BEST PRACTICE
ENVIRONMENTAL
MANAGEMENT
IN MINING

Managing Sulphidic Mine Wastes and Acid Drainage

Environment Australia

ACKNOWLEDGMENTS

Environment Australia wishes to thank the following people for their assistance in producing this booklet: the principal authors John Johnston, Environment Tasmania, Gavin Murray, Placer Pacific Limited, with contributions from Dr Ian Ritchie, Australian Nuclear Science & Technology Organisation; the review team comprising Graham Terrey, Ian Lambert, Stewart Needham and Dr David Jones; and the steering committee comprising representatives of the mining industry, government agencies and peak conservation organisations — the Minerals Council of Australia (MCA), the Australian Petroleum Exploration Association (APEA), the Australian Institute of Mining and Metallurgy (AusIMM), individual mining and energy companies, research institutions, the Australian Conservation Foundation (ACF) and the Australian Minerals and Energy Environment Foundation (AMEEF). The steering committee assists the authors without necessarily endorsing their views.

Cover Photo: Kidston Gold Mine Limited, 40 km south of Einasleigh, north Queensland. Waste dump drainage collection dam is shown with pump back facility at north dump.

Photo: Placer Pacific Limited

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Environment Australia incorporates the environment programs of the Federal Department of the Environment, Sport and Territories.

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FOREWORD

Environment protection is a significant priority for our society. A major role for government is setting environment standards and ensuring that individuals and organisations meet them. Increasingly, however, government, industry and community organisations are working as partners in protecting our environment for present and future generations.

Representatives of the minerals industry in Australia and Environment Australia (the environmental arm of the Federal Government) are working together to collect and present information on a variety of topics that illustrate and explain best practice environmental management in Australia's mining industry. This publication is one of a series of booklets aimed at assisting all sectors of the mining industry — minerals, coal, oil and gas — to protect the environment and reduce the impacts of minerals production by following the principles of ecologically sustainable development.

These booklets include examples of current best practice in environmental management in mining from some of the recognised leaders in the Australian industry. They are practical, cost-effective approaches to environment protection that exceed the requirements set by regulation.

Australia's better-performing minerals companies have achieved environmental protection of world standard for effectiveness and efficiency — a standard we want to encourage throughout the industry in Australia and internationally.

These best practice booklets integrate environmental issues and community concerns through all phases of mineral production from exploration through construction, operation and eventual closure. The concept of best practice is simply the best way of doing things for a given site.

The case studies included in these booklets demonstrate how best practice can be applied in diverse environments across Australia, while allowing flexibility for specific sites. Each booklet addresses key issues by presenting:

- basic principles, guidance and advice;
- case studies from leading Australian companies; and
- useful references and checklists.

Mine managers and environmental officers are encouraged to take up the challenge to continually improve their performance in achieving environment protection and resource management and apply the principles outlined in these booklets to their mining operations.

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EXECUTIVE SUMMARY

The problem of acid drainage, traditionally referred to in Australia as acid mine drainage (AMD) and in North America as acid rock drainage (ARD), encompasses all issues associated with the actual and potential environmental effects of sulphide oxidation resulting from mining activities. Its significant potential for long term environmental degradation makes it one of the biggest environmental issues facing the mining industry. Once established in mining wastes such as waste rock stockpiles or tailings impoundments, acid drainage may persist for tens to hundreds of years and be difficult and costly to remediate. Increased mobility of dissolved metals is an associated problem which may occur even when the rate of sulphide oxidation does not result in net acid generation.

Factors contributing to acid drainage can be classed as primary, secondary and tertiary. Primary factors are those directly involved in sulphide oxidation - typically, this occurs when sulphide-bearing rock is exposed to atmospheric oxygen and moisture, initiating a number of chemical reactions that produce sulphate and acidity. Secondary factors - such as the presence of other minerals able to neutralise acidity - consume or alter those products. Tertiary factors are the physical conditions (materials, minesite topography, climate etc.) that influence the rate of sulphide oxidation as well as the migration of sulphide oxidation products (that is, sulphate, metals etc.).

The mechanisms controlling sulphide oxidation and acid generation are not fully understood. Best practice environmental management for acid drainage is a developing field in which many questions still remain unanswered. Our understanding of the problem is being advanced on two fronts through:

- ongoing research into the geochemistry of sulphide oxidation and the factors influencing oxidation rates; and
- managing and remediating current acid drainage problems in the field.

Best practice environmental management for sulphidic mine wastes requires a risk management approach. While the primary focus is to prevent acid generation, there is a hierarchy of appropriate management strategies as follows:

- minimise oxidation rate and isolate higher risk materials from exposure;
- minimise potential for transport of oxidation products from source to receiving environment; and
- contain and treat acid drainage to minimise risk of significant off-site impacts.

While evaluation of minesite prevention and remediation strategies is an ongoing process, there is a number of well established best practice principles for minimising acid drainage. These include early recognition of sulphide oxidation potential and incorporation of prevention strategies into the various stages of mine planning, design, operation and closure.

Mine planning to minimise acid drainage is the most cost effective and desirable solution to the problem. Treatment is less desirable due to the long term nature of acid drainage and associated high treatment costs.

Environmental management systems for mineral deposits/mining projects containing sulphide minerals should include, as a high priority, clear objectives and strategies for dealing with the risk of acid drainage. Mechanisms to monitor and review performance and, where necessary, revise management strategies, are an essential part of best practice.

Environmental management of acid drainage requires an understanding of the geochemistry of the ore body for use in predictive tools. Prediction can be achieved through static and kinetic testing of mine rock, which can also provide information on likely metal/sulphate (oxidation products) loads and concentrations. This information should be incorporated into the mine geological model and mining schedule to provide for the necessary selective handling and disposal of higher risk materials, subject to site-specific considerations.

Where acid drainage exists as a result of past mining activities the range of remediation options may be limited and expensive. Treatment options may be cost effective under some circumstances. However, due to the long duration of sulphide oxidation processes, treatment may be required for many years. Prevention and management at source is the preferred strategy for acid drainage abatement.

The principles of preventing and remediating acid drainage involve a combination of mechanisms including:

- exclusion of oxygen from sulphidic mine wastes;
- control of water flux within wastes and management of site hydrology to minimise potential for transport of oxidation products (sulphate, metals etc.);
- neutralisation of acid drainage with alkaline materials; and
- monitoring to characterise wastes and determine the effectiveness of remediation measures.

The choice of the most appropriate prevention/remediation measures will be affected by site-specific constraints and the characteristics of the sulphide containing material. Frequently, innovative and unique strategies are necessary to make the best use of available resources. This booklet presents a range of strategies and case studies that demonstrate current approaches to achieving best practice in managing acid drainage to minimise its associated environmental impact and long term liabilities. Long term monitoring and evaluation are required to demonstrate the effectiveness of strategies currently being implemented.

In order to determine the most appropriate solutions for sulphidic mine waste management at any specific site, a full assessment (cost benefit analysis) of all potential prevention and remediation options is required prior to implementing the selected management strategy. In most cases, this may involve lengthy field evaluation and testing to establish the applicability of each strategy to the particular site.

CONTENTS

INTRODUCTION

This booklet addresses environmental management to avoid or minimise potential environmental impacts associated with the oxidation of sulphidic mine wastes produced by mine excavation and processing. These oxidation processes are traditionally referred to in Australia as acid mine drainage (AMD) and in North America as acid rock drainage (ARD). Acid drainage is used in this document to refer to all issues associated with the actual and potential environmental effects of sulphide oxidation resulting from mining activities. Acid drainage is one of the most significant environmental issues facing the mining industry. It affects most sectors of the industry including coal, precious metals, base metals and uranium.

Experience to date has shown that its effects include acid drainage from waste rock stockpiles and tailings residue emplacements (impacting on downstream water quality), development of acid conditions in exposed surface materials (potentially affecting rehabilitation), increased solubility and/or release of metals (irrespective of actual pH) and increased salinity or solute loads (oxidation and neutralisation products).

Ferguson and Erickson (see Further Reading) note that acid drainage "arises from rapid oxidation of sulphide minerals, and often occurs where such minerals are exposed to the atmosphere by excavation from the earth's crust. Road cuts, quarries, or other rock excavations can expose these minerals, but metalliferous mines are a primary source since economically recoverable metals often occur as orebodies of concentrated metal sulphides (for example, (iron) pyrite, Fe S_2; (copper) chalcopyrite, $CuFeS_2$; (zinc) sphalerite, ZnS)." The production of acid sulphate soils, a major problem throughout coastal areas of the world, is also a result of the oxidation of pyrite in soil of marine and estuarine origins.

The environmental consequences of acid drainage can be substantial. For example, in the United States an estimated 20 000 km of streams and rivers are affected by acid drainage which has a deleterious effect on aquatic life in streams and in some cases precludes their beneficial use by other water users. Significant impacts on groundwater and soil can also occur as a result of mine derived acid drainage.

In 1994 the Canadian Mine Environment Neutral Drainage Program (MEND) estimated the cost of remediating acid generating mine wastes in Canada to be in excess of $3 billion.

The impact of acid drainage in Australia has not been fully quantified and the cost of remediation is unknown. White (1995) estimates the area of acid sulphate soils in Australia to be 1 000 000 hectares. In early 1996, the Office of the Supervising Scientist and the Australian Centre for Minesite Rehabilitation Research commissioned a study of the extent and nature of acid drainage effects from the minerals industry in Australia. Testing of mine wastes from over sixty coal, gold and base metal mines by Environmental Geochemistry International (1992) revealed that up to forty percent of the materials tested were potentially acid forming.

Acid drainage can continue long after mining operations are complete. Historical mines in the Rio-Tinto region of Spain have been a source of acid drainage for over 2000 years. Abandoned mines can represent a substantial liability for industry and government once the economic resource at a site has been mined out. High remediation costs and the persistence of acid generation, once established, results in acid drainage being a major environmental issue for mine operators, the community and regulators.

Substantial savings can result where mine planning incorporates strategies for the management and disposal of acid generating wastes. Addressing the risk of acid drainage should be an integral part of mine planning and environmental management systems for the minerals industry (coal, uranium, base metal and precious metal projects).

Best practice for the management of acid drainage is a developing science and there are no comprehensive solutions to the problem. Therefore, this booklet addresses best practice for sulphidic mine waste management from a risk management perspective and presents a number of case studies highlighting strategies currently being implemented by the minerals industry. The success of these strategies will depend on long term evaluation and monitoring as, in many cases, there has been insufficient time to assess their performance fully.

In addition, research is continuing into the mechanisms influencing oxidation of sulphide minerals and predictive techniques to provide a more effective risk management approach. A summary of the extent of current understanding and management of acid drainage in Australia is provided in the proceedings of the Second Australian Acid Mine Drainage Workshop held at Charters Towers, Queensland in March 1995 (see Further Reading).

1. WHAT IS ACID DRAINAGE

Oxidation of sulphidic minerals is a natural process resulting from their exposure to atmospheric conditions. In mining situations this process is accelerated when large volumes of sulphide rich materials are exposed. Acid drainage resulting from oxidation of these materials may impact on the immediate and wider environment.

The iron sulphide mineral, pyrite, tends to be the most common sulphide mineral present in mining situations. Historically, the term acid mine drainage (AMD) has been applied to the impacts of pyrite oxidation. AMD in coal mining environments is characterised by low pH (leachate pH values may be as low as 2) and high sulphate (>2 000 mg/l) and iron. In some circumstances, usually where other metal sulphides occur, elevated levels of soluble metals may be present in non-acidic effluents. Therefore, the potential for and nature of acid mine drainage will be site-specific and a function of the type of mineral deposit.

Typically, acid drainage occurs as runoff or seepages from waste rock stockpiles, tailings impoundments or coal rejects. Acid drainage may also be discharged from underground mine workings via adits or shafts or seep from open pit walls where groundwater is intercepted.

In some cases, as the acid drainage stream is aerated, a characteristically reddish brown stain forms which discolours drainage channels and stream beds. This results from the oxidation of ferrous iron in solution which forms a precipitate of insoluble iron (hydroxide) precipitates.

Photo: John Johnston
Comstock Creek, Mt Lyell, Queenstown, Tasmania.
Shows metal precipitates from acid drainage.

Mining and extraction of sulphide bearing minerals tends to greatly increase the potential for acid drainage. During mining operations rock material is broken up, greatly increasing its surface area, and thus exposing sulphide minerals to accelerated weathering processes. Under these conditions the sulphide minerals oxidise or react with oxygen and water at varying rates. It is the rate of sulphide oxidation which will largely determine whether there is a significant potential for acid drainage.

Under the normal pH range of soils and water (pH 5-7), metals released by weathering of minerals generally precipitate and are relatively immobile. However, under lower pH conditions, these can remain in solution and be transported off site where they may have a deleterious effect on aquatic ecosystems and other downstream water users. Impact on groundwater and soils may also occur as a result of acid drainage discharges.

Acid drainage is not exclusively confined to mine operations and may occur in any large earthmoving operation which results in the exposure of sulphide minerals, eg road construction, dam building and airport construction. Oxidation of pyrite is principally responsible for acid sulphate soils frequently encountered in coastal areas where soils are developed for agriculture or urban development. Most frequently, acid sulphate soils develop when low lying coastal areas are drained, lowering the water table and exposing pyrite in the soil to oxidising conditions.

Acid drainage also occurs naturally in areas of outcropping sulphide bearing rock. This has previously been used as an exploration tool for mineral deposits where analysis of stream water samples for sulphate and metals has helped to identify the location of sulphidic ore bodies.

2. FACTORS INFLUENCING ACID DRAINAGE

A range of physical, chemical and biological processes can influence the generation of acid drainage and, typically, these factors vary on a site-specific basis. They can be grouped into primary, secondary and tertiary controls (Ferguson & Erickson). Primary factors are directly involved in the generation of sulphide oxidation products; secondary factors consume or alter those products; and tertiary factors are the physical conditions (materials, minesite topography, climate etc.) that influence the significance of any sulphide oxidation, the potential for migration into the wider environment and consumption of oxidation products.

Photo: John Johnston

Mt Lyell, Queenstown, Tasmania. Monitoring of acid drainage leachate from Magazine Waste Rock Dump. Continuous monitoring records flow, pH and conductivity. Periodic sampling for metals enables accurate quantification of effluent load and determination of the success of dump encapsulation in reducing leachate flow (water ingress) and metal loads (reduced oxygen).

2.1 PRIMARY FACTORS

Factors influencing the oxidation of sulphide minerals can be summarised as follows.

- water availability for oxidation and transport;
- oxygen availability;
- physical characteristics of the material;

and to a lesser degree:

- temperature;
- pH;
- ferric/ferrous iron equilibrium; and
- microbiological activity.

Where oxidation occurs in the absence of bacterial catalysts it is known as abiotic and where bacteria catalyse the reaction it is known as biotic. The oxidation rate of pyrite is accelerated by the bacteria Thiobacillus ferrooxidans (iron oxidising) and Thiobacillus thiooxidans (sulphur oxidising), which are associated with nearly all cases of acid drainage. Maximum oxidation of pyrite occurs between a pH of 2.4 and 3.6, rapidly decreasing above this level. Under acid conditions ferric iron is, in itself, a powerful oxidising agent which, in turn, may attack other sulphide minerals, increasing the rate of sulphide oxidation and generation of oxidation products.

Given that water and oxygen are the principal driving factors for AMD it is logical to isolate the material through various approaches, including encapsulation, as a means to reduce water and oxygen availability. However research is required to determine whether the present isolation approaches (such as encapsulation and the thickness and management of capping materials) provide the desired effect in the long term. There are measurements which suggest some encapsulation methods may not provide a long term solution, ie less than 100 years (see Bennett and Pantelis 1991). More measurements are required to evaluate the long term effectiveness of present isolation, cover and encapsulation design methods and provide better alternate management approaches.

Photo: John Johnston

Mt Lyell, Queenstown, Tasmania. Remediation of the Magazine Waste Rock Dump. Involves compacting clay on the surface of the dump to inhibit the ingress of water and oxygen. Oxygen permeating the dump enables oxidation of pyritic wastes producing sulphate, ferrous iron and acidity. Water permeating into the dump becomes acidified and leaches metals and other elements from the waste rock into water catchments.

2.2 SECONDARY FACTORS

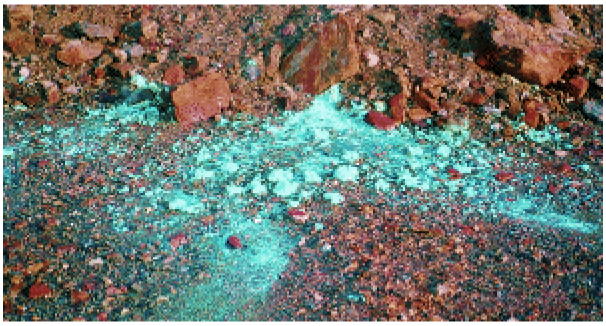
An important factor influencing the acidity generated, and hence pH, is the presence of other minerals able to neutralise acidity. Carbonates are the only alkaline minerals which naturally occur in sufficient quantities to be considered effective in the control and prevention of acid drainage. Silicate minerals and aluminosilicate, such as mica and clay minerals, have some acid consuming ability but are of minor significance relative to the carbonates.

The amount of alkaline material in the rock may be sufficient to offset the acid producing potential of the material and acid drainage will not eventuate as long as the reaction rates of the respective materials are similar. However, in some cases the reaction kinetics are such that metals are mobilised even though acid conditions do not occur. In these situations, sulphate and these metals are indicators of the oxidation process and may be indicators of impending acid drainage problems.

The pH of the reaction media may also influence the ferrous/ferric iron equilibrium. At low pH ferric iron acts as an oxidant, while at pH values greater than 3.5 ferric iron will precipitate as ferric hydroxide $Fe(OH)_3$. Sulphide oxidation rates have also been shown to increase with increasing partial pressures of oxygen, an effect that is more pronounced when catalysing bacteria are active.

Photos: Department of Minerals and Energy (WA)

Teutonic Bore, 270 km north of Kalgoorlie, Western Australia. Acid rock drainage from lowgrade poly metallic ore/spoil can occur in low rainfall areas (215 mm per year). Copper sulphate crystals have formed on the surface of ore/spoil.



Photos: Department of Minerals and Energy (WA)

2.3 TERTIARY FACTORS

Climatic regimes can largely determine the impact of acid drainage, the most significant climatic factors being rainfall and temperature. Moisture is rarely limiting to the oxidation reaction; however, surface runoff and infiltration resulting from rainfall are the main mechanisms for transporting oxidation products into receiving environments. The rate of sulphide oxidation is substantially lower in water than in air, owing to at least a four orders of magnitude difference in diffusion rates. So saturation of sulphidic wastes offers a major oxidation control strategy.

In wetter climates, control of acid drainage may permit adequate dilution of reaction products to be achieved in receiving waters thus minimising the potential effects on aquatic ecosystems.

In drier climates, while oxidation of sulphide minerals may be occurring in mine wastes, the hydrological balance is such that there is only minimal transport of oxidation products. Infrequent rain may result in oxidation products accumulating in wastes over long dry periods and their release to the environment being controlled by geochemical processes. However, even in these circumstances the oxidation products may accumulate at the surface, causing revegetation problems on disturbed land.

Photo: John Johnston

Mt Lyell, Queenstown, Tasmania. Batter slopes covered with compacted clay. Slopes are a maximum 2.5:1, and 5 m high. Batter design, with runoff drains on each bench, minimises the potential for erosion of the encapsulating clay layer and allows placement and retention of a 250 mm revegetation layer of soil material over the compacted layer on the slope.

The physical nature of mine wastes also affects their acid generating potential. The rate of acid generation is a function of the surface area of sulphides exposed for oxidation. Oxidation may be limited to the surface of compacted, fine grained, weathered stockpiles, compared with stockpiles made up of coarse materials where wind action (air pressure gradients) and exothermically driven air circulation will allow oxidation throughout the stockpile. Acid drainage is a function of material characteristics such as particle size, hardness, resistance to weathering and permeability. These physical characteristics determine oxygen flux and water flux (percolation rates) through a waste stockpile, which subsequently determines oxidation and leachate generation rates.

The chemistry of receiving waters may be an important factor in determining the impact of acid drainage transported into rivers and streams. Metal toxicity in water can be affected by water hardness or the amount of alkalinity in the water. Where waters are alkaline this will tend to neutralise acid drainage and promote the precipitation of metals to less toxic forms. Dissolved organic matter (carbon) may complex metals in solution, affecting toxicity or bio-availability to aquatic organisms.

3. IMPLICATIONS OF ACID DRAINAGE FOR MINE OPERATORS

The prevention and control of acid drainage is a major issue for mine operators at sites where sulphide minerals occur. Ongoing risk assessment of acid drainage potential and sulphidic waste management during planning, development, operation and closure of mining developments will result in substantial environmental and economic benefits.

Inadequate control of acid drainage can result in substantial economic liabilities for both mine operators and regulators as a result of the long term environmental degradation. In 1994 the Canadian Mine Environment Neutral Drainage Program (MEND) estimated the cost of remediating the impacts of acid drainage in Canada to be in excess of three billion dollars.

Historically the environmental significance of acid drainage was not fully appreciated. The legacy of many abandoned mine sites producing acid drainage, which is the source of ongoing environmental damage, highlights the inadequate understanding of acid drainage in the past. Remediation of abandoned mine sites is often extremely costly and the cost of acid drainage abatement at older mine sites may exceed the remaining resource value.

In Australia the best documented example of acid drainage remediation is the Rum Jungle mine in the Northern Territory. The site was rehabilitated between 1982-86 at the then cost of $18.6 million[*]. Rehabilitation objectives were to reduce acid drainage impacts on the Finniss River, make the site safe to the public and improve the aesthetic appearance of the mine area. (See Bennet J.W. et al, 1989 in Further Reading.)

Photo: John Johnston

Acid mine drainage from a century old mine adit. Dundas Western Tasmania.

The Mount Lyell Mine in Western Tasmania was the site of continuous copper mining and processing from 1893 to 1994. A century of mining with little control of acid drainage has degraded over forty kilometres of rivers and streams which are consequently unable to support aquatic life of any significance. The Mount Lyell ore deposit contains in excess of 10 percent sulphide and acidic discharges from the lease area carries in excess of two tonnes of copper a day into downstream catchments. Acid drainage is generated as a result of the underground mining operation which comprises a caving operation beneath a substantial open cut and unconsolidated waste rock stockpiles on the lease which contain approximately 50 million tonnes of sulphidic waste (see McQuade et al., OSS Report 104 in Further Reading).

Photo: John Johnston

Mt Lyell mine, Queenstown, Tasmania. Oxygen and temperature monitoring of a waste rock stockpile by ANSTO.

Predictions, based on oxygen and temperature profiles within waste rock stockpiles, estimate that, in the absence of remediation strategies, oxidation will continue at a diminishing rate for another six hundred years.

Acid drainage clearly presents a number of potential problems for mine operators:

- impact on mine water quality limiting the reuse of mine water and process water and creating corrosion problems for mine infrastructure and equipment;
- impact on aquatic ecosystems in downstream environments resulting from acidity and dissolved metals;
- impact on riparian communities along the downstream drainage channels (for example, tree deaths);
- possible impact on groundwater quality, particularly shallow aquifers;
- impairment of the beneficial use of waterways downstream of mining operations for purposes such as stock watering, recreation, fishing, or irrigation;
- difficulties in revegetating and stabilising mine wastes; and
- potential long term liability for mine operators, regulators and the community.

For new developments where initial assessment identifies an acid drainage risk, a thorough analysis should be undertaken during the feasibility stages of project evaluation. The acid drainage risk analysis should include:

- characterising the acid generating potential of the materials;
- characterising the mobility of metals and other environmentally significant constituents of acid drainage;
- estimating the potential for oxidation products to migrate to the environment; and
- estimating the environmental sensitivity and assimilation capacity of the host environment.

More recently, mine operators have adopted a range of techniques to identify the potential for acid drainage and have implemented innovative strategies to control and minimise the problem. In this way treatment costs and post operational problems associated with acid drainage can be minimised.

[*] Marszalek, A.S. 1996

4. PREDICTION AND IDENTIFICATION OF ACID DRAINAGE

Best practice environmental management can be achieved through the early recognition of the potential for acid drainage and the adoption of appropriate risk management strategies. The range of factors affecting sulphide oxidation rates and subsequent acid drainage must be thoroughly understood so that sound decisions can be made to minimise impacts of acid generating material disposal practices.

Photo: Renison Limited

CSIRO scientists setting up a bank of piezometers in tailings to study dam hydrology at Renison Tin Mine, Tasmania.

The first step is to characterise the mine rock types. As well as geological assessment, this may be facilitated by a number of geochemical tests, broadly classified as static and kinetic tests, which are designed to determine the capacity of particular rock types to produce acid drainage.

Static testing (Section 4.2) comprises a range of simple, relatively fast and inexpensive screening tests designed to assess the potential for acid mine drainage in samples by evaluating the acid generating and acid neutralising processes. Kinetic tests are used to confirm the findings of static testing, to evaluate the rate of sulphide oxidation, predict acid drainage characteristics, and to assess potential management techniques. In the absence of a standardised approach to kinetic testing, interpretation of results must be done with care and based on professional experience.

Initially, reference should be made to other mining operations in the region, particularly any mines situated in the same stratigraphic or geological sequence which may provide some information on the acid generating characteristics of similar ore bodies and host rocks.

The earliest opportunity to identify the potential for acid drainage at a specific site is during the exploration stage when drilling is occurring to'prove up' an ore body.

Drill cores can provide information on:

- structure and form of pyrite and associated sulphide minerals such as:
    - surface area per unit volume of pyrite in host rocks;
    - characteristics of associated minerals and potentially neutralising carbonates;
- percentage of pyrite relative to other potentially neutralising carbonates;
- fabric and texture of rocks, that is, alteration and hardness;
- concentration of metals and elements which may be mobilised by sulphide oxidation;
- solubility of constituent elements under different environmental conditions; and
- oxidation state of minerals.

Core material can be used for geochemical testing and mineralogical examination utilising microscopic examination and X-ray diffraction analysis to characterise sulphide and carbonate species. Sampling for prediction of acid drainage should be ongoing and may include drill cuttings or rock chip sampling from outcropping rock units or active mining and development faces.

Hence, the project geologist has a critical role to play in the initial identification and assessment of acid drainage potential. Relevant information should be logged and recorded from drill core, and development waste and ore zone core samples retained for further testing (for example, metallurgy/processing). This information can be integrated with the geological model for the mineral deposit and form the basis of initial mine planning strategies.

4.1 SAMPLING

Sampling of drilling products (for example, cuttings, core etc.) to determine sulphide and carbonate content should be representative, based on accepted statistical procedures, and similar to the process used to determine other geological characteristics such as ore grade and reserves.

Representative profiles of all geological units should be sampled. It is important to identify and quantify low sulphide containing materials and alkaline materials as well as material containing visible sulphides. This information is required so that consideration can be given to utilisation of acid neutralising material in the assessment of appropriate management strategies.

The number of samples required and the sampling intensity will be project specific and depend on a number of factors including:

- geological variability and complexity of rock types; and
- the level of confidence in predictive ability.

Samples should be stored in a cool, dry environment to minimise sulphide oxidation prior to testing. Geochemical static tests may require as little as 2 grams of sample and kinetic testing a minimum of 500 grams. It is preferable to collect more sample than required for testing to allow for any heterogeneity and repeat analysis to validate results. However, samples composited over large intervals or different units should be avoided.

4.2 GEOCHEMICAL STATIC TESTS

Identifying the geochemical nature of waste samples is necessary to assess their potential for sulphide oxidation leading to acid generation. Static tests evaluate the balance between acid generation potential (oxidation of sulphide minerals) and acid neutralising capacity (dissolution of alkaline carbonates and other relevant minerals). Current best practice static tests comprise:

- acid base accounting or net acid producing potential (NAPP) test;
- net acid generation (NAG) test;
- saturated paste pH and conductivity (EC); and
- total and soluble metal analysis.

These procedures are discussed below (after Miller & Jeffery 1995) using common Australian terminology and units.

Photo: John Johnston

Acid leachate from waste rock stockpiles, Mt Lyell, Tasmania.

NET ACID PRODUCING POTENTIAL (NAPP)

Net acid producing potential (NAPP) is determined by subtracting the estimated acid neutralising capacity (ANC) of a sample from the estimated total potential acidity of the sample. Neutralising capacity comprises primarily carbonates and silicate minerals and, to a lesser extent, exchangeable cations on clays. Potential acidity is calculated from the content of total or reactive sulphur in the sample.

The NAPP procedure consists of three components:

- maximum potential acidity (MPA)
- acid neutralisation capacity (ANC)
- sample classification

MPA is calculated by determining the sulphur content of the sample as a percentage and multiplying the sulphur content by a conversion factor. Assuming complete oxidation of all the sulphur, the conversion factor generates kilograms of acid that can theoretically be produced from one tonne of material with that sulphur content.

ANC quantifies the ability of the sample to buffer or neutralise acid produced by the oxidation of sulphur in the material. The ANC is determined by reacting a ground sub-sample with a known quantity of acid (usually hydrochloric acid or sulphuric acid) to determine its neutralising capacity.

Interpretation of static test results involves subtracting ANC from the potential acidity. The sample result is given as Net Acid Producing Potential (NAPP).

A sample with NAPP greater than zero is usually classified as potentially acid forming while a sample with an NAPP equal to or less than zero is classified as non-acid forming. A result close to zero (in the range + to - 2) is often regarded as a zone of uncertainty, although the overall acid generation potential will be small.

While the NAPP indicates the acid generating potential, it does not quantify the reactivity of the material. The reactivity will determine whether acid conditions are likely to occur in the field. However, it is important that the NAPP test (acid base accounting) only be used as a screening process.

An understanding of the nature of sulphur present in samples is essential to interpreting the NAPP procedure correctly. It is important to differentiate between sulphide content and total sulphur. For example, organic sulphur frequently found in coal wastes and sulphate sulphur in highly weathered materials are not a major source of acid.

NET ACID GENERATION (NAG) TEST

A recently developed static test used to evaluate further the acid producing potential of a sample is the Net Acid Generation (NAG) test. This procedure estimates the net acid potential directly. The test offers advantages in that it is simple and fast, requiring the minimum of laboratory equipment and can provide an indication of sulphide reactivity and available neutralising potential usually within twenty four hours.

NAG testing comprises the addition of a strong oxidising agent such as hydrogen peroxide to a prepared sample and the measurement of the solution pH and acidity after the oxidation reaction is complete. Reaction kinetics can also be monitored during the test to assess sample reactivity.

A NAG pH result greater than 4 classifies the sample as non-acid forming. A NAG pH result less than or equal to 4 confirms that sulphide oxidation generates an excess of acidity and classifies the material as higher risk.

The NAG and NAPP test procedures are complementary in that the NAPP provides the theoretical maximum potential for acid generation and neutralisation to derive the theoretical balance, while the NAG test is a direct measure of the net result of the balance of these reactions. The NAPP and NAG procedures alone are not sufficiently definitive tests on which to base planning and operations decisions for mine development.

SATURATED PASTE PH AND CONDUCTIVITY

The simplest static test is the saturated paste pH and conductivity (EC) test which gives a preliminary indication of the in situ pH of the mine waste material and the immediate reactivity of the sulphide minerals and acid neutralising minerals present in the sample. A representative sample of crushed (<1 mm) mine rock is saturated with enough distilled water to create a paste and the pH and EC of the mixture is determined after a period of equilibration (usually twelve to twenty four hours). A sample with a pH less than 4 indicates the sample is naturally acid regardless of the NAPP, while an EC greater than two deciSiemens per metre (dS/m) — a measure of electrical conductivity — indicates a high level of soluble constituents.

TOTAL AND SOLUBLE METAL ANALYSIS

Sulphide oxidation may enhance the solubility of metal constituents in the waste, thereby significantly increasing heavy metal mobility and total dissolved metal concentration in acid drainage. The chemical properties of the waste determine the mobility of the metals, while both chemical and physical factors affect their potential for migration from the source.

Initial screening should compare metal concentration in the solids with that of the background soils and country rocks in the area (or with the average crustal abundance). Statistical methods are available to determine whether any enrichment is significant.

4.3 GEOCHEMICAL KINETIC TESTS

Geochemical kinetic tests involve established site or laboratory tests to simulate weathering and oxidation of rock and process waste samples over time under exposure to moisture and air. The tests can provide an indication of the oxidation rate, time periods for onset of acid generation (lag time) and the effectiveness of control techniques which may limit the reaction rates of oxidising material. The tests also provide data for prediction of metal release and loading in drainage and leachate from waste materials.

Columns and humidity cells are currently the most frequently used laboratory based kinetic test techniques. Humidity cells have largely been developed by the coal industry for testing overburden materials. The lag period for these wastes is typically of short duration and standard testing procedures typically run for 8-10 weeks, although longer duration tests are being evaluated. This is inadequate for materials with longer lag times as frequently occur at other mine types. Column tests are considered more representative of field conditions and have the additional advantage of allowing remediation measures to be tested and compared, although these have to be designed carefully. Expert assistance should be sought when selecting and interpreting kinetic tests.

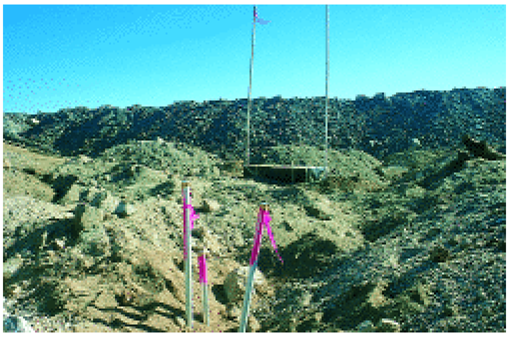


Photo: Placer Pacific Limited

Kidston Gold Mine Limited. Hydrological monitoring installations in waste dump cover trial (paddock dumping concept).

4.4 INTERPRETATION OF TEST RESULTS

The NAPP and NAG tests are useful screening tools to assess the likelihood of acid drainage developing through accelerated oxidation and neutralisation reactions. Despite the level of interpretation required, NAPP and NAG tests are the preferred method for characterising mine rock and process wastes for both the industry and regulators. Static testing is the first step in the systematic evaluation of materials to be disturbed and generated by mining operations. When interpreting the results of all predictive testing it is important to seek professional assistance and evaluate all testwork results in light of the prevailing extremes in field conditions. State Government Departments of Mines, Chamber of Mines or the Minerals Council of Australia can provide guidance.

5. SULPHIDE OXIDATION MANAGEMENT/ACID DRAINAGE CONTROL STRATEGIES

Essential control factors include:

- understanding the physical and chemical factors in sulphide oxidation;
- geochemical characterisation of waste materials for acid generating potential;
- classifying and quantifying the acid generating risk of all materials to be disposed of throughout the mine life;
- developing appropriate mine planning and selective handling and disposal practices for materials of different risk;
- management commitment to implementing the preferred management strategies;
- work force training to identify and manage these different materials;
- monitoring to evaluate the performance of remediation strategies;
- evaluating monitoring effectiveness; and
- revising and evaluating strategies to mitigate sulphide oxidation.

Current best practice environmental management of sulphidic mine wastes requires assessment of risk of acid generation in mine wastes, the early characterisation and classification of all materials, and developing strategies to minimise oxidation of these materials. Where significant sulphide oxidation is unavoidable, the preferred strategy is to contain oxidation products and isolate the higher risk materials. A less desirable option is to treat the resulting acid drainage and its impacts.

Photo: John Johnston

Diversion drainage around waste rock dumps and clay lining of drains (where necessary) is important to minimise the ingress of water to the dump.

When considering acid drainage management, a distinction must be drawn between historical mines and new mining operations. Technical options for managing acid drainage are considerably greater at new mine sites where control strategies can be implemented as part of the mining plan. With historical sources of acid drainage, abatement measures may be limited by economic constraints and the severity of impacts.

The most cost effective management strategy for sulphide oxidation is integration of oxidation and hydrological controls throughout all stages of mine operations, from mine planning to mine closure, and working in a coordinated manner to minimise the risk of acid drainage developing.

Basically, control strategies require the exclusion of one or more of the inputs that result in oxidation, that is, sulphide minerals, oxygen or water. Where acid drainage generation cannot be eliminated, it may be treated or its release regulated to a rate that will not significantly affect the receiving environment.

Minimising acid drainage requires control of:

- sulphide oxidation and acid generation rates by regulating oxygen, water, bacteria or other limiting factors, for example, alkalinity;
- water percolation through the material to inhibit migration or transport of oxidation products from the source;
- control of alkalinity and acidity balance so oxidation products and other soluble constituents are precipitated and immobilised within the material.

Reducing oxygen availability is the most effective control on oxidation rate. A low oxygen permeability (diffusion) cover is also likely to restrict water movement into and through the material thus reducing both oxidation rate and product transport. Best practice environmental management requires site-specific adaptation of local resources and an understanding of the local environment to produce the most appropriate form of cover.

Photo: John Johnston

Mt Lyell, Queenstown, Tasmania. Clay is an ideal cover material for the encapsulation of waste rock dumps to inhibit water and oxygen ingress. Placing a dump near a clay resource can reduce rehabilitation costs.

Covers to achieve this can be broadly defined as water covers and soil covers. Water covers provide the most effective control of sulphide oxidation rates. Soil covers can only approach the efficiency of water covers when a proportion of the cover material remains saturated, which reduces the diffusion rate of oxygen through the cover. However, soil covers also offer the advantage of reducing the water flux/transport medium through the material. An example of effective cover use is provided in Case Study 6. A list of treatment options is at the end of this chapter in Table 1.0.

5.1 SOIL COVERS

Soil covers may comprise low sulphide content waste rock or materials specifically borrowed to cover waste materials and are usually selected for their particular characteristics such as compaction rates and low permeability. Such cover materials are often clay subsoils or oxide wastes. Synthetic membranes such as geotextile fabrics can achieve a high efficiency in water exclusion and have been used for covering low grade ore stockpiles to prevent oxidation prior to processing.

All available cover materials should be evaluated, based on their capacity to minimise oxygen and water availability.

Photo: John Johnston

Spreading of clay on Magazine Waste Rock Dump at Mt Lyell. Following spreading, clay is compacted to achieve the desired permeability (1 x 10 $^{-9}$ *mm/s) to inhibit oxygen and water permeating into the dump. The dump surface is graded to a perimeter diversion drain to control runoff and minimise erosion. A 250 mm thick uncompacted revegetation layer is placed over the compacted layer to seal it and prevent erosion.*

Oxygen control is best achieved if the pore space of a portion of the cover remains saturated, or within about 10% of saturation. This layer will substantially reduce the oxygen flux through the cover, as the diffusion coefficient of oxygen through water is at least one order of magnitude smaller than that in air. Design of a soil cover system may require three zones that have the following properties:

- a zone, usually the base zone, with high water retention properties, which provides the greatest barrier to oxygen diffusion ('water retention' zone);
- a zone to act as a water reservoir to ensure that some portion of the water retention zone remains close to saturation; and
- a surface zone that protects the cover from erosion ('barrier' zone).

In many cases the surface and barrier zones provide a growth medium for vegetative cover which also helps to minimise erosion and control percolation. In some cases a 'capillary break' zone underlies the water retention zone to limit the upward migration of soluble constituents to the surface which may affect the vegetative cover. In practice the frequently coarse nature of waste materials and their low water content means that they act as their own 'capillary break'.

The three zone concept was applied to the rehabilitation of the Rum Jungle mine site in Batchelor, Northern Territory. The main objective in using the layered system on the waste rock stockpiles was to reduce the water flux. However, post-rehabilitation monitoring has shown that, owing to the extreme rainfall variations between the tropical wet and dry seasons, the cover system was effective in reducing the oxygen flux only during the wet season, due to the climatic (rainfall) extremes experienced during the wet and dry seasons in the Northern Territory.

While reducing the water flux through waste material may not significantly reduce the oxidation rate, installation of a soil cover has the definite advantage of reducing the quantity of drainage emanating from the base. The stored oxidation products may also be effective in helping to reduce the overall oxidation rate of the residual sulphide minerals.

Photo: Renison Limited

Renison Limited, Renison Tin Mine, Western Tasmania. Sub-aqueous disposal of tailings at Dam C. Where beaches are visible, sulphidic tailings are covered with inert tailings to control oxidisation.

5.2 WATER COVERS

When stored under water, unoxidised sulphidic mine wastes are largely chemically unreactive. The use of water as a cover material has a similar objective to a saturated soil cover in that it reduces the availability of one of the principal reactants — oxygen. The maximum concentration of dissolved oxygen in natural waters is approximately 25 000 times lower than that found in the atmosphere (due to the lower diffusion coefficient of oxygen in water). Once the available oxygen in water is consumed, the rate of reaction is reduced as its rate of replacement is relatively slow. The resultant diminished availability of oxygen is the single most effective inhibitor to sulphide oxidation.

Water covers are more readily achieved in temperate climates. Other methods to ensure saturation may be required in drier climates, for example, establishing a permanent wetland on tailings impoundment surfaces, or designing a complex layered cover to trap precipitation on the tailings surface and inhibit evaporation. While the use of natural or artificial lakes as repositories for mine wastes may compromise other beneficial uses of these waterbodies, in some instances it may be the best available option. There are example of minesites in Canada and Sweden where lake environments are being used for tailings and waste rock disposal. Details of rehabilitating a mine pit by converting it to an aquatic habitat and potential water resource are provided in a paper by Sinclair and Fawcett (see Further Reading).

As a long term management strategy, subaqueous impoundment of sulphidic wastes is attractive as lake sediments tend to be a stable environment for sulphides. In addition to the low concentration of available oxygen, sediments have a natural tendency to become chemically reducing due to high organic matter levels and biological activity.

Acid generating wastes, disposed of underground as backfill in mined-out workings, can be flooded at the end of mine life, thus minimising long term sulphide oxidation rates.

5.3 SELECTIVE HANDLING AND ISOLATION OF SULPHIDIC WASTES

The objective of this strategy is to isolate reactive or higher risk wastes for selective disposal either separately or within non-reactive (lower risk) materials. Geochemical testing enables the classification and field identification of different waste types for selective handling and disposal. Figure 9 shows how sulphidic waste can be isolated within a waste stockpile.

Selective handling and placement of mine wastes requires integration of sulphidic waste management practices into the mine planning schedule, along with education and training of the workforce to facilitate operational practices in the selective handling of higher risk materials.

The mine plan for underground operations may incorporate successive backfilling and selective underground disposal of sulphidic wastes, including tailings return underground as sandfill or thickened paste, thereby reducing the amount of acid generating material requiring disposal above ground. Incorporation of cement to bind tailings fill has the advantage of introducing an additional source of alkalinity (as well as strength and stability) to the material.

In some cases, it may be preferable to segregate highly reactive wastes within a separate facility to permit intensive treatment and control strategies.

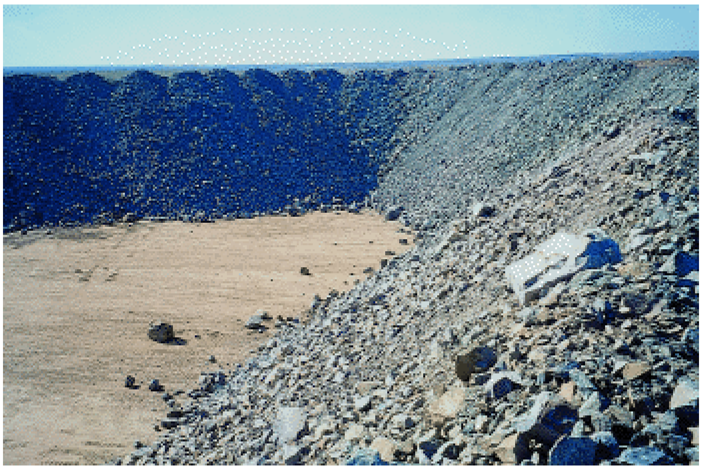


Photo: Placer Pacific Limited

Placer Pacific Limited, Osborne Mines (approximately 130 km south of Cloncurry, North West Queensland). Waste rock dump showing void left in centre of dump to 'encapsulate' high suphide containing waste rock.

5.4 BLENDING

Where both acid generating and acid consuming materials are present in waste, materials blending (or mixing or co-disposal) may be a viable option, usually conducted in conjunction with other prevention strategies such as encapsulation and/or soil covers. The objective is to balance alkalinity and acid generating potential to minimise the risk of net acid generation. The operating practices involved in the mining operation will largely determine the feasibility of this option.

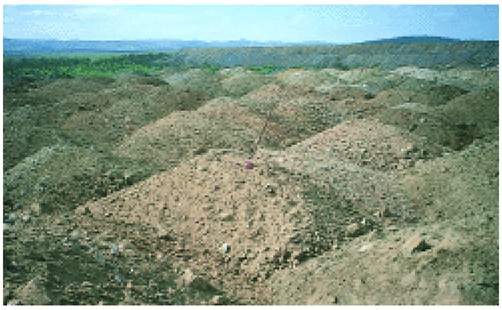


Photo: Placer Pacific Limited

Placer Pacific Limited, Kidston Gold Mine. Waste dump cover trial showing 'paddock' dumping concept.

Other alkaline products may also be available for blending. In the coal industry, flyash or kiln dust may provide a useful source of alkalinity which can be incorporated into pyritic overburden and coal waste rejects to minimise acid drainage potential.

At base metal mines coarse lime rejects from the processing plant may contain residual alkalinity which could be blended with acid producing materials during disposal. Practices such as these can assist in reducing the overall risk of acid drainage.

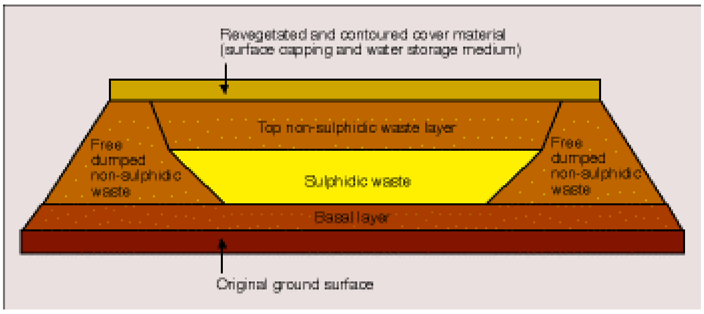


Figure 9.0. Schematic of isolation strategy

Construction of surface drains to divert runoff and minimise the upstream catchment of operational areas is an effective management strategy to reduce the volume of surface water on site which could come into contact with acid producing material or contaminated water. This will reduce the potential for off-site environmental impacts from acid drainage.

With many base metal mines pyrite removal may be an option through incorporation of pyrite flotation cells into the mill circuit. This will significantly lower the pyritic content of tailings and reduce the potential for sulphide oxidation while producing a saleable product or small amount of pyrite rich material for selective disposal.

5.5 BACTERIAL INHIBITION

Certain bacteria (APB) are known to increase greatly the rate of acid production from pyritic materials. Bactericides have been developed which inhibit the growth of these micro-organisms. Their primary effect is minimising the catalytic role played by the bacteria in converting ferrous iron to ferric iron under acid conditions (where ferric iron is the principal oxidant).

Because this is only a short term solution and only partially effective, bactericides need to be part of an integrated systems approach to managing sulphidic wastes. Most frequently they are applied to temporary ore stockpiles or to waste rock stockpiles to delay the onset of acid conditions, or to reduce secondary treatment costs such as lime dosing of drainage/runoff waters, while other more permanent solutions are implemented.

To date this technology has largely been used for rehabilitation in the US coal industry to assist establishment of an active vegetation cover prior to the onset of significant acid generation.

DESIGN APPROACH	STRATEGY	FEATURES
Proactive: Preventative Measures	1. Selective Handling/Encapsulation	AMD producing waste (or tailings) is selectively handled and surrounded with benign, non acid producing materials like oxide mine wastes to limit flow of air and water into waste and AMD flow out. Benign material is used for foundation and containment bunds to form a cell structure with the surface covered with compacted benign material (usually clay) either staged or at the closure of the mine. See Figures 10.0 and 11.0
	2. In-pit Disposal	Similar in concept to encapsulation. Method is useful where a mined out pit of sufficient size is available. With effective mine planning an early closure of one of a series of mined pits allows for in-pit disposal of AMD wastes. Depending on permeability, the pit wall and floor may require encapsulation layers, including a surface cover. In temperate climates, surface cover may be provided by a water cover of sufficient depth instead of a compacted fill material. Surface water management and diversion options should be part of the design features. See Figures 10.0 and 11.0
	3. Blending/Mixing/Co-disposal	Involves the blending/mixing and co-disposal of AMD wastes/tailings with benign non acid producing materials or even acid neutralising materials. Historically used at coal mining operations, co-disposal consists of constructing small cells within a waste dump which are rapidly filled and covered to reduce AMD generation and water ingress. Cells are constructed using benign waste materials of low permeability. Option of mixing tends to be for mine waste rock rather than tailings and relies on the neutralising capacity of the mixed benign material rather than encapsulation. See Figures 10.0 and 11.0
Proactive:	4. Micro-encapsulation	A process of coating certain mine

Preventative Measures		wastes to prevent pyrite oxidation. Mechanism involves leaching the waste with a phosphate solution with hydrogen peroxide. The surface of pyrite is oxidised by the peroxide to release iron oxides which react with the phosphate solution to form a phosphate precipitate. This forms a passive surface coating over the waste rock fragments.
	5. Uncontrolled Placement with Downstream Collection and Treatment of Water	Option for marginal acid producing wastes where subsequent acid drainage is recovered and treated downstream. Collection/recovery systems can include catchment ponds, drains, trenches and groundwater bores. Treatment/disposal systems include chemical treatment (eg lime dosing) controlled release and dilution by adjacent streams, evaporative disposal, process reuse, and wetland filter treatment. Each system should be considered in the context of site specific characteristics. This option can be applied as a possible remedial measure. See Figure 12.0
Reactive: Remedial Measures	1. Covering	Option involves the construction of a low permeability cover over an existing waste rock dump, mainly using locally available borrow or benign waste, to reduce the infiltration of surface water and infusion of air into the dump. Cover design should include detailed hydrological and seepage modelling to optimise cover thickness. See Figure 12.0
	2. Downstream Collection and Treatment of Water	Option as a remedial measure for marginal acid producing wastes where subsequent acid drainage is collected and treated downstream. See Option 5 above for details and Figure 12.0.
	3. Removal	Removal of waste rock or tailings is an option but is not usually considered in view of the costs involved. There may be advantages in selective removal of severe AMD waste from an existing dump for isolation either within an open cut, void or at a suitably prepared waste dump site.

Table 1.0: A Summary of Engineering Options to Manage Acid Mine Drainage for Mine Waste Dumps and Tailings Storages (after Marszalek 1996)

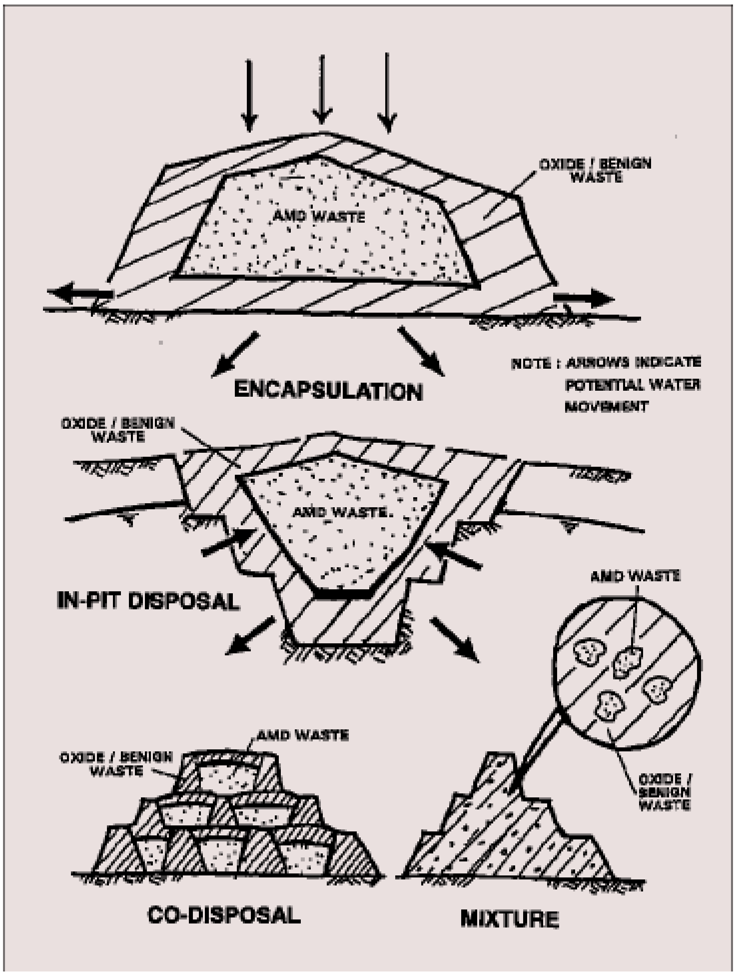


Figure 10.0: Methods for AMD control in waste rock dumps using a range of encapsulation and co-disposal options. (after Marszalek 1996)

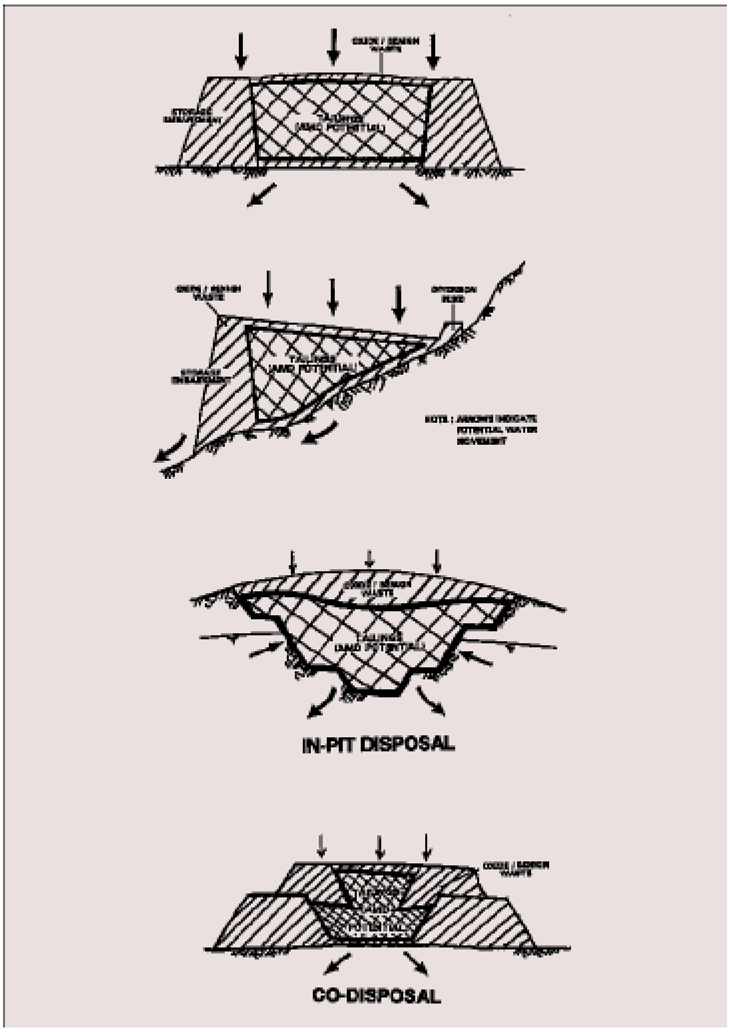


Figure 11.0: Methods for AMD control in tailing storages using a range of encapsulation and co-disposal options. (after Marszalek 1996)

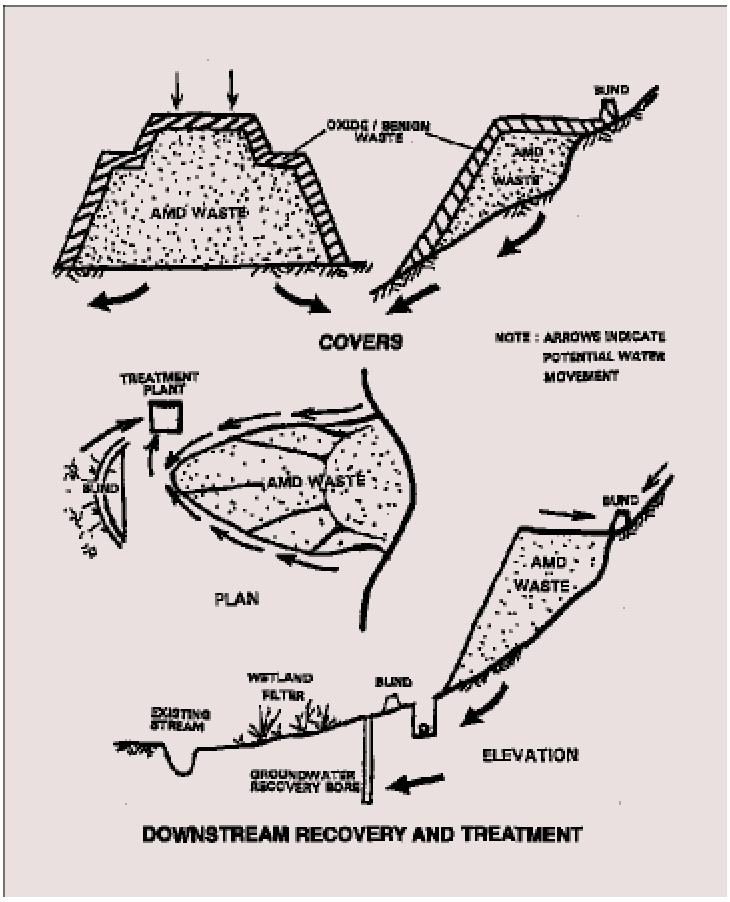


Figure 12.0: Methods for AMD control in waste rock dumps using covers and downstream collection and treatment of water options. (after Marszalek 1996)

6. TREATMENT STRATEGIES

Whilst management to reduce the production of acid drainage is the preferred option, it may be impossible to stop it completely. Treatment of the acidic effluent will normally be necessary to control off-site environmental impacts. The mining industry has developed a number of treatment strategies to minimise the potential for these impacts.

6.1 TREATMENT SYSTEMS

The most common strategy for treatment of acid drainage is collection and neutralisation with alkaline reagents such as:

- limestone (calcium carbonate);
- hydrated lime (calcium hydroxide);
- quick lime (calcium oxide);
- caustic soda (sodium hydroxide); or
- caustic magnesia (magnesium oxide),

followed by a settlement stage to recover the fine metal precipitates (hydroxides). The appropriate alkaline reagent will depend on cost and availability, and the target pH of the final effluent.

Photo: John Johnston

Acid drainage is toxic to stream aquatic life where it leaches from waste rock stockpiles and adits, Comstock Creek, Western Tasmania.

Neutralisation is effective and reliable. Drawbacks include:

- high establishment and ongoing costs (a maintenance intensive system — cost of limestone or other alkaline reagents make treatment one of the most expensive remediation options);
- it treats the resultant effluent instead of avoiding its production; and
- it produces a precipitate sludge that requires separate disposal.

As a result of these factors, treatment is best considered an interim measure. Ongoing treatment of acid drainage post mine closure is not an attractive option due to the time scales involved, typically measured in decades or centuries, thus presenting a long term liability for the industry. Where feasible, treatment should be replaced by more cost effective abatement measures directed at controlling the source of acid generation.

METAL RECOVERY

When present in sufficient concentration, dissolved metals in acid waters may represent an economic resource. Recovery of metal through solvent extraction and electrowinning or other extraction technologies may be commercially viable. A discussion of this technique appears in the *Office of the Supervising Scientist Report 108* (listed at the end of this booklet under Further Reading). Under some circumstances it may be economic to accelerate the oxidation of waste heaps to provide a metal enriched effluent to improve the feasibility of metals recovery.

Solvent extraction, leaching and electrowinning technologies generally result in a raffinate waste which may be more acid than conventional acid drainage, containing essentially the same constituents minus the metal targeted for recovery. Conventional alkaline treatment technologies are usually necessary to neutralise such effluent after metal has been extracted (see also OSS Report 108).

6.2 PASSIVE SYSTEMS

Passive alkalinity producing systems are designed to introduce alkalinity into drainage waters. These systems are best suited to relatively low flow and low acidity waste streams but may also be used to raise alkalinity levels in waters infiltrating sulphide wastes.

PASSIVE ANOXIC LIMESTONE DRAINS

In order to reduce the maintenance requirements of mechanical treatment systems, passive alkalinity addition systems have been developed. One such treatment system which has been applied with varying results is the Passive Anoxic Limestone Drain (PALID). Acid drainage is usually passed through a constructed channel of coarse limestone gravel which excludes oxygen (that is, under anaerobic conditions). Oxygen exclusion minimises the precipitation of metal hydroxides within the drain and on the limestone particles, which would reduce its efficiency.

Subsequent aeration and ponding of the discharge from the drain results in precipitation of metal hydroxides in the settling pond and a clear decant (supernatant). Passive Anoxic Limestone Drains are generally considered to have a relatively short effective life as the alkaline materials in the drain will be consumed requiring some ongoing maintenance of the system. Generally, they do not suddenly cease to function; their efficiency reduces over time.

SUCCESSIVE ALKALINITY PRODUCING SYSTEMS

Successive alkalinity producing systems (SAPS) are designed to avoid some of the problems of PALIDs by increasing alkalinity levels in 'clean' runoff/drainage streams and introducing these streams into acid drainage streams.

The alkalinity is achieved by using either anoxic limestone drains or open limestone drains. Problems associated with sludge and armouring decreasing the efficiency of alkaline materials are avoided under the anoxic conditions. Conventional aerobic settling ponds follow these systems, providing for the collection of precipitated sludges. For greater efficiency SAPS can be followed by wetland 'polishing' systems, which generally produce high quality (low metal concentration) effluents.

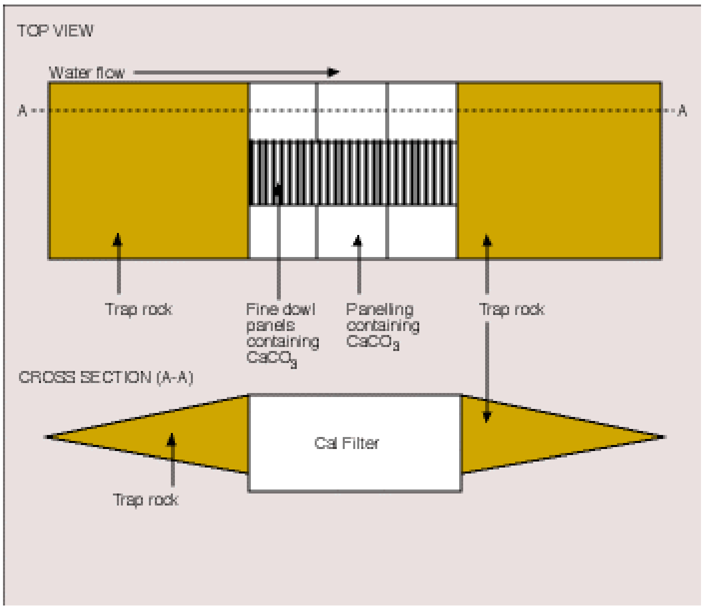


Figure 13.0 Typical passive anoxic limestone drain—'Cal Filter'

Panelling of Cal Filter reduces flow rates, allowing for longer resident times. The panelling specifications are customised to obtain optimal resident times, taking into

account the gradient and acidity of water to be treated.
(Courtesy of Limephos Enterprises Pty Ltd, Atherton, Queensland.)

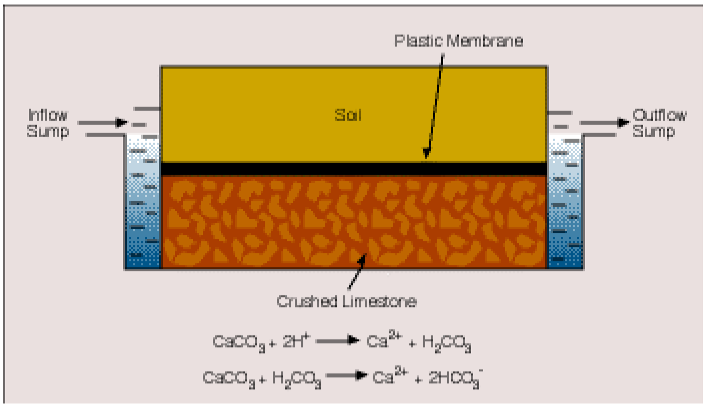


Figure 14.0 Cross section through an anoxic limestone drain

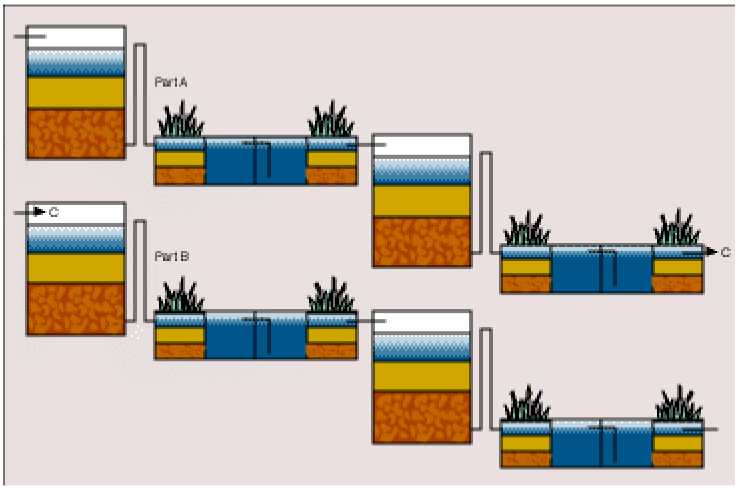


Figure 15.0 Successive alkalinity producing systems—Mt Lyell Remediation system

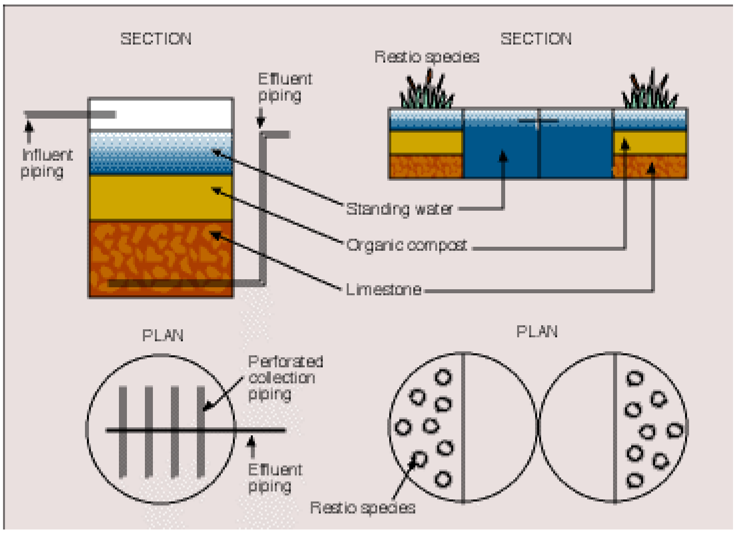


Figure 16.0 Successive alkalinity producing systems—Mt Lyell Remediation system

WETLAND TREATMENT SYSTEMS

Wetlands provide an alternative low maintenance passive treatment system and can usefully be combined with other treatment systems, including PALIDs and SAPS, as a final treatment stage for previously treated acid drainage.

Wetlands rely on a number of chemical and biological processes to attenuate acidity and metals. Many of the physio/chemical/biotic processes which occur in wetlands are poorly understood; however, the net effect is the removal of metals which become complexed in the substrate, and an increase in the pH due to alkaline materials and/or sulphate reduction. An outline on the use of wetlands for AMD is provided in Jones D. R et. al. 1995 and Noller B. N et. al. 1996 (see Further Reading).

Photo: Renison Limited

Water sampling of Lake Pieman on the west coast of Tasmania, to assess the possible impact of tailings dam discharges.

Wetlands can also be established on the surface of tailings impoundments to maintain a saturated and reducing environment, thereby reducing oxygen availability to sulphide waste materials beneath.

A further strategy to enhance wetland treatment for acid drainage (high sulphate waters) currently being trialed experimentally is the use of sulphate reducing bacteria (SRB). These bacteria are naturally occurring in wetlands and sediments and experimentally have been utilised to treat acid streams.

Design criteria for wetlands are dependent on the flow rates required to be treated, acidity, and metal concentrations in the acid drainage. Some wetland designs incorporate a pre-treatment of effluent with alkalinity producing systems to reduce acidity levels and enhance metal precipitation/reduction.

Limitations to wetlands establishment include difficulties in treating large flows, physical relief and land available for large wetland ponds. Under some circumstances the substrate may become clogged with precipitate sludges or saturated with metals thereby reducing the wetland's performance over time.

In these cases the wetland can be drained, the sediments removed and the wetland re-established. This highlights the need for ongoing management of wetlands used for such purposes.

7. MONITORING STRATEGIES

Monitoring is an essential component of sulphidic waste management. Early detection of significant sulphide oxidation is critical to the successful implementation of avoidance and control strategies, and is integral to a best practice risk management approach to the problem. Essential components of a monitoring program comprise:

- background studies to identify environmental values requiring protection, including ecosystem characteristics and catchment water quality;
- classification of all materials during the mine development and operational phases to provide information for waste management;
- point source monitoring to locate any sites of sulphide oxidation and acid generation;
- monitoring of catchments and groundwater systems upstream and downstream of mine operations to determine the nature and scale of any off site impacts and enable the recognition of long term and short term trends; and
- monitoring of control/prevention strategies to determine effectiveness, which may need to continue post mine closure.

Both flow volume and concentration load data are necessary to characterise acid drainage adequately and to evaluate potential off-site impacts.

Photo: Renison Limited

Renison Tin Mine. Measuring water levels in piezometers on tailings Dam B to collect data for modelling tailings dam hydrology.

The most common indicator of sulphide oxidation is sulphate (SO_4). Some other possible indicators are iron, copper, zinc, manganese, lead and cadmium, and major ions such as calcium, magnesium, aluminium, sodium and potassium. High sulphate concentrations in drainage and a reduction in alkalinity, even when the pH is still about neutral, highlights sulphide oxidation. Decreases in pH and increases in metal concentration may lag behind the increases in sulphate concentration due to buffering and neutralisation processes.

Specific variables such as total dissolved carbon and alkalinity should be determined for receiving waters to provide information on their buffering capacity. This information is useful in predicting both the potential and actual impact on receiving waters.

Monitoring of operations should include a detailed inventory of all waste types, materials classification and production levels:

- static and kinetic testing data to classify wastes and identify selective handling requirements;
- production volumes of respective waste rock types; and
- storage location and date of emplacement of identified mine wastes.

Non-acid producing rock types, and the presence of carbonates, should also be recorded and their suitability as cover materials assessed, as they may be useful in remediation strategies.

Waste rock stockpiles containing higher risk material require monitoring to assess stockpile behaviour. Monitoring of oxygen and water flux conditions may be required to evaluate the performance of the management strategy. Where rehabilitation strategies include the use of covers, monitoring of cover performance may include:

- oxygen ingress diffusion rates determined by analysis of oxygen partial pressures within a stockpile;
- temperature profiles through a stockpile which indicate if exothermic oxidation reactions are occurring;
- water flux through a stockpile, which may be determined by lysimeters and/or piezometers; and
- physical stability (cracking, erosion etc.) of any cover material.

Long term monitoring is an important consideration as many mining landforms such as waste rock stockpiles, tailings impoundments and mining voids may become permanent landscape features with potential for long term environmental impact.

Photo: John Johnston

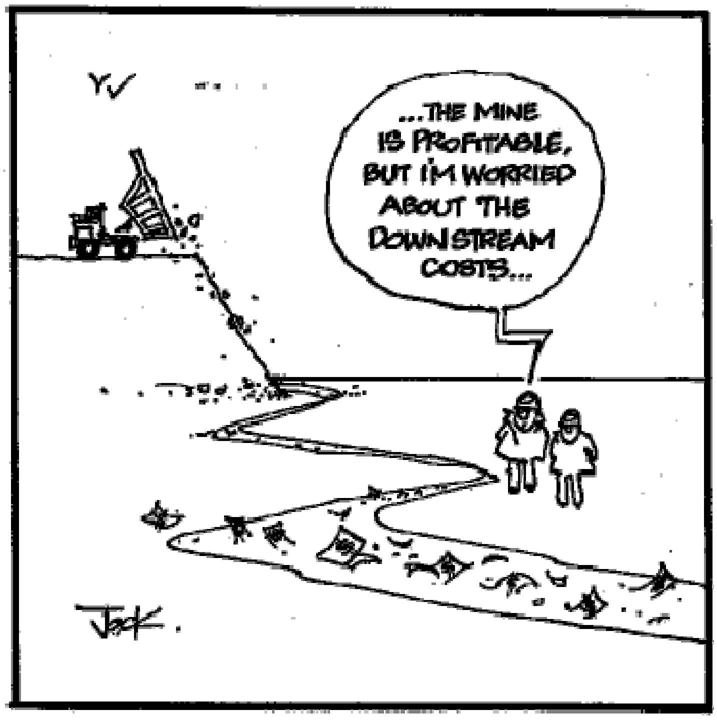
Monitoring of acid leachate from waste rock stockpile for flow, conductivity and pH prior to rehabilitation, Mt Lyell, Tasmania.

The major factors that determine the level of long term environmental risk posed by acid drainage at closed minesites are:

- the characteristics and behaviour of the mined materials;
- the geographical characteristics of the site including its location; and
- the regional climatic conditions.

Therefore, all of these factors require monitoring to assess fully the level of risk. The results will provide useful information for mine closure planning. The mine closure plan should incorporate strategies to minimise the risk of long term impacts on the environment from acid drainage. As far as possible, passive management systems should be incorporated to reduce the need for ongoing maintenance and costs.

CONCLUSION



Mining is normally a temporary land use to recover resources for the benefit of the community. This benefit may be offset substantially if poor management results in long term degradation of the mined area and surrounding environment from, for example, the effects of acid mine drainage.

Best practice environmental management of sulphidic mine wastes must involve a risk management approach incorporating:

- assessing mine waste characteristics for sulphide oxidation potential;
- assessing environmental risk based on site-specific factors;
- implementing mine design principles and mine management practices to avoid or minimise these risks;
- identifying environmental values to be protected and designing monitoring programs for early identification of sulphide oxidation/acid drainage;
- mine planning and mine closure strategies that minimise the potential for off-site impacts associated with sulphide oxidation and acid drainage; and
- ensuring long term effectiveness of the management strategies implemented.

Where the risk of significant impact is high, the need for subsequent high cost remediation strategies can be reduced by building prevention measures into environmental management systems during mine planning and development.

The initial step in controlling sulphide oxidation is the early characterisation of higher risk (acid producing) materials, and materials with potential for use in remedial measures. An inventory should be developed, updated and refined to characterise and quantify mine wastes adequately throughout the life of the mine. The subsequent incorporation of this information into block modelling and mine planning will enable the development of effective strategies to manage sulphide oxidation in these wastes.

Acid base accounting provides an appropriate means of screening material to characterise its acid producing potential. Kinetic testing is also required to estimate the rate of oxidation, potential oxidation product loads, and metal concentrations in any acid drainage from these materials. However, sampling protocols are critical to ensure that the risks are quantified with a high level of confidence. Acid base accounting should continue through all phases of project evaluation and development.

Best practice environmental management may require the implementation of a range of site-specific measures based on local conditions and available resources to minimise the risk of environmental impact from acid drainage. The most effective management strategies will require a thorough understanding of the factors contributing to the formation of acid drainage, the specific characteristics of the waste material being dealt with, and the range of strategies available to control and/or treat acid drainage where effective control is not achievable. More research is needed to identify answers to the suppression and treatment of acid mine drainage, in both generic and site-specific aspects. Consistent with the best practice approach, many companies are expending considerable resources on research and development associated with sulphide mine waste management and the control of acid drainage.

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CASE STUDY 1

GREGORY OPEN CUT COAL MINE, BHP AUSTRALIA COAL

The Gregory Coal Mine is an open cut mine located on a lease of 6 500 ha some 60 km north east of Emerald in the Bowen Basin, Central Queensland. The strata just above the main coal seam are pyritic. The pyrite generates acid unless preventative measures are taken as part of the mine operations.

The climate of the area is sub-tropical, semi-arid with about 80% of the annual average rainfall of 620mm falling in the warmer months of October to May. Annual average evaporation exceeds rainfall by a factor of three.

Photo: BHP Australia Coal

BHP Australia Coal, Gregory Coal Mine, 60 km north east of Emerald, Queensland. Rehabilitation of mine spoil in foreground with strip mining in background.

Assessment of the exploration drilling for the Gregory Mine in the late 1970s identified the potential for acid generation. Therefore, mine planning and more particularly operational planning identified measures to minimise the generation of acid. Operational measures were introduced from day one of mining.

MEASURES TO REDUCE ACID GENERATION

The following outlines the operational measures introduced to reduce acid generation.

- Temporary Reduction of Acid Generation from Wastes by Covering with Water

The fine wastes and tailings from the coal preparation process are slurry pumped to tailings impoundments or to mined out pits. The disposal of these wastes by covering with water reduces the rate of acid generation.

The supernatant water from these disposal areas is returned to the preparation plant for reuse in coal washing. Although this returned water usually requires some neutralisation in a lime treatment plant, the deep sub-aqueous disposal of the tailings reduces the total volume of acidic water generated at the mine.

Reuse of the water in the tailings disposal cycle also reduces the total demand for raw water on local water resources by the mine.

- Permanent Covering of Wastes with Benign Material.

All coal-like wastes and particularly the coarse rejects from the coal preparation plant are returned to mine pits. This negates the construction of reject/waste dumps with a very high potential for acid generation. The dumped rejects are subsequently covered with spoil derived from the excavation of the next mine pit-strip. The rejects are returned to mine pits as part of the coal haulage movements, generally maintaining a shorter haulage route and quicker haulage cycle.

Photo: BHP Australia Coal

BHP Australia Coal, Gregory Coal Mine, near Emerald, Queensland. Rejects are returned to mine pits which removes the need to build reject/waste dumps. These wastes are subsequently covered with spoil.

As no reject dumps are constructed, there is no requirement for special rehabilitation of reject dumps. This significantly reduces overall rehabilitation costs and minimises the future risk of acid generation from massive reject dumps.

- Selective Handling

Selective handling and some rehandling of pyritic spoil materials is necessary to reduce acid generation in the mine spoil. Selective handling was identified prior to the start of mining, this practice is a usual practice at the Gregory Mine and not a special practice with additional costs.

The aim in the selective handling is to place the pyritic spoil deep in the spoil profile. This is generally accomplished by rehandling by the dragline of identified pyritic spoil into the first pass spoil valleys. The rehandling places the pyritic spoil at depth and reduces the overall regrading requirement of the spoil as part of the mine rehabilitation activities. Deep placement of the potentially acid generating spoil also ensures more successful revegetation of the mine spoil because benign non-toxic materials are used as a cover.

Photo: BHP Australia Coal

BHP Australia Coal, Gregory Coal Mine, near Emerald, Queensland. With the use of benign materials as a cover, and deep placement of acid generating spoil, this allows *more sucess with revegetation of mine spoil. Weak vegetation establishment due to poor placement of spoil materials will require further patch-up works.*

Should acid generating spoil remain on the surface, or be exposed during normal regrading of spoil, the regrading of the spoil materials is altered in the field to ensure burial of the pyritic materials. Small equipment has also been used to "patch-up" rehabilitation where acid generation has caused problems or where topsoil cover is insufficient.

WATER MANAGEMENT STRATEGY

Recognition of the potential for acid drainage at Gregory Mine during mine planning also led to the development of a sound, comprehensive water management strategy. Drainage unaffected by mining activities is diverted away from or directly through the mine area. This drainage is therefore not contaminated by the mine workings.

Mine drainage, and particularly mine process water and water which accumulates in mine pits, potentially is contaminated by acid mine drainage. Therefore, this drainage is captured and reticulated back to the mine industrial area where it is available for dust suppression and if required for use in the coal preparation plant.

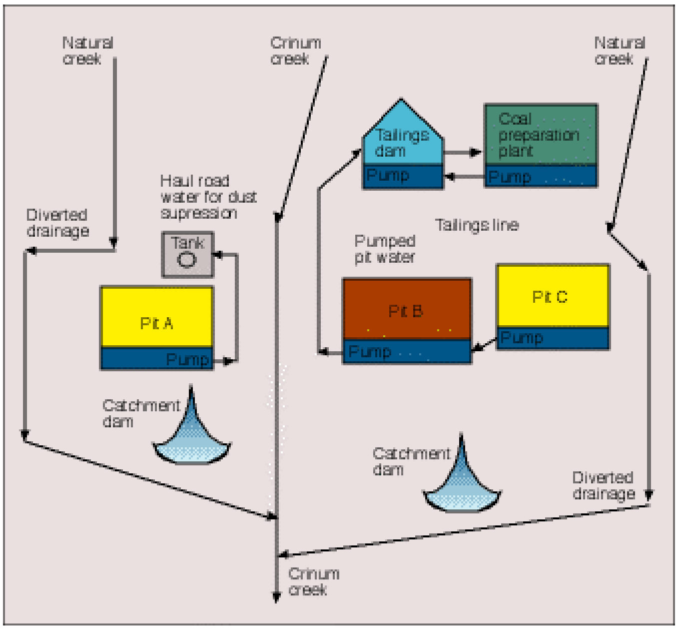


Figure 1.0 Schematic water management system at Gregory Open Cut Mine.

This water management system reduces the requirements for raw water from external supply sources and reduces the need to release water from the mine area into local water resources. Therefore, downstream water users are not put at risk; releases of mine water occurring only when there are flood flows in local streams and mine waters are well diluted.

The early identification of the potential for acid generation from near-coal strata at Gregory Mine has allowed the development and implementation of measures to mitigate the risks of acid formation. The implementation of these plans has allowed mining costs to be controlled, site water consumption to be moderated and site rehabilitation costs to be reduced.

CASE STUDY 2

CADIA - WASTE BLOCK MODELLING FOR ACID MINE DRAINAGE PREDICTION AT THE CADIA PROJECT

INTRODUCTION

Newcrest Mining Limited has utilised a waste block modelling approach (based upon protocols developed by AGC-Woodward Clyde) at its Cadia project in New South Wales to identify potential acid generating material within the deposit.

The Cadia gold/copper deposit is located 25 km south of Orange, NSW. Average annual rainfall is 800 mm which is spread evenly throughout the year. Average annual evaporation is approximately 1 100 mm. The deposit contains approximately 200 Mt of ore and 270 Mt of waste rock that will be mined over a 12 year period.

The area is historically an active mining area with exploration and mining dating back more than 140 years to the discovery of gold and copper in 1857.

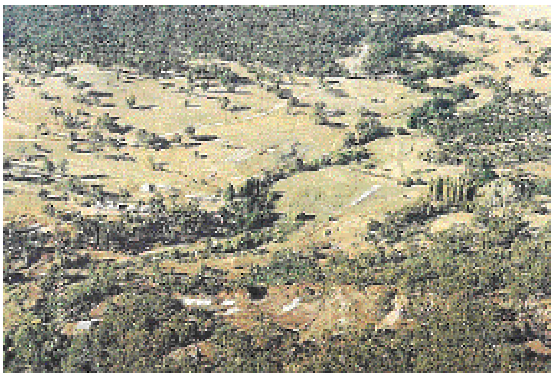


Photo: Newcrest Mining

Aerial view of the Cadia Project.

Photo: Newcrest Mining

Cadia Hill viewed from adjacent hills.

Geology

The Cadia Hill mineralisation is indicative of a relatively oxidised and low sulphide system, reflected by low abundance of pyrite, typically less than 1%. The sulphide minerals occur in two associations — as inclusions in quartz veins and as fine to medium ground disseminations in the monzonite porphyry and volcanic host rocks.

The dominant sulphide mineralogy is pyrite (FeS_2), chalcopyrite ($CuFeS_4$) and minor bornite (Cu_5FeS_4). The sulphides are generally fracture controlled and associated with sheeted quartz veins. Where carbonate is present in the waste rock it is predominantly calcite, manifesting as cross-cutting veins and as a pervasive alteration of the waste rock minerals.

Sampling strategy and testwork

Based on early identification/classification of the mine waste, a mine waste schedule has been formulated to facilitate selective placement of waste rock within the waste stockpile and so minimise potential acid drainage.

An extensive geological database on the site has been compiled from logging of drillcore at one metre intervals. The general sampling approach adopted is shown in Figure 2.0.

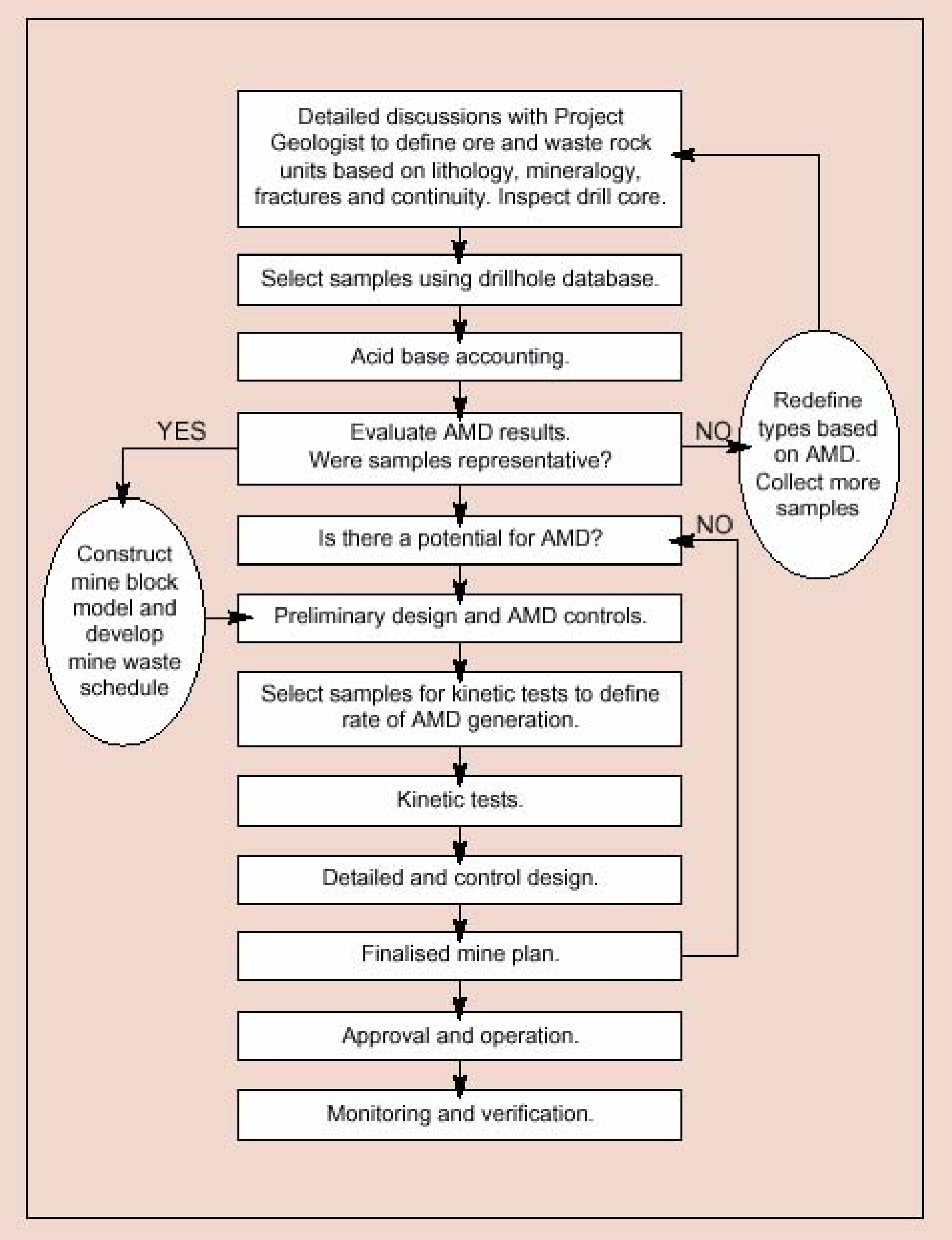


Figure 2.0 Evaluating Acid Mine Drainage Potential

Criteria for the selecting material from the database for testing include:

- lithology;
- sulphide abundance;
- sulphide form;
- carbonate abundance;
- carbonate form;
- oxidation state;
- alteration mineralogy; and
- structure.

Each of these criteria has the potential to influence the acid generating or neutralising capacity of individual rock types.

Thirty six separate combinations of physical and mineralogical characteristics for the eight waste rock types were identified which had the capacity to influence the acid drainage potential.

On the basis of results from static testing, four waste types were selected for longer term kinetic testwork:

•	monzonite	high pyrite and low carbonate
		high carbonate and low pyrite
•	volcanic	high pyrite and low carbonate
		high carbonate and low pyrite

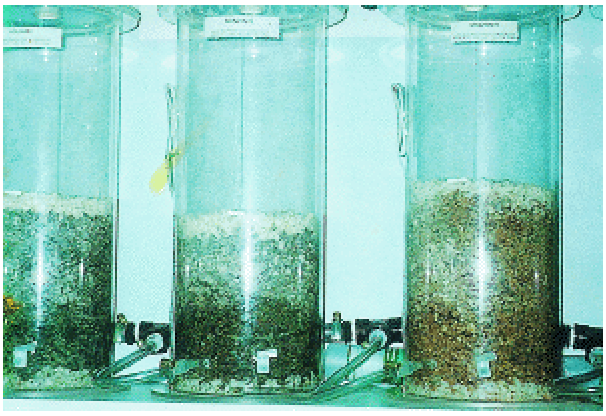


Photo: Newcrest Mining

Long term column testwork has been initiated to further assess the quality of waste rock leachate.

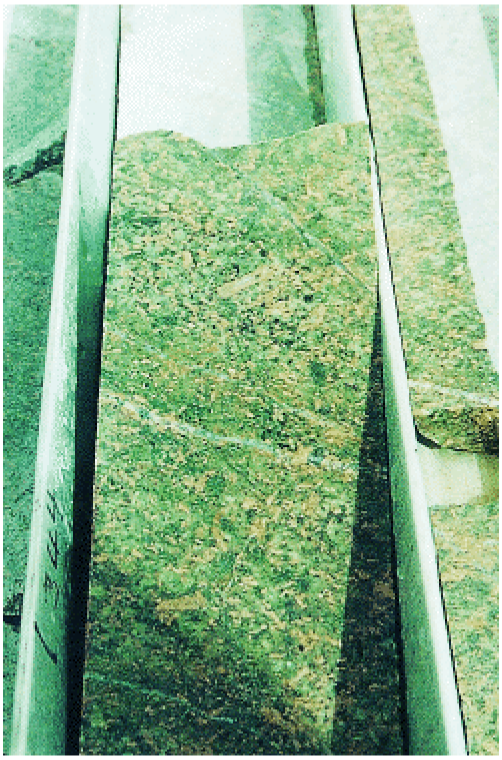


Photo: Newcrest Mining

Newcrest Mining, Cadia project near Orange, New South Wales. Drill core used in the environmental/ geochemical waste characterisation study.

Classification of waste rock

The static testwork identified three main waste types:

Type I	potentially acid forming (total sulphur >0.25% and MPA:ANC ratio of 1:1 or less);
Type II	indeterminate (total sulphur >0.25% and MPA:ANC ratio of 1:3 or less); and
Type III	non-acid forming (total sulphur <0.25% and MPA:ANC ratio of 1:3 or greater).

Mine Block Modelling

These waste rock sample characteristics provide a set of parameters for waste classification into potentially acid producing, indeterminate or acid neutralising. Each waste rock type is classified in these terms and the information integrated into the database.

Once classified, the waste rock distribution and volume as a proportion of the total waste volume is determined by mine block modelling and percentage volumes are estimated for the three 'types' (Type I-III) of waste.

With the volume and position of acid producing material defined, this information is integrated into the mining schedule to determine how much and when potential acid drainage material will be produced during mining.

Results

Figure 3.0 shows the distribution of the waste block types with respect to the ore.

The static testwork and block modelling has identified a small percentage of potentially acid producing waste than can be located in discrete blocks within the proposed pit area. Using the mining schedule, this material can be identified during mining and selectively handled for placement in specific cells in the waste stockpile for blending with waste rock of high neutralising potential.

A significant volume of non-acid forming and acid neutralising waste can also be blocked out and selectively used in the construction of the waste stockpile, for example, to encapsulate and/or blend with potentially acid forming waste, and for use as rock armour on the outer batters of the waste stockpile.

Conclusions

The use of a sampling program based on geological characteristics to test for acid producing rock (and block modelling to identify the spatial distribution and amount of acid producing material at Cadia) has resulted in:

- minimising the amount of waste material to be selectively handled;
- developing cost effective waste handling programs; and
- integrating the strategy for handling acid-forming waste with the operational mine schedule.

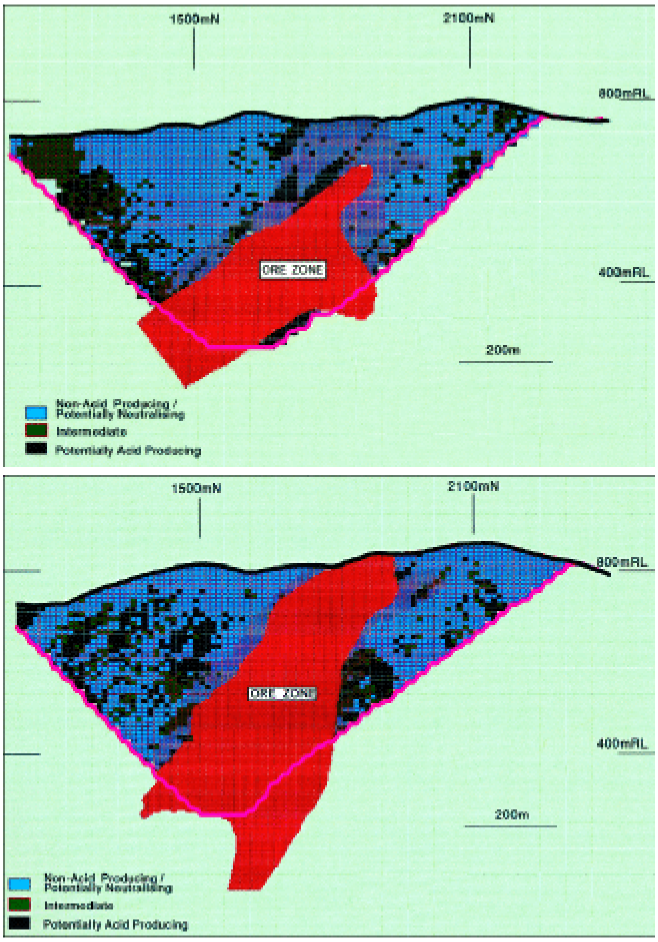


Figure 3.0 Typical Cross-Sections ANC/MPA Block Model

CASE STUDY 3

BHP MINERALS, CANNINGTON

Location

North-west Queensland approximately 200 km south east of Mt Isa.

Climate

The climate is sub-tropical, characterised by a relatively short and unreliable wet season. Average annual rainfall is 440 mm, falling mainly between December and March. Average pan evaporation is 3 000 mm per annum.

Average daily air temperature ranges from 25°-35°C in December to10°-25°C in July.

Metals Produced

Silver, lead and zinc as sulphide concentrates.

Type of Operation and History

Cannington silver was discovered in 1990 by drill testing of a magnetic anomaly identified during a regional aeromagnetic survey. A decision was taken to proceed with the development of the deposit in 1996 following positive results from a feasibility study which included an underground bulk sampling program undertaken in 1994. Construction of permanent surface facilities commenced in 1996 and commissioning is scheduled for November 1997. The mine will produce approximately 1.5 million tonnes of ore per annum over a mine life of approximately 20 years.

Sources of acid drainage

The project will produce both waste rock and mill tailings. A proportion of the waste rock and the tailings material will contain reactive sulphide minerals in concentrations that may produce acid conditions if not managed appropriately. Waste rock will be stored on the surface in engineered waste rock stockpiles. The coarse fraction of the tailings material will be returned underground as mine backfill and only the fine fraction will be placed in the tailings dam.

Planning to Minimise Environmental Impact

Geochemical investigations were undertaken during the exploration phase to characterise the waste materials. Soils and subsoils to be moved in the construction of surface facilities were also evaluated in the program. Materials were characterised based on their Net Acid Producing Potential (NAPP), determined from the difference between the Maximum Acidity Potential (MAP) and the Acid Neutralising Capacity (ANC). The results were correlated with Net Acid Generation (NAG) test results. Salinity was included as an additional parameter in the planning process.

The NAG test proved to be a cost effective measure of the acid forming potential of sulphidic waste materials under field conditions.

Measures to Reduce Environmental Impacts

Five main material types were identified through the characterisation process. These materials are listed below along with the specific management prescriptions for each material.

Material Type	Geochemical Characteristics	Management Prescriptions
1A	Non-acid forming Nil/low/moderate salinity (NAG pH >4 & EC 1:5 < 0.8 dS/m) (NAG pH >4 & EC 1:2 <1.5 dS/m)	Suitable for general construction use and general fill. No specific geochemical constraints. Suitable for rehabilitation works
1B	Non-acid forming High salinity (NAG pH > 4 & EC 1:5 0.8-1.3 dS/m) (NAG pH > 4 & EC 1:2 1.5-2.5 dS/m)	Suitable for general fill. Undesirable for rehabilitation use due to salinity. Avoid placing within 300mm of final surfaces.
1C	Non-acid forming Extreme salinity (NAG pH > 4 & EC 1:5 > 1.3 dS/m) (NAG pH > 4 & EC 1:2 > 2.5 dS/m)	Can be used for general fill provided it is isolated within the core of any embankment (for example, water storage). Do not place within 500mm of rehabilitation surface.
II	Potentially acid forming Low risk (3 < NAG pH < 4)	Not suitable for construction use or general fill unless placed and compacted within the core of embankments and isolated from leaching. Do not place within 1m of final surfaces or outer edge of stockpile#.
III	Potentially acid forming High risk (NAG pH < 3)	Should be buried and isolated from leaching. Place and compact Type III materials in layers. Locate material towards the centre of the stockpile area. Do not place within 1m of final surface or within 5m of the outer edge of the stockpile. Place compacted Type 1C over the Type III material before placing soil cover for rehabilitation#.

EC	Electrical Conductivity of a one part soil to 5 parts water slurry (1:5), or a one part soil to 2 parts water slurry (1:2).
NAG	Net Acid Generation test result
#	Type II and Type III materials can be converted to Type I material by blending with limestone or other acid neutralising materials.

Materials produced during the development of underground and surface works associated with the bulk sampling program have been handled in accordance with the above guidelines. Type III material has been placed in a stockpile adjacent to the decline. The area was initially stripped of topsoil (200 mm) and subsoil (300 mm) and the subgrade compacted using a self propelled vibrating roller prior to the placement of the waste rock. The waste rock was placed and compacted in 500 mm layers until the design height of the stockpile was achieved. The compacted material was then covered with 500 mm of clay to reduce the ingress of rain water and oxygen. The clay was then covered with a protective layer (1m) of Type I material.

Waste rock dump covered in clay.

Photos: BHP Minerals

Another view of clay capped waste rock at Cannington.

Test work has demonstrated that the tailings material will have a moderate sulphur content ranging from 1 to 2.5% sulphur which will generally be balanced by the medium to high acid neutralising capacity of the material. The results also indicate that the reactive sulphide content is sufficiently high to cause salting problems under exposed evaporative drying conditions. A cover will therefore be required to avoid salt pan development and generation of dust.

Based on the work undertaken to date it is believed that a simple single layer cover will be adequate for the majority of the tailings material. The cover will be designed to provide adequate depth for plant growth and prevent salt migration to the surface. Further test work is planned to optimise the design of the cover for the tailings impoundment. An evaluation of salt profiles in the natural soils of the area indicates that a 600 mm cover constructed from natural soils in the surrounding area will be sufficient to achieve the rehabilitation objectives.

Photo: BHP Minerals

Decline stage I. Waste rock stockpile, built on limestone pad.

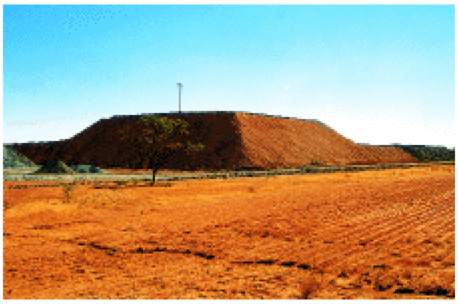


Photo: BHP Minerals

Type III stockpile and clay seal plus Type I material (rock) on top.

Monitoring

The geochemical stability of the existing waste rock stockpile is being monitored utilising thermistors and oxygen probes inserted within the Type III material to determine the effectiveness of the design. Any increase in temperature and associated reduction in oxygen levels would be indicative of active oxidation of sulphide minerals and the associated potential for acid generation. Runoff and leachate will be monitored if it occurs. Since establishment of the monitoring program in May 1995 temperatures and oxygen levels have remained stable. The waste rock stockpile has not generated any leachates to date.

A detailed geochemical monitoring program will be implemented following commissioning of the milling operations to provide information necessary to finalise the design of the final cover for the tailings impoundment. The tailings facility will be a zero discharge operation.

Benefits of Management Program

Failure to adequately identify and manage the potential for sulphidic oxidation and acid generation can result in significant impacts on the environment and substantial clean up costs for the mine operators. The geochemical characterisation of waste materials and the development of handling options during the planning phase of the Cannington project will ensure that the potential for acid generation is minimised and controlled in a cost effective manner. Environmental values will be protected during the operation of the mine and final decommissioning will be facilitated without the requirement for expensive post-mine remediation programs.

Photo: BHP Minerals

Laying thermistors and oxygen probes to monitor temperature and oxygen inside dump.

Photo: BHP Minerals

Oxygen and temperature monitoring control box on probes within Type III stockpile.

CASE STUDY 4

PLACER PACIFIC LIMITED

A Risk Management Approach to the Acid Drainage Problem

The Placer Dome Group (PDG) is a precious and base metal mining group of companies based in Canada, with major operating subsidiaries in Australia, Canada, South America and the USA. In Australia, the operating subsidiary, Placer Pacific Limited, manages five operating mines and exploration activities within Australia and the Asia-Pacific region.

The PDG Boards of Directors have approved an environmental policy and associated strategic plans that require acid drainage risks to be addressed fully for all operations. This approach also requires appropriate controls to be implemented which minimise potential acid drainage and associated environmental impacts during operations and after closure. In accordance with good environmental management, PDG has initiated and conducted, since 1990, comprehensive acid drainage reviews of each major operation and exploration project. These reviews provide information to enhance internal environmental operating plans and rehabilitation plans for all minesites. Research projects have been established at several sites where additional study programs are required to enable a more comprehensive assessment.

PDG Corporate Philosophy

The PDG Environmental Management Group has grouped its activities into four general categories for acid drainage potential: future mines (advanced exploration projects/acquisitions); newly designed/constructed mines; existing/operating mines; and decommissioned/rehabilitated mines. While there are different philosophies and strategies developed for each group, there is a set of underlying principles which apply generically to acid drainage prediction as outlined below:

- Each minesite is unique with respect to geology, climate and site configuration and, hence, the application of rigorous routine prescriptive practices is not appropriate.
- Sulphide mineral reactivity is highly variable and acid drainage may not occur at all, or be delayed for several years following material exposure from mining. Consequently, it is never too late to assess the acid drainage potential at existing mines using predictive methods with additional integration of empirical site information.
- Prediction and prevention of acid drainage is the most desired and simplest control approach for all sites.
- The results of the predictive assessments may justify changes in mining operations and waste disposal practices to reduce the potential of acid drainage.
- The application of predictive methods at an early stage of an advanced exploration project will allow a phased approach to further studies and, if necessary, detailed planning of waste rock and tailings disposal.
- Internal training of PDG technical staff in the prediction, assessment, and control methods for acid drainage is an integral component of good environmental management.
- Ongoing applied research is needed at sites with significant acid drainage potential to track the success of the implemented prevention strategies and to augment the knowledge base for the development of improved techniques within PDG and the minerals industry.
- Continued and significant support is required for generic research through industry task forces and at individual PDG sites to allow a better understanding of the processes associated with acid drainage.

Risk Management Approach

The PDG program consists of a team approach composed of several key players and facilities. These personnel vary with the classification of the project, but the common denominator is a joint effort between corporate personnel, specialised experts and the exploration/design/operating personnel who will eventually be required to apply the end product. An experienced site geologist and a mine design engineer assist the environmental personnel in the initial overview risk assessment and provide continuity for ongoing risk assessment and control strategy development.

The PDG management approach is outlined in Figure 4.0:

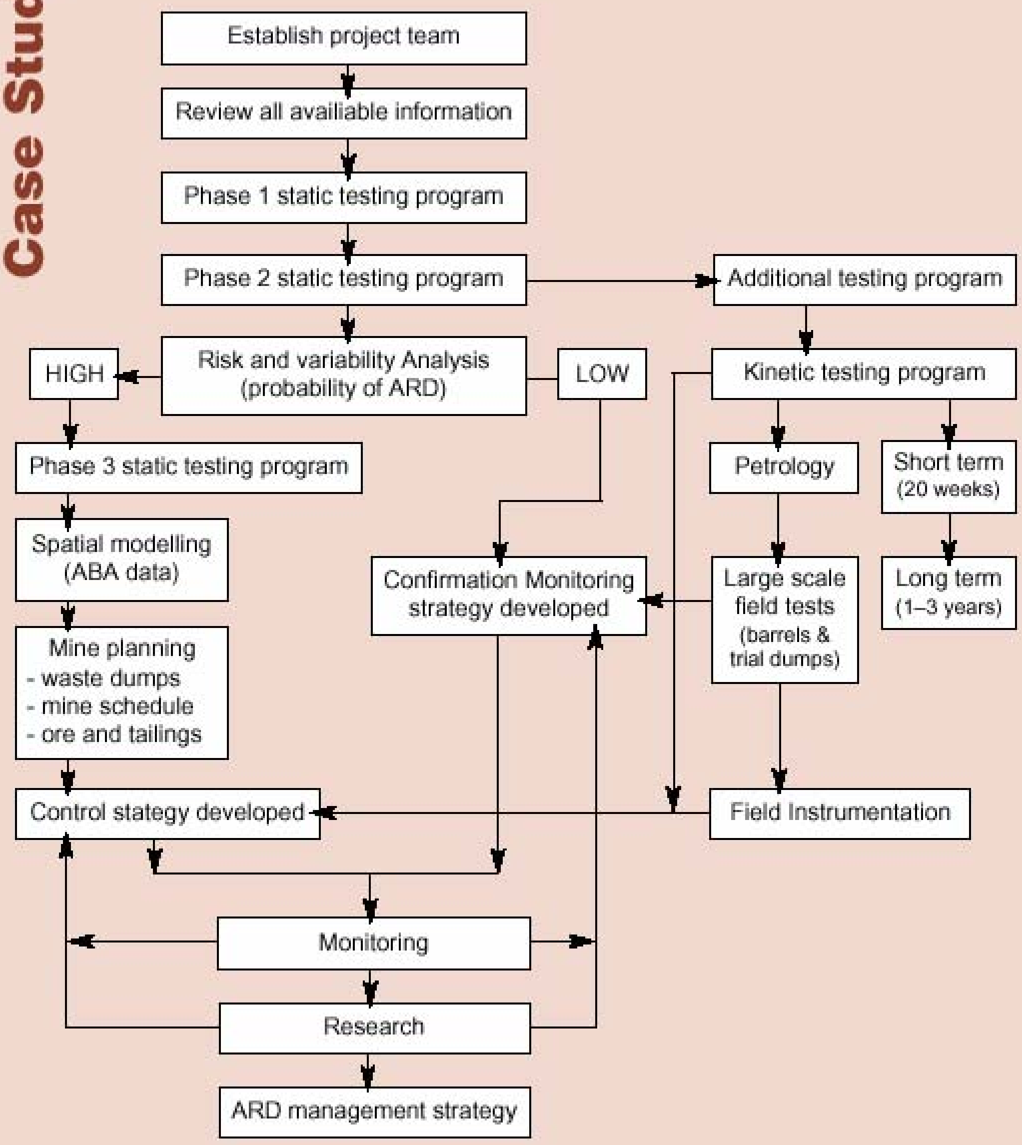


Figure 4.0 Placer approach to ARD assessments of new and existing mines

CASE STUDY 5

RENISON TIN MINE, TASMANIA

Location

Western Tasmania, in the Pieman River catchment, 135 km south of Burnie.

Climate

Wet, cool with occasional snow. Average annual rainfall of 2 252 mm spread throughout the year. Average pan evaporation is 500 mm.

Mean monthly temperature ranges from 3 to 22°C with an annual mean of about 15°C.

Metals Mined

Tin

Type of operation and history

Tin as cassiterite was discovered in 1890. Various small companies operated in the field until the current operations began in 1966. Today Renison is one of the world's largest underground tin mines. Ore is primarily mined by flatback cut-and-fill and benching methods using trackless diesel equipment and decline access to working areas. A shaft was recently commissioned to access deep ores. A complex mineral processing plant produces a cassiterite concentrate for export.

Sources of acid drainage

The tin ore contains about 45% of the very reactive iron sulphide mineral pyrrhotite, resulting in a Net Acid Producing Potential (NAPP) of greater than 600 kg H_2SO_4 per tonne.

Acid drainage is found in:

- mine waters pumped to the surface during mine dewatering (30%);
- decant and seepage waters from tailings impoundments (55%); and
- runoff from historic workings and miscellaneous sources from the current operations, such as the ore stockpile and small waste rock stockpiles (15%).

Strategic planning to minimise environmental impact of acid drainage generation

One of the primary considerations is to develop management strategies that will not compromise water quality within the Pieman River catchment after the life of the mine.

With precipitation exceeding evaporation by about 1 500 mm per annum, water discharge from the lease is inevitable.

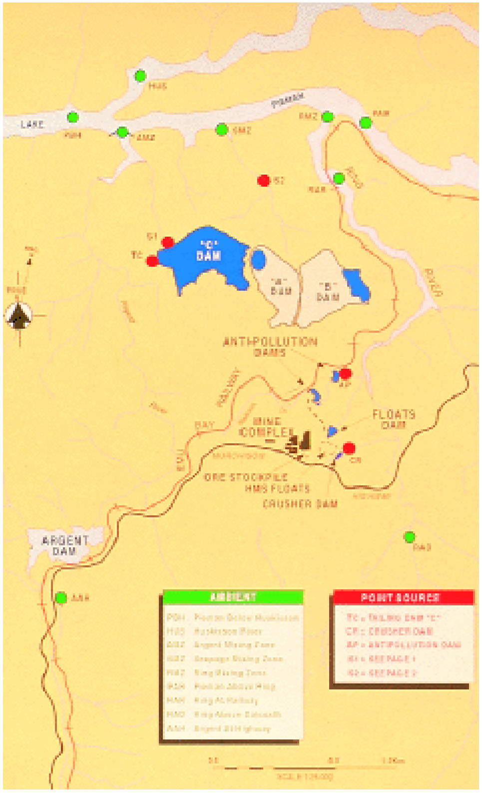
Treatment of acidic waters with slaked lime is a part of the mine's current practice. Modelling of the oxidation process occurring in the tailings impoundments indicates that, at current oxidation rates, acid waters would be discharged from the tailings impoundments for many decades after mine closure. It would not be realistic to maintain water treatment over this time scale.

Under these circumstances the management focus is on eliminating oxidation at source, or reducing oxidation rates, such that water quality within the catchment will not compromise the long term ecological integrity of the State Reserve on the Pieman catchment downstream of the mining operation.

Monitoring

- Weekly sampling of all point source discharges from the mine (six stations);
- bimonthly sampling of ambient waters in and around Lake Pieman (nine stations); and
- bimonthly sampling of catchment waters as part of a joint program with State Department of Environment and Land Management, State Hydro-electric Commission and various mines operating in the catchment (fifteen stations).

Map of Renison Tin Mine showing tailings impoundments and monitoring stations.

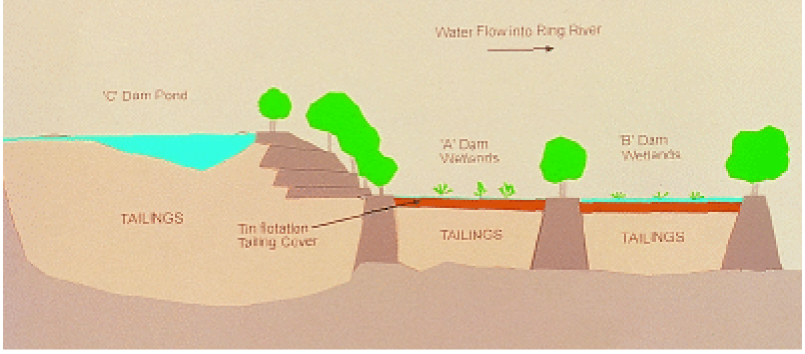


Tailings Impoundment Close-Out Model

The tailings produced during mineral processing are a composite of three separate waste streams. One of these, Cassiterite Flotation Tailings (CFT), is low in sulphur with a net acid neutralising capacity. It makes up 25% of the tailings by mass and has potential as a suitable cover material on the other tailings materials.

Research has shown that CFT would quite readily support plant growth and, if maintained at 80% saturation, would provide a very effective barrier against oxygen diffusion by reducing oxidation rates to negligible levels.

Renison's tailings impoundment management plan is for subaqueous disposal of tailings into dam C during mining, leaving a stable permanent pond at mine closure. Decant waters will discharge into tailings impoundments A and then B. These dams will be covered with CFT to a depth of 0.5 to 1 metre and wetlands developed on top. The wetlands will be designed to act as polishing ponds for Dam C effluent before it is discharged to receiving waters. Specific cells for the sequential bio-removal of iron and manganese need to be developed.



Renison Tin Mine. Conceptual Model of close-out plan for Renison tailings impoundments.

Research work is continuing to further develop the close-out plan. Tailings impoundment hydrology, dam C water chemistry and wetland cell design are being modelled for subsequent implementation. Complementing this research is a joint mining industry funded research program on the speciation and fate of metals in the waters of Lake Pieman.

Research on the close-out model is primarily aimed at ensuring that the community is not left with an environmental legacy that may compromise water quality for future generations. Knowledge gained is being used by Renison and others to improve tailings dam management from an environmental perspective. Contemporary practice has seen an 80% reduction in mass discharges from tailings dams, setting new benchmarks for the future.

Renison Limited, Renison Tin Mine. Natural colonisation of wetland species on inert tailing cover material (CFT) on dam A within two years of placement.

Photo: Renison Limited

CASE STUDY 6

MT LEYSHON

Introduction

The Mt Leyshon Gold Mine is located 24 km south of Charters Towers, Queensland. It is a large open-pit mine, producing gold and silver. The operation is owned by Mt Leyshon Gold Mines Limited, which is a member of the Normandy Mining Group.

Operations began in 1987 and were initially restricted to the heap-leaching of oxide ore. Ongoing testwork revealed a much larger resource of unoxidised ore at depth, which lead to the construction and operation of a conventional carbon-in-pulp (CIP) plant. Throughput is currently 5.5 Mt year.

Climate and Geology

Mean annual rainfall at Charters Towers is 660 mm, with most rain occurring from November to March. Most rainfall is received in high intensity storms with high runoff rates. Average pan evaporation is 1 965 mm. Average maximum and minimum temperatures are 30°C and 177deg;C respectively.

The Mt Leyshon orebody is hosted in an intrusive breccia and igneous complex approximately 1.6 km in diameter. Polymetallic mineralisation (Au-Fe-Cu-Zn-Pb-Ag-Mo-Bi) is hosted in breccias and associated intrusives. A second host, the Mine Porphyry, accounts for approximately 15% of the mineralisation.

Development of a Rehabilitation Strategy

As found at many metalliferous mines, the primary (unoxidised) waste rock contains varying levels of sulphides, mainly in the form of pyrite. The rehabilitation strategy for the waste dumps must therefore be designed to minimise the potential for AMD. This case study describes the development of a rehabilitation strategy to meet this objective. A more complete description is given in Orr (1995).

The rehabilitation strategy for the dumps at Mt Leyshon is the construction of a sealing layer over the bulk waste to:

1. Reduce infiltration to very low levels;
2. Prevent convective transport to oxygen; and
3. Have the potential to reduce diffusive transport of oxygen.

This strategy is shown schematically in Fig. 5.0.

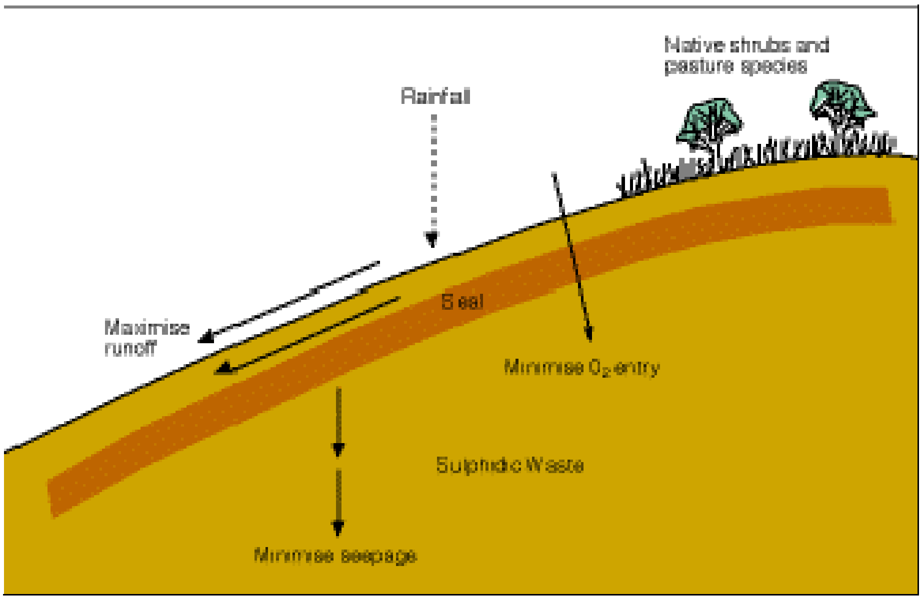


Fig. 5.0. The chosen waste dump strategy for Mt Leyshon Gold Mine.

Compaction trials

A key issue in implementing this strategy was the availability of material suitable for seal construction. The clay reserves on-site are limited and the costs of using clay would be relatively high. Oxide heap-leach material has been used to seal some areas of the dump, but the saturated hydraulic conductivities achievable through compaction of this material are limited to about 10^{-6} m s^{-1}. Compaction of in situ waste dump material to form a low permeability seal was seen as having potential benefits and trials were conducted on-site. Fig. 6 shows a plan of the first compaction trial using mine waste. The four major waste types at the mine were laid in strips to a depth of about 1 m. Three different compaction methods were run at right angles to these strips, namely:

1. A control strip with no compaction except for that produced by the bulldozer when pushing out the strip;
2. A fully loaded haul truck with a total weight of about 360 t; and
3. A BH-1300 impact roller (photo). When towed at a speed of around 12 km per hour, the large steel (8t) drum of this machine impacts on the ground with great force. The claimed advantages of this device over the more usual vibrating drum roller are good compaction at depth and relative insensitivity to the moisture content of the material.

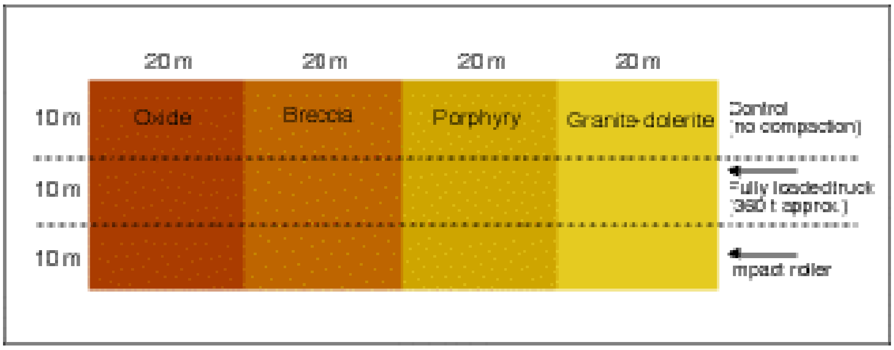


Fig. 6.0. Layout of the waste rock compaction trial at Mt Leyshon Gold Mine

The BH-1300 impact roller at work compacting porphyry on a waste dump at Mt Leyshon Gold Mine.

Testwork conducted during the trial included compaction tests (sand replacement method) and hydraulic conductivity. Hydraulic conductivity was measured directly using an 'infiltrometer' built on-site which measures infiltration rate over a relatively large area (1 m^2).

The key finding from the first compaction trial was that the porphyry waste was soft enough to be readily compacted (none of the other waste types were shown to be suitable for use as a seal material). Both the haul truck and the impact roller were able to obtain high densities at depth . The use
of a truck was discontinued due to the good apparent performance of the impact roller as compaction. Routine truck travel was considered unrealistic if a consistent specification was required.

Modelling of long-term performance

To quantify the performance of the possible porphyry seal configurations, infiltration was modelled using the 'SWIM' model as described in Crees et al. (1994). The role of mathematical modelling in the assessment of rehabilitation strategies was seen as very important, because of the cost and time required for field trials. (The very variable rainfall received on-site means that meaningful estimation of long-term infiltration rates via direct measurement would require several years of monitoring at least). The results of the modelling indicate that very low levels of infiltration can be achieved using the impact roller on the porphyry, e.g. 1.7% of incident rainfall for a 1 m thick layer compacted to give $1x10^{-8}$ m/s saturated hydraulic conductivity.

Geochemical assessment of the seal

Having examined the physical characteristics of the porphyry material, it was necessary to assess its geochemical characteristics. Representative samples were collected from drill core and areas of compacted seal, and analysed for sulphur and net acid producing potential (NAPP). The results showed that, unlike the other main primary wastes, the porphyry has significant acid neutralising capacity.

Material Availability and Scheduling

So far, field compaction trials, infiltration modelling and waste characterisation confirmed the feasibility of using porphyry as a waste dump sealing material. It was then necessary to consider the availability of rehabilitation material over the life of the mine, with respect to total availability and timing of material from the pit.

Following examination of the rehabilitation materials balance for the mine, it confirmed availability of material to support future rehabilitation strategies for the different sites.

Attention was next given to materials scheduling. The production of porphyry waste from the pit is controlled by the mining schedule. Stockpiling and rehandling must therefore be carried out to provide a supply for rehabilitation purposes as required and rehandling can be minimised with careful planning.

Additional Construction Details

Selective Handling of Bulk Waste

Before application of the porphyry seal, oxide waste and low-sulphur primary waste is placed around the periphery of the dump to provide additional isolation of the more reactive material (Figure 7). The porphyry is dumped over this surface before shaping and compaction waste porphyry for capping is selected on a blast by blast basis using Net Acid Generation (NAG) test criteria.

Compaction on Dump Batters

Testwork showed that the impact roller did not achieve good compaction running down the batters, as it tended to push the porphyry down with it. In addition, the average 1:4 slope was too steep to allow safe compaction along the contour. These difficulties were avoided by adopting a terraced landform (Figure 8) which reduces the effective slope angle from 1:4 to 1:5, allowing the impact roller to travel along the slope at optimum speed. Each compacted bench overlaps the preceding bench, resulting in a zone of continuous compaction from the base to the top of the dump. The face of each porphyry bench is rock armoured to minimise erosion, and the lip of each bench is shaped to provide a graded drain. This terraced landform reduces the potential for erosion and allows easier access for seed and fertiliser application and maintenance.

Quality Control

Following the implementation of the waste dump sealing strategy, a quality control program was implemented. This allows a rapid assessment of quality of work, so that practices can be modified in response to changes in results. Also, it provides an ongoing record of results to allow verification that commitments made in the Environmental Management Overview Strategy (the key approval document in Queensland) are being fulfilled. All rehabilitated areas are sampled on a 50 m x 50 m grid. At each point, the following is recorded:

1. Seal thickness;
2. Seal surface compaction;
3. Seal sulphur content and net acid generation (NAG); and
4. Topsoil thickness

The data is recorded with survey coordinates, allowing the production at any time of a plan of the dump with all these parameters shown. The performance of the seal is also being measured directly using lysimeters which measure the net infiltration through the seal.

The benefits of apply the rehabilitation strategy have been:

- approximate halving of cost per unit area of rehabilitating waste dumps;
- avoiding the need of using other rehabilitation materials that are of limited supply;
- achieving a high quality outcome for the sealing of the dumps;
- aid the reduction of the security deposit which is based on demonstrated performance and the cost of rehabilitation at the time of mine closure.

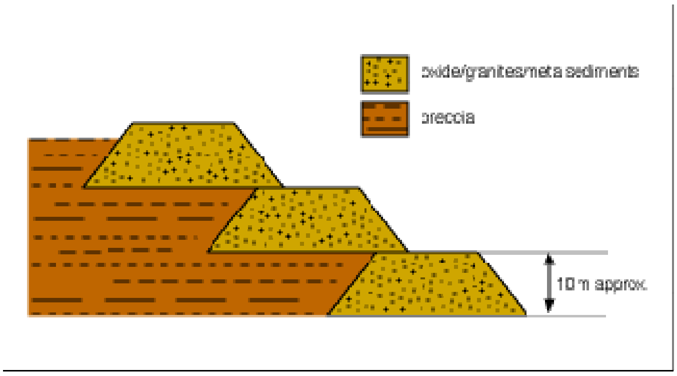


Fig. 7.0. Formation of dump batters

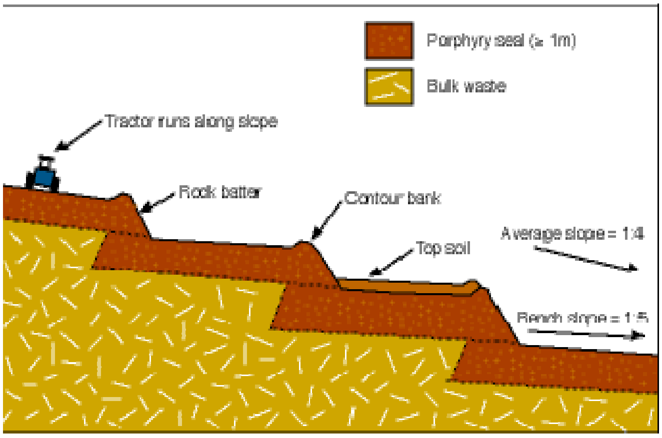


Fig. 8.0. Detail of compaction on dump batter

CASE STUDY 7

CLARENCE COLLIERY PTY LIMITED

Clarence Colliery is a 2.6 million tonnes per year thermal coal mining operation near Lithgow, New South Wales. The mine is also located in the headwaters of the Woolangambe River, a major drainage channel through the Blue Mountains National Park.

The coal preparation plant washes coal to achieve customer ash specifications with some 160 000 tonnes of rejects produced per annum. This reject material has a sulphur content of 0.16% and if not well managed would result in a leachate with a pH of about 3.5 and elevated levels of some heavy metals.

In managing the reject material area Clarence has worked to:

- minimise the permeability of the material by the mixing of fine and coarse coal reject materials;
- reduce permeability further through mechanical compaction;
- achieve the desired level of mechanical compaction through the use of a cone penetrometer which measures compaction;
- prepare the annual extension to the reject emplacement area in December for the next 12 months, with transfer of native tree seed stock onto progressively rehabilitated areas, thus maximising the change of natural rehabilitation with the summer rainfall. (Note: the preparation of the reject emplacement area involves the immediate placement of cleared vegetation and soil onto an area to be rehabilitated); and
- treating residual leachate, from the reject coal area generated during the operational phase of mining, through the mine water treatment plant.

Benefits

- reduced quantities of leachate requiring treatment;
- maximising compaction to reduce the amount of disturbed land;
- reducing the long term requirement for management; and
- reducing the risk of spontaneous combustion.

To further reduce the residual leachate coming from reject emplacement areas and potential groundwater contamination, Clarence is examining the feasibility of mixing the coal washery reject wastes with a benign fine clay residue from the local sandmine. This will provide multiple benefits in;

- reducing acid generation in the rejects;
- reducing the quantity of clay fines to be managed as tailings; and
- allowing the rejects/clay mixture to be deposited in the sand mine voids.

This latter benefit will provide a stable foundation for rehabilitation of the sand mine while reducing the disturbed area necessary for placement of future coal washery rejects.

CASE STUDY 8

PT KALTIM PRIMA COAL, KALIMATAN, INDONESIA

Introduction

PT Kaltim Prima Coal (KPC), an Indonesian incorporated company owned by British Petroleum Co Plc of the UK and RTZ-CRA of Australia and the UK, has mined coal at Sangatta since 1992. The mine is approximately 200 km north of Balikpapan on the east coast of Kalimantan in Indonesia. The company currently mines 11.5 million tonnes annually using trucks and shovels in a conventional open cut operation. The climate at KPC is equatorial with high seasonal rainfall and low wind velocities. Rainfall averages 2 500 millimetres annually and falls mainly as tropical thunderstorms.

Acid mine drainage was detected at the mine in its second year of operation. Since then, significant resources have been invested by the company to understand the nature of the problem and to integrate acid control in the mining process.

Photo: PT Kaltim Prima Coal

Pt Kaltim Prima Coal, Kalimantan, Indonesia. Sampling spoils from blast holes.

Strategies for acid control

KPC's strategy for controlling acid drainage focuses on selective emplacement of acid-forming material and the exclusion of oxygen from overburden sulphide, thereby stopping pyrite oxidation. Several conditions exist where potential acid generation has to be controlled. These include:

- existing dumps constructed prior to the understanding of the acid generation problem;
- new dumps being built as a part of the current operations; and
- exposed coal floors rich in pyritic material during the mining operation.

Each requires a different approach.

Controlling acid production from surfaces of existing dumps

Prior to identifying the acid production potential at the mine, some early dump surfaces were covered with acid producing overburden. All early dump surfaces have been sampled to ascertain the chemical nature of their external layers and, where acid-producing material has been identified, the surface has been encased with non reactive material.

Research on cover designs has shown that the oxygen barrier has to achieve permeability of less than 10^{-8} ms^{-1} with less than 10% air voids. Under the conditions prevalent at KPC, this is achieved by either:

- placing 2.0 metres of non acid-forming overburden and 0.5 metres of topsoil over pyritic material; or
- compacting half a metre of clay to the engineering criteria stated above, followed by covering with 0.5-1.0 metre of topsoil to foster rehabilitation.

Strict engineering and geotechnical procedures must be followed to achieve adequate clay compaction for oxygen exclusion.

New dumps and selective placement of overburden

Present day dumps are constructed with the aim of preventing acid drainage occurring. This is achieved by ensuring that all highly reactive overburden is buried in the core of dumps, away from a fluctuating water table and oxygen.

With knowledge gained from the overburden geochemistry study and local geotechnical constraints, KPC has produced guidelines for constructing waste dumps at its minesite.

The objectives of the guidelines are to:

- achieve long-term geotechnical stability of dumps;
- build dumps that resist erosion scour during construction and rehabilitation; and
- exclude potentially acid-forming rocks from dump surfaces.

To achieve these objectives it is imperative to emplace acid-forming material selectively under non acid-forming material. For medium to long term stability all materials in the outer 10 metres of the dumps must be non acid-forming. A typical cross section of dumps at KPC is shown in Fig 17.0.

An important practice is that final drainage design works stabilise the surfaces and minimise any future exposure of acid producing materials.

Photo: Kaltim Prima Coal

Loading spoils for selective placement.

Photo: Kaltim Prima Coal

Selective spoils placement at Kaltim Prima Coal.

Interim dumps

An intermediate dump face is an exposed face that will be over-dumped at a later stage. It includes any dump face that is exposed for two months or less.

Interim overburden management specifications are as follows:

- any material that is highly acid-forming should be buried deep within the dump;
- such material should be placed in prepared cells within the dump, below the projected long-term water table where it will not be subjected to fluctuating water levels;
- non acid-forming overburden should form the outer five metres of intermediate dump faces; and
- top surfaces of intermediate benches should be covered with at least one metre of non acid-forming material.

Coal floors

Pyritic materials at KPC are mainly associated with coal roofs and floors. While roof materials are removed as part of the mining process and placed within the core of the dumps, floor material could be left exposed for lengthy periods. To prevent the production of acid, floors are either dug out and placed in cores of dumps along with coal roofs, or covered according to the engineering specifications listed above.

In a limited number of cases, acid is produced from exposed coal floors prior to remedial action being implemented. Currently, such acid water from coal floors is collected and treated with lime to achieve acceptable water chemistry prior to final discharge. Two portable acid neutralisation plants are intermittently used for this purpose. The plants have been very useful because of their cost effectiveness and their mobility, as they can be moved to particular locations to provide short to medium term treatment of acid water. A passive wetland biological filter to polish discharge water is planned to be constructed in 1997.

Photo: PT Kaltim Prima Coal
Portable water treatment plant.

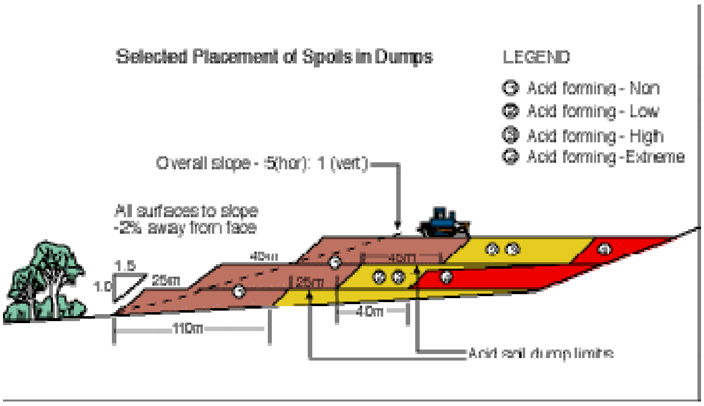


Figure 17.0 A typical dump profile showing selective placement of mine spoil

Rehabilitation

Fundamental to any post-mining land use is re-establishment of vegetation. The effective control of acid formation is critical to any rehabilitation program. Some post-mining land uses being considered by KPC are production forestry, agriculture and recreation.

More than 450 000 trees have been planted on 450 hectares on KPC's leases since mining commenced. In 1996, the target was 206 hectares, an area exceeding that cleared for mining for the first time. This trend will continue and areas of 200-400 hectares are planned to be rehabilitated each year. A detailed description of the rehabilitation program is provided in Michaelsen, D and Macmillan, S (1996) under Further Reading.

Conclusions

Acid drainage is endemic in East Kalimantan, associated not only with mining, but also with any earthworks exposing pyritic materials. It is important to manage acid drainage because of its deleterious effects on water chemistry, animals and vegetation. In the mining context, perhaps the most significant impact is that acid-producing surfaces will not revegetate.

A number of lessons have been learnt from KPC's experiences with acid drainage:

- acid prevention has to be integrated into the mining process; (Ideally, the control program begins at the mine exploration stage when valuable baseline information about potential acid formation can be obtained at relatively low cost. Waste rock analysis is essential.)
- the stratigraphically controlled occurrence of acid-forming materials in steeply dipping rocks, coupled with a mining method based on horizontal benches, has complicated the accurate modelling of net acid generation at the mine; (The approach taken by KPC has, however, provided adequate information to manually schedule materials for selective placement within dumps. The strategies described in this case study have shown to be cost-effective.)
- acid production must be prevented rather than treated; (If the acid-producing potential of overburden is understood before the mining commences, the problem can be arrested before it becomes costly. Selective placement of spoils has proven an effective way to control acid production from open cut mining operations.) and
- acid control strategies must be implemented completely and in a timely manner to be effective. (A partially implemented acid control program is non effectual—water quality continues to deteriorate and rehabilitation will not succeed.)

In summary, experience at KPC suggests that it will be significantly more cost effective to prevent the problem than trying to remedy it. KPC is continually striving to improve its environmental performance by applying best practice approaches to the prevention of acid drainage.