Australian Government
Department of Industry
Tourism and Resources

MANAGING ACID AND METALLIFEROUS DRAINAGE

LEADING PRACTICE SUSTAINABLE
DEVELOPMENT PROGRAM FOR
THE MINING INDUSTRY

SOCIAL
ECONOMIC
ENVIRONMENTAL

MANAGING ACID AND METALLIFEROUS DRAINAGE

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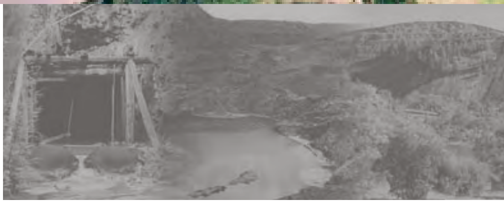

FEBRUARY 2007

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Leading Practice Sustainable Development Program for the Mining Industry

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Cover images:
Acid and Metalliferous Drainage from underground mine workings, western Tasmania
Pit water affected by Acid and Metalliferous Drainage at the Mt Morgan mine site, Queensland
Aerial view of Brukunga Mine, South Australia
All photos courtesy of Earth Systems

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FOREWORD

The Australian mining industry is well aligned to the global pursuit of sustainable development. A commitment to leading practice sustainable development is critical for a mining company to gain and maintain its "social licence to operate" in the community.

The handbooks in the *Leading Practice Sustainable Development Program for the Mining Industry* series integrate environmental, economic and social aspects through all phases of mineral production from exploration through construction, operation and mine-site closure. The concept of leading practice is simply the best way of doing things for a given site. As new challenges emerge and new solutions are developed, or better solutions are devised for existing issues, it is important that leading practice be flexible and innovative in developing solutions that match site-specific requirements. Although there are underpinning principles, leading practice is as much about approach and attitude as it is about a fixed set of practices or a particular technology. Leading practice also involves the concept of 'adaptive management', a process of constant review and 'learning by doing' through applying the best of scientific principles.

The International Council on Mining and Metals (ICMM) definition of sustainable development for the mining and metals sector means that investments should be: technically appropriate; environmentally sound; financially profitable; and socially responsible. *Enduring Value*, the Australian Minerals Industry Framework for Sustainable Development, provides guidance for operational level implementation of the ICMM Principles and elements by the Australian mining industry.

A range of organisations have been represented on the Steering Committee and Working Groups, indicative of the diversity of interest in mining industry leading practice. These organisations include the Department of Industry, Tourism and Resources, the Department of the Environment and Heritage, the Department of Industry and Resources (WA), the Department of Natural Resources and Mines (Qld), the Department of Primary Industries (Victoria), the Minerals Council of Australia, the Australian Centre for Minerals Extension and Research and representatives from mining companies, the technical research sector, mining, environmental and social consultants, and non-government organisations. These groups worked together to collect and present information on a variety of topics that illustrate and explain leading practice sustainable development in Australia's mining industry.

The resulting publications are designed to assist all sectors of the mining industry to reduce the negative impacts of minerals production on the community and the environment by following the principles of leading practice sustainable development. They are an investment in the sustainability of a very important sector of our economy and the protection of our natural heritage.

The Hon Ian Macfarlane MP
Minister for Industry, Tourism and Resources

1.0 INTRODUCTION

KEY MESSAGES

- Any activity that exposes common sulfide minerals to air has the potential to generate long-lived water pollution issues.
- AMD risk should be fully evaluated prior to mining. Effort should be focussed on prevention or minimisation, rather than control or treatment.
- Leading practice in this area is evolving - there are no universal solutions to AMD problems and specialist expertise is often required.

This handbook addresses the theme of Acid and Metalliferous Drainage (AMD), which is one theme in the Leading Practice Sustainable Development Program. The program aims to identify the key issues affecting sustainable development in the mining industry and to provide information and case studies that identify a more sustainable approach for the industry.

Managing Acid and Metalliferous Drainage to minimise risks to human and environmental health represents one of the key challenges facing the mining industry. Acid and Metalliferous Drainage affects most sectors of the mining industry, including coal, precious metals, base metals, uranium and industrial minerals. Any type of mining, quarrying or excavation operation that affects common sulfide minerals such as pyrite has the potential to generate long-lived water pollution issues. Over the last 30 or 40 years, as mining operations have evolved from low tonnage underground operations to large-tonnage open cut operations, the mass of sulfidic material with the potential to create Acid and Metalliferous Drainage has increased exponentially.

As Acid and Metalliferous Drainage enters waterways, mixtures that may contain sulfuric acid, high concentrations of toxic metals and low oxygen concentrations can present a major risk to aquatic life, riparian vegetation and water resource use for many kilometres downstream. Local communities depend on waterways for their livelihood. Clean water is essential for drinking, crop irrigation and stock watering, and is vital to sustain aquatic life. In the past, mining activities that damaged ecosystems and impacted heavily on communities were largely condoned. Today, poor practice cannot be tolerated if mining is to be sustainable. Successful management of Acid and Metalliferous Drainage is vital to ensuring that mining activities meet increasingly stringent environmental regulations and community expectations and that the industry's reputation is maintained.

Once a mining operation has ceased, poor water quality in the form of Acid and Metalliferous Drainage may continue to impact on the environment, human health and livelihood for decades or even centuries. A well known mine site in the Iberian Pyrite Belt in Spain, for example, has been generating Acid and Metalliferous Drainage for more than 2000 years.

The crucial step in leading practice management of Acid and Metalliferous Drainage is to assess the risk as early as possible. 'Risk' includes environmental, human health, commercial and reputation risks. Progressive evaluation of Acid and Metalliferous Drainage risk, commencing during the exploration phase and continuing throughout mine planning, provides the data necessary to quantify potential impacts and management costs prior to significant disturbance of sulfidic material. There have been instances recently where reputable mining companies have concluded during the planning phase that the risk of Acid and Metalliferous Drainage and associated management costs render a project unviable. When projects proceed at sites where Acid and Metalliferous Drainage is a potential risk, efforts should focus on prevention or minimisation, rather than control or treatment.

At decommissioned and older operating mine sites where Acid and Metalliferous Drainage characterisation and management has been poor, high remediation and treatment costs continue to impact on the profitability of mining companies. The term 'treatment in perpetuity' has entered the mining vernacular as a result of intractable Acid and Metalliferous Drainage issues that prevent the relinquishment of mining leases, despite the closure of mining operations. Such situations are inconsistent with sustainable mining and must be avoided.

Leading practice management of Acid and Metalliferous Drainage continues to develop—there is no universal, or 'one-size-fits-all', solution to the problem. This handbook outlines current leading practices for Acid and Metalliferous Drainage management from a risk management perspective and presents a number of case studies highlighting strategies that are currently being implemented by the industry. The success of these strategies will depend on long-term evaluation and monitoring as, in many cases, there has been insufficient time to fully assess their performance.

This handbook covers all phases of a mining project, from exploration and feasibility through to operations and closure. It is applicable to prospects, operating and decommissioned mines and legacy sites. It is a resource for mine planners and mine managers, but will also be relevant to environmental staff, consultants, government authorities and regulators, non-government organisations, interested community groups and students.

It is worth noting that Acid and Metalliferous Drainage can also result from the disturbance of acid sulfate soils, which occur naturally in geologically recent estuarine and mangrove swamp environments, or even at some construction/tunnelling sites. Acid and Metalliferous Drainage generation and management in these environments is similar to mine sites. See Dobos (2006) for further guidance.

Specialist expertise may be required to implement certain aspects of this handbook. It is particularly important that expert advice is sought during the identification and prediction process (Section 5) and prior to the selection of long-term minimisation and control strategies (Section 7).

1.1 Sustainable Development

Based on the widely accepted Brundtland Commission definition, sustainable development is 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. In recent years, this definition has been applied to the mining sector by government, community and non-government groups as well as by the mining industry itself.

To provide a framework for articulating and implementing the mining industry's commitment to sustainable development, the Minerals Council of Australia has developed *Enduring Value—the Australian Minerals Industry Framework for Sustainable Development*. Enduring Value is specifically aimed at supporting companies to go beyond regulatory compliance and to maintain and enhance their social licence to operate. Enduring Value's risk-based continual improvement approach is reflected in this handbook.

1.1.1 Environment and community

Stakeholders and communities place different emphasis on the social, environmental and economic aspects of sustainability. Indigenous communities, for example, may emphasise cultural and social issues. Some communities will evaluate the performance of engineered rehabilitation measures for Acid and Metalliferous Drainage over several decades, while others will demand 'in perpetuity' solutions. Consequently, the size of bonds or financial sureties for these mining projects can be significant.

When considering the environmental implications of AMD and other mine-related impacts, a common principle used by communities and non-government organisations is the 'Precautionary Principle'. This principle states that where scientific evidence is uncertain, decision-makers should take action to limit continued environmental damage and should err on the side of caution when evaluating proposals that have the potential to seriously or irreversibly impact the environment. Given the challenges and scientific uncertainties encountered in the management of Acid and Metalliferous Drainage, application of the Precautionary Principle is vital.

Communities expect that all decisions concerning the management of Acid and Metalliferous Drainage will be based on more than just economic costs. While decisions need to be informed by thorough technical investigations and insights, strategies adopted must include local community aspirations and values and incorporate 'whole-of-mine-life' planning into day-to-day operations. All decisions on Acid and Metalliferous Drainage management must therefore integrate social, economic and environmental aspects to achieve a strong sustainability outcome for all concerned.

Section 9 of this handbook provides more detail on reporting to communities and stakeholders. Readers are invited to refer to the *Community Engagement and Development Handbook* and the *Working with Indigenous Communities Handbook* in this series.

1.1.2 Business

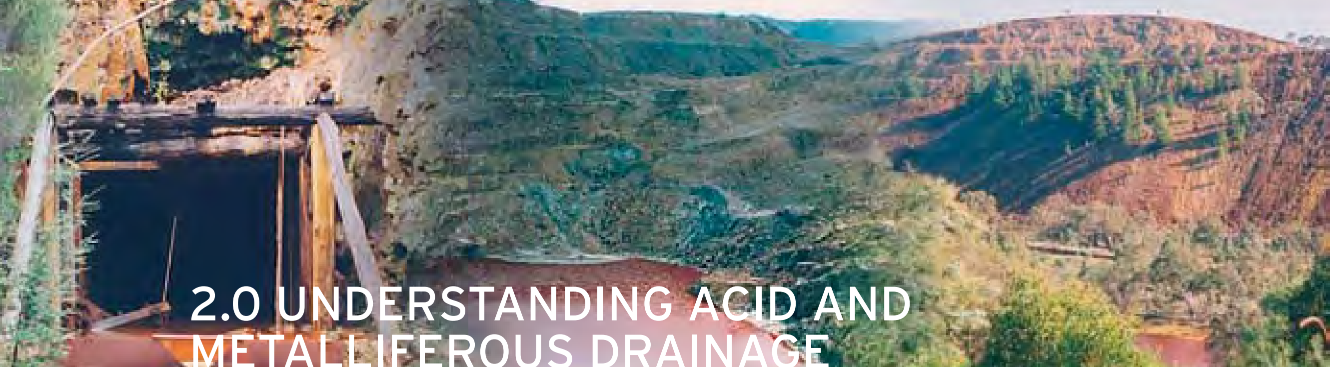
At present, leading practice AMD risk management is not understood or practised widely, despite many examples of excellence that exist throughout the industry.

The Enduring Value framework provides mining companies with a vision for sustainable development as well as guidance on practical implementation. Leading practice companies also have targeted policies and procedures relevant to managing AMD in place that are binding on management, employees and contractors. Additional commitment to environmental certification, participation in initiatives such as the International Network for Acid Prevention (INAP), the Mine Environmental Neutral Drainage (MEND) program and Acid Drainage Technology Initiative (ADTI), as well as regular involvement of AMD experts in operational decision-making, all lead to improved business performance that can exceed regulatory requirements.

There is ample evidence of the consequences of failing to predict and manage Acid and Metalliferous Drainage for individual operations and the mining industry as a whole. These consequences can include significant unplanned spending on remedial measures, damage to reputation and the introduction of more stringent regulatory requirements. Unplanned cost escalations have frequently ranged between $50–100 million where operations have had to implement an AMD management strategy during the closure phase.

Newmont's estimated closure liability is in the order of several hundred million dollars globally (Dowd 2005). A large proportion of this relates to the prevention of Acid and Metalliferous Drainage from tailings storage facilities, waste rock piles, exposed pit walls and other disturbances. Newmont Australia's estimated closure costs for sites in which it maintains a financial interest is around US$150 million, of which greater than 65 per cent is for waste management (Dowd 2005). Further examples of the cost of managing short and long-term affects of AMD are provided in MEND (1995), USEPA (1997) and Wilson et al. (2003). While the cost of AMD management during operations can be significant, it is often small in comparison with the long-term costs that would otherwise be incurred.

The risks presented by inadequate Acid and Metalliferous Drainage management can be significant. Aside from the large scale and cost of remediation and clean-up when things go wrong, inadequate management creates the perception that the industry is reactive and unable to avoid harmful impacts by design. Neither stance fits well with the industry's aim of making a strong contribution to sustainable development and earning and maintaining its social licence to operate.



2.0 UNDERSTANDING ACID AND METALLIFEROUS DRAINAGE

KEY MESSAGES

- The acronym ‘AMD’ is defined here as Acid and Metalliferous Drainage.
- AMD can be identified visually and characterised chemically.
- AMD sources include waste rock piles, ore stockpiles, tailings storage facilities and tailings dams, open cuts, underground mines and heap and dump leach piles.
- Acidity load is the principle measure of potential AMD impact at a mine site. It is dependent on acid (pH), mineral acidity (metal concentrations) and flow rates.

2.1 Types of AMD

Acid and Metalliferous Drainage (AMD) has traditionally been referred to as 'acid mine drainage' or 'acid rock drainage'. In this handbook the term AMD recognises that not all problematic drainage related to the oxidation of sulfides is acidic (see below). At some sites, near-neutral but metalliferous drainage can be just as difficult to manage as acid water. There are sites where acid generation has been adequately neutralised by natural mineral assemblages, effectively stripping the water of toxic metals, but leaving a highly saline leachate.

AMD can display one or more of the following chemical characteristics:

- low pH (typical values range from 1.5 to 4)
- high soluble metal concentrations (such as iron, aluminium, manganese, cadmium, copper, lead, zinc, arsenic and mercury)
- elevated acidity values (such as. 50–15 000 mg/L $CaCO_3$ equivalent)
- high (sulfate) salinity (typical sulfate concentrations range from 500–10,000 mg/L; typical salinities range from 1000–20 000 µS/cm)
- low concentrations of dissolved oxygen (such as less than 6 mg/L)
- low turbidity or total suspended solids (combined with one or more of the above).

Key indicators of AMD presence include (see Figure 1):

- red coloured or unnaturally clear water
- orange-brown iron oxide precipitates in drainage lines
- death of fish or other aquatic organisms
- precipitate formation on mixing of AMD and background (receiving) water, or at stream junctions

- poor productivity of revegetated areas (such as waste rock pile covers)
- vegetation dieback or soil scalds (such as bare areas)
- corrosion of concrete or steel structures.

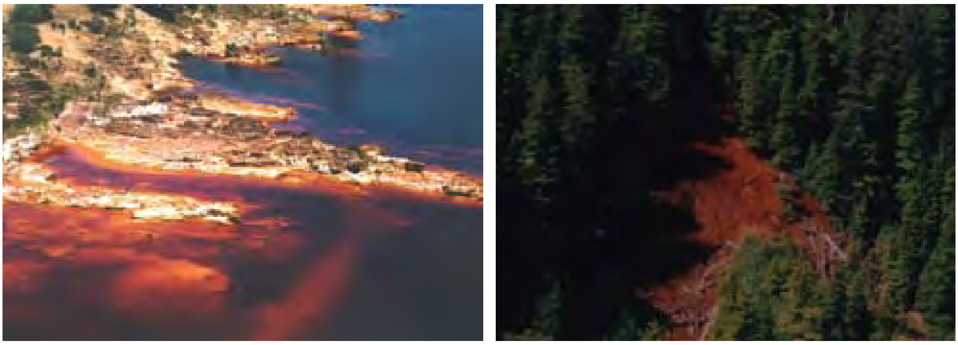


Figure 1: Visual indicators of AMD include orange precipitates in drainage lines (top left) and areas of vegetation dieback (bottom right)

A key indicator of AMD risk is the abundance of sulfide minerals that are exposed to air and water. The most common acid-generating sulfide minerals include pyrite (FeS_2), pyrrhotite (FeS), marcasite (FeS_2), chalcopyrite ($CuFeS_2$) and arsenopyrite ($FeAsS$). The acid and acidity contributions of these and other sulfide minerals can be calculated using a spreadsheet-based tool called ABATES (see link in Glossary). Not all sulfide minerals are acid-generating during oxidation, but most have the capacity to release metals on exposure to acidic water.

Situations where reactive sulfides can be routinely exposed to air and water include waste rock piles, ore stockpiles, tailings storage facilities, pits, underground mines, heap and dump leach piles (refer to Section 2.5). Leading practice AMD management involves strategies to minimise the interaction between reactive sulfides and air, water or both.

2.1.1 Acid drainage

The generation of acid (H^+) occurs typically when iron sulfide minerals are exposed to both oxygen (from air) and water. This process can be strongly catalysed by bacterial activity. Sulfide oxidation produces sulfuric acid and an orange precipitate, ferric hydroxide ($Fe(OH)_3$), as summarised in Reaction 1.

Reaction 1

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \Leftrightarrow Fe(OH)_{3\ (s)} + 2\ SO_4^{2-} + 4\ H^+$$

Iron sulfide + Oxygen + Water ⇔ *Ferric hydroxide + Sulfate + Acid*

(orange precipitate)

There are two key processes involved in the generation of acid (H^+) from iron sulfide.

- Oxidation of sulfide (S_2^{2-}) to sulfate (SO_4^{2-})
- Oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) and subsequent precipitation of ferric hydroxide.

These can be represented in the following three reactions[1].

Reaction 1a

$$FeS_{2\,(s)} + 3\_\ O_{2\,(g)} + H_2O_{(aq)} \Leftrightarrow Fe^{2+}_{(aq)} + 2SO_{4\,(aq)}^{2-} + 2H^+_{(aq)}$$

Iron sulfide + Oxygen + Water ⇔ *Ferrous iron + Sulfate + Acid*

Reaction 1b

$$Fe^{2+}_{(aq)} + \_\ O_{2\,(g)} + H^+_{(aq)} \Leftrightarrow Fe^{3+}_{(aq)} + \_\ H_2O_{(aq)}$$

Ferrous iron + Oxygen + Acid ⇔ *Ferric iron + Water*

Reaction 1c

$$Fe^{3+}_{(aq)} + 3H_2O_{(aq)} \Leftrightarrow Fe(OH)_{3\,(s)} + 3H^+_{(aq)}$$

Ferric iron + Water ⇔ *Ferric hydroxide + Acid*
(orange precipitate)

Once sulfides have been oxidised to sulfates, it is difficult to avoid oxidation of aqueous ferrous iron to ferric iron and subsequent iron hydroxide precipitation. This precipitation stage is acid-generating (Reaction 1c).

The interaction between dissolved ferric iron (Fe^{3+}) and fresh iron sulfide minerals can also lead to significant acceleration of the acid generation process, as represented in the following reaction.

Reaction 2

$$FeS_{2\,(s)} + 14\,Fe^{3+}_{(aq)} + 8\,H_2O_{(aq)} \Leftrightarrow 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+$$

Pyrite + Ferric iron + Water ⇔ *Ferrous iron + Sulfate + Acid*

As acid water migrates through a site (for example, through waste rock piles, stockpiles, pit wall rock or groundwater), it further reacts with other minerals in the surrounding soil or rock material and may dissolve a range of metals and salts. To some extent, the acid becomes neutralised by the minerals it dissolves, which has the effect of increasing pH.

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[1] These reactions, when combined, are equivalent to Reaction 1.

However, the neutralisation of acid is normally at the expense of increased toxic metal concentrations (acidity) in the resulting drainage. As acid water encounters any common aluminosilicate or sulfide mineral, partial dissolution and neutralisation results. While increases in pH are desirable, the concomitant rise in toxic metal concentrations is not. At many sites, there is insufficient natural neutralising capacity within geological materials to raise the pH of drainage to near-neutral levels. Consequently, acid drainage characterised by low pH and elevated toxic metals is the most common form of AMD experienced at mine sites.

2.1.1 Metalliferous drainage

Occasionally, the acid generated is completely neutralised by the dissolution of common carbonate minerals such as calcite, dolomite, ankerite and magnesite. Since the solubility of many toxic metals is pH-dependent, the neutralisation process can lead to precipitation of metals such as aluminium, copper and lead, and thus their removal from the drainage. However, at near-neutral pH, concentrations of toxic components such as zinc, arsenic, nickel, and cadmium can remain elevated. As with acid drainage, metalliferous drainage will also generally contain high (sulfate) salinity.

Non-acid metalliferous drainage is less common than acid drainage, due to the requirement for specific sulfide minerals (for example, sphalerite and arsenopyrite) and a local excess of carbonate neutralisation.

2.1.2 Saline drainage

In situations where acid drainage is completely neutralised by local carbonate resources, and the resulting drainage contains no toxic metal residues, the potential remains for drainage to be a sulfate salinity issue. The sulfate salinity of the neutralised drainage primarily depends on the relative proportions of calcium and magnesium in the neutralising carbonate materials. If magnesium is the dominant component of the neutralising material, for example, high salinity is more likely to be an issue, due to the high solubility of magnesium sulfate. Conversely, if calcium is the dominant component, then the formation of gypsum precipitates will contribute to lower salinity levels.

Saline drainage generated specifically as a result of sulfide oxidation is relatively rare, in comparison with acid and/or metalliferous drainage. Nevertheless, sulfate salinity can be an important indicator of AMD issues at mine sites, and may require similar management strategies (that is, control of sulfide oxidation).

2.2 Acid and Acidity

Acid is a measure of hydrogen ion (H^+) concentration which is generally expressed as pH, whereas acidity is a measure of both hydrogen ion concentration and mineral (or latent) acidity. Mineral or latent acidity considers the potential concentration of hydrogen ions that could be generated by the precipitation of various metal hydroxides by oxidation, dilution or neutralisation.

In general, acidity increases as pH decreases, but there is not always a direct relationship between acidity and pH. Based on the earlier description of metalliferous drainage, it is possible to have AMD with an elevated acidity but neutral pH values. It is therefore important to quantify the contributions of both hydrogen ion concentrations (acid) and mineral contributions (latent acidity), in order to determine the total acidity (acid + latent acidity) of a stream or water body. Acidity is generally expressed as a mass of calcium carbonate ($CaCO_3$) equivalent per unit volume (for example, mg $CaCO_3$ / litre).

Acid can be easily measured in the field using a calibrated pH probe. Estimates of acidity can be measured in a laboratory or estimated from water quality data using a formula such as Equation 1, which is broadly suitable for coal mine drainage[2]. If more detailed input water quality data is available, shareware such as AMDTreat or ABATES may be used to obtain accurate acidity estimates (see Glossary).

Equation 1

$$\begin{aligned}\text{Acidity } (mg/L\ CaCO_3) \quad = \quad 50 \times \{ & 3 \times [\text{Total Solube Fe}] / 56 \\ & + 3 \times [Al^{3+}] / 27 \\ & + 2 \times [Mn^{2+}] / 55 \\ & + 1000 \times 10^{-(pH)} \}\end{aligned}$$

Note: [ ] denotes concentration, mg/L

2.3 Acidity Loads

Acidity load refers to the product of the total acidity (acid + latent acidity) and flow rate (or volume) and is expressed as 'mass of $CaCO_3$ equivalent per unit time' (or mass $CaCO_3$ equivalent for a given volume of water). If flow rate or volume data is available, then the measured or estimated acidity values can be converted into acidity load as shown in Equation 2, or using the ABATES shareware.

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[2] Equation 1 is applicable to sites such as coal mines where Fe, Al and Mn represent the dominant components of acidity.

Acidity load *(tonnes $CaCO_3$/day)* = 10^{-9} x 86,400 *(conversion factor)*
x Flow rate *(L/s)*
x Acidity *(mg/L $CaCO_3$)*
(Equation 2a)
or…
Acidity load *(tonnes $CaCO_3$)* = 10^{-9} *(conversion factor)*
x Volume *(L)* x Acidity *(mg/L $CaCO_3$)*
(Equation 2b)

Acidity load is the principle measure of potential AMD impact at a mine site. Consequently, AMD management planning and costs need to focus on those areas of a mine site that potentially can release the greatest acidity load.

2.4 Factors Influencing AMD Generation

Many factors will influence the generation and transport of AMD and therefore the concentration and load of pollutants at a point downstream of a source. The primary factor influencing AMD generation is the oxidation of sulfide minerals. The chemistry of the AMD will change as the solution moves through the system and interacts with other geologic materials.

Factors affecting sulfide oxidation include the:

- concentration, distribution, mineralogy and physical form of the metal sulfides
- rate of supply of oxygen from the atmosphere to the reaction sites by advection and/or diffusion
- chemical composition of pore water in contact with the reaction sites, including pH and the ferrous/ferric iron ratio
- temperature at the reaction sites
- water content at the reaction sites
- microbial ecology of mineral surfaces.

Factors affecting secondary interactions include the:

- concentration, distribution, mineralogy and physical form of neutralising and other minerals
- flow rate and flow paths of water
- chemical composition of pore water.

Section 6 discusses the way in which these factors can be incorporated into an assessment of AMD risk. Their use in the prediction and modelling of AMD is described in Section 5 and methods to alter certain factors to control the generation and release of AMD are outlined in Section 7.

2.5 Sources of AMD

In assessing the balance of acidity load at a site it is essential to have a good understanding of the local geology, mineralogy and geochemistry—characterising all materials that are exposed, handled or processed during mining operations. The exposure of unconsolidated materials (such as waste rock and tailings) or bedrock (such as the walls of a pit or underground workings) to air and water has the potential to generate AMD. Carbonates are the only alkaline minerals that occur naturally in sufficient quantities to be considered effective in neutralising acidity and decreasing metal concentrations. Silicate and aluminosilicate minerals (for example, biotite and chlorite) have significant neutralisation capacity, but reaction kinetics render them largely ineffective in most situations. However, not all sulfide minerals produce acidic drainage, nor do all carbonate minerals neutralise acidity. Low quality drainage may persist at near-neutral pH due to elevated metalliferous concentrations (refer to Section 2.1.1).

The assessment of lithologies and process streams is essential for the development of management strategies for handling mining wastes. It may be possible, for example, to implement strategies such as segregation, selective placement, co-disposal or blending and/or encapsulation on the basis of the assessment. These strategies are discussed in detail in Section 7. The overall goal of the management strategies, however, should be to minimise, or wherever possible, eliminate the footprint of potentially acid forming material. This can only be achieved if site planners and managers have a thorough understanding of the geochemical character of the materials disturbed (or exposed to air) as a result of mining, and knowledge of the overall balance of acidity load from these materials.

2.5.1 Waste rock piles

In general, waste rock piles are placed above ground where they remain unsaturated, containing about five to 10 per cent water. Alternatively, waste rock may be returned to a pit, where it may be partially inundated with groundwater. In both cases, any unsaturated zones of suldific waste rock are susceptible to AMD generation. AMD may seep from the toe of the waste rock pile or migrate beneath the pile into groundwater. This can have adverse impacts on water quality during operations and post-closure.

The overall process of AMD generation for a waste rock pile is represented schematically in Figure 2. The behaviour of a given system will always be time-dependent and will depend on the materials' physical properties such as porosity, grain size (surface area), diffusion coefficient, gas permeability, hydraulic conductivity and thermal conductivity. Geographical location will determine factors such as air density, precipitation, temperature, prevailing winds, vegetation and seasonal variability.

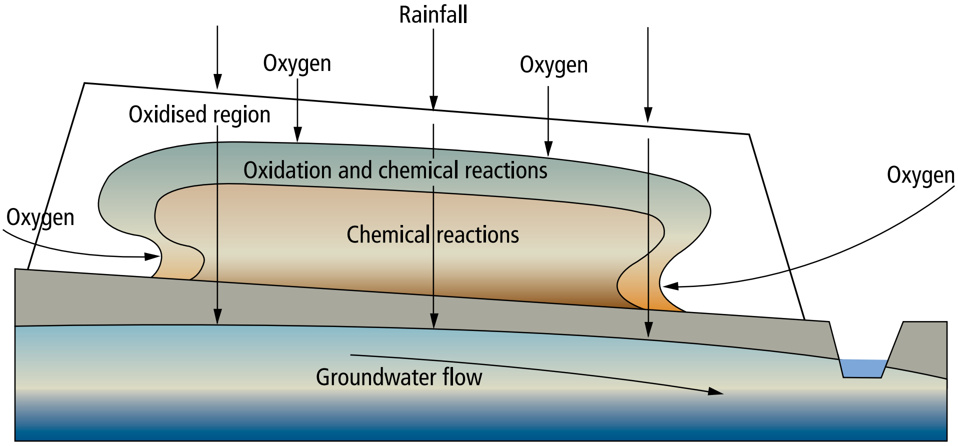

Figure 2: Schematic representation of AMD generation and polluant migration from a waste rock (Ritchie 1994)

2.5.2 Ore stockpiles

Ore stockpile properties are generally similar to those of waste rock, but sulfide concentrations are often higher. Their longevity is relatively short, as they are eventually processed. Nevertheless, low-grade ore stockpiles may be present for decades, representing potentially long-term AMD sources. In addition to water quality issues, AMD generation may result in substantial reduction in the grade of the stockpiled ore.

2.5.3 Tailings storage facilities and tailings dams

Tailings produced during ore processing are typically disposed to a tailings storage facility in slurry form. Sulfidic tailings can represent a significant source of AMD due to their fine particle size. Sub-aqueous disposal of tailings in water-holding structures, such as dams, can be an effective AMD control strategy. However, as most existing tailings storage facilities are not designed as water-holding structures, tailings can progress towards unsaturated conditions (for example, post-closure) and therefore become a potentially long term AMD source.

Seepage from tailings storage facilities is generally to groundwater, while surface water is often reused on site (during operations) or may be discharged via a spillway structure (post closure). AMD generated in tailings storage facilities can therefore adversely affect surface and groundwater quality, both on and off site. Off site contaminant transport via groundwater is an inevitable consequence of unsaturated tailings storage facilities containing sulfidic material but can be minimised by appropriate rehabilitation strategies.

2.5.4 Pits or open cuts

Wall rock in pits or open cuts[3] may contain sulfidic minerals that have the potential to generate AMD. The extent to which groundwater is lowered around a pit during mining affects the amount of sulfidic material exposed to air and the resulting acidity load that is generated. AMD from the wall rock may seep into the pit or the local groundwater system. This can affect the quality of water pumped from pit sumps or groundwater bores during operations. AMD can also have significant long-term impacts on pit water quality after mine closure.

2.5.5 Underground mines

Issues associated with wall rock in underground workings are similar to those for pits. Any sulfides exposed to air, as a result of dewatering, are a potential source of AMD. This can affect the quality of water that is collected underground and reused, treated or discharged during operations. At the completion of mining, flooding of the underground workings prevents further AMD generation. However, the mine voids may contain low quality water as a result of sulfide oxidation prior to, and during, the flooding process.

2.5.6 Heap and dump leach piles

Bioleaching of base metal sulfides is gaining favour as the technology matures and the size of operations increases. At the time of decommissioning, the remaining sulfides in the dumps or piles of spent material represent a potentially long-term source of AMD. The presence of an engineered pad liner underneath a leach pile allows all drainage to be collected during decommissioning and post closure, facilitating AMD management. However, in the case of dump bioleach operations, where no effective liner exists, the generation and transport of AMD from the spent dump material to the environment may be on a par with that from sulfidic waste rock piles.

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[3] Surface mines are commonly referred to as pits or open cuts. The term "pits" is used throughout this handbook for consistency.

3.0 LEADING PRACTICE DECISION MAKING FOR AMD

KEY MESSAGES

- Characterisation of AMD risk should commence during exploration and continue through pre-feasibility, feasibility and operations phases.
- An AMD Management Plan for site operation and closure should be developed during the feasibility phase.
- Mining should only proceed if closure planning conducted during the feasibility phase demonstrates that AMD can be managed from both technical and economic perspectives.

The development of a mine occurs in a number of phases, commonly described as exploration, pre-feasibility, feasibility, operations and closure. The risk of AMD can prevent a project from progressing beyond feasibility phase, and have significant implications for project performance if it does proceed.

It is never too early in the life of a project to establish the key parameters needed to assess and manage the potential for AMD.

Leading practice decision making for AMD begins with an understanding of the site geology. Understanding the geological environments in which mineral or coal deposits are formed is the key to managing AMD from mine materials. Methods for identifying and predicting AMD are addressed in detail in Section 5.

3.1 Pre-Mining

Few mineral resources are homogeneous and relatively little is understood about them and their host rocks in the pre-mining phases. However, it is important during the pre-mining phases that the project team, including geologists, mine planners, environmental scientists and AMD experts, ensures that an adequate geological and geochemical database is compiled to clarify baseline conditions and the risk of AMD. A typical progressive test work program is summarised in Table 1. Knowledge of the likely wastes that will be generated and materials exposed (Section 5.3) and the constraints this will place on the mining operation is vital (Scott et al. 2000).

As shown in Table 1, a detailed closure plan needs to be developed and costed for a site during the feasibility phase. This must remain a 'living document', as the mine proceeds, with regular reviews and updates based on new technologies, stakeholder inputs, changing mine conditions and community expectations.

Table 1: Acid and Metalliferous Drainage investigations and leading practice decision making during the pre-mining phases of project development

Phase	Monitoring / investigation	Description / comments* (refer also to Sections 5 and 8)	Leading practice decision making
Exploration: reconnaissance	Visual	Evidence of the potential for AMD (e.g. sulfidic minerals, stained seepage, iron precipitates).	If there is no indication of AMD potential at this stage, further AMD characterisation is still necessary and should be extended during prospect testing (see below).
	Water quality	Analysis of surface water samples for acidity, metals, sulfate and salinity.	
Exploration: prospect testing	Visual	Evidence of the potential for AMD.	If there is no indication of AMD potential, no further characterisation is required, unless a new area of the resource is explored and found to have different geology. If there is an indication of AMD potential, more detailed characterisation is required during resource definition (see below).
	Water quality	Analysis of surface and groundwater for acidity, metals, sulfate and salinity.	
	Geochemistry (preliminary static test work)	NAPP/NAG or POCAS test work, including analysis of sulfur and carbon in drill chippings (if available) and outcropping lithologies. At least 3–5 representative samples should be tested for each key lithology/alteration type.	
Exploration: resource definition	Visual	As above.	If there is no indication of AMD potential, no further characterisation is required, unless a new area of the resource is explored and found to have different geology.
	Water quality	As above.	If there is an indication of AMD potential, further investigations are required in the next phases of project development.
	Geology/ mineralogy	Identification of geological/lithological types and mineral phases in the mineralised and waste rock categories using traditional methods (petrology). Development of preliminary block models (see Section 5.7).	

Phase	Monitoring / investigation	Description / comments* (refer also to Sections 5 and 8)	Leading practice decision making
Exploration: resource definition	Geochemistry (detailed static test work)	NAPP/NAG or POCAS test work, including analysis of sulfur (as sulfide) and carbon (as carbonate) minerals in drill chippings for different geological types and mineral phases. At least 5–10 representative samples should be tested for each key lithology/alteration type.	By the end of the Resource Definition phase, there should be enough information to characterise the AMD potential of the ore body (high and low grade ore) with reasonable accuracy, although further information may be required for waste rock and tailings characterisation.
	Geophysical	Methods such as induced polarisation/self polarisation (IP/SP to detect disseminated sulfides), magnetics and electromagnetics (EM to detect massive sulfides) may be used to better define the extent of AMD potential.	
Pre-feasibility	Visual	As above.	Potential AMD impacts and associated management costs should be evaluated for a range of mining, processing and closure options.
	Water quality	Establish baseline water quality (acidity, metals, sulfate, salinity, etc.) and environmental values of surface and groundwater resources potentially affected by the project. This information forms a vital part of the environmental approvals process. Develop preliminary site water balance model.	Initial capital costs and ongoing operating and closure costs to manage AMD must be factored into project financial analysis to help distinguish between options and ensure a proactive approach to AMD management. This enables a preferred project option to be selected and taken into the feasibility phase. The preferred option will be the basis for application for approvals to conduct the project.

Phase	Monitoring / investigation	Description / comments* (refer also to Sections 5 and 8)	Leading practice decision making
Pre-feasibility	Geology/ mineralogy	Continue to refine block models (see Section 5.7).	Where feasible and economically viable, the mining and processing approaches can be optimised to minimise AMD generation from waste material or tailings, or steps can be introduced to "concentrate" it to a smaller fraction.
	Geochemistry (detailed static test work; preliminary kinetic test work)	Several hundred representative samples of high and low grade ore, waste rock and tailings should be collected for geochemical test work. Sufficient samples to populate a block model with a reliable distribution of NAPP data on ore, waste and wallrock. Kinetic tests should be established for at least 1–2 representative samples for each key lithology/ alteration type. Initial tests may be relatively simple, increasing in complexity if AMD is identified as a problem.	Some consultation with regulators and community may take place during pre-feasibility and this may provide valuable feedback for helping to select between project options.
Feasibility	Visual	As above.	All AMD data should be reviewed to develop a preliminary AMD Management Plan that is well integrated with the mining plan. This should be costed as input to the project Net Present Value (NPV). There should be a strong emphasis on developing AMD minimisation strategies that allow realistic costing of options for operations.
	Water quality	Revise baseline water quality and site water balance model.	
	Geology/ Mineralogy	Continue to refine block models (see Section 5.7). Use models to develop life of mine waste mining schedule and optimise mine plan and layout of facilities.	

Phase	Monitoring / investigation	Description / comments* (refer also to Sections 5 and 8)	Leading practice decision making
Feasibility	Geochemistry (detailed static and kinetic test work)	Review previous geochemical data for high and low grade ore, waste rock and tailings. Improve density of NAPP data for block model if necessary, and conduct sufficient NAG test work to cross check NAPP data for key lithologies. Continue kinetic tests on waste rock and tailings samples. Kinetic tests using blends of different materials (e.g. acid-generating and acid consuming materials) may be established to explore AMD management options. AMD experience from other mines with similar climate and geology should be reviewed in detail if available. If there are still insufficient data to assess AMD potential and provide a convincing management plan for approval, additional sampling, test work and refinement of block models will be required.	Planning and operational approaches to managing AMD need to be well detailed and backed by sound technical arguments. Procedures for ongoing monitoring of AMD management performance need to be detailed. A Closure Plan must be developed and seen to be workable and convincing. Closure costs need to be factored into project financials, and need to be known to +/- 20%, based on a refined conceptual model with detailed designs. Although the Closure Plan must be seen to be workable for the purposes of approvals, there will need to be trials and other research carried out during mining operations. A thorough scientific approach and transparency are key factors in expediting approvals and proceeding to the operations phase. A project concept that minimises impacts and provides a safe and stable landscape after closure is consistent with the objective of sustainable development. Preparation of an Environmental Impact Assessment (EIA) is completed and the approvals process is normally commenced just after the end of the Feasibility phase. At this point a preferred project has been selected but may still be subject to revision during final design work and as a result of feedback from stakeholders (community and regulators) during the approvals process.

3.2 Operations

During operations, the management of acid-generating material can be a complex process involving a number of different strategies dependent on the characteristics of the ore and waste, local climate and landscape (refer to Section 7). It is essential that an AMD Management Plan be developed during the feasibility phase, and revised in response to changing conditions encountered during mining operations.

Day-to-day AMD management could involve the identification, characterisation, scheduling, transport, segregation, selective placement, co-disposal and sometimes blending of sulfidic and carbonate-bearing materials, as well as extensive monitoring. This complex process is time consuming, labour intensive and frequently costly, without the benefit of being income-generating, and hence requires serious commitment by mine management and staff. Regular in-house performance evaluation (refer to Section 8) is important.

The performance evaluation process should provide feedback into regular updates of the Closure Plan (refer to the *Mine Closure and Completion Handbook*). If initial management strategies are found to be ineffective, then research into developing alternatives should be undertaken while suitable equipment and experienced personnel are still available on site, such that the new approach can be implemented at lowest cost. New developments in AMD abatement technology should be considered for evaluation and testing as part of the evolving AMD management and closure planning process. Regulators and community groups also need to be consulted during the planning process so that their evolving needs are met.

3.3 Closure

At the time of mine closure, it should be assumed that most of the preparatory work required to protect the environment has been undertaken as part of a well-conceived Closure Plan implemented throughout the operations phase. If this was not the case, there could be a significant risk of adverse impacts including high costs to retrofit solutions at such a late stage. Dowd (2005) discusses closure planning deficiencies at the Woodcutters Mine in the Northern Territory (see case study).

Ideally, the closure phase will consist largely of the last stages of decommissioning, including demolition of infrastructure, final land-forming, revegetation and commencement of a post-closure monitoring program.

Since AMD issues can have a long lag time before they become evident, it may be necessary to monitor the success of revegetation, the effectiveness of cover systems, and any impacts on water resources for many years until good evidence of stability is available and sign off can be obtained from the regulator.

It should be remembered that many of the AMD management technologies are still relatively new (less than 30 years old) so there are very few long-term benchmarks of success in achieving environmentally safe and stable landforms. The long-term performance of closure measures needs to be demonstrated, initially through techniques such as modelling, but will always need to be verified through achievement in the field. Companies should be prepared to conduct long-term monitoring post-closure where AMD risks and potential consequences are judged to be high. Such a responsible approach will enhance the reputation of the industry and help to maintain its social licence to operate. Closure issues are dealt with comprehensively in the Leading Practice Sustainable Development *Mine Closure and Completion Handbook.*

CASE STUDY Closure and Completion: Woodcutters Mine, N.T.

The former Woodcutters Mine near Darwin in Australia's Northern Territory involved underground and open cut mining of a large lead-zinc deposit between 1985 and 1999. At closure the residual mine waste was contained in two large tailings dams containing highly sulfidic net acid-generating material and a waste rock pile. The waste rock pile contained significant amounts of sulfidic material from the original open pit and had been open to the tropical monsoonal climate for many years.

A detailed cost-benefit assessment was conducted for five alternative closure scenarios, involving combinations of *in situ* rehabilitation or relocation of the tailings and waste rock. Based on this assessment, the initial Closure Plan was to:

- relocate the sulfidic tailings material into the open pit and flood the remaining capacity of the pit, to prevent future AMD generation from the underlying tailings
- rehabilitate the waste rock storage facility *in situ* using a dry cover system.

In 2000, Newmont Australia Ltd (formerly Normandy) commissioned a leading practice multi-disciplinary study to finalise the site Closure Plan, including a final rehabilitation plan for the backfilled open pit and cover design for the waste rock pile.

Whole of site groundwater flow and solute transport modelling was conducted to assess the impact of AMD from the waste rock, in pit tailings and former tailings dam footprints, on groundwater quality. The modelling results were then linked with stream flow analysis to evaluate long-term risks to the receiving aquatic environment for several closure scenarios. Based on the modelling results and exposure risk assessment, the study found that:

- the waste rock pile required a two-layer cover consisting of
  - a low permeability soil cover, to minimise water migration into the waste rock material and reduce the rate of sulfide oxidation within the pile
  - an overlying 'store-and-release' layer, to provide a growth medium for vegetation and protection of the low permeability soil cover
- the open pit needed to be backfilled to near surface with clean material (following tailings relocation), rather than left as a pit lake as originally envisioned.

All major earthworks related to closure, including construction of the final waste rock pile cover and regrading/capping of the backfilled open pit, were completed in 2004.

The technical studies on cover design and groundwater impacts were used, in conjunction with long-running assessments of metal levels in stream biota and sediments, to develop quantitative success criteria for post-closure performance, and ultimately lease relinquishment.

A detailed monitoring plan was developed to assess post-closure performance. Throughout the design process, Newmont consulted with regulatory agencies and local stakeholders (traditional owners), who were very supportive of the integrated approach to final closure design used at Woodcutters.

Whilst the ultimate execution of site closure and rehabilitation activities demonstrated application of current leading practice sustainable mining principles, a number of strong lessons resulted from this case study. These are summarised below (Dowd 2005):

- Initial optimal placement of waste material coupled with progressive rehabilitation during mining operations would have substantially reduced the closure costs
- The closure process would have been expedited if site closure criteria had been developed and agreed to in consultation with regulatory bodies and primary stakeholders during the operational life of the mine
- Significant cost savings could have been achieved if rehabilitation activities had started prior to de-mobilisation of mine equipment and staff/contractors.

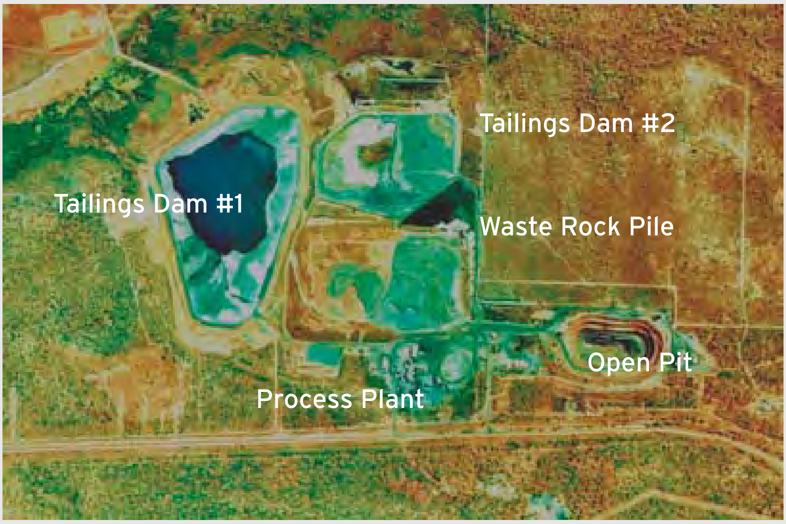


Figure 3: Woodcutters mine site in 1998 prior to decommissioning and rehabilitation

Figure 4: Rehabilitated mine site in 2005, following construction of cover over the waste rock pile, with revegetation to be completed

4.0 REGULATORY FRAMEWORK

KEY MESSAGES

- Commonwealth and state government regulation aims to protect the environment, including land and water resource use, biodiversity and cultural heritage.
- The key Commonwealth regulations that are relevant to AMD are the Environment Protection and Biodiversity Conservation Act, National Environment Protection Measures (NEPM) and ANZECC/ARMCANZ Water Quality Guidelines.
- The ANZECC/ARMCANZ Water Quality Guidelines provide a risk based approach to the development of site discharge standards.

The Commonwealth, state and local Governments have legislation and guidelines in place that are relevant to mine site AMD management. The aim is to protect environmental aspects such as biodiversity, water resources (quantity and quality), landforms, existing and potential future land uses, and cultural and environmental heritage.

The state and territory governments have primary responsibility for oversight and regulation of mining operations. This is often administered through a mining resources agency, a natural resource management agency and/or a statutory environment authority. The Commonwealth is primarily involved where issues of national environmental significance have been established or where there are agreed national frameworks for managing certain environmental aspects.

Australian mining companies operating overseas must comply with the legislation of the host country. It may also be necessary to consider international guidelines, such as the World Bank / IFC (e.g. IFC, 2004) and World Health Organisation guidelines (e.g. WHO, 2004), where the national legislation does not provide specific water quality guidelines for mining operations. Leading practice can be demonstrated by compliance with the most stringent guidelines available.

4.1 State/Territory governments

The primary means by which state and territory governments regulate AMD is through the standard authorisations required for a mining project, including mining leases, environmental impact assessments and water resources. Although the exact structure, legislation and regulatory regime applicable to AMD varies somewhat between jurisdictions, in general they all seek to minimise environmental impacts during operations and achieve sustainable landforms following rehabilitation through the minimisation of pollutant release.

Key considerations under state and territory legislation include:

- identification and assessment of AMD risks in the environment and social impact assessment
- determination of financial bonds based on adequate management of AMD issues post closure
- management of compliance with national water quality guidelines
- availability, quality and use of local and regional water resources.

4.2 Commonwealth government

The key relevant regulatory instruments provided by the Commonwealth Government are the *Environment Protection and Biodiversity Conservation Act 2000* (EPBC Act), National Environment Protection Measures established by the Environment Protection and Heritage Council, and the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* developed by the Australian and New Zealand Environment Conservation Council (the ANZECC/ARMCANZ Water Quality Guidelines). The guidelines are discussed in detail in Section 4.3.

Under the EPBC Act, the Commonwealth can require an environmental impact assessment when there is potential for a mining project to impact areas of 'national environmental significance' including:

- world heritage properties
- national heritage places
- wetlands of international importance
- threatened species and ecological communities
- migratory species
- Commonwealth marine areas
- nuclear actions (including uranium mining).

The National Environment Protection Measures (NEPM) aim to reduce existing and potential impacts of emissions and substances and provide a framework for the collection of broad-based information on air, land and water emissions. The National Emissions Inventory NEPM is an internet database designed to report on the types and amounts of certain chemicals being emitted to air, land and water and is accessible to the public. The inventory is administered through state and territory governments. Mining operators should determine whether they are required to register. More information is available at www.npi.gov.au.

4.3 ANZECC/ARMCANZ Water quality guidelines

Leading practice management of AMD requires careful understanding and compliance with the ANZECC/ARMCANZ Water Quality Guidelines. A table summarising the guidelines for freshwater ecosystems, marine ecosystem, irrigation and general use, livestock drinking water, aquaculture, recreational use and aesthetics is available at www.deh.gov.au/water/quality/nwqms/volume1.html. Guidelines for drinking water, developed by the National Health and Medical Research Council, are available from www.nhmrc.gov.au/publications/synopses/eh19syn.htm. This section briefly illustrates how to apply the guidelines when assessing impacts of substances on water quality.

The guidelines provide an innovative risk-based approach using decision frameworks that can be tailored to local environmental conditions. For aquatic ecosystems, the guideline trigger values equate to ecologically low-risk levels of physicochemical indicators for sustained exposures. The three differing levels of protection are an important aspect of the water quality guidelines. It has been recognised that for some environmental values it may not be feasible to protect all water resources to the same level. For aquatic ecosystems, the guideline trigger values are set at four different levels of protection, 99 per cent, 95 per cent, 90 per cent and 80 per cent, where the protection level signifies the percentage of species expected to be protected. The levels of protection are:

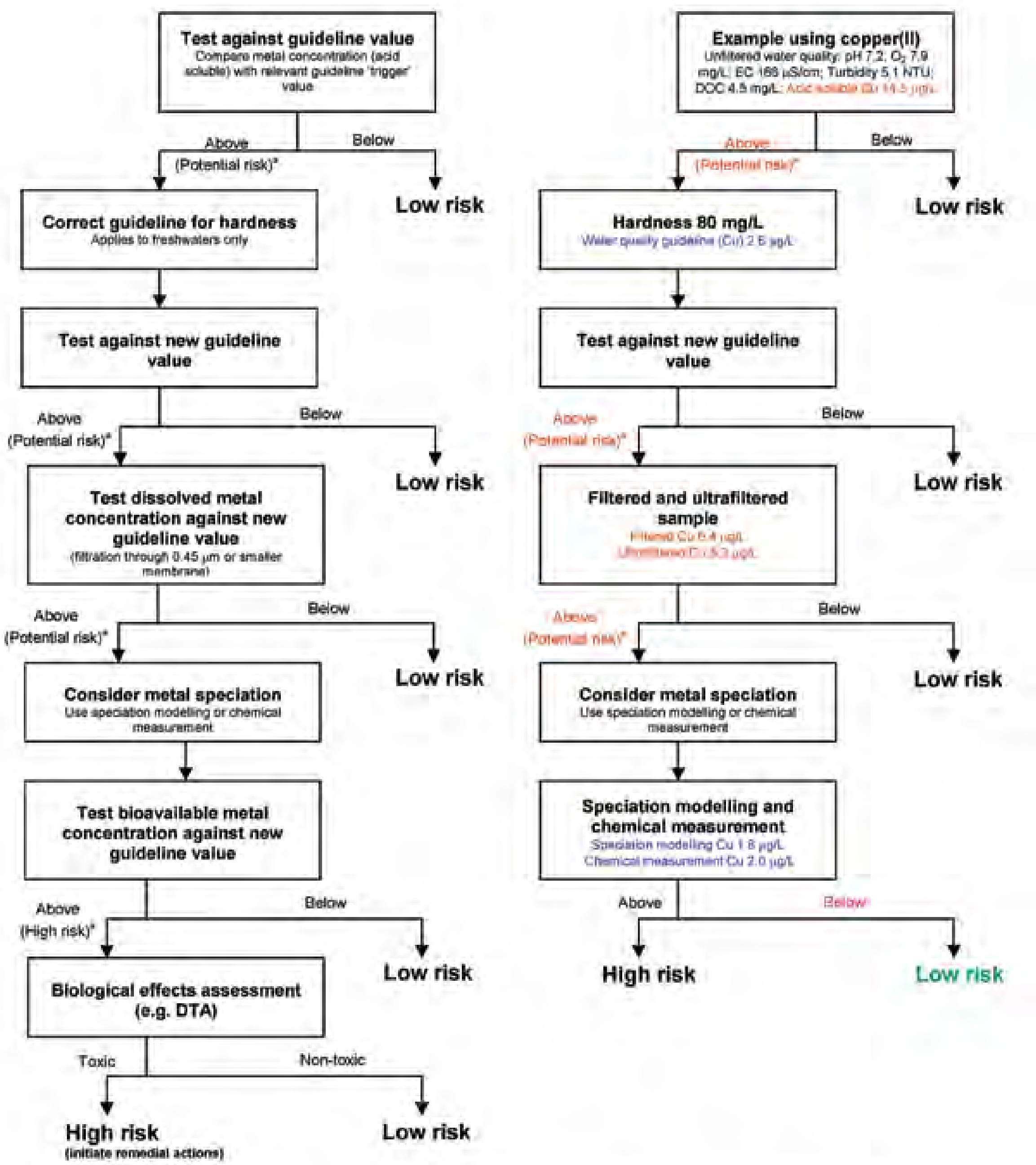
- high conservation/ecological value (99 per cent)
- slightly-moderately disturbed (95 per cent)
- highly disturbed ecosystems (90 to 80 per cent).

For most mine sites, guideline trigger values would likely be assigned at the 95 per cent level, since the ecosystem may be slightly to moderately disturbed. In addition, the natural mineralogy of mineralised areas is likely to lead to elevated chemical concentrations in regional water bodies.

The guideline trigger values are derived from biological dose-response data, and are indicative of the bioavailable fraction of a chemical indicator. For metals, the fraction of their concentration that is present as the free metal ion, or as weak complexes that are able to dissociate at a cell or gill membrane, will be more bioavailable than metals in strong complexes or adsorbed to colloidal and/or particulate matter.

Guidelines based on total metal concentrations are likely to be overprotective, but they recognise that the measurement of bioavailable metal concentrations is not a trivial exercise. From a regulatory standpoint therefore, it is appropriate to test for guideline conformity, in the first instance, on the basis of total metal concentrations. These measurements are both simpler and less expensive to undertake, with less opportunity for sample contamination. Where guideline trigger values are exceeded on the basis of the total metal concentration, it is appropriate that a measurements hierarchy of increasing complexity be prescribed that will provide an increasingly refined approach to identify the specific metal species that are exerting toxic effects. A decision tree outlining the hierarchy of measurements and an example of hierarchy application is illustrated for copper in Figure 5.

The defined guideline trigger values can be modified into regional, local or site-specific guidelines by taking into account factors such as the variability of the particular ecosystem or environment, soil type, rainfall or level of exposure. Trigger values are concentrations that, if exceeded, would indicate a potential environmental problem. They ‘trigger’ further investigation and potential refinement of the guidelines according to local conditions. These guidelines do not promote a single number guideline, but rather guideline values that are determined individually according to local environmental conditions. Although it is not considered mandatory to use the decision-based approach, it is recognised that its application reduces the amount of conservatism necessarily incorporated into the guideline trigger values, thereby producing values more appropriate for a particular water resource. The decision framework provides more flexibility and scope to water managers.



[a] **Further investigations are not mandatory; users may opt to proceed to management/remedial action**

Figure 5: Decision tree for application of guideline trigger value with respect to chemical speciation (left) and (right) example of application of decision tree using copper (II) (adapted from ANZECC/ARMCANZ (2000).

5.0 IDENTIFICATION AND PREDICTION OF AMD

KEY MESSAGES

- An increasingly detailed sampling and analytical program is required to characterise geologic materials as a project evolves from an exploration to a mining phase.
- The acid base account and net acid generating test provide an initial screening of AMD potential and determine the need for more detailed investigation.
- Static tests take a 'stocktake' of the minerals present and their potential to cause or alleviate AMD. Kinetic tests can be used to assess how AMD may develop over time.
- Geological block models based on static test data can be used to facilitate waste management.

5.1 Introduction

The primary purpose of a mine materials geochemical assessment is to guide management decisions. It is critical that a phased assessment program is carried out to ensure sufficient data are available at all phases of the project cycle. Leading practice can only be achieved through early recognition of the potential for AMD.

Geochemical assessment aims to identify the distribution and variability of key geochemical parameters (such as sulfur content, acid neutralising capacity and elemental composition) and acid-generating and element leaching characteristics. A basic screening level investigation is essential and should commence at the earliest possible stage. The need and scope for detailed investigations will depend on the findings of initial screening. Since some studies such as leach tests or sulfide oxidation rate measurements require a long time frame to provide the necessary data, it is important to initiate this work well ahead of key project milestones.

Reference to other mining operations in the region, particularly those situated in the same stratigraphic or geological units, may provide empirical information on the likely geochemical nature of similar ore types and host and country rocks. Early indications can also be provided by exploration drill cores, as suggested in Section 3. Leading practice includes logging key indicators such as sulfide and carbonate type, abundance and mode of occurrence. All samples should be analysed for total sulfur content as a minimum, and include key environmental elements in all drill core assays. Mineralogical investigations should examine the type and mode of occurrence of sulfide and carbonate minerals.

A number of procedures have been developed to assess the acid-forming characteristics and metal-leaching behaviour of mine materials. The most widely used screening method is based on the Acid Base Account (ABA) which is a theoretical balance between the potential for a sample to generate acid and neutralise acid. The ABA's simplest form is known as the Net Acid Producing Potential (NAPP).

Some sulfur minerals do not generate acid (but may contribute to metalliferous drainage), and there are different forms and reactivities of AMD-generating minerals and AMD-neutralising minerals. As a result, there is a level of inherent uncertainty in prediction based solely on the theoretical ABA. Mineralogical investigations, elemental analysis, sulfur and carbonate speciation, acid neutralising capacity, reactivity, and the Net Acid Generation (NAG) test (a rapid direct oxidation procedure) are used to address this uncertainty. AMD prediction is greatly enhanced by using a combination of tests, in particular, independent tests such as NAPP and NAG.

5.2 Sampling

Sample selection is a critical task and must be given careful consideration at all stages of a project. Samples should represent each geological material that will be mined or exposed and each waste type, for current and projected mine plans. Sampling design normally utilises drill hole cross-sections through the deposit.

The number and type of samples will be site-specific and depend on the phase of project development (refer to Table 1), but must be sufficient to adequately represent the variability/heterogeneity within each geological unit and waste type. Factors such as grain size, structural defects, alteration, brecciation and veining must therefore be considered in sample selection. Through the exploration phase to final feasibility, all drill hole samples should be assayed for total sulfur, as a minimum requirement.

Although drilling and sampling will focus on ore zones in the exploration and pre-feasibility phase, samples of host and country rock should be increasingly represented as the project develops. This will ensure that adequate data are available to produce block models and production schedules by geochemical waste types (refer to Section 5.7).

Key sampling guidelines are listed below (Scott et al. 2000):

- drill core and percussion chip samples should represent no more than 10 metre intervals and cover individual geological types and ore types
- each composite sample should not be obtained from more than one drill hole
- each sample should be approximately 1–2 kg. The sample should be crushed to nominal 4 mm size, then riffle split to produce 200–300 g for pulverising to minus 75 micron. The minus 4 mm and pulverised splits should be retained for testing.

5.3 Geochemical static tests

5.3.1 Acid Base Account

The Acid Base Account (ABA) evaluates the balance between acid generation processes (oxidation of sulfide minerals) and acid neutralising processes (dissolution of alkaline carbonates, displacement of exchangeable bases and weathering of silicates). It involves determining the maximum potential acidity (MPA) and the inherent acid-neutralising capacity (ANC).

The total sulfur content is commonly used as an estimate of pyritic sulfur to calculate MPA (MPA = %S x 30.6). However, if the sulfide mineral forms are known then allowance can be made for non-acid- generating and lesser acid-generating sulfur forms to provide a better MPA estimate. The use of total sulfur is a conservative approach because some sulfur may occur in forms other than pyrite. Sulfate-sulfur minerals (gypsum, anhydrite, alunite) and native sulfur, for example, are non-acid-generating sulfur forms. Also, some sulfur may occur as other metal sulfides (such as covellite, chalcocite, sphalerite and galena) which yield less acidity than pyrite or, in some cases, are non-acid-generating.

The ANC is typically determined by addition of hydrochloric acid to a sample, then back-titration with sodium hydroxide to determine the amount of acid consumed. The ANC measures the capacity of a sample to neutralise acid. Like MPA, the ANC determination is not precise and prone to potential interferences and may not represent the ANC that is actually available to neutralise AMD. Iron-containing carbonates such as siderite, ankerite and ferroan dolomite are potential concerns.

Two measures of the ABA are calculated—the Net Acid Producing Potential (NAPP) and the ANC/MPA ratio. The NAPP is a qualitative measure of the difference between the capacity of a sample to generate acid (MPA) and its capacity to neutralise acid (ANC)[4]. The NAPP, MPA and ANC are expressed in units of kg H_2SO_4/t and the NAPP is calculated as follows[5]:

$$\text{NAPP} = \text{MPA} - \text{ANC}$$

If the MPA is less than the ANC then the NAPP is negative, indicating that the sample may have sufficient ANC to prevent acid generation. Conversely, if the MPA exceeds the ANC then the NAPP is positive, indicating that the material may be acid-generating.

The ANC/MPA ratio provides an indication of the relative margin of safety (or lack thereof) within a material. Various ANC/MPA values are referenced in the literature for indicating safe values for prevention of acid generation. These values typically range from 1.5 to 3. As a general rule, an ANC/MPA ratio of 2 or more signifies that there is a high probability that the material will remain near-neutral in pH and should not be problematic with respect to AMD.

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[4] There are several nomenclature variations for static test parameters in the literature. For example, Net Neutralisation Potential (NNP) refers to the difference between the Neutralisation Potential (NP) and Acid Potential (AP). The NNP is generally expressed as kg $CaCO_3$/t.

[5] The NAPP can also be estimated using the ABATES shareware (see Glossary).

While the NAPP value (and ANC/MPA ratio) provides an indication of the potential for acid generation from a sample, additional test work is required to predict the potential for metalliferous or saline drainage (see below).

5.3.2 Net Acid Generation (NAG) Test

The NAG test is used in association with the NAPP to classify the acid-generating potential of a sample.

The NAG test involves reaction of a sample with hydrogen peroxide to rapidly oxidise any sulfide minerals. Both acid generation and acid neutralisation reactions occur simultaneously and the net result represents a direct measure of the amount of acid generated. A pH after reaction (NAG pH) of less than 4.5 indicates that the sample is net acid-generating. The amount of acid is determined by titration and expressed in the same units as NAPP (kg H_2SO_4/t).

Several variations of the NAG test have been developed to accommodate the wide geochemical variability of mine materials and to address potential interferences. The two main static NAG test procedures currently used are the single addition NAG test and the sequential NAG test. The sequential NAG test may be required for high sulfide sulfur samples to provide a measure of the total acid-generating capacity, and for samples with high total sulfur and high ANC.

Specific methodologies are also required for evaluating material with a high organic carbon content such as coal washery wastes.

5.3.3 AMD sample classification

Individually, the NAPP and NAG tests have limitations, but in combination the reliability of AMD prediction is greatly enhanced. The risks of misclassifying Non-Acid Forming (NAF) material as Potentially Acid Forming (PAF), and PAF material as NAF, are substantially reduced by conducting both NAPP and NAG tests. The NAPP calculation can be compared to NAG test results to classify samples and identify uncertainties requiring follow up. Typical classification criteria for primary geochemical material types based on NAPP and NAG test data are shown in Table 2.

Further subdivision based on site-specific needs can be applied to identify samples with varying acid-generating capacities, acid neutralising capacities or metal leaching potential (see following section).

Table 2: Typical geochemical classification criteria based on NAPP and NAG test data^

Primary Geochemical Material Type	NAPP (kg H_2SO_4/t)	NAG pH
Potentially Acid Forming (PAF)	> 10*	< 4.5
Potentially Acid Forming-Low Capacity (PAF-LC)	0 to 10*	< 4.5
Non Acid Forming (NAF)	Negative	≥ 4.5
Acid Consuming (ACM)	less than -100	≥ 4.5
Uncertain#	Positive	≥ 4.5
	Negative	< 4.5
	Positive	< 4.5

^ State/territory guidelines for geochemical classification should also be checked.

* Site-specific but typically in the range 5 to 20 kgH_2SO_4/t.

Further testing required to confirm material classification.

5.3.4 Elemental composition

The elemental composition of representative samples of each lithology, soil/rock type and waste types should be determined and assessed in relation to the degree of enrichment or depletion compared to background soils and rocks. Options for evaluation include an elemental enrichment factor (EEF) and a geochemical abundance index (GAI). The EEF simply compares the concentration in the sample to background, while the GAI compares the concentration with median soil abundance data using a geostatistical approach based on a log scale. These comparisons are used to identify any elements (especially metals and metalloids) that occur at concentrations well above normal background values and may require further investigation, such as kinetic test work (see Section 5.4), to assess their environmental significance.

Some elements such as arsenic may be a concern at concentrations that are not significantly elevated relative to background concentrations. It is therefore important that the form of the elements be considered in this assessment.

5.3.5 Mineralogical analysis

Mineralogy is essential to understanding the minerals and weathering processes that drive AMD generation, as agents of AMD neutralisation and as secondary minerals that both retard and promote acid release and toxic metal migration from mine facilities.

The focus should be to identify sulfur and carbonate mineralogy, abundance and mode of occurrence. Silicate mineralogy should aim to identify and quantify any minerals with potential long-term AMD- neutralising properties (such as anorthite, olivine and chlorite). The AMD-generating and AMD-neutralising capacity of common sulfide and carbonate minerals from mineralogical data can be calculated using the ABATES shareware (see Glossary).

CASE STUDY Characterisation/Prediction: Sari Gunay, Iran

A definitive feasibility study carried out by Zar Kuh Mining Company (70 per cent Rio Tinto) for the development of the Sari Gunay gold deposit located in Iran demonstrates the benefit and importance of gathering an extensive sulfur and multi-element database from drill core during early stages of project development.

A resource model database consisting of more than 15 000 sulfur and elemental assays on one metre intervals of drill core was compiled during exploration, pre-feasibility and feasibility studies so that the information was available at a time when it could be incorporated into mine planning. These data identified the presence of sulfur within waste rock and ore as an issue for the project due to the potential for generation of AMD and contamination of water resources.

To minimise future problems from AMD a program of testing was initiated to calibrate the resource model database so that mine planning could optimise waste rock and ore production for AMD control. Drill core intervals were carefully selected to represent the likely variability within each geological rock type which resulted in 101 samples that were assayed for sulfur, ANC and NAG (see Section 5 for description of test).

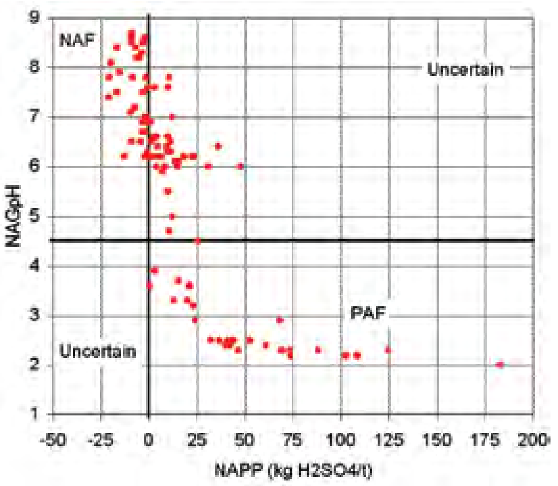

Figure 6: Geochemical classification plot for Sari Gunay waste rock samples showing NAGpH versus NAPP, with AMD classification domains indicated.

The average sulfur grade of the selected samples was 0.76%S and the average ANC was 7 kgH_2SO_4/t. Approximately 60 per cent of the samples were NAPP positive indicating that such materials might be a source of acid. About 40 per cent of samples were NAPP negative and unlikely to generate acid and most of these have ANC/MPA ratios greater than 2 indicating a high factor of safety.

Figure 6 is a geochemical classification plot showing NAGpH versus the NAPP value for the 101 waste rock samples. Potentially Acid Forming (*PAF*), Non-Acid Forming (*NAF*) and Uncertain Classification (*UC*) domains are indicated and are as defined in Section 5.3.3.

Although many samples plot within either the *PAF* or *NAF* domains, there are a number of samples that plot in the upper right uncertain domain. Additional testing including mineralogy, sulfur forms and Sequential NAG test were conducted on uncertain samples and confirmed that most were NAF. In these samples the NAG test was shown to be a more reliable measure of the acid generating capacity than the NAPP.

Based on the NAPP and NAG test results, three AMD categories were identified and defined as follows:

- *NAF*: Non-Acid Forming
- *PAF*: Potentially Acid-Forming with acid-generating capacity less than or equal to 10 kgH_2SO_4/t
- *High PAF*: Potentially Acid-Forming with acid-generating capacity greater than 10 kgH_2SO_4/t.

The distribution of sulfur values within each of these waste rock categories showed that essentially all samples classified as *PAF* and *High-PAF* had a total sulfur content of more than 0.25%S and all High PAF had more than 1%S. Although a cut-off of 0.25%S will include some samples classified as *NAF*, this value was used for planning purposes as it provides a conservative estimate of the amount of *PAF* waste rock.

Based on these results the following criteria where adopted:

Waste Rock Geochemical Classification Criteria

Geochemical Waste Type	Criteria
High PAF	> 1.0% Total Sulfur (as S)
PAF	0.25 to 1.0%S
NAF	<0.25%S

These criteria were applied to the resource model data base and through mine optimisation studies the following quantities and annual production schedule for each geochemical waste type were generated:

Year	NAF ktonnes	PAF ktonnes	High PAF ktonnes
1	1200	0	0
2	1527	0	0
3	0	1500	0
4	819	1681	0
5	2207	2696	0
6	2701	2399	0
7	2925	2038	0

Year	NAF ktonnes	PAF ktonnes	High PAF ktonnes
8	0	5094	0
9	0	4163	0
10	0	1736	0
11	0	1154	55
TOTAL	**11380**	**22462**	**55**

The results indicated that about one third of the waste rock will be NAF and two thirds will be PAF, with only a small amount of High PAF mined and this will all occur in the last year of operation. NAF rock is produced up to year seven and from year eight to the end of mine life at year 11, all waste rock will be PAF. The schedule identified a need to re-handle NAF material to allow encapsulation of all PAF waste.

The selected design option is to incorporate all waste rock within the tailings dam and embankment to facilitate tight control on materials placement. All High PAF will be placed within the tailings storage and all PAF waste will be placed, compacted and encapsulated within the embankment.

This case study demonstrates that prediction and quantification of AMD issue early in project development allows control strategies to be integrated with mine planning and engineering design to minimise long-term AMD liabilities.

The Sari Gunay site

5.4 Geochemical kinetic tests/pollutant generation rates

Kinetic test procedures include a number of measurements over time, and are used to assess a range of AMD issues including sulfide reactivity, oxidation kinetics, metal solubility and the leaching behaviour of materials. Kinetic tests typically involve some form of leaching and are carried out under optimal oxidation conditions to provide data on likely lag times and oxidation rates, and to identify elements of potential concern for water quality. The purpose of these tests is to determine the fundamental geochemistry of each material type for management and to assist scale-up predictions. Scale-up may include field-based test piles and can be assisted by mechanistic and empirical models. However, modelling can be inconclusive due to site-specific factors, necessitating a cautious approach to design, coupled with operational testing, to refine and update predictions and guide management decisions.

5.4.1 Laboratory

Laboratory kinetic testing typically involves subjecting a crushed sample of mine rock or mill tailings to wetting, drying and flushing cycles. During the wetting and drying cycles it is important that pore spaces are not saturated so that oxygen is readily available throughout the sample. Column leach tests and humidity cell tests are commonly used. The leaching regime is normally selected to optimise oxidation and ensure an adequate sample is available for analysis, but can also be adjusted to simulate field conditions. A larger range in particle size and sample volume can be accommodated in column leach tests compared to humidity cells. Columns are typically loaded with 2.5 kg of minus 4 mm size material, up to 35 kg of minus 40 mm size. Larger column sizes can be utilised, if required, to further examine scale-up factors. Kinetic leach test results may be used to evaluate:

- oxidation rates (directly by oxygen consumption and indirectly by calculation of the sulfate release rate)
- element solubility and leaching behaviour
- lag time to onset of AMD and evolution of AMD characteristics
- blends and treatments.

Kinetic leach tests need to operate for at least six months and typically 12 to 24 months before sufficient data are available for effective interpretation of the AMD characteristics of a material. Longer time frames may be involved for evaluating the performance of specific treatments or soil/rock type blends.

A kinetic NAG (KNAG) test has been developed to provide a qualitative indication of the lag to onset of AMD from a sample. The test can be completed within 24 hours.

5.4.2 Pilot scale field trials

The main purpose of field trials is to scale up laboratory tests to better reflect site climatic conditions and particle size distributions. Field trials may also be used to evaluate mitigation options, in particular, blends and covers.

Typical field trials include the following designs and scale:

- barrel and crib scale leach test (100 to 500 kg)
- test pads (10 m x10 m x 3 m and typically 500 tonnes)
- trial piles (typically 15 to 20 m pile height; instrumented for monitoring temperature, oxidation, hydrology and seepage chemistry). Examples include the Batu Bersih pile at the Grasberg Mine, Indonesia (Andrina et al. 2003) and the Diavik Diamond Mine in Canada (Blowes et al. 2006).

5.4.3 Full scale field trials

Well-designed instrumentation and monitoring programs provide the opportunity to observe the behaviour of full scale piles. These observations allow the effectiveness of AMD control measures to be determined, the need for any additional controls to be quantified and compliance with regulatory requirements to be demonstrated. In addition, measurements at full scale can be used to test and refine models that incorporate parameters obtained from small scale trials, leading to greater confidence in predictions of future behaviour.

In undertaking field measurements it is very important to be aware of the timescales associated with processes that occur at full scale. The response time of a waste rock pile to changes in oxygen supply rate, for example, can be hours to days. On the other hand, the time for changes in pollutant generation rates in a pile to be detected in samples from a groundwater monitoring well can be years to decades. A discussion of timescales associated with different AMD processes in full scale piles has been provided by Ritchie (1994).

Table 3 sets out the most commonly used measurements that are made in full-scale field trials and briefly describes their value. Examples of the deployment of such instrumentation and the use of the data obtained can be found in Andrina et al. (2003), Blowes et al. (2006), Patterson et al. (2006) and Ritchie & Bennett (2003).

Whilst the instrumentation and measurement protocols are relatively straightforward, interpretation of the field data generally requires expert understanding of a complex set of inter-related physical and chemical processes.

Table 3: Typical measurements made in full scale field trials

Measurement	Method of Measurement	Information Obtained	Remarks
Pore gas oxygen concentration profile	Sampling tubes and portable gas analyser or on-line oxygen probes; installed in drilled holes or during pile construction	Location of oxidising material; rate of oxidation; dominant gas transport mechanisms	Provides good qualitative and quantitative information; rapid response to change in conditions in pile.
Temperature profile	Thermistor strings; installed in drilled holes or during pile construction	Location of oxidising material; rate of oxidation	Provides good qualitative information but difficult to quantify; slow response to change in conditions in pile.
Water infiltration rate	Lysimeters	Pollutant transport rate through the pile; effectiveness of cover systems	Debate continues over designs and data interpretation; may take years to collect meaningful data.
Chemical composition of drainage	Surface water sampling and groundwater piezometers	Pollutant concentration and loads released from the pile	Large amounts of data; very slow response to change in conditions in pile.

5.5 Modelling oxidation, pollutant generation and release

Complex weathering and mineral-solution geochemical processes take place in mine materials when exposed to atmospheric conditions. Process rates may vary with position (such as in a pile) and over time. There are feedback mechanisms between many of the processes, leading to non-intuitive system behaviour. Sophisticated modelling techniques are required to predict AMD behaviour with any degree of confidence.

Reactive-transport models provide a means of describing the potentially complex behaviour of AMD generation, migration and evolution at mine sites. They need to take into account sulfide mineral oxidation, gas transport, heat transport, water and solute movement, and neutralisation processes involving the dissolution of carbonates and aluminosilicates. They require site-specific input data, which are inevitably sparse, both spatially and temporally. The models are most useful as tools to:

- test hypotheses and 'what-if' scenarios (for example, evaluate the effectiveness of different AMD control strategies, both in the short and long-term)
- help interpret field monitoring data
- determine the sensitivity of a system to particular input and design parameters
- provide time-dependent input to ecological risk assessment programs (see Section 6).

Many reactive-transport models have been developed, with varying capabilities and levels of complexity. Some models take a sequential approach in which the transport and reaction processes are solved separately, with or without iteration between the steps. Others take a one-step approach in which the physical transport and geochemical reactions are solved simultaneously. An example of the latter type of model is SULFIDOX which was developed by ANSTO as a specialised tool to enable modelling of unsaturated waste rock piles and heap leach piles to be modelled. It includes the coupling of oxygen and heat transport, pile oxidation processes with kinetically controlled mineral reactions and unsaturated flow. Examples of its use are described by Linklater et al. (2005, 2006).

A comprehensive overview of the application of, and advances in, reactive-transport modelling of mine materials has been undertaken by Mayer et al. (2003) (Figure 7).

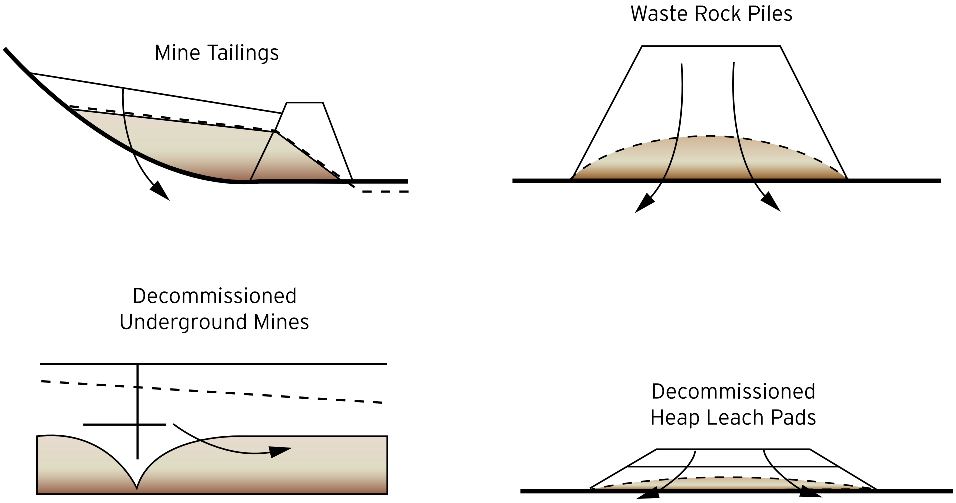

Figure 7: Reactive-transport models (Mayer et al. 2003)

5.6 Interpretation of test results

The results of static and kinetic test work primarily provide information on the AMD characteristics of individual samples to enable the primary geochemical material types to be defined and quantified. As presented in Section 5.3.3, five primary AMD geochemical material types can be defined and further types may be defined based on metal content and leaching potential, and lag time to onset of AMD. Based on the specific geochemical characteristics of each type, material specifications for segregation and placement can be developed for managing AMD.

The second level of interpretation focuses on predicting mine site behaviour as a whole and evaluates the risk of developing problems associated with the oxidation of sulfides. This requires:

- knowledge of the quantity, occurrence and distribution of different geochemical material types in the deposit
- details of the waste production schedules for these geochemical rock types
- knowledge of physical characteristics of the materials and likely pile oxidation mechanisms
- dumping sequence by waste type
- climatic conditions
- water balance and other parameters that influence AMD generation (refer to Section 2.4).

Expert advice should be sought at an early stage of project development to assist site personnel with interpretation of results, definition of geochemical material types and an understanding of implications for operations, materials management and closure.

5.7 Modelling of materials composition and scheduling

Leading practice can only be achieved through pre-mining recognition of AMD potential. The AMD potential for individual lithologies can be assessed from the results of static and kinetic test work programs outlined above. However, the likelihood of a site developing AMD problems and the identification of management options depends on the quantities of each material type disturbed (or exposed to air) and the production schedule.

Geological block modelling (for metalliferous deposits) or grid/layer modelling (for coal deposits) are recommended and commonly used to generate production schedules by geochemical waste types. The development of block or grid/layer models enables an understanding of the timing of exposure of PAF materials. This can have significant implications for mine planning (such as design of waste rock piles), as well as mine site operational management on a daily, weekly, monthly and yearly basis.

The block or grid/layer models are distinctively different from the geological model used to design the sampling program. Block modelling for waste is similar to ore resource modelling and is used to calculate material volumes and hence tonnages. The availability of data to define the waste is commonly low, relative to the data collected for orebody definition. As AMD characterisation tests are carried out on selected samples, it may be necessary to identify parameters within the geological database that correlate with the specific geochemical waste types at a site. Expert advice may be necessary to assist with this task. Parameters that are commonly used in block or grid/layer models include:

- total sulfur
- carbon (total carbon or carbonate carbon)
- carbon to sulfur ratio

- geological rock, lithology, alteration type
- specific element contents.

The block size used in these models must be robust and practical to facilitate implementation by mine managers. If the blocks are either too small or too large, they may not be appropriately segregated during mining.

In addition to waste production schedules, it is necessary to define the geochemical material types exposed on final pit walls and exposures, back-fill and cave zones in underground mines. This is to assist water quality predictions during mining, in final voids (pit lakes) and underground workings.

CASE STUDY Characterisation/Prediction: Cloverdale Mine, W.A.

Cloverdale mine is one of several mineral sand mines operated by Iluka Resources Limited (Iluka) in the south-west of Western Australia. The mines are located in deep sandy soils formed by marine regression and transgression events 1.5–2.3 Mya. AMD is a potential risk at these sites and is typically associated with fine-grained framboidal pyritic material in the pit walls, ore and overburden material.

In the early stages of mine planning at Cloverdale, a detailed survey was undertaken to map the extent of acid-generating materials within the orebody and adjacent areas. The acid-generating materials were classified as either Actual Acid Sulfate Soils (AASS) or Potential Acid Sulfate Soils (PASS), in accordance with state legislation and guideline documents.

The first phase of the survey involved a drilling program, comprising approximately 0.5 drill holes per hectare over the entire resource area (224 hectares). Drill holes extended two metres below the proposed pit floor and samples were collected at one metre vertical intervals. A total of 112 holes were drilled and 2232 samples were collected for analysis during this phase. The results were used to broadly identify significant areas containing acid sulfate soils.

In the second phase of surveying, the drilling intensity increased to 1.5 drill holes per hectare, to more accurately delineate the horizontal and vertical distribution AASS and PASS within the overburden, ore and pit floor materials. Samples were collected at one metre vertical intervals in the non-acid-generating zones and 0.5 metre intervals in areas known to contain acid sulfate soils, resulting in a total of 2778 samples collected.

A total of 239 holes were drilled and 5010 samples were analysed. Field pH and field peroxide pH (pHFox) analyses were conducted on all samples. The pHFox is comparable to a field NAG test, and is determined by oxidising the sample with peroxide prior to measuring pH. This method can supplement field pH measurements by providing a more realistic indication of long-term AMD issues. Sulfide analyses were conducted on selected samples using the chromium reducible sulfur (SCr) method, which is not subject to interference by organic sulfur or sulfates. In addition, soils classified as AASS (field pH <4.5) were analysed for Total Actual Acidity (TAA).

Figure 8: Geologist directing separation of acid-generating ore material—Yoganup West

The SCr results were used to develop a relationship between pyrite content and pHFox so that a 3D model of PASS (SCr >0.03%) could be developed over the mine area using data from all 5010 samples. The 3D model provided an accurate representation of acid sulfate soil distribution and volume within the mine pit and surrounding materials.

The survey data and 3D model of acid-generating materials assisted mine management to better understand the possible extent of AMD issues at the Cloverdale site. Mine planners have utilised this information during development of the mining schedule, to minimise the impact of AMD associated with pit dewatering, mining and acid-generating materials handling. The information has also been used to estimate AMD management costs, (such as treatment costs), during operations, and AMD's overall economic impact on the project. An AMD Management Plan was also developed for the site, to provide a basis for day-to-day management of acid-generating materials throughout the mine life.

6.0 ASSESSING THE RISK OF AMD

KEY MESSAGES

- Risk can be environmental, financial or reputational.
- A useful risk management strategy is to rank potential AMD hazards and then develop protocols to manage these hazards.
- Preservation of environmental values (such as drinking or stock water) is a key water management principle.

History and experience within the global mining industry have shown that AMD can be a significant, high-priority risk.

Within Australia, as in other jurisdictions, corporate governance law requires a company to identify, evaluate and manage all significant risks it faces. A prudent approach is to develop a focussed risk review program covering AMD issues which addresses:

What are the hazards posed by AMD within a company and are these hazards being properly managed by the operations to minimise the environmental, financial and reputational risk?

In describing the results of Rio Tinto's review of AMD risk, Richards et al. (2006) make the important point that compliance with pertinent government regulations and permit conditions does not necessarily guarantee AMD is being managed in the most practical, robust and cost-effective manner. The review of AMD risk highlighted several classes of issues that had typically been inadequately addressed, resulting in a heightened level of risk. It is likely that these issues, listed below, require additional management attention throughout the mining industry:

- geochemical characterisation of materials
- monitoring of potential groundwater impacts
- management of groundwater impacts
- waste rock segregation
- cover design
- flooding of workings.

Given the broad range of issues that need to be addressed in assessing AMD risk, a company is likely to engage the services of experts in the field to implement a review.

A risk assessment approach, as described in this section and the Tom Price case study, can provide input to new projects' design, to ensure that the next generation of mines has the best possible chance of effectively managing AMD and enhancing sustainable development.

CASE STUDY Tom Price Mine, W.A.

Acidic and metalliferous drainage, as well as spontaneous combustion (self-heating) problems, are known to be associated with the iron ore deposits that mine un-oxidised Mount McRae Shale (MCS) as waste in the Hamersley Province of Western Australia. When un-oxidised, the MCS is a black, carbonaceous and sulfide bearing shale (pyritic black shale) that poses both an AMD and self-heating risk.

Management of pyritic black shale at Tom Price, and all other Rio Tinto Iron Ore sites in the Hamersley Province, is carried out in accordance with a Black Shale Management Plan. The plan's management strategy is broadly based on the following principles:

- identification of black shale distribution and character
- minimisation of exposure and mining of pyritic black shale
- identification and special handling of pyritic black shale that must be mined
- encapsulation of pyritic black shale inside inert waste rock piles to limit water contact and allow the piles to be revegetated
- placement of pyritic black shale below the water table in backfilled open pits.

Assessment of the plan has indicated that it has been successful in preventing spontaneous combustion. In regard to AMD, however, it has been concluded that pyritic oxidation can still occur throughout the piles and generate pollutants that have the potential to lead to AMD.

Mining activities should not lead to degradation in ground or surface waters whereby an existing environmental value of the water is lost (see Section 6.2). Consequently, Rio Tinto Iron Ore has initiated a detailed AMD mitigation and management strategy that aims to preserve the environmental values of the regional water resources. Mining activities should not lead to degradation in ground or surface waters whereby an existing environmental value of the water is lost (see Section 6.2). The strategy includes the following aspects:

- quantification of background surface and ground water quality and the potential release of contaminants into groundwater from each waste facility
- monitoring of groundwater and determination of groundwater flow patterns and mass transport
- geochemical characterisation of pyritic black shale and other mined lithologies
- waste rock pile and pit wall source term evaluation from both *in situ* and *ex situ* characterisation
- optimisation of cover design via modelling and monitoring of trial cover systems and future waste rock dumping strategies to minimise the overall risk of AMD (for example, placement of pyritic black shale below the water table in backfilled open pits).

Preservation of environmental values requires knowledge of the natural background variability of water resources, as well as how they are used in the Tom Price region. The site monitors both ground and surface water quality. The AMD management program aims to quantify the potential release of contaminants into ground or surface waters and implement mitigation strategies, if necessary, to reduce risk to environmental values.

Black shale that has greater than 0.02% S is deemed to be either 'hot' or 'cold' and is selectively placed within the waste rock piles. At the Tom Price mining operations the middle MCS (approximately 14–24 m from the footwall zone and upper McRae shale contact) is the most reactive and is classified as 'hot' and managed differently to 'cold' black shale elsewhere in the MCS. This selective placement negates the potential for the material to spontaneously combust. The AMD potential of the material is assessed from measurements of intrinsic oxidation rate, acid base accounting and kinetic column studies. In addition, a range of *in situ* measurements are made in the waste rock piles. These measurements are used to quantify the potential for the generation and release of contaminants from each of the waste facilities. A regular monitoring program has been implemented to confirm the continuing effectiveness of the control strategies.

Figure 9: South east Prong pit wall: Footwall zone (left) to Mount McRae shale (right)

The Tom Price mine operation has developed and is continually upgrading groundwater models. The models are used to assess the influence of final pit voids on groundwater movement in regional aquifers and whether the mine site has the potential to influence water receptors (such as permanent surface water bodies and water extraction bores used for livestock) in the region.

Mineral waste management at the Tom Price operation involves an integrated approach. Accountabilities and actions for all groups that work with black shale are clearly described in the management plan. An AMD management group meets monthly to ensure common focus and direction, resolve misunderstandings, prioritise projects and agree on changes to the plan. Implementation of the management plan ranges from initial characterisation and modelling, through project development, mine planning, production and closure. The objectives of the planning are not only to quantify risk to environmental values but to mitigate the potential for risks to occur.

6.1 Risk and liability—lessons from a corporate review

In 2003 Rio Tinto began an AMD risk review program across its global operations and in 2006 reported the method and major findings of the first two years (Richards et al. 2006). The approach used and lessons learnt from this program may be applied within mining companies of any size, leading to positive sustainable development outcomes.

Rio Tinto took a two-stage approach. The first involved the development of a Hazard Screening Protocol to rank the potential AMD hazard posed by mining, based on the innate physical and chemical setting of each site. Broad issues examined as part of the assessment were assigned numerical values (weights) that were combined into a final hazard score. As shown in Table 4, the broad issues were: geology (45 per cent) incipient AMD risk (five per cent), scale of disturbance (25 per cent), transport pathways (10 per cent) and sensitivity of the receiving environment (15 per cent).

The second stage involved a Risk Review Protocol to focus on how an operation manages the innate AMD hazards posed by mining operations and how it reduces overall risks (financial, environmental, health and reputation). To minimise the development of future liabilities, the protocol was intended to identify latent as well as current issues, with particular attention paid to the long-term implications of management strategies and practices.

The Risk Review Protocol was divided into 11 key performance areas that covered all aspects of successful AMD management (Table 5). Individual elements that contribute to each key performance area are also listed. As with the screening procedures, the individual elements represent a holistic approach to the characterisation and management of AMD. It should be emphasised that the assessments need to be applied to all sites and site materials, including overburden, tailings and perhaps even some construction materials.

Table 4: Factors used in the Rio Tinto Hazard Screening Protocol (Richards et al. 2006)

Broad Issue	Factor	Weight
Geology	Ore deposit type	30%
	Host and country rock neutralisation potential	10%
	Known AMD issues on site	5%
Incipient AMD risk	Time since last major operational change	5%
Scale of disturbance	Total waste stored on site	15%
	Footprint of disturbed area	10%
Transport pathways	Water availability	7%
	Metal released to the environment*	3%
Receiving environment	Proximity of surface water bodies	5%
	Alkalinity of water body or groundwater	5%
	Proximity of protected or inhabited areas	5%

* Refers to the dissolved flux of metals that are discharged to the environment through approved permitted discharge points and approved operating practices.

Table 5: Key performance areas and elements used in the Rio Tinto AMD Risk Review Protocol (Richards et al. 2006)

Key Performance Area	Element
Site baseline characterisation	Characterisation of existing mine wastes
	Climate
	Hydrology and hydrogeology
	Surface and groundwater chemistry
	Ecosystem characterisation
Waste material and wall rock characterisation	Geologic setting
	Geochemical characterisation of rack masses and process wastes
	AMD geochemistry of pit walls and workings
	Physical characteristics of wastes
Materials management	Integration of AMD characteristics into mine planning
	Design of waste disposal facilities
	Waste material management
AMD generation processes	Sulfide oxidation
	Oxygen transport
	Oxidation products and in situ chemical reactions
	Infiltration and internal water movement
AMD migration pathways and fluxes	Surface water discharge and contaminant loading
	Groundwater flow and contaminant flux
Potential receiving environments	Assimilative capacity of the receiving environment
	Ecological sensitivity of the receiving environment
Integrated conceptual understanding	Conceptual models
	Numerical models
	Development of performance and closure criteria
AMD mitigation program	Mitigation strategy
	Implementation of the mitigation strategy
Monitoring and ongoing assessment	Monitoring strategy
	Data management and assessment
	Feedback mechanisms
Management skills and resources	Clear accountabilities and roles
	Institutionalised procedures and information management
	Adequate resources
Stakeholder relationships	Stakeholder relationships

6.2 Assessment of risk to environmental values

Environmental values are particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and which require protection from the effects of pollution, waste discharges and deposits. They were often referred to as 'beneficial uses' in water quality literature but this term has lost favour because of its exploitative connotations (ANZECC/ARMCANZ 2000). The guiding principle relevant to the selection of water quality criteria for Australian mine sites should be the preservation of environmental values. This principle is consistent with existing government requirements and non-government organisation expectations, as well as those of many mining corporations. It allows some flexibility in the selection process based on the different geochemical and environmental conditions that may be relevant to a particular mine site.

In relation to water management, a number of environmental values have been recognised (ANZECC/ARMCANZ 2000). They include: aquatic ecosystems, primary industries (irrigation and general water uses, livestock drinking water, aquaculture and human consumption of aquatic foods), recreation and aesthetics, drinking water, industrial water and cultural and spiritual values. Water quality criteria guidelines for aquatic ecosystems, primary industries and recreation and aesthetics have been given by ANZECC/ARMCANZ (2000). Criteria for drinking water are given by NHMRC (2004). No water quality guidelines are provided for industrial water or cultural and spiritual values. In general, guidelines for the protection of aquatic ecosystems are more stringent than those for drinking water, which are more stringent than those for primary industries and recreation.

Background water quality should be the basis for determining environmental values.
Mining activities should not lead to water quality degradation such that the most conservative guideline of environmental values defined for a water body is compromised. This does not mean that there must be no measurable impacts, but rather that impacts be minimised so that the water quality is not degraded to the point where any existing environmental value is lost.

Strategies that mining companies should employ to demonstrate the preservation of environmental values include:

- ensuring that pertinent maximum concentration or trigger value guidelines for different water environmental values (or uses) are not exceeded in receiving water bodies
- ensuring that discharge does not result in a statistically significant change in key water quality parameters (no change occurs that is outside the seasonally relevant background concentration plus (or minus) two standard deviations)
- demonstrating that the discharge will not have ecological impacts on the basis of site-specific ecotoxicological studies.

The criterion specified for each parameter of concern would be the minimum value derived from each of these three strategies. For each of the three cases, the water quality criteria will either be applied to the receiving water body (less conservative—allows for a mixing zone) or to the actual point of discharge (more conservative—does not allow a mixing zone).

6.3 Ecological risk assessments

Following the review of overall AMD risks (Section 6.1) and considered risks to environmental values (Section 6.2), the next logical phase is to assess the risk to a particular ecosystem.

Probabilistic ecological risk assessment (ERA) provides a means to evaluate the risk posed by any environmental hazard to the organisms living within the receiving environment. Quantitative, probabilistic ecological risk assessment uses data provided by any site-specific modelling or monitoring to evaluate the likelihood that pollutant concentrations and/or loads will either exceed any regulatory criteria or exceed any threshold of unacceptable impact in the receiving environment. The probability of terrestrial, aquatic or atmospheric exposure to contaminants at a specific site is determined from measured or modelled concentrations. The load and concentration of pollutants over time released to a stream from a waste rock pile, for example, can be predicted by SULFIDOX (Linklater et al. 2005) and chemical speciation along the stream can be predicted by PHREEQC (Parkhurst & Appelo 1999).

AQUARISK (see Glossary), developed by ANSTO, is currently the only software product that enables probabilistic ERAs to be undertaken for freshwater ecosystems impacted by AMD (Twining 2002 and Brown & Ferris 2004). AQUARISK provides the means to link site-specific environmental engineering options with the probable ecological impact of AMD in the receiving environment and provides a quantitative basis for stakeholder discussions.

Another approach that is increasingly being used for ecological analysis and decision-making is the application of Bayesian Decision Networks. Bayesian Decision Networks (BDNs) are graphical representations of probability, made up of nodes (representing variables) connected by arcs (arrows) that represent dependencies. The power of such network models lies in their potential to capture the patterns of connections and interactions within a complex system and provide a sound knowledge base for making environmental management decisions. The predictive accuracy of the model can be improved as additional data become available, allowing for adaptive management processes. The greater use of empirical data over qualitative judgements will improve the robustness and scientific credibility of ecological decision-making (Pollino & Hart 2006).

7.0 MINIMISATION, CONTROL AND TREATMENT OF AMD

KEY MESSAGES

- AMD minimisation or control strategies are strongly favoured over treatment.
- Selection of optimal AMD minimisation and control strategies depends on climate, topography, mining method, material type, mineralogy and available neutralisation resources.
- Active identification and segregation of AMD generating waste can be an effective minimisation strategy.
- Long term containment of AMD generating materials usually requires engineered cover systems ranging from soil and vegetative covers to water covers.
- Selecting the right passive or active treatment technology based on site acidity loads and metals present will ensure that water quality targets are met.

Strategies for managing AMD fall into three general categories:

- minimisation of oxidation and transport of oxidation products
- control to reduce contaminant loads
- active or passive treatment to allow water reuse or discharge.

From a sustainability viewpoint, minimisation is preferred to control and the latter is favoured over treatment.

7.1 Minimisation and control

Selection of optimal minimisation and control strategies for a particular site may depend on climate, topography, mining method, material type (such as waste rock, tailings, wall rock and heap leach), soil/rock types, mineralogy and available neutralisation resources, and inter-relationships between these.

7.1.1 Selective placement of waste materials

Selective placement of waste materials is the preferred AMD management practice during mine operations. Waste characterisation facilitates identification of appropriate disposal options. Key steps involved in this process are included in previous sections.

Waste materials are excavated and delivered to designated waste storage facilities. The tonnage and types of different materials directed to waste rock piles should be recorded on a daily basis so that future materials placement reviews can be made. This is particularly important if sulfide oxidation rates are slow or lag times are protracted, and AMD is released to the environment many years after mining.

Selective placement of reactive waste materials and their encapsulation with benign waste materials is the preferred AMD management practice during mining operations. Typically PAF material is segregated and placed in secure locations within engineered facilities. The waste storage site will inevitably contain surface drainage channels, and may also contain permeable ground allowing seepage to groundwater. In steep terrain, natural valleys are usually selected for waste storage to maximise the storage volume for a given containment wall size.

Every effort should be taken to divert upstream clean water around the waste storage facility. Drainage channels and valley floors, however, will continue to accept clean surface water flows from upstream of the waste storage and should, therefore, be lined with free-draining, benign material to pass these flows beneath reactive wastes. There may be a need to cap these buried drains with a clay seal or geomembrane to limit the migration of contaminated seepage from the reactive wastes placed above them. Alternatively, the free-draining, benign material could be taken to full storage height above natural drainage channels.

7.1.2 Waste rock piles

Waste rock, coarse-grained processing wastes and spoil piles are generally constructed loose by end-dumping from haul trucks or dragline buckets. This results in the ravelling of the coarsest-grained particles forming a base rubble zone, and the formation of discontinuous, angle of repose layers within the pile that alternate fine and coarse-grained material (Figure 10). If trucks are used, the upper surface of the pile becomes traffic-compacted. The pile is an 'oxidation reactor', with a ready input of oxygen provided through the base rubble zone and the coarse-grained angle of repose layers.

Figure 10: Base rubble zone (left image); angle of repose and trafficked layers (right image)

For waste rock piles, reactive waste rock (PAF) should typically be placed on a base layer of benign (NAF) waste rock, tied into the lined natural drainage channels, and encapsulated with benign waste rock (Figure 11). During construction of the waste rock pile it will be difficult to limit oxygen and rainfall ingress. The top of the completed waste rock pile should be covered, primarily to limit rainfall ingress and also to reduce oxygen ingress. To limit the accumulation of rainfall storage within the pile and subsequent seepage from the pile, the reactive waste rock could be constructed in cells to full height and covered progressively.

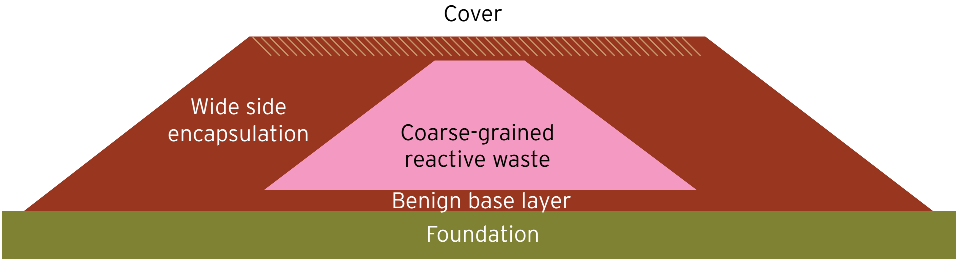

Figure 11: Encapsulation of coarse-grained reactive waste

7.1.3 Tailings storage facilities

The potential oxidation of reactive tailings is driven mainly by the diffusion of oxygen through the desiccated surface of the tailings. The oxidation products may then be transported by tailings water and/or rainfall runoff from the tailings surface or seepage through the tailings.

Since tailings are conventionally deposited in slurry form (at various solids concentrations), their surface storage requires some containment or encapsulation (Figure 12). However, the form of encapsulation varies. A base liner may or may not be required, depending on the ground conditions and the risk posed by the tailings water. In the early phases of a mine's life, the containment wall generally comprises borrow material or run-of-mine weathered rock. Later, it may involve the use of rehandled dry tailings, with an outer protection of benign waste rock and/or soil.

In some cases, where excess benign waste rock is available and the tailings storage facility is in close proximity to the pit, a wide encapsulation of waste rock may be placed around the tailings storage facility. This has the added advantage of providing a buffer against the possible future loss of encapsulation through erosion.

The tailings should be deposited as dry as possible. Evaporative drying by cycling tailings deposition between cells should be taken advantage of to limit seepage during operation. The containment limits exposure of the tailings to oxygen, but its main purpose is to contain them and to reduce lateral seepage. Recharging of the tailings by fresh tailings deposition and/or rainfall may require the removal of excess water, which can be re-cycled to the processing plant if suitable for reuse, or possibly evaporated. Following closure of the tailings storage facility, the impact of ongoing rainfall runoff will need to be considered—possibly requiring a low percolation cover and/or a spillway.

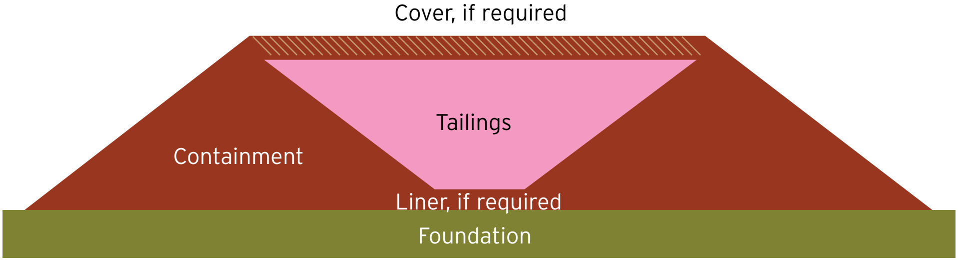

Figure 12: Encapsulation of reactive tailings

Most mine waste storages are located on the surface, resulting in an elevated landform. A distinction needs to be made therefore between the treatment of the flat top surface and that of the sloping sides of the storage.

7.1.4 Soil covers on flat tops

Soil covers comprise one or more layers of soil-like materials intended to limit the percolation of rainfall and/or the ingress of oxygen into stored reactive wastes. Soil covers must maintain an acceptably low risk of harm to society and the environment over a very long period. They must also be resistant to breakthrough by erosion, plant roots, or burrowing animals. Possible components of a soil cover could involve (in sequence from the surface):

- topsoil—normally a key component, requiring a high water storage capacity, a reasonable nutrient cycling capacity, and sufficient depth for plant roots (>> 0.5 m)
- capillary break—durable, benign fresh rock with minimal fines, if required to limit root penetration into the underlying seal, requiring a low Air-Entry Value (<< its thickness) and low water storage capacity
- sealing layer—a key component comprising compacted clay if available or compacted mine wastes, requiring a low hydraulic conductivity (< 10^{-8} m/s) to hold up rainfall infiltration, and a high air-entry value (to maintain saturation)
- capillary break—if the mine wastes are saline and/or potentially acid forming, to limit the uptake of contaminants into the cover.

In dry climates, where it is difficult to maintain the soil cover in a saturated state, the main function of a soil cover is to limit the percolation of rainfall into the wastes. Rainfall-shedding or barrier covers are likely to perform poorly in seasonal climates and to fail in semi-arid and arid climates, where the vegetation cover would be poor and the sealing layer would be prone to cracking and root penetration, and erosion. A compacted clay sealing layer on soft tailings is bound to fail due to ongoing consolidation of the soft tailings. While compacted clays may initially provide a hydraulic conductivity of less than 10^{-8} m/s or 300 mm/year, cracking will increase this by about one hundred-fold and they will no longer seal as designed (Figure 13).

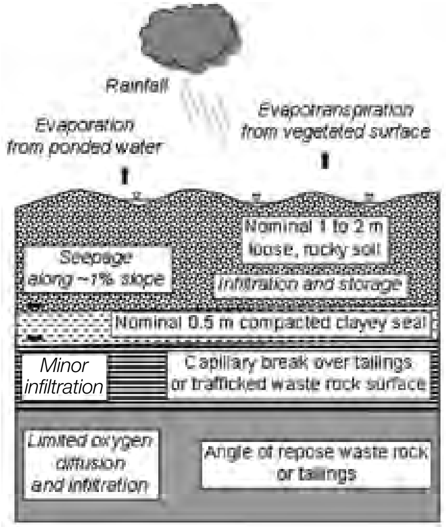

Figure 13: Schematic of store/release cover (Williams et al., 1997)

Recognising the potential shortcomings of a shedding or barrier cover at dry climate mine sites, the 'store/release' cover system was developed during the mid-1990s for covering waste rock piles at Kidston Gold Mines in north Queensland (Williams et al. 2006). The store/release cover system is designed to store wet season rainfall without shedding it, since this would lead to erosion of the cover, and to release stored water through the dry season through evapotranspiration, with no net wetting up or drying out of the cover from year to year.
A store/release cover can significantly limit percolation of the average annual rainfall (Williams et al. 2006), thereby reducing ongoing wetting of the underlying mine wastes and seepage.

Factors crucial to the success of a store/release cover are:

- a hummocked / truck-dumped top surface to prevent runoff
- sufficient thickness of loose, rocky soil to store prolonged heavy rainfall events
- a sealing layer of sufficiently low hydraulic conductivity to hold up the majority of the rainfall infiltration stored in the loose rocky soil layer
- a sustainable vegetative cover to transpire the stored rainfall that is not evaporated.

In wet climates, where it is difficult to stop rainfall percolation, the main function of a saturated soil cover is to limit oxygen ingress and so limit the oxidation of the stored reactive wastes and the production of AMD. A shedding or barrier cover typically comprises a compacted clayey soil seal about 0.5 m thick, overlain by a growth medium as thin as 0.3 m, which may support grasses but is quite inadequate for most shrubs and trees. A well-graded sealing material and thicker growth medium are desirable. Shedding or barrier covers have been used with reasonable success, both on flat surfaces and steep slopes, at a number of wet climate mine sites, including the Savage River Iron Ore Mine in north western Tasmania and in wet climates overseas. A well-vegetated cover can handle the high rainfall while limiting excessive erosion.

Numerical modelling is generally applied to the design of covers, and a number of suitable computer programs are available for this purpose. They are commonly based on the finite element method and incorporate unsaturated soil mechanics parameters. Most analyses are now two-dimensional, and they are driven by historical climatic data for the site. When designing soil covers using models, it is necessary to understand the geochemical and geophysical characteristics of the material to be covered and also the materials available to construct the covers. Every soil and rock will behave differently and laboratory testing will be necessary to provide the input parameters for the models.

Depending on the availability of soil materials and its variability, many tests may be required to adequately characterize the soils. Monitored trials are generally required to verify the cover design and to select the most appropriate vegetation species for a particular mine site. Installation of monitoring equipment and interpretation of the collected data will be required to 'prove' the cover's performance and also to 'recalibrate' the model based on actual performance monitoring data. Since covers are dynamic systems that are crucially dependent on the vegetation cover and its ability to cope with any climatic variations, long-term monitoring is essential.

The results of long-term cover monitoring are discussed by Taylor et al. (2003), O'Kane Consultants Inc. (2003) and Williams et al. (2006). Wilson et al. (2003) attempted to place in perspective the short and long-term integrity of various cover systems, ranging from simple vegetative covers to composite covers used for landfills, and costing from $10 000 to $400 000/ha. Among the mid-cost range covers typically used at mine sites, compacted clay, barrier-type covers costing about $35 000/ha are known to perform poorly, while store/release covers costing about $50 000/ha have performed far better.

7.1.5 Treatment of outer slopes

The outer slopes of mine waste storages are necessarily steep, and are problematic due to the following practices:

- reshaping (flattening) slopes by dozing—this reduces the 'roughness' of the surface by crushing and burying coarse-grained materials, resulting in increased runoff and decreased erosion resistance
- increasing slope lengths by flattening slopes of a given height—this increases their catchment and the potential erosion for a given surface treatment
- concentrating rainfall runoff in contour and downslope drains—this increases the potential for tunnelling and gully erosion
- drainage structures are often inadequate due to underlying settlement, particularly on contour benches and at connections
- fine-grained and/or dispersive growth media placed on steep slopes, which are particularly prone to erosion.

Waste rock pile and tailings storage facility outer slopes generally have adequate geotechnical and erosional stability. However, the conventional rehabilitation of such slopes can result in a final slope with adequate geotechnical stability but inadequate erosional stability. Alternative approaches to creating stable final slopes, drawing upon surrounding natural analogues, offer the potential to produce sustainable slopes of high geotechnical and erosional stability, and improved aesthetics. Natural slopes are generally concave-shaped, and are armoured with rock, cemented cap rock and vegetation.

The methods used to stabilise mine waste storage outer slopes will vary greatly depending on the climate and surface materials. Heavy vegetative cover may be highly successful in reducing erosion in some areas, whereas areas with seasonal, arid and semi-arid climates may not support sufficient vegetative cover to control erosion. Such areas will require other erosion protection strategies, including the limitation of slope catchment or the placement of a surface cover of coarse-grained benign waste rock. Rock may be mixed with underlying material or some fines may be added to the mix to enhance water retention and the potential for some revegetation.

While contour and downslope drains have a poor performance history, substantial rock-filled gullies could be constructed to handle excessive rainfall runoff. Angle of repose final slopes, which limit the cost of slope construction, may be possible on the upper part of the slope, provided that some profiling of the slope is conducted (i.e. incorporating concave slope profiles). Concave slope profiles, which mimic natural slopes, limit the loss of sediment from the slope. Monitored trials are generally required to develop the most appropriate slope treatments for a particular mine site.

7.1.6 Water covers

The most effective way to restrict the exposure of reactive wastes to oxygen is to deposit them permanently under water, a technique that succeeds because of the limited amount of dissolved oxygen in water and the low diffusion rate of oxygen through water. However, water covers are only viable when an assured supply or storage of water is available.

For surface reactive waste storages, this will require valley containment in a catchment of sufficient size to maintain a water cover over the wastes, incorporating a water dam and spillway (see case study on the Benambra tailings dam in this section). This normally requires a net positive water balance climate, generally limiting its application in Australia to Victoria, Tasmania and, possibly, the wet tropics. A number of water covers over reactive tailings have been used in Canada (Ludgate et al. 2003).

A flooded pit may also provide the potential for a permanent water cover over reactive wastes deposited in pit, but again this is normally limited in Australia to Tasmania and the wet tropics. Another option is pit backfilling, where sulfidic material is maintained below the recovered water table level and the rest of the void is filled with benign material.

Flooded underground workings may also provide the potential for the permanent storage of reactive wastes under water. Both in-pit and underground storage of reactive wastes may sterilise a future ore body and limit the potential to re-process the wastes.

To be effective, water covers require the topography and rainfall to provide a minimum water depth of 1.5 to 2 m, preferably more, depending on the potential for the re-suspension of fine-grained reactive wastes by surface wave action and currents (Catalan & Yanful 2002). The greater the flushing of the water cover the better. Metal release mechanisms are highly site-specific, depending on waste management prior to the placement of the water cover, waste mineralogy, biological factors, and the water cover depth.

7.1.7 Blending and co-disposal

Blending of materials has not been routinely adopted in the Australian mining industry, mainly due to the logistical problems and cost associated with scheduling, delivering and mixing significant volumes of mine wastes.

Blending and co-disposal does occurs in underground mines, and the pumped co-disposal of coal washery wastes is reasonably common in the coal industry. PAF material is sometimes mixed with cement or a mixture of cement and tailings and placed in underground voids as backfill. The cement has inherent neutralising capacity.

The blending of PAF waste rock material with carbonate rock or co-disposal with carbonate-bearing waste rock material has been attempted at several sites with only limited success. The armouring of carbonate grains with neutralisation precipitates significantly inhibits the dissolution of carbonate minerals.

CASE STUDY Water Cover: Benambra Tailings Dam, Vic

The Benambra Mine in East Gippsland, Victoria, was operated by Denehurst Limited as an underground base metal mine from 1992 to 1996. During operations, 927 000 tonnes of ore was processed on site and nearly 700 000 tonnes of sulfidic tailings was pumped to a nearby tailings dam. The Victorian Department of Primary Industries—Minerals and Petroleum (DPIMP) has been responsible for the site since 1998 and recently managed a successful rehabilitation program.

Earth Systems assisted DPIMP in the development of a detailed rehabilitation strategy to restore the site to as near pre-mining conditions as possible. The key environmental risk was the potential for AMD generation from the tailings dam.

The Benambra tailings dam was engineered as a competent water-retaining structure, and prior to rehabilitation contained about 160 ML of supernatant water, with near-neutral pH and elevated zinc, arsenic, copper, lead and manganese levels. The tailings were deposited via a central spigot, producing an irregular bathymetry of the tailings surface. As a result, the depth of water varied from 0–8 m and in some areas the tailings were exposed to air.

The primary objective of site rehabilitation was to manage AMD in the tailings dam by creating a permanent water cover over the tailings and utilising passive treatment systems for long-term water quality control. This was achieved through the following activities:

- Diversion channels around the tailings dam were removed and original creek alignments were reinstated in the upstream catchment, to direct water back into the tailings dam. This facilitates maintenance of a permanent water cover with a minimum depth of two metres and provides dilution of the tailings dam water.
- A spillway was constructed to allow controlled release of water and ensure long term geotechnical stability of the dam wall. Long term climate and water balance modelling was conducted to determine the required spillway elevation to maintain the minimum two metre water cover at all times.
- The tailings were levelled and covered with limestone sand to minimise resuspension of tailings in the water column and therefore minimise the potential for sulfide oxidation near the water surface.
- An organic matter layer was installed above the limestone to provide an additional barrier to prevent tailings resuspension, and to inhibit migration of dissolved oxygen from the water column into the tailings, thus further minimising sulfide oxidation.
- The tailings dam perimeter was revegetated to provide a constant supply of organic inputs (leaf litter) to the tailings dam via natural decomposition processes. This promotes reducing conditions, minimises interaction between tailings and dissolved oxygen in the water column and consumes oxygen.

- Passive alkalinity addition systems were installed to raise the naturally acidic pH of creek water to near-neutral levels prior to entering the tailings dam. This maintains low metal concentrations in the tailings dam water.
- The dam wall was strengthened by creating a 4:1 (H:V) downstream batter slope to maintain geotechnical stability in the event of a 'maximum credible earthquake'.
- An anaerobic vertical upflow wetland was installed to passively treat seepage from the base of the dam wall.

Rehabilitation works at the tailings dam were implemented over a five-month period in 2006. A permanent water cover now exists over the tailings and automated water quality monitoring is underway. Vegetation growth around the dam perimeter and establishment of a self-sustaining biological remediation system within the dam will ensure long-term passive water treatment through natural biological processes.

Figure 14: Aerial view of the Benambra tailings dam during rehabilitation works

7.2 Treatment

7.2.1 Introduction—why and when do we need to treat?

AMD treatment can be a costly part of mining operations and potentially an even more costly post closure liability if the propensity for sulfidic materials to produce AMD is not recognised and managed appropriately from the start of mining operations. It is both good business and leading practice therefore to avoid and minimise AMD (using the methods described in Section 7.1) and only treat AMD as a third priority (Section 7.2) when other approaches have failed.

AMD treatment should be considered not only for protection of environmental values of waterways but also for cases where:

- reuse of mine or process waters is required in areas where available water supply is limited
- Process process or other critical equipment requires protection from corrosion, or fouling by scaling
- Water water in pits or underground workings must be removed to regain access to an ore resource (this is an especially important factor in the context of resource sterilisation)
- Groundwater groundwater is contaminated by a plume of AMD and the plume needs to be remediated.

The potential requirement for post-closure management of AMD is often not apparent during operations, because as the extent of the issue may be hidden by long lag times. Furthermore, AMD produced during operations can be managed at relatively low cost, for example, by storing AMD in process or pond water circuits, or by co-disposal with tailings (a hidden part of cost of production). At closure, these management options are no longer available.

No single treatment approach can provide a total ‘walk-away’ solution, as all systems require a degree of long-term monitoring and maintenance. Selection of the appropriate AMD treatment method (or combination of methods) invariably depends on site-specific conditions, including water composition and treatment targets. The whole treatment process (including sludge disposal) needs to be systematically assessed before the most cost-effective option can be identified. This process is likely to require the expertise of a water treatment specialist. More detailed information and guidance is provided in the Team NT toolkit at www.acmer.uq.edu.au/publications/attachments/TEAMNTToolkit.pdf and Taylor et al. (2005).

The contamination of groundwater by mining operations historically has received significantly less attention in Australia than contamination of surface water. This is probably largely due to many mines being remote from competing users of groundwater resources. However, in some locations, and especially in the EU and the USA, groundwater contamination has required very costly remedial action.

Preventing the further spread of solutes by containment and recovery can be a difficult, costly and very long-term proposition. A general ’rule of thumb’ is that one year of groundwater contamination requires 10 years of pump and treat, to remediate the plume. Consequently, emphasis in the design and location of waste rock piles, ore stockpiles, and tailings storage facilities at new mine sites, should be on prevention or minimisation of future groundwater impacts.

AMD treatment technologies described in this section are generally applicable to both surface water and extracted groundwater.

7.2.2 General considerations for selection of treatment systems

Water composition—metals and pH are the most common targets for treatment of AMD, but the removal of major ions, such as magnesium and sulfate may also be required.

Water volume (or flow rate)—the cost of water treatment is a function of both flow rate to be treated and the composition of the water. In many cases, the flow rate is the primary driver for sizing a treatment system, whether active or passive. Efforts should be made to constrain the volume/flow rate requiring treatment, both during operations and post-closure.

Treatment targets—targets for treated water quality will be site-specific and depend on a number of factors, including issues relating to protection of plant and equipment from corrosion, as well as protection of receiving waters' environmental values.

Derivation of treatment targets requires consideration of the risk assessment framework detailed in ANZECC/ARMCANZ (2000), as described in Section 4.3. The Mt Morgan case study in this section demonstrates an application of this approach. Computer software to assist with selection of AMD treatment methods and cost estimates is described in the Team NT toolkit document and Taylor et al. (2005).

CASE STUDY Active Treatment: Mt Morgan Mine, Qld

Mt Morgan Mine near Rockhampton, in Queensland, has an open pit containing highly acidic and metalliferous water that currently has a predicted 50 per cent probability of overflow into the adjacent Dee River. The challenge is to maintain the pit water at a maximum operating level (MOL) that will reduce this probability to five per cent during the next five to 10 years when rehabilitation works will be undertaken to substantially reduce the volume of water reporting to the pit.

AMD will be treated by chemical neutralisation and discharged to the adjacent river to initially attain, and subsequently maintain, the MOL in the pit (Jones et al. 2003). Design specification of the treatment plant required calculation of the neutralant demand of the AMD, and screening test work on a range of potentially available neutralants.

Progressive addition of a neutralant (milk of lime slurry) to the Mt Morgan pit water enabled metal removal to be determined as a function of pH. The percentages of key target metals remaining in solution as a function of pH are shown in Figure 15.

The iron (Fe), aluminium (Al) and most of the copper (Cu) were removed from solution as the pH increased from 2.8 to 5.2. Around 20 per cent of the zinc (Zn) remained in solution at pH 5.2. By pH 7.3 all of the zinc had precipitated. However, it was not until the pH reached 9 that manganese (Mn) was effectively removed from solution. The amount of aluminium in solution began to increase as the pH exceeded 9.5. This results from the amphoteric nature of the Al^{3+} ion; the soluble anion $Al(OH)_4^-$ forms above pH 9 and thus the initially precipitated $Al(OH)_3$ begins to dissolve.

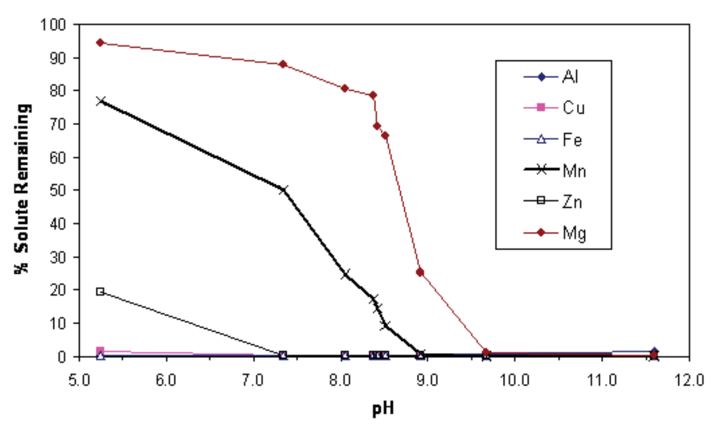

Figure 15: Removal of metals from Mt Morgan pit water as a function of pH (Jones et al. 2003)

The test work identified three potential target pH values (7.5, 8.5 and 9.0) for a treatment endpoint. If significant removal of Mn was not required then pH 7.5 would suffice. At this pH, the concentrations of Al, Cu, and Zn (the more toxic metals) would be reduced to very low levels. Complete removal of Mn would necessitate raising the pH to 9, which would require a doubling in the amount of lime required, as the Mg in solution would concurrently consume alkalinity due to the precipitation of $Mg(OH)_2$. Since Mn was unlikely to represent a significant toxicological risk to downstream aquatic biota, complete removal of Mn was not considered necessary.

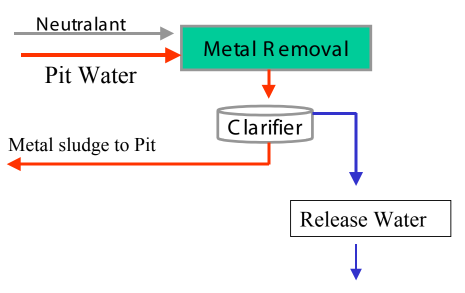

Figure 16: Process flow for the Mt Morgan lime neutralisation plant

Neutralisation test work, in conjunction with supply cost estimates, indicated that a one-stage treatment plant (Figure 16) using lime reagent was the most cost-effective treatment approach. A two-stage limestone and lime system was not cost-competitive by virtue of the combined capital and operating costs of two reagent delivery systems.

The treatment plant (Figure17), incorporating high density sludge recycle, was constructed in early 2006 and is currently undergoing commissioning.

If Mg and SO_4 removal is required to reduce the salinity load, then dosing with lime to pH 10.8 could be an option. Lime is the only reagent suitable for this purpose (alternative reagents such as calcite or magnesite would not produce sufficiently high pH). This approach is technically feasible, but would substantially increase lime consumption (and cost) given the high concentration of Mg^{2+}. The removal of major ion salts remaining after lime treatment may be more appropriately facilitated by reverse osmosis, a method that would also remove the Mn remaining in solution.

Figure 17: Pit water treatment plant adjacent to the AMD-filled open pit at Mt Morgan (March 2006)

7.2.3 Treatment technologies—active or passive?

AMD treatment systems can be categorised as either active or passive. The common attributes of a passive treatment system are no or minimal requirements for active (electric or diesel) pumping, and no requirement for remote-powered addition of chemical reagents.

Whether an active or passive method is suited to a given AMD application can be determined by assessing the acidity load of the influent AMD. Passive treatment approaches can be economically attractive in the right circumstances, but have some significant limitations. They are best suited to the treatment of waters with low acidity (<800 mg $CaCO_3$/L) and low acidity loads (100–150 kg $CaCO_3$ per day), with steady flow rates. There have been many examples where this rule has not been followed in the design and implementation of passive treatment systems, and the inevitable consequence has been overload and failure to meet treatment targets.

A passive wetland treatment system that failed is shown in Figure 18. A wetland initially designed to treat pH 5 water, and which operated successfully for three years, was overwhelmed when large unanticipated volumes of strongly acidic seepage began to discharge from an adjacent covered waste rock pile. Despite the installation of engineered open limestone drains upstream of the wetland, there was insufficient neutralising capacity for the increased acidity load. An active treatment system has now been commissioned to treat this water.

Figure 18: Wetland constructed to polish seepage from a covered waste rock pile. Left panel shows the wetland during initial years of neutral drainage. The right panel shows the wetland after it was overwhelmed and rendered ineffective by breakthrough of highly acidic and metal rich seepage.

In the event of slightly acidic to near-neutral mine drainage, such as pH 5-8, very large flows (within limits defined by required residence time and available area) can be directly treated by wetland systems at lower cost and with potentially better output water quality than can be achieved by active water treatment.

Figure 19 can be used to determine the applicability of different AMD treatment systems based on the acidity load of influent AMD.

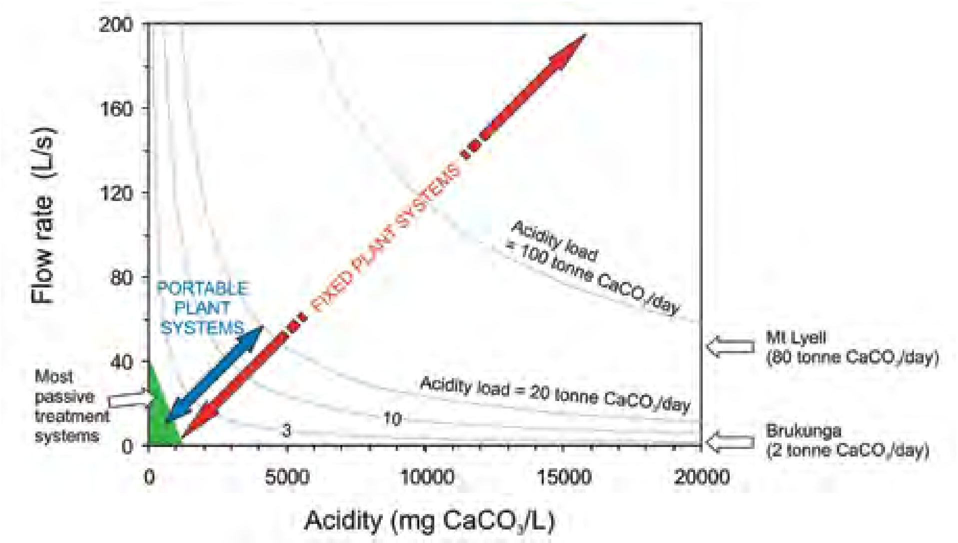

Figure 19: The selection of appropriate treatment approaches can be initially based on daily acidity loads. Passive treatment solutions are not suited to treatment tasks requiring in excess of approximately 150 kg CaCO3 per day equivalent.

7.2.4 Active treatment systems

The advantage of active treatment systems is that they can be engineered to accommodate a wide range of acidity loads (see Figure 19). However, the selection of an appropriate active treatment technology, or combination of treatment technologies that will provide robust and economically viable service very much depends on the composition of the source water and the required treatment targets. There are four basic types of active treatment technologies:

- precipitation of metal hydroxides by addition of neutralising agents to raise pH, or precipitation of metal sulfides
- ion exchange—a resin bed is used to take out metals in positively or negatively charged forms
- membrane separation (reverse osmosis, electrodialysis)—this will remove both major ion salts and metals to low levels. It is a secondary treatment step that would follow first stage neutralisation of acidity by pH adjustment. Rigorous pre-treatment is required to remove solutes (especially, iron, manganese, and calcium sulfate and carbonate) that can rapidly and irreversibly foul the costly membranes
- bioreactor systems for the removal of metals and sulfate.

By far the most common and lowest cost form of active treatment is chemical neutralisation using fixed plants or portable equipment for *in situ* treatment. *In situ* treatment can become a viable option when the cost of collecting and pumping AMD to a fixed plant exceeds the cost of building a smaller, portable plant (Taylor et al. 2005). Most metals of concern can potentially be removed by raising the pH to the required level. However, mercury (Hg), molybdenum (Mo), chromium-VI (chromate) and arsenic-III (arsenite) cannot be managed by pH control alone. Design of a plant to treat AMD requires calculation of the neutralant demand of the water, and screening test work to determine which of a range of potentially available neutralants will be the most cost-effective to meet the required treatment target.

There are two components of acidity that need to be considered—acid (H^+) and mineral (latent) acidity, as defined in Section 2.2. Total acidity values can be determined from soluble metal concentrations and pH values using tools such as ABATES (see Glossary).

Choice of the most appropriate neutralising agent for a given application requires consideration of:

- pH needed to meet water quality targets
- cost (cost of supply plus cost of operational use)
- rate and extent of pH increase;
- occupational health and safety (OH&S) issues
- dosage rate (i.e. mass of neutralant/m^3 of water required)
- extent of preparation (e.g. grinding) and delivery system needed
- ease of settling and volume of sludge produced and chemical properties of the sludge (note the cost of sludge disposal may be comparable to the initial treatment cost).

The most commonly used neutralising agents for large-scale treatment of AMD are lime (quicklime, hydrated lime), magnesite, magnesium oxide and limestone. This is due to the ready commercial availability of these reagents, non-proprietary nature, well-proven technologies for their use, cost-effectiveness and manageable occupational health and safety properties for large-scale application.

The most important factor in neutralant selection is the target pH required to meet water quality discharge objectives. Whilst limestone is the lowest cost reagent, the maximum pH that it can achieve is around 7. This will not be high enough to remove metals such as manganese, nickel, zinc, cobalt and cadmium, to acceptable levels.

Engineered sulfate-reducing bacterial systems have been developed by BioteQ www.bioteq.ca (BioSulphide®) and Paques www.paques.nl (THIOPAQ®). Sulfate-reducing bacteria contained in a high-rate bioreactor reduce sulfate to sulfide and sulfur. This process can produce water containing <300 mg/L sulfate and also removes metals that form insoluble sulfides (copper, cadmium, nickel and lead, as well as arsenic, selenium and molybdenum). The technology has been in operation at full-scale since the mid-1990s and several plants have been installed. This technology is best suited to situations where high levels of control can be provided, and where commercial metal recovery is possible.

7.2.5 Passive treatment systems

There are four basic classes of passive treatment systems:

- oxic and anoxic limestone drains or riffle channels to neutralise low pH water
- assisted chemical neutralisation—use of solar or water power to drive reagent dispensing systems
- wetlands (surface and sub-surface flow, with or without added limestone)
- a new class of high intensity sulfate reducing system.

Historically, the use of passive systems to treat AMD have achieved mixed success, largely as a result of application to unrealistically high acidity load situations. However, if a passive treatment system is designed and operated within its chemical and physical load limitations, it can provide a very effective and low-cost treatment alternative. Whilst they cannot be regarded as walk-away solutions, correct implementation will minimise maintenance and maximise life expectancy.

Single-stage active or passive treatment systems that use chemical neutralants alone, may have difficulty meeting stringent targets aquatic ecosystems protection, depending on the range of metals and other solutes in the source water. This is where a second-stage passive biological (for example, a wetland) polishing system can provide a distinct advantage, by achieving the required water quality without the large capital and operating costs associated with secondary and tertiary active treatment technologies.

However, wetlands cannot rapidly adjust to a sudden deterioration in water quality or to a major short-term increase in flow rate. They work best at pH values greater than five under steady-state conditions, with a residence time of 10–15 days. They require a relatively constant inflow rate from a pond in which the mine water is initially collected (and pre-neutralised if required), and must be protected from storm events using a split-weir diversion system.

The design lifetime of a passive treatment system is a key issue. In some cases, significant volumes of mine water requiring treatment may only be produced during the operations phase, prior to rehabilitation of source material (such as waste rock piles) or cessation of dewatering operations. In these cases, there would obviously be less emphasis on long-term (post-closure) sustainability. The need for self-sustaining systems becomes much more critical following site decommissioning. Passive treatment systems accumulate toxic metals, and the resultant long-term implications for closure planning should be addressed when this type of system is considered.

7.2.6 Highlight points

Regardless of emerging technologies, pH control with cost-effective neutralisation reagents will remain for some time the most widely used and lowest cost first-stage approach to both passive and active AMD treatment. Active treatment using calcium-based reagents is likely to remain the prime choice for neutralising medium to high-strength (low pH) AMD, and for treating those systems where the acidic water flow rate varies over a large range. Passive treatment systems are restricted to low acidity load situations where the flow rate of the water to be treated is relatively steady through time. Wetland systems offer an attractive option for final treatment of pre-neutralised water and for circumstances where the pH of influent AMD is above pH 4.5.

8.0 MONITORING AND PERFORMANCE EVALUATION

KEY MESSAGES

- An effective monitoring program underpins the implementation of a site AMD Management Plan.
- A typical monitoring program will incorporate AMD issues related to waste rock and ore piles, tailings storage facilities, tailings dams, pits / open cuts, underground mines, heap and dump leach piles.

8.1 Monitoring purpose

The main purpose of an AMD monitoring program is to provide relevant information that can be used by site planners and managers as a basis for informed decision-making. An effective monitoring program will facilitate the AMD Management Plan implementation for the site and can reduce or eliminate AMD impacts on the environment, community and mining operations.

Regardless of the project phase (exploration through to operations) there are a number of issues to consider when developing a monitoring program. Typical elements of an AMD monitoring program, during exploration/feasibility and operations, are outlined in Table 6. However, monitoring programs need to be site-specific and take into consideration the phase of project development and the sensitivity of the surrounding environment and community. Other key points to consider are:

- the nature of the material being handled, including volumes and reactivity
- likely composition of leachate generated from the material
- likely downstream receptors and baseline concentrations of significant analytes
- turnover of material including rate and the ability of personnel to access the material
- sampling technique, preparation and preservation requirements
- maintenance of sample integrity and chain of custody
- reference to appropriate guideline limits
- turnaround times for both the material being mined and analyses. If the turnaround of material being mined is relatively short, then analysis techniques need to be applied which allow for a rapid turnaround of data
- representative sample size
- government regulations and licensing requirements.

The monitoring program should provide information to facilitate leading practice AMD management in the short and long-term. It is essential that monitoring data are usable and that a solid communication forum exists between environmental monitoring staff and site planners and managers. Careful interpretation of monitoring results (refer to Section 5.6) is also critical for the ongoing development and implementation of an AMD Management Plan.

If management practices are not effective then actions need to be taken to rectify the situation before long-term impacts arise. A quick resolution will often prevent excessive acidification before it becomes impractical or cost prohibitive. Education and involvement of the workforce is essential to the successful management of AMD issues.

Table 6: Typical elements of an Acid and Metalliferous Drainage monitoring and performance evaluation program

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
General	Meteorology	Rainfall, evaporation, temperature, etc.	Baseline; Daily	Daily	n/a
	Hydrology–upstream and downstream of site	Flow rate	Baseline; Daily	Daily	n/a
	Surface water quality–upstream and downstream of site	General water quality parameters (field)	Baseline; Quarterly	Daily/ weekly; Event-based	State/national water quality guidelines for ambient surface water (e.g.ANZECC/ARMCANZ, 2000). Baseline and upstream.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline; Quarterly	Weekly/monthly; Event-based	
	Hydrogeology–upgradient and downgradient of site	Groundwater levels	Baseline; Monthly/ quarterly	Weekly/monthly	n/a
		General water quality parameters (field)	Baseline; Monthly/ quarterly	Weekly/monthly	State/national water quality guidelines for groundwater. Baseline and upgradient data.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline; Quarterly/ yearly	Monthly/ quarterly	
	Social and cultural (e.g. downstream water use)	Downstream water uses (e.g. drinking, fishing/aquaculture, irrigation/ farming, livestock, washing, bathing, small scale mining, hydropower, recreation, cultural significance, etc.)	Baseline; Yearly	Quarterly/yearly	Baseline data on downstream water uses.

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
	Vegetation (e.g. vegetated waste rock pile covers, other rehabilitated areas, natural vegetation adjacent to site)	Extent of vegetation cover, dieback or bare patches (if any), diversity of flora and avifauna	Baseline; Quarterly/ yearly	Monthly/ quarterly	Baseline data on natural vegetation or rehabilitated areas.
	Aquatic fauna– upstream and downstream of site	Algae, macroinvertebrates, fish, larger vertebrates, etc.	Baseline; Half-yearly (seasonal) / yearly	Quarterly/ half-yearly (seasonal) / yearly; Event-based	Baseline data on downstream aquatic fauna.
	Site water balance and acidity balance	Flow rates / pump rates, acidity loads	Baseline	Daily	Sufficient but not excessive volume of water on site.
		Water levels and volumes in storage facilities	n/a	Daily	
	Discharge points	Flow rates	n/a	Daily; Event-based	n/a
		General water quality parameters (field)	n/a	Daily; Event-based	State/national/ international water quality guidelines for discharge water (e.g. IFC, 2004). Mixing zones important.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Monthly/quarterly; Event-based	
	Production geochemistry	Geochemical classification of soil/ rock (static tests)	n/a	As required for operational control (e.g. blast holes, face samples).	Modelled predictions.
		Geochemistry of mill tailings (static tests)	n/a	As required.	Modelled predictions.

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
Waste rock and ore stockpiles	Waste rock and ore material	Waste rock and ore production rates, mass/volume of waste rock piles and ore stockpiles	Modelled predictions	Daily	Modelled data.
		Geochemical characterisation of lithologies (static & kinetic tests)	Baseline; as required	As required	n/a
		Sulfide oxidation rates / pore space oxygen concentrations (*in situ*)	Baseline; as required	As required	n/a
	Hydrology (surface water runoff and surface seepage)	Flow rates (surface water runoff, surface seepage)	n/a	Weekly	n/a
	Water quality (surface water runoff and surface seepage)	General water quality parameters (field)	n/a	Weekly	Baseline and upstream data. Predicted water quality.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Monthly	
	Hydrogeology (water in waste rock piles; groundwater upgradient, beneath and downgradient of piles)	Infiltration rates in waste rock piles (pore pressure / hydraulic/lysimeter data)	n/a	Quarterly	Target/design infiltration rates.
		Water levels; volume of pore water in waste rock piles; mass/volume of waste rock exposed to oxygen	n/a	Monthly	n/a

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
		Geophysical survey (e.g. electromagnetic; resistivity) to map sub-surface conductivity and seepage flow pathways	As required	As required	n/a
		General water quality parameters (field)	n/a	Monthly	State/national water quality guidelines for groundwater. Baseline and upgradient.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Quarterly	
Tailings storage facilities, tailings dams	Tailings material	Milling and tailing production rates, mass/volume transferred to tailings storage facilities	Modelled predictions	Weekly	Modelled data.
		Geochemical characterisation (static & kinetic tests)	Baseline; as required	As required	n/a
	Hydrology (supernatant water)	Volume, water level, flow rate of tailings into facility, flow rate of decant pumps, spillway flow rates	n/a	Daily	n/a
	Hydrology (surface seepage)	Flow rate	n/a	Weekly/monthly	n/a
	Water quality (supernatant water and surface seepage)	General water quality parameters (field)	n/a	Weekly	Site-specific water quality criteria (for on site use) or discharge water quality guidelines (e.g. IFC, 2004).
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Monthly	

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
	Hydrogeology (pore water in tailings; groundwater upgradient, beneath and downgradient of tailings storage facilities)	Water levels; mass/volume tailings exposed to oxygen	Baseline	Monthly	n/a
		Geophysical survey (e.g. electromagnetic; resistivity) to map sub-surface conductivity and seepage flow pathways	As required	As required	n/a
		General water quality parameters (field)	Baseline	Monthly	State / national water quality guidelines for groundwater. Baseline and upgradient data.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline	Quarterly	
Pits / open cuts	Pit wall material (groundwater cone of depression)	Mass/volume of material exposed to oxygen	Modelled predictions	As required	Modelled data.
		Geochemical characterisation of lithologies (static & kinetic tests)	Baseline; as required	As required	n/a
	Pit hydrology/stormwater	Dewatering pump flow rates	n/a	Daily	n/a
	Pit water quality	General water quality parameters (field)	n/a	Weekly	Water quality criteria (for on site use) or discharge water quality guidelines (e.g. IFC, 2004).
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Monthly	

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
	Pit hydrogeology (groundwater cone of depression)	Groundwater levels, flow rates (e.g. dewatering bores)	Modelled predictions	Weekly	Modelled data.
		General water quality parameters (field)	Baseline	Weekly	Water quality criteria (on site use) or discharge water quality guidelines (e.g. IFC, 2004).
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline	Monthly	
Under-ground mines	Dewatered material (cone of depression)	Mass/volume of material exposed to oxygen	Modelled predictions	Monthly	Modelled data.
		Geochemical characterisation of lithologies (NAG, NAPP)	Baseline; As required	As required	n/a
	Hydrogeology (groundwater cone of depression)	Groundwater levels and flow rates (dewatering bores)	Baseline	Weekly	n/a
		General water quality parameters (field)	Baseline	Weekly	Water quality criteria (for on site use) or discharge water quality guidelines (e.g. IFC, 2004).
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline	Monthly	

Facility	Component	Parameters	Frequency*		Performance evaluation criteria
			Exploration/ feasibility phase[1]	Operations phase	
Heap and dump leach piles	Ore material	Ore production rates, mass/volume of ore in leach pad	Modelled predictions	Daily	Modelled data.
		Geochemical characterisation of lithologies (NAG, NAPP)	Baseline; As required	As required	n/a
	Hydrology (surface water runoff and surface seepage)	Flow rates	n/a	Daily	n/a
	Water quality (surface water runoff and surface seepage)	General water quality parameters (field)	n/a	Weekly	Water quality criteria (for on site use). Predicted water quality.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a	Monthly	
	Hydrogeology (groundwater upgradient, beneath and downgradient of heap leach pad /leach piles)	Groundwater levels	Baseline	Weekly	n/a
		Geophysical survey (e.g. electromagnetic) to map sub-surface flow	As required	As required	n/a
		General water quality parameters (field)	Baseline	Weekly	State / national water quality guidelines for groundwater. Baseline and upgradient.
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	Baseline	Monthly	

			Frequency*		
Facility	**Component**	**Parameters**	**Exploration/ feasibility phase[1]**	**Operations phase**	**Performance evaluation criteria**
Other facilities	Hydrology (water storages, sediment basins, etc.)	Flow rates	n/a	Event-based; as required	n/a
	Water quality (water storages, sediment basins)	General water quality parameters (field)	n/a	Event-based; as required	Water quality criteria (on site use) or discharge water quality guidelines (e.g. IFC, 2004).
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a		
	Road runoff/surface seepage water quality (e. g. haul roads, exploration roads)	General water quality parameters (field)	n/a	Event-based; as required	
		Total suspended solids, acidity/ alkalinity, major ions and ligands, metals (laboratory)	n/a		

* Monitoring frequency for some locations may need to be higher during the wet season (and high flow periods) and lower during the dry season (and low flow periods). A higher frequency will also be required before/during off site discharge (e.g. in the case of downstream surface water monitoring).

[1] Monitoring frequency during the exploration/feasibility phase will depend on the expected time before commencement of operations.

8.2 Performance Evaluation

The monitoring program should be designed to monitor the impacts of AMD and compliance with relevant regulations during the operations phase. Monitoring also needs to examine the performance of the management methods employed to reduce the impacts of AMD. It may also be valuable to set site-specific targets for performance evaluation, such as water quality criteria for on site reuse, such as processing, infiltration and leaching rates, to provide further direction to the monitoring program. Typical performance evaluation criteria for an AMD monitoring program are outlined in Table 6.

Communication of results, both internally and externally (see Section 9), is crucial to the overall success of the AMD management strategy. It is only with adequate communication that appropriate changes will be made in the operations phase and prevent many of the long-term issues and difficulties faced at mine closure.

Data acquired during the exploration/feasibility and operations phases should provide the basis for generating and then updating a site Closure Plan, in consultation with relevant stakeholders (see Section 9). If sufficient detail is obtained during these initial phases to enable implementation of effective minimisation or control strategies during operations, then it is likely that monitoring during and post closure, will be significantly reduced in scope and frequency.

9.0 REPORTING TO COMMUNITIES AND STAKEHOLDERS

KEY MESSAGES

- Regular and transparent reporting to the community and other stakeholders over the life of a mining project is a key aspect of earning and maintaining a social licence to operate.
- There are currently no satisfactory technical solutions to some aspects of AMD management, but research and development is continuing.

Clear and transparent reporting is a fundamental aspect of earning and maintaining a social licence to operate. The annual collection and analysis of data, and the regular public release of data, as well as ongoing community consultation and engagement, are integral to responsible AMD management. The collection and public release of data is commonly a legislative requirement, however, it is also critical leading practice for any company aspiring to sustainability. Vehicles for reporting on AMD should include:

- Annual company sustainability reports—information on social, economic and environmental aspects of a mining operation (or a company as a whole)
- National Emissions Inventory (NEI)—emissions to land, air and water are commonly reported as part of an annual sustainability report (discussed in Section 4.2)
- Community and stakeholder consultation/engagement—reports, fact sheets, information kits, presentations, meetings and dedicated web sites (refer to the *Community Engagement and Development Handbook* in this series)
- Global Reporting Initiative (GRI)—a global framework for corporate sustainability reporting at www.globalreporting.org.

The identification of potential AMD issues at the exploration and feasibility phases is critical, as these phases are often linked with community consultation, environmental impact assessment and regulatory approvals. A transparent and accountable operation will be viewed favourably with respect to its commitment to sustainability.

Comprehensive data on sulfidic materials and AMD needs to be collected and analysed throughout the mine life and rehabilitation stages. At present there is limited systematic AMD data reporting by mining companies. The extent of sulfidic materials mined annually is not distinguished in public reporting—only the issue and its management commonly are addressed. Very little reporting of waste rock volumes is carried out by mining companies (Mudd 2005).

To demonstrate leading practice, explicit reporting of waste rock (as well as tailings and other potential AMD sources) and the proportion of which is sulfidic, could be incorporated into reporting requirements.

Given the high profile nature of problematic sites, demonstrated sound management and public accountability for AMD outcomes is imperative. The data can be synthesised into formal company sustainability reports, utilising and expanding on the NEI and GRI frameworks, or released as specific studies for a particular project.

Many communities hold legitimate concerns over the long-term performance of engineered structures to isolate and rehabilitate sulfide materials and AMD. Extrapolation into the future is a very difficult technical issue. Consultation can help identify locally-appropriate strategies for AMD issues and ensure that economic, technical and regulatory constraints are addressed.

Some aspects of AMD management are yet to develop satisfactory technical solutions. Where AMD is predicted and there are no adequate technologies to manage it, it is necessary to use the ‘precautionary principle’.

10.0 CONTINUING IMPROVEMENT IN THE MANAGEMENT OF AMD

A significant amount of research has been conducted over the last two decades to understand the nature of AMD and to develop practical solutions to manage its generation and release. The triennial proceedings of the international conference on acid rock drainage record the progress made since 1988 (Barnhisel 2006).

A collection of research reports and links to AMD networks can be found on the web site of the International Network for Acid Prevention (INAP) www.inap.com.au. INAP is an industry group created to help meet the global challenge of dealing with AMD. It mobilises AMD information and experience and promotes research and innovation.

Much of the research to date has concentrated on techniques to control the overall pollutant generation rate from waste rock piles and tailings storage facilities. Control measures such as selective placement of waste rock and the use of covers (earthen and water) are currently accepted as leading practice (see Section 7). Whilst research is still needed to quantify the actual effectiveness of many widely-adopted methods of AMD management and to establish the long-term sustainability of those methods, significant benefits may be achieved by investigating and developing new approaches to the problem at all stages of the mining process.

Within the context of sustainability, there are opportunities for AMD research outcomes to reduce the environmental footprint of mining significantly. Breakthrough technologies may be discovered to increase metal recovery, reduce the volume of sulfidic wastes, reduce the reactivity of the wastes or reduce AMD releases to the environment.

10.1 Emerging technologies and Future Research

Technologies emerging from current research efforts include:

- INAP initiative - A worldwide guide (GARD) that captures and summarises best science and a risk-based approach to acid rock drainage management
- a passive, high-rate sulfate and metal removal, technology provided by the IMPI® process which has been developed over the past decade in South Africa (Pulles et al. 2003)
- Permeable Reactive Barriers (PRBs) for *in situ* passive groundwater treatment (Blowes et al. 2000 and Vidic 2001)
- a practical method to measure the intrinsic oxidation rate (IOR) of geologic materials within hours to days (Bennett & Mackenzie 2005)
- chemical micro-encapsulation of individual sulfide grains to retard oxidation
- lowering the acidity load in drainage water from piles by applying alkalinity-producing covers (Miller et al. 2003, 2006 and Taylor et al. 2006)

- displacing oxygen in decommissioned underground mines (Taylor & Waring 2001)
- down hole logging of ABA parameters, development of on-line oxygen probes, and further refinement of techniques for the measurement of NAPP and NAG values.

The following research areas may deliver rewards in the future:

- improving the incorporation of characteristic properties of sulfidic materials into geological block modelling, mine optimisation and scheduling software to improve the confidence in waste management
- modifying grinding circuits and process flowsheets to reduce the sulfide content of waste streams, leading to cleaner production
- increasing the amount and quality of water recovered from tailings to reduce water consumption and reduce the volume of drainage
- developing new technologies for measuring and monitoring sulfide-containing wastes to improve the understanding of the effectiveness of AMD controls and reduce the risk associated with them.

Significant advances in AMD management may result from a few well-chosen demonstration sites in Australia, building on the experience of Sweden (Höglund & Herbert 2003). At these sites the full suite of available and innovative techniques could be applied, developed and tested.

11.0 CONCLUDING REMARKS

The significant, long-lived and highly visible impacts of AMD from historical mining activities continue to damage the environmental credibility of the mining industry. Legacy sites have served to alert society to the dangers of poor management practices and as a result community expectations and environmental performance targets have been progressively rising. Legacy site issues are no longer tolerated for new mining projects. Sustainable development requires proactive AMD management, commencing from the exploration phase and full closure planning and costing that comprehensively accounts for all facets of waste management prior to commencement of mining. This handbook provides a good starting point for both understanding and managing the AMD issue.

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WEB SITES

- Department of Environment and Heritage, www.deh.gov.au
- Department of Industry, Tourism and Resources, www.industry.gov.au
- Leading Practice Sustainable Development Program, www.industry.gov.au/sdmining
- International Network for Acid Prevention www.inap.com.au
- Ministerial Council on Mineral and Petroleum Resources, www.industry.gov.au/resources/mcmpr
- Minerals Council of Australia, www.minerals.org.au
- Enduring Value, www.minerals.org.au/enduringvalue
- National Environment Protection Measures, www.ephc.gov.au/nepms/nepms.html
- World Bank, www.worldbank.org/mining
- Australian Centre for Minerals Extension and Research www.acmer.uq.edu.au/

GLOSSARY

AASS	Actual acid sulfate soil.
ABATES	A software tool to assist with mine site water quality management. It was developed to assist mining companies with acid-base accounting and water quality assessment. Available for free download at www.earthsystems.com.au/tools.htm.
Acid	A measure of hydrogen ion (H^+) concentration; generally expressed as pH. Acid is not equivalent to acidity (see definition below).
Acid base account	An Acid Base Account (ABA) evaluates the balance between acid generation processes (oxidation of sulfide minerals) and acid neutralising processes. It can involve determination of the maximum potential acidity (APP) and the inherent acid neutralising capacity (ANC), both defined below.
Acid drainage	A form of Acid and Metalliferous Drainage (AMD), characterised by low pH, elevated toxic metal concentrations, high sulfate concentrations and high salinity.
Acidity	A measure of hydrogen ion (H^+) concentration and mineral (latent) acidity; generally expressed as mg/L $CaCO_3$ equivalent. Measured by titration in a laboratory or estimated from pH and water quality data.
Acidity load	The product of acidity and flow rate, generally expressed as mass $CaCO_3$ equivalent per unit time.
Acidity load balance	The acidity load balance for a mine site takes into account water volumes and flow rates as well as acidity (see definition above), and incorporates all mine facilities that are potential sources of AMD, for example, waste rock piles, ore stockpiles, tailings storage facilities, pits, underground workings, heap leach piles and mine construction materials.
ACMER	Australian Centre for Minerals Extension and Research, a unit within the Sustainable Minerals Institute, University of Queensland, www.acmer.uq.edu.au

Active treatment	Process in which chemicals or natural materials are added to AMD to improve water quality. Operator control can vary from relatively simple batch treatment to a sophisticated computerised treatment plant with multiple additives and detailed process monitoring and control www.inap.com.au. Active treatment involves regular reagent and labour inputs for continued operation, compared with passive treatment (see below) that only requires occasional maintenance. Active treatment systems can be engineered to deal with any acidity, flow rate and acidity load.
ADTI	Acid Drainage Technology Initiative www.unr.edu/mines/adti/
Alkaline cover	A soil cover, such as water shedding or store-and-release cover (defined below), that has an 'alkalinity generating' component deployed above, within or at the base of the cover. The aim is to minimise infiltration and ensure that any water that migrates through the cover contains substantial alkalinity (defined below).
Alkalinity	A measure of the capacity of a solution to neutralise an acid.
AMD	Acid and Metalliferous Drainage (see detailed definition in Section 2.1).
AMDTreat	Software that can be used to predict and model AMD treatment costs. The software provides many different treatment options both for passive and active treatment systems. Available for free download at www.amdtreat.osmre.gov
AMIRA	AMIRA International Limited www.amira.com.au
ANC	Acid Neutralising Capacity, expressed as kg H_2SO_4 equivalent per tonne.
ANSTO	Australian Nuclear Science and Technology Organisation.
APP	Acid Producing Potential, expressed as kg H_2SO_4 per tonne.
AQUARISK	Software developed by ANSTO to enable probabilistic ecological risk assessments to be undertaken for freshwater ecosystems impacted by AMD www.hearne.com.au/aquarisk/
ASS	Acid sulfate soils.
Blending	Mixing of potentially acid-generating mine wastes with alkaline materials to create a composite material in which acid produced is at least partially consumed *in situ* by surrounding alkaline materials.
Block model	A three-dimensional model of the distribution of ore and waste materials with different geochemical properties (metalliferous mines). Also see 'grid/layer model'.

Co-disposal	Combined disposal of coarse-grained (waste/rejects) and fine-grained (tailings) waste streams; used extensively in the Australian coal industry.
EIA	Environmental Impact Assessment. In this handbook, the term EIA also refers to Environmental Impact Statement (EIS), Environment Effects Statement (EES).
GRI	Global Reporting Initiative <www.globalreporting.org/home>.
Grid/layer model	A two-dimensional model of the distribution of ore and waste materials with different geochemical properties (coal mines). Also see ‘block model’.
Heap leach spent ore	Material remaining after recovery of metals and some soluble constituents through heap leaching and heap rinsing of ores (MMSD 2002).
INAP	International Network for Acid Prevention www.inap.com.au/
Kinetic test	Procedure used to measure the magnitude and/or effects of dynamic processes, including reaction rates (such as sulfide oxidation and acid generation), material alteration and drainage chemistry and loadings that result from weathering. Unlike static tests, kinetic tests measure the behaviour of a sample over time www.inap.com.au
Lag time	Time delay between the disturbance or exposure of acid-generating materials and the onset of acidic drainage.
Lithology	A soil or rock type defined by a distinct set of physical and mineralogical characteristics.
Low grade ore stockpile	Material that has been mined and stockpiled, with sufficient value to warrant processing, either when blended with higher-grade rock or after higher-grade ore is exhausted, but often left as ‘waste’ (MMSD, 2002).
MEND	Mine Environment Neutral Drainage www.nrcan.gc.ca/ms/canmet-mtb/mmsl-lmsm/mend/default_e.htm
Metalliferous drainage	A form of Acid and Metalliferous Drainage (AMD), characterised by near-neutral pH, elevated heavy metal concentrations, high sulfate salinity.
Micro-encapsulation	Technology for the prevention or minimisation of AMD from pit walls. This method, also referred to as sulfide passivation, is designed to prevent air and water reacting with individual sulfide crystals by chemical encapsulation.

NAG	Net Acid Generation test, also referred to as 'single addition NAG test'. Peroxide is used to oxidise any sulfides in a sample, then any acid generated during oxidation may be partially or completely consumed by neutralising components in the sample. Any remaining acidity is expressed as kg H_2SO_4 per tonne. A 'sequential NAG test' involves a series of NAG tests on a sample. This may be required if a sample cannot be fully oxidised using the conventional NAG test.
NAPP	Net Acid Producing Potential, expressed as kg H_2SO_4 per tonne. Calculated by subtracting acid neutralising capacity (ANC) from acid producing potential (APP).
NEI	National Emissions Inventory (replaces National Pollutant Inventory, NPI).
PADRE	Partnership for Acid Drainage Remediation in Europe www.padre.imwa.info/
PASS	Potential acid sulfate soil.
Passive treatment	Passive treatment systems are best suited to AMD with low Acidity (<800 mg CaCO3/L), low flow rates (<50 L/s) and therefore low Acidity Loads (<100-150 kg $CaCO_3$/day). Also see 'active treatment'.
PHREEQC	Software for simulating chemical reactions and transport processes in natural or contaminated water wwwbrr.cr.usgs.gov/ projects/GWC_coupled/phreeqc/
POCAS	Peroxide Oxidation – Combined Acidity and Sulfate analytical test work procedure.
Precautionary principle	This principle states that, where the scientific evidence is uncertain, decision-makers should take action to limit continued environmental damage and should err on the side of caution when evaluating proposals that may have a serious or irreversible impact on the environment.
Saline drainage	A product of Acid and Metalliferous Drainage (AMD), characterised by high sulfate salinity but near-neutral pH and low concentrations of heavy metals.
Soil cover	One or more layers of soil-like materials intended to limit the percolation of rainfall or the ingress of oxygen, or both, into AMD-generating materials.

Static test	Procedure for characterising the physical or chemical status of a geological sample at one point in time. Static tests include measurements of mineral and chemical composition and the analyses required for Acid Base Accounts.
Store-and-release cover	Cover system designed to minimise the infiltration of water to underlying materials by incorporating materials with high water storage capacity and plants with high rates of evapo-transpiration.
TAA	Total actual acidity. TAA refers to the acidity generated from a 1:20 soil solution extract without prior peroxide oxidation.
Tailings	Finely ground materials from which the desired mineral values have been largely extracted. Approximately 98 per cent of the material mined for processing is discharged as tailings. At coal mines, tailings represent the coarse and fine rejects from the coal washery (MMSD, 2002).
Tailings dam	Facility designed for the storage of saturated tailings material and supernatant water produced during ore processing. Tailings dams, unlike tailings storage facilities, are designed as competent water-holding structures.
Tailings storage facility	Facility designed for the storage of unsaturated tailings material produced during ore processing. These facilities, unlike tailings dams, are not suitable for storage of supernatant water.
Waste rock	Material such as soils, barren or uneconomic mineralised rock, that surrounds a mineral or coal orebody and must be removed in order to mine the ore. This is generally referred to as waste rock in metalliferous mines or overburden, interburden, interseam or spoil in coal mines (MMSD, 2002).
Water cover	Layer of surface water (such as in a tailings storage facility or pit) or groundwater (for example, in a backfilled pit) intended to limit the ingress of oxygen into AMD-generating materials.

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