

MANAGEMENT OF SULFIDIC MINE WASTES AND ACID DRAINAGE

HANDBOOK

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ACMER Management of Sulfidic Mine Wastes Project

September 1999



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1. Introduction

The management of sulfidic mine wastes and, in particular, acid drainage (AD) is an important issue in the Australian mining industry. The Mt Lyell and Rum Jungle minesites are probably the best known of Australian examples where AD has had a significant environmental impact. It is certainly not unique to Australia. In fact it has been a major problem for many mines throughout the world.

Mining companies are now beginning to experience how AD can escalate the cost of mining in the starting phase (increased rehabilitation bonds), operating phase (building of engineered containment structures and treatment of recycled water) and decommissioning, when water has to be treated prior to discharging from mining leases, perhaps for hundreds of years. The total cost of dealing with potentially acid forming sulfidic waste in Australia has been estimated to be approximately \$40,000 per hectare. The cost of remediating abandoned minesites is higher, approximately \$100,000 per hectare.

Senior mining industry officers in mining companies and government regulatory authorities have a responsibility to be aware of AD issues and how they can be controlled.

This awareness booklet has been designed to give mining professionals and other interested parties a brief summary of what we know about AD. It also describes the technology that is available to assist the industry in dealing with the issue.

Readers are also directed to a best practice booklet by Environment Australia titled "Managing Sulfidic Mine Wastes and Acid Drainage" and to the AMEEF publication "Groundwork" (Number 1, Volume 2, September 1998) on acid drainage.

2. How and when does sulfide oxidation and acid drainage occur?

AD can occur when sulfide minerals, particularly pyrite (FeS_2), pyrrhotite (approx. FeS) and marcasite (FeS_2), but also chalcopyrite (CuFeS_2) and arsenopyrite (FeAsS), oxidise in the presence of oxygen and water. The reaction is:

sulfide mineral + oxygen + water = sulfate + acidity + metals

Most often, the principle cause of AD is the oxidation of pyrite found in gold, base metal, coal and other types of mines.

Any stored waste material such as a waste rock dump, or a tailings dam, or any excavated mining face such as an open pit, which has high enough concentrations of pyrite and/or other sulfides, has the potential to generate and release acid and dissolved metals. This released water can adversely affect revegetation of the site and the quality of the receiving streams outside of the mining area.

The amount of acid released from stored waste material is dependent on the concentration and rate of oxidation of the sulfides, nature and quantity of acid consuming minerals in the waste, and the amount of water passing through or over the waste material. The chemistry is complex, and it is difficult to determine when acid generation will occur. Acid generation can occur almost immediately the rocks are exposed to air and water, or can take tens of years to fully develop. The release of acid can continue over tens to thousands of years (e.g. Rio Tinto, Spain).

Initially, the principal factor controlling the rate of oxidation of pyrite is oxygen in the presence of water. However, as the pH of the water decreases with increasing acidity, ferric ions (Fe^{3+}), produced from the oxidation of iron sulfides, become more dominant in the oxidation process (i.e. the ferric ion becomes a stronger oxidising agent than oxygen). Below about pH 3.5-4.0, the increased rate of oxidation and acid formation is due largely to the presence of ferric ions. Note that even under highly acidic conditions, the presence of oxygen is still required for the formation of ferric ions.

Commonly, the amount of atmospheric oxygen needed to generate acid in mine wastes is low, less than a few percent of the oxygen content in air.

Generated acid may not migrate if there is a sufficient volume of acid neutralising minerals in the rock material, such as calcite and dolomite. However, metals such as arsenic, zinc, copper, cadmium and manganese may continue to migrate, even at near neutral pH.



Pyrite on the left hand side has commenced reacting before pyrite on the right side. It is often difficult to estimate when pyrite oxidation will start to occur.

3. Release of metals during the oxidation process

Metal sulfides, which do not contain iron in their molecular structure, such as covellite (CuS), galena (PbS), millerite (NiS) and sphalerite (ZnS), do not have the capacity to generate significant acid. These sulfides are generally far less reactive than the iron bearing sulfides, partly because their crystal structures provide them greater chemical stability. However, once oxidised, they can be a source of metal salts which can be readily leached into the surrounding environment. Chalcocite (Cu_2S) is acid consuming.

The oxidation process can release elevated concentrations of dissolved metals in drainage, even if sufficient acid consuming minerals are present to neutralise the generated acid. For instance, copper can be released from chalcopyrite, arsenic from arsenopyrite, zinc from sphalerite and lead from galena.

Some elements which can be environmentally harmful at low concentrations in water commonly occur as minor constituents in solid solution in sulfide minerals. Examples include manganese, cobalt, cadmium and mercury in sphalerite; and antimony, bismuth, arsenic, selenium and thallium in galena. These toxic metals are made soluble, or released as ions into the water phase, when their sulfide hosts are oxidised.

The types of contaminants generated by the oxidation process will vary depending on the nature of the materials and the minerals present:

- (a) At one extreme, acidity, high sulfate and soluble iron concentrations can result from the oxidation of iron sulfides alone.
- (b) The other extreme is a neutral leachate with no appreciable sulfate concentration, but a high concentration of one or more heavy or toxic element ions.
- (c) Most commonly, it is a combination of a) and b).



Acidic and metal-contaminated stream, Queensland.

4. Where does acid drainage occur?

Acid drainage has the potential to occur anywhere on a mine where sulfides are exposed to atmospheric oxygen and water, e.g. exposed pit face, low grade stockpile, haul road, underground mine, waste rock dump, tailings embankment, tailings dam and spent heap leach material. There needs to be water passing over or through the waste material to transport the acid to the environment.

It can also occur in a wide variety of climates from semi-arid Australia where temperatures exceed 40°C in summer, to Arctic Sweden where pyrite is oxidising at temperatures close to 0°C. Pyrite oxidation is exothermic and generates its own heat.

Results from a survey of Australian mines conducted in 1996-97 (Harries 1997), indicated that the excavation of material with some pyrite content occurs at many mines. Responses to the survey also indicated that approximately 37% of mines appear to be managing some potentially acid-generating wastes. The magnitude of the issue varied from significant to minor.



Typical iron oxide coating on a mined rock face resulting from acid generation

Some historic and abandoned mines which have released acid include Agricola (Qld), Ardlethan (NSW), Brukunga (SA), Captain's Flat (NSW), Drake (NSW), Horn Island (Qld), Kangiara (NSW), Mt Lyell (Tas), Mt Morgan (Qld), Ottery (NSW), Peelwood (NSW), Rum Jungle (NT), Teutonic Bore (WA) and Sunny Corner (NSW).



Oxidation of pyrrhotite in tailings soon after deposition.

5. What are its effects?

Most mining operations have to discharge water to streams outside of their operating licence areas. Mines in more humid climates discharge more water than mines in semi-arid climates. However, regardless of the location, the quality of discharged water has to meet a specified standard. Water quality standards are values set for parameters such as pH, turbidity, and concentrations of sulfate, iron and other metals and non-metals. The Australian and New Zealand Environment and Conservation Council water quality guidelines are commonly used as a basis for establishing mining license water quality conditions for discharge and receiving water (see Appendix). They are designed to protect downstream aquatic and semi-aquatic ecosystems, drinking water and water for agricultural use.

An unexpected generation of significant acid on a site can result in the following:

- exceedance of discharge water quality standards and possible adverse effects on downstream animals and plants, potentially leading to fines and litigation;
- non-budgeted cost of establishing a water treatment plant to neutralise acidic water prior to recycling (acidic water will corrode machinery and is not compatible with many metallurgical processes);
- cost of treating water prior to discharge off-site, so that discharge water quality standards can be met (this may have to be done for many years);
- additional rehabilitation costs which will be incurred to slow down the rate of acid generation;
- possibility of never legally being released from a performance bond;
- discouraging potential investors from joint venturing or buying the operation;
- discouraging banks from lending money to the operation; and
- restrictions placed on the company to further access other potential mining areas.

6. Prediction methods

A simple rule of thumb is that if any pyrite is visible in a portion of a pit face, or part of a waste dump, then detailed predictive AD investigations should be conducted. However, mining companies are advised to always exercise caution, and they should characterise all waste materials, regardless of whether pyrite is visible.

Another valuable exercise to determine the risk of AD is to visit older mines of a similar type and ask about the quality of their water discharges, or what remediation measures they may have had to undertake and whether they have been successful.

The first and most important aspect for any investigation into the potential of AD is that the site geologist should know the rock types, and the content and distribution of pyritic sulfides in the ore and waste rock units. The geologist should be able to block-model the waste rock units and pyrite concentrations in the same way that gold or base metal or coal resource modeling is conducted. It is most cost-effective to start this process in the exploration stage of mining. As a minimum, %sulfur and %carbon should be analysed from drill samples.

After determining the number of waste rock categories (separate geological units with different concentrations of pyrite), the geologist and a qualified geochemist should determine an appropriate number of samples that will be representative of each category. It is most important that a sufficient number of samples are collected to effectively characterise elements such as the pit walls, low grade ore, overburden and tailings materials. One of the alarming results of the 1996-97 survey of the Australian mining industry (Harries, 1997) was the generally very low number of samples collected for testing and characterisation of waste materials. Obviously, taking only a few samples will increase the risk of a misleading assessment.

Sample characterisation methods to assess potential acidity currently being used in Australia are:

Static Tests which determine both the total acid generating and total acid consuming potential of a sample and are used to predict the potential of the rock to produce acid. These include:

- paste or slurry pH tests to measure the surface acidity of rocks;
- Acid-Base accounting tests which determine the Maximum Potential Acidity (MPA) and Acid Neutralising Capacity (ANC) of samples;
- Net Acid Producing Potential (NAPP) which is the theoretical balance between a sample's capacity to generate acid and its capacity to neutralise the acid that is generated ($NAPP = MPA - ANC$); and
- Net Acid Generation (NAG) test using hydrogen peroxide to stimulate oxidation to assess how much acid production may occur.

Kinetic Tests which give information on the rate and timing of the oxidation process. The common tests are:

- kinetic NAG - a quick and efficient method to determine whether a material will generate acid and how long it will take; and
- column leach tests - require a minimum of four months and are usually conducted over two to three years. This provides information on the oxidation rate, lag period for acid release, and metal release rate for the short and long term quality of water in the field. These tests can be used to compare different placements of materials in the field such as layering of different wastes, or blending.

More detailed information on these tests can be obtained from the ACMER, or consulting companies specialising in this type of work. ACMER is currently preparing a manual of "Field Techniques to Quantify AMD-Related Processes". Included in the manual will be descriptions of how to conduct the above mentioned tests.

Results of these tests will place a waste material type into one of five categories, which are:

- Acid Consuming Material, non-sulfidic (ACM);
- Non-Acid Forming - Low Sulfur (NAF-LS);
- Non-Acid Forming - High Sulfur (NAF-HS);
- Potentially Acid Forming - Low Capacity (PAF-LC); and
- Potentially Acid Forming - High Capacity (PAF-HC).

If a site contains either PAF-HC, PAF-LC or NAF-HS material, then management of the oxidation and water drainage from this material must be given serious attention.

Attention must also be given to NAF-LS and ACM materials if they host unstable secondary minerals which have precipitated from the oxidation of metal sulfide minerals. Drainage from materials in this category may, for example, have elevated concentrations of metal salts. Aqueous metal concentrations can sometimes exceed toxic values when drainage waters have near neutral to alkaline conditions ($6 < pH < 9-10$).

It is important that sites should budget for the continual characterisation and monitoring of waste materials during the life of the project.



Kinetic testwork on tailings in plastic tanks.

7. Prevention measures

The oxidation of sulfides leading to the formation and release of sulfate and acid, and the liberation of metals into water, are the most extreme effects of the oxidation process. Prevention objectives are to significantly reduce the oxidation of sulfides occurring at source. This can be done by inhibiting the input of oxygen which is the principal ingredient for the initiation of oxidation and the acid generation process. (Note that with available oxygen and no infiltration of water, the natural moisture content of waste rock is sufficient for considerable in-situ acidification from the oxidation of much of the contained pyrite.)

In situations where there is ready entry of oxygen permitting the oxidation of sulfide to proceed at a rate which generates significant heat, there will be surface venting of SO_2 and acidic gaseous vapors and, at times, precipitation of native sulfur where these vapors cool to ambient temperatures in the absence of excess rainwater. Where venting occurs on waste rock and tailings storages, it is commonly manifested as small cones on the surfaces of these structures.



“Dry” oxidation (combustion) occurring at and near the surface of a waste rock dump.

Management strategies available to deal with AD are to:

- locate the source of AD;
- assess the chemistry of the leachate and its potential effects;
- install interim treatment system whilst waste handling measures are developed and integrated with the mine plan;
- look at selective handling of AD wastes;
- design burial/sealing program to isolate AD wastes;
- ensure that run-on water is diverted and rainfall water is readily shed to minimise the quantity of contaminated water; and
- install water polishing system to “tidy-up” drainage quality (e.g. anoxic limestone drain and wetland).

Location, climate (arid, semi-arid or humid), availability and cost of appropriate materials and other factors, will dictate the most appropriate management strategy.

A common method of control is the placement of an engineered cover over the top of PAF waste materials. Single or multi-layered covers for the control of AD are built to:

- limit oxygen ingress by maintaining a high degree of saturation, i.e. the cover always maintains some layering of moisture to stop oxygen getting down into the waste materials (more suited to humid, wet climates);
- function as a water infiltration barrier as a result of low permeability clay being used in the construction of one or more layers;
- function as a water infiltration barrier by compacting appropriate waste materials so that rainfall run-off is maximised and water infiltration is minimised (more-suited to semi-arid climates);
- function as a moisture storage and release layer, whereby the layers are designed to capture by infiltration as much of the rainfall as possible and allow the evapotranspiration process to release the water back into the atmosphere (more suited to semi-arid climates);
- function as a non-acid generating oxygen consuming cover layer over PAF materials;
- provide a suitable medium for revegetation which is consistent with the current and final landuse in the area;
- maintain physical stability and integrity against erosional processes; and
- maintain physical integrity against the heat and potential vapor pressures resulting from the oxidation of stored pyrrhotite wastes (i.e. no venting through the engineered cover).



Venting at the surface of a pyrrhotite tailings deposit with precipitation of yellow sulfur.

The placement of potentially acid-forming wastes under permanent water cover, such as a pond or lake, is also an option. However, this is only possible in locations and climates where sufficient water cover can be constantly maintained. The exposure of potentially “reactive” rocks to the processes of lake stratification, water mixing, overturn events and natural inputs of oxygenated water need to be considered.

Ocean disposal of waste materials, mainly tailings, has been successfully carried out by some mines located near deep seas.

In practice, building a cover in arid to semi-arid climates to prevent or reduce oxygen ingress into a waste dump is a difficult proposition. The performance of the cover is a function of the oxygen diffusion coefficient and thickness. A 10-50 metre cover is possible in some situations and can control oxidation.

Several companies have opted for designs which reduce infiltration of water, rather than oxygen. Although this strategy will continue to allow oxidation and acid generation to take place in the dump, the argument is that little or no AD emanating from the dump is the lesser of two problems.

All of the above strategies require considerable thought and planning. It is recommended that if a strategy is needed, the advice of an expert professional should be sought.

The long term post-mining control of erosion and the protection of engineered cover systems is of paramount importance.



Coarse material depositing at the boundary of coalescing faces of an advancing waste dump – a preferred pathway forming for movement of oxygen and water.

8. Mitigation action to reduce acid drainage effects

In the event that AD does occur, or sufficient evidence is obtained that it is likely to occur, the following actions should be undertaken:

- notify the appropriate authorities;
- choose an appropriate group of professionals to deal with the issue;
- determine the source of the acid or sulfate;
- quantify the problem;
- conduct an initial risk assessment;
- define and review engineering options;
- conduct a more detailed risk assessment with a cost-benefit analysis comparing options; and
- obtain agreement on the appropriate mitigation option.

Methods which can be considered to manage the discharge of AD include:

- AD containment and evaporative disposal (a short term measure only in drier climates);
- AD controlled discharge to receiving waters outside of the mining lease area (this depends on flow rate, quality of discharge and effect on receiving water quality);
- collection and treatment in perpetuity of AD (data from a Canadian mining study and the Brukunga, South Australia investigation concluded that this was the cheapest option); and
- options described as “Prevention Measures” in Section 7 above (Canadian mining data show that the placement of engineered covers on waste materials was the highest cost option).

9. Monitoring

Sites containing sulfidic wastes should be regularly monitored. Stored waste materials (e.g. waste rock dumps, tailings dams), which are potential long term sources of AD or potential sources of discharge of poor quality water, should be monitored, as well as any discharge from those sources.

The monitoring plan should not only satisfy the site's legal requirements, but should also provide the operator with sufficient data to identify any trends. Any trends in the data, even before groups of points become statistically "significantly" different from the previous average, may be indicative of important changes taking place. These data should then be used to make present and future assessments of water quality, including the potential of acid generation.

Monitoring of stored waste materials should include measurements of the:

- surface chemistry and soluble constituents in the outer oxidation zone;
- amount of water infiltration into the dump (using lysimeters in waste rock dumps and piezometers in tailings impoundments);
- temperature changes (spatially and temporally in a monitoring hole/s); and
- rate of oxidation in the waste materials (sampling for oxygen in a monitoring hole/s).

Data from these measurements will give a pointer as to whether acid generation is occurring in the material at depth and, if so, an estimation can be attempted of the flow rate of future AD. In respect of waste rock dumps, however, there is very little industry knowledge about flow paths and rates of flow.

The installation of devices to measure the above parameters in stored waste materials is a specialist operation.

Drainage water emanating from stored materials should be routinely monitored for the following physical and chemical parameters:

- drainage flow rate;
- pH;
- salinity (electrical conductivity);
- acidity;
- alkalinity;
- major cations and anions (to achieve an approximate charge balance);
- iron; and
- other appropriate metals such as manganese, arsenic, zinc, copper, cadmium and aluminium depending on site specific mineralisation.



Equipment established at and below the surface of a waste dump at Mt Whaleback, WA, to monitor infiltration of rainwater into and evaporation out of the surface of the dump

Awareness of potential AD should increase if an upward or downward trend in pH is observed, along with a change to one or more of the other parameters, particularly sulfate, calcium and alkalinity. It may become appropriate to monitor for additional metals when changes start occurring to the pH of drainage.

It may also be appropriate, depending on the location of the mine and its situation, to monitor groundwater quality downstream of stored waste material sites. Parameters to be monitored should be the same as those for drainage monitoring above. Instead of flow rates, however, the permeability of the groundwater rocks being monitored should be determined (a once only procedure).

10. Risk assessment

Risk is exposure to the consequences of uncertainty. It has two elements, viz.

- probability of an event occurring; and
- consequence if it were to happen.

Under this definition, risk is defined by the following equation:

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

Depending on the objective of a risk assessment, the probability of an event occurring and the cost of the consequence can be qualitative or quantitative. Qualitative risk assessment is based on a rating system (e.g. high, moderate, low), while quantitative risk assessment assigns values to the individual components of risk, e.g. a value between 0 and 1 for probability and cost as the measure of consequence.

Determining the types of events and their consequences is only a part of what has to be done. The real objective of the risk management process is to reduce risk exposure and make achieving or exceeding planned objectives more likely. The process requires the systematic application of management policies, processes and procedures to the tasks of identifying, analysing, assessing, treating and regularly monitoring risk.

Risk management is a valuable tool in facilitating improved environmental planning and business outcomes.

The risk of acid drainage AD or unacceptable quality of near neutral drainage initially relates to the source materials, that is, which of the materials, if any, will react and release contaminants. The probability of AD is usually assessed using the static and kinetic geochemical testwork summarised in Section 6. Summarising this testwork again, the results of these tests will place a waste material type into one of five categories, which are:

- Acid Consuming Material, non-sulfidic (ACM);
- Non-Acid Forming, Low Sulfur (NAF-LS);
- Non-Acid Forming, High Sulfur (NAF-HS);
- Potentially Acid Forming - Low Capacity (PAF-LC); and
- Potentially Acid Forming - High Capacity (PAF-HC).

It is reasonable to initially assume that without a suitable mode and environment of disposal, the following material classifications will have the following risks with respect to the probability that exposure of the material will result in unacceptable water quality:

- ACM - very low risk;
- NAF-LS - low to moderate risk;
- PAF-LC and NAF-HS - moderate risk; and
- PAF-HC - high risk.

If PAF and NAF materials are identified, further assessment should be conducted which may lead to an evaluation of prevention options discussed in Section 6.

The consequences to the environment from AD depend on many factors. Consideration should be given to not only the effects on the ecosystem should AD occur, but to other impacts as well, such as on stakeholders. Landowners and occupiers and other users of water and land are likely to seek action for the amelioration of any substantial degradation.

For more information on how to conduct a risk assessment, the reader is referred to the ACMER Handbook "Risk Assessment Framework for the Management of Sulfidic Wastes" (Lee 1999).

11. Potential liability

The legal liability of a mining company for:

- rehabilitation associated with decommissioning a mine, and
- remediation costs in the event that something goes wrong, either during the operation or after decommissioning,

is dependent upon the conditions attached to a mining permit, a security deposit which may be held by the regulatory authority which granted the permit, and past and current legislation which is relevant to the operation.

Neither the regulatory authorities nor the public want to spend taxpayer's money rehabilitating abandoned mines which discharge poor quality water. Nor do they want to fund the rehabilitation of mining ventures which, for one reason or another, might have their operations suspended prematurely and which might also discharge poor quality water.

There are several abandoned mines in Australia with AD discharges which have had to be partially rehabilitated by government agencies. Examples of these are Agricola, Qld (just under \$1 million), Captains Flat, NSW (\$2.3 million), Horn Island, Qld (\$2.2 million less the owner's security deposit of \$500,000 less \$600,000 raised by sale of the company's assets), Mt Lyell, Tas (\$2 million) and Rum Jungle, NT (\$18.6 million).

Overseas examples of liability include Summitville, USA (total rehabilitation liability estimated at US\$100 million), Leadville, USA (clean-up costs estimated at US\$290 million in 1986) and a large operation in Utah where an estimated liability is between US\$500-1,200 million.

Some companies have found that the cost of managing AD has been or will lead to a net loss for the mining project.

Increasingly, by reason of abandoned mine experiences and public pressure, regulatory authorities in Australia are critically reviewing security deposits before the granting of permits. This has come about essentially because of mounting national and international pressure on the mining industry to achieve better environmental performance.

New mining ventures, which include the handling of sulfidic wastes, are likely to have their management plans critically evaluated by regulatory authorities before the amount of the security deposit is established.



Will a pit lake with poor quality water be a long term liability for your company ?

There are no strict formulae for the establishment of an appropriate security for a mining permit. However, poor or inappropriate performance by a company may attract more than the usual scrutiny when it applies for another permit.

Security deposits are now becoming an important cost factor in the mining industry. A high deposit in the order of many millions of dollars can result in the curtailment of a new mining operation or an expansion of an existing mine.

Good management of existing and new mining operations is a means of limiting the amount of security for a new permit. Hopefully, this booklet will be a useful tool to assist in the improved management of sulfidic mine wastes.

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13. Bibliography

Lee, M.C., (1999). Handbook on Risk Assessment Framework for the Management of Sulfidic Mine Wastes. (ACMER, Brisbane).

Australian and New Zealand Environment and Conservation Council (1992). Australian Water Quality Guidelines for Fresh and Marine Waters. (ANZECC, Canberra).

Australian Minerals and Energy Environment Foundation (1998) Groundwork. Special Feature Acid Drainage. Publication Number 1, Volume 2.

Australian/New Standard 4360 (1995) Risk Management.

Comarmond, J. (1997). Chemical methods for predicting the acid mine drainage/acid rock drainage potential of mine wastes in Australia. Appendix A, SSG Report No. 125. (Supervising Scientist, Canberra).

Dobos, S., (1998). Acid Mine Drainage-AMD, Acid Rock Drainage-ARD, and to be realistic, Management of Sulfidic Mine Wastes. In 'Proceedings of ACMER Short Course on Minesite Environmental Management', 2-4 December 1998, Darwin.

Environment Australia, (1997). Managing Sulfidic Mine Wastes and Acid Drainage. Best Practice Environmental Management in Mining Booklet. (Environment Australia, Canberra).

Evangelou, V.P. (1995). Pyrite Oxidation and Its Control. (CRC Press, New York).

Fell, R., Miller, S. and de Ambrosio, L. (1993). Seepage and contamination from mine waste. In 'Proceedings of the Conference on Geotechnical Management of Waste and Contamination', Sydney, NSW, 22-23 March, 1993. (A.A. Balkema, Rotterdam, Netherlands).

Harries, J. (1997) Acid Mine Drainage in Australia - Its Extent and Potential Future Liability. SSG Report No. 125. (Supervisory Scientist, Canberra).

Morin, K.A. and Hutt, N.M. (1997). Environmental Geochemistry of Minesite Drainage, Practical Theory and Case Studies. (MDAG Publishing, Vancouver, B.C.).

Proceedings of the Acid Mine Drainage Workshop, Strahan, Tasmania, (1992). Proceedings. Tasmania Chamber of Mines Ltd.

Grundon, N.J. and Bell, L.C.(Eds) (1995). Proceedings of the Second Australian Acid Mine Drainage Workshop. 28-31 March 1995, Charters Towers. (Australian Centre for Minesite Rehabilitation Research, Brisbane).

McLean, R.W. and Bell, L.C.(Eds) (1998). Proceedings of the Third Australian Workshop on Acid Mine Drainage. 15-18 July 1997, Darwin. (Australian Centre for Minesite Rehabilitation Research, Brisbane).

Scott, P. (1998) Mini workshop 2 - Acid drainage and mine waste geochemistry. From Minewater Conference, June 14-15, 1998. (Woodward-Clyde, Brisbane).

14. Glossary

The following is a glossary of the same and different acronyms commonly used in Australian and North American writings on the subject of acid drainage. Note that in Australia, acid base accounting calculations are based on the net acidity of samples (kg of H₂SO₄/t), whereas in North America it is based on the net neutralising potential available (kg of CaCO₃/t).

Australia	North America
AMD-acid mine drainage from minesites	AMD-acid mine drainage from minesites
ARD-acid rock drainage not related to mining activity	ARD-acid rock drainage not related to mining activity
AD-acid drainage, source not defined	AD-source not defined
MPA-maximum potential acidity	AP-acid potential
ANC-acid neutralising capacity	NP-neutralisation potential
NAPP-net acid producing potential (MPA-ANC)	-
-	NNP-net neutralisation potential (NP-AP)
ANC:MPA ratio	TNPR-total net potential ratio
-	NMD-neutral mine drainage

15. Some useful formulae

$$\text{kg H}_2\text{SO}_4 = 0.98 \times \text{kg CaCO}_3$$

$$\text{pyrite\%} = \text{sulfur\%} \times 120/64$$

$$\text{sulfur\%} = \text{pyrite\%} \times 64/120$$

$$\text{carbon\%} \times 81.66 = \text{kg H}_2\text{SO}_4/\text{t neutralising capacity (assuming that all the carbon is calcium carbonate)}$$

$$\text{MPA (kg H}_2\text{SO}_4/\text{t)} = 30.59 \times \text{sulfur\% (assuming the sulfide is pyrite)}$$

$$\text{ANC (kg H}_2\text{SO}_4/\text{t)} = 0.98 \times \text{kg CaCO}_3/\text{t}$$

16. APPENDIX A - Summary of ANZECC Water Quality Guidelines

The following four tables have been copied from the Australian and New Zealand Environment and Conservation Council, November 1992 "Australian Water Quality Guidelines for Fresh and Marine Waters".

Table 1: Summary guidelines for protection of aquatic ecosystems

Indicator	Units	Fresh waters	Marine waters
<i>Biological</i>		It is premature to recommend specific values for these indicators. The need for biological evaluation is recognised, and these indicators are identified as important characteristics of ecosystem function (Section 2.2)	
<i>Physico-chemical</i>			
Colour & clarity		< 10% change in euphotic depth ¹	< 10% change in euphotic depth
Dissolved oxygen ²	mg/L	> 6 (> 80-90% saturation) (Section 2.3.3)	> 6 (> 80-90% saturation) (Section 2.3.3)
Nutrients/nuisance growths			
PH		6.5-9.0	< 0.2 pH unit change
Salinity	mg/L	< 1000 (about 1,500 µS/cm)	
Suspended particulate matter/turbidity		< 10% change seasonal mean concentration (see also colour & clarity)	< 10% change seasonal mean concentration (see also colour & clarity)
Temperature ³		< 2°C increase	< 2°C increase
<i>Toxicants</i>			
Inorganic toxicants	all µg/L		
Aluminium		< 5.0 (if pH ≤ 6.5) < 100.0 (if pH > 6.5)	NR
Ammonia		20.0-30.0 (Table 2.3)	NR
Antimony		30.0	500.0
Arsenic		50.0	50.0
Beryllium		4.0 ⁴	NR
Cadmium		0.2-2.0 ⁵	2.0
Chromium		10.0	50.0
Copper		2.0-5.0 ⁵	5.0
Cyanide		5.0	5.0
Iron		1,000.0 ⁶	NR
Lead		1.0-5.0 ⁵	5.0
Mercury		0.1	0.1
Nickel		15.0-150.0 ⁵	15.0
Selenium		5.0	70.0
Silver		0.1	1.0
Sulfide		2.0	2.0
Thallium		4.0	20.0
Tin (tributyltin)		0.008	0.002
Zinc		5.0-50.0 ⁶	50.0
Organic toxicants			
Acrylonitrile		NR	NR
Benzidine		NR	NR
Dichlorobenzidine		NR	NR
Diphenylhydrazine		NR	NR
Halogenated aliphatic compounds			
Hexachlorobutadiene		0.1	0.3
Halogenated ethers		NR	NR
Isophorone		NR	NR
Monocyclic aromatic compounds			
Benzene		300.0	300.0
Chlorinated benzenes		(Table 2.8)	NR
Chlorinated phenols		(Table 2.9)	(Table 2.9)
Phenol		50.0	50.0
Toluene		300.0	NR
Nitrosamines		NR	NR
Pesticides			
Organochlorine		(Table 2.10)	(Table 2.10)
Organophosphate		(Table 2.10)	(Table 2.10)
Acrolein		0.2	0.2
Phthalate esters			
di-n-butylphthalate		4.0	NR
di(2-ethylhexyl)phthalate		0.6	NR
other phthalate esters		0.2	NR
Polyaromatic hydrocarbons			
Chlorinated naphthalenes		NR	NR

Polychlorinated biphenyls	0.001	0.004
Polychlorinated dibenzo- <i>p</i> -dioxins	NR	NR
Polycyclic aromatic hydrocarbons	3.0	3.0

SPM: Suspended particulate matter; NR: no recommendation made at this time
 Notes

1. For systems where depth is greater than 0.5x euphotic depth (Z_{eu}). For waters shallower than 0.5 Z_{eu} , the maximum reduction in light at the sediment bed should not exceed 20%
2. Measured over at least one, but preferably several, diurnal cycles
3. Or use formula in Section 2.3.7; no data for temperature reductions
4. Higher values may be acceptable in hard waters
5. Depends upon hardness of water
6. Provided iron not present at Fe(II)

Table 2: Summary of quality guidelines for raw waters for drinking purposes subjected to coarse screening

Parameter	Guideline values (mg/L, unless otherwise stated)
Biological parameters	
Micro-organisms:	
Total coliforms	Up to ten coliform organisms may be occasionally accepted in 100mL. Coliform organisms should not be detectable in 100mL of any two consecutive samples. Throughout any year, 95% of samples should not contain any coliform organisms in 100 mL
Faecal coliforms	No sample should contain any faecal coliforms in 100mL
Algae	Up to 5,000 cells/mL may be tolerated; levels of 1,000-2,000 cells/mL of cyanobacteria may result in problems
Toxic parameters	
Inorganic:	
Arsenic	0.05
Asbestos	NR
Barium	1.0
Boron	1.0
Cadmium	0.005
Chromium	0.05
Cyanide	0.1
Lead	0.05
Mercury	0.001
Nickel	0.1
Nitrate-N	10.0
Nitrite-N	1.0
Selenium	0.01
Silver	0.05
Organic:	
Benzene	10.0 µg/L
Benzo(a)pyrene	0.01 µg/L
Carbon tetrachloride	3.0 µg/L
1,1-Dichloroethene	0.3 µg/L
1,2-Dichloroethane	10.0 µg/L
Pentachlorophenol	10.0 µg/L
Pesticides	(Table 4.2)
Polychlorinated biphenyls	0.1 µg/L
Tetrachloroethene	10.0 µg/L
2,3,4,6-Tetrachlorophenol	1.0 µg/L
Trichloroethene	30.0 µg/L
2,4,5-Trichlorophenol	1.0 µg/L
2,4,6-Trichlorophenol	10.0 µg/L
Radiological:	
Gross alpha activity	0.1 Bq/L
Gross beta activity (excluding activity of ⁴⁰ K)	0.1 Bq/L
Aesthetic parameters	
Physical:	
Colour	15.0 Pt-Co
Taste & odour	Not objectionable*
Turbidity	Site-specific determinant
Chemical:	
Aluminium	0.2
Ammonia (as N)	0.01
Chloride	400.0
Copper	1.0
Oxygen	> 6.5 (> 80% saturation)
Hardness (as CaCO ₃)	500.0
Iron	0.3
Manganese	0.1
Organics (CCE & CAE)	0.2
pH	6.5-8.5
Phenolics	0.002
Sodium	300.0
Sulfate	400.0
Sulfide	0.05
Surfactant (MBAS)	0.5
Total dissolved solids	1,000.0**
Zinc	5.0

NR: No guideline recommended at this time; MBAS: Methylene blue active substances

* Engineering & Water Supply Department suggests combined concentration of geosmin and methylisoborneol should be less than 20 ng/L

** Levels in excess of 500 mg/L cause a deterioration in taste

Table 3: Summary of guidelines for irrigation water quality

Parameter	Guideline (mg/L, unless otherwise stated)	Comment
<i>Biological parameters</i>		
Plant pathogens	-	*
Human and animal pathogens	1,000 faecal coliforms/100 mL	Tentative value. Geometric mean of not less than 5 water samples taken per month; no more than 20% should exceed 4,000 organisms/100 mL
Algae	Should not be visible	
BOD ₅	-	No guideline recommended
<i>Major ions</i>		
Bicarbonate	-	No guideline recommended due to interaction with other factors
Chloride	30-700 (Tables 5.2, 5.3, 5.4)	Maximum concentration should be set according to sensitivity of crop
Sodium	Soils: Figure 5.1; crops Table 5.5	
Total dissolved solids	Table 5.6	
<i>Heavy metals and trace ions**</i>		
Aluminium	5.0	High toxicity in acid soils
Arsenic	0.1	
Beryllium	0.1	
Boron	0.5-6.0	Table 5.8
Cadmium	0.01	Higher toxicity in acid soils
Chromium	1.0	Limit chromium (VI) concentration to 0.1 mg/L
Cobalt	0.05	
Copper	0.2	
Fluoride	1.0	
Iron	1.0	
Lead	0.2	
Lithium	2.5	Citrus: 0.075 mg/L
Manganese	2.0	If acid soils, limit to 0.2 mg/L
Mercury	0.002	
Molybdenum	0.01	
Nickel	0.2	
pH (CaCl ₂)	4.5-9.0	
Selenium	0.02	
Uranium	0.01	
Vanadium	0.1	
Zinc	2.0	1 mg/L is recommended for sandy soil below pH 6
<i>Pesticides</i>		
Insecticides	-	No guidelines recommended
Herbicides	Table 5.9	
<i>Radioactivity</i>		
	Gross Alpha 0.1 Bq/L	
	Gross Beta 0.1 Bq/L	

* All surface waters used in WA plant nurseries in *Phytophthora* susceptible areas must be chlorinated to 2 mg/L residual chlorine

** Higher maximum concentrations may be recommended in neutral to alkaline soils, as discussed in the detailed guidelines in the paragraphs following

Table 4: Water quality guidelines for livestock watering (mg/L, unless otherwise stated)

Parameter	Guidelines	Comment
<i>Biological parameter</i>		
Pathogens and parasites	1,000 faecal coliforms/100 mL	Geometric mean for not less than 5 water samples taken per month; no more than 20% should exceed 5,000 organisms per 10 mL.
Algae	Up to 10,000 cells/mL may be tolerated, depending on the algal species present.	
<i>Major ions and nutrients</i>		
Calcium	1,000.0	
Nitrate-N	30.0	30 (horses), 40 (cattle), 60 (sheep)
Nitrite-N	10.0	
Sulfate	1,000.0	
Total dissolved solids	3,000.0	(Table 5.12)
<i>Trace elements</i>		
Aluminium	5.0	
Arsenic	0.5	
Beryllium	0.1	
Boron	5.0	
Cadmium	0.01	
Chromium	1.0	
Cobalt	1.0	
Copper	0.5	0.5 sheep, 1.0 pigs and poultry, 5.0 cattle
Fluoride	2.0	
Iron	-	No guideline recommended
Lead	0.1	
Magnesium		(Table 5.13)
Manganese	-	No guideline recommended
Mercury	0.002	
Molybdenum	0.01	
Nickel	1.0	
Selenium	0.02	
Uranium	0.2	
Vanadium	0.1	
Zinc	20.0	
<i>Pesticides</i>	See guidelines raw water for drinking water supply (Chapter4)	
<i>Radioactivity</i>	See guidelines raw water for drinking water supply (Chapter4)	
<i>Other organic toxicants</i>	See guidelines raw water for drinking water supply (Chapter4)	