FROM CONCEPT TO BEST PRACTICE - INNOVATIONS IN AMD PREVENTION AND MANAGEMENT

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ABSTRACT

This paper reviews a wide range of technologies to combat acidic and metalliferous drainage (AMD), spanning characterisation, prevention, mitigation and treatment.

In most cases we are now in the testing and proving phase of the burst of new approaches developed in the 1990s. Since 2000, major innovations have appeared in the field of passive treatment systems where overcoming the rate limiting step of lignocellulose degradation has paved the way for much more efficient reduction of sulfate. The advent of rapid alkalinity release agents provides for greater rates of neutralisation of acidic water in passive water treatment systems and for the development of effective alkalinity generating covers. There have been substantial advances in technical understanding of the processes needed to create sustainable pit lakes, and this knowledge is being successfully applied at an increasing number of sites.

Arguably "dry cover" technology for covering waste rock and tailings is still in the developmental phase since the modern applications of this approach have yet to be tested over decadal time scales. Experience over the past decade strongly suggests the need to build contingency into closure systems for sulfidic sites as one technology may not provide 100% of the solution. For example, it may be prudent to consider combining a cover over a waste rock dump or a tailings storage facility with a downgradient permeable reactive barrier.

Currently there are no technologies for the long term protection of sulfidic faces in pits that cannot be flooded, and no field-proven technologies for sulfidic material in levels above the final flooded level in decommissioned underground mines.

1.   INTRODUCTION

The ultimate success of an innovation in the environmental management of sulfidic mine wastes occurs when that innovation is accepted and widely implemented as best practice by industry. Broad acceptance comes about when an innovation has been proven to be technically successful at field scale, practical to implement, and cost effective for the magnitude of the potential environmental problem it is seeking to remedy.

The aim of this paper is to not only introduce a selection of newer innovations but also to revisit "older" innovations that have become, or are in the process of becoming, "best practice". Revisiting this latter category is very important because there have been substantial learnings from these applications. Today's best practice needs to evolve to accommodate the new findings which were not initially apparent when the primary innovation was first introduced to the industry. In many ways this secondary cycle of innovation can be described as continual improvement, and may be just as important as the primary innovation

in ensuring the long term sustainable application of a given technology. Current best practice becomes either tomorrow's standard performance benchmark, or worse, substandard practice.

Whilst advances in prediction methods will help to better define the nature and extent of the issue, and hence guide project feasibility assessment and waste handling programs, they will not a *priori* substantially change our ability to minimise or control AMD, once a potential problem issue is identified or has developed at an operating mine site. Ultimately the technical research community and industry practitioners should be working together to develop and implement integrated and effective avoidance, minimisation or control strategies for AMD that apply to all stages through the project life cycle. An example is the use of temporary covers or compacted layers between lifts on a waste rock dump to minimise ingress of water or oxygen through the many years that often pass between initial exposure and final rehabilitation of sulfidic material.

The issue of covers for operational and post closure management of waste will be a specific focus of this paper given the considerable importance of sustainable cover systems for the long term containment of sulfidic mine waste. Arguably the technology for covering waste rock and tailings, especially so called "dry" covers, is still in the developmental phase since the modern applications of this approach have yet to be tested over decadal time scales. Performance to date suggests that many of the installed covers will require considerably greater remedial intervention than was initially envisaged based on original theoretical modelling predictions.

Water covers, for those geographical regions in which the water balance is favourable (equatorial tropics and sub-temperate latitudes in the northern and southern hemispheres), represent a more mature and developed technology. Nevertheless, even for water covers there has been an evolution of the technology as more detailed knowledge and field experience has been gained with both the physical and geochemical issues associated with application to a range of different conditions.

Treatment of water during the operational phase of mining of sulfidic material is still often required, recognising the difficulty of ensuring an ultimate level of protection while fresh mine faces are still being exposed. However, if active treatment is needed post closure, and such treatment was not planned as part of a properly designed closure strategy, then containment and minimisation have been at the very least partially ineffective, and at the worst completely ineffective. Some recently published comparative analysis of long term costs suggests that under certain circumstances long term active treatment may in fact be cost effective and of lower risk compared with the uncertainties associated with long term performance of engineered cover options, and the need to undertake periodic repair work on such systems (Morin and Hutt 2006). This raises questions for regulators about the long term liability and ownership of mine sites.

2.   PREDICTION

2.1   Materials Characterisation

Whilst prediction is vital at an early stage in project life, and an ongoing program of testwork essential for those sites with an identified AMD risk, most of the current problems ascribed to "inadequate" prediction are arguably the result of not investing enough on it, rather than not having good enough techniques. The conclusions from a recent comparison between mine water quality predictions in EIS documents with actual operational and closure outcomes at 25 major hardrock minesites in the USA provides salutary insight into the importance of an

adequate program of geochemical characterisation at the project development stage (Maest et al. 2005). In particular, the mitigation measures proposed in the approved EISs to address predicted AMD issues were found in practice to be insufficient to meet the originally predicted water quality outcomes. This poorer than anticipated performance at many sites may be as much a result of a shortfall in the application of AMD characterisation test methods and the inadequacies of models used to extrapolate from characterisation test results to water quality impacts, as much as it represents a shortfall in performance of mitigation technologies. That is, the incorporation of sufficient mitigation measures into the operations plan is contingent on the magnitude of risk identified by the initial characterisation program.

A recent review (Maest et al. 2005) summarised the available static and kinetic test methods and made detailed comment on their limitations. Improving the reliability of the current routine suite of static test methods will be of great benefit since a much greater number of samples providing greater resolution of problematical material, especially at the operations stage, can be processed by these tests rather than by kinetic or column tests.

Much of the recent research on prediction has focussed on refining existing static test methods to accommodate the occurrence of mineral phases that can result in false results (positive or negative) being produced by NAPP and NAG test methods, and with correlating the results from these static tests with much more time consuming and costly kinetic and column leach tests (Stewart et al. 2006). The availability of effective neutralising capacity is especially important, since overestimation of available neutralising capacity has arguably been the key factor leading to underestimates of AMD risk. Two developments specifically address this issue:

(1)   modification of the Acid Neutralising Capacity (ANC) test to account for the effect of siderite; and

(2)   inclusion of acid neutralising characteristic curve measurements as part of the standard characterisation test suite, especially early on when the properties of waste lithotypes are being determined.

3.   MITIGATION – OPERATIONS AND CLOSURE

3.1   Co-Mixing of Waste Rock and Tailings

The fundamental problem with waste rock dumps is that they can contain up to 30% void space – which acts as a conduit for both water and air. If these voids were able to be filled with a fine-grained material such as tailings then it is possible that the resultant mixture could be much more resistant to oxidation and penetration of water than waste rock alone, with the tailings being contained within a more geotechnically stable bulk matrix. Laboratory and small scale field trials have indicated that this methodology may have considerable promise (Wilson et al. 2006). However, it is still very much in the developmental phase and has some way to go before being trialled at full scale.

3.2   Paste Tailings

Above grade, as distinct from mine backfill, applications of paste tailings (> 65% solids) technology has been implemented at an increasing number of sites over the past decade. This is because of its advantages in reducing the problems associated with the deposition of aqueous slurries, in particular, by reducing the geotechnical risks with containment and the difficulties of accommodating consolidation in cover design. With the use of a higher solids content paste, the typical two degree beach angle can be increased to ten degrees or more with no runoff water and minimal shrinkage crack development through desiccation. Since

the material also contains a much lower content of water when initially deposited, there is also much less seepage of interstitial fluid to occur both during operations and over the long term, during the drawdown phase of the phreatic surface that will occur following closure of the facility. In the case of in pit tailings there will be potentially less interstitial water available for transport into the groundwater flow field.

Separation of the coarse and fines fractions typically occurs along the gradient of the beaches formed in aqueous slurry tailings deposition systems, resulting in coarser material closer to the wall. Lateral sand lenses can also be produced as the discharge position is rotated around the periphery. As a result of this particle separation, preferred flow pathways for both oxygen and water are produced, thus potentially exacerbating the oxidation potential of the highest risk parts of the sulfidic tailings mass. The heterogeneity also adds considerable complexity to the application of hydrochemical modelling for assessing the likely efficacy of proposed closure options of such impoundments, making reliable prediction of long term performance much more difficult.

In contrast, paste tailings are deposited as an essentially homogeneous, non-segregating mass. The long term behaviour of such a mass is intrinsically more predictable and will facilitate more robust assessment of closure options and post closure performance. In addition, paste technology readily facilitates the incorporation of a neutralising reagent such as crushed limestone or other geochemical modifying agents with little risk of segregation during the deposition process.

Paste tailings thus offer a potentially lower risk pathway for the operational and post closure management of sulfidic tailings material. However, the extent of risk reduction will be site specific and the substantially increased capital and operating requirements of paste tailings will need to be balanced against the geochemical properties of the tailings that are being deposited.

Several studies are underway to monitor the short to intermediate term behaviour of test cells and tailings storage facilities constructed with paste tailings. However, the technology is still too young to afford a longer term assessment of its net benefit in maintaining the long term geochemical integrity of above-grade tailings post decommissioning.

3.3   Waste Segregation

3.3.1   Tailings desulfurisation

One of the issues presented by sulfidic tailings is the need to provide an infiltration and/or oxygen-limiting cover at closure – if a water cover is not an option. In many cases fine-grained material sourced from elsewhere is proposed as one of the components of such a cover system. Presuming that such material is available, this requires the opening of a borrow pit to extract often quite large volumes, and the consequent need to rehabilitate the footprint of the borrow area. Costs for sourcing of this material can be very high if substantial haulage distances are involved.

However, tailings are, by their very nature, fine-grained and may have many of the properties, apart from sulfide content, required for an effective infiltration and oxygen diffusion limiting cover layer. This realisation led to initial trialling and subsequent full scale application of desulfurisation of tailings – that is, the intentional removal of a large proportion of the sulfides (usually by froth flotation, although gravity separation may be an option in some cases) to produce a high value product that can be used for progressive containment/rehabilitation (for example, in a multi-celled TSF) during operations. Indeed a

slurry tailings system provides the ideal hydraulic method for conveying and placing such a cover layer (for example, Duckett and O'Kane 2006). Desulfurised tailings are being used for cover placement at the Inco Copper Cliff operations in Sudbury, Canada (Hanton-Fong et al. 1997), and desulfurised tailings were also being proposed to be used as the final cover layer at the former Renison Bell Mine in Australia. The application of a desulfurised tailings cover at Renison was strongly supported by detailed geochemical and reactive transport modelling (Romano et al. 2002).

Despite its technical attractions, and some examples of full-scale application, hydraulic placement of a fine-grained cover layer of desulfurised tailings is still a relatively novel approach that has yet to evolve to the status of accepted best practice in the industry.

3.4 Engineered Covers

3.4.1 "Dry" covers

The issue of whether an infiltration limiting cover alone will suffice or whether infiltration limitation needs to be combined with an oxygen-limiting layer is site specific and will depend on the sulfide content, the reactivity of the sulfides, and the extent of pre-oxidation prior to covering.

For well-oxidised waste, an infiltration-limiting cover is the primary option that would be considered. The object of an infiltration-limiting cover is to reduce the annual load of solutes exiting the dump. The extent to which this is able to be achieved depends on the balance between infiltration and the limiting solubility of oxidation products. What is certain, however, is that this strategy alone will not reduce the concentrations of solutes in seepage and is likely to considerably extend the duration of the washout period from the covered dump. However, the annual reduction in load may make the difference between being able to use a passive treatment option such as a wetland or permeable reactive barrier to manage the situation, rather than having to install an active treatment system.

In recognition of the above limitation, hybrid infiltration-limiting and alkalinity-producing cover systems have been proposed. Such an approach does not require the Maximum Potential Acidity (MPA) of the wastes to be stoichiometrically matched by the mass of alkalinity stored in the cover. The basis for this type of cover design is that water percolating through the alkaline material produces a weakly alkaline solution that generates neutralisation precipitates when it comes into contact with acid salts. While such relatively inert precipitates may occlude porosity in micropores within waste rock piles, the real benefit is provided by the progressive lining (passivation) of the surfaces of contiguous macropores. The precipitates thereby incrementally isolate reactive sulfides from the infiltrating porewater. In this way, alkalinity in the percolating water is consumed at progressively greater depths within the pile as surface passivation extends downward. Low cost limestone has been employed for this purpose in the past. However, under most rainfall environments, the rate of delivery of alkalinity is too low relative to the rate of acid generation for an appreciable improvement to be recorded over decades or even centuries. A notable exception to this has been the successful implementation of a limestone cover and a limestone- blended waste rock dump in the very high rainfall environment at the Freeport mine (Miller et al. 2003).

Recently, the concept of high alkalinity delivery covers has been proposed (Taylor et al. 2005). Such covers were devised to accommodate all climatic and geological settings, in the hope of generating improvements in the water quality discharging from either new or existing waste rock piles within a few years, rather than decades. These covers incorporate specialised alkaline materials that offer enhanced solubility and dissolution rate

characteristics. Carefully prepared caustic magnesia and a specialised form of magnesium enriched precipitated calcium carbonate are currently being tested in field trials at the Brukunga mine site near Adelaide (Figure 1). Early demonstration results look very promising. Additional work has been conducted by Solid Energy using fly-ash as the alkaline capping material (Weber et al. 2008).

Fig. 1. Setup of field test pads to evaluate high alkalinity producing cover designs at Brukunga, South Australia

At this workshop and at previous conferences, many papers have been presented on the construction of different types of covers, and the short to intermediate term performance of these systems. In this context it is especially extant that the rate of infiltration (as measured by % of Mean Annual Precipitation) has often been found to have increased by one to three orders of magnitude in a few short years after construction (Rykaart et al. 2006). One clear message that is starting to emerge is that covers should not be regarded as "in perpetuity" walk away solutions and that ongoing treatment of surface water or groundwater may need to be combined with a cover system to meet ongoing environmental discharge performance targets. To quote Rykaart et al. (2006):

"Significant effort appears to be going into the design of soil covers, and some great advances have been made in terms of numerical modelling, for example. There is a great appreciation for the complexity behind how soil covers work, and the science of understanding how these unsaturated soil systems function is well developed (at least in temperate climates). However, there appears to be a disconnect between these highly

sophisticated design philosophies and the practicality of constructing covers that are expected to perform in accordance with the design, for undetermined time periods."

Much of the falloff in performance of cover systems can be attributed to unanticipated changes in material properties and physical problems in the structure as a result of inappropriate construction methodology or poor quality control.

3.4.2   Water covers

The theoretical basis of water covers is that the rate of diffusion of oxygen through water is approximately 10,000 times slower than through air. The concept of water covers as a technically acceptable method for tailings rehabilitation originated from field observations and measurements of historic sulfidic tailings deposits in Canada that had been partly covered by sedge vegetation. This site contrasted markedly with other sites where the tailings had dried out and strongly acidic and metalliferous conditions had developed. It was deduced at this time that maintenance of saturated conditions had reduced the rate of oxidation. This observation led to an extensive laboratory and field test program between 1989 and 1996. The work was sponsored by the Canadian MEND program and the British Columbia Acid Drainage Task Force (MEND, 1997, 1998). The results from this program of work confirmed the field observations and led to the production of the first set of design principles for a water cover. At this time it was recognised that the depth of the water layer and that the potential for re-entrainment of the surface layer of tailings into the water column were important factors affecting long term performance. Subsequent testwork and field trials in impoundments resulted in recommendations for minimum depth and fetch length to minimise the effect of wave-induced entrainment.

Guidelines for the implementation of water covers were produced (MEND, 1998) and the concept was first implemented at a number of sulfidic tailings dam sites in Canada during the closure and rehabilitation of uranium mine tailings containment facilities in the Key Lakes area of Ontario (Ludgate et al. 2003).

Unfortunately, in the case of one of the impoundments, secondary geochemical reactions that followed the establishment of chemically reducing condition in the developing organic-rich bed of the biologically maturing lake resulted in the accelerated release of radium from the sediments (Martin et al. 2003). This occurred because of the microbial reduction of the sulfate (to sulfide) in the barium sulfate precipitate that had been formed as a result of the addition of $BaCl_2$ to the original tailings stream to remove the dissolved radium from the water column. The water cover worked very well to prevent oxidation of the sulfidic tailings but in this case there was a specific radiometric issue which resulted in a secondary water quality problem. It is likely that water treatment may be required for several decades until the release of radium from the surface layers of tailings reduces to environmentally acceptable levels.

The above case, and several others (Martin et al. 2003) illustrates that the possibility of longer term secondary biogeochemical processes affecting performance must be considered in the conceptual design and planning phase of a water cover system. Additional contingency measures must be included if this is identified as a significant risk factor.

Water covers have now been implemented at many locations around the world – including Australia in Tasmania (Rosebery, Henty, and proposed at Renison Bell) and in Victoria (Benambra).

A water cover was the logical choice for control of AMD from tailings at the abandoned Benambra base metal mine in Victoria, as the dam was designed from the start to be a competent water holding structure, rather than being a "simple" TSF (tailings storage facility). Hence there was an already existing appropriate margin of safety for the use of this facility to contain water over the long term, and a very costly upgrade was not required for the water cover option. When the site was rehabilitated by the Victorian Government (DPIMP) in early 2006, a minimum 2m water cover was the foundation of the rehabilitation strategy. The dam wall was raised and buttressed to strengthen it against significant earthquakes, and all sulfidic waste from across the site was disposed of in the dam (Figure 2). Full details of the successful rehabilitation program and preliminary results are provided by Oxley et al. (2008).

While water covers can be a relatively uncomplicated and cost effective solution for tailings dams (engineered water containing structures), the vast majority of tailings impoundments are constructed as solids storage facilities (TSF) that do not provide for sustained water holding capacity. Water covers over such structures can be engineered, but require considerably more effort, expense and possibly maintenance than conventional dams. A hybrid cover system – a central permanent pond with a peripheral annulus of "dry" cover – may be an option to ensure that the phreatic surface is kept sufficiently low in proximity to the dam wall. The Henty cover system is an example of this. It is critical that future TSF design take account of the need to sustainably optimise saturation of the tailings mass, such that geochemical integrity can be maintained over the long term.

Fig. 2.   Work in progress to implement a water cover for the Benambra (Victoria) tailings dam

There is one instance in Indonesia (the Rio Tinto Kelian Mine) where the water cover concept has been extended to waste rock, in addition to tailings, as part of the site closure

process (McGuire 2003). This approach involving a waste rock dam is a world first. In this instance a very large water-retaining dam wall was constructed. Sulfidic waste rock was placed behind it, with the placed rock to be permanently flooded at closure. As of November 2007 the level of water in the impoundment had risen above the final level of the covered waste rock and a continuous water cover established. Ongoing monitoring of this system is in place to confirm that it meets water quality closure objectives.

Water covers have clearly become established as industry best practice for primarily unoxidised tailings material when the geochemistry, climate, catchment and net water balance permit. Water covers are not recommended for sulfidic waste (tailings or waste rock) that has appreciably oxidised and contains a large load of readily soluble oxidation products. For oxidised material an infiltration limiting cover would be a more suitable option.

4.   FINAL VOIDS

4.1   Protection of Exposed Wall Rocks

Maintenance of water quality in final voids is a critical issue for those cases where closure water quality objectives mandate some form of biological compatibility – for example wildlife or stock watering, human drinking quality or aquaculture. One of the keys to good initial water quality is the protection of in-pit sulfidic material – exposed wall rocks, in-pit waste rock or tailings - from oxidation prior to the covering of this material with water. In-pit tails or waste rock can be covered with an interim protective layer – in much the same way as a cover is designed for above grade waste rock or tailings. However wall rocks are a more difficult matter and a lengthy time of contact with air and water may occur from initial exposure as the open pit develops through to final covering of the exposed sulfidic wall rocks with water. As a consequence, considerable effort has been devoted to the development and testing of mixtures of chemical components designed to protect walls from oxidation. This technology is analogous to the use of passivating chemicals for the intermediate term protection (source control) of waste rock, and most of the proposed methodologies had their origin in laboratory and field studies to develop chemical coating layers to passivate sulfides in waste rock (see Olson et al. 2006; Moncrieff 2006).

Four candidate technologies, of quite different chemical types, were subjected to side-by-side comparative field scale (16mx16m panels) testing by the USEPA's National Risk Management Research laboratory between 2000 and 2003 (U.S. Environmental Protection Agency, 2005). The technologies tested were:

- a phosphate and metal complexing-based product;
- a magnesium oxide passivation technology;
- a potassium permanganate technology; and
- a furfuryl alcohol resin sealant (FARS).

The demonstration was conducted at Golden Sunlight Mines, Inc. (GSM) an active open-pit gold mine located near Whitehall, Montana. The four technology providers spray applied their materials, which were in a liquid form, to a designated 16m-high by 16m-wide area on the highwall. Each of the technologies aimed to create an inert layer or coating on the sulfidic material, reducing contact with the atmospheric oxygen/water

The primary objective of this demonstration was to determine the impact of the treatments on the designated plot areas compared to the untreated area of the highwall. To achieve this objective, the highwall at the project site was geologically, hydraulically, and geochemically

characterized prior to technology application. The core extracted from the highwall was rubble for approximately the first one metre and contained numerous fractures to approximately three metres from the drill face. It could thus be assumed that the sulfide minerals between 0 and 3 metres into the highwall were being exposed to water and air and thus able to produce AMD. To evaluate and determine if the protection objectives had been achieved, two test procedures were used - humidity cell (HC) testing of wall rock samples in the laboratory, and a field mine wall sampling method.

Physical stabilisation of the highwall in the field was only observed for the FARS technology plot. The other three technologies provided chemical passivation of the wall but not physical stabilisation. Physical stabilisation is actually an important attribute for a high wall treatment because the intrinsic physical instability of highwall environments means that stress fracturing of the wall can destroy the initial continuity and integrity of the applied protective layer.

Each mine wall station was evaluated to determine the percent reduction in the cumulative metal loading per unit area in the rinsates over the monitoring period relative to the untreated control/background area. The concentration of each metal in the rinsates was converted to a mass loading per unit area based on the volume of the rinsate and the surface area of the mine wall station. A cumulative mass of each metal for each mine wall station was calculated over the duration of the test period. Percent reduction was based on the difference between the average mass per unit area of each metal generated from treated areas relative to the mass per unit area of metal from the untreated control station.

The results from the highwall residual wash sampling indicate that in the field the technologies did not perform as well as the samples analysed in the laboratory in a controlled environment. The FARS technology was the best performing, reducing the soluble loads of all of the metals on the wall by at least 75% and, in some cases, up to 91% compared to the untreated plot. The FARS not only reduced the total metals leaching from the highwall, but it physically stabilized the fractured wall rock, an additional important attribute.

It was concluded that additional larger scale and longer term field testing will be required before pit wall coating technologies can be recommended as being an effective control technology over the longer term.

4.2   Final Void Water Quality

4.2.1   Open pits

The rapid filling of mine pit lakes has been advocated for some time to minimise the potential for occurrence of acid conditions via the oxidation of wall rocks, or of sulfidic waste rock or tailings deposited in the base of the pit. However, the long term prognosis for these pits may still not be good, particularly if the sustainable maintenance of water consistent with aquatic ecosystem protection or drinking water quality guidelines is the closure objective. Whilst there are very good computer models (e.g. DYRESM) that can predict the physical limnology (e.g. establishment of thermocline; potential for overturn) of pit lakes, being able to reliably predict (using biogeochemical computer codes) the outcome of the interaction between physical, geochemical and biological processes in evolving pit lakes is still the subject of much active research.

Pine Creek in the Northern Territory is the location of the first large open pit (the Enterprise Pit) in Australia to be rapidly flooded, via a creek diversion, to minimise generation of acid

water following decommissioning (Jones et al. 1997). The floodway cutting through to Pine Creek was completed in December 1993, and flooding commenced in the 1993/1994 wet season. The pit was fully filled by the middle of the 1994/1995 wet season. The Enterprise pit waterbody is 850m long, 200-300m wide, and 100-130m deep, and is typical of the open pits produced at many hard rock metal mines (Figure 3). The walls of the pit contained some areas of exposed sulfidic material. The pit is connected at one end to Pine Creek during the wet season, and is partially flushed each year. This annual flushing is an integral component of the water quality management strategy. A water quality profile monitoring program has been in place since the start of the flooding operation in the 1994 wet season. Consequently, the evolution of the chemical status of this water body has been reasonably well documented. Water quality still meets criteria for irrigation and stock watering after 14y.

Fig. 3. Pine Creek Minesite in August 2000, showing completed rehabilitation works. Note the proximity of the flooded Enterprise Pit to the township of Pine Creek

Water quality problems are more likely to occur if there is little available neutralising capacity in the wall rocks, too little alkalinity in the water column, or inputs of acidic and metalliferous water from rehabilitated waste rock dumps lying within the catchment of the pit. Of course the pit lake can be limed to initially trim its pH, but this is unlikely to be a walk-away solution, and it could be very expensive if repeated dosing is required. One of the problems is that a newly created lake system is typically bereft of sufficient nutrients and organic matter to kick start the development of a level of biological productivity that would be expected in a natural lake of similar dimensions. Accordingly, the field of limnological biomanipulation of pit lakes has been an active area of research over the past decade.

Whilst most research on pit lakes has been focussed on restoring already acidic systems, there is also the need for research to be directed towards the more subtle manipulation that will be needed to address an initially pH neutral lake with low levels of buffering capacity in the water column. The initiation of biological productivity in this type of system has three purposes- (a) to provide a carbon source to drive sulfate reduction in the hypolimnion, (b) to provide a concentration of phytoplankton in the water that is sufficiently high to absorb and remove from solution low concentrations of trace metals, and (c) to increase the pH of the water column by the process of photosynthesis.

Despite the considerable promise that has been shown by field scale work to date, there remains much more to be done to develop a technical understanding sufficient such that for a given pit lake the proposed methodology can be relied upon for the long term maintenance of water quality. There have been several recent examples where attempts to created stably stratified systems with anoxic hypolimnions of appropriate composition have not worked as was initially anticipated (Fisher and Lawrence 2006; Park et al. 2006), necessitating subsequent remedial action. In particular there have been issues of production of excess hydrogen sulfide gas in anoxic hypolimnions created by either the addition of organic matter (for example, Island Copper in British Columbia) or the stimulation of biological productivity by the addition of nutrients. This problem can occur for those systems where there is an excess of soluble sulfate relative to dissolved metals (Fe, Cu, Zn) available for precipitation as metal sulfides, and hence excess H_2S gas can be generated. Since the oxidation of pyrite commonly involves the early physical separation of iron from the drainage by precipitation of ferric hydroxide, it is not uncommon to have a significant stoichiometric excess of sulfate relative to iron in AMD.

4.2.2 Underground mine voids

For underground mines, there are currently no effective demonstrated methods to minimise or control AMD from higher levels post closure once the void has flooded to the topographically lowest portal or shaft. There are many examples in Australia and overseas where flooded abandoned mines located in regions of steep topography continue to produce ARD since the higher levels cannot be flooded. The GaRDS technology was developed to address this issue. GaRDS stands for Gas Redox and Displacement System, and involves the displacement of air from underground workings with a bacterially generated gas mixture consisting of carbon dioxide and methane (see Taylor et al. this volume). This technology is still awaiting a definitive field trial to evaluate its potential.

5. WATER TREATMENT

5.1 Active Treatment

5.1.1 Lime-based processes

The addition of lime, with sludge recycle (Figure 4), remains the clear treatment choice for large scale active water treatment to reduce acidity and metal concentrations, despite the number of other technologies that have been developed and tested at pilot scale over the past decade. This predominance is likely to remain so for the indefinite future. The reason for this is robustness of the technology, ease of implementation, and the non-proprietary and relatively low cost of calcium-based reagents (Taylor et al. 2005).

Variants on the process, involving staged addition of lime, have been used to selectively remove particularly problematical components (eg arsenic) at pH values lower than where metal hydroxides precipitate, thereby reducing the volume of As-containing sludge that is

produced (U.S. Environmental Protection Agency 2005). This approach substantially reduced the volume of sludge needing to be placed in a hazardous waste containment facility, thus markedly reducing the overall cost of the water treatment..

Fig. 4. High density sludge lime neutralisation plant at Brukunga (South Australia)

5.1.2 Sulfate reduction

Many papers have been published on laboratory and pilot scale processes that involve the microbial reduction of sulfate to sulfide. Concerns about the energy requirements (supply of organic carbon or hydrogen), toxicity of hydrogen sulfide and problems with effectively separating out the fine-grained metal sulfide precipitates have to date limited industry application of this approach. One additional issue to consider is that although the metal sulfide precipitates produced by such processes can be attributed a notional economic value, the value may be considerably less than based on content of individual metals. The reason for this is that there is often a financial penalty incurred at smelters for mixed metal sulfides, especially those contaminated with As, Cd or Sb. The net economic viability of a proposed sulfate-reduction treatment process incorporating metal recovery very much depends on the site specific composition of the water. Pilot trials should address the inevitable annual variability in composition of waters to be treated.

A more recent variant on the use of biogenically-produced hydrogen sulfide for treatment of metal-containing water uses elemental sulfur as the starting point in a stand-alone hydrogen sulfide generator (Bratty et al. 2006). The amount of electron donor (e.g. acetic acid or

sucrose) required to reduce sulfur to sulfide is only one-quarter of that required to reduce sulfate, hence considerably reducing operating costs. At least five commercial scale plants using this technology have been commissioned in the USA and Canada.

Sulfate in mine water is receiving increasing attention worldwide as a major contaminant of concern. There are two reasons for this – firstly as a contribution to salinity impacts from mines, and secondly as a modifier of freshwater sediment environments as a result of microbial reduction of sulfate to hydrogen sulfide in the porewater of sediments containing organic carbon. Single step removal of sulfate using reverse osmosis (RO) is usually not possible since many mine waters also contain substantial concentrations of calcium. Precipitation of gypsum on membranes is fatal to this type of treatment system. Recent developments in RO membrane technology claim to have substantially reduced problems with gypsum fouling, but this technology is yet to be demonstrated at full scale in the mining industry.

The conversion of sulfate to elemental sulfur has been implemented at full scale at a number of sites. This is quite an expensive technology that uses methanol, ethanol, or sucrose as the carbon source for the sulfate-reducing bacteria (SRB). Commercial systems such as THIOPAQ®, developed and marketed by Paques (www.paques.nl), a Netherlands-based corporation and those developed by BioteQ, a Canadian company are employed strategically at sites with chemically favourable AMD. These engineered SRB plants can produce product water containing <300 mg L^{-1} sulfate and also remove to very low levels metals that form insoluble sulfides (Cu, Cd, Ni, Pb as well as As, Se and Mo). The technology has been operated at full scale since the mid-1990's and several plants have been built. Some of these plants are now economically viable businesses based on metal recovery from AMD streams alone.

5.2 Passive Treatment

5.2.1 Sulfate reduction

The most substantive recent advances in passive treatment technologies have come from obtaining a much better understanding of the process of bacterial sulfate reduction, and the dependence of this process on supplied organic carbon. Reduction of sulfate generates both sulfide (to precipitate metals) and alkalinity (to neutralise acidity).

In particular, the alkalinity contributed by sulfate reduction can extend the lifetime of limestone that is typically added to passive acid mine water treatment systems. Prior to work conducted over the past decade key issues such as predicting carbon substrate longevity, frequency of replacement of substrate and assessing probability of treatment failure were hampering the application of passive treatment for acidic mine water - from both technical and economic perspectives.

Researchers in Europe and South Africa have shown that the key step limiting treatment efficiency is the rate at which cellulose can be converted to low molecular weight compounds such as acetate that can be directly used by iron and sulfate reducing bacteria.

Considerable research in South Africa has been carried out to develop a passive treatment process using plant biomass as a carbon source (Pulles et al. 2003). The final product of this process is elemental sulfur (Figure 5). Despite initially very promising indications for this technology, further testing appears to have not resolved the issue of incomplete conversion of sulfide to sulfur, and the resulting hazard posed by hydrogen sulfide. Notwithstanding this problem in the second stage, the major breakthrough that was made in accelerating

lignocellulose degradation in the first stage of the process - to release much of the previously unavailable carbon to sustain high rates of bacterial sulfate reduction – provides a very promising route for much more efficient and higher rate passive treatment of minewater.
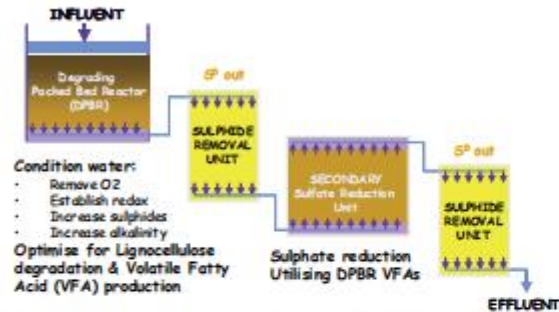

Fig. 5.   Schematic flow sheet for South African IMPI® passive sulfate reduction technology (courtesy of Pulles Howard and Delange Inc)

5.2.2   Anoxic limestone drains

Anoxic limestone drains were originally developed as a passive treatment methodology for relatively low grade acidic drainage in the Pennsylvanian coalfields in the United States. Unfortunately, this superficially attractive technology has in many cases been applied in situations where it is not applicable – and there have been many failures. – as a result of hydraulic plugging by aluminium and ferric hydroxide precipitates. In those cases where this technology is applicable (dissolved oxygen < 1mg L^{-1}; ferric iron <1mg L^{-1}; aluminium < 1mg L^{-1}) it works well (Skousen and Ziemkiewicz 2005), but these situations are limited in occurrence, especially in the Australian context. In addition, practical limitations on the scale of such systems generally places an upper daily acidity load limit of close to 150 kg of $CaCO_3$ acidity.

5.2.3   Passive alkalinity delivery systems

The life expectancy of most passive treatment systems is more a function of the rate of surface passivation of reagents than complete reagent consumption. This observation means that the pore space available to accommodate neutralisation precipitates can be equally as important as the mass of reagent in passive treatment systems, in terms of determining their longevity. The simple way to overcome this commonly debilitating issue is to prevent interaction between acid and metalliferous water and the neutralising reagent. This can only be achieved in situations where unpolluted water can pass through alkaline materials and transport dissolved alkalinity into the AMD affected water.

This technique is only used infrequently as its efficacy is limited by the low solubility and slow dissolution rate of natural carbonate minerals in near neutral water. With the development of compounds that have been prepared for rapid alkalinity release (for use in alkalinity producing covers; Taylor et al. 2005), there are now opportunities to deploy such materials in passive treatment systems that utilise interaction with unpolluted water. Clean water that is in contact with specially prepared caustic magnesia samples have generated alkalinity values of up to 200-300 mg L^{-1} $CaCO_3$ within minutes. Simple engineered systems can be envisaged that utilise these compounds to passively deliver substantial alkalinity to AMD affected waters. Saturation pH values of 9-10 can be expected with these compounds.

5.4   Permeable Reactive Barriers for Groundwater Treatment

Given the difficulties associated with the traditional pump and treat approach – especially for the case of low yielding fractured rock aquifers - a new generation of *in situ* treatment methods have been developed. The treatment process may involve abiotic and biological processes acting individually or in synergistic combination. These systems are termed "permeable reactive barriers" by virtue of the fact that the groundwater is treated as it passes through the reactive zone. These systems are "barriers" to the target solutes and not to the flow of water. PRBs are subject to similar limitations as passive treatment systems for surface water. That is, they are best suited to relatively low load but long duration applications – for example downgradient interception of a broadly dispersed plume.

Many papers and reviews on PRB technologies have been produced (for example, Vidic 2001, Wright and Conca 2006). In summary, this class of technologies comprises:

(a)   barriers in which sulfate is reduced to sulfide and metals are precipitated as insoluble sulfides. Because the barrier is located below the groundwater table there is minimal risk of future re-oxidation of the precipitated metal sulfides. This type of barrier may need to be supplemented with additional neutralising capacity (e.g. lime or limestone) depending on the total acid load;

(b)   barriers in which metals are precipitated as insoluble forms (for example the use of crushed apatite to precipitate metal phosphates);

(c)   barriers in which inorganic (e.g. Cr (VI), Se (IV), U(VI)) ions are reduced to insoluble forms; and

(d)   barriers in which nitrate and organic compounds are degraded by microbial or inorganic (e.g. reduction by metallic iron) processes.

In general, zerovalent iron (scrap iron or iron filings) appears to be the most versatile and broadly effective of the inorganic materials that can be used in the reactive barrier, provided that the pH is not acidic. The reason for this is that chemical reduction is a major process driving the detoxification of many metals and organic compounds. In particular, arsenic has been shown to be very efficiently removed by zerovalent Fe to less than 5 μg L^{-1} from starting levels of 10mg L^{-1} (Bain et al. 2003). In the case of an acidic plume a neutralant (limestone alone or in combination with organic matter to drive sulfate reduction) would need to be added in combination with the iron.

Over the past decade permeable reactive barrier technology has evolved from pilot scale tests to mature full scale applications in many locations. PRBs have been applied to plumes originating from both waste rock dumps and tailings dams.

A variation on the PRB concept that has been investigated with encouraging results at the laboratory and pilot field scale, is the incorporation of organic matter with tailings as the near final layers are being deposited (Hulshof et al. 2006). The objective of this approach is to

promote sulfate reduction and generate alkalinity at source, thus minimising the generation of a metal-rich plume that will be progressively elutriated through the tailings mass and ultimately impact groundwater beneath the tailings dam. This is an example of a possible prevention measure for the dose out of a sulfidic tailings dam.

A PRB could potentially be implemented as a contingency measure, or as a final polishing treatment, for seepage from a landform that has been capped by an engineered cover system. This scenario especially applies to waste that has undergone a substantial degree of oxidation before being capped. In this situation it is inevitable that some seepage containing elevated metal concentrations will find its way to the groundwater, especially during above average wet seasons. However, given the observation that the performance of cover systems often deteriorates from initial expectations, installation of a downgradient PRB may potentially be a lower cost investment than having to carry out post construction remedial works on a covered landform. Limited available data suggests that many PRBs are dealing with acidity loads of no more than 100 tonnes CaCO₃ per year, and generally a lot less.

6. EDUCATION AND TECHNOLOGY TRANSFER

Discussion of technology innovation and implementation would not be complete without reference to manuals and guidebooks that are produced to both educate and assist with the uptake of new best practice technologies. These materials bridge the more technical content provided by fora such as this conference and practitioners on the ground. It has been the authors' experience that they are of especial value to small to intermediate size mining companies, which do not have the benefit of dedicated technical services personnel. Ideally the case studies presented in such materials should provide balanced coverage of both successful and not-so-successful applications of technologies, so that the learning from past implementations can be clearly communicated through the breadth of the industry.

Most of the major recent national and international publications are listed on the ACMER website: http://www.acmer.uq.edu.au/publications/industry.html. Some of these are available for immediate download whilst web-links are provided for the locations of the rest.

In recent years in Australia the following freely available publications have been produced:

(1) TEAM NT; Technologies for the Environmental Advancement of mining in the Northern Territory – Toolkit (2004). This publication arose out of a Northern Territory Minerals Council Inc project funded by AusIndustry and managed by the Northern Territory Government. Topics covered include toxicology of arsenic, cover systems, water treatment technologies for surface and groundwater and the benefits of adequate risk assessment and planning. This publication contains practical information of relevance for mining executives, mining engineers and environment staff.
http://www.acmer.uq.edu.au/publications/attachments/TEAMNTToolkit.pdf

(2) Managing Acid and Metalliferous Drainage (2007) Handbook
This publication represents a substantial updating of the Managing Sulfidic Mine Wastes and Acid Drainage handbook produced by Environment Australia in the mid-1990's as one of the volumes in the Best Practice Environment Management series. The new handbook is part of the Leading Practice Sustainable Development series currently being produced by the Commonwealth Department of Resources Energy and Tourism. It should be used in conjunction with the other volumes in the new series that address mine rehabilitation, mine closure and completion, tailings management and mine water management. In common with the earlier series, produced by Environment Australia, these new booklets are being

translated into many overseas languages and provide an especially valuable resource for mining companies with overseas operations.
http://www.ret.gov.au/Section/ResourcesandEnergy/Pages/LeadingPracticeSustainableDevelopmentProgramfortheMiningIndustry.aspx

On the international scene, INAP (International Network for Acid Prevention) is currently managing production of the Global Acid Rock Drainage (GARD) Guide. This will contain detailed descriptions of the current state of the art in prediction, prevention and mitigation technologies accompanied by case studies from around the world. The GARD Guide will represent the most comprehensive compilation of AMD-related material to date.

7. CONCLUSIONS

A wide range of technologies to combat AMD have been covered in this paper. In most cases we are now in the testing and proving phase of the burst of new approaches developed in the 1990s. What we have seen is the implementation of such approaches as new best practice, only to discover that not all the issues that needed to be addressed had been accounted for. It has been identified that some of these technologies require another phase of evolutionary development. For example, our theoretical understanding and ability to numerically simulate the performance of cover systems has been tempered by the realities posed by changes in material properties over the longer term, by the need to pay much greater attention to construction quality control and methods of construction, and by the impacts of biology. The interplay between biogeochemical and physical processes has also posed challenges for the attainment of required water quality in pit lakes, and for the sustainability of wet covers.

It is important that new approaches continue to be tested and, in particular, that those approaches which don't yield the required outcomes be rapidly communicated to the rest of the industry. It can become apparent very quickly if a water treatment process is not performing, but it can take years or decades for performance problems to be detected for a cover system in a semi-arid area. – especially if there is insufficient monitoring in place.

What is being flagged by experience over the past decade is the need to build a degree of contingency into closure systems for sulfidic sites, and accept that one technology may not provide 100% of the solution over periods of decades. For example, it may be prudent to consider combining a cover over a waste rock dump or a tailings storage facility with a downgradient permeable reactive barrier.

Since 2000, major innovations have appeared in the field of passive treatment systems where overcoming the rate limiting step of lignocellulose degradation has paved the way for much more efficient reduction of sulfate. The advent of rapid alkalinity release agents has opened the way for greater rates of neutralisation of acidic water in passive water treatment systems and for the development of effective alkalinity generating covers.

Currently there are no technologies for the long-term protection of sulfidic faces in pits that cannot be flooded, and no field-proven technologies for sulfidic material in levels above the final flooded level underground mines.

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