TEAM NT:

Technologies for the Environmental Advancement of Mining in the Northern Territory

Toolkit

An Australian Government Initiative

AusIndustry

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PREFACE

The Northern Territory is a special place to live and work. It still embodies the Australian dreams of youth and freedom, of *a sunburnt country* with vast horizons, of a land abounding in *nature's gifts.* Our mines are remote, tiny dots sometimes set in pristine conditions, but always set on the *sweeping plains* of a very old, weathered landscape. They are subject to monsoonal seasons with *droughts and flooding rains* every year, typical of the renowned Top End.

The traditional owners of the Northern Territory have eloquently described our monsoonal seasons in detail. Our Indigenous peoples make up a third of the population of the Northern Territory, a ratio ten times that of any other state or territory. Currently, they own about half of the land.

With wealth for toil: mining here is both an extreme challenge and rewarding. All the normal challenges of a risky industry exist here but the environmental challenges are multiplied by cyclonic rains, high temperatures and extreme levels of evaporation on a yearly cycle. Our mighty rivers are essentially groundwater fed for much of the year. Most smaller rivers and streams are ephemeral and groundwater influenced for part of the year.

Our population is about a quarter of a million, that is a density of one person for every 6 square kilometres. As 1% of Australia's population, we produce far more than 1% of Australia's export earnings! The Mineral and Energy sector is by far the major contributor to the Territory's Gross State Product.

We in the tropical north would like to avoid the environmental mistakes of the south while development pressure is relatively low. However, there is a lack of skilled workers in so many fields. The rapid turnover of staff in the bigger companies means that hard gained corporate knowledge is often lost. How can we learn from the lessons of the past if we have already forgotten what we knew the year before last?

The Pine Creek Geosyncline covers a large area in the monsoonal belt of the Northern Territory and is rich in minerals. Gold, uranium, copper, lead and zinc ores are best known. The accompanying minerals often contain high levels of arsenopyrite.

Many of the gold rich areas were already well known in the nineteenth century (ref: *Pegging the Northern Territory – A history of mining in the Northern Territory, 1870-1946* by Timothy G. Jones, Northern Territory Government Printer 1987). Many of the historical areas such as Union, Brock's Creek, Pine Creek, Fountainhead, Cosmopolitan and Howley have been mined over and over again. Each time, this has been achieved by reaching deeper and deeper into the earth for ever lower grades of ore in less weathered rock. This has been accompanied by an exponentially increasing quantity of waste per metal unit recovered.

Over the past few decades it was large, sometimes international, companies that revisited these areas. They in turn sold on to small companies when the best grades of ore ran out. The leases bought by the small to medium sized enterprises (SMEs) ranged in rehabilitation status from world's best practice at the time, to partially rehabilitated "geochemically unstable" sites, to virtually "abandoned" sites. Apart from Rum Jungle, there has been little monitoring of rehabilitation performance by industry or government. There is a paucity of data on the long term effectiveness of the technologies used.

It is not uncommon in the current situation for companies to control sites with environmental legacies and liabilities larger than their market capitalisation. Perhaps the "glitter of gold" blinded them to the net value of the purchased lease. Even large international companies, with all their technical expertise, often underestimate the liability of the chronic issues associated with the generation of acid rock drainage.

Increasing environmental awareness by governments and the community has led to higher expectations for rehabilitation. No longer is it acceptable to fill in a few holes, cover the waste rock dump with a layer of growth medium not designed to minimise oxygen and water ingress, or use dilution as the principal solution to pollution. Conversely, unrealistic community expectations abound that assume rehabilitation can restore a site to a similar condition as it was before mining began.

Whole-of-life mine planning offers many opportunities to optimise the handling of waste. Such planning can minimise the development of mine drainage containing high concentrations of metals and reduce costs overall for the whole venture - *A dollar spent wisely now can save nine dollars later* (Dr Kevin Morin in the *Stitch in Time* TEAM NT workshops).

For small companies, shareholder expectation for returns today is the driver for maximising immediate cash flow and, as a result, it may not be possible to make large provisions for whole-of-life mine planning or closure. In contrast, bigger companies that have a portfolio of projects at different stages in their life cycles can more easily offset additional environmental planning and management costs for one operation against others. One of the major factors causing companies to postpone or avoid altogether whole-of-life mine planning has been the shifting, or lack of, compliance goalposts in relation to closure criteria.

While prevention is best, once oxidation and other natural weathering processes are well advanced - and this can occur during the active mining (operational) period - prevention is no longer realistic. Efforts then need to be concentrated on slowing the transport of weathering products and the application of treatment technologies (Prof David Blowes and Dr Kevin Morin during the TEAM NT workshops).

The monsoonal tropics provide the hardest settings for the design of cover systems that will minimise the ingress of oxygen and water over the long term (Mike O'Kane during the TEAM NT workshops).

Technologies that are developed and tested in the Northern Territory are of value anywhere in Australia, however the reverse is not always true. The industry suffers from major knowledge gaps about environmental management of mining in monsoonal conditions. Even when information is known, it may not be correctly applied. For example, mean rainfall data has been used in the design of some water holding structures but serial cyclones have made a mockery of calculations based on procedures used in southern climes.

The TEAM NT Project

In 2003-2004, AusIndustry awarded an Innovation Access Program grant to the Northern Territory Minerals Council Inc. for a project to be known as TEAM NT: Technologies for the Environmental Advancement of Mining. The aim of AusIndustry's Innovation Access Program was:

> *"to promote innovation and competitiveness by improving Australian access to global, leading edge research and technologies and facilitate their uptake by Australian firms, particularly small to medium enterprises (SMEs) and researchers".*

In awarding the grant, AusIndustry commented that:

> "*the competitiveness of much of Australia's mining sector is influenced by its effectiveness in managing mine sites and mining wastes so that these do not impose long term economic, environmental or health costs on the industry and ensure that the industry continues to have public support and access to future mining resources".*

During the life of the project, a series of internationally recognised specialists were brought to Darwin to:

- participate in workshops on SME mine sites;
- provide technical material on their speciality areas;
- present public seminars; and
- meet members of the mining industry and associated industries and government on a one-to-one basis.

The project was managed by the technical team of Northern Territory Government Mining and Petroleum Management Division.

A total of twelve mine site workshops were held. Each workshop began with a presentation from an invited specialist, followed by a site visit and presentations on major issues affecting that site and relating to the specialist's expertise. Most of the day was spent working as a multidisciplinary group analysing the issues and evaluating possible solutions while considering economic, financial and social aspects. Many cutting edge technologies were examined for feasibility of application in the Northern Territory. A great deal of technical information was exchanged during the workshop sessions.

The workshops were attended by a range of mining personnel: directors and CEOs as well as operational staff from the SMEs, visiting corporate and technical staff from large international companies, Charles Darwin University staff, regulators and technical staff from various departments of the Northern Territory and Commonwealth governments.

In total, forty five different entities participated in the workshops and seminars. About a hundred and fifty work days of time were given by the industry to the main activities of the project. Every major lease-holder in the Territory was represented.

Comments made by attendees at the mine site workshops included:

- “Culture changing”
- “We wouldn’t have kept giving it so much support if it hadn’t been so worthwhile.”
- “When is the next one? Please make sure I am invited.”
- “We would be delighted to supply lunch/accommodation/aeroplane fuel….”
- “Yes, I will fly up again from Perth to be present. I have paid for my main consultant to attend as well.”

One major mining company flew corporate staff from Adelaide to attend. One small mine owner drove for days, from Kalgoorlie to the Gulf over hazardous dirt roads, to ensure there would be enough vehicles for visitors to see his site.

The many challenges and technologies addressed during the workshops have been sorted into six broad chapters in this “Toolkit”. The chapters cover some of the key challenges facing the mining industry, characterisation and prediction, arsenic, modern cover systems, and treatment of polluted surface and groundwaters.

Dr Jack Ng and Prof Barry Noller provided the most current knowledge about arsenic. Some of the major revelations from their input are presented in the chapter on arsenic. For example, arsenic laden water is “sweet” to drink and the effects may manifest decades after the water is no longer consumed. Recent studies indicate that humans turn arsenic into a form that prevents the repair of DNA. In the tropics, consumption is often more than twice the amount assumed when drinking water standards are set. The impact of arsenic is also increased by ultraviolet light. This puts workers at particular risk in the monsoonal tropics. In contrast, aquatic organisms metabolise arsenic differently to humans and in a way that protects them from harm.

Dr Kevin Morin’s presentations on “A Stitch in Time” gave wonderful examples of how *a dollar spent wisely now can save nine dollars later*. This highlighted phrase is also appearing in corporate documents written by people who played no part in the project, emphasising the economic benefits of good environmental risk analysis and planning. Dr Morin is an advocate for traditional water treatment being used for as long as mine drainage occurs. His vast experience of the geochemistry of mine sites around the world have led him to the view that cover systems only slow down the process of acid rock drainage. He argued that this increases the period of impact leading to greater overall cost and more risk to the environment.

Prof David Blowes’ presentations highlighted the fact that groundwater impacts may not be apparent for years, decades or even centuries. He provided us with some very interesting case studies involving different types of passive reactive barriers. These barriers can be used to intercept and treat contaminated groundwater plumes *in situ* as an alternative to conventional pump and treat technologies.

William Pulles presented an exciting new water treatment technology from South Africa. His definition of passive treatment has wide application and is thought provoking:

> *"A water treatment system that utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life".*

It became very clear during the TEAM NT sessions that there are no walk-away solutions to acid rock drainage. The Pulles philosophy towards maintenance requirements is:

- For passive treatment to be sustainable, it must be designed for and subjected to ongoing maintenance.
- For maintenance actions to be sustainable, they must be undertaken by a profitable business.
- For a profitable business to be sustainable, it must generate regular cashflow.

For passive treatment systems to continue to operate successfully they must have regular, albeit infrequent, maintenance.

Mike O'Kane provided valuable insights into the physical principles underpinning modern cover design. His presentations helped us to understand why the covers of yesteryear do not meet the more stringent objectives we have today. Mike's philosophy is that cover systems should be designed to accommodate natural processes, such that their performance will be maintained for the long term. He strongly advocates that ongoing monitoring of cover performance is essential to ensure that the industry has the data to support continued improvement and refinement of cover design principles.

Bob Amaral raised issues relating to placement of containment structures in catchments, and the design of waste containment structures.

- Tailings dams or waste rock dumps should be located at the top of catchments to minimise the contribution of surface run-on (or groundwater intrusion) to the water balance.
- Modern design for structures used to manage urban and industrial wastes provides security of containment for possible contaminants to a far higher degree than is the norm for most mine wastes. These types of approaches have been judged as too expensive for use in the mining industry, except perhaps for the containment of process liquors. However, as groundwater becomes more valued as a resource, and regulations require prevention or mitigation of impacts on groundwater, then the approaches used by the modern urban waste management industry might well prove to be the most cost effective strategy.

This "Toolkit" distils much of the information and debate in the workshops. Some of the material will be familiar. Some may be new. We hope that this document sparks many more people in the industry to plan more, think more, investigate and develop better understandings of their sites, and to seek further information and help.

The industry is able to prevent many of the current problems with waste management and acid rock drainage if it just remembers what it already knows and applies it.

The solution to existing mine drainage issues on legacy sites is difficult both technically and economically. It can be addressed if governments and industry have the will to resource the solutions that are presented here.

During the workshops, members of a major company and a director of an SME independently put forward a partial solution. "*If the Majors undertake the research and technical studies needed to provide well founded cost effective solutions, the Minors could implement many of the actual works on the ground".*

However, there still remains a tremendous need to develop and test cost effective technologies for the prevention, management, remediation and treatment of acid rock drainage, particularly in the monsoonal tropical extremes.

The approaches examined during the TEAM NT workshops and summarised in this document offer real promise for the advancement of environmental management of mining in the Northern Territory. It is now over to industry to implement these approaches and prove that mining can be a sustainable industry in the 21st century.

Pamela Sanders
Mines and Petroleum Management Division
30 September 2004.

1. CHALLENGES

1.1 Overview

In this section some of the key challenges confronting mining enterprises in the Northern Territory are summarised under the generic headings:

- Solid waste management;
- Water management;
- Landform stability;
- Rehabilitation;
- Planning;
- Shifting goalposts; and
- Protection of potential resources.

These challenges were discussed in much detail during the TEAM NT workshops.

The issues are similar to those experienced in other locations of Australia, but there are a number of unique features resulting from the extremes of the tropical monsoonal climate. These unique features are highlighted.

1.2 Management Issues for Solid Wastes

Many of the impacts of mining wastes are neither transient nor short term. Unless these wastes are appropriately contained and rehabilitated, they have the potential to adversely impact on the environment over long periods of time.

For most mining operations in the Northern Territory, waste rock and tailings are the major waste streams. Usually waste rock is placed in an above ground waste rock dump by dump trucks, while tailings are pumped to specially constructed tailings storage facilities. These two waste streams have significantly different physical properties and very often different geochemical properties.

The properties of waste can be defined based on the extent of weathering:

- Oxide - rock that has been subjected to the natural weathering processes of exposure to oxygen and water, with its constituent minerals undergoing changes as a result, and containing essentially zero sulfide mineralisation. The typical depth of the oxidised weathering zone is 20-30m. Oxide rock is typically soft and non-competent.
- Transition - this is rock that is incompletely oxidised, lying between the base of complete weathering and the underlying unaltered primary rock. Owing to its variable nature, transition waste can cause the most problems with respect to predicting geochemical behaviour.
- Primary - this is rock from beneath the base of oxidation. It is fresh and not affected by weathering. Primary rock is generally hard and competent and is the most favoured for use in construction of dam walls and roads. Great care needs to be taken that reactive primary rock is not used in areas where leachate can adversely impact on the receiving environment. A number of instances have been noted where leachate from primary rock used to construct walls of tailings dams, bunds or roads is one of the major sources of metal-rich drainage onsite.

Mine drainage containing elevated levels of metals is the product of accelerated weathering of waste (rock or tailings), typically occurring as a result of the oxidation of sulfide minerals. The pH of such drainage can range from very acidic to neutral or even weakly alkaline. When the rate of release is higher than the capacity of the receiving environment to assimilate the load, there can be adverse impacts on the receiving environment.

Acid mine drainage (AMD) or acid rock drainage (ARD) are the generic terms used to describe the low pH subset of mine drainage. ARD occurs when the acid produced by the oxidation of sulfides exceeds the neutralising capacity of the host rock. However, it is vitally important to recognise that mine drainage does not have to be acidic to contain environmentally significant concentrations of dissolved metals.

A waste with a moderately negative net acidification potential value can still produce a leachate with a substantial salt or metal load; it's just that it won't be acidic. Indeed, pH neutral or slightly alkaline mine drainage can contain high concentrations of metals such as As, Cd, Co, Mn, Ni and Zn. The concentrations of major ions salts (typically Mg, SO4) can also be of major importance in their own right, irrespective of whether they are accompanied by heavy metals, in the event that saline seepage or runoff is produced.

An effective characterisation program for mine wastes assesses total solute load likely to be produced including major ion salts. It does not only test for the propensity of a material to produce a net acidic leachate. Characterisation is discussed in more detail in Chapter 2.

Many of the mines in the Northern Territory are located in the Pine Creek Geosyncline and most have issues with leachates from the oxidation of sulfides (Figures 1.1 and 1.2, Table 1.1) as a result of the ubiquitous occurrence of significant levels of iron sulfide minerals (Ormsby et al., 1994). The pH values of the mine waters shown in Table 1.1 range from highly acidic to near neutral, but all contain high concentrations of dissolved metals. These data clearly show that neutral mine drainage can contain environmentally significant levels of metals.

Figure 1.1: Highly acidic and metal rich seepage emanating from the base of an ineffectively capped waste rock dump.

Table 1.1: Example compositions of mine waters from six (A-F) gold and base metal mines in the Northern Territory.

Analyte	Units	A	B	C	D	E	F
pH		6.6	6.0	4.2	3.7	3.2	2.1
EC	µS/cm	4118	980	1680	4080	11290	--
Fe	mg/L	<0.002	29	0.1	--	550	359
Al	mg/L	0.014	0.32	7.5	217	620	116
SO4	mg/L	2650	590	890	4840	9080	2230
As	µg/L	4	350	83	--	250	11000
Cd	µg/L	140	48	--	5570	40	24
Co	µg/L	15	135	--	4240	8000	258
Cu	µg/L	7	0.9	1450	6280	11000	6400
Mn	µg/L	2560	2190	--	142000	74100	1910
Ni	µg/L	572	627	--	4310	12800	810
Zn	µg/L	42600	1310	10390	131000	5330	6940

Figure 1.2: Iron staining on rocks in a creek impacted by ARD.

The oxidation of iron disulfide minerals is most often the primary source of the acid in waste since pyrite and marcasite (different crystal forms of FeS_2) are typically the most abundant sulfides in mining wastes. In the Pine Creek Geosyncline, arsenopyrite can also be an important component of the sulfide mineralisation in waste. The implications of this to environmental and occupational health and safety issues in the industry are addressed in detail in Chapter 3.
The overall chemistry of the oxidation reaction for pyrite is shown below:

$$2FeS_2 + 15O_2 + 7H_2O \longrightarrow 2Fe(OH)_3 + 4SO_4^{2-} + 8H^+$$

Oxygen and water are the key inputs to the oxidation process that results in the production of acid. The acid produced may dissolve the surrounding minerals and liberate other metals present in the non-sulfide fraction.

Water is also the vector for the acid and metals produced and is the medium *via* which a localised site impact can be transformed into a much more serious regional one. Consequently prediction of the likely composition and environmental impact of mine drainage requires a detailed understanding of both the physical and chemical processes that are taking place in sulfidic wastes.

1.3 Water Management

General

The monsoonal tropics of the Northern Territory are characterised by five months of high rainfall, during which 1500mm of rain generally falls. The rain is typically delivered during intense high energy events and with cyclones, can exceed these amounts significantly. For the remaining seven months of the year there is virtually no rain and net annual evaporation can be as high as 2500 mm (Figure 1.3).

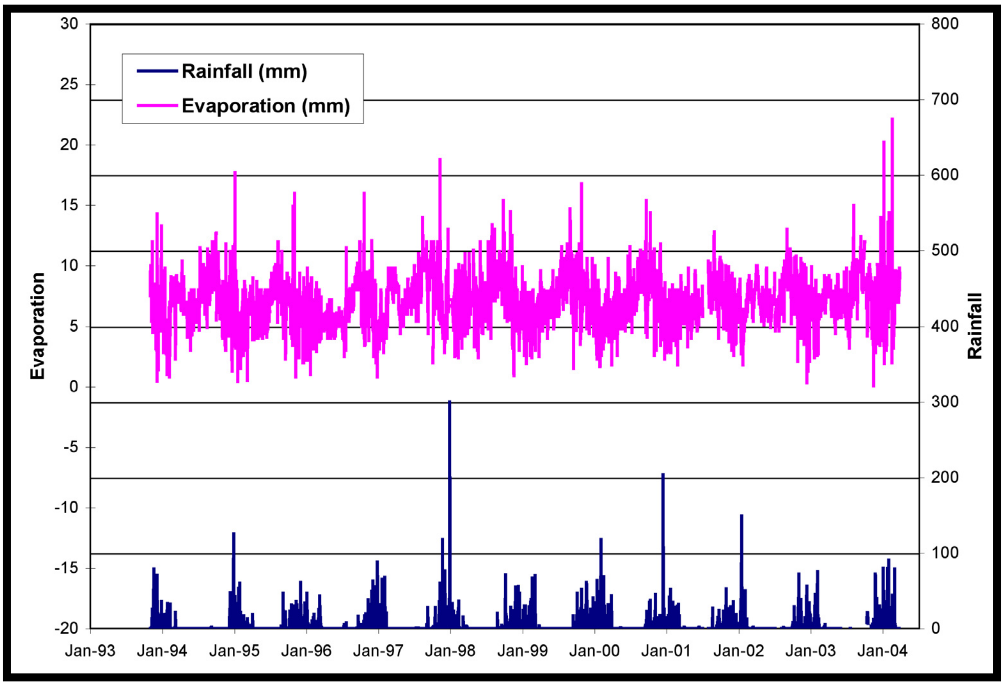

Figure 1.3: Northern Territory dry seasons are completely dry with high evaporation rates. Wet seasons can be characterised by cyclonic rains.

This hydrologic regime is more extreme than anywhere else in Australia and necessitates close attention to both hydraulic engineering design and volumetric storage aspects. Landform surfaces and hydraulic structures must be resistant to highly erosive forces. Much of the runoff and seepage from mine sites may also need to be contained since the concentrations of metals can be too high for direct release.

Water management may require active tracking of stream hydrographs, which typically rise and fall by orders of magnitude over periods of hours or days. Thus discharge system capacity must be sufficient to inject large volumes of mine water into the peak of hydrographs, such that dilution will be sufficient to reduce metal concentrations below applicable water quality guideline values. This procedure is very demanding on personnel and monitoring resources (both technically and from a health and safety standpoint), and has a low tolerance for error. In extreme events, there may be no access to control structures and the management systems cannot be used.

Active tracking of hydrographs for water management is only possible during the operational life of a mine. It is not an option post closure when there will be no water management personnel onsite, nor is it generally an option for legacy sites.

An excess of water containing concentrations of solutes that are too high for direct discharge is one of the major problems that often confronts mine sites in the tropical and subtropical regions of Australia.

This situation is typically the result of a mismatch between the catchment area needing to be contained (eg waste rock stockpiles and ROM pad) and the available volumetric capacity of the mine water management pond system. Indeed this situation is often further exacerbated by the unnecessary capture of clean water that should have been kept out of the management zone by appropriate bunding. Under these circumstances a smaller volume of more concentrated water (which could be stored) is diluted by cleaner water, resulting in a much larger volume of water that is still of too poor a quality to discharge.

Catchment isolation by bunding or by location of waste containment structures (especially tailings dams) at the head of catchments is the lowest cost method for minimising capture of water in a mine water system.

In the Top End of the Northern Territory, the occurrence of a distinct and extended dry season offers the possibility of using evaporation during the dry to dispose of a substantial volume of water, thus effectively concentrating the solutes in the mine water system. However, this approach can only work if there is a good design match between the wet season storage capacity of the mine water retention pond system and the surface area available for evaporation during the dry.

Careful consideration during the design phase to this aspect of water management can substantially reduce contaminated water management problems during operations. In particular a sensitivity analysis should be done using a combination of design events and ranges of annual rainfall amounts to optimise the storage capacity. It is not appropriate to use average rainfalls to design retention systems in the monsoonal tropics.

Tailings Dams

It became apparent during field visits conducted as part of the TEAM NT program that the footprint of many tailings dams was greatly in excess of what was actually needed for the amount of contained tailings. There were several reasons for this:

- less ore was processed than originally planned;
- dam walls were kept as low as possible to minimise upfront costs to the project; and
- the beach area was maximised to enhance tailings consolidation.

During a project's life, one of the most obvious consequences of an excessive footprint is the accumulation of a large amount of water during the wet season. The large surface area also facilitates oxidation of sulfides during the dry. The effects of this can be most obviously manifest in a low pH and elevated concentrations of metals in the surface runoff. However, a much more insidious consequence can be the development of a plume of oxidation products that will be washed down through the tailings profile (by infiltration of ponded surface water) and subsequently impact on surface water (via toe seepage) or groundwater. Large surface area to volume ratios for tailings dams greatly increase the potential for legacy risk from sulfidic tailings.

At closure, the presence of a large exposed surface area will greatly increase the overall cost of rehabilitation since the cost is generally proportional to the surface area that needs to be covered or stabilised.

There are at least two strategies that can be used to minimise the tailings footprint:

- progressive filling and covering of a series of smaller cells, commissioning a new cell only when required; and
- deposition of thickened tailings to create a domed water-shedding structure.

Operations should consider the longer term economic, environmental and closure cost benefits of staged expansion of tailings storage facilities, such that the exposed surface area is kept at any one time to a minimum consistent with safe and effective operational practice.

Technologies for the treatment of surface and ground waters are described and discussed in later chapters of this document.

1.4 Land-form Stability

Long term land-form stability is a significant issue to address during mine rehabilitation and closure planning. Failure to adequately account for the natural process of weathering and erosion can lead to severe adverse environmental impacts even during the operational phase. Figure 1.4 shows gully erosion on the batter slopes of a rehabilitated mine landform. The internal slopes of water containment ponds are also very susceptible to erosion if not adequately protected (Figure 1.5).

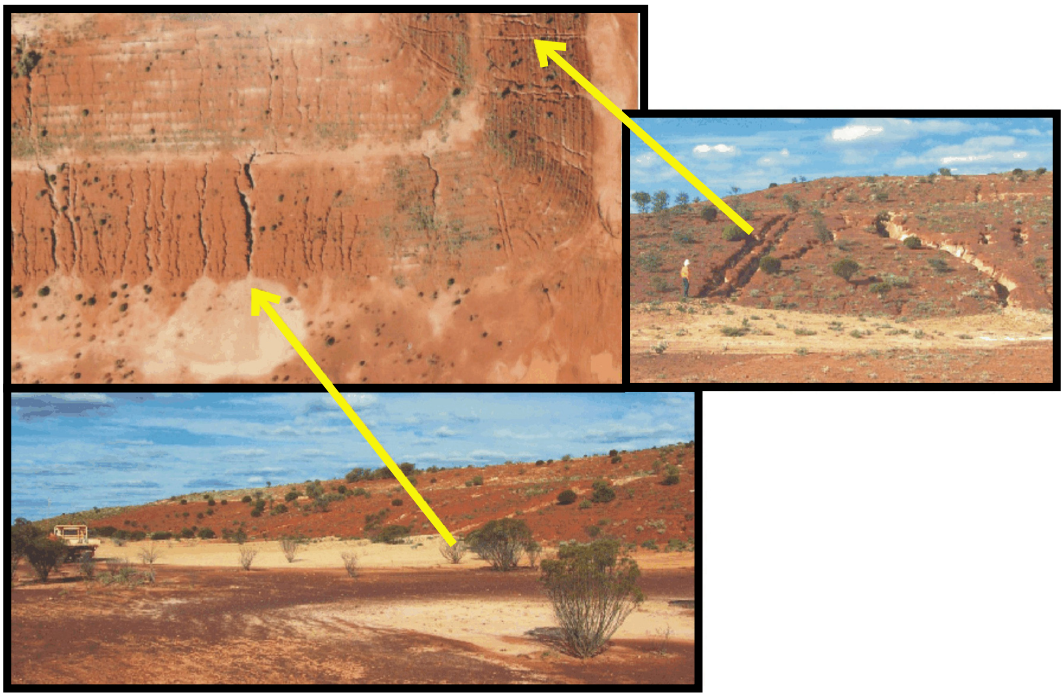

Figure 1.4: Examples of waste dump erosion and long term land-form instability (courtesy of M. Fawcett).

Figure 1.5: Erosion on walls of a containment pond

The need to properly manage surface runoff is just as important in arid Australia as it is in the higher rainfall parts of the country. The reason for this is that initiation of erosion is related to soil/rock material properties and the velocity of surface water flow. Surface water flow velocity for a given slope relates directly to the intensity and duration of a rainfall event. Although the total annual rainfall in arid Australia is substantially lower than coastal areas, the intensity and duration of events is often similar; there are just fewer events per year.

A guiding principle should be to avoid concentrating surface flows wherever possible, as this creates the highest likelihood of initiating erosion. In conjunction with this, flow velocities should be kept as low as possible. In the absence of site/material specific data, water velocities should be kept below 0.5 m/sec in unlined diversion drains. It also should be remembered that virtually all constructed erosion control and water management structures will require ongoing maintenance to assure their performance. The costs of ongoing maintenance should be factored into any decision on designs for management methods.

1.5 Rehabilitation

Because of the relative short term or intermittent nature of mining, there is now an expectation by the broader community that mining sites will return to a more conventional land use. It is only through successfully achieving sustainable rehabilitation over the long term that the mining industry will convince society that mining can be a net positive activity. This is particularly the case in the most environmentally sensitive locations.

The primary functions of rehabilitation are to slow down the processes of oxidation/weathering and rates of erosion for waste storage structures to a point where the resulting products are produced in small enough quantities, or at low enough rates, that the receiving environment can absorb and assimilate them without adverse impacts, or with impacts that are low enough to be acceptable to the community.

Historically, rehabilitation planning has often been left until well into the operational phase. The real cost is not determined until far too late in the project timeline, so that initial estimates were found to be as much as 10 times too low, especially if waste material was already generating metal-rich leachate. The mining industry is coming to realise that early and detailed rehabilitation planning is of prime importance from every aspect: economically, environmentally and socially.

“A dollar spent wisely now, can save nine dollars later on.”

- Dr Kevin Morin, TEAM NT workshops, 2003

Expensive earthworks undertaken with the principal aim of providing a substrate for revegetation may improve landscape stability, provided that close attention is paid to slope angles and flow path lengths on the surface of a mine landform. If the surface of a covered landform is not appropriately shaped then severe gully erosion can occur (Figure 1.6).

Figure 1.6: Massive erosion near the top of a rehabilitated waste facility in the Northern Territory - despite the presence of a vegetated cover. The integrity of the cover has been breached.

If the waste material is still geochemically unstable, a “cosmetic” cover can lead to a sense of false security in the short term by virtue of a healthy and aesthetically pleasing cover of vegetation. Then in the longer term, a major liability can manifest as a result of the eventual breakthrough of leachate containing high concentrations of metals.

In the Top End of the Northern Territory, the extremes of wet and dry impose additional challenges for successful rehabilitation. During the wet, rehabilitated mine landforms must be capable of resisting high energy and prolonged rainfall events, whilst simultaneously storing sufficient water to sustain vegetation during the dry. Hence the growth medium layers need to be thicker and more robust than in more temperate climates where there is a more even distribution of rainfall throughout the year.

Wetting and drying cycles can seriously compromise the integrity of clay-based cover or barrier systems which are commonly used in more temperate climates, unless the clay layer has been sufficiently protected from such extremes.

The large fluctuations (up to several metres) in groundwater table levels pose a special challenge for in-pit or below-grade placement of sulfidic material in the Northern Territory. The regular saturation and desaturation of sulfidic material, if it is present in the active groundwater zone, provides ideal conditions for the oxidation of sulfides in the dry, and subsequent dissolution and transport of the oxidation products during the wet.

The driver for thorough planning is the demonstration of successful rehabilitation. This is vitally important to the mining industry if it is to continue to be allowed to access and utilise natural resources.

1.6 Planning

Environmental management planning for a mining project should be synonymous with whole-of-life mine planning, and should start at the pre-feasibility stage. Too often cash flow considerations and pressures to begin the operational phase of a mine lead to poor closure rehabilitation planning or to deferment of planning and cost provisioning until near the end of operations. Often such planning is seen as the sole responsibility of an environmental officer with little authority within the management hierarchy. Agreements on closure criteria may be left until well into the rehabilitation process with the risk that works undertaken may be inappropriate.

Planning for management of waste streams from a mine is absolutely fundamental to minimising potential adverse impacts. Critical points to consider are summarised below.

- ***Waste rock and tailings management decisions, at least to an advanced conceptual stage, must be made before a mine commences operations.***
- ***Before informed decisions can be made on various potential management strategies, both the short and long-term physical and geochemical properties of the waste rock and tailings or other waste streams must be understood, as well as a complete understanding of the environmental setting for the operation.***
- ***It is absolutely critical the rehabilitation planning is undertaken in a holistic manner; that is, when planning for rehabilitation of an individual aspect of a site, its relationship to other aspects of the site are taken into account.***
- ***Rehabilitation solutions are site specific and rarely can methodologies/designs from one site be transferred to another without modification. Site specific investigations are usually required to determine the unique material properties, hydrogeology, climate and setting for each site.***

Figure 1.7 illustrates a typical life-of-project timeline for a small/medium sized modern Australian mining operation. The key learning from this is that the operational phase of a mining project may be less than 30% of the time that a mining company is actively involved with the site. Given that there have been few "sign-offs" of the rehabilitation of mining sites in Australia in recent times, the timeline for the postoperative phase shown in Figure 1.7 may be a substantial underestimate.

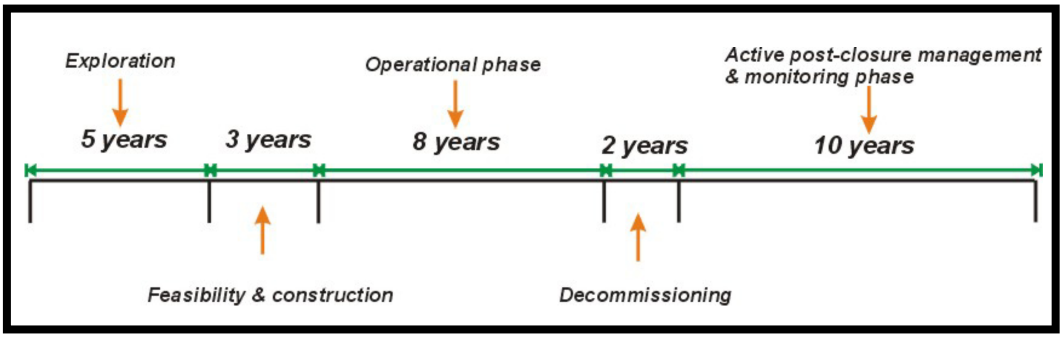

Figure 1.7: Indicative whole-of-project life timeline (courtesy of M. Fawcett)

Commencing rehabilitation planning at the earliest stage of an operation allows for consideration of the maximum number of rehabilitation strategies or options. It also allows them to be implemented for the lowest possible cost, as illustrated in Figure 1.8. The examples given in Table 1.2 apply just as readily to other waste streams generated from mining operations.

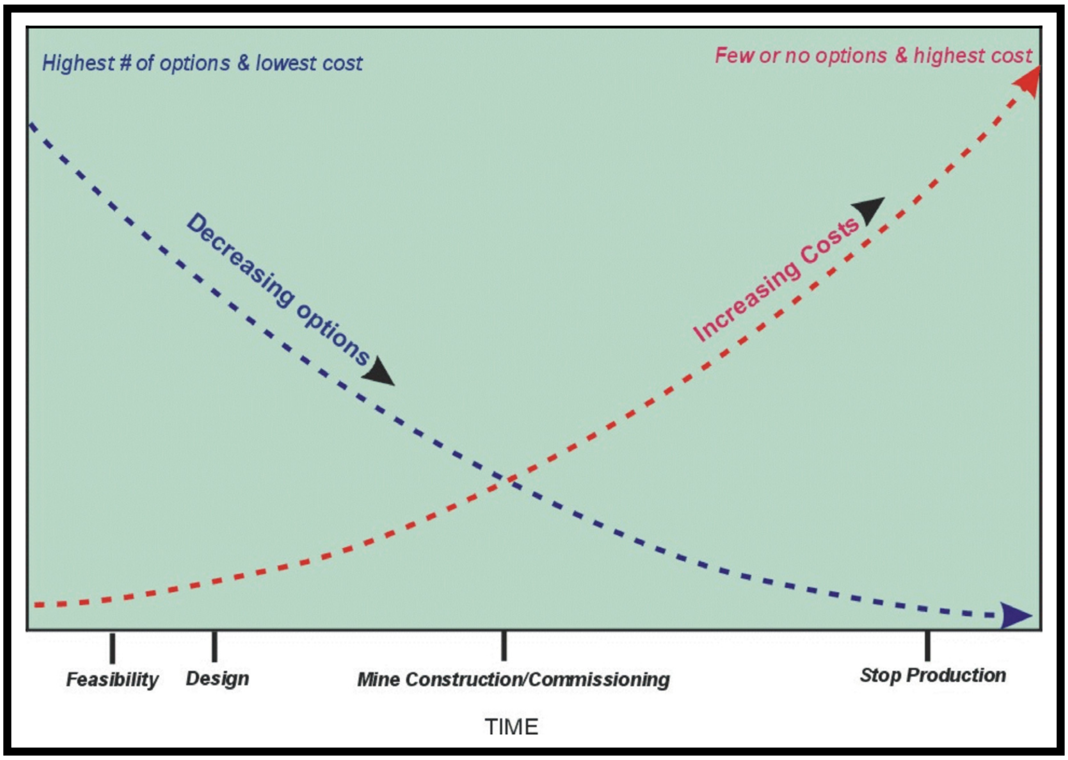

Figure 1.8: Relationships between rehabilitation options available and costs through time (courtesy of M. Fawcett)

Table 1.2: Maximising rehabilitation options for a waste rock dump (WRD) by early planning.

Issue	**Issue addressed before WRD construction**	**Rehabilitation issues not addressed until WRD construction is completed**
Location	Location of a WRD can be optimised to ensure that the lowest possible haulage cost is achieved while minimising the potential for long term environmental impacts.	Selecting the WRD location based on the shortest haul may provide short-term savings, but may result in the WRD being located where long term environmental impacts are not acceptable without ongoing active management and intervention.
Rehabilitation Options	Allows for all potential options to be considered and innovative methodologies to be considered. Additionally there is time to conduct trials to optimise performance and minimise implementation costs.	The operator is faced with “after the fact” options which are often limited by the prohibitive costs of shifting or significantly rehandling the WRD. In the worst case there may be no economically viable “walk away” rehabilitation options and the operator will then be faced with management of the site in perpetuity.
Groundwater	Potential to site WRD in a location where interaction with groundwater is minimised.	WRD may be sited where the interaction with groundwater creates circumstances for a continuing impact on aquifers regardless of the rehabilitation option selected.
ARD potential	ARD or leachate drainage issues recognised before the dump is constructed, allows for management strategies to be designed before waste placement commences. Allows for designs to include progressive encapsulation within benign materials to exclude oxygen and minimise production of soluble oxidation products within the waste.	Potential ARD producing material is mixed throughout the dump requiring expensive works in order to manage. Suitable rehabilitation materials may have been contaminated with ARD producing material through the failure to identify and segregate waste types during mining. Due to the time lag in ARD commencing, there is potential for a WRD to have been “rehabilitated” in the belief that there would not be an ARD problem only for it to emerge later. In these circumstances the value of most if not all of the works done previously is lost.
Land-form	Land-form design can be optimised to facilitate progressive rehabilitation and minimise long term erosion. Stability can be incorporated into the initial design once the physical characterisation is completed.	A constructed land-form may require extensive reshaping or other works and ongoing maintenance to meet long term stability requirements and ensure encapsulation and containment of problematic materials.
Cost	Lowest possible cost plus opportunities to spread cost over the life of a mine through progressive rehabilitation.	Cost likely to be substantially higher and will be incurred in a short time period at mine closure when cash flow may have ceased.
Relinquishment	Facilitate relinquishment in the shortest possible time which also ensures the minimum costs for maintenance, management and monitoring. Progressive rehabilitation allows for the development and demonstration of successful strategies before mine closure and will save many years waiting time to demonstrate success compared with initiating rehabilitation at closure.	May require construction of a water treatment plant and treatment of seepage from the WRD for decades if not centuries. (There are now many instances in North America where mining companies are committed to managing and treating water discharging from their mine-sites for periods of up to 200 years.) In the worst case, the WRD cannot be economically rehabilitated to a state that will achieve relinquishment, thus preventing the mining company from ever achieving relinquishment and release of securities.
Stakeholder perceptions	Demonstrates to stakeholders the mining company’s commitment to environmentally sustainable operating practices. Successful closure and rehabilitation outcomes will help sway public opinion in favour of continued access to land and further potential resources.	Potential to reinforce poor perceptions of mining held in the general community. Unsuccessful rehabilitation will continue to build public resistance to further access to resources by mining companies.

A common failure historically, has been to undertake rehabilitation works without clearly defined objectives. The most frequently encountered examples of this are where waste rock dumps or tailings storage facilities have been "capped" without the eight fundamental questions listed in the Cover Systems section in Chapter 4 being addressed adequately. In the worst case this has resulted in the complete loss of any value from the works undertaken and the need for a complete rework of the rehabilitation effort. The consequences of this are not only financial but also an extension of the timeline for lease relinquishment beyond all planning horizons.

1.7 Shifting Goalposts

One of the major challenges to operational environment management and successful mine closure planning is the issue of "shifting goalposts", resulting from either a change in the mine plan or evolving compliance standards. The issue of shifting goalposts is a significant challenge both for operators and regulators, and particularly so for mines with longer lives and for the reworking of previously closed-out sites. As illustrated in Figure 1.7 it may be some 20 years after the start of a project that the rehabilitated site is offered to the regulators and stakeholders for "sign off".

If the closure criteria at the time of project inception were the minimum acceptable, then there is a considerable risk that regulatory requirements and community standards will have evolved substantially over the intervening 20 year period to closure. What was acceptable 20 years ago may no longer be acceptable. This means that to the maximum extent possible, operations must try to anticipate likely movements in standards and build them into evolving closure objectives. A good guide to trends in standards is to look to North America and Europe as possible indications of how standards are changing.

Regularly review site environment targets, goals and closure objectives to ensure they reflect current and anticipated regulatory and community expectations

Examples of evolving standards are provided by the recent decrease in drinking water quality guidelines for arsenic from 50 µg/L to 7 µg/L, and the promulgation through Federal and State jurisdictions of the 2002 ANZECC water quality guidelines.

Changes in Scope

Often the original environmental approval documentation for a mining operation (EIS, PER, etc.) relates to a quite different scope of operation to that existing at closure. This is quite normal and is usually the result of discoveries of additional ore and changes or improvements in technology over the operation's life. This becomes a potential problem when the environmental management and closure plans have not evolved to incorporate these changes.

Ensure that ALL environmental documentation reflects the current scope of the operation.

As a mine changes during its operational phase, it is important to ensure that environmental documentation, baseline data collection and the rehabilitation goals and strategies are regularly reviewed to ensure they both reflect, and are applicable to, the current scope of the operation. Examples of changes to operations that can impact on the environmental management plan include:

- waste dump or tailings storage facilities either increasing in footprint or number;
- changes in ore types;
- changes in processing technology and reagents;
- additional satellite operations;
- shift to or from underground operations; and
- purchase of nearby mines from which ore is brought in for processing.

Case Study

Collect samples from the right location!

An example of risks arising from a change of scope is the case where a company had undertaken a waste characterisation programme in preparation for development of an open pit resource. However, in the intervening seven years the size of the proposed pit was reduced dramatically to optimise the recovered metal. Later it was found that the majority of the samples characterised fell outside the boundaries of the new pit, and the results from the original characterisation program were no longer applicable.

1.8 Protection of Potential Resources

Protection of potential economic resources is an issue that must be considered throughout the life of a mining operation. There are three major categories of resource protection:

- ensuring that waste storage facilities, plant and other infrastructure are not placed over potential orebodies;
- managing waste streams so they do not contaminate each other (for example ensuring that low-grade ore stockpiles are not diluted with waste rock, or that waste destined for capping of sulfidic material is not contaminated with reactive material, or using tailings indiscriminately for rubbish disposal); and
- ensuring that access to remaining ore is not rendered uneconomic (unnecessarily dismantling or backfilling ramps, shafts, etc).

There has been a long history of reprocessing tailings in Australia. Examples abound in Western Australia, where some tailings have now been treated twice since the ore was originally processed in the late 1800's. The practice of using tailings dams as rubbish dumps both during operations and also during site closure can jeopardise the future potential value of those tailings, by making their re-treatment uneconomical due to the costs associated with managing the contamination.

Production information is likely to be valuable to the industry at a later time and should be preserved. This information includes quality and quantities of waste as well as details of its placement.

As a general rule waste streams should not be contaminated with other materials as it downgrades their potential to be reprocessed at a later date

A vital component of final void closure planning is considering the potential for access to further resources at a later date. The possibility of either extracting further low-grade resources from open pits or the potential to access potential deeper ore-bodies have often been given as reasons to leave open pits untouched. However, simply leaving a pit open and allowing it to flood naturally over a long period of time, either through groundwater inflows and/or accumulation of runoff, is likely to reduce opportunities to access further resources at a later date. The reason for this is that slow filling invariably results in poor water quality (Figure 1.9).

Figure 1.9: Open pit slowly filling with acidic water – sulfidic rock is oxidising in the pit walls and in the waste in the foreground.

Rapidly flooding an open pit in order to preserve water quality will, in some cases, be the best approach to preserving access to potential resources. This gives the greatest chance of creating a water body of reasonable quality by limiting the opportunity for sulfide oxidation to occur in the pit walls. Having reasonable quality water will make it far more practicable to dewater the pit at a later date to access further reserves, as it may be possible to discharge this water directly to the environment without first having to undertake expensive water-treatment. In addition, good quality water in a pit may be a valuable resource in its own right throughout much of the Northern Territory, as a water supply during the long dry season.

Case Study

Water Quality and Flooding of Pits

In the Northern Territory there are two pits that were rapidly flooded – in one instance this was planned, and in the other it occurred accidentally. In both these pits water quality has remained good, opening the potential for beneficial use of the waterbody or easy dewatering in order to re-access potential orebodies. In contrast, there are numerous instances where slow passive filling has occurred. These pits invariably contain very poor quality water. In a number of cases this has severely impacted the economics of resuming mining since the water has to be treated before it can be discharged.

1.9 References and Further Reading

Ellerbroek, D.A., Jones, D.R. and Townley, L.R. 1996, 'Managing the hydrology and water quality of final voids after mining', in *Post-Mining Landform Stability and Design Workshop, Brisbane, 18-20 September 1996*, pp. 111-121, Australian Centre for Minesite Rehabilitation Research, Brisbane.

Fawcett, M.N.R. 1999, 'Provisioning for mine closure', presentation to *ACMER Short Course: Environmental issues in decommissioning and temporary closure of mine sites, Townsville, Queensland, October 1999.*

Ormsby, W.R., Nicholson, P.M. and Butler, I.K. 1994, 'Gold and base metal mineralisation in the central Pine Creek Geosyncline', in *1994 AUSIMM Annual Conference: Australian mining looks north – the challenges and choices, Darwin, Northern Territory, 5-9 August 1994,* ed C.P. Hallenstein, AUSIMM Publication Series No 5/94, pp. 11-20.

Phillip, M. and Myers, K. 2003, 'Regulatory perspective: development of closure plan with adequate financial assurance for the protection of groundwater quality at the Chino Copper Mine', *6th International Conference Acid Rock Drainage, Cairns, Queensland, July 2003.*

Younger, P.L. 2002, *Mine waste or mine voids: which is the most important long-term source of polluted mine drainage?* University of Newcastle, 2002.

2. MINE WATER PREDICTION

2.1 Overview

Adverse environmental impacts from mine drainage have invariably resulted from one or more of the following factors:

- incorrect prediction of the weathering behaviour of the various waste streams once they have been exposed on the land surface;
- insufficient storage capacity onsite to contain runoff and seepage produced during the wet season (catchment sizing and water balance issues);
- failure of a monitoring program to provide early warning of deterioration in water quality; and
- insufficient or inappropriate treatment methodology (eg a wetland that is too small to polish the volume of water produced, or is overwhelmed by highly acidic water).

The first three items will be addressed in this chapter whilst technologies for water treatment will be discussed in Chapters 5 and 6.

Mine drainage containing elevated levels of metals is the product of accelerated weathering of waste (rock or tailings), typically occurring as a result of the oxidation of sulfide minerals. The pH of such drainage can range from very acidic through neutral to even weakly alkaline.

Acid mine drainage (AMD) or acid rock drainage (ARD) are the generic terms used to describe the low pH subset of mine drainage. However, it must be recognised that mine drainage does not have to be acidic to contain environmentally significant concentrations of dissolved metals (Table 1.1). A waste with a moderately negative Net Acid Producing Potential (NAPP) value can still produce a leachate with a substantial salt or metal load; it's just that it won't be acidic. Indeed, pH neutral or slightly alkaline mine drainage can contain high concentrations of metals such as Cd, Mn, Ni and Zn. The concentrations of major ions salts (typically Mg, SO4) can also be of major importance in their own right, irrespective of whether they are accompanied by heavy metals, in the event that saline seepage or runoff is produced.

Traditionally there has been a focus on predicting the potential for production of ARD from mine sites through simple acid-base accounting methods. Many mine operators have experienced problems with metal rich leachates having originally believed that ARD would not occur due to:

- over-reliance on simple acid–base accounting methods;
- failure to consider the results in conjunction with other indicators;
- limited sampling; and/or
- changes in the scope of operations.

A prediction that indicates absence of ARD should not, by itself, be construed as giving a "clean bill of health", as oxidation of sulfides and leaching of metals can occur over a wide range of pH values.

Inadequate characterisation of the geochemical properties of mine wastes, and consequent incorrect predictions of leachate quality, has been the single largest cause of unanticipated adverse environmental impacts from mining operations. The focus of a waste characterisation program must be on determining whether leachate is likely to contain environmentally unacceptable concentrations of major ion solutes and metals – irrespective of whether it is acidic or not.

Failure to predict long term geochemical behaviour of waste materials and their storage facilities can usually be attributed to one or more of the following factors:

- An insufficient number of samples was analysed.
- The samples analysed were not representative of the actual waste produced.
- The analytical methodologies used were incorrect or inappropriate.
- Lab-scale testing did not accurately represent the kinetics of the reactions under actual field conditions.
- Lag-time for ARD production was not recognised.
- Failure to recognise that preferential flow paths will develop within the structures.
- Assessors making an assumption that the materials within the structure are homogeneously mixed; in fact most if not all waste dumps and tailings storage facilities are highly heterogeneous (Figures 2.1 and 2.2).

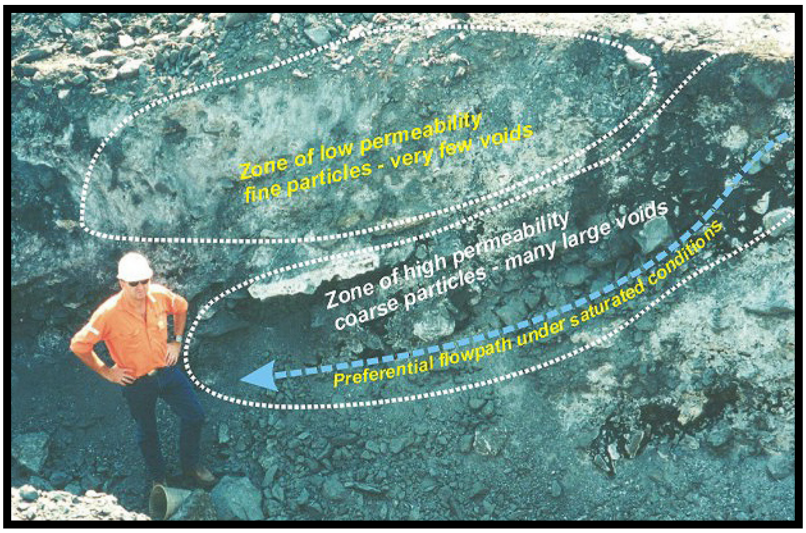

Figure 2.1: View of an opened-up waste rock dump showing zones of different particle sizes (courtesy of M. Fawcett).

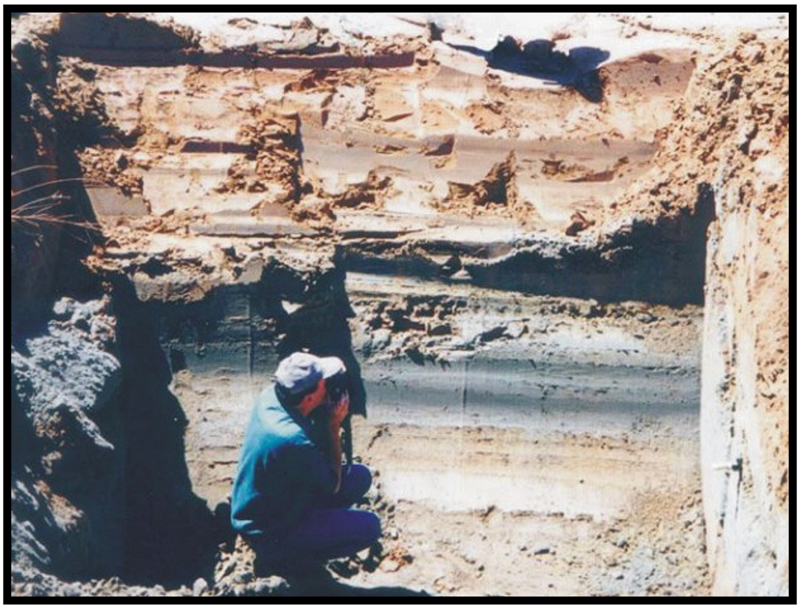

Figure 2.2: Tailings profile showing variations in both ore type and extent of oxidation (courtesy of M. Fawcett).

Another potential risk of inadequate characterisation is the case where ARD is predicted, but in fact under actual field conditions does not occur. This second category of incorrect characterisation can be just as expensive to a mine operator as the first, if costly and unnecessary remediation strategies are implemented. In both these cases an unfavourable outcome could probably have been avoided if adequate characterisation and planning had been undertaken prior to construction of the waste storage.

> ***"A stitch in time saves nine".***
>
> - Translation to mining language
>
>   ***$1 spent well now saves $9 later***
>
> - Corollaries:
>   - ***$1 spent poorly now is a waste of a $1***
>   - ***$1 spent unwisely now can lead to $9 later ($10 altogether)***
>
> ***- Kevin Morin, TEAM NT workshops, 2003***

Case Study

A failed waste encapsulation strategy

Prior to mining, a mine recognised that some of the waste rock would be net-acid-generating and would release ARD. Extensive column testing showed that acidic water from net-acid-generating rock could be neutralised when it flowed through sufficient thicknesses of net-acid-neutralising rock.

Expensive design and double handling of waste rock created a "stacked" series of net-acid-generating and net-acid-neutralising rock that would ensure no ARD flowed from the toe of the dump. A clay cover was placed on top.

Within a few years, ARD was flowing from the dump slopes. Water in the acidic layers was short-circuiting through the coarse acidic rock and bypassing the finer neutralising rock. This occurred because the design was based on one-dimensional column testwork and failed to account for preferential flow pathways. The ARD is now being collected and treated with a treatment plant. Toe seepage was pH 8, so ARD at the base had in fact been prevented there. However, zinc concentrations were around 20 mg/L and were toxic, so the neutral water also had to be collected and treated in a treatment plant.

This expensive "stitch in time" provided no substantial benefit to the environment, because a treatment plant had to be built anyway to attenuate the metals in both the ARD and the pH neutral drainage. Millions of dollars were thus "lost" by using a physically inappropriate design.

2.2 Geochemical Characterisation – When and How Much

2.2.1 When to start

Prediction of the geochemical properties of the various materials to be mined from a site should commence during the exploration phase of any project. Some very important basic information can be collected during the logging of exploration drill core and/or drill cuttings, at little or no extra cost.

Information that can be collected that will enhance prediction of properties and long term behaviour includes:

- estimates of sulfide % (visual);
- determination of sulfide types (visual); and
- presence or absence of carbonates.

Ore should not be overlooked in a characterisation program. Ore (especially low grade ore) can remain in stockpiles for extended periods of time, and seepage and runoff from ore stockpiles will report to the mine water management system.

In many mining operations there is the potential for concentration of sulfide minerals in waste streams produced by gravity concentration or pre-flotation of gangue sulfides (eg pyrite). Tailings will contain both the non-target sulfide minerals and target minerals in the event that high recoveries are not achieved, so the tailings produced from pilot metallurgical testwork should also be characterised for drainage potential. Indeed tailings may contain higher concentrations of reactive sulfides than waste rock.

Start collecting data on material properties at the earliest opportunity, eg during the exploration phase. Include ore grade, especially low grade, material in the assessment.

When a new company is considering taking over a previously worked lease, the original geochemical characterisation data, if available, should be rigorously reviewed to ascertain if the level of risk was adequately determined. In particular it should be determined if adequate mitigation measures had been implemented in the event of an identified risk. If the historical data are not available then a site inspection may reveal if low pH and high electrical conductivity (EC) seepage is being produced. If data are not available for such a “brownfield” site then it is recommended that a characterisation program be undertaken as if the site were a “greenfield” operation.

2.2.2 Sampling Frequency

The availability of samples for testing will depend on the stage of the project. For example, at pre-feasibility there may be only a limited amount of core available for testwork. However, based on the geological interpretation of the structure of the orebody, each significant rock type (>2% of total) from at least 10 cores should be screened for key geochemical parameters to provide an indication of the likely environmental handling costs (during operation and at closure).

As a project advances beyond pre-feasibility and there is more extensive delineation of the orebody, the materials characterisation program should be correspondingly expanded. This is particularly important if the earlier assessment indicated a significant potential risk for the waste.

A distinction should be made between the waste characterisation program that is used to build the mine block model and the waste characterisation program that proceeds concurrently with operations. The delineation drilling pattern used to construct the block model is typically much coarser than is the resolution of the day-to-day mining program. The results from the delineation drilling characterisation are also typically focussed on the ore zone.

Because the sampling grid is focused on the ore zone, the predictions of at-risk or problematic waste material can have a large error factor. There is a need to refine the waste model as operations proceed. Definition of the material requiring selective placement can be based on the results of characterisation done on drill chips obtained from a representative number of holes from the blast pattern.

Although there are no absolute guidelines on the number of samples that should be tested, there are a number of suggested frequencies discussed in the United States Environmental Protection Agency (USEPA) Technical Document on Acid Mine Drainage (USEPA 1994). These range from 1-50 samples per million tonnes of each potentially at risk rock unit. In practice, the frequency will be determined by the structure of the orebody (the ratio of waste to ore) and the mining method.

Frequencies greater than these are usually required on operating sites to ensure effective management of waste streams. The frequency of testing is related to the variability of individual units and the properties of each discrete geological unit. It is important to understand that sampling and testing frequency are both site and material specific and that the numbers of samples selected must be statistically valid.

“As a general rule it is recommended that a minimum of 100 samples per significant geologic unit be tested as a first pass.”

- Dr Kevin Morin, TEAM NT workshops, 2003

2.2.3 Prediction Methodologies

There are a number of prediction methodologies or techniques ranging from “simple” to more complex that can be used to determine reactivity of materials and likely composition of leachate (Figure 2.3). Many of these tests are complementary in the information they provide and at least two need to be applied to gain sufficient confidence in the robustness of the prediction.

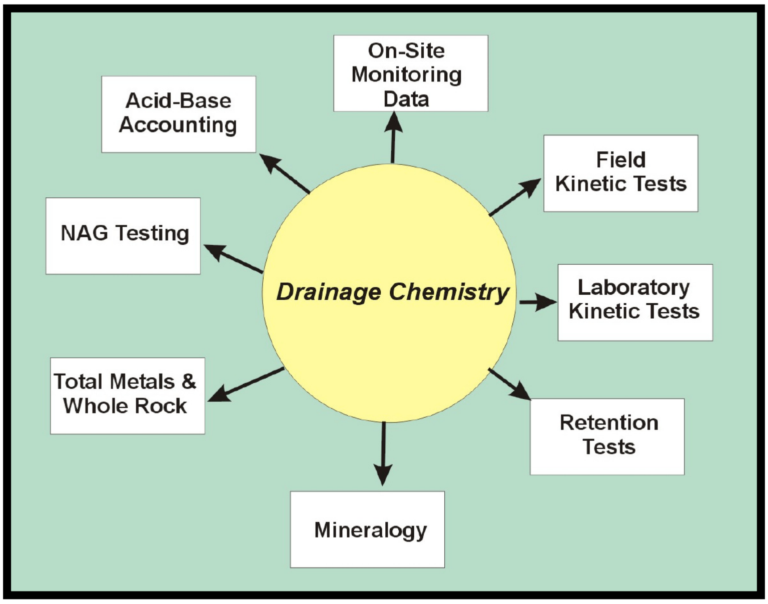

Figure 2.3: The Mine Drainage Chemistry Wheel – A summary of prediction methodologies (Dr Kevin Morin, TEAM NT workshops, 2003).

Prediction methodologies can be divided into two basic types: static and kinetic.

Static methods involve laboratory testing of finely pulverised material and include mineralogy, whole rock analysis, acid-base accounting (ABA) and net acid generation (NAG) methods (the left hand side of Figure 2.3).

The advantages of static tests are that they are relatively cheap and quick to run, especially in comparison to kinetic tests. Accordingly, static tests (especially ABA) are the most widely applied in the mining industry. However, if the results produced are not assessed in conjunction with other geochemical and mineralogical information, serious errors can result.

Kinetic tests involve column or heap leach methods in which the size of the particles to be tested approaches that in the field, and percolation of water through the material to simulate the influence of infiltrating rainwater. The more complex column and field kinetic tests are often required where the ratio of neutralising to acid generating capacity is sufficiently close on the basis of ABA screening testwork to yield an inconclusive prediction.

No one single test should be relied on to produce conclusive evidence on the properties of leachate likely to be produced from mining wastes. There is a substantial body of case studies that show that the long term leachate properties of mining wastes can be dramatically different to those originally predicted using a single type of testing. The use of multiple techniques will give a greater degree of confidence in the predicted properties of materials tested.

Static Test Suite (Element Content, ABA and NAG Testing)

The concentrations of elements in a sample can show if they are substantially elevated relative to normal crustal abundance – or above "background" level in the immediate vicinity of the target orebody. If the concentrations are elevated then this provides a "flag" that the rock type may potentially be a source of leachable metals.

The sulfide content of the sample, in combination with an assessment of sulfide mineralogy will provide a strong indication if it is likely to be a source of saline leachate. Saline drainage can be a significant issue in its own right irrespective of whether the pH is net acid.

The next level of assessment involves determining whether a rock type is likely to be a net acid producer. The ABA test produces a maximum acid producing (AP) and a maximum neutralising potential (NP) or acid neutralising capacity (ANC). In Australia the AP and NP are usually expressed as kg per tonne of sulfuric acid produced or consumed (kg/t H_2SO_4). A positive difference between AP and NP means that a sample is a net acid producer, and vice versa for a negative number.

Sobeck et al. (1978) standardised the ABA methodology. It is defined by the USEPA as *Method EPA-600/2-78-054, Field and Laboratory Methods Applicable to Overburdens and Minesoils.*

The ABA test has been described as "the most popular, most misunderstood, and most abused method for predicting overall drainage chemistry" (Morin, 1997).

The most serious problem with ABA is that the standard Sobek test that is used to measure the NP can seriously overestimate the amount of effective neutralising capacity that is available.

In addition, a static test does not account for the following points:

- Neutralising capacity may not be available at the same rate as acid is produced.
- The neutralising material may not be homogeneously mixed with the acid producing material under field conditions.

There are case studies in Australia where waste rock dumps with high theoretical net acid neutralising capability have become sources of acid mine drainage due to the actual kinetics of the reaction not conforming with the simple NAPP = AP - NP calculation.

There are some steps that can be readily implemented in an ARD screening procedure to guard against overestimating neutralising capacity. This involves the more rigorous characterisation and mineralogical assessment of a subset of submitted samples to "calibrate" the routine ABA screening procedure.

The first step is assessing the mineralogy of the waste to determine if the bulk of neutralising capacity is likely to come from carbonate (pH neutral to higher pH end) or aluminosilicate (low pH end) neutralising capacity. The relative contribution of these neutralising components can be quantified by measuring the acid neutralising characteristic curve of the waste and identifying the pH regions where there is maximum buffering capacity.

Thus it can be clearly determined if the standard Sobek procedure (which involves reacting the sample with hydrochloric acid) is overestimating effective neutralising capacity. In practice it is only neutralising capacity above pH 3.5 that will be available to mitigate against the most serious manifestations of ARD.

One of the static tests that can be used to complement the standard ABA approach is the NAG test. The NAG test, which involves accelerated oxidation by hydrogen peroxide of the sulfide in a waste material, can provide a very useful screening test for those wastes that do not contain significant graphite, oxidisable organic matter or manganese oxides. In the first instance the NAG test pH provides an indication if the material is likely to be net acid producing.

However, the chemical composition of the supernatant produced by the NAG procedure is of equal if not greater value. Whether the final pH is acidic or not, the concentrations of salts and metals in the supernatant will provide an indication of the likely solute load. This is especially important to avoid the misclassification of a non net acid producing waste as environmentally innocuous.

As a minimum it is recommended that acid-base accounting, neutralising curve characterisation, NAG and mineralogy assessments be applied to the range of waste lithotypes.

Kinetic Tests

Kinetic tests differ from static tests in that they attempt to reproduce the actual oxidation and water infiltration conditions likely to be encountered in the field within waste rock dumps, tailings storages, etc. Generally they use larger volumes of sample material and take considerably longer to complete.

Kinetic tests are especially important for those instances where the results from static testing have yielded inconclusive results. For example, a ratio of AP to NP that is not sufficiently large when mineralogy is taken into account, to confidently predict that acidic drainage will not be produced.

Morin and Hutt (1997) and Lapakko (2002) describe the range of **laboratory kinetic tests** available. These range from humidity cells in which the material being tested is reacted under moist unsaturated and fully oxygenated conditions, with periodic flushing of oxidation products, to large scale leaching columns containing individual wastes or layers of materials to simulate encapsulation options.

Field Scale Kinetic Tests represent the ultimate in kinetic testwork whereby large piles of candidate waste types are subjected to oxidation and leaching under actual environmental conditions. This scale of testwork provides the most realistic evaluation of the effects of mixing different types of materials in different configurations. It is almost impossible to simulate the coupling between water flow and oxygen ingress that will occur at full scale in the laboratory.

This form of testing can show whether a given option is likely to prove successful in practice in mitigating the risk of ARD. Field scale test piles are also often used to test the effectiveness of other mitigation options such as cover type.

Field scale tests need to be run for several years to provide data that will reflect the longer term dynamics within a waste pile. This especially applies to waste in arid zones where rain is very infrequent.

2.3 Water and Solute Balances

Issues associated with site water balances were a recurrent theme during the many field visits undertaken as part of the TEAM NT program.

An accurate site water balance, and the specific subcatchment contributions to the balance, is one of the most important aspects of mine site management in the monsoonal tropics. In particular, changes to catchment boundaries around stockpiles or retention ponds can have major impacts on the volumes of water that need to be contained onsite during the wet season. The site water balance model must be regularly updated to capture changes in catchment areas, and the implications of these changes to water quantity and quality addressed in the Mine Management Plan.

Use of the balance model to plan for adequate provision of process water during the long dry is as important as ensuring adequate retention during the wet for environmental management reasons. It is not an uncommon occurrence for operations in the Top End to run out of the primary reserve of process water during below average rainfall years, as a result of a shortfall in onsite storage capacity.

Very few sites have a solute balance for their water management system, despite concentrations of dissolved salts having important implications from both environmental and process perspectives. The build up of certain metals in a process water circuit can seriously compromise the efficiency of hydrometallurgical processes. An example would be the inputs of seepage containing elevated concentrations of Co, Ni and Zn into the process system. These metals complex with cyanide and reduce the efficiency of the gold extraction process.

In the case of water management during the wet season, the ability to release (or not to release) water from site will be governed by the load (product of concentration and volume) of metals being delivered to the receiving waterway.

Simply measuring concentrations of dissolved metals will not enable the contribution of a specific source to be put in the context of the overall site. Such an approach may indeed precipitate costly management action (for either process or environmental reasons) that is either not warranted or is directed to the wrong area. This is yet another example of “a dollar spent wisely can save nine dollars later”.

Flow data, obtained from pump records or weir height flow calibrations, are essential for good site management.

2.4 Monitoring

Monitoring is often regarded as an unnecessary expense rather than as an investment, especially if funds are limited. However without a well-focussed (cost effective) basic monitoring program, an operation cannot effectively manage either its process or its environmental footprint.

Effective monitoring programs save time and money by properly identifying issues requiring management attention. A lot of money can be wasted if the nature and magnitude of the problem is not correctly identified. Indeed money could be invested to "solve" an issue that wasn't actually a problem.

$1 spent incorrectly now will be a waste of $1. Meanwhile, the real problem could get worse and cost $9 later to solve, making a total of $10 expended. This is the mine management corollary of the proverb - "A stitch in time saves nine". Effective monitoring at all stages of an operation's life provides the information to identify what type of "stitch" is needed and when it should be applied.

Monitoring forms an important part of the geochemical characterisation of a site, and is especially important in the context of providing early warning of a developing mine drainage issue. Traditionally, monitoring is synonymous with routine water quality measurements of pH and EC using field instruments and chemical analysis of grab samples. However, other forms of monitoring onsite are also of real value.

There are five primary reasons for undertaking monitoring:

- To establish the impact of the operation in the context of its geographical location (**baseline monitoring**). This data is very valuable when closure criteria are being negotiated as baseline data may show the effect of mineralisation in the area on water quality.
- To check whether the operation may be impacting on the environment and if so, to what extent (**impact monitoring).** The results from this monitoring will indicate if additional control or mitigation strategies are needed through the operational life of a mine.
- To evaluate compliance with regulatory standards (**operational compliance monitoring**);
- To determine whether rehabilitation works are performing as predicted (**closure performance monitoring**).
- To ensure that the process is working efficiently and that there is minimal loss of reagents that could negatively affect economics or impact on the environment (eg efficient reclaim of cyanide process water from a gold mine tailings dam).

The purpose of impact or compliance monitoring is to check on a regular basis whether the operation is having an impact on the receiving environment and ensure that commitments and statutory obligations are being met.

For impact or compliance monitoring to be most effective, it is necessary to have collected sufficient suitable background or baseline monitoring data. The effect of the operation needs to be clearly distinguished from its context. For example, water quality in the catchment might already be impacted by historic or other current mining activity. It is only when compared with pre-mining (baseline) conditions that the significance of impacts can be assessed. This stresses the need to begin collecting baseline information early in the project feasibility phase before the site undergoes any significant or additional physical disturbances.

A typical compliance monitoring program for a Northern Territory operation involves the collection of weekly grab samples for chemical analysis. However, metal concentration data in the absence of flow does not provide any information about solute loads. This is especially important during the wet season when flow rates can range over orders of magnitude and when the extent of dilution of seepage by surface runoff can similarly vary. Concentration data alone do not allow the significance of a particular stream to be assessed in the context of its proportional contribution to solutes loads being produced on the site as a whole.

Continuous monitoring technology has advanced substantially over the last decade, to the extent where datasondes can be purchased for a relatively low cost. This instrumentation enables the simultaneous and continuous recording of pH, flow and EC. The results from the weekly chemical analyses can be used to obtain a relationship between key parameters and EC and thus enable their concentrations, and ultimately loads to be integrated across the hydrograph. This approach to monitoring enables sources to be ranked according to real contribution and also provides the rigorous data needed to confirm the performance of mitigation measures that may have been implemented onsite.

A correctly designed impact/compliance monitoring program will provide early warning of changes in system behaviour that could indicate the need for management action. In general, the earlier the warning, the lower the cost of remedial measures that may be required, and the greater the range of options that may be available. Nowhere is the adage "a stitch in time saves nine" more apt.

Management sometimes assumes that if only low levels of impact are being measured then monitoring is of little value. However, such data can be used to provide reassurance to stakeholders, and will be particularly valuable during the closure period when progress towards attainment of closure criteria is being assessed.

However, monitoring programs notwithstanding, there are many examples where operations have collected vast amounts of expensive monitoring data, then failed to interpret it adequately. Sometimes the water quality data were erroneous due to contamination of samples at collection or during processing. This highlights the essential need for training of site staff, quality control of data, and the regular assessment of the data that are acquired. Initial interpretation may be as simple as the site personnel responsible entering the most recent batch of data into a spreadsheet, then plotting it to check if trends are occurring over time ("control charting").

Another difficulty can arise when the scope of an operation changes over time and the monitoring program is not modified to reflect the changed circumstances.

The purpose of **performance monitoring** is to ensure that environmental control works onsite are performing as expected. Post-closure, the role is to check and document the performance of rehabilitation works against predicted or required outcomes, to ensure that closure criteria will be met.

An additional outcome of performance monitoring is to provide actual field data that can be used to refine and calibrate models used in the design of rehabilitation works, in particular for groundwater and cover designs.

Monitoring programs should be reviewed annually to ensure that they remain relevant both in terms of the parameters being monitored as well as monitoring locations and frequency.

Case Study

Value of baseline monitoring

In order to access a resource at the base of a pit that contained low pH water and high concentrations of metals, the water had to be treated to the extent that discharge of treated water would not compromise the existing wet season quality of water in the receiving waterway. The key issue in this context was that the waterway was already impacted by historical mining activity in the catchment. The ANZECC Water Quality Guidelines accommodate this situation by allowing for the derivation of local water quality criteria in the event that sufficient monitoring data are available.

In this case many years of monitoring data were available. A cost effective combination of lime treatment and wetland polishing, coupled with catchment dilution was estimated to produce levels of metals less than both the historical median values in the receiving waterway and the applicable ANZECC 80% percent ecosystem protection guideline values. The outcome was that this treatment strategy would enable the required volume of treated water to be discharged within the timeframe needed for access to the base of the pit at a much lower treatment cost.

2.5 Final Cautions

ARD is one end of a continuum of pH values that can be potentially produced by oxidation of sulfides within a waste stockpile. Even if all of the geochemical testwork indicates that a site will not produce acid drainage this does NOT mean that it will not produce runoff or leachate containing concentrations of metals or salts too high for discharge to the receiving environment.

The objective of a waste characterisation program should be on solute load prediction from mine waste, and NOT solely focussed on whether the leachate or runoff will be acidic or not. There are many metals that are very soluble and very mobile between pH 6 and 9 (eg Zn, Cd, Co, Mn, Ni, As Se, Sb). These metals can cause major issues for mine water management on sites if this issue has not been foreseen and accounted for in planning at project inception.

It should never be assumed that waste with low levels of sulfide (eg <0.5%) will not be an environmental issue. If an operation produces millions of tonnes of such waste, and most of this sulfide oxidises, then this still represents a huge reservoir of oxidation products that are available to be leached by infiltrating rainwater.

2.6 References and Further Reading

California Mining Association, 1992, *Mine waste management*, eds I.P.G. Hutchison and R.D. Ellison, Lewis Publishers, Boca Raton.

Lapakko, K. 2002, *Metal mine rock and waste characterisation tools: an overview,* International Institute for Environment and Development, World Business Council for Sustainable Development, Report #67, April 2002. Available from: http://www.unr.edu/mines/mlc/presentations_pub/Pub_LVW/workbook5.pdf

Lee, M. 1999, *Management of sulfidic mine wastes and acid mine drainage*, Australian Centre for Mining Environmental Research.

Mineralogical Association of Canada, 2003, *Environmental aspects of mine wastes*, eds J.L. Jambor, D.W. Blowes and A.I.M. Ritchie, Short Course Series, Vol. 31, Vancouver, British Columbia.

Morin, K.A. and Hutt, N.M. 1997, *Environmental geochemistry of minesite drainage: practical theory and case studies*, MDAG Publishing, Vancouver, British Columbia.

Price, W.A. 1999, 'Examples of how a regulator minimises the risks and prevents impacts from metal leaching and acid rock drainage', in *Proceedings: Sudbury 99: Mining and the Environment II, Sudbury, Ontario, 13-17 September 1999*, pp. 961-970.

United States Environmental Protection Agency, 1994, *Technical Document on Acid Mine Drainage*, Washington, D.C.

Additional sources of information about mine waste characterisation and the latest research in the field are available from:

Australian Centre for Mining Environmental Research (ACMER).
www.acmer.com.au.

International Network of Acid Prevention (INAP).
www.inap.com.au

Mine Environmental Neutral Drainage (MEND) Program in Canada.
http://www.nrcan.gc.ca/mms/canmet-mtb/mmsl-lmsm/mend/default_e.htm

3. ARSENIC

3.1 Context

Arsenic (As) is one of the most important trace elements that needs to be addressed by the environmental and occupational health and safety management programs of gold and base metal mining industries. The reason for this is that arsenic is a demonstrated human carcinogen and that arsenic water quality guidelines have been substantially lowered in recent years.

Arsenic is of especial concern in the Northern Territory owing to the ubiquitous occurrence of low to medium levels of arsenopyrite in the orebodies of the Pine Creek Geosyncline.

The current national environmental guideline values for arsenic in water and soil are summarised in Table 3.1 below. This table is a compendium of criteria for drinking water (National Health and Medical Research Council (NHMRC) 1996), protection of aquatic ecosystems (Australian and New Zealand Environmental Consultative Council (ANZECC) 2002) and contaminated soil (National Environment Protection Council (NEPC) 1999).

The drinking water limit of 7µg/L is based on the consumption of 2L of water per day. However, in the Northern Territory daily consumption can be up to 10L per day for heavy work in hot conditions. Most mine sites recommend that workers drink at least 4 to 5 litres per day. The Australian guideline limit of 7 µg/L should therefore be considered to be very much an upper limit for potable water at mine sites in the Territory.

Arsenic is one of the few trace elements where the human drinking water quality guideline value is lower than that for aquatic ecosystem protection.

Table 3.1: Current Australian criteria for arsenic (ANZECC, 2002; NEPC, 1999; NHMRC, 1996).

Water	
• Drinking Water (NHMRC, 1996)	7µg/L
• Protection of Aquatic Ecosystem (ANZECC, 2002)	50µg/L
Soil (Health Investigation Levels from NEPC, 1999) [a]	
• Level A (Residential + child contact)	100mg/kg
• Level D (Residential + vegetable garden)	400mg/kg
• Level E (Parks and recreation)	200mg/kg
• Level F (Commercial and industrial)	500mg/kg

[a] Note: a typical "background" range in non-mineralised areas is 1-50 mg/kg

The assessment of the health effects of contaminated soil is based on the nature and duration of exposure and likely risk. Note that the criteria listed by NEPC (1999) are for contaminated sites and are not specifically derived for mined land, although they can be inferred to account for exposure from such wastes based on a conservative assessment (Ng et al., 2003a).

The concentrations of arsenic in surface and groundwater not associated with arsenic-containing mineralisation are typically in the range of 1-10 µg/L. Elevated concentrations of up to 100-5,000 µg/L can be found in areas of sulfide mineralisation and mining. Elevated levels (>1 mg As/L) in water of geochemical origins have also been found in Taiwan, West Bengal, India and more recently in most districts of Bangladesh.

Data for groundwater at various mine sites in the Northern Territory shows that arsenic is elevated at several sites in the Pine Creek Geosyncline (Noller and Parker, 1998) when compared with the drinking water criterion. Some "typical" arsenic and iron (Fe) groundwater concentration data are provided in Table 3.2. It should be noted that the very high value for Pine Creek was obtained from a bore that intersected a gold orebody.

Table 3.2: Soluble arsenic and iron concentrations (µg/L) in groundwater from several mine sites in the Northern Territory (Noller and Parker, 1998).

Location	**As**	**Fe**
Toms Gully	70	1095
Goodall	118	12
Pine Creek	670	<50
Cosmo Howley	28	200
Mt Todd	110	400

3.2 Geochemistry of Arsenic

An overview of the geochemistry of arsenic provides the background to understand its mobility in the environment (Cullen and Reimer, 1989; Jones, 1995).

The most common of the arsenic minerals that may be of importance in the mining environmental context is arsenopyrite, FeAsS. Arsenopyrite is the primary mode of occurrence of arsenic in the Pine Creek Geosyncline. Arsenic is also found as a substituent in many other forms of sulfide mineralisation. When these sulfides are exposed on the surface (in waste rock or tailings), the arsenic and sulfide components oxidise to soluble sulfate and arsenite (AsO_3^{3-}) or arsenate (AsO_4^{3-}). Under moderately reducing conditions, such as in groundwater, arsenite, As(III), may be the dominant form. Arsenate, As(V), is generally the stable form in oxygenated surface environments.

Under more strongly reducing conditions, corresponding to the reduction of sulfate to sulfide, As_2S_3 (orpiment) can be formed. This compound has a very low solubility. The arsenic can also be incorporated into the lattice structures of pyrrhotite (FeS) and pyrite (FeS_2) if sufficient Fe^{2+} (ferrous iron) is available to permit the formation of these minerals. This latter process is likely to be a very important sink (in wetlands or ponds) for arsenic in mine drainage waters rich in sulfate.

Movement of arsenite or arsenate in the surface and subsurface environment is controlled by the form of arsenic and the mineralogy of the soil or rock that it contacts. In a non-absorbing sandy loam, arsenite is 5-8 times more mobile than arsenate. Soil pH also influences arsenic mobility. At a pH of 5.8, arsenate is slightly more mobile than arsenite, but when the pH changes from acidic to neutral to basic, arsenite increasingly tends to become the more mobile species, though mobility of both arsenite and arsenate increases with increasing pH.

When present at trace levels, the solution concentrations of arsenite and arsenate are likely to be controlled by adsorption on iron, manganese, and aluminium hydroxides and oxides, and aluminosilicate minerals within the pH range 3 to 8. Below pH 3, the solubility of arsenate is probably limited by the precipitation of ferric arsenate. Above pH 8 the affinity of arsenite and arsenate for metal oxides declines, and their role in attenuation of arsenic diminishes.

At high pH, a series of calcium arsenate compounds, homologous with calcium phosphate minerals such as apatite, can limit the solubility of arsenic. Indeed, the arsenate anion readily substitutes for phosphate, and the precipitation of phosphate minerals could be a major sink for this element. Substantial amounts of arsenic can also co-precipitate with calcium carbonate, $CaCO_3$, which forms under alkaline conditions.

For pH values greater than 11, it has been proposed that “basic calcium arsenate”, $Ca_4(AsO_4)_2(OH)_2.H_2O$, controls the solubility of the arsenate anion. Precipitation of arsenate by the addition of lime is a well-established water treatment technology, and the precipitation of the basic calcium arsenate phase could account for the effectiveness of this process. However, it should be noted that arsenite is not precipitated by lime, and a pre-oxidation step will be needed if a significant proportion of the total dissolved arsenic is initially in this form. Arsenite is also not as effectively removed as arsenate by co-precipitation with ferric hydroxide.

3.3 Mechanisms of Uptake and Biological Transformations of Arsenic

Arsenic ingestion studies in humans indicate that both As(III) and As(V) are easily absorbed from the gastrointestinal tract.

Inorganic arsenic is rapidly cleared from blood with a half-life of about 2 hours. It is for this reason that blood arsenic is considered to be a useful bioindicator only for recent and relatively high level exposures (Ellenhorn, 1997).

Inorganic arsenic is eliminated primarily via the kidneys. Studies in humans voluntarily ingesting a known amount of either As(III) or As(V), indicate that 45% to 75% of the dose is excreted in the urine within a few days to a week (Buchet et al., 1981; Tam et al., 1979).

Arsenic metabolism is characterised by two main types of reactions:

- oxidation/reduction reactions which interconvert arsenite and arsenate; and
- methylation reactions in which trivalent forms of arsenic are sequentially methylated to form mono-, di- and trimethylated products (Figure 3.1).

Controlled ingestion studies indicate that both arsenate and arsenite are extensively methylated in humans, with the dimethylated product, DMA, being the principal methylated metabolite excreted in human urine.

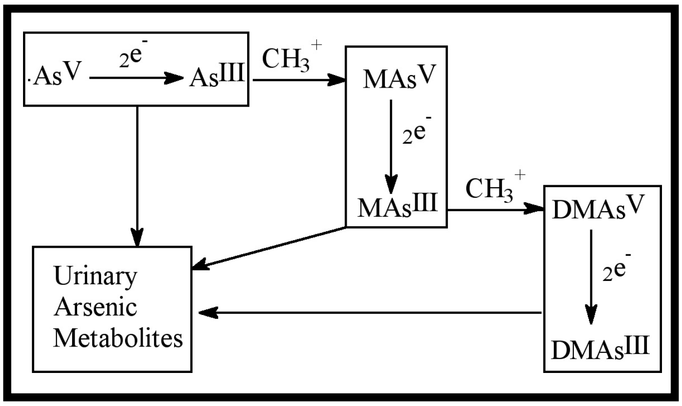

Figure 3.1: A mechanistic scheme for the methylation of inorganic arsenic to mono-, di-, and tri-methylated metabolites. Arsenate must be reduced to trivalent (arsenite) forms in order to be methylated.

3.4 Occupational Health and Safety

It is well documented and understood that arsenic is acutely toxic in large doses. Whilst acute toxicity was an historical possibility for mining industry workers exposed to arsenic-based pesticides, this risk has been reduced by the phasing out of these compounds for general use. The other possible area for acute exposure remains at smelter sites where arsenic trioxide is produced and stockpiled as a by-product of the process of roasting of sulfide ores.

Chronic low level exposure is the most likely route that needs to be considered for mine workers in mineral provinces containing elevated levels of arsenic in the ore or waste. There are three potential exposure routes that need to be considered: airborne exposure, dermal exposure and potable water consumption.

3.4.1 Airborne Exposure

Arsenic may be present in mine air in the form of dust or in dissolved form in water droplets produced by drilling and entrained in the mine ventilation system. Underground mines, especially developmental drives, are the highest risk for this exposure route. Arsenic may also be present in dust from grinding circuits or concentrate handling areas.

The extent of uptake of inhaled arsenic will depend largely on the size of the inhaled particulates. Absorption of deposited arsenic is highly dependent on the solubility of the chemical form of the arsenic.

Available human data are insufficient to quantitatively estimate the extent of uptake that occurs via the respiratory tract.

Occupational studies, in which both the concentration of inorganic arsenic in the breathing zone and urinary excretion of inorganic arsenic and its metabolites were determined, provide information on arsenic absorption. These studies demonstrate that excretion of inorganic arsenic and sometimes total arsenicals and methylated metabolites are significantly increased in workers exposed to higher levels of arsenic in their breathing zone, compared to unexposed workers. This indicates that arsenic is absorbed from the respiratory tract, but does not provide sufficient information to quantitatively estimate the extent of arsenic absorption by this route.

Inhalation of As-containing water vapour and dust by mine workers should be limited given that there is evidence of uptake by the respiratory pathway.

3.4.2 Dermal Exposure

Dermal exposure could occur through contact with solutions containing elevated concentrations of Arsenic. This is most likely to occur in the developmental drives of underground mines. Dust could also adhere to the skin.

From a toxicological viewpoint, the dermal exposure pathway (ie adsorption through unbroken skin) is not generally regarded as important.

3.4.3 Potable Water Consumption

The highest risk for drinking water supplies is arsenic contained in groundwater extracted for potable use. The arsenic is usually in its more toxic arsenite form in groundwater.

Epidemiological evidence indicates that arsenic concentration exceeding 50 µg µg/L in the drinking water would not be protective of public health. Ingesting inorganic arsenic through drinking water containing elevated levels of arsenic can cause multi-site cancers in the human body. For people who are exposed to arsenic levels >50 µg µg/L in drinking water, the cancer risk could be as high as 1 in 100 (Morales et al., 2000). In the Northern Territory, with its higher rate of water consumption than the 1-2L per day consumption that is generally assumed for health risk-based analysis, consuming water with 50 µg/L As would have an even higher risk.

Populations exposed to arsenic in drinking water, generally at levels of several hundred micrograms per litre or higher, are reported to have increased risks of skin, bladder, and lung cancers in Taiwan (Chen et al., 1985), Argentina, and Chile. The current evidence also suggests that the risks of liver and kidney cancer may also be increased following exposure to inorganic forms of arsenic.

The most recent research results (Tran et al., 2002 and other researchers) have shown that the mechanism of cancer induction by arsenic probably involves inhibition of the DNA repair mechanisms in cells.

In addition to increased risk of cancer, long term exposure to elevated levels of arsenic can also lead to various diseases such as conjunctivitis, hyperkeratosis, hyperpigmentation, hypopigmentation, gangrene, cardiovascular disease, peripheral vascular disease (including black foot disease) and disturbances in the nervous system.

Once the above symptoms appear, the damage done by exposure to arsenic is irreversible. In this context it should be noted that it may take many years following exposure for cancers to develop.

3.4.4 Other Interactions

Selenium in the form of selenite suppresses the toxicity of arsenic. The concentrations of selenium present in drinking water, foodstuffs and in the body should therefore also be quantified as part of human biomonitoring studies to assess the effect of exposure to arsenic (Gebel, 2000).

The latest research is showing that inorganic forms of arsenic (arsenic trioxide, sodium arsenite and arsenate) are co-mutagenic with other chemicals and UV light. More importantly, a recent study has demonstrated that arsenic enhanced the number of skin cancers in mice induced by UV exposure (Rossman et al., 2001). These findings are very significant for arsenic–related occupational health issues in the Northern Territory, with its high UV intensity.

3.5 Arsenic and Issues Associated with Rehabilitation of Mine Sites

As discussed above, arsenic can become mobile as a result of the oxidation of the host sulfide mineralisation in waste rock or tailings. The concepts of waste characterisation and cover design detailed in Chapters 2 and 4 of this document are directly applicable to developing appropriate site specific management strategies for operation and closure to limit the environmental legacy of arsenic in waste.

A related issue is that of developing site closure criteria for arsenic in exposed surface soils or waste. The National Environment Protection Council Health Investigation Level (NEPC HIL) criteria summarised in Table 3.1 should be used as a first pass screening tool. In the event that a waste or surface soil exceeds the NEPC HIL for arsenic, the next stage would be to obtain a measure of the bioavailability of the arsenic (Ng et al., 2003a). If the arsenic is largely not bioavailable then a concentration above the relevant NEPC HIL can be shown not to be an issue. However, this assessment is only valid if the mode of occurrence of arsenic is known, and if it is not likely to become more bioavailable through time. For example, arsenic contained in arsenopyrite would not be found to be very bioavailable using standard tests. However, oxidation of the arsenopyrite will produce secondary minerals in which the arsenic is much more readily available. The validity of the health risk assessment approach must be considered in this context.

Bioavailability, however, is one of many factors that needs to be considered when assessing the risks from metal uptake associated with rehabilitated mine waste. The exposure to the mine waste material (to animals and thence to humans) will be influenced by the percentage of ground cover, the potential for metal accumulation by vegetation, and the duration and intensity of grazing by cattle and native animals (Ng et al., 2003a).

In the Northern Territory in particular, the extent of uptake into bushfoods (both terrestrial and aquatic) may need to be considered in the context of post rehabilitation hunter/gatherer use by traditional owners. For example, arsenic can be accumulated by freshwater mussels in streams impacted by arsenic-containing runoff and seepage. The speciation of arsenic may need to be determined in the event that the total concentration of arsenic in the edible mussel tissue exceeds food consumption guidelines since, as indicated above, the form of arsenic will determine the risk for toxicity following ingestion.

3.6 Recommendations for mine sites where Arsenic exposure is a possible OH&S risk factor

- Given the carcinogenic and toxicological risks associated with chronic exposure to relatively low concentrations of arsenic, risk assessment incorporating occupational exposure studies would be warranted for those situations where workers could be chronically exposed to airborne arsenic For example, use of personal dust monitors or vapour monitors to quantify exposure to arsenic containing aerosols from drilling and roof leakage during mine development could be used.
- Reliance should not be placed on blood arsenic levels as providing a satisfactory indicator of the effects of chronic exposure to low levels of arsenic.
- Potable water supplies should be routinely monitored for their content of arsenic. It should be noted that arsenic concentrations can increase through time as a result of drawdown of the water table and resultant oxidation of arsenic-containing sulfide minerals in the country rock. Thus initial absence of significant arsenic in a water supply does not mean that will always be the case, especially for a mine located in a known problematic zone such as the Pine Creek Geosyncline.
- Care should be taken in the methods used for collection and preservation of samples for potable water analysis since oxidation and precipitation of Fe in the groundwater could lead to loss of arsenic from solution. For this reason and as stipulated by the Australian drinking water quality guidelines, total arsenic concentrations should be measured and reported in the first instance.
- Values of arsenic approaching 50 µg/L will not be protective of human health in the Northern Territory given the higher rates of water consumption and the likely co-mutagenic effects with UV light. Indeed, even levels of 7 µg/L may lead to an unacceptable probability of long term effects on the health of workers.
- The type of technology that will be most suitable for removing arsenic from a potable water supply will depend on the major ion composition of the water, the levels of other metals that might also need to be reduced, and the size of the required supply. A mixed bed deioniser followed by an RO unit should provide water that meets the drinking water quality standards under most circumstances. However, it is possible that for a groundwater supply that contains sufficient iron (eg Toms Gully or Mt Todd in Table 3.2) a simple holding (oxidation and sedimentation) tank with a decant could remove the arsenic to required levels. The effectiveness of this approach would need to be demonstrated on a case-by-case basis on a regular basis.

3.7 References and Further Reading

Buchet, J.P., Lauwerys, R. and Roels, H. 1981, 'Comparison of the urinary excretion of arsenic metabolites after a single oral dose of sodium arsenite, monomethylarsonate, or dimethylarsinate in man', *Arch. Occup. Environ. Health*, 48, 71-79.

Chen, C.J., Chuang, Y.C., Lin, T.M. and Wu, H.Y. 1985, 'Malignant neoplasms among residents of a blackfoot disease-endemic area in Taiwan: high-arsenic artesian well water and cancers', *Cancer Res.,* 45, 5895-5899.

Cullen, W.R. and Reimer, K.J. 1989, 'Arsenic speciation in the environment', *Chem Rev.*, 89, 713-764.

Ellenhorn, M.J. 1997, 'Arsenic', in *Ellenhorn's medical toxicology: diagnosis and treatment of human poisoning*, *2nd ed.,* Williams and Wilkins, Baltimore, pp 1538-1542.

Gebel, T. 2000, 'Confounding variables in the environmental toxicology of arsenic', *Toxicology*, 144, 155-162.

Jones, D.R. 1995, 'The leaching of major and trace elements from coal ash', in *Environmental aspects of trace elements in coal*, eds D.J. Swaine and F. Goodarzi, Kluwer Academic Publishers, pp. 221-255.

Morales, K.H., Ryan, L., Kuo, T.L., Wu, M.M. and Chen, C.J. 2000, 'Risk of internal cancers from arsenic in drinking water', *Environ. Health Perspec.,* 108: 399-411.

Ng, J.C., Noller, B.N., Bruce, S. and Moore, M.R. 2003, 'Bioavailability of metals and arsenic at contaminated sites from cattle dips, mined land and naturally occurring mineralisation origins', *Proceedings of the Fifth National Workshop on the Assessment of Site Contamination. NEPC Workshop, Adelaide 2002*. In press.

Noller, B.N. and Parker, G.K. 1998, 'Arsenic, resulting from mineralisation, in surface and groundwaters', *Australian chemistry resource book*, ed C. Fogliani, Royal Australian Chemical Institute, Queensland.

Rossman, T.G., Uddin, A.N., Burns, F.J. and Bosland, M.C. 2001, 'Arsenite is a cocarcinogen with solar ultraviolet radiation for mouse skin: an animal model for arsenic carcinogenesis', *Toxicol. Appl. Pharmacol.,* 176, 64-71.

Tran, H.P., Prakash, A.S., Barnard, R. and Ng, J.C. 2002, 'Arsenic inhibits the repair of DNA damage induced by benzo(a)pyrene', *Toxicol. Letters,* 133, 59-67.

WEB Resources:

Australian Guidelines:

ANZECC guidelines:
http://www.deh.gov.au/water/quality/nwqms/pubs/wqg-ch3.pdf

Drinking Water Quality Guidelines:
http://www.nhmrc.gov.au/publications/synopses/eh19syn.htm

NEPC Soil Quality Guidelines:

http://www.ephc.gov.au/pdf/cs/cs_01_inv_levels.pdf

World Health Organization:
http://www.who.int/water_sanitation_health/dwq/arsenic/en/

United Nations Synthesis Report on Arsenic in Drinking Water:
http://www.who.int/water_sanitation_health/dwq/arsenic3/en/

Contents of UN report

- Source and behaviour of arsenic in natural waters
- Environmental health and human exposure assessment
- Exposure and health effects
- Diagnosis and treatment of chronic arsenic poisoning
- Drinking water guidelines and standards
- Safe water technology
- Communication for development
- Strategies to mitigate arsenic contamination of water supply

4. COVER SYSTEMS

The monsoonal tropics of the Northern Territory, by virtue of their annual seasonal oscillation between flood and drought conditions, represent one of the most difficult of all regimes to produce a cover system that will function effectively for the long term.

4.1 Key considerations

The installation of cover systems or "capping" is one of the most common rehabilitation methods used for controlling infiltration into waste rock dumps (WRDs), tailings storage facilities and heap leach pads. However, despite this strategy being used for many years by the mining industry throughout the world, there has been a mixed record of success and failure.

There was a time when simply placing a "cap" of soil or rock over the surface of a WRD or tailings dam was considered adequate for rehabilitation. If vegetation was then successfully established, the exercise was judged to be a success. However, there are numerous examples the world over (including the Northern Territory) of capped and vegetated mine landforms producing seepage with high metal concentrations which continue to have an unacceptably high impact on the environment.

It is only relatively recently (less than 10 years) that rigorous design of covers began by applying the fundamental principles of geotechnical engineering and unsaturated flow. This has produced a new generation of engineered covers that look beyond the initial decade of liability.

Generally cover systems need to achieve some or all of the following objectives, depending on site specific circumstances:

- limiting infiltration of water to a predetermined rate;
- limiting oxygen diffusion to a predetermined rate;
- long term resistance to erosion;
- containment of the covered material within the structure;
- support for self sustaining vegetation communities; and
- prevention of capillary rise bringing oxidation products to the surface.

How these objectives are achieved will vary with site specific circumstances but must accommodate the following factors:

- climatic conditions;
- hydrogeological conditions;
- community acceptance of impact levels to the receiving environment;
- type and design of the cover system selected;
- physical and geochemical properties of the material to be covered;
- physical and geochemical properties of available cover materials; and
- colonisation by fauna and flora.

Cover system designs are both site and material specific – they cannot be transferred from one application to another without site specific investigations.

Before embarking on the design of a cover system for a waste facility, the questions in the box below must be answered.

Key questions when specifying a cover system:

1. ***Why are we going to cover the waste facility?***
2. ***What specific issues are we managing?***
3. ***What do we want the cover to do?***
4. ***How will the cover achieve what we want it to do?***
5. ***What variables will affect the cover's performance?***
6. ***How will we measure whether the cover is performing as required?***
7. ***Will the cover's performance increase or decrease over time?***
8. ***How long will the cover remain effective?***
9. ***What remedial actions will be necessary if the cover fails to perform?***

Until these questions have been asked, and rigorously answered, there is little point in proceeding with a cover system since it is unlikely to meet the desired objectives.

It is recommended that to answer these questions, an operator should seek the assistance of a range of experienced practitioners if such expertise is not available in-house. Preferably, a multidisciplinary team from several companies and/or consultancies should be assembled to gain a consensus based on site specific characteristics. This approach should overcome the danger of individual bias and getting a "one size fits all solution", and will result in the best overall solution. The team should include hydrogeologists, geochemists, geotechnical engineers, biologists and engineers or others with practical site experience in earthworks management and quality assurance.

What has often been attributed as the "failure" of a cover has in fact been the failure during the design process to take into account all the other factors that affect a structure and the complexity of the environment in which it is located. What has often been found is that the cover system did in fact perform as well as could have been expected based on the design that was selected, but that other critical factors were not taken into account during the specification process.

One of the most common causes of failure in rehabilitation designs for waste storage facilities has been a tendency to treat them as structures isolated from their physical position within the landscape (Figure 4.1). Only when they are intimately linked to the surrounding physical environment can effective and sustainable rehabilitation strategies be developed.

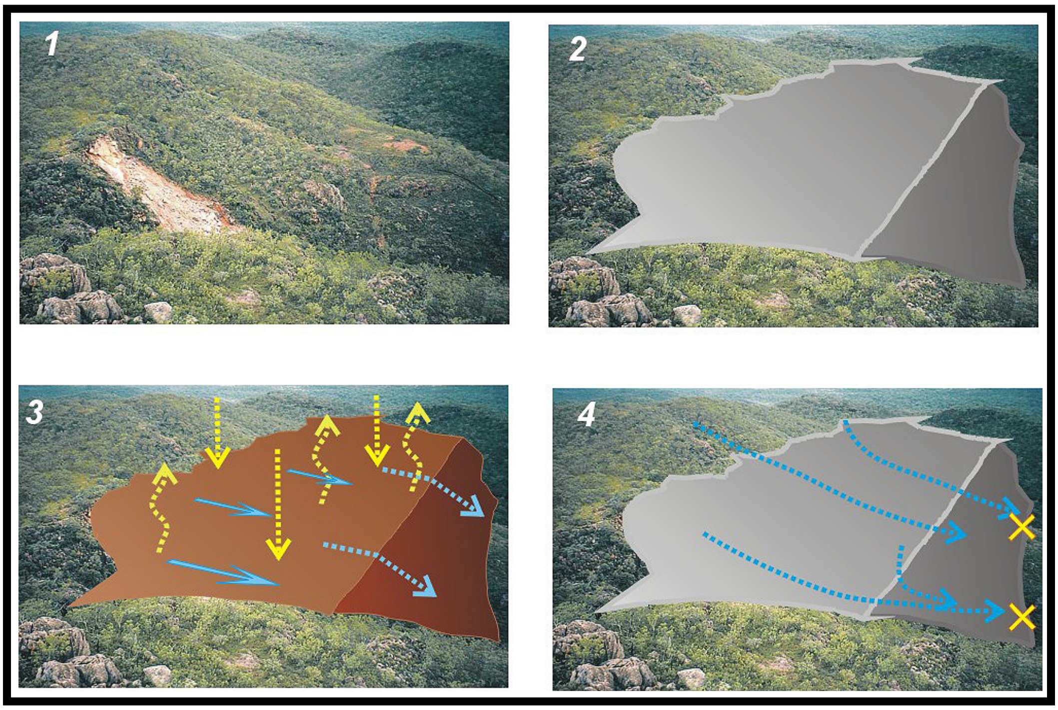

Figure 4.1: Factors influencing seepage from a WRD constructed in a valley: (1) location; (2) waste facility constructed in a valley; (3) factors accounted for in cover design - rainfall, evapo-transpiration, runoff and seepage; and (4) factors historically often not accounted for in cover design – pre-existing water courses, springs, mounding of the water table, and water table 'moving' from the existing topography into the waste facility (courtesy of M. Fawcett).

No matter how good the technical design, poor quality control during construction can introduce a fatal flaw. It is becoming increasingly apparent from investigation of cover system failures that inadequate quality control was a primary contributing factor.

4.2 Cover design

4.2.1 Overview

Covers are often classified into two basic types: "wet" and "dry". Wet-covers, as the name implies, are where the waste material is covered by a permanent layer of water (eg a permanently flooded tailings impoundment). As climatic conditions in the Northern Territory mean that construction and maintenance of a wet-cover in above-grade locations is in most cases impractical (the exception being pit lakes) this section deals only with dry-covers.

Dry-covers can range from a simple single layer of earth/soil/rock to complex multi-layered systems constructed from a variety of materials. Examples of the range and complexities of covers are shown in Figure 4.2.

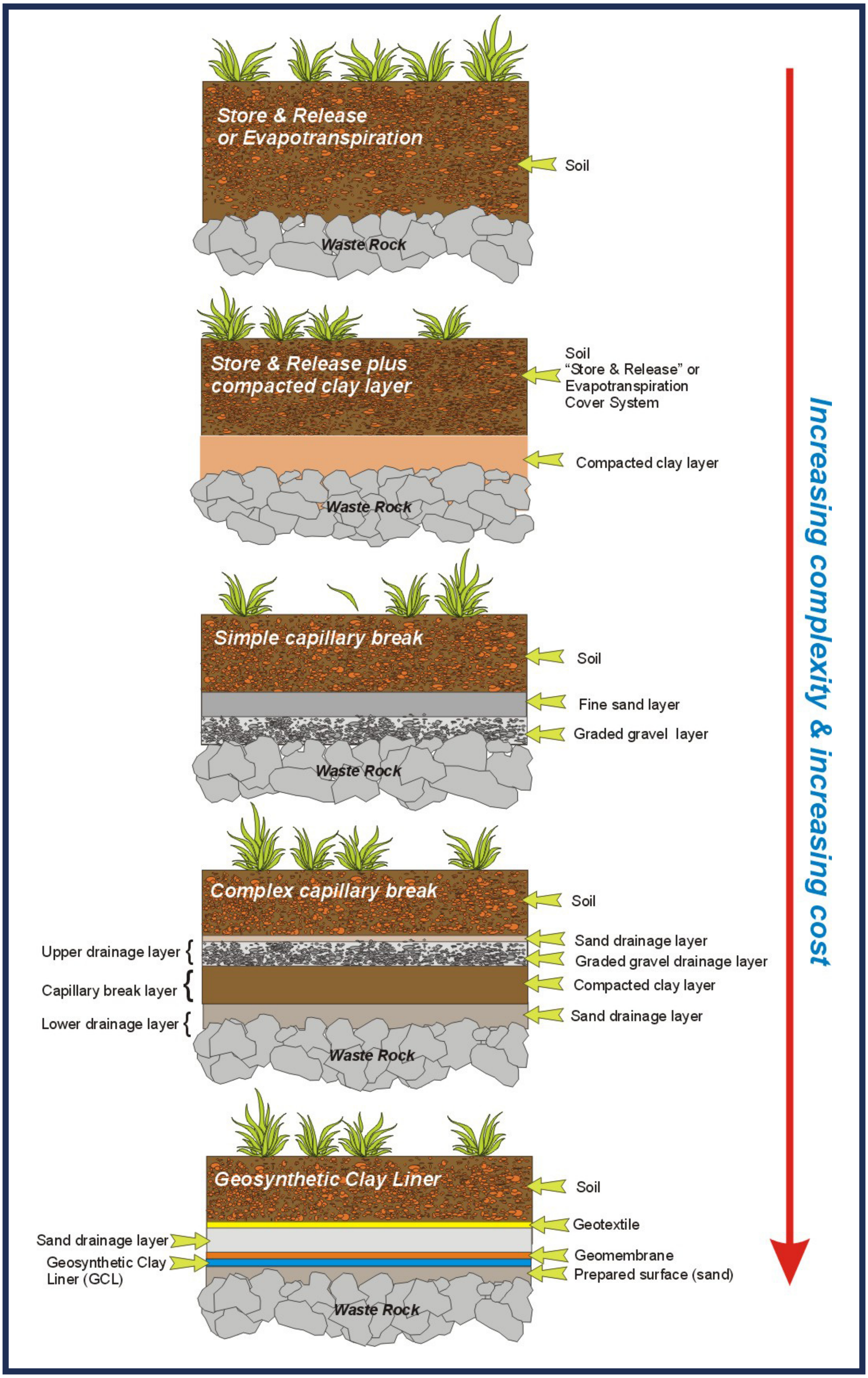

Figure 4.2: Range of cover types from simple to complex and from less costly to much more expensive (courtesy of M. Fawcett).

The three primary objectives of a cover system are to function as:

- a water infiltration barrier for the underlying waste material by incorporating a moisture storage and release layer and/or a low permeability layer;
- an oxygen ingress barrier to the underlying waste material by maintaining a high degree of water saturation within a layer or zone of the cover system, thereby minimizing the effective oxygen diffusion coefficient and ultimately controlling the flow of oxygen to the reactive waste material; and
- a growth medium for vegetation.

The term "dry" cover can convey an incorrect impression for the function as an oxygen ingress barrier, since the oxygen excluding capability is in fact provided by a water-saturated layer of fine-grained material. The water fills the voids of the material and in an operational sense, is functionally equivalent to a water cover. It's just that the water is held in the fine-grained layer by capillary action, rather than being present as a continuous layer of water. However this very property presents a risk for failure if it is broken in some manner.

Another important purpose of dry cover systems is to provide a medium for establishing a vegetation cover that meets final land-use objectives. A sustainable vegetation community will enhance the long term stability of the structure by harmonising the impacts of wind and surface water erosion on the cover system with the natural environmental processes. Vegetation can also play an important role in enhancing the performance of dry cover systems by increasing evapotranspiration.

When designing cover systems, an important goal is to keep them as simple as possible for the following reasons:

- **Cost** - an effective cover that can be constructed from run-of-mine waste placed progressively during mining will cost up to an order of magnitude less than a complex multi-layer cover using manufactured materials (screened gravels, geosynthetics and geofabrics).
- **Life of design** - highly engineered covers containing barrier layers designed to resist the natural processes of the surrounding environment will inevitably fail over relatively short periods of time when compared to designs that accommodate natural, long term processes such as weathering and evolution of soil profiles.

The design of a cover system must take into account that up to 60% of the structure will be sloping surfaces (batters). If this is not taken into account, both structural and performance failure will result. It is recommended that two-dimensional software be used to assess the geotechnical properties of slopes and to specifiy design requirements for long term stability.

A major issue of critical importance is the need for quality assurance/quality control during construction. The simpler the design, the easier it is to assure quality.

A significant proportion of the construction budget should be allocated to quality control. In this context it should be noted that most earthwork construction jobs are done on a fine margin. Hence the level of quality control required must be included in the tender specifications to ensure it is included in the estimates.

It is strongly recommended that an independent (of the contractor) geotechnical engineer be engaged to review the proposed quality control program, to conduct audits on the test method and its frequency of application, and to review results. This is often best done by the design engineer (with adequate field experience).

4.2.2 Tailings and Waste Rock – Key Differences

Although identical design concepts apply for covers over both waste rock and tailings, there are fundamental differences in the geotechnical properties of these materials. It is essential the detailed engineering design of the cover addresses this difference.

Waste rock is generally physically competent and provides a trafficable working surface. In contrast, tailings are generally supersaturated and very soft, requiring additional consolidation or strengthening at the surface before a cover can be placed. The method of deposition of tailings, as well as its depth, will have a critical bearing on the design of the cover.

The peripheral discharge, subaerial method of tailings placement results in the coarser fraction being preferentially deposited closer to the margins, with the slimes fraction concentrated in the middle. The consequence of this is that not only will the centre be more difficult to work on, but it will also undergo substantially greater consolidation over the long term. If the tailings deposit is very thick (eg in-pit tailings) then many metres of consolidation will be likely, and must be accommodated by the cover design. This differential consolidation means that the capping material will need to be much thicker over the central region. That means that the initial profile must be more convex during construction, such that the final shape of the landform will still be water shedding. This factor increases the initial risk of erosion damage.

The use of central deposition of thickened or paste tailings will reduce the problems of differential settling. This also reduces physical segregation.

Whilst consolidation is less of an issue for waste rock, differential settlement is nevertheless an important factor that must be addressed as part of the design process. The higher the dump, the greater the potential for consolidation. Differential settlement of only a few decimetres could lead to failure of an engineered cover. This is particularly so for a cover that depends on the integrity of a compacted clay layer or a geosynthetic clay liner (GCL) to limit infiltration or the ingress of oxygen.

It has been found overseas that the development of stress fractures can be a major cause of “failure” for a cover system. It should be noted that lysimeters would not necessarily detect this problem due to their very limited footprint for detection. This is another reason to monitor the overall water balance of a dump over enough time to assess its overall performance.

The more simple a cover design, the less susceptible it is to damage by differential settlement.

4.2.3 Covers for Northern Territory Conditions

There are two basic climatic regimes in the Northern Territory; the Top End has distinct wet and dry seasons, while central and southern regions of the Territory are characterised as arid. These two climatic conditions require different approaches to cover system design.

Arid and Semi-arid Zones

Arid and semi-arid zones in the Northern Territory are subject to some monsoonal storm events. However, these low rainfall zones (under 500mm) are normally characterised by net evaporation exceeding rainfall throughout the year. In these zones, cover systems are subject to extended dry periods and the effect of evapotranspiration is particularly significant. It is difficult and usually not economically feasible in these climates to construct a cover system that maintains a saturated layer (greater than 85%) that significantly reduces oxygen diffusion across it.

However, the evaporative demands can be beneficial in arid and semi-arid climates, resulting in a reduction of infiltration of water to the underlying sulfidic waste material. A homogeneous surface cover layer with a well graded texture and sufficient storage capacity can retain water during the rare rainfall events. Subsequently, it releases a significant portion of pore water to the atmosphere by evapotranspiration during the extended dry periods. The net infiltration across the cover system is therefore minimal. However, there are significant erosion problems that must be designed for and managed to protect this surface 'storage' layer. Well graded material has an even wide spectrum of sizes.

The objective of this cover is to minimise seepage by preventing net infiltration into the underlying waste material. It is often referred to as a "store and release" cover system (Figure 4.2 top and Figure 4.3). The material used to construct the store and release system also functions as the growth medium.

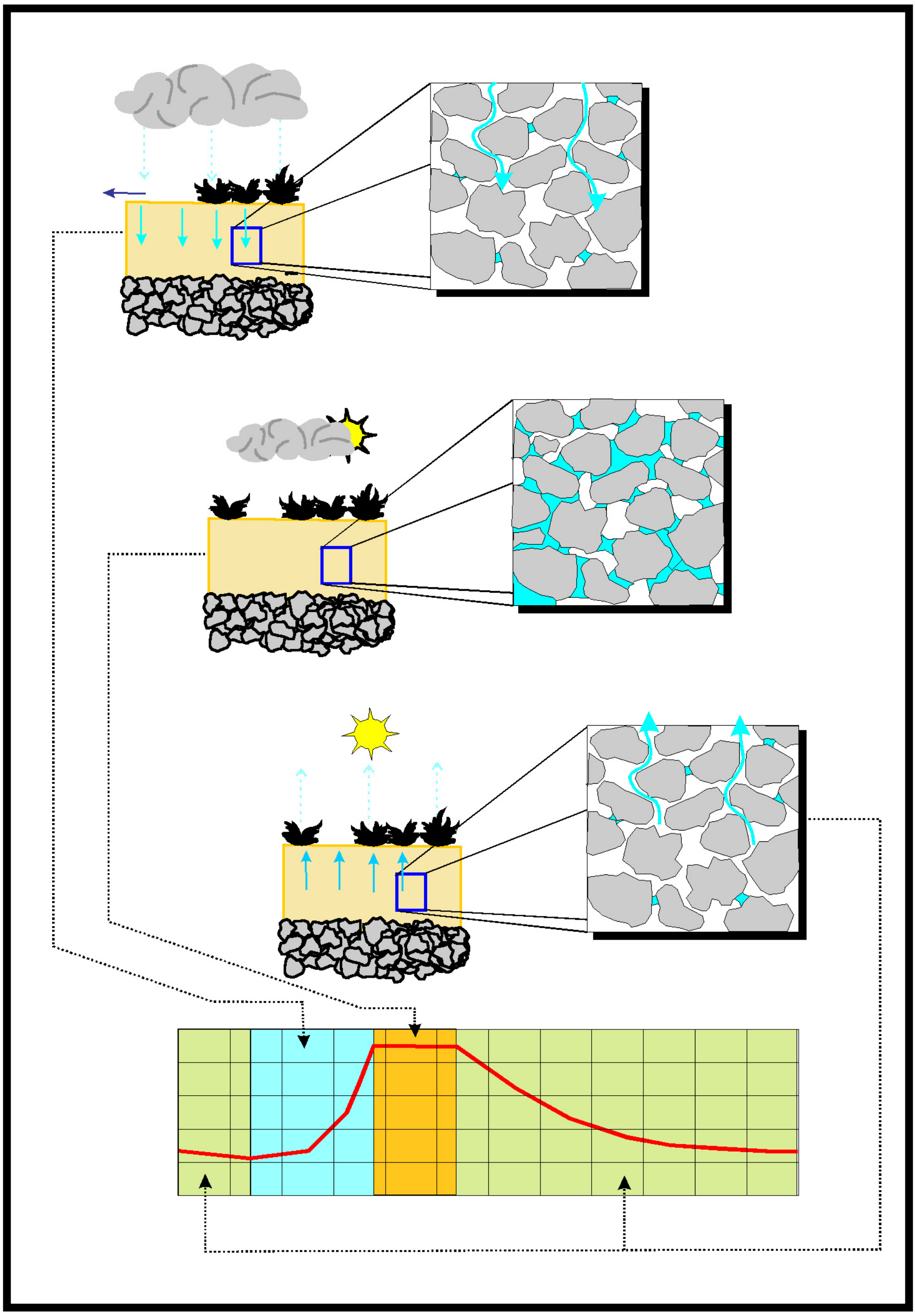

Figure 4.3: Operation of a "Store and Release" cover through an annual climate cycle (courtesy of M. Fawcett).

Wet and Dry Zone

In the Top End with its distinct wet and dry seasons, each year has conditions similar to the arid zone with large net evaporation followed by rainfall greatly exceeding evaporation. Under these conditions, a simple store and release system cannot cope with the excess moisture during the wet season. It is therefore necessary to incorporate a barrier (low-permeability layer) to infiltration as well as the store and release layer. Again, erosion of the top layer is a major issue (Figure 4.2).

> ***"The Top End is one of the most difficult climates for designing covers due to the seasonal variations between net evaporation (dry season) and high rainfall when precipitation exceeds evaporation (wet season)."***
>
> ***- Mike O'Kane, TEAM NT workshops, 2003***

The purpose of the barrier layer is to restrict the rate of water movement through to the underlaying waste. However this layer still requires the overlying store and release growth medium which also helps to control net percolation to the underlying waste.

The main benefit of the compacted or low permeability layer is to hold the majority of the moisture in the store and release layer to evapotranspirate in the next cycle. It may also assist with lateral flow along the barrier layer as "run off". For long term and sustainable performance, a sufficient thickness of growth medium is required to confine the store and release process within that layer. If the drying cycle is allowed to extend into the compacted clay layer, there is a risk it will permanently damage that layer, leading to high permeability into the underlying waste during the wet cycle.

The retained moisture in the low permeability layer creates a "blanket" or saturated cover over the reactive waste material. This saturated layer limits oxygen diffusion into the underlying waste material. But it is emphasised that an appropriate thickness of overlying growth medium is key to limiting oxygen diffusion in a sustainable manner.

Figure 4.4 illustrates the impact that thickness of the growth medium has on the saturation level of the compacted clay layer. Maintaining 85% saturation is required if the layer is to function effectively as an oxygen diffusion barrier (Figure 4.5).

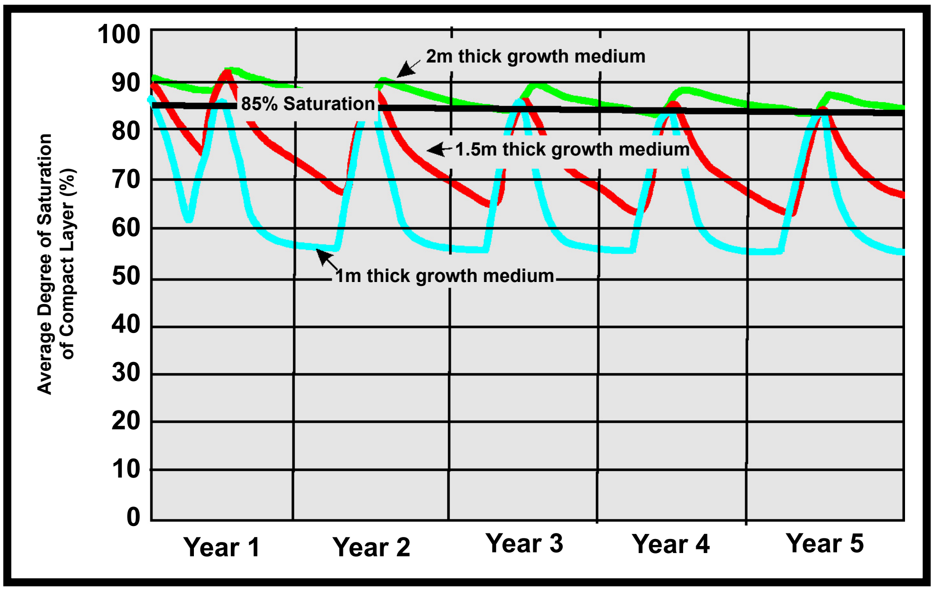

Figure 4.4: Effect of growth medium thickness on % saturation of compacted clay layer (M. O'Kane, TEAM NT workshops, 2003).

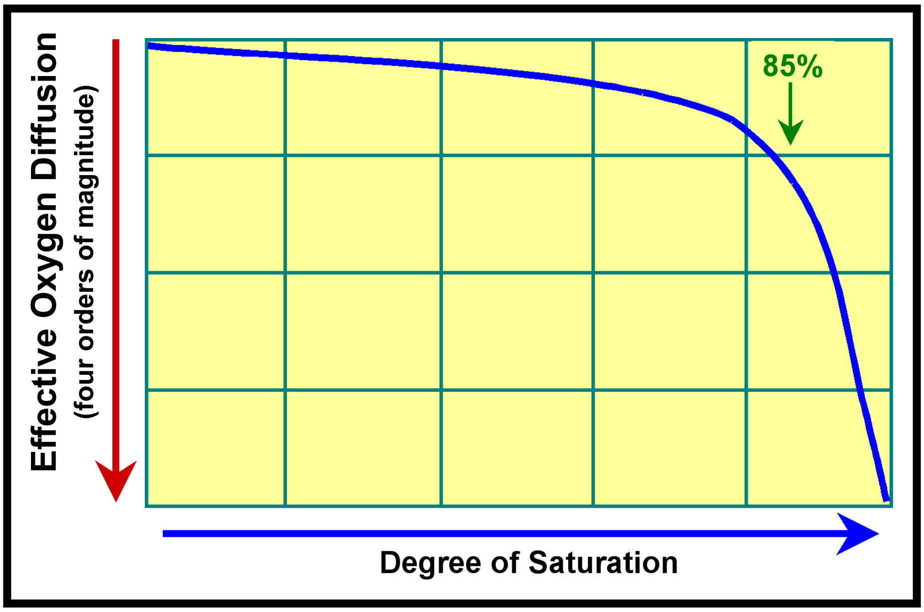

Figure 4.5: Relationship between oxygen diffusion coefficient and moisture saturation, showing 4 orders of magnitude decrease above 85% moisture saturation in soil (M. O'Kane, TEAM NT workshops, 2003).

The computer simulation in Figure 4.4 shows that for this particular site/material, the cover thickness must be two metres or more to maintain saturation above 85% throughout the year. If the compacted clay layer were subjected to drying cycles below 85%, it would likely result in permanent changes to its physical properties, resulting in increased infiltration and decreased ability to maintain water saturation. Hence seepage and oxidation would increase, resulting in leachate drainage from the base of the dump throughout the year.

Factors affecting cover life

When designing a cover system, specific attention must be paid to those factors that can compromise the long term effectiveness of the cover (Wilson et al., 2003). Moisture saturation, layer thickness and differential settlement have been addressed above. However in the Top End, specific additional factors need to be considered. These include erosion and biological activity.

The intense storm events characteristically have high erosive capacity. Thus the surface of any cover must be protected to prevent gully erosion and loss of the growth medium layer over time. Protection from erosion can be afforded by adding a rock mulch layer, designing low-slope angles, minimising sub-catchment size and planting with appropriate vegetation. Drop down structures and drains often fail because they are not designed to cope with a maximum event. Using annual averages for design criteria is not acceptable practice in either the monsoonal tropics or arid areas.

Biological activity includes burrowing animals and the potential for root penetration. Termites are the most broadly active and potentially damaging creatures in the Northern Territory. If the soil cover layer is not thick enough, they will breach the integrity of the underlying compacted clay layer. A thickness of two metres should be adequate to accommodate termite activity.

Tree root penetration is still a topic of current research. A cover system is not a typical soil profile and the behaviour of tree roots, compared with that in natural terrain, remains to be fully defined. However, the deeper the growth medium, the less of an issue this will be. In general, tree roots track moisture, and only grow more deeply to locate water. When the growth medium is too thin (too little moisture stored through the dry season) then the roots will likely penetrate the compacted clay layer and potentially compromise its integrity. This is another reason for sensitivity analysis during the design phase, incorporating an allowance for evapotranspiration to ensure that the growth substrate is sufficiently thick to accommodate the target vegetation.

Given that experience worldwide indicates that there is inevitably some loss in cover performance in the 5 to 10 year period after construction, it may be prudent to place more conservative specifications on the initial design. For example, if the design specification for hydraulic conductivity produced from modelling calculations is 10^{-8} m/s then perhaps the construction specification should be set at 10^{-9} m/s, to allow for imperfections in construction and changes in material properties.

Northern Territory Case Study 1

Rum Jungle cover

The Rum Jungle waste rock cover represented good practice at the time of installation (mid-1980's) and for the first ten years did meet its original design objectives. In this case the growth medium was only 15-25cm thick and the clay layer was 15-22cm thick (Taylor et al., 2003).

Since the growth medium was so thin, the compacted clay layer was subject to wetting and drying cycles that compromised its physical properties. This has allowed infiltration of water and oxygen diffusion to increase progressively. An additional contributing factor in this case was that the thickness of the clay layer varied considerably as a result of inadequate quality control during construction.

It should also be noted that trees were deliberately excluded from the surface of this cover. Thus tree root penetration was not a contributing factor. However, investigation of the cover profile showed that the clay layer had been extensively penetrated by termites, which are, as noted earlier, a major risk factor for covers in the Northern Territory.

Application of modern soil science theory, computer modelling packages, and knowledge about biological factors to the design of a cover for a Rum Jungle type environment, yields the design illustrated in Figure 4.6. It was found that the growth medium needed to be a minimum of 2m thick to protect the clay layer from periodic desiccation, and to minimise the impact of biological factors.

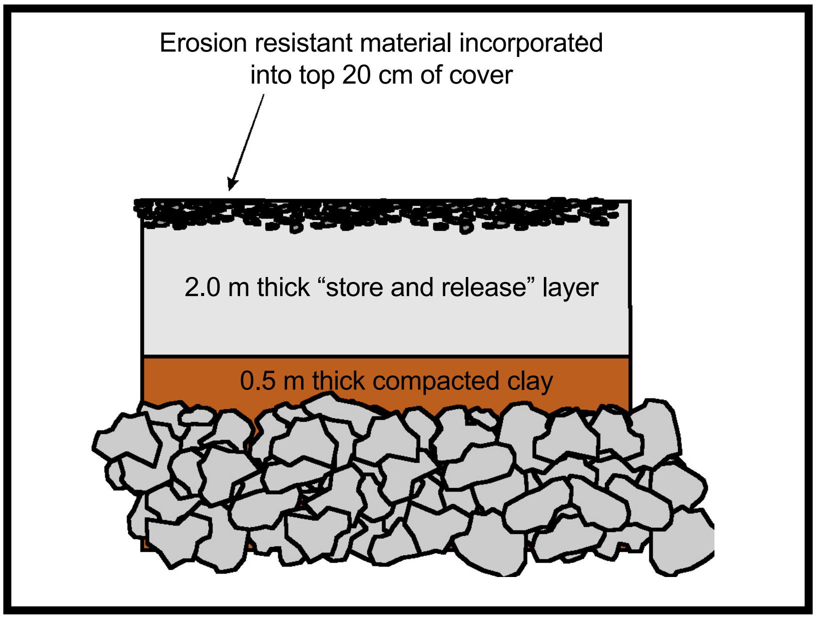

Figure 4.6: A typical design of a combined store and release and compacted clay layer cover for the Top End (courtesy of M. Fawcett). Each cover needs to be individually designed.

Northern Territory Case Study 2

"A stitch too late"

A WRD containing highly reactive net acid producing sulfidic material was capped with a soil cover at the end of mine life. Good vegetative growth was established on the surface. A wetland equipped with entry drains lined with course limestone was constructed in the flowpath downgradient of the dump to polish the seepage (circumneutral and containing low, but significant concentrations of metals) being produced at that time.

Unfortunately, three years later there was a heavy wet season and breakthrough of highly acidic and metal rich seepage occurred at the toe of the waste dump. The design capacity of the wetland was completely overwhelmed and collapsed (died). The WRD remains a source of high grade ARD to this day, and the seepage is pumped back to the adjacent open pit to prevent impact on the local streams. The consequence of this is the accumulation of a large volume of acidic water in the pit. The cost of treating this water has effectively sterilised the remaining resources in the area of the pit.

This case study illustrates the critical need to design the rehabilitation strategy to accommodate site specific requirements. In this case, oxidation of the waste had occurred prior to placement of the cover. Hence minimising infiltration (the transport vector for oxidation products) was critical. It is now apparent that the cover design did not limit infiltration to the extent necessary for this type of climate.

4.3 Sources of Cover Materials

4.3.1 Overview

As indicated above, the basic materials for the construction of a cover include clay with appropriate permeability and moisture retention characteristics, and a large volume of well-graded material to form the "store and release" growth medium. The effort and cost required to obtain material with the correct specification should not be underestimated. It is recommended that a quantity survey be done of available materials as early as possible in the cover design and specification process since some designs may not be possible. A favoured design may require modification if it is too costly to source the material required.

If there is a source of appropriate clay on the mining lease then it will need to be extracted. The "borrow" area will also need to be rehabilitated and the cost should be added to the overall cost of the cover.

Run-of-mine waste rock (providing it's benign) can frequently make ideal cover material (especially for the growth medium "store and release" layer) due to it's well graded nature. This material should be identified early in the planning and operational stages of mining and stockpiled separately so that it is readily available (minimum haul distance) for closure.

Even if the waste does not initially have the optimum particle size distribution, altering the design or energy factors of the blasts may produce a much better suited cover material. Indeed, it may even be cheaper in the long run to slightly increase the cost of blasting, if it can produce a product that can be directly used for cover construction. The success of these options is predicated on adequate geochemical characterisation to define the volume of waste that is potentially suitable for a cover. It also assumes that material specifications for the cover have been developed as part of the life-of-mine plan.

Using mine waste streams (tailings/waste rock) can be the most economical method of constructing a cover system provided it has the required characteristics.

Tailings can also be an ideal source of fine-grained material for the cover of WRDs or tailings dams. The sulfide fraction can be separated by gravity concentration or flotation to produce a desulfurised tailings stream. This may be done as part of the routine metallurgical process, or as a reprocessing activity at the end of mine life. Although such processing will increase the cost, it may well be much cheaper than other options. Examples of the proposed use of desulfurised tailings in covers for sulfidic material are found at Renison Bell mine in Tasmania (Romano et al., 2002) and at the Inco Copper Cliff operations in Sudbury, Canada (Hanton-Fong et al., 1997).

Such a scheme is likely to be most cost effective if carried out as part of a progressive rehabilitation strategy. For example, the progressive capping of tailings cells as each is filled to capacity. It should also be noted that if a source of suitable, well sorted material is not available onsite and expensive haulage is required, then it may be cheaper to use onsite grinding facilities to produce the specified materials from benign waste

Case Study

Use of run-of-mine waste for cover construction

The case study below (Figure 4.7) is an example where the rehabilitation strategy was planned before construction began. This allowed scheduling for selection of materials for placement and ensured availability of the required run-of-mine materials.

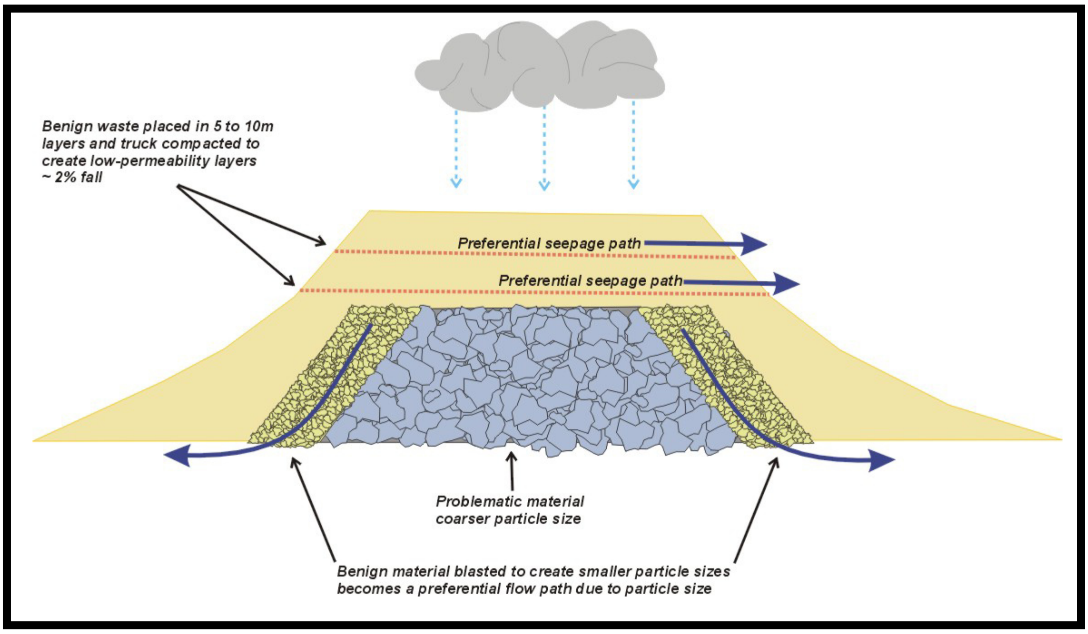

Figure 4.7: Schematic showing selective placement of run-of-mine waste to produce an effective cover for reactive material (courtesy of M. Fawcett).

(Continued)

The moisture infiltration properties of the WRD were controlled to more effectively isolate problem waste by implementing the following strategy:

- Problem waste was identified and placed within the central section of the dump.
- The problem waste was surrounded by a layer of benign waste rock that was blasted using a higher powder factor to create a smaller average particle size. (The smaller particle size creates and maintains a preferential flow path for unsaturated conditions.)
- The remainder of the WRD was constructed from benign run-of-mine waste rock, in 5 to 10 metre lifts. The purpose of the lifts was to create layers compacted by haul-truck traffic. (Typically tip-heads on WRDs have an approximate 2% fall to them. This fall, combined with the lower permeability running surface, creates layers that encourage lateral instead of vertical seepage. However the design must consider the direction of the lateral seepage when the WRD is completed (ie it is no good having the lateral seepage ponding to the centre).

The cost to the operator of implementing these techniques increased the operating costs. However, this was during the positive cash flow phase of the project. If covering the reactive waste had been left to the end of the mine's life, the cost of covering problem materials would have been much higher. It was also likely to have been far less effective and to have required significant ongoing maintenance or treatment at a time when cash flow had stopped.

The deferral of covering problem materials allows oxidation to progress substantially. The waste would have been a source of contaminated runoff and seepage during operation. Covering material that had already begun to oxidise would also have compromised the effectiveness of any cover, since the material would be an active source of leachable solutes.

4.4 Monitoring

Without an effective monitoring system in place, it will not be possible to determine if the performance specifications of the cover design have been achieved. This is especially important for reactive materials where problems may not manifest themselves for several years when a contaminated seepage front emerges from the toe of the covered landform, or high metal concentrations are detected in groundwater observation bores. Elements of a covering monitoring program are illustrated in Figure 4.8.

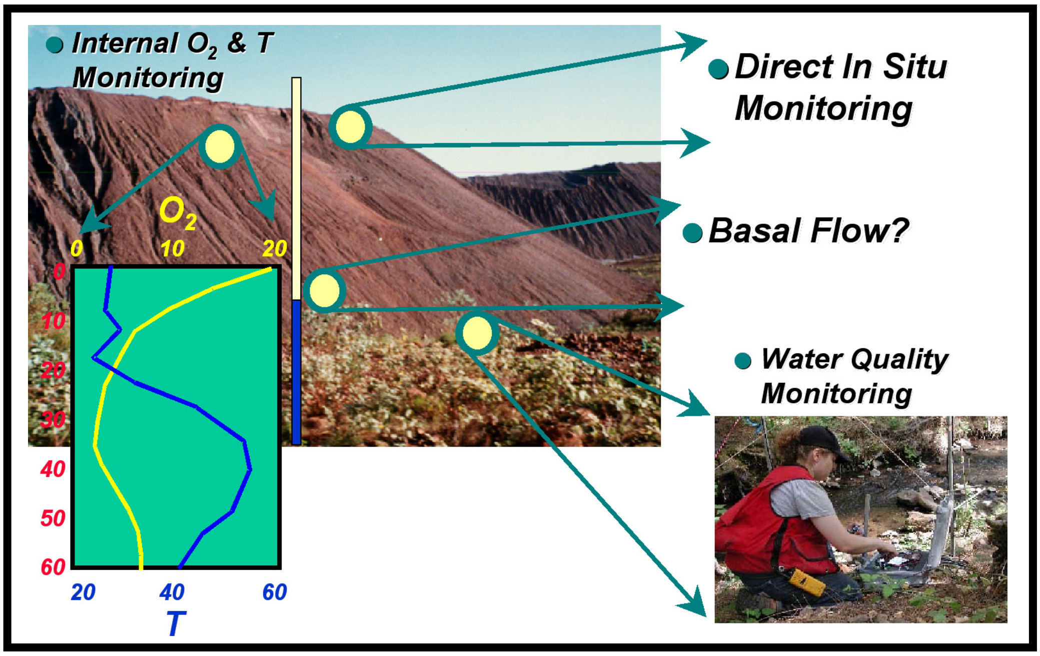

Figure 4.8: Components of a cover performance monitoring program (courtesy of O'Kane Consultants Pty Ltd).

Monitoring should comprise, at a minimum, sufficient measurements to establish an overall water balance for the covered landform. This will enable the ratio of infiltration to incident rainfall to be determined and enable the reduction in infiltration to be assessed. The water balance method is the most direct, and also the least prone to artifacts.

The quality or loadings of water reporting to the collector drains used to measure the water balance can also provide considerable insight into the perfomance of the cover system.

Lysimeters are potentially useful for measuring net infiltration, in addition to their role of collecting samples of interstitial water for chemical analysis. However, they should always be used in conjunction with a water balance since lysimeters can only measure small and limited areas. For example, macro scale cracking of a cover as a result of differential settlement may not be detected by a lysimeter unless it is immediately underlying the crack. If lysimeters are to be used to monitor infiltration then sufficient must be installed to provide a degree of confidence in the results. At least four are required for each horizontal and inclined surface.

It must also be noted that it is imperative to correctly install lysimeters to take into account their potential for disrupting flow pathways. In such cases, they may produce completely erroneous data. Constructing and installing a lysimeter is not a simple case of burying a stone filled container within the waste.

The performance of an oxygen limiting clay layer can be inferred from the output of moisture sensors installed through the cover. Likewise, the seasonal behaviour of the “store and release” growth medium layer can be monitored.

Direct measurements of oxygen concentration and temperature can be made by installing sample tubes and a thermistor array, respectively, in a bore hole through the cover. The oxygen concentration gradient provides a measure of the effectiveness of the cover in reducing sulfide oxidation, as does the temperature differential.

Finally, it is essential to have a realistic set of action plans prepared to implement if monitoring results reach predetermined trigger points. If the possible failures, resulting trends and remedial actions are included in the design stage, early and practical intervention may save an unstable situation sliding into an expensive failure. Maintenance and remedial materials can be stockpiled ready for such an event and other ‘savings’ prepared. Interception drains for collecting and monitoring seepage could be designed for conversion to a Permeable Reactive Barrier (see Chapter 6) in the event performance deteriorates over time. This would save time and cost if it became a necessary remedial action at a later stage.

4.5 Summary of Key Issues

WRDs and tailings storages must be considered as intimate parts of the overall landscape when planning for capping and rehabilitation. Often covers appear to have “failed” when in fact there was a failure to account for other mechanisms interacting with the waste facility. For example, there may have been inflow of groundwater from valley walls within a tailings or WRD, or poor quality control during construction, especially when a compacted clay layer is involved. The latter has been identified world wide as a major contributing factor to performance problems with engineered covers.

The progress of waste oxidation prior to capping is a key factor in determining the specifications for controlling infiltration. Many waste dumps are open for years before capping is carried out. During this time, oxidation can result in the accumulation of soluble oxidation products. These oxidation products are then readily leached out by infiltrating waters.

The extent of oxidation will determine the limits for oxygen or water ingress (or both) to prevent unacceptable loads of solutes exiting the waste storage via seepage pathways. The level of infiltration control (and hence cost of the cover) for a non-oxidised dump will be much less than that for an oxidised dump.

The results from monitoring the performance of cover systems worldwide have shown that a clay layer in multi-layer cover systems is the most susceptible to failure. In a tropical monsoonal climate, a protective growth medium layer at least 2m thick must be placed over the clay layer to prevent it from failing.

It should not be assumed that limiting infiltration will greatly reduce the load of solutes in seepage from a dump. This especially applies to the case of an oxidised dump where there is already a substantial reservoir of soluble salts. In this case the rate of infiltration would need to limit the extent that soluble secondary minerals could be dissolved and transported out of the WRD. The controlling factor would be the export loading of dissolved metals.

Covering a sulfidic waste soon after it is extracted, and before significant oxidation has occurred, provides the best chance for long term rehabilitation success. Otherwise a solute legacy will already have been created, and it will be more difficult and costly to reduce the contaminant loadings to the required level.

Where a dump may already be producing contaminated seepage prior to being covered, it may be necessary to combine the cover with interception and treatment technologies. The use of "pump and treat" technology or Permeable Reactive Barriers to intercept and treat groundwater plumes is described in Chapter 6.

4.6 References and Further Reading

Hanton-Fong, C.J., Blowes, D.W. and Stuparyk, R.A. 1997, 'Evaluation of low sulfur tailings in the prevention of acid mine drainage', in *Proceedings: 4th International Conference Acid Rock Drainage (ICARD), Vancouver, British Columbia, 31 May-16 June 1997*, pp. 835-851.

O'Kane, M., Ayres, B., Christensen, D. and Meiers, G. 2002, *CANMET-CETEM manual on cover system design for reactive mine waste*, O'Kane Consultants Report No. 689-01, June 2002. Click here for further information

Romano, C.G., Mayer, K.U., Jones, D.R., Ellerbroek, D.A. and Blowes, D.W. 2002, 'Effectiveness of various cover scenarios on the rate of sulfide oxidation of mine tailings', *J. Hydrology*, 271,171-187.

Taylor, G., Spain, A., Timms, G., Kuznetsov, V. and Bennett, J. 2003, 'The medium-term performance of waste rock covers - Rum Jungle as a case study', in *Proceedings: 6th International Conference Acid Rock Drainage (ICARD), Cairns, Queensland, 14-17 July 2003*, eds T. Farrell and G. Taylor, AUSIMM Publication Series No 3/2003, pp. 383-397.

Williams, D., Currey, N.A., Ritchie, P. and Wilson, G.W. 2003, 'Kidston waste rock dump design and "store and release" cover performance seven years on', in *Proceedings: 6th International Conference Acid Rock Drainage (ICARD), Cairns, Queensland, 14-17 July 2003*, eds T. Farrell and G. Taylor, AUSIMM Publication Series No 3/2003, pp. 419-426.

Wilson, G.W., Williams, D.J. and Rykaart, 2003, 'The integrity of cover system – an update', in *Proceedings: 6th International Conference Acid Rock Drainage (ICARD), Cairns, Queensland, 14-17 July 2003*, eds T. Farrell and G. Taylor, AUSIMM Publication Series No 3/2003, pp. 445-451.

Further detailed references on cover design and performance are available from the conference proceedings of the 5th and 6th International Acid Rock Drainage Conferences and the Mining and Environment Conferences held in Sudbury, Ontario, in 1999 and 2003. Information about recent research on cover systems in Australia is available from the Australian Centre for Mining Environmental Research (ACMER): www.acmer.com.au.

5. SURFACE WATER TREATMENT

5.1 Introduction

Water treatment may be necessary when the load of salts and metals in water to be discharged is too high. For example the loadings leaving a mine site may exceed the capacity of a receiving waterway to dilute and attenuate the concentrations to levels predicted to be protective of the aquatic ecosystem or other defined beneficial uses of the waterway.

Water treatment can also be required for mine or process waters to enable water reuse or to protect equipment onsite, or when water in open pits or underground working must be removed to gain access to an ore resource. The latter aspect is an especially important one for the monsoonal tropics.

During the field visits for the TEAM NT project, several mines were visited where the surface catchment for tailings dams (and waste rock dumps) was greatly in excess of what was desirable from a water management perspective. This situation can result in the production of a substantial amount of acidic and metal rich runoff during the wet season. At one site this water was polished through a constructed wetland prior to discharge to the receiving waterway.

Whilst metals and acidity are the most common target for water treatment, the removal of major ion salts, such as magnesium and sulfate, may also be required in those instances where increased salinity could adversely impact the receiving waters. Salinity may be a special issue for the wet-dry tropics where high rates of evaporation during the dry season can concentrate the water to such an extent that soluble salts crystallise from solution (Figure 5.1).

Figure 5.1: Magnesium sulfate evaporite salts in a seepage collection channel downstream of a reactive sulfidic waste rock dump in the Northern Territory.

The extensive use of amfo-based explosives means that waste rock typically contains significant concentrations of leachable residual ammonia and nitrate. Ammonia and nitrate are also cyanide degradation products and are typically found in toe seepage from gold mine tailings dams. The presence of ammonium and nitrate in seepage from mine landforms is receiving increased attention with respect to the input of nutrients to receiving waterways.

In this section, an overview is provided of key attributes (positive and negative) of active and passive treatment technologies that have been applied to mine water treatment. An introduction is given to emerging technologies that have considerable promise. Two case studies are presented.

5.2 Current Treatment Technologies

5.2.1 Active Treatment

There are four basic types of active treatment technologies.

- Precipitation by:
    - addition of lime or other neutralising agents, alone or in combination with adsorbent materials, to raise pH and precipitate metal hydroxides (the most common active treatment technology for ARD);
    - addition of sulfide to precipitate metal sulfides; or
    - addition of an oxidising agent (eg chlorine to precipitate manganese dioxide).
- Ion exchange - a resin bed is used to take out metals in positively or negatively charged forms (especially attractive for more dilute waters containing lower concentrations of major ion salts).
- Membrane separation (reverse osmosis, electrodialysis) - will remove both major ion salts and metals to low levels. This technology is especially suited to the removal of high loadings of major ion salts and the removal of heavy metals to very low levels. However, rigorous pre-treatment may be required to remove solutes that could irretrievably foul the costly membranes.
- Bioreactor systems for the removal of metals and sulfate (sulfate reduction coupled to metal precipitation) and nutrients (nitrification/denitrification) to remove ammonia and nitrate.

An example of a lime dosing plant incorporating quicklime storage silos and a ball mill slaker to produce a milk of lime suspension for mixing with ARD is shown in Figure 5.2.

Figure 5.2: Lime treatment plant for ARD showing lime storage silos and mixing system at base of silos.

The advantage of active treatment systems is that they can be engineered to accommodate a wide range of pH, flow rates and solute loads. However, the selection of an appropriate active treatment technology that will provide robust service is very dependent on the composition of the source water and the required discharge targets. Pre-treatment stages may well be required in the event that the water contains solutes that would poison or foul the final steps of the treatment process. Membrane-based processes are especially vulnerable to fouling (most commonly by iron and manganese oxyhydroxides and gypsum). Very careful attention needs to be paid in the design stage to the composition of water that is input to a membrane system.

5.2.2 Passive Treatment

There is a wide range of chemical and biological-based technologies represented by this class. The common attributes are no or minimal requirements for active (electric or diesel) pumping, and no requirement for powered addition of chemical reagents. There are four basic classes:

- passive chemical neutralisation - pH neutralisation for low pH (ARD water), including oxic and anoxic limestone drains or riffle channels;
- assisted chemical neutralisation – use of solar or water power to drive reagent dispensing systems;
- wetlands (surface and sub-surface flow); and
- a new class of high intensity sulfate reducing systems.

The major operational issue with the passive limestone drain systems is their potential to become passivated by coatings of metal hydroxides or gypsum. Anoxic limestone drains are not recommended for water containing more than several tens of mg/l of Al owing to their tendency to become fouled. Coating of limestone aggregate can be minimised in more strongly flowing surface drains but there will be a compromise between the minimum particle size required to prevent physical scouring, and the surface area available for treatment.

Assisted neutralant dispensing systems (eg Aquafix, Neutramill or HALT systems) are essentially mini-active chemical treatment units that can treat small scale low pH sources of AMD in areas remote from power sources (Taylor and Waters, 2003). The Neutramill can operate on solar power, whilst the HALT (Hydro-Active Limestone Treatment) uses water energy to drive a sub-aqueous ball mill.

Wetlands make use of a range of processes including adsorption and sulfate reduction to remove metals from solution. Wetlands have many attractions for the treatment of mine drainage since they have the potential to provide an aesthetically attractive, low cost, low maintenance and sustainable alternative to expensive chemical treatment plants. However, there are a number of key factors that must be taken into account when designing and/or considering the suitability of wetlands for mine water treatment.

Active or passive physicochemical treatment systems may have difficulty meeting stringent final discharge targets for protection of aquatic ecosystems, depending on the range of metals and other solutes in the source water. Wetland polishing systems can have a distinct advantage in some cases. When correctly designed, they can achieve the required targets without the large capital and operating costs associated with secondary and tertiary active treatment systems.

Unlike chemical treatment plants, wetlands cannot rapidly adjust to a sudden deterioration in water quality or to a short term major increase in volumetric flow. They work best under steady state conditions and thus will need to be fed at a relatively constant rate from a pond in which the mine water is initially collected, or protected from storm events using a split weir system.

Mixed success has been achieved with use of wetlands to treat ARD, largely as a result of overly optimistic expectations for the technology. The usual causes for failure are:

- The size of the wetland is too small for the input acid load resulting in progressive failure through the system.
- The pH is too low to sustain required levels of sulfate reduction.

- There is an unexpected decrease in quality of feedwater resulting in the overwhelming and killing of the wetland.

An example of the third dot point above is provided in Figure 5.3. A wetland initially designed to treat pH 5 water, and which operated successfully for three years, was overwhelmed when large volumes of strongly acidic seepage suddenly began to be produced by an adjacent covered waste rock dump. Although engineered with open limestone drains in the input end, there was insufficient neutralising capacity for the high acid load.

Figure 5.3: Wetland constructed to polish seepage from a covered waste rock dump. Top panel shows the wetland just after construction. The bottom panel shows the wetland after it was overwhelmed and killed by breakthrough of highly acidic and metal rich seepage.

Wetlands are NOT suited to the direct treatment of low pH water with high metal loads. An input pH of at least 4 (and preferably 4.5) is the starting point for a successful and sustainable wetland treatment system. One of the reasons for this is that the activity of sulfate reducing bacteria (the most important source of alkalinity production and metal removal potential in a wetland for treating sulfate-rich water) declines markedly at pH values less than 4.5.

In the event that the input pH is less than 4, pre-neutralisation will be required prior to wetland treatment. This can be achieved by an upfront limestone drain, assisted neutralant dispensing system, or a full scale active chemical treatment plant, depending on the total acid load. Since mine waters with a pH of less than 4 invariably contain elevated concentrations of Fe and Al, a sedimentation basin should be located between the primary source and the start of the wetland to trap ferric and/or aluminium hydroxide precipitates. A conceptual passive treatment system for the treatment of an initially low pH mine water is illustrated in Figure 5.4.

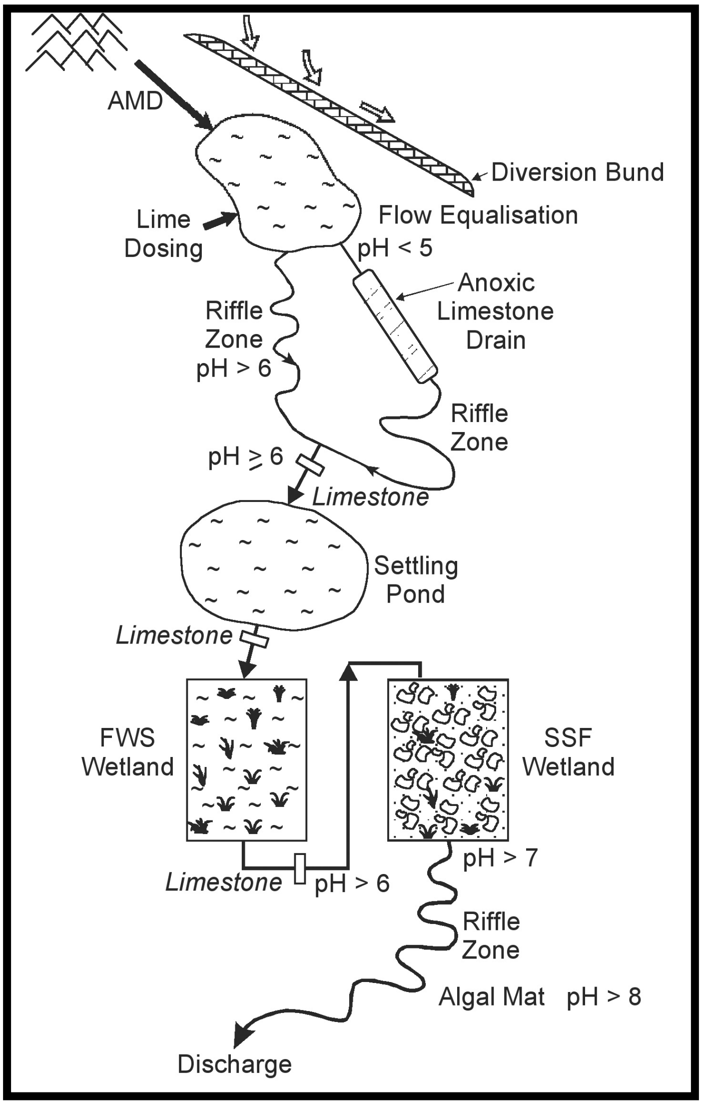

Figure 5.4: Schematic of a conceptual passive treatment system for high strength ARD

Wetlands have been most successful as water treatment systems when the initial pH is between 4.5 and 8. An outstanding example of a full scale surface wetland to treat pH neutral mine water is the RP1 wetland at the Ranger Uranium mine in the Northern Territory (Figure 5.5). This wetland reduces inflowing U concentrations of 10 mg/L to around 50 µg/L in the outflow.

Figure 5.5: Aerial photograph (looking south) of the Ranger Mine RP1 constructed wetland. The wetland is 350m long (north-south) and 250m wide. It comprises 8 treatment cells, with the water entering from the top left (Cell 1) and leaving at the bottom right.

The requirement for initial pH values generally in excess of 4.5 for wetlands means that this type of treatment system is best suited to the low acid load end of the ARD spectrum. This is illustrated in Figure 5.6, showing the optimum domain of application of passive and active treatment technologies. It must be noted that the range of applications in Figure 5.6 is controlled by the acid load of the mine water. In the event of circumneutral mine drainage, very large flows (within limits) can be treated with results the equal of, or superior to, conventional lime dosing.

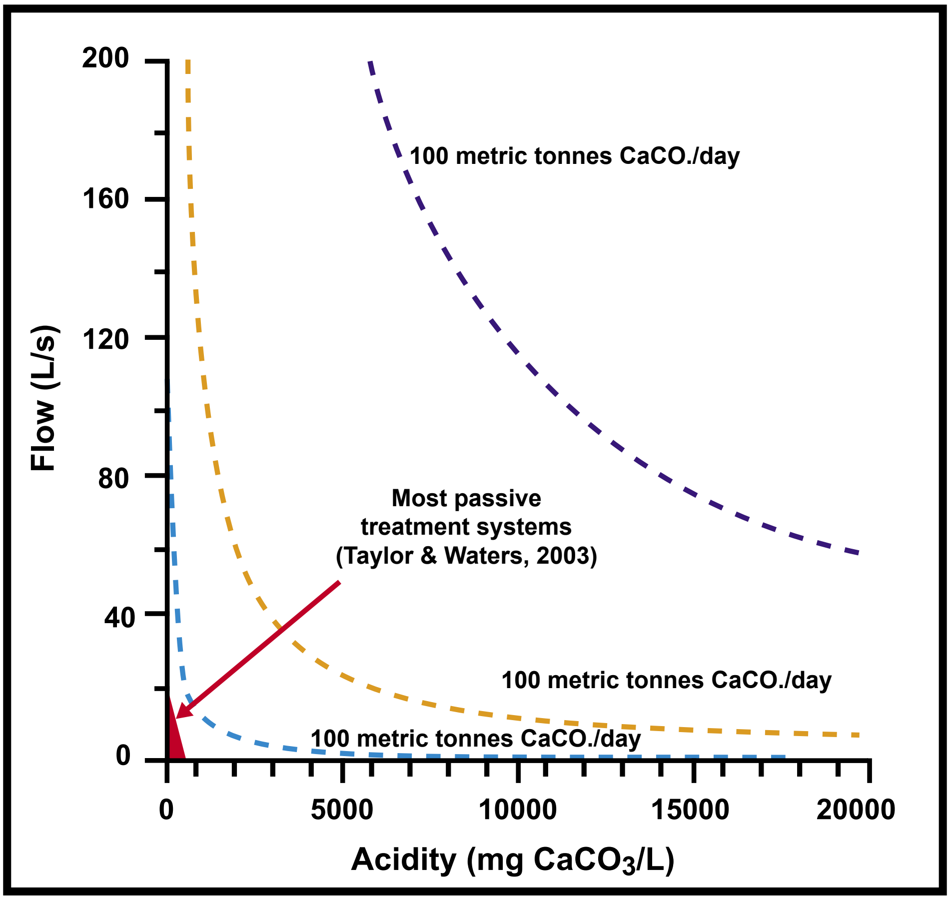

Figure 5.6: Range of application of passive and active (chemical neutralisation) treatment types (after Taylor and Waters, 2003).

The most important considerations governing the selection and location of a site for a constructed wetland are:

- availability of enough land with a suitable topography to provide the hydraulic head needed to maintain passive flow through the system;
- absence of large water inflows during storm events;
- sufficient year-round supply of water to ensure that the wetland remains in a permanently saturated condition; and
- potential for impact on groundwater quality.

Wetlands designed for the removal of metals as sulfides (via microbial sulfate reduction) must be maintained wet all year round to sustain anaerobic strongly reducing conditions and avoid exposure of the sediments to oxidising conditions. The wetland must not be allowed to dry out or else the sulfides will reoxidise to produce acid, and remobilise the initially trapped metals.

The design lifetime of a wetland treatment system is a key issue. In some cases significant volumes of mine water requiring treatment may only be produced during the life of the mine, prior to rehabilitation of source material (eg waste rock dumps) or cessation of dewatering operations. In this case there would obviously be less emphasis on long term (post closure) sustainability.

The need for self sustaining systems becomes much more critical following site decommissioning since not only will there be few, if any, staff onsite but there will no longer be a direct cash flow to support high operating costs.

Passive treatment systems will accumulate heavy metals. The long term implications of this for closure planning should be addressed when a wetland system is being planned. For example, a wetland established in an ephemeral creekline to polish water from mine dewatering bores may have perennial flow for years, until operations cease. Then ephemeral flow is reinstated and the sediments dry out during the dry season, with the risk of oxidation of sulfides and re-mobilisation of metals. The footprint of the wetland may need to be rehabilitated to protect the downstream environment.

Performance monitoring will be required throughout the life of a passive treatment system. Typically, the frequency and spatial intensity of monitoring will need to be highest during the initial establishment and proving phase. The monitoring program should be designed to both measure both the end-of-pipe quality and provide an early warning of a decline in performance in the upstream components of the system.

Passive systems for the treatment of more concentrated sources of ARD are unlikely to be walkaway and maintenance free. For these cases pre-neutralisation systems will require replenishment, sedimentation ponds will need to be periodically cleaned, and the substrate in some of the more heavily impacted upstream wetland cells may need to be replaced.

5.3 Emerging Technologies – Sulfate Removal

The removal of sulfate from mine water is becoming an increasing issue in many locations, as a result of concerns about degradation of surface water resources by inputs of salinity. Sulfate (and associated Mg) is typically a major ion component of mine water as a result of the oxidation of sulfides contained in the waste, and the accelerated weathering of the host rock.

Mine drainage water does not have to be acidic to contain appreciable concentrations of sulfate. It is strongly recommended that an assessment be made of potential major ion salt load at the same time ARD screening is carried out to ensure that high sulfate pH-neutral water is not an unexpected legacy.

Two microbiological-based technologies have been developed to remove sulfate (by reduction of sulfate to elemental sulfur) at rates sufficiently high to provide a viable route for the treatment of large volumes of mine water (hundreds to thousands of cubic metres per day). The input feed pH must be greater than 4.5 for sulfate reduction to operate at the required high rate, so water with a pH less than 4.5 would need to be pre-neutralised.

The first is an active treatment process, THIOPAQ®, developed and marketed by Paques (www.paques.nl), a Netherlands-based corporation (Figure 5.7). Hydrogen, methanol, ethanol or sucrose can be used as the electron donor for the sulfate-reducing bacteria that are maintained in a high-rate bioreactor. This process can produce water containing <300 mg/L sulfate and also removes metals that form insoluble sulfides to very low levels (Cu, Cd, Ni, Pb as well as As, Se and Mo). The technology has been operated at full scale since the mid-1990's and many plants have been installed. It has also been used for the treatment of sulfate-and metal-rich groundwater. This active bioreactor technology would be best suited to situations that permit high levels of control to be provided, such as in a process plant environment.

Figure 5.7: Paques biosulfide metal removal pilot plant (courtesy of Kennecott Copper USA)

Another option for high rate sulfate removal, but in the context of a "passive" low maintenance operating framework, is provided by the IMPI® process developed over the past decade in South Africa (Pulles et al., 2003). An extensive R&D program has produced a process that will run on locally available biomass (eg grass and/or woodland vegetation) and not require the highs levels of control or inputs of energy needed by a typical high rate bioreactor technology such as the THIOPAC process. This breakthrough has been achieved by sustainably accelerating by one to two orders of magnitude the rate of degradation of bulk cellulosic material, such that this no longer limits the activity of the sulfate-reducing bacteria. Prior to this development, passive biological treatment systems were not viable candidates for removal of significant loadings of sulfate.

The IMPI process has been specifically designed to operate unattended over extended periods, with flow through the reactors being driven by gravity. Elemental sulfur is produced by the process which consists of an upfront cellulose degrading and sulfate reducing reactor followed by a sulfide oxidising unit (Figure 5.8). Approximately 80% of the sulfide produced is converted to elemental S. The water emerging from the sulfide oxidising reactor contains elevated levels of alkalinity and ammonia. It is necessary to remove this ammonia in a polishing wetland prior to final discharge to the receiving environment.

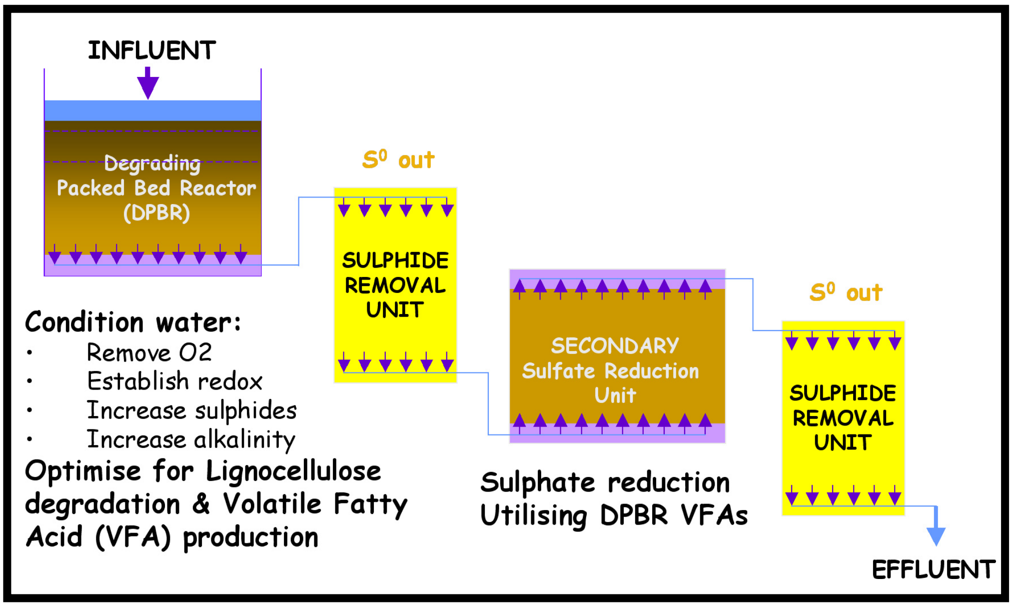

Figure 5.8: Schematic flow sheet for South African IMPI® passive sulfate reduction technology (courtesy of Pulles, Howard and Delange, Inc)

The IMPI treatment units can be established in lined in-ground pits that are covered with earth to produce a low-relief mounded surface.

In common with the THIOPAQ process, the IMPI process can also remove metals from solution.

Eucalypt species have been successfully tested as feedstock in pilot scale testwork so the process should be able to be deployed in Australia. The process of sulfate reduction generates alkalinity so that it is conceivable that a cascade system of reactors could be used to treat water with initial pH <4.5, with the first reactor in the cascade being used to produce the "seed" volume of neutralant. Thus the process, once initiated and operating at steady state, could provide a considerable offset to the lime that may have been initially required to neutralise input water at startup. In particular, cascade implementation of the reactor units for the IMPI process could potentially achieve a completely self sustaining system whereby all alkalinity needed to adjust the pH of initially acidic input water is provided by sulfate reduction (Figure 5.9).

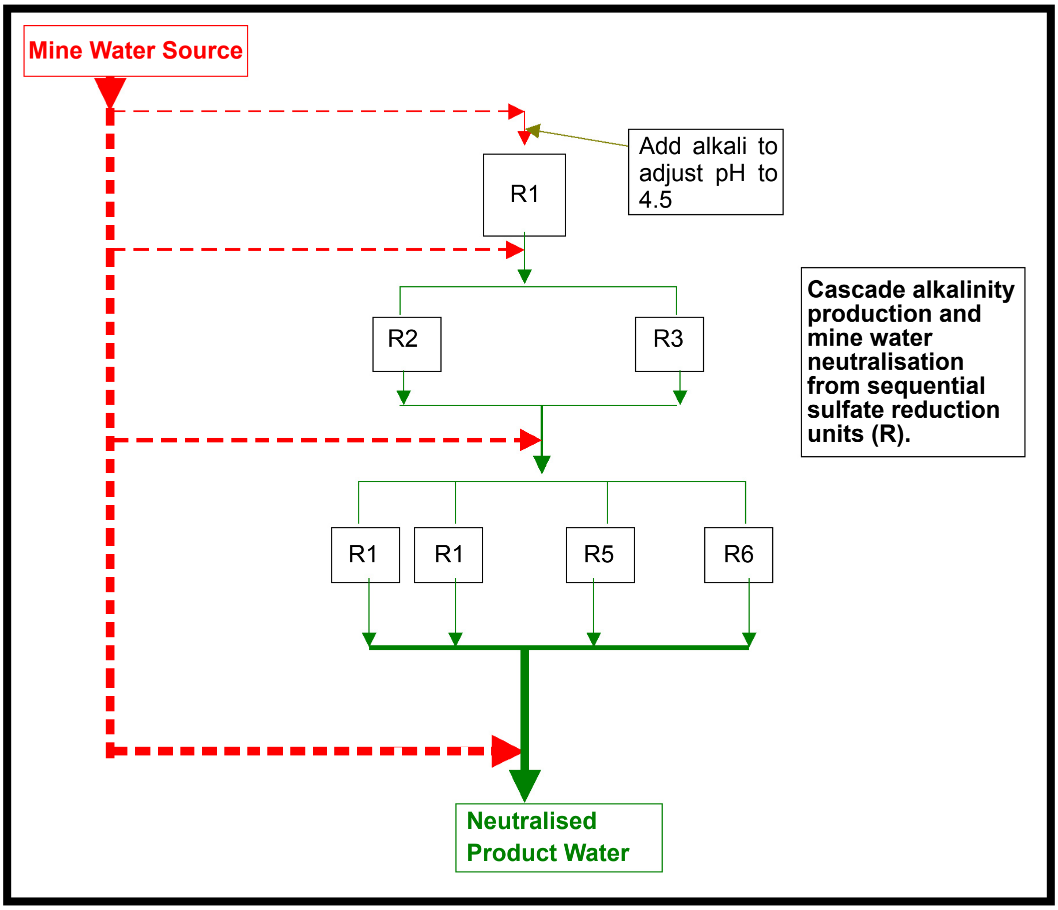

Figure 5.9: Schematic of potential cascade application of IMPI reactor units (R) to progressively neutralise acidity and remove sulfate and metals from ARD.

A potential application of this process would be to add alkalinity and organic carbon to pit water to sustain a higher pH and kick start the carbon cycle. Water would be withdrawn from the pit, pass through the reactors, and be returned to the pit.

It is estimated that a 1 tonne/d sulfate removal plant (1000m^3/d @ 1000mg/L SO_4) would require five full scale 4-stage IMPI modules. The capital cost of this would be approximately AUD$520K. In contrast, the capital cost of the THIOPAQ process would be approximately double, with an 8-fold higher operating cost (W. Pulles, TEAM NT workshops, 2003).

The IMPI process has successfully progressed through intermediate scale piloting and is now entering the large scale piloting phase. This passive sulfate reducing technology has considerable potential for treating sulfate-rich mine drainage at both operating and legacy mine sites. It is estimated that a treatment rate of 5ML/d of 100 mg/L sulfate-containing water is the practical upper flow limit for application of the technology.

5.4 Case Studies

Case Study 1

Active chemical treatment of acidic water to prevent overflow of an open pit

The legacy mine site of Mt Morgan near Rockhampton in Queensland has an open pit that currently has a predicted 50% probability of overflow. The challenge is to maintain the water level at a maximum operating level (MOL) that will reduce this probability to 5% during the next five to ten years when rehabilitation works will be undertaken to substantially reduce the volume of water reporting to the pit. An annual volume of water will be treated by chemical neutralisation to initially attain, and subsequently maintain, the MOL with the treated water to be discharged to the adjacent river. Design of the treatment plant required the neutralant demand of the water to be determined and screening testwork done on a wide range of potentially available neutralants.

> ***The most critical initial consideration is calculating the neutralant demand of the water to be treated. There are two types of acidity that need to be considered – actual and incipient.***

Actual acidity is measured using a pH probe and represents the free proton acidity. Incipient acidity is dependent on the dissolved concentrations of metals. As the pH increases these metals will be hydrolysed to their hydroxide forms, consuming proton acidity in the process. The total acidity is equal to the sum of hydrogen ion activity (calculated from pH) and the sums of incipient acidity from metals such as Fe, Al, Mn, Cu and Zn.

An example is provided in the box below showing the contributions of actual and incipient acidity to the composition of a high strength ARD water. It is clear that calculating neutralant demand from the measured pH alone would have greatly underestimated the amount of neutralant required to precipitate all of the Fe and Al. It is also clear that in this particular case Cu, Mn, and Zn represent only a small additional increment to the total neutralant demand.

Calculation of Neutralant Demand

The total neutralant demand (expressed as mg/L $CaCO_3$ neutralising equivalents) is calculated using the formula below:

$$\textbf{Neutralant} = 50x(1000\ 10^{-pH} + \Sigma z_n[M_n]/AW_n\ )$$

where z_n = charge of metal ion M_n (for example n=2 for Zn^{2+}),

$[M_n]$ = concentration of metal M_n in mg/L and

AW_n = atomic weight of metal M_n.

An example of the use of this formula for a high strength ARD is provided in the table below. The composition of the water is given in the left hand columns.

Parameter	Concentration mg/L	Charge	Atomic Weight	$CaCO_3$ mg/L (Neutralant Demand
Acidity				
pH (2.8)				79
Metal				
Fe	220	3	56	591
Al	630	3	27	3500
Mn	83	2	55	151
Cu	35	2	64	55
Zn	23	2	65	35
Mg	1290	2	24	5310

Target pH for Treatment

Addition of milk of lime slurry to the Mt Morgan pit water shown in the table below enables metal removal to be determined as a function of pH. The percentages of each of the key target metals remaining in solution as a function of pH are shown in Figure 5.10.

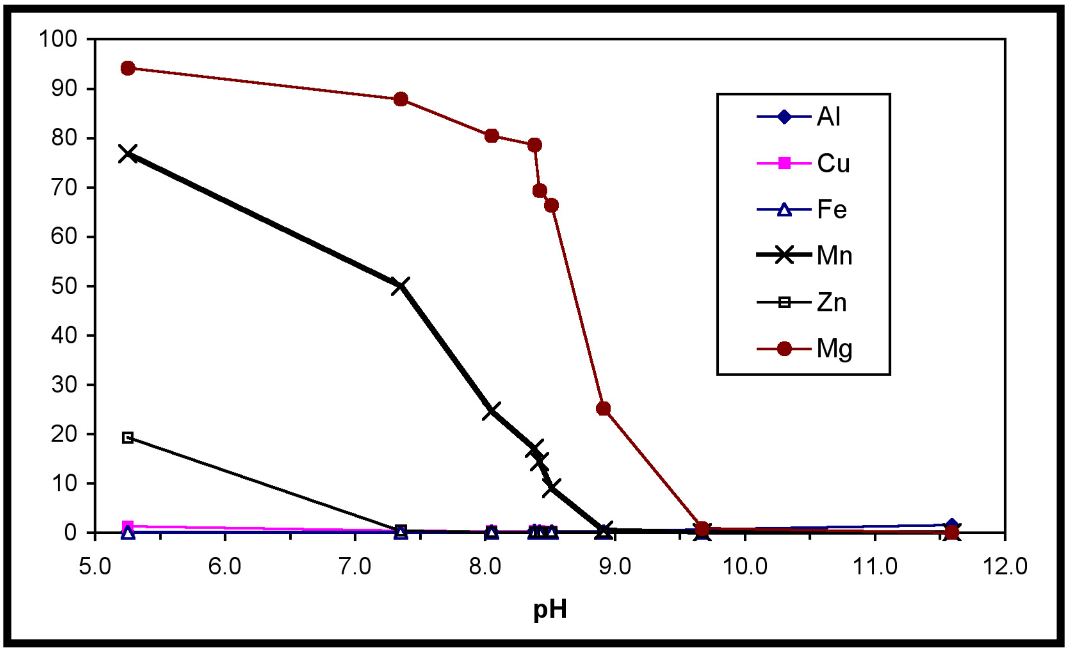

Figure 5.10: Removal of metals from Mt Morgan pit water as a function of pH (Jones et al., 2003).

All of the Fe and Al and most of the Cu are removed from solution by pH 5.2. Approximately 20% of the Zn is still in solution at this pH. By pH 7.3 all of the Zn has been precipitated. Manganese is the most difficult of the metals to remove. It is not until pH 9 is attained that all of the Mn is removed from solution. The amount of Al in solution begins to increase significantly again for pH values in excess of 9.5. This was to be expected since Al^{3+} is an amphoteric ion. The soluble anion $Al(OH)_4^-$ forms above pH 9 and thus the initially precipitated $Al(OH)_3$ begins to dissolve.

The testwork identified three potential target pH values (7.5, 8.5 and 9.0) for a treatment endpoint. If significant removal of Mn is not a consideration then pH 7.5 would suffice. At this pH the concentrations of Al, Cu, and Zn - the major potential toxic species in the source water - would be reduced to very low levels. Complete removal of Mn would necessitate raising the pH to 9. However, the penalty for this would be a doubling in the amount of lime required since the Mg in solution would concurrently be consuming alkalinity as a result of the precipitation of $Mg(OH)_2$. Since low mg/L concentrations of Mn are not considered to be a significant toxicological risk to aquatic biota (Mn is about 1000 times less toxic than Cu and 100 times less toxic than Zn; ANZECC, 2000) then complete removal of Mn should not be required. Figure 5.11 illustrates the flow sheet for a one stage treatment plant.

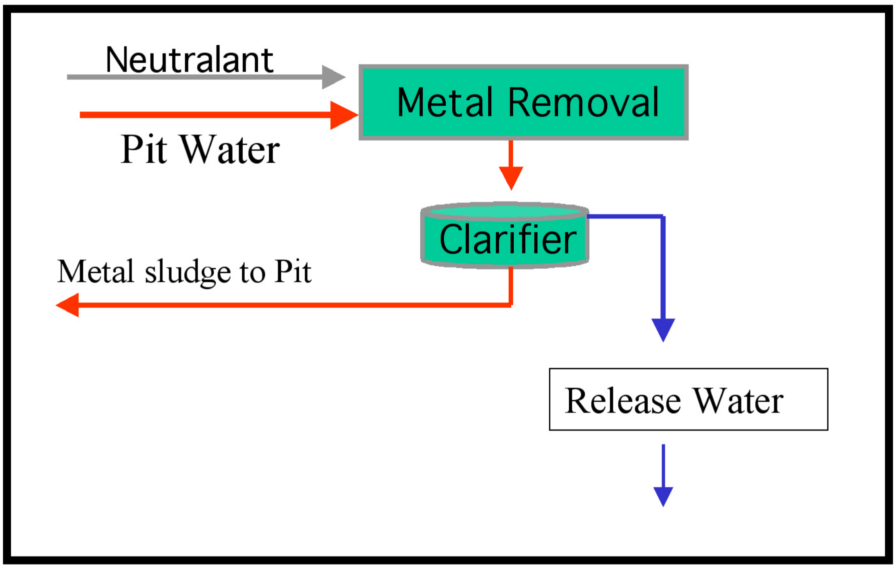

Figure 5.11: Process flowsheet for first stage chemical neutralisation - metal removal.

If removal of Mg and a significant proportion of the SO4 is required to further reduce the total dissolved solids (salinity) load, then dosing with lime to pH 10.8 could be an option. This approach would certainly be technically feasible, although it would very substantially increase lime consumption (and cost) given the high concentration of Mg^{2+}. Note that lime and perhaps sodium or potassium hyroxides are the only reagents that could be used for this purpose. Calcite could not be used since it cannot produce sufficiently high pH values in solution.

The removal of high concentrations of major ion salts may be more appropriately facilitated by reverse osmosis. This route would also remove the Mn remaining in solution after initial lime treatment. An example flow sheet for a treatment plant to remove both major ions and metals is shown in Figure 5.12. The additional carbonation (Ca removal) and microfiltration steps are required to protect the RO membranes from fouling by gypsum or entrained solids.

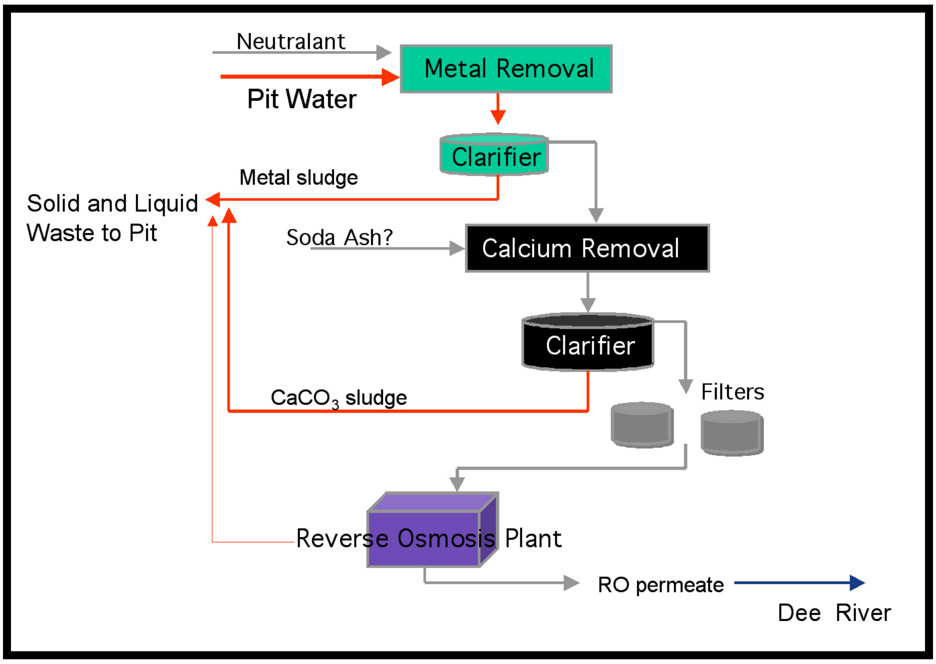

Figure 5.12: Conceptual process flowsheet for complete treatment of water (metals plus major ions) by lime softening/carbonation followed by reverse osmosis desalination.

Key Considerations for Selection of Neutralant

The five primary characteristics that need to be considered for a candidate neutralising agent are:

- the rate and extent of pH increase;
- the dosage rate (ie mass/m^3 required);
- the extent of preparation such as grinding and the delivery system needed;
- the ease of settling and the volume of sludge produced; and
- cost (the cost of supply plus the cost of operational use).

The most commonly used neutralising agents for large scale treatment of ARD are lime (quicklime, hydrated lime), magnesite, magnesium oxide, and limestone. The reason for this is the ready commercial availability of these reagents, the well proven technologies for their use, and their cost effectiveness for large scale application.

Whilst limestone can be a much less costly reagent than lime or magnesium oxide, the maximum pH it can effectively achieve is around 7. Limestone is an excellent neutralant when the primary objective is the substantial removal of acidity, Fe, Al and Cu as in the example case study. Limestone would not suffice to reduce the concentrations of Mn (or Ni, Cd and Zn) to required levels in the event that these metals were the main solutes of concern.

A two-stage dosage system could be an attractive option – using lower cost limestone to raise the pH to 7, and higher cost lime to treat to pH 9. However, the cheaper overall cost of using limestone and lime may be more than offset by the capital and operating costs needed for two storage and injection systems. The economics will depend on the composition of water to be treated. For strongly acid water with high concentrations of Fe and Al relative to other dissolved metals, the additional capital cost for a dual delivery system could be more than offset by the lower cost of the limestone to neutralise to pH 7 and remove the Fe and Al.

Another key factor to bear in mind is the dosage rate required. The purchase price of a potential neutralant might be low by virtue of its being a waste product, or an impure variant of a premium product. This upfront "saving" can be more than offset by greater transport costs, larger storage requirements, larger mixing and dosing systems, and increased volumes of sludge by virtue of the larger dosage rate that is needed.

Case Study 2

Combined Active Treatment and Wetland Polishing

In order to access an underground resource via the base of a flooded open pit, approximately 9,000 ML of acid and metal-rich water needed to be removed. Direct discharge of this water was not possible owing to the high acidity and elevated concentrations of Fe, Al, Co, Mn, and Ni, even allowing for the fact the ANZECC 80% ecosystem protection guidelines were to be applied in the receiving waterway. The acceptance by the regulatory authorities of the 80% protection level followed an analysis of the historical monitoring data for the receiving waterway, where it was found that attaining metal values corresponding to this level of protection would actually represent a substantial improvement over the historical situation.

Neutralisation testwork with quicklime showed that adjustment of the pH to 7 removed the acidity, Fe and Al and substantial proportions of the Co and Ni. However, the concentrations of the latter two metals were still well above the 80% ecosystem protection guidelines. Addition of more lime to achieve a pH around 9 could have been used to remove the residual metals but the amount required would have greatly increased the consumption rate (kg/m3) of this costly reagent.

An alternative option, using wetlands for polishing the first-stage treated water was then investigated. A series of ponds (old alluvial gold workings) containing naturally established wetland were available onsite (Figure 5.13). These ponds were the remnants of an historical alluvial mining operation.

Figure 5.13: Naturally established wetland pond to be used for polishing treated water.

The capacity of the wetland soil and sediments to bind Co and Ni was determined and found to be more than sufficient to strip the Co and Ni to required levels.

Thus by combining first stage lime dosing treatment with wetland polishing, a hybrid treatment system was developed that will operate at substantially less cost than if lime treatment to a higher pH was the sole treatment method that could have been used to meet the required target.

5.5 References, Further Reading and Resources:

Jones, D.R. and Chapman, B.M. 1995, ‘Wetlands to treat acid mine drainage - facts and fallacies’, in *Proceedings: 2nd Australian Acid Mine Drainage Workshop, Charters Towers, 28-31 March 1995*, pp. 127-145, eds N.J. Grundon and L.C. Bell, Australian Centre for Minesite Rehabilitation Research, Brisbane, Australia.

Jones, D.R., Laurencont, T. and Unger, C. 2003, ‘Towards achieving sustainable water management for an acidic open cut pit at Mt Morgan, Queensland’, in *Proceedings: 6th International Conference Acid Rock Drainage (ICARD), Cairns, Queensland, 14-17 July,* eds T. Farrell and G. Taylor, AUSIMM Publication Series, No. 3/2003, pp. 513-519.

Kadlec, R.H. and Knight, R.L. 1996, *Treatment wetlands*, Lewis Publishers, New York.

Pulles, W., Rose, P., Coester, L. and Heath, R. 2003, ‘Development of integrated passive water treatment systems for the treatment of mine waters’, in Proceedings: 6th International Conference Acid Rock Drainage (ICARD), Cairns, Queensland, 14-17 July 2003, eds T. Farrell and G. Taylor, AUSIMM Publication Series, No 3/2003, pp. 801-807.

Taylor, J. and Waters, J. 2003, ‘Treating ARD - how, when, where and why’, *Mining environmental management*, May 2003, pp. 6-9.

Software

AMDTreat - Free from the U.S. Government (Office of Surface Mining Reclamation and Enforcement) at: http://www.amdtreat.osmre.gov/amdtreat.asp

This program provides users with a method to predict and model water treatment costs for mine drainage problems. The program provides many different treatment options both for passive and active treatment systems. It allows a user to estimate the cost of constructing and operating passive treatment systems such as vertical flow ponds, anoxic limestone drains, anaerobic ad aerobic wetlands, and manganese removal beds. Help screens are provided to explain the key elements of each of these treatment system components. The program will also calculate the capital cost (using user definable values) of constructing active or chemical treatment systems for caustic soda, ammonia, pebble quick lime and soda ash.

6. GROUNDWATER INTERCEPTION AND TREATMENT

6.1 Context

Dewatering of both open cut and underground mining operations is normally essential. This may be to simply remove water collecting in the mine. More importantly, dewatering may be necessary to depressurise the rock or weathered materials to improve their stability and strength. The water extracted may require treatment prior to discharge to surface receiving waters because of elevated concentrations of heavy metal or major ion salts.

Contamination of surface water by mining operations has historically received more attention in Australia than groundwater contamination issues. In part, this has been due to the visibility of surface water contamination. Many mines in Australia are in remote locations and have had few competing beneficial users of groundwater resources. However, in some locations in Australia (typically process-plant associated), and especially in the EEU and the USA, the issue of groundwater contamination has resulted in some very costly remedial action being required.

Groundwater is an important long term issue in the Northern Territory, where groundwater provides base flow during the dry season for many of the important river systems.

In contrast to surface water, the precise flow path of groundwater is often hard to define. Some gravel or sand aquifers are the exception. Furthermore, preventing the further spread of solutes by containment and recovery can be difficult, costly and a very long term proposition.

Each year that a groundwater plume develops can translate to ten years of pump and treat operations to recover the plume and restore groundwater quality.

Consequently, the emphasis in the design and location of waste and ore stockpiles and tailings dams at new mine sites - for those cases where there is a potentially valuable groundwater resource - should be on prevention or minimisation of future groundwater impacts. The exception to this could be in areas where the groundwater is so saline (eg Kalgoorlie) that it doesn’t have any other beneficial use. However even for this case, care may still need to be exercised since contamination of the water by particular solutes could compromise its use by other industrial processes.

The key learning that has come from many studies of groundwater plumes associated with waste rock dumps and tailings impoundments is that times of travel can be very long. In many cases, decades or even longer periods may pass before a plume reaches an environmental receptor.

It is essential that the groundwater monitoring system be capable of providing sufficient early warning that a plume is developing. The earlier that this can be detected the greater the chance of containment and the lower the cost of remedial action. Detailed consideration of near-field hydrogeology will be required to produce the required design specification.

More to the point, if monitoring systems are located too far away, or in hydraulically inappropriate locations, a developing contaminant plume may go undetected for so long that it will be too late for mitigation of the source term to be effective in preventing the impact. Recovery from this situation will likely be very costly and require a long period of active management. A general “rule of thumb” is that one year of groundwater contamination can translate to ten years of pump and treat to recover and treat the plume.

The above context especially applies to tailings impoundments that contain low levels of residual neutralising capacity. It is vitally important that "early warning" symptoms of potential for development of a contaminated groundwater plume be recognised (Figures 6.1 and 6.2).

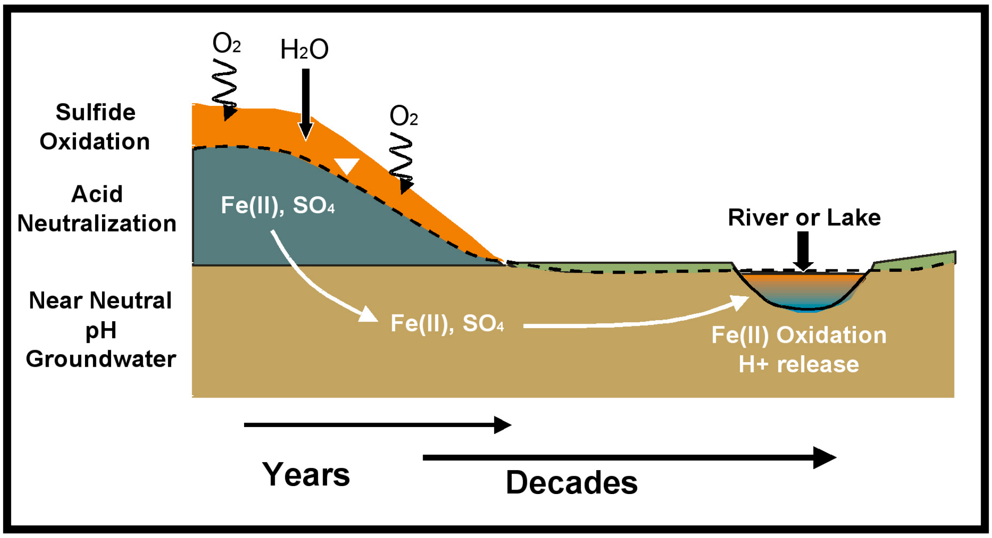

Figure 6.1: Schematic showing solute generation and timescales of transport processes from source to impact (after Blowes et al., 2003a).

Figure 6.2: A photograph of the visual effects of emergence of a saline groundwater plume in a stream bed in the Northern Territory.

In the context of a sulfide oxidation issue, early warning is typically provided by upward trends in sulfate, manganese and nickel, and a decrease in total alkalinity. It is recommended that tailings impoundments be equipped with at least two sets of multilevel water quality monitoring piezometers such that the composition and evolution of porewater within the impoundment can be tracked. This will quantify the source term and provide the earliest warning.

Many detailed studies of sulfidic tailings deposits have shown that the peak rate of oxidation occurs in the period after the surface of the tailings dries out. This may happen in the event that there is a long delay between the next deposition cycle (eg a rotating peripheral spigot system) or in the period following cessation of operations and before rehabilitation is completed. The maximum beneficial effect of an oxygen-excluding cover will be achieved only if it is placed shortly after deposition ceases, and before there has been substantial desaturation of tailings and development of an unsaturated zone. If many years have elapsed since cessation of operations, then peak oxidation will have occurred and the oxidation products will be in the process of being eluted downwards through the tailings profile (Figures 6.3 and 2.2). For this type of system, remedial efforts should focus on preventing transport of oxidation products by minimising infiltration, rather than by excluding oxygen.

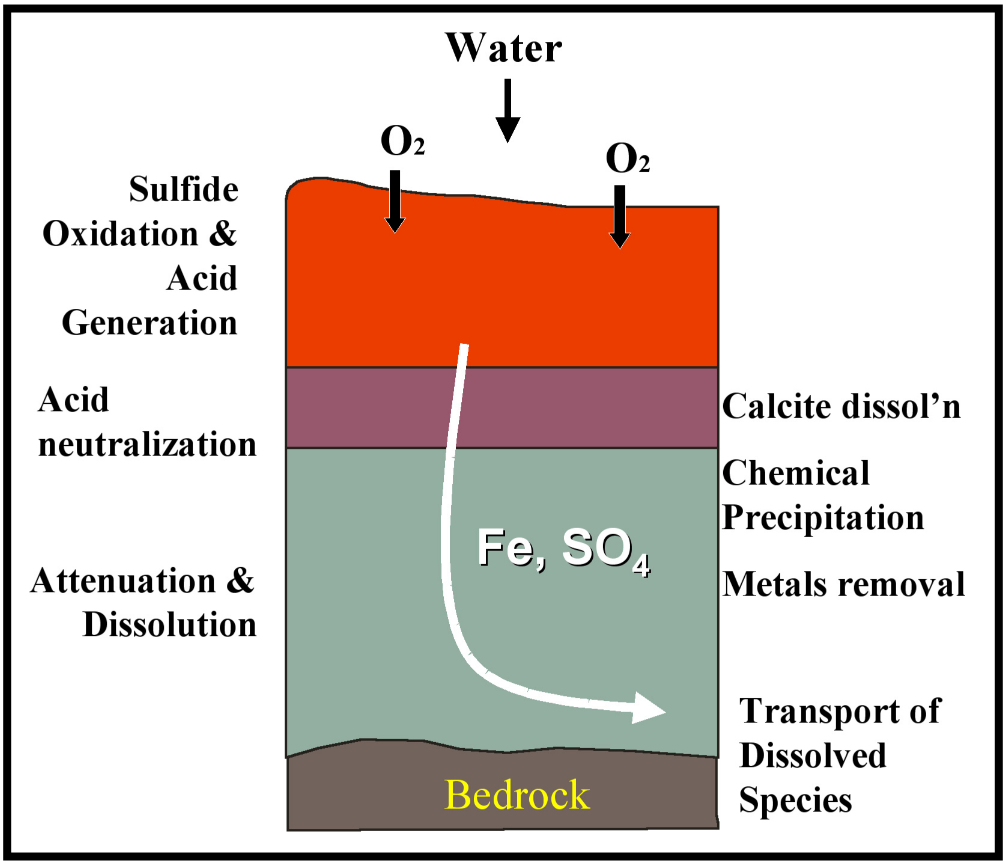

Figure 6.3: Geochemical processes in a tailings dam that control evolution of seepage water quality (from Blowes et al., 2003)

A very important point to note from Figure 6.1 is that ferrous iron is the primary iron oxidation product found at depth in sulfidic tailings dams. When measured *in situ* the pH of this deep pore water is usually found to be near neutral, or even slightly alkaline. This pH condition could lead to complacency since the conclusion, in the absence of chemical analysis, could be that there is “not a problem”. However, when this water ultimately emerges at the ground surface downgradient of the tailings dam, the ferrous iron will oxidise to ferric iron and precipitate as ferric hydroxide, with two equivalents of acidity being produced per equivalent of ferrous iron oxidised.

6.2 Groundwater Remediation

Traditionally, when contamination was identified via monitoring bores and remedial action required, the response has been analogous to that of contaminated surface water – contain, pump and treat. In the case of groundwater, containment can potentially be achieved by grout or slurry curtains accompanied by pumping to reverse the hydraulic gradient. The captured water can then be treated by an appropriate process as discussed in Chapter 5. However, it should be noted that groundwater contamination by hydrocarbons has been a significant issue at a number of mine sites. Treatment of hydrocarbon contamination typically involves phase separation and adsorption of the “dissolved” fraction by activated carbon.

Given the difficulties associated with the traditional pump and treat approach – especially for the case of low yielding fractured rock aquifers - a new generation of *in situ* treatment methods has been developed. The treatment process may involve abiotic and biological processes acting individually or in synergistic combination. These systems are termed “permeable reactive barriers” by virtue of the fact that the groundwater is treated as it passes through the reactive zone. These systems are “barriers” to the target solutes and not to the flow of water.

Comparisons of the relative timeline costs of “pump and treat” and passive barrier technologies (for a case where both types of technology can be considered as viable technical options) show a steadily rising cumulative cost for “pump and treat” compared with the *in situ* treatment. The continuous rise of the cost for pump and treat largely reflects the need for continuous inputs of energy and active management to drive the system. Disposal of treatment sludge can be an additional substantial cost for the pump and treat option. In relation to the time required for treatment (and hence total cost) it should again be emphasised that for each year that a groundwater plume has developed ten years of pump and treat to recover the plume are likely to be necessary.

The major advantage of a permeable reactive barrier (PRB) is that the treatment can take place passively over many years, without the need for active pumping and treatment and associated control and management systems. However, the length of time required for treatment may be prohibitive if there is not simultaneous reduction of the strength of the contaminant source. Thus a PRB may need to be used in conjunction with other control technologies if the timeframe for cleanup is a critical issue. Reduction of the contaminant source should be an early step in all remediation strategies.

Many papers and reviews on PRB technologies have been produced and several references are provided in the recommendations for further reading. In summary, this class of technologies comprises:

- barriers in which sulfate is reduced to sulfide, and metals are precipitated as insoluble sulfides. Because the barrier is located below the groundwater table there is minimal risk of future re-oxidation of the precipitated metal sulfides. This type of barrier may need to be supplemented with additional neutralising capacity such as lime or limestone, depending on the total acid load.
- barriers in which inorganic (eg Cr (VI), Se (IV), U(VI)) ions are reduced to insoluble forms; and
- barriers in which nitrate and organic compounds are degraded by microbial or inorganic processes such as reduction by zerovalent iron.

In general, zerovalent iron (scrap iron or iron filings) appears to be the most versatile and broadly effective of the materials that can be used in the reactive barrier. The reason for this is that chemical reduction is a major process driving the detoxification of many metals and organic compounds.

Arsenic has been shown to be very efficiently removed by zerovalent iron to less than 5 µg/L from starting levels of 10mg/L (Bain et al., 2003). This has especial relevance to the Pine Creek Geosyncline of the Northern Territory, where arsenic tends to occur at elevated levels in the groundwater. Metallic iron could be used for *in situ* treatment or deployed *ex situ* in a column to strip arsenic from water used as a potable supply.

***In situ* permeable reactive barrier systems have advanced beyond experimental technology and there are now many full scale applications in Europe, the USA and Canada. Successful implementation requires:**

- ***good understanding of the load of solutes (through time and space) needing to be treated;***
- ***appropriate definition of the hydrogeological environment downgradient of the source; and***
- ***selection of the most appropriate (source dependent) combination of reactive materials for use in the barrier.***

The PRB concept has recently been extended with success to the use of layers of organic matter added to the base of a new tailings storage area. The premise is that sulfate reduction will become established in the base of the tailings dam and that metals and sulfate present in the pore water will be removed at source, thus preventing the development of a contaminated groundwater plume.

A PRB could also be implemented as a contingency measure, or as a final polishing treatment, for seepage from a landform that has been capped by an engineered cover system. This scenario especially applies to waste that has undergone a substantial degree of oxidation before being capped. In this situation it is inevitable that some seepage containing elevated metal concentrations will find its way to the groundwater, especially during above average wet seasons.

6.3 Case Studies

Case Study 1

Interception of an acidic and metal rich plume originating from an oxidising tailings impoundment Nickel Rim, Sudbury Ontario (Blowes et al., 1999).

This PRB was the first full scale installation in the world designed to treat acidic groundwater using the process of in situ sulfate reduction. It was installed in 1995 so there is almost a decade of intensive monitoring data available to evaluate its performance. The conceptual flow line schematic for this study is shown in Figure 6.4 with illustrations of barrier construction and design provided in Figures 6.5 and 6.6.

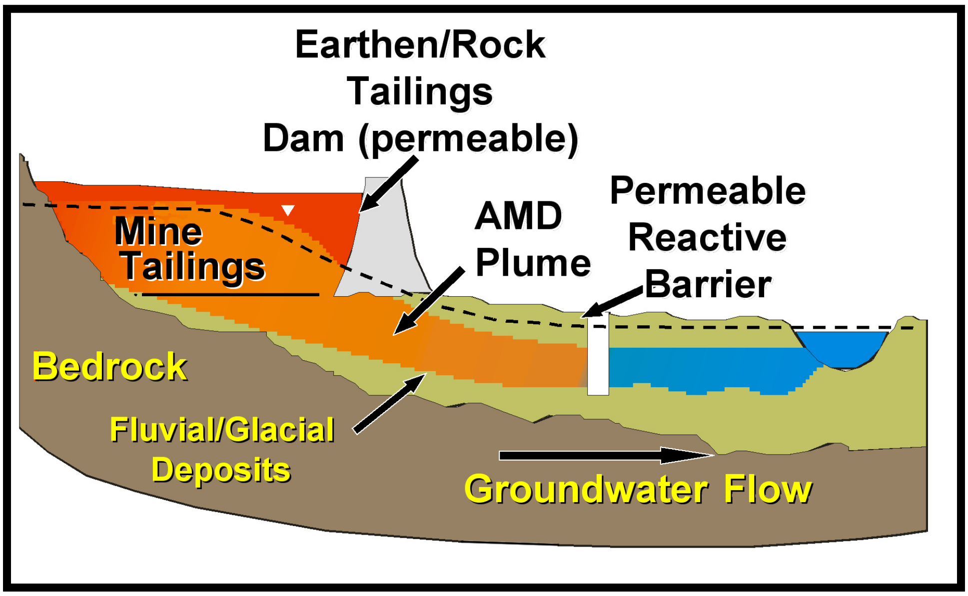

Figure 6.4: Schematic illustrating the location of the PRB relative to the source for Case Study 1 (from Blowes et al., 2003b).

Figure 6.5: Case Study 1: Installation of barrier (top) to intercept an acidic plume downstream of the Nickel Rim tailings impoundment at Sudbury, Ontario (courtesy of D. Blowes, University of Waterloo).

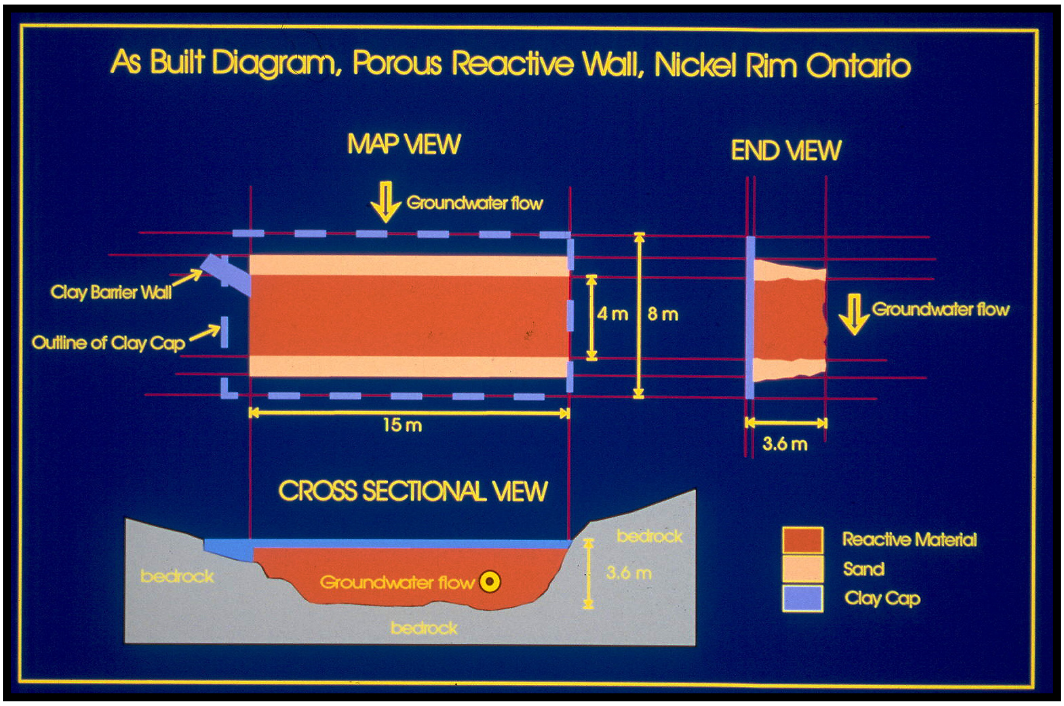

Figure 6.6: Case Study 1: Schematic showing details of the barrier design to intercept an acidic plume downstream of the Nickel Rim tailings impoundment at Sudbury, Ontario (courtesy of D. Blowes, University of Waterloo).

The active fill material in the barrier consisted of a mixture of woodchips, leaf compost, municipal waste and limestone. The role of the limestone was to provide sufficient initial pH neutralisation (pH>5) to enable the anaerobic process of microbial sulfate reduction to become established. The mixture of organic carbon provides the energy source for sulfate reducing bacteria. The process of sulfate reduction produces both alkalinity and sulfide - neutralising the acidity of the input water, precipitating the metals as insoluble sulfides and carbonates, and simultaneously reducing the concentration of sulfate.

$$SO_4^{2-} + 2CH_2O \longrightarrow H_2S + 2HCO_3^-$$

The compositions of the input and treated waters are provided in Table 6.1. At the prevailing groundwater flow velocity of 15m/year, the barrier is conservatively estimated to remain active for at least ten years.

Table 6.1: Indicative compositions of input and treated groundwater for the PRB installed at Nickel Rim, Sudbury, Ontario.

Parameter	Inflow	Outflow
pH	4-6	
Alkalinity mg/L	0	800-2700
Fe mg/L	1000	80
Al mg/L	30	<DL
Ni mg/L	30	0.6
SO_4 mg/L	4,000	1,500

Case Study 2

Experimental in-river PRB in the Northern Territory.

This case study illustrates the experimental use of metallic iron to reduce concentrations of dissolved copper seeping into a river bed.

Groundwater seepage containing appreciable concentrations of dissolved copper is entering a freshwater stream. A bund of metallic iron scrap ("zerovalent iron") was placed across the river channel to act as a permeable reactive barrier (Figures 6.7 and 6.8).

Figure 6.7: Location of permeable barrier of scrap (zerovalent) iron across river channel.

Figure 6.8: Iron scrap cemented with copper stripped from the water.

The mode of operation is the galvanic reduction of dissolved copper to metallic copper. The copper plates out on the surface of the iron. Concentrations of copper were reduced from 110 to 28 mg/L in water passing through the barrier. This environmental water treatment process is analogue to the "cementation" process used industrially to recover copper from low grade heap leach operations.

6.4 References and Further Reading

Bain, J., Spink, L., Blowes, D.W. and Smyth, D. 2003, 'The removal of arsenic from groundwater using permeable reactive materials', in *Proceedings of Sudbury 2003: Mining and the Environment, Laurentian University, Sudbury, Ontario, 25-28 May 2003.*

Benner, S.G., Blowes, D.W., Gould, W.D., Herbert Jr, R.B. and Ptacek, C.J. 1999, 'Geochemistry of a permeable reactive barrier for metals and acid mine drainage', *Env. Sci. Technol.*, 33, 2793-2799.

Blowes, D.W., Ptacek, C.J., Benner, S.G., McRae, C.W.T., Bennet, T.A. and Puls, R.W. 2000, 'Treatment of inorganic contaminants using permeable reactive barriers', *J. Contam. Hydrol.*, 45, 123-137.

Blowes, D.W., Ptacek, C.J. and Jurjovec, J. 2003a, 'Mill tailings: hydrogeology and geochemistry', in *Environmental aspects of mine wastes*, eds J.L. Jambour, D.W. Blowes and A.I.M. Ritchie, Short Course Series, 31, 95-116, Mineralogical Association of Canada, Vancouver, British Columbia.

Blowes, D.W., Bain, J.G., Smyth, D.J. and Ptacek, C.J. 2003b, 'Treatment of mine drainage using permeable reactive materials', in *Environmental aspects of mine wastes*, eds J.L. Jambour, D.W. Blowes and A.I.M. Ritchie, Short Course Series, 31, 361-376, Mineralogical Association of Canada, Vancouver, British Columbia.

Puls, R.W., Powell, R.M., Paul, C.J. and Blowes, D.W. 1999, 'Groundwater remediation of chromium using zerovalent iron in a permeable reactive barrier', in *Innovative subsurface remediation*, eds M.L. Brusseau, D.A. Sabatini, J.S. Gierke and M.A. Annable, ACS Symposium Series, 725, 182-194, ACS, Washington, D.C.

Vidic, R.D. 2001, 'Permeable reactive barriers: case study review', *Groundwater Remediation Technologies Analysis Centre technology evaluation report*, TE-01-01, University of Pittsburgh. WEB: http://www.gwrtac.org/pdf/PRBtmp.pdf.