibility to closure.

Performance evaluation and monitoring and a working ARD management plan with clearly defined operating procedures, department duties and responsibilities and key performance indicators are essential. Diligent supervision and regular technical review are necessary to ensure the ARD management plan evolves along with the ever changing mine and mineral processing plans at a site.

Designing and controlling the internal structure of waste rock dumps to minimise gas transfer and direct seepage away from problematic material is a major issue for the future of the industry when mining sulphidic materials. Constructing dumps from the bottom up in small lifts with compacted intermediate sealing layers may need to become the base case option, so that the true cost of ARD management is considered early in the project cycle. Differing these costs and relying on future mitigation actions such as covers, is likely to become less acceptable and difficult to permit.