

CHAPTER 6

Prevention and Mitigation

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PREDICTION
•
PREVENTION
•
MANAGEMENT

The International Network for Acid Prevention

Global Acid Rock Drainage Guide

GARDGUIDE
BY INAP

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Chapter 6

From GARDGuide

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6.0 PREVENTION AND MITIGATION

6.1 Introduction

The most recent and widely accepted methods for the prevention and mitigation of ARD (see Chapter 1 for definition) are presented in this Chapter. Discussions include the principles and objectives for prevention and mitigation and definitions and terms, suitability and applications, expectations and limitations, and primary references. While this chapter focuses on environmental technologies, regulatory, social, economic, and sustainability issues must always be managed within the applications of all prevention and mitigation techniques.

As discussed in Chapter 2, sulphide mineral oxidation occurs naturally as part of the sulphur cycle. In the context of ARD management during mining, the goal of mitigation measures is often to maintain or control the rate of sulphide mineral oxidation so that ARD formation is prevented or reduced to minimal or acceptable levels. Absolute prevention of ARD may require that all reactive sulphide bearing minerals remain virtually isolated from atmospheric oxygen. However, absolute prevention of ARD may not always be required for protection of environmental quality.

The basic approaches to prevent ARD are similar at coal mines and hard rock mines: reducing oxygen ingress and reducing the flow of water that can act as a transport medium for oxidation products. Coal mines may make use of low-permeability covers, or selectively place pyritic material high in the backfill so that it will not be exposed to ground water. Pyritic material can also be mixed with alkaline strata or some added alkaline material or by-product (e.g., fly ash, steel slag), to neutralize acidity and inhibit high rates of pyrite oxidation that can occur when the pH gets low enough to permit iron-oxidizing bacteria and ferric oxidation of pyrite to become significant (Brady et al., 1990; Perry and Brady, 1995; Rich and Hutchison, 1990; Rose et al., 1995; Skousen and Larew, 1994; Smith and Brady 1998; Wiram and Naumann, 1995). These latter techniques have also been applied with some modifications at hard rock mines, as will be discussed later in this chapter.

The implementation of methods for prevention and mitigation depends on the mine development stage, deposit type, geochemistry, climatic regime, terrain (or topography), surface water, geology, groundwater, and aquatic and terrestrial ecosystems. Material availability, land management and land use requirements, receptors, risk, cost, maintenance, sustainability and regulatory requirements will also influence the approach selected.

It is important to recognize that the science and engineering of ARD management, especially related to prevention and mitigation, are evolving. There are no off-the-shelf solutions that can be applied at all sites that will guarantee acceptable water quality through prevention of ARD or leaching of soluble constituents from mine rock, tailings or other mine materials. Therefore, the planning for and management of mine material handling and storage should be considered in a risk-based framework. While a risk-based approach should apply to other aspects of ARD such as prediction, as discussed in Chapter 5 of this Guide, it is especially relevant to the planning and implementation of prevention and mitigation methods that will inevitably have unique features and issues that are associated with site-specific and mine-specific conditions.

Prevention and mitigation of ARD is an exercise in water quality management. One important feature of managing water quality associated with mine materials is delay times between implementation of remedial activities and observed or measured water quality from a facility such as a mine rock stockpile or a tailings impoundment. Delay times between implementation and monitoring or measurement of effects often result in the need for long periods of monitoring or testing to determine the outcomes of implemented methods. There is a growing foundation of long-term studies and case histories for prevention and mitigation strategies in the literature and in practice at many operations. With the exception of water covers that are relatively well understood, the scientific and engineering community are on an ongoing learning curve for many of the other ARD management approaches. Therefore, prevention and mitigation planning should be undertaken with due consideration of key uncertainties and appropriate management of risks to achieve the desired outcomes. While it is not practical to wait years or decades to confirm successful performance of proposed waste management methods, adaptive management techniques are needed and appropriate to respond to unexpected responses while maintaining environmental protection and cost control.

An understanding of delayed responses to test conditions or mitigation activities is important to anticipate potential outcomes and to correctly interpret data collected from tests or full-scale facilities. In some cases, delays can result from chemical behavior. The time to deplete neutralization potential (NP) and to the onset of low-pH conditions is an obvious example of such delays. In this case, we understand the process of NP depletion and with the appropriate data, the depletion times can be estimated even if test results did not exhibit depletion.

There are other, more subtle, changes that can also occur over time that can represent delays as well. For example, Rinker et al. (2003) showed that neutral drainage from humidity cell tests of mine rock from a nickel deposit exhibited delays of 20 to 50 weeks before exhibiting nickel concentrations that exceeded 0.01 mg/L. In that case, the elevated nickel values were triggered by a pH shift from 8 to 7.5. After recognizing the mechanism that was responsible for the increased nickel, the process and the outcome can be accounted for and therefore managed as required. Similar delays in metal release were observed in field-scale mine rock pile tests at a copper-zinc mine in South America. The test piles had been operating for four years with relatively low metal concentrations in the drainage. A shift in pH from 7.5 to 6.3 resulted in the release of copper and zinc concentrations in the tens of mg/L range in the drainage samples.

Although delays from chemical processes like those described in the previous paragraph can occur, the more common causes of delays are generally related to the hydraulics of rock piles and tailings facilities, or a combination of hydraulics and chemical reactions. The hydraulics or hydrology of mine rock piles and tailings deposits are relatively well understood and can be evaluated with proven science and engineering principles. Combining the hydraulic and chemical behavior is somewhat more complex, but conceptual models can be developed and translated to quantitative models or calculations as discussed in Section 5.5. Nonetheless, the monitoring of such facilities to assess performance of mitigation measures is not always straight forward. For example, it is not easy to measure leaching or water quality effects in a field-scale rock pile. Therefore, it is often necessary to collect and monitor drainage at the base of the pile. Depending on the size of the pile, this could represent years of delay between the changes that may occur in the pile and those observed in the drainage. The processes would therefore normally be modeled to better understand the expected water quality and timeframe for anticipated changes, and the modeling results would guide the monitoring program.

This chapter emphasizes examples and case histories in an attempt to assist the reader in understanding approaches to prevention and mitigation strategies that have been applied and for which performance data are available.

6.2 Goals and Objectives of Prevention and Mitigation

Prevention is a proactive strategy that obviates the need for the reactive approach to mitigation. Mitigation will be the usual initial course of action for an existing case of mine drainage that is adversely impacting the environment. Despite this initial action, subsequent preventative measures may also need to be considered in the context of reducing future contaminant load, and thus reducing the ongoing need for mitigation controls. For example, the amount of seepage requiring treatment may be reduced if the current source strength is reduced.

For both prevention and mitigation, the strategic objectives must be identified because, to a large extent, these strategic objectives will define the control methods that need to be used. The process of identifying the strategic objectives should consider the following:

- Quantifiable risks to ecological systems, human health, and other receptors
- Site-specific discharge water quality criteria
- Capital, operating, and maintenance costs of mitigation or preventative measures
- Logistics of long-term operations and maintenance
- Required system longevity

- Risk of system failure and identification of potential modes of failure

ARD/ML prevention is the key to avoid costly mitigation. ARD, NMD, and SD are all the result of natural weathering processes that occur under atmospheric conditions. The primary goal of the prevention is to stop contaminated drainage from leaving the mine site at its source by minimizing reaction rates, leaching, and the subsequent migration of weathering products from mine waste to the environment.

A typical objective for ARD control is to satisfy environmental criteria using the most cost-effective technique. Technology selection should consider predictions for discharge water chemistry, advantages and disadvantages of treatment options, risk to receptors, and the regulatory context, including permitted discharge water quality (see Chapter 9).

6.3 Approach to Acid Rock Drainage Prevention and Mitigation

Prevention of ARD can be achieved through a risk-based planning and design approach that is applied throughout the mine life cycle. However, prevention is primarily accomplished in the assessment and design phases. The prevention process aims to quantify the long-term impacts of alternatives and to use this knowledge to select the option that has the least impact. Mitigation measures implemented as part of an effective control strategy should require minimal active intervention and management.

The primary approach to the prevention and mitigation of ARD is to apply methods that minimize the supply of the primary reactants for sulphide oxidation, and/or maximize the amount and availability of acid neutralizing reactants. These methods may involve one or more of the following:

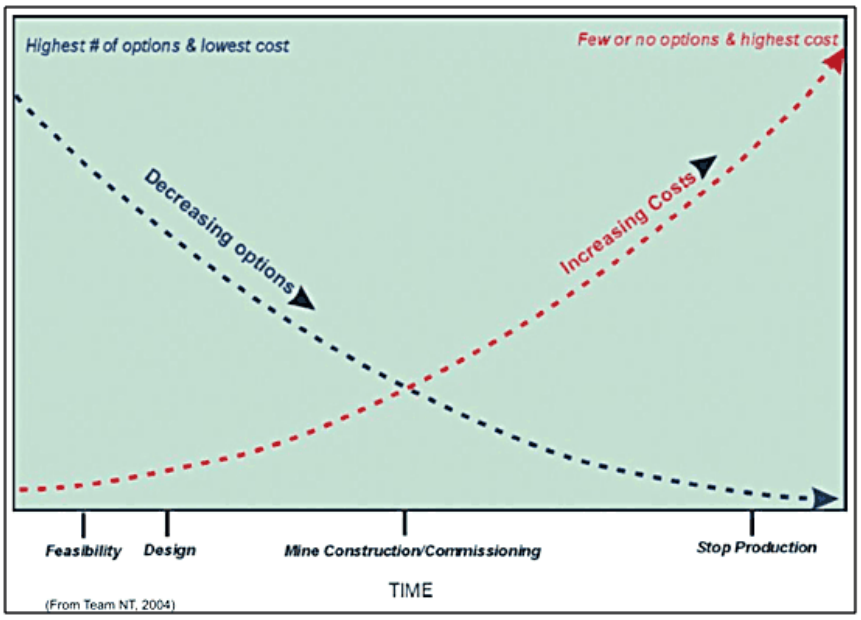
- Minimizing oxygen supply because of diffusion or advection
- Minimizing water infiltration and leaching (water acts as both a reactant and a transport mechanism)
- Minimizing, removing, or isolating sulphide minerals
- Controlling pore water solution pH
- Maximizing availability of acid neutralizing minerals and pore water alkalinity
- Controlling bacteria and biogeochemical processes

Factors influencing selection of the above methods include the following:

- Geochemistry (i.e., sulphide/carbonate content and reactivity) of source materials and the potential of source materials to produce ARD
- Type and physical characteristics of the source, including water flow and oxygen transport
- Mine development stage – (More options are available at early stages.)
- Phase of oxidation – (More options are available at early stages when pH may be near neutral and oxidation products have not significantly accumulated.)
- Time period for which the control measure is required to be effective
- Site conditions – location, topography, and available mining voids, climate, geology, hydrology and hydrogeology, availability of materials, and vegetation
- Criteria for discharge
- Risk acceptance by company and stakeholders

In general, more options and more effective options are available earlier in the mine life, as indicated in Figure 6-1. More than one measure, or a combination of measures, may be required to achieve the desired objective.

Figure 6-1: Options and Effectiveness with Time (TEAM NT, 2004)



6.4 Drivers of Acid Rock Drainage

The primary drivers of ARD can be classified in three distinct categories of physical factors, geochemical weathering processes, and climate and physical environment. Each is described below in Sections 6.4.1 through 6.4.3.

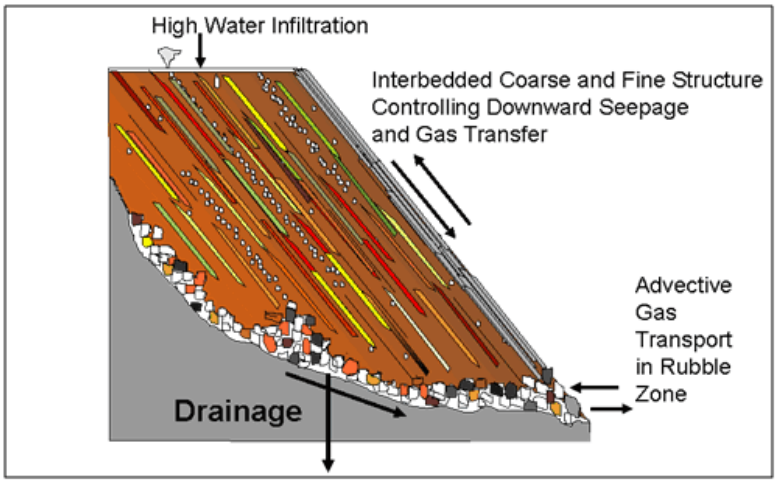
6.4.1 Physical Factors

The structural nature and physical environment of the ARD source material influences selection of the most appropriate method(s) for prevention and mitigation. Typical mining and non-mining related sources of ARD are reviewed in Chapter 4. Specific mining related examples include the following:

- Waste rock – coarse, highly permeable unsaturated porous overburden material (boulder to sand size) deposited in the mine pit or as rock piles above the natural topography
- Tailings and coal refuse – fine, variably saturated or unsaturated porous material (clay to sand size) derived from ore processing or beneficiation, generally deposited in engineered impoundments
- Spent ore and heap leach residues
- Open or filled pits, containing rock debris, massive and fractured rock
- Underground mine structures, shafts, drifts, and stopes
- Block cave rubble zones (can be transitional between waste rock and fractured rock medium characteristics)

The structural nature and physical environment of each source must be described with respect to the water table, seepage and flow, degree of saturation, oxygen, heat, and solutes to provide a detailed level of understanding of how geometry, hydraulic properties, and structure influence control mechanisms, behavior, and performance. For example, Figure 6-2 illustrates processes that occur within a waste rock dump and are influenced by structure. By necessity, solutions to prevent or mitigate ARD will therefore be site specific.

Figure 6-2: Waste Rock Pile Structure and Processes (Wilson, 2008b)



6.4.2 Geochemical Weathering Processes

Factors that control the generation of ARD and other mine drainages (see Chapter 1) are described in Chapter 2. The integration and coupling of ARD factors must be used to assess the best approach to prevention and mitigation of ARD. Controls may be targeted at each aspect of the ARD generation process.

6.4.3 Climate and Physical Environment

A physical environment is formed when water and energy budgets are coupled with the terrain, landforms, surface topography, soils, stratigraphy and geology, surface hydrology, hydrogeology, and flora. Together these factors comprise an "earth system" and need to be considered in developing the most suitable methods for prevention, control, and mitigation of mine discharges.

For example, in open pit hard rock mines, most of the mine wastes are typically stored on the surface and exposed to atmospheric conditions. Because the main source of mine drainage is meteoric water, local climate has a direct influence on the selection of prevention and mitigation methods for ARD. The Köppen system (Peel et al., 2007) is a well known method for climate classification. Methods for prevention and mitigation that are suitable in a tropical humid climate, such as Borneo, Indonesia, may fail in a dry climate such as the Pilbara region of Western Australia or the polar climate in the Northwest Territories of the Canadian Arctic.

Sample Climate Classification (Köppen system)

- Tropical humid
- Dry
- Mild mid - latitude
- Severe mid - latitude
- Polar
- Highland

6.5 Phased Approach

A phased approach to the implementation of methods for prevention, control, and mitigation is recommended. Experience based on direct observation is of great value for decision analysis (adaptive management) and the design of systems for prevention and mitigation.

For example, longer-term data for some ARD methods (e.g., water covers) are now available. As discussed in Section 6.1, time frames associated with mine life cycles are decades and sometimes centuries, so the time frames required for the verification of prevention and mitigation methods may be long.

Scientific Method

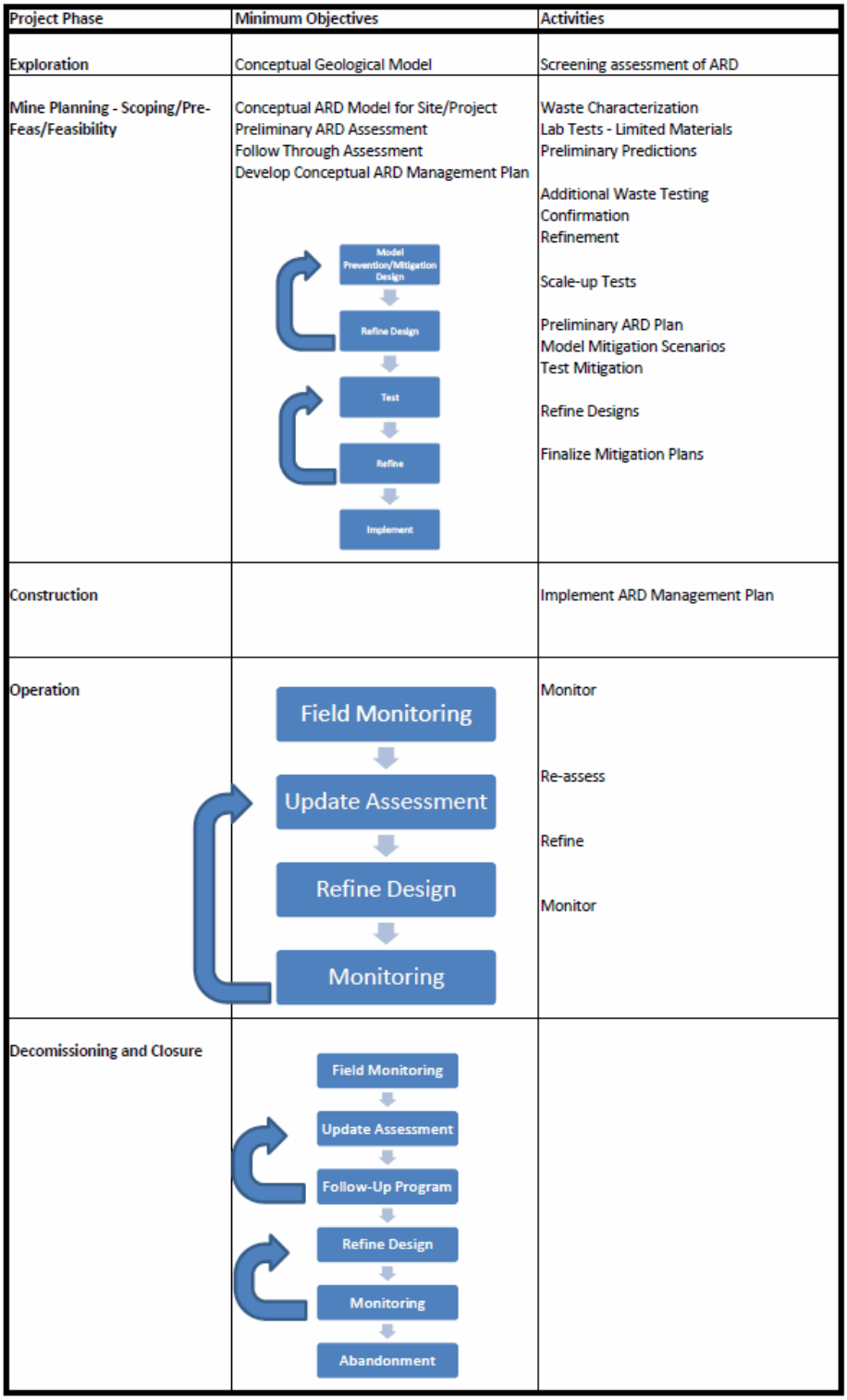
- Question
- Hypothesis
- Experiment
- Analysis
- Conclusions

Therefore, assessment, design, testing and refinements should take place at all phases of the project although varying in intensity of effort. During exploration, activities are minimal and a screening assessment of a few representative samples for ABA would be adequate. During project planning, the effort should be consistent with the advancement of the project, with preliminary efforts at the scoping stage to identify possible risks and issues, to more advanced and intensified assessment and identification of preferred ARD management options for various mine components.

These concepts have been articulated in Chapters 1 and 5 and are illustrated in Figures 1-2 and 5-1. Figure 6-3 builds on Figure 5-1 with an emphasis on the development of prevention and mitigation strategies and plans. Because of the site-specific nature of methods and the evolving nature of scientific

understanding and engineering experience, there is a need for continuous feedback, assessment and refinement at the various stages of mine planning, development, operations and decommissioning.

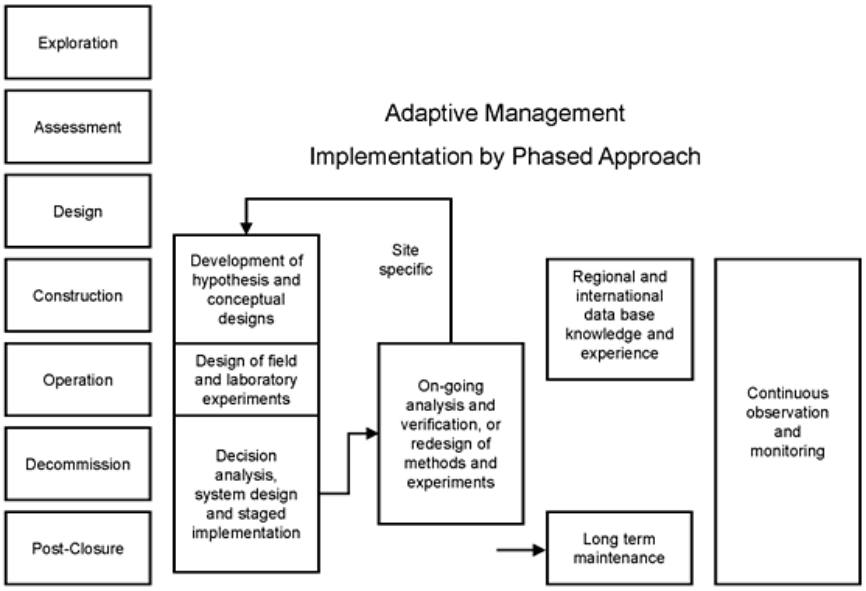
Figure 6-3: Adaptive Management Approach to Prevention and Mitigation of ARD



The observational approach based on scientific methods is the most appropriate approach. The ARD prevention plan should be as robust (based on scientific and engineering methods) and flexible as possible so that it can be adapted based on observed performance. Figure 6-4 illustrates adaptive management and implementation using a phased approach, which begins with the development of hypotheses and conceptual designs based on site characterization and problem definition. The phased process can begin and enter at any stage of mine development. The key step is to develop a system design that leads to the basis for analysis and the capacity to make decisions. The process should include a staged approach that allows ongoing analysis, verification, and improvement in system design. Regional and local experience at nearby mines, where available, should also be used to minimize redundant investigations and to optimize the most successful methods for prevention and control. The phased approach leads to development of a monitoring and

maintenance program that reinforces and improves system design and performance.

Figure 6-4: Adaptive Management Implementation by Phased Approach

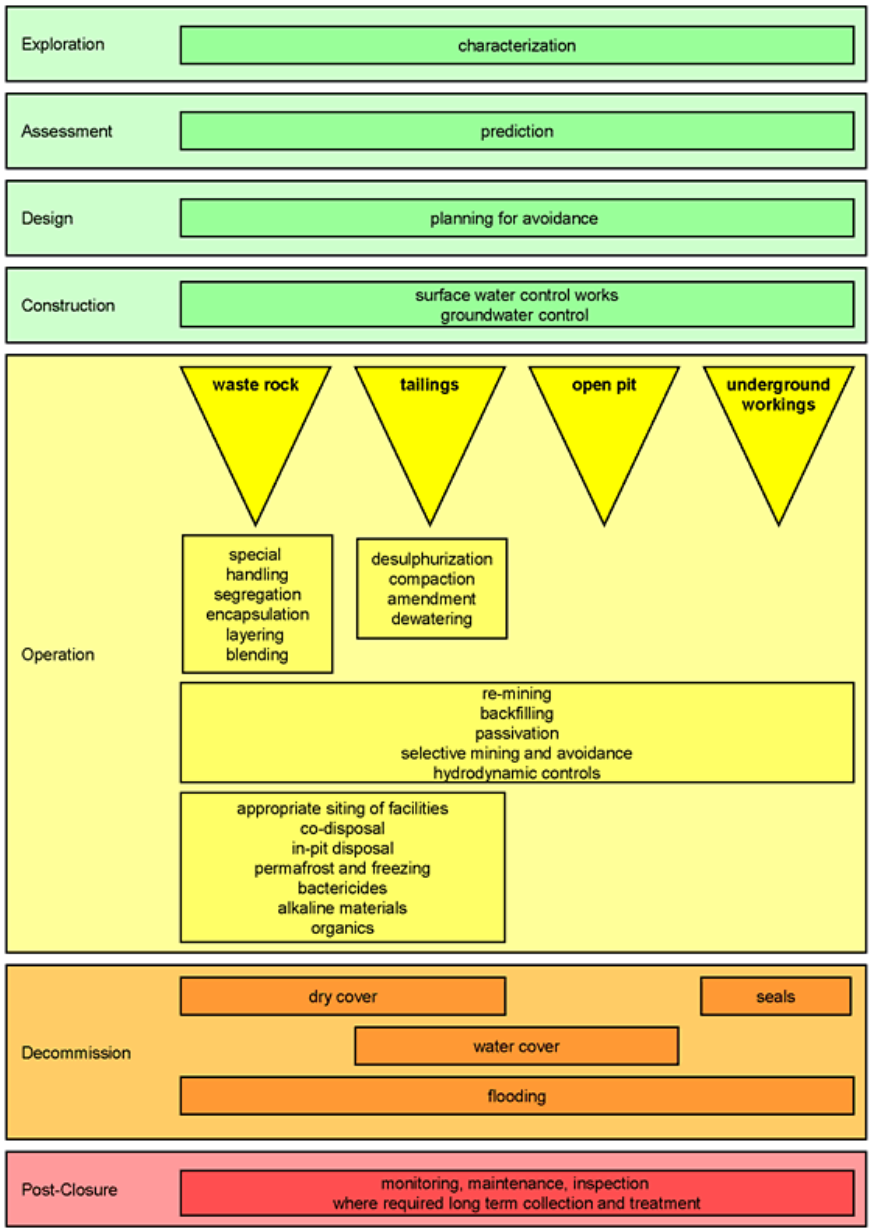


6.6 Overview of Best Practice Methods

This section presents a summary of the methods available for prevention and mitigation of mine drainage, as shown in Figure 6-5. The purpose of this section is to provide an overview of best practice methods. Detailed design manuals, such as MEND (2001), MEND (2004a) and DWAF (2007), are provided in the reference section.

Technically, "prevention" implies plans or activities before the fact that will result in no undesirable effects as a result of mine waste management. For example, direct deposition of unweathered sulphide tailings under water during operations to prevent acid generation and metal leaching may be considered a preventive action. "Mitigation" can be applied to prevent the occurrence of ARD or as a corrective action to an existing condition. For instance, oxidized acidic tailings can be flooded to mitigate water quality effects by preventing future acid generation, but soluble metals may be released from past oxidation. Because some methods can be applied during the planning stages as true "prevention" strategies as well as corrective strategies for existing conditions to mitigate ARD and water quality impairment, the prevention and mitigation methods have not been separated in the following discussion. However, where appropriate, cautionary notes have been added in the text to indicate where performance of particular methods may differ when applied to fresh, newly deposited materials versus historic, previously exposed materials with soluble loads of acidity and/or other constituents. For example, flooding of both fresh non-oxidized and pre-acidified tailings can be beneficial. However, as mentioned above, the pre-acidified tailings will need to be managed appropriately to account for the acid and metals that will be flushed from the tailings and the time that will be required before the overlying water quality approaches the desired criteria or target concentrations.

Figure 6-5: Methods for Prevention and Mitigation of ARD



6.6.1 Avoidance

Sites that generate ARD with a high solute load and concentrations of contaminants can incur significant long-term ARD treatment costs that can impair the economic success and, in some cases, the viability of a project. Measures for ARD prevention, mitigation, and treatment must therefore be included in evaluation of mine lifecycle costs, both for processing wastes that are derived from the ore and overburden or waste rock that must be stripped to access the ore. The result of this overall assessment may be a decision not to mine a particular rock mass at some mines, or to mine in a manner that might initially be thought to be more costly (ADTI, 1998).

Early avoidance of ARD problems is a best practice technique that may be achieved through integrating the results of characterization and prediction, described in Chapters 4 and 5, with mine planning, design, and waste management strategies.

Avoidance is not synonymous with non-development in mining. Avoidance includes the decision not to extract a particularly reactive rock type that will be too difficult to manage in the future. This may require the development of mine designs that avoid or work around difficult rock types through alteration of mine access, inclines, stopes, and open pit designs.

6.6.2 Re-mining

Historical legacy sites that are currently generating ARD are some of the most difficult to remediate because significant volumes of reactive wastes may need to be managed or even moved. However, sometimes abandoned surface or underground mines can be re-mined to remove valuable material that remains. Re-mining provides opportunities to improve waste disposal systems and reduce or remove sulphide minerals.

Re-mining methods used include the following:

- Excavation and milling of waste rock and tailings deposits
- Covering and burial of existing waste piles with new benign waste
- Push-back of existing pits walls to excavate and process reactive rock, leaving lower grade non-reactive wall rock
- Excavating areas previously mined by room-and-pillar methods, extracting the reactive rock along with the remaining commodity (e.g., coal), also called “daylighting”
- Re-handling wastes and moving them to improved storage facilities

Typically, at coal mines, re-mining and reclamation reduce acid loads by:

1. decreasing infiltration rates
2. covering acid-producing materials
3. removing the remaining coal which at many sites is the source of most of the pyrite.

However, re-mining can also expose pyritic overburden strata and so can actually degrade water quality unless supplemental abatement measures, such as alkaline addition, are used (Hawkins, 1998). Therefore, an assessment of re-mining options should consider the potential long-term costs for mitigation and treatment of drainage versus the potential for increased recovery of resources. At many sites, the value gained from extraction can finance further opportunities to mitigate ARD (PaDEP, 1998 Chapter 17).

6.6.3 Special Handling Methods

Specialized handling procedures for mine waste products, including tailings and waste rock, are often adopted as part of a strategy to minimize ARD. This is often the first step in implementing the ARD management plan. The handling procedures are based on the result of the ARD prediction program (Chapter 5). Special handling approaches are discussed in this chapter and in Chapter 9.

6.6.3.1 Incorporation in Mine Plan

Mine waste handling may be incorporated into mine planning to minimize exposure of materials to atmospheric conditions and minimize the volume of material left on surface at closure. Examples of common practices include the following:

- Use of tailings backfill for underground support. This method can also reduce overall costs compared to conventional hydraulic backfill.
- Subaqueous disposal of reactive wastes in mine voids, including placing mining wastes into open pits and underground workings. The economic feasibility of this practice is highly site specific, but is fairly common, and the approaches are well developed. Mined-out pits can provide a void for storage of tailings, waste rock, or seepage water. Pits provide the potential for long-term geologically stable containment while traditional impoundments often require monitoring and maintenance to ensure stability of the constructed embankments over the long term.
- In-pit disposal of tailings or waste rock may be combined with other strategies, such as subaqueous or underwater disposal, alkaline addition, cover technologies, and sulphate reduction, which are described later in this chapter.
- Minimization of the waste footprint to reduce capping and revegetation costs, or to reduce the surface area exposed to precipitation and oxidation.
- Avoidance of placing waste storage facilities near sensitive receiving environments or regionally significant aquifers.

6.6.3.2 Segregation

Segregation of waste rock (also referred to as selective handling) involves physical separation of PAG and NAG materials (MEND, 2001). While segregation on its own does not prevent ARD, it is often a necessary step within the mitigation plan. PAG materials may be used or placed in engineered configurations to minimize impacts to the receiving environment. Commonly, one attempts to either ensure that PAG material is kept completely saturated (to minimize exposure to air) or to minimize surface and groundwater contact with PAG materials while maximizing water contact with alkalinity generating materials. Segregation of ore and waste is standard mining practice, and similar techniques may be used to separate waste types (see Chapter 9). The development of an ARD management plan that involves segregation generally proceeds as follows:

- The mine waste plan is developed based on detailed geochemical characterization using procedures defined in Chapters 4 and 5 and appropriate models (i.e., block models for open pits).
- Waste management and operational monitoring programs are established to identify and segregate materials before handling, transport, and deposition.
- Special handling procedures are developed, such as cellular construction of waste piles or purpose-built repositories for reactive materials with

system design to provide isolation and sealing (e.g., subaqueous disposal of reactive wastes or storage of PAG rock within tailings impoundments). Waste rock lifts might be compacted or covered with thin layers of lower permeability material to inhibit infiltration and oxygen transfer.

At coal mines, the PAG material is typically placed on a pad of non-reactive rock so that it is elevated above any fluctuating water level in the pit. The material should be compacted and treated with alkaline material to neutralize the acid-producing potential, capped with a layer of low permeability material, and then covered with non-acid-producing material and topsoil to reduce water and air movement into the reactive rock. Further information on special handling at coal mines may be found in Perry et al. (1998: http://www.dep.state.pa.us/dep/deputate/minres/districts/cmdp/chap14.html), Skousen and Ziemkiewicz (1996), and Hawkins (2004).

6.6.3.3 Tailings Desulphurization

The concept of desulphurization of tailings to prevent ARD has been considered since the early 1990s (Bois et al., 2004). The concept is based on the separation of non-economic sulphide minerals into a low-volume stream, leaving the majority of the tailings with a low sulphur content that will be less reactive and preferably non-acid generating. The two tailings streams can then be managed differently. The high-sulphur material can be selectively deposited in the tailings pond to remain submerged in water during operations and post closure. Alternatively, the high-sulphur tailings can be managed to ensure that they will be covered by the low-sulphur material after closure if assessment shows that this approach is considered protective of water quality during operations and in the long term. In any case, there will be a need to manage the high-sulphur tailings that presumably will represent only a small fraction of the total tailings volume produced during the operation.

Desulphurization can be achieved in different ways, depending on the ore type and metallurgical process used to extract economic minerals from the ore. A separate flotation circuit or additional flotation cells to increase sulphide removal in the mill can be constructed. Bois et al. (2004) showed that metal mine tailings containing about 20% S could be separated by flotation, into materials containing 0.5% S and 43% S. Hesketh et al. (2010) also demonstrated sulphur removal by flotation technology and achieved a low sulphur tailings with 0.22% S that was non-acid generating with a net neutralization potential (NNP) of 25 kg-$CaCO_3$/t.

Sulphur separation was used at a mill that processed nickel sulphide ore in Canada. The sulphur was initially removed to lower the sulphur content in coarse-grained tailings that were used for mine backfill. The fine fraction or cyclone overflow was utilized as a low-sulphur cover material on existing high-sulphur tailings (Martin and Fyfe, 2011).

Sulphur separation can also be achieved as an objective of metallurgical processing of ore, for porphyry copper ores, for example. Metallurgical separation of sulphur in ore can be used to increase efficiency of copper recovery producing a “rougher” tailings with a low sulphur content and a “cleaner” tailings with a high sulphur content. Examples of such metallurgical processes have resulted in low-sulphur tailings that contain less than 0.03% S with a positive NNP and will not generate acid. The corresponding high-sulphur tailings stream can contain on the order of 5 to 10% S, and would typically represent less than 10% of the total tailings mass. At a proposed copper mine in Central America, the high sulphur tailings will be deposited under water into the pond within the tailings impoundment during operations and then will also be covered by low-sulphur tailings at the end of the operation (AMEC, 2010).

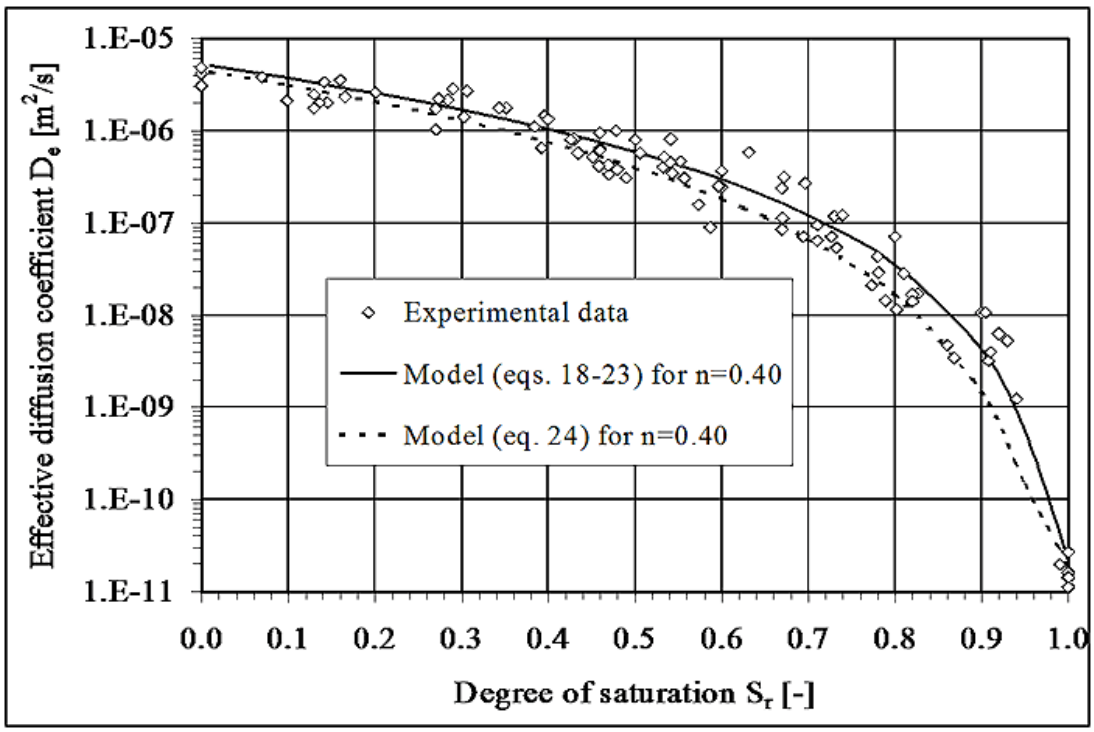
Depyritized tailings with non-acid generating or acid consuming characteristics may be stored in large-volume repositories. Relatively clean tailings materials may also be used for other prevention and mitigation methods, such as soil covers (Sjoberg-Dobchuk et al., 2003). The acid generating characteristics of the depyritized tailings should be verified to ensure that it is not acid generating before it is used as a cover material.

In general, the feasibility of this sulphide separation option depends on the characteristics of tailings and therefore must be assessed for site-specific conditions. The flotation processes must be sufficiently effective to remove enough sulphide minerals to render the remaining tailings as non-acid generating. The cost of the process may be offset by the production of a relatively clean tailings material that can potentially be used to provide a final cover layer, rather than having to mine or import material from elsewhere **(MEND, 2001; Bussière, 2007; Strathcona Case Study)**.

6.6.3.4 Compaction and Physical Tailings Conditioning

Control of physical properties of tailings may be accomplished by methods including thickening, filtration, compaction, and gradation control. The purpose of conditioning is to improve physical properties, such as reduction of hydraulic conductivity, to limit the ARD process. For example, a decrease in porosity may result in a decrease in both hydraulic conductivity and oxygen diffusion. Figure 6-6 (Aubertin, 2005) illustrates the relationship between the coefficient of oxygen diffusion and degree of saturation for soils or porous media. It illustrates that oxygen diffusion rapidly decreases by 3 to 4 orders of magnitude as the degree of saturation increases above 85%. The concept described here has been successfully implemented at a number of sites, including the multi-layered cover design at the Les Terrains Auriferes (LTA) site in Quebec, Canada described by Bussière (2007). This case was also reported as a MEND study and can be found on the web site http://www.mend-nedem.org/.

Figure 6-6: Coefficient of Diffusion versus Degree of Saturation for Saturated Porous Media (from Aubertin, 2005)



Traditional disposal of tailings slurry to impoundments by hydraulic deposition typically produces a beach of coarser material near the spigot and finer materials further from the spigot. The beach materials are usually above the water table and are unsaturated and therefore prone to oxidation. Sulphide segregation may occur on beaches due to the higher specific gravity of pyrite versus other non-sulphide minerals including carbonates. Finer tailings tend to have lower permeability, water retaining capacity and resistance to air entry, and are more likely to be saturated. However, finer materials are often unconsolidated and prone to liquefaction and settlement that make reclamation more difficult.

For geotechnical reasons, the embankments for tailings impoundments are generally designed to be well drained and unsaturated. Construction of embankments with sulphide-bearing tailings may pose significant ARD risks compared to construction with inert materials.

Several methods are available to improve physical properties of tailings (Bussière, 2007). Tailings can be thickened (removal of water) to produce a non-segregating material or paste (ACG, 2006). Selection of thickening technology depends on tailings geochemical and physical characteristics and must be reviewed on a site by site basis. Compaction of placed materials will decrease oxygen diffusion and void ratios, decrease water permeability, increase water retention, and increase saturation levels. Installation of wick drains or blast densification can achieve the same result, depending on the tailings deposit.

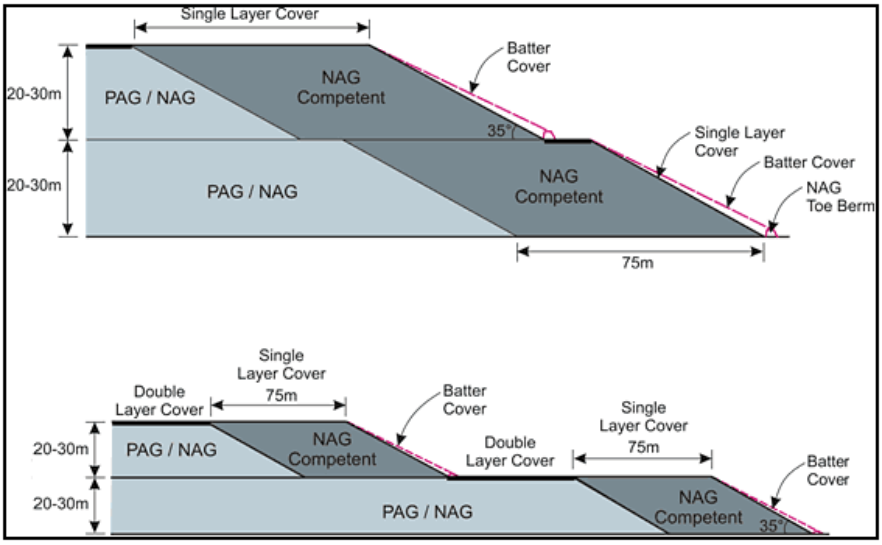
Layering tailings deposits with clean or low sulphur layers may decrease oxygen gradients and limit oxygen diffusion. Tailings gradation and fines content may be adjusted to create fine layers that maintain high saturation (Figure 6-7) and restrict oxygen flow to underlying sulphide-bearing coarser layers. This method of layering is best implemented as a closure approach to create a cover, and may be achieved through controlled tailings discharge management and deposition planning.

6.6.3.5 Encapsulation and Layering

Encapsulation and layering involves placing acid producing and acid consuming materials (typically waste rock) in geometries designed to control or limit ARD. The effectiveness of the encapsulation and layering is governed by availability of materials, the general balance between acid producing and acid neutralizing materials, the type and reactivity of acid-consuming material, deposit geometry, the nature and flow of water through the deposit, and chemical armoring of alkaline materials (MEND, 1998a and 2001; Miller et al., 2003 and 2006). Layering of waste rock and tailings materials is discussed below in Section 6.6.3.7.

Encapsulation has been applied for acidic historic tailings that were moved to expand a pit at a gold mine in the Timmins region, Ontario Canada. The acidic Pamour tailings were relocated in 2006 **(Pamour Case Study)**. The tailings were placed on a layer of neutral tailings containing excess carbonate minerals and covered by similar material. Experimental studies were also completed to evaluate final water quality and results were reported in MEND, 2010.

Figure 6-7: Example Waste Rock Encapsulation Strategy



6.6.3.6 Blending

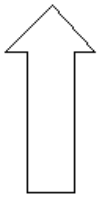
Blending is the mixing of waste rock types of varying acid generation and neutralization potential to create a deposit that generates a discharge of acceptable quality. The effectiveness of blending as an option depends on the availability of materials and the mine plan, the general stoichiometric balance between acid producing and acid neutralizing materials, geochemical properties, reactivity of waste rock types, flow pathways created within the deposit, and the extent of mixing and method of blending. Homogeneous and thorough mixing is generally required to achieve maximum benefit (MEND, 1998a and 2001). Evidence from field trials indicates limited success with mixing of waste rock types using haul trucks, but better mixing of waste rock with limestone was achieved using a conveyor system and stacker (Miller et al., 2006).

Operational experience indicates that, for effective blending of PAG rock with limestone, it is essential that all size fractions within the blend be at least acid-base neutral (i.e., NPR (ANC/MPA) of at least 1). Since the run of mine particle size of limestone is generally coarser than PAG rock, the acid base balance or NPR of the bulk waste rock needs to be greater than one. Experience with rock types at Freeport (Indonesia) and Ok Tedi (Papua New Guinea) indicates that well-mixed PAG and limestone rock needs to have a bulk NNP of more than 150 kg $CaCO_3$/t (or net acid production potential (NAPP) of less than 150 kg H2SO4/t). The actual blend will depend on site factors and particle size distribution for each rock type.

6.6.3.7 Co-disposal

Co-disposal is the disposal of waste rock with tailings. Co-disposal can take several forms, which vary depending on the degree of mixing, as summarized in Table 6-1 (Wickland et al., 2006).

Table 6-1: Forms of Co-Disposal (from Wickland et al., 2006)

Co-disposal Type	
Homogeneous mixtures - Waste rock and tailings are blended to form a homogeneous mass – "paste rock."	Increasing degree of mixing
Pumped co-disposal – Coarse and fine materials are pumped to impoundments for disposal (segregation occurs on deposition).	
Layered co-mingling – Layers of waste rock and tailings are alternated.	
Waste rock is added to a tailings impoundment.	
Tailings are added to a waste rock pile.	
Waste rock and tailings are disposed in the same topographic depression.	

Co-disposal has the potential to limit ARD as follows:

- Co-disposal of highly reactive waste rock within saturated tailings impoundments
- Layered co-mingling of thickened tailings and waste rock
- Thorough mixing of paste or filtered tailings with waste rock to create "paste rock"

In each case, loadings of leaching products can be reduced as a result of restricted access to oxygen as well as reduced flow rates through the deposit

compared to conditions within a typical waste rock pile.

For ideal mixing, the void space of waste rock particles are filled with finer tailings particles which typically have a higher moisture content, thereby limiting the transport of oxygen and water relative to deposits of waste rock alone. Amendment of tailings with alkaline materials is possible, and co-disposed materials will have a lower rate of ARD production than only blending of waste rock types. Benefits and considerations for co-disposal are listed in Table 6-2.

Table 6-2: Benefits and Considerations of Co-Disposal

Additional Benefits	Considerations
▪ Minimization of footprint or volume required for disposal ▪ Physical stability ▪ Possible use as cover material ▪ Possible elimination of the tailings dam ▪ Creation of an elevated water table within deposits	▪ Waste production schedule and sequencing ▪ Proportions of waste rock to tailings, or strip ratio ▪ PAG/NAG ratio ▪ Erodibility of gap graded mixtures ▪ Methods for mixing and placement with respect to maximum particle size ▪ Limitations on future remining of tailings

Pumped co-disposal of coarse and fine coal beneficiation wastes has been implemented at coal mines in the United States, Australia, and Indonesia since the 1990s (Williams et al., 1995), though pumped co-disposal typically results in a segregated deposit. Co-disposal is used in South African coal operations where coal slurry is placed within a dam constructed of coarse reject. Mixing waste rock and tailings for blended co-disposal and paste rock at operating hard rock mines appears promising, but is in the research stage and, as of 2012, has not been implemented at full scale.

6.6.3.8 Permafrost and Freezing

Permafrost or ice covers approximately 25% of the earth's surface, and the mine operator may take advantage of cold conditions to control weathering and drainage. Permafrost is generally defined as ground that remains below 0º Celsius for more than 2 years. The term permafrost does not imply ice or water content.

Freezing of materials to control acid generation has been used as a strategy to control ARD at several northern sites (MEND, 2004b). However, it should be noted that chemical activity does not stop at 0º Celsius, and freezing point depression, caused by higher concentrations of dissolved solids in water, may result in unfrozen water in mine waste materials at temperatures well below freezing.

Periodic warming of the surface during summer periods in zones of permafrost results in thaw within an upper "active zone." Strategies for limiting chemical weathering may include a cover that prevents penetration of the active zone into PAG materials so that the PAG materials remain frozen (MEND, 2009).

Tailings deposition planning may be optimized to promote freezing during winter months and limit thawing during summer months. Thermal analysis is required to predict long-term freezing of reactive materials. Experience has shown that tailings will freeze on cold sites, such as at the Nanisivik Mine, Nunavut, Canada (Claypool et al., 2007).

As a general rule, permafrost encapsulation requires approximately -8º Celsius mean annual air temperature. One possible limitation of relying on freezing alone is the potential for climate change associated with global warming (MEND, 2001 and 2004b).

6.6.4 Additions and Amendment Methods

Methods for use of amendments and additions are described below in Sections 6.6.4.1 through 6.6.4.4.

6.6.4.1 Passivation

Passivation is the treatment of reactive rock surfaces to limit release of leaching or oxidation products by creating a chemically inert and protective surface layer. Few systematic studies have been performed, especially at the field scale, and operational use of passivation techniques is essentially non-existent.

Under EPA's Mine Waste Technology Program, MSE Technology Inc (MSE) conducted three comparative evaluation studies to evaluate several ARD passivation and microencapsulation technologies. Laboratory-based weather accelerated conditions were studied for two commercial technologies. This work indicated that the KEECO treatment (see below for more detail) was successful in preventing or delaying ARD with the initial consequence of generating very high pH levels. This work also indicated that the MT2 EcoBond treatment (see below for more detail) delayed the onset of ARD.

A field multi-cell evaluation of four treatment technologies (KEECO, potassium permanganate, EcoBond, and lime) indicated that the permanganate and

lime technologies were able to prevent or delay ARD formation. An evaluation demonstration of four technologies on an open-pit mine highwall indicated that all treatments reduced the concentrations of SO4-2 removed and reduced the mobility of metals from the highwall.

Several of the technologies that have undergone investigation are discussed in more detail in the following sections.

Potassium Permanganate

A potassium permanganate based passivation technology was developed by DuPont (DeVries, 1996) and is owned by University of Nevada, Reno (UNR). The pyritic rock surfaces are first rinsed with a solution of lime, sodium hydroxide, and magnesium oxide at a pH >12, followed by treatment with potassium permanganate. The overall reaction generates a manganese/iron/magnesium surface, which is resistant to further oxidation and substantially reduces the ARD generation. Pilot-scale experiments have shown that passivation with potassium permanganate can substantially reduce contaminant release for more than 5 years, but the long-term stability of this treatment still needs to be established. Treatment of freshly mined surfaces has shown the greatest success, and requires the lowest consumption of reagents compared to treatment of aged reactive rock surfaces, which often have high acidity and contain an oxidation rind that limits the effectiveness of passivation (Miller and Van Zyl, 2008).

Phosphate Coatings

Application of soluble phosphate together with hydrogen peroxide generates an inert surface layer. The hydrogen peroxide oxidizes pyrite and produces ferric iron, which reacts with the phosphate to produce a surface-protective coating of ferric phosphate on pyrite surfaces. Evangelou (1998) proposed an alternative coating technique involving the formation of an iron oxide/silica coating on pyrite surfaces.

The application of phosphate fertilizers was proven to be an effective short-term method. However, the results of long-term field trials demonstrate that coarsely granulated waste rock was not coated by secondary phosphate solid phases and that amendment by phosphate rock or phosphate fertilizer did not improve leachate quality compared to the unamended waste (Mauric et al., 2011).

Laboratory experiments (Harris and Lottermoser, 2006) demonstrated that the application of bulk industrial chemicals (potassium permanganate and water-soluble phosphate fertilizer Trifos, Ca(H2PO4)2) to partly oxidized, polymineralic mine wastes can inhibit sulphide oxidation and metal and metalloid mobility. Chalcopyrite and galena were found to be abundantly coated with metal, metal-alkali and alkali-phosphate. The technique was ineffective at suppressing oxidation of arsenopyrite and preventing the release of arsenic from mine waters.

Combined Phosphate and Thiocyanate Treatment

Combined phosphate and thiocyanate treatment has been presented as an effective coating technology (Olson et al., 2005) to prevent ARD generation. Thiocyanate at low concentrations is a strong and selective inhibitor of microbial iron oxidation, which prevents severe ARD generation that lessens the effectiveness of phosphate in precipitating Fe and Al phosphate coating on pyrites. The technology was tested at the Red Dog zinc-lead mine in northwestern Alaska on sulphidic waste materials at a kg scale in laboratory humidity cell and column leach tests and at 600-ton scale in field trials (Olson et al., 2005). Thiocyanate addition reduced ARD generation by 50% or more compared to untreated sulfidic waste. Low dosages of phosphate materials combined with thiocyanate treatment reduced ARD generation beyond that was achieved with thiocyanate alone.

High-pH Aluminum Waste

Treatment of acid generating pyritic rock surfaces with high-pH aluminum waste (ITRC, 2008) offers certain benefits that can not only neutralize acidic rocks but also provide a passivation layer for the remaining rock. In this treatment, waste from aluminum smelters, which generally has a high pH, is mixed with either the acidic waste rock or an acid drainage solution. The resulting precipitate on the rock surface serves to limit further oxidation of reactive surfaces.

EcobondTM

Metal Treatment Technologies (MT2) has developed a proprietary phosphate-based solution, which aims to generate a stable and insoluble ferric–phosphate coating on the acid generating rock. The technology forms a stable iron phosphate complex on acid generating rock that is intended to resist hydrolysis and prevent further oxidation.

Silica Micro-Encapsulation (SME)

Klean Earth Environmental Company (KEECO) has developed a proprietary silica microencapsulation treatment to coat acid generating rock surfaces. The silica treatment was found to prevent acid generation for over six years (Eger and Antonson, 2002, 2004; Eger and Mitchell, 2007).

6.6.4.2 Alkaline Materials

A relatively common approach to mitigation of ARD is the control of solution pH by the addition of alkaline materials. Methods for use of alkaline materials include blending with waste rock, amendment of tailings, placement of alkaline material above or below wastes as liner or cover materials, and treatment of drainage (BC AMD, 1989; PaDEP, 1998, Chapter 13; Miller et al., 2003 and 2006; and Taylor et al., 2006).

Addition of alkaline materials can control ARD, provided intimate blending can be achieved; this is often a difficult task. The effectiveness of the method is dependent on the pathways of movement of water through the system, degree of mixing, and the nature of the contact between acidic rock and the alkaline materials. If the mixture is not homogeneous and there is not good contact between the materials, then localized “hot spots” of acid generation may occur.

The type, purity, reactivity, availability, and proportion of the alkaline material are also important. Common additives at metal mines include limestone ($CaCO_3$) and lime (CaO or Ca(OH)2). Liquid forms are considerably diluted relative to solid forms and have limited longevity, but may provide better penetration of the acid generating mine waste.

At coal mines, limestone is often the least expensive and most readily available source of alkalinity. It has a neutralization potential (NP) between 75 and 100% of $CaCO_3$ equivalent, and is safe and easy to handle. On the other hand, it has no cementing properties and cannot be used as a barrier or low-permeability material. Fluidized Bed Combustion (FBC) ash generally has NP values between 20 and 40% of $CaCO_3$ equivalent, and tends to harden into a cement after wetting (Skousen et al., 1997a). Other power-generation ashes, like flue gas desulfurization (FGD) products, may also have significant NP, which can represent suitable alkaline amendment materials (Stehouwer et al., 1995). Kiln dust, produced by lime and cement kilns, contains similar NP levels as FBC ash, but also contains 50 to 70% un-reacted limestone. Kiln dust absorbs moisture and hardens upon wetting (Rich and Hutchison, 1994), and is widely used as a stabilization and barrier material at coal mines in the US.

Steel slags, when fresh, have NP values from 45 to 90% of $CaCO_3$ equivalent. Steel slag can be used as an alkaline amendment as well as a medium for alkaline recharge trenches. Slags are produced by a number of processes, so care is needed to ensure that candidate slags are not prone to leaching metal ions like Cr, Mn, and Ni. Potential sources of alkaline material should be checked by a complete analysis (see Chapter 5) to evaluate the possibility of adverse effects on leachate water quality.

Use of alkaline materials overlying acid generating mine waste can provide a long-term source of alkalinity, may lead to formation of a “chemical cap” (i.e., a hardpan) at the interface between alkaline and acid generating material, and may produce a passivating coating on the surface of acid generating particles. However, the effectiveness of this approach depends on the solubility of the neutralizing agent and the flux of infiltrating water available to carry the alkalinity down to the underlying sulphidic waste. Use of alkaline materials underneath acid generating mine waste may result in formation of a passivating coating on the surface of alkaline particles, thus reducing considerably the effectiveness of this strategy. Benefits and limitations of alkaline amendments are summarized in Table 6-3.

Table 6-3: Benefits and Limitations of Alkaline Amendments

Configuration	Benefits	Limitations
▪ Liquid amendment	▪ Excellent initial control of solution pH ▪ Versatile - allows localized treatment ▪ Proven to work	▪ Time - alkaline materials are consumed by even pH-neutral water ▪ Readily flushed from storage facility ▪ Cost and availability of reagents ▪ Particle size and release of alkalinity ▪ Effort for mixing or blending
▪ Layering	▪ Easy to implement and manage	▪ Difficult to obtain mixing of alkaline and acid leachate due to preferential flow
▪ Encapsulation and Alkaline Cover	▪ Easy to implement and manage ▪ Versatile and allows localized treatment	▪ Cost and availability of material ▪ Time and release rate of alkalinity ▪ Alkaline materials are consumed by pH neutral water
▪ Blending	▪ Excellent pH control ▪ Proven to work	▪ Cost of mixing and blending ▪ Availability of materials

6.6.4.3 Examples of Alkaline Materials Applications

Limestone, $CaCO_3$

Rotary drum stations have been used in West Virginia to grind limestone into a powder form before application into acidic streams (Zurbuch, 1984; 1996).

Kiln dust

Rich and Hutchison (1990; 1994) reported a successful operation where 2% lime kiln dust was added to refuse at a coal preparation plant in West Virginia. The kiln dust prevented acid formation and it improved the strength of the refuse pile by absorbing moisture from the filter cake, allowing easy access for large haulage trucks. At that time, eight preparation plants in the eastern USA were using this technique.

Steel Slag

Extensive reclamation efforts at the Broken Aro Mine in Ohio, USA utilized slag beds receiving both ARD and clean water (Rose, 2010). The slag beds were used in combination with diversion of surface water, vertical flow ponds, settling ponds and other technologies to remediate contaminated waters (Laverty et al., 2007). The slag beds were found to contribute large amounts of alkalinity. Similar success of slag bed utilization was reported at the Huff Run watershed in Ohio (Hamilton et al., 2007).

6.6.4.4 Use of Organic Matter

Organic materials can be mixed directly with wastes to consume oxygen and promote metal reduction in an anoxic environment by naturally occurring bacteria. Bacteria can reduce available sulphate and create insoluble metal sulphide precipitates in the presence of suitable organic substrates. Examples of organic substrates include sewage sludge, municipal landfill waste, and pulp and paper waste. Similar concepts are described as a passive treatment method in Chapter 7. The method is limited by exhaustion of organic materials. Use of organics as part of a cover design is discussed in Section 6.6.6.2.3. A possible concern in using organic matter is that the reducing conditions generated can dissolve precipitated iron and manganese hydroxides. The latter, especially, can be problematic at coal mines.

6.6.4.5 Bactericides

In limited circumstances, anionic surfactants (the active cleansing surfactants used in detergents and shampoo) can be used to control bacteria that extract energy from the oxidation of iron, and thereby control the rate of pyrite oxidation (Kleinmann and Crerar, 1979; Kleinmann et al., 1981). The effectiveness of anionic surfactants was found to be short term and repeated application of chemicals was required (Loos et al., 1989).

The bacteria can thrive in the very acidic water because they are protected from it by a phospholipid cytoplasmic membrane. This greasy coating allows the internal enzymes of the bacteria, which require a near-neutral pH, to function normally in an acid environment (Langworthy, 1978; Ingledew, 1982). At low concentrations, anionic surfactants induce seepage of the H+ into the bacteria, which slows down iron oxidation by decreasing the activity of the pH-sensitive enzymes. Slightly higher surfactant concentrations kill the bacteria (Kleinmann, 1979, 1998).

Anionic surfactants have been successfully used in combating ARD from coal refuse, reducing acid generation by 60 to 95%. They work best on fresh, pyritic materials like the reject material from coal preparation plants. There, surfactant solutions are applied to refuse conveyor belts or sprayed by trucks onto the coal refuse 3 to 4 times a year (Rastogi, 1996). The surfactants can also be applied to older coal refuse piles, but there will be a lag period before their benefit is observed as acid already formed has to be washed out (Kleinmann and Erickson, 1981, 1983). However, applying them to sites that have already been reclaimed is inefffective because the surfactants bind to soil and dirt.

Anionic surfactants have occasionally been used at surface mines, including metal mines (Parisi et al., 1994), but often the effects at such sites have been minimal and/or short-lived. Surfactants, therefore, are not considered to represent a permanent solution to ARD. Eventually, the compounds either leach out of the rock mass or break down.

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6.6.5 Water Management Methods

Methods for water management include diversion of site surface drainage and groundwater. Water acts as a transport mechanism and as a reactant. However, the amount of water required for sulphide oxidation is virtually always present in excess, except in extremely arid environments. The primary role of water management is to reduce infiltration and thereby reduce the volume of affected drainage and potentially the contaminant loading. It is generally more cost effective to treat smaller volumes of more concentrated water than larger volumes of less concentrated water that still fails to meet discharge standards. Water management should be assessed at the local watershed scale (DWAF, 2006).

6.6.5.1 Hydrogeological and Hydrodynamic Controls

Hydrogeological controls for groundwater systems include both barriers and higher permeability features. The objective of hydrogeological controls is to control the flow of groundwater. The use of hydrodynamic control options is site specific and depends on site conditions, including climate, topography, geology, hydrology, and hydrogeology.

An example of hydrogeological containment is disposal of tailings in an open pit with a pervious surround. A granular filter layer is placed between the pit wall and the low-permeability tailings to provide a high hydraulic conductivity pathway for regional groundwater flow. Because the tailings have a lower hydraulic conductivity than the surrounding granular layer, groundwater preferentially flows around, rather than through, the tailings (e.g., Rabbit Lake Mine, Collins Bay, Saskatchewan, Canada). This can reduce the constituent loadings from the tailings pore water to the surrounding groundwater and thereby to the surface water environment.

6.6.5.2 Dewatering

Dewatering involves lowering the hydraulic head to change the hydraulic gradient. Clean upgradient groundwater can be collected before encountering reactive wastes. Examples include pit dewatering to reduce seepage into pits and shallow groundwater collection ditches upgradient of tailing ponds and waste rock piles. The collection of contaminated water using groundwater pumping is considered part of treatment (see Chapter 7). Conventional hydrogeology science can be applied to design control measures, such as well spacing and pumping rates.

6.6.5.3 Diversion

Control of surface water can minimize flow through PAG materials and thereby reduce the volume of ARD. Surface water diversion may include upstream ditching or impervious channels to divert drainage around impacted areas. Drainage works must be sized based on catchment hydrology, including snowmelt and storm events, and will typically require ongoing maintenance (because of debris accumulating, sloughing, and animal activity) to ensure long-term performance. Therefore, the best long-term solution may involve selecting storage sites that minimizes the need for surface diversion (ADTI, 1998).

In contrast, alkaline recharge trenches (Caruccio et al., 1984) are surface ditches that are intentionally constructed to allow water to slowly infiltrate into the coal mine backfill. Trenches can improve water quality at down-gradient seeps by causing the water to flow through alkaline material before it infiltrates. Early research used relatively small trenches to divert the surface water that naturally collected during precipitation events. These demonstrated minimal benefits since water movement into the backfill was limited by rainfall and the water did not move uniformly through the backfill (Caruccio and Geidel, 1989). More recent applications of this technology used water pumped from ponds into the alkaline trenches to greatly accelerate the movement of alkalinity into the backfill (Ziemkiewicz et al., 2000).

Exploration boreholes can be a source of groundwater flow that can be controlled by proper grouting following drilling. Hydraulic mine seals (discussed in Section 6.6.5.5) emplaced in underground workings are another way in which groundwater can be manipulated. Conventional grouting methods can be applied to fractured rock, but complete sealing may be difficult because water can still migrate using alternative lower permeability pathways. Grouting may also result in the build-up of large pressure-heads that have safety implications in underground mines, especially where the host rock contains karst features. French drains and soil-bentonite-slurry cut-off walls may be used at surface mines.

At many sites that have been successfully inundated, the volume of water being discharged can sometimes be large. Reducing the rate of surface infiltration may be required. Much of the surface water may enter the underground coal mine through subsidence-induced fractures that have intercepted streambeds and are partially or even completely draining the streams. These small fractures are often hidden from view by stream sediment. Hand-held geophysical instruments can be used to locate the areas where significant amounts of water are flowing underground. Small holes can be drilled or hammered into the stream less than 1 m into the rock beneath the sediment, and used to inject grout beneath the streambed. The intent is not to seal the entire fracture, but rather to seal cracks that have reached near to the stream and serve as water conduits, draining the stream into the mine (Ackman and Jones, 1991). The approach has restored 85 - 100% of stream flow and has been used to reduce infiltration into active mining operations. For more detail regarding this method, click here: Reduction of Surface Infiltration

Control of groundwater in discharge areas can be challenging to achieve and maintain. A drainage system may help to keep a mine pit relatively dry, especially at coal mine sites where water is infiltrating through the high wall. This is particularly important when the pit floor contains acid-forming materials, and when this pyritic material cannot be completely inundated when the mine is closed. Pipes or French drains have been used.

PAG waste materials should not be placed in a groundwater discharge zone (DWAF, 2006; ADTI, 1998; and TEAM NT, 2004). Soil covers may divert water and limit infiltration, and are discussed in Section 6.6.7.

6.6.5.4 Flooding

Flooding of underground or surface mine voids with water has the potential to significantly inhibit the supply of oxygen so that ARD production is not a concern (see Section 6.8.7.1). The scientific basis for the approach is also provided in MEND (2001). However, caution must be used with flooding of previously oxidized wastes because stored oxidation products may be dissolved during the initial inundation of pits, wastes, or workings. Flooding can release soluble products to the flood water and therefore provisions may be required to adjust pH to neutralize acidity or to mitigate unacceptable concentrations of other constituents.

Factors to be considered for flooding include the status of the mine plan and schedule of waste production, potential for mobilization of stored oxidation products, availability of open workings or pits, and capacity to store waste products (note that mined material will increase in volume by approximately 25% to 30% [swell factor]). ARD from block caves and glory holes may be difficult to manage as access may be restricted. However, flooding may be possible depending on bottom drainage conditions.

In humid and temperate climates with a positive water balance, flooding of underground and open pit operations will typically occur after closure. Consideration should be given to the potential soluble products that may be dissolved into the flooding waters, and implementation of mitigation strategies may be required. Mitigation may depend on the expected outflow pathways from the mine void(s). Outflow directly to surface water may require different considerations than outflow through subsurface pathways. There may be ongoing contributions of loadings from zones that will remain above the expected final water level in the mine opening(s). Water quality effects should be predicted (see Chapter 5) in order to assess the potential risks and to develop water management strategies, if required, after flooding.

There are examples of flooding to mitigate ARD and metal leaching as reported by MEND (1995) for in-pit disposal practices. One example cited was the potential relocation of weathered nickel-rich mine rock, that had elevated soluble nickel levels, to a mined-out pit at a uranium mine. The rock has been subsequently relocated in the pit, covered by a one-meter layer of till and flooded. Water quality in the pit is expected to be acceptable at closure.

Flooding after closure has also been selected as a preferred option for tailings at a number of sites. One of the best known success stories is represented by the reclamation of pyritic tailings in the Elliot Lake uranium district of Ontario, Canada (DES, 2011). Several tailings impoundments operated from the 1950s to the 1990s when decommissioning was completed. One of these, the Denison tailings management area, serves as a good example of reclamation by flooding (**Denison Case Study**). Acid generating tailings that were located in low-lying areas and in former lakes were flooded by constructing and raising dams to develop a water cover. Acidity from the tailings was treated as necessary to attain neutral pH prior to discharge. The acidity, and therefore

the need to treat and consequent lime demand, declined over several years. Most flooded tailings in the Elliott Lake district no longer require treatment for control of pH or metals.

Occasionally, water discharges from stratified mine pools. The water quality may then initially be acceptable as the infiltrating surface waters tend to be less dense than the more stagnant and concentrated water beneath. This stratification may become a concern if the deeper water reaches the level of the discharge.

6.6.5.5 Seals

When decommissioning an underground mine, knowledge of the areas within the mine that are geochemically most reactive and knowledge of water ingress and discharge locations will enable design and implementation of a rational ARD management plan aimed at controlling the flow of water to minimize water quality deterioration. This process would involve construction of seals and also perhaps reinforcing of some areas in advance of flooding to accommodate water flow. Use of seals and reinforcements is a good example of prevention and minimization by design.

Hydraulic seals limit movement of air and water through mine workings. Seals can be used to promote flooded conditions. Flooding of mine workings may generate considerable hydraulic heads and, therefore, require rigorous engineering design. An example case study for underground mine flooding is described in Lang (2007) for the Millennium Plug installed at the Britannia Mine in British Columbia, Canada. For the Britannia Mine, a concrete plug was placed within a tunnel to prevent effluent from being released to the environment, and caused flooding of the mine to prevent oxygen entry and further acid generation. The plug also resulted in water storage within the mine that served as a reservoir prior to treatment.

Sealing of drifts, adits (horizontal), and stopes (angled mine workings) is common when decommissioning an underground mine. Seal construction may include brick and mortar walls to contain concrete pumped between the seals. Horizontal seals or plugs can be left with through piping that may be opened to allow drainage of mine waters, if necessary. Where safety of workings is a concern for the construction of seals, particularly in old mine sites, concrete seals can be placed remotely through drill holes. Seals at active mines are rarely constructed remotely.

Three common and successful approaches to constructing seals include pressure grouting of adjacent ground, increasing the length of the seal to increase the seepage flow path length, and installation of secondary seals (ADTI, 1998 and ERMITE, 2003).

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6.6.6 Engineered Barriers

Engineered barriers can be applied to either cover waste or to provide a bottom barrier or liner, each with their own unique performance requirements. From an ARD mitigation purpose, covers are typically designed to limit the ingress of water and oxygen into the underlying waste. Liner systems are typically designed to act as a barrier for contaminant flow from the overlying waste into the receiving environment.

6.6.6.1 Liners

There are a multitude of low-permeability materials, ranging from synthetic to geosynthetic to natural, that can be utilized in liner systems. There are also a multitude of liner system designs that can be applied. The combination of the design and the materials will determine the leakage rate of the liner system.

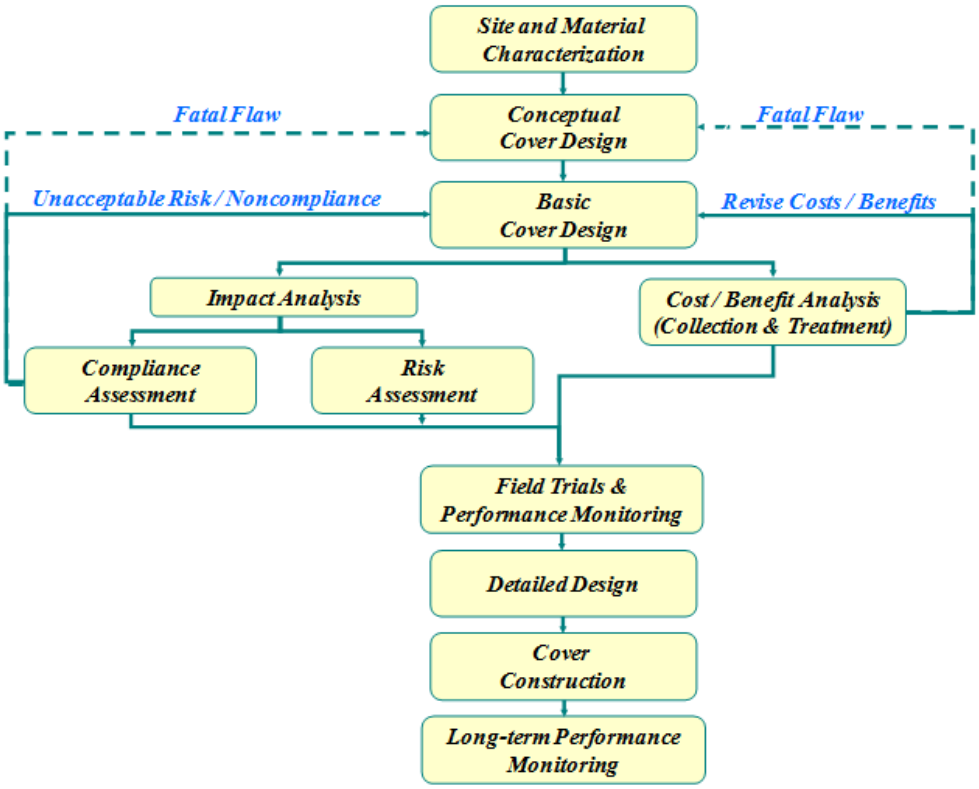
Given the relatively high cost of liner systems, it is important to quantify the performance requirements of the liner system so that the design and required materials can be optimized in terms of cost. Risk-based approaches are typically used to quantify the required liner performance against the risk of downstream receptor impact. It is also important to evaluate the robustness of the liner materials (durability, compatibility and life expectancy) against the geochemical characteristics of the drainage that will report to the liner system.

6.6.6.2 Dry Cover Methods

Dry covers are typically earthen, organic, or synthetic materials placed over mine wastes. The term “dry” cover is used to contrast them from water or “wet” covers, which are discussed in Section 6.6.7. The primary purpose of placing dry covers over reactive waste material is to minimize ARD and ML production and to minimize its transport. In addition, dry covers can also be designed to provide a suitable rooting zone for vegetation, and have minimal erosion through design of stable landforms.

Performance criteria for a given dry cover should be developed on a case-by-case basis, with due consideration of the short-term and long-term impacts on the receiving environment at a particular site (O’Kane and Wels, 2003). The objective is to determine the appropriate level of control (e.g., oxygen ingress and/or net percolation) required by the cover system. Figure 6-8 puts forward a methodology for developing site-specific performance criteria for a dry cover designed to control ARD/ML and/or gas fluxes. The methodology links the predicted performance of a cover system to groundwater, surface water, and air quality impacts.

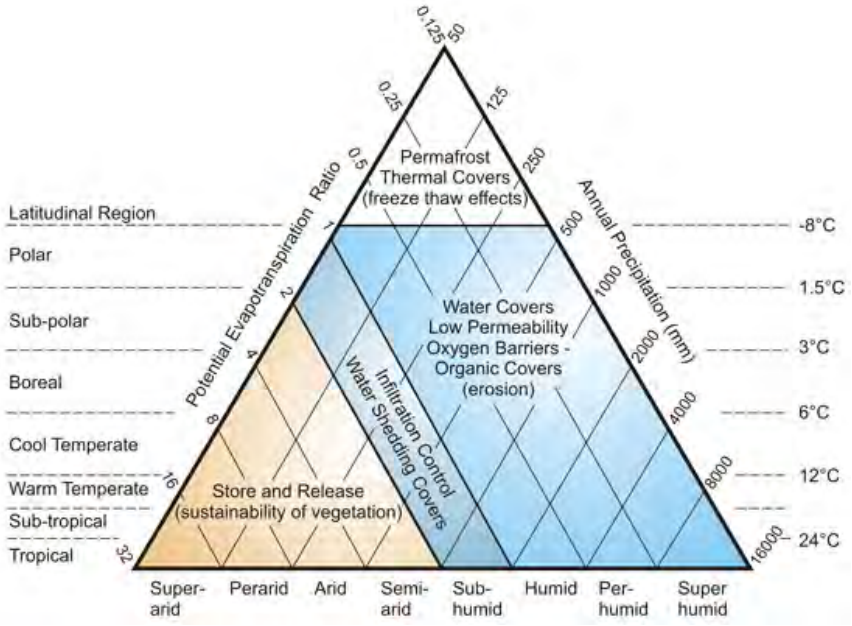
Figure 6-8: Flow Chart for the Dry Cover Design Process (adapted from O'Kane and Wels, 2003)



In the long term, dry cover systems must interact with climate, hydrology, human activity, vegetation, animals, and settlement of underlying material. Figure 6-9 which is a tri-linear plot of climate classification, rainfall, and temperature, provides general guidance on appropriate cover types for climates ranging from arid to high rainfall and tropical to polar. Oxygen barrier covers with low water permeability prevent oxygen entry by maintaining high water saturation. These covers are best suited to climate regimes where the potential evapotranspiration to precipitation ratio is less than 1.0. It is difficult to maintain saturation in dry climates where the potential evapotranspiration ratio is greater than 1.0; therefore, the design objective for the cover becomes the minimization of infiltration through water diversion, runoff and shedding, or store and release mechanisms. It is recommended that substantial caution be used when selecting a particular dry cover design based on "annual" criteria for characterizing the climate at a site. Numerous sites exist where precipitation exceeds potential evaporation on an annual basis; however, the site may experience hot, dry months where evaporation greatly exceeds rainfall. These dry summer conditions can make it difficult to design a cover system that meets all objectives throughout the year. In many instances, where the potential evaporation exceeds precipitation on an annual basis, the site might experience high intensity and short duration rainfall conditions, which may exceed the storage capacity of the cover material. Particular caution is required when there is potential for consecutive significant rainfall events, which limit the time frame for evapotranspiration to remove moisture from the previous event and therefore increase the net percolation (MEND, 2004a).

For the purposes of this guide, dry covers are divided into the following categories: soil covers (Section 6.6.6.2.1), alkaline covers (Section 6.6.6.2.2), organic covers (Section 6.6.6.2.3), covers of sulphide-bearing but net neutralizing materials (Section 6.6.6.2.4), and synthetic covers (Section 6.6.6.2.5). It should be noted, however, that organic and synthetic materials are often a component of a multi-layer soil cover. Gas barriers are briefly described in Section 6.6.6.2.6, while vegetation and landform design in relation to dry covers are discussed in Sections 6.6.6.2.7 and 6.6.6.2.8, respectively. Monitoring is briefly discussed in Section 6.6.9 and in more detail in Chapter 8; however, specific details on performance monitoring for dry covers are included in Section 6.6.6.2.9.

Figure 6-9: Covers and Climate Types (modified from Holdridge et al., 1971 by Wickland and Wilson)



6.6.6.2.1 Soil Covers

Soil covers generally involve the use of granular earthen materials placed over mine wastes (MEND, 2001). The objectives of a soil cover will vary from site to site, but generally include (i) dust and erosion control; (ii) chemical stabilization of acid-generating mine waste (through control of oxygen or water ingress); (iii) contaminant release control (through improved quality of runoff water and control of infiltration); and/or (iv) provision of a growth medium for establishment of sustainable vegetation (MEND, 2004a).

The following definitions are provided for clarification of terminology:

Dry Covers Nomenclature

- Alkaline Covers – Cover systems designed to release alkalinity to infiltrating waters. Alkalinity generally consists of dissolved carbonate species that are derived from the dissolution of limestone ($CaCo_3$).
- Dry Covers – Cover layer(s) consisting of earthen or synthetic materials in contrast to "wet" covers that involve water.
- Organic Covers – Covers consisting of organic material that may act as a reductant (electron donor) that can scavenge or remove oxygen and possibly drive other reducing reactions such as sulphate reduction.
- Soil Covers – Cover layer(s) constructed with natural earth materials that can include mine rock.
- Store and Release Covers – Cover system that is constructed to reduce net infiltration by storing moisture during higher precipitation periods and releasing moisture via evapotranspiration in dryer periods.
- Sulphide – Net Neutral – Cover material that may contain sulphide minerals as well as excess NP to prevent net acid production. There are many examples of tailings with such properties. Such a layer can scavenge oxygen and prevent further oxygen ingress.
- Synthetic Covers – Cover systems constructed with synthetic layers such as geosynthetic clay layers, various plastics or bitumen. The primary objective of such covers is to reduce net infiltration.

Key factors to consider in the design of a soil cover include:

- The climate regime at the site
- The reactivity and texture of the mine waste material
- The geotechnical, hydrologic, and durability properties of economically available cover materials
- The hydrogeologic setting of the waste storage facility
- Long-term erosion, weathering, and evolution of the cover system

Another key factor is that performance of a soil cover on a sloping surface can be much different compared to that on a horizontal surface. The ability of soil covers to function as oxygen ingress and water infiltration control will be different than that predicted by idealized one-dimensional numerical models (Boldt-Leppin et al., 1999). The difference in performance relates to site climate conditions, the slope length and angle, and hydraulic properties of the cover materials (Bussiere, 2007). Some documented case studies of "soil cover failures" are in fact a result of the soil cover being designed for a horizontal surface while being constructed on a sloping surface.

Soil store and release covers perform best in wet/dry climates with high potential evaporation equal to 2 or 3 times precipitation. These covers generally consist of a monolithic layer of well-graded granular material placed with sufficient moisture storage capacity to limit percolation of meteoric waters to the

underlying waste material. At many sites, a chemically inert run-of-mine waste material can be used to construct a store and release cover over mine wastes to reduce or control ARD production. Despite the perceived simplicity of constructing such a cover, a gap- or well-graded material will segregate when haul trucks are used to place the material (MEND, 2001). Angle-of-repose coarse layers form, which increase water infiltration and act as preferential flow paths with flow and storage characteristics different from the rest of the cover layer. Following cover placement, the material may have to be mixed to ensure that a homogeneous layer has been created. An "enhanced" store and release cover can be created by compacting the upper waste material first (Christensen and O'Kane, 2005). The compacted waste layer "holds" infiltrating meteoric waters within the overlying cover material for an increased period of time during wet periods, providing the opportunity for evapotranspiration and thus reduces the amount of runoff, and can decrease oxygen concentrations and increase the capacity for dissolution of carbonate minerals (Strock, 1998). The stored water is evaporated back to the atmosphere, rather than reporting as net percolation into the underlying waste material.

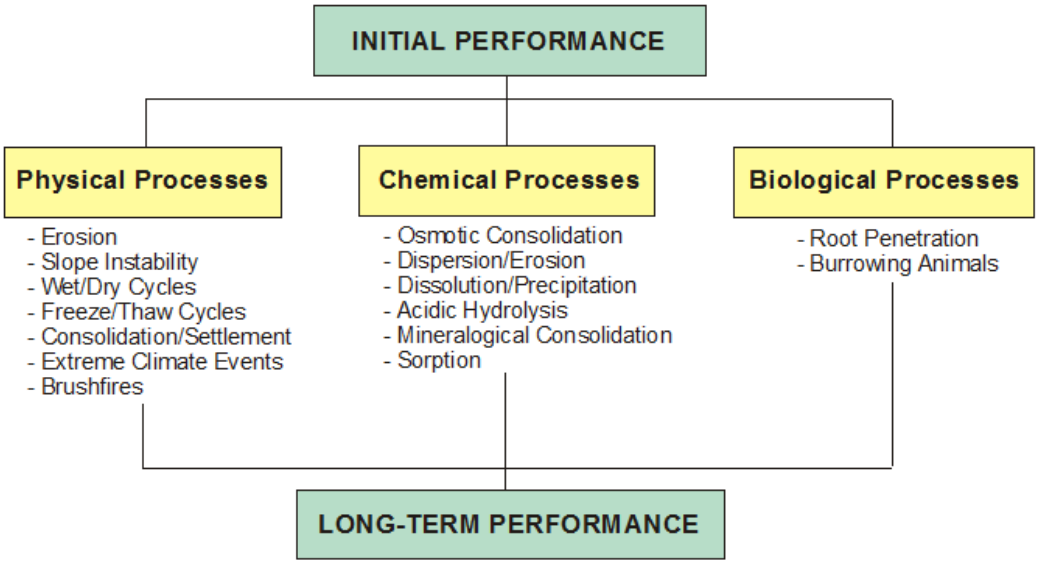
Single soil layers were also used in North America for revegetation of mining wastes and it was hoped that they would reduce ARD. However, in general, they were not effective. Engineered multi-layer soil covers for ARD control became popular in the 1990s with the development of the science of unsaturated media that enabled prediction of evaporation from soil cover systems (e.g., the SoilCover Model). Multi-layer systems in wet climates often include a relatively loose layer for vegetation roots, a compacted fine grained layer that maintains a high moisture content to reduce oxygen transfer, and a coarser capillary break that prevents upward migration of soluble salts from the underlying mine wastes. In general, compacted clay rich barrier cover designs function best in wet tropical and temperate climates. An example of a recently designed multi-layer soil cover for reactive mine waste is the one constructed over the backfilled open pit at the Whistle Mine near Sudbury, Ontario, Canada (Ayres et al., 2007).

Multi-layer soil covers may also include a capillary barrier to maintain a tension saturated layer within the cover system and thus mitigate oxygen ingress. A fine-textured material placed between an underlying and overlying coarse-textured material can result in a capillary barrier for downward as well as upward moisture migration from the "sandwiched" layer (MEND, 2004a). The lower hydraulic conductivity of the fine-textured layer (usually compacted), combined with the lower capillary barrier, also provides a control on net percolation to the underlying waste material. The design of a capillary barrier is dependent on the contrast between the hydraulic properties of both the coarse and fine materials. Capillary barriers, unlike compacted clay barriers, do not rely solely on a low hydraulic conductivity layer to restrict moisture movement into the underlying material. Processes that increase hydraulic conductivity, such as desiccation and freeze/thaw cycling, do not necessarily decrease the effectiveness of a capillary barrier (MEND, 2004a).

Often in the design and construction of a multi-layer soil cover system, the focus of the design is on the barrier layer. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium (Ayres et al., 2004). The growth medium layer serves as protection against physical processes, such as wet/dry and freeze/thaw cycling, as well as various chemical and biological processes. An inadequate growth medium layer will not properly protect the barrier layer, leading to possible changes in its performance (see INAP, 2003). One of the most common factors leading to failure of multi-layer soil cover systems is an inadequate thickness of growth medium material over the lower hydraulic conductivity layer (e.g., Rum Jungle in the Northern Territory, Australia). One key factor to consider during the design of a multi-layer cover system is the available water holding capacity of the growth medium layer to ensure that plant demands for soil water can be satisfied under drier climatic conditions, thus minimizing the potential for root penetration and desiccation of the barrier layer.

The longevity of a soil cover design should be evaluated in relation to site-specific physical, biological, and chemical processes that will alter as-built performance and determine long-term performance (Figure 6-10). It is noted, however, that in many respects the impact of biological and chemical processes specific to a site on long-term cover performance can only be evaluated from a qualitative perspective. In contrast, many of the physical processes affecting long-term performance are quantifiable using state-of-the-art technology, provided that adequate materials characterization data are available. Recent reviews based on 10 to 15 years of cover performance data indicate that covers may limit, but do not stop, infiltration and sulphide oxidation (Wilson, 2008a; Wilson et al., 2003; and Taylor et al., 2003). However, the achieved reduction in oxidation (and attendant ARD and metal leaching) may be sufficient to meet design goals and at a minimum can reduce water treatment requirements.

Figure 6-10: Conceptual Illustration of Processes Affecting Long-Term Performance of Soils Covers (from INAP, 2003)



Examples of soil cover designs are shown in Figure 6-11 (MEND, 2001). Considerations for use of soil covers are listed in MEND (2001) as well. The simplest case (i.e. the base method cover system design) is typically evaluated first during the conceptual and/or preliminary cover system design phase, and then complexity added until the desired design objectives are met. In general, increasing complexity in the design of a cover system implies increased cover system performance, but would also typically entail increased costs and a more difficult cover system to construct. Note, however, that an increase in performance is not necessarily true for all climate conditions. For example, a store and release cover in arid or semi-arid climate conditions can provide the same level of control on net percolation as compared to a cover system with a low hydraulic conductivity barrier layer or a capillary barrier cover system (MEND, 2004a). Considerations for use of soil covers are listed in Table 6-4 and an excellent similar compilation is provided in MEND (2004a).

Figure 6-11: Sample Soil Covers Designs (from MEND, 2001)

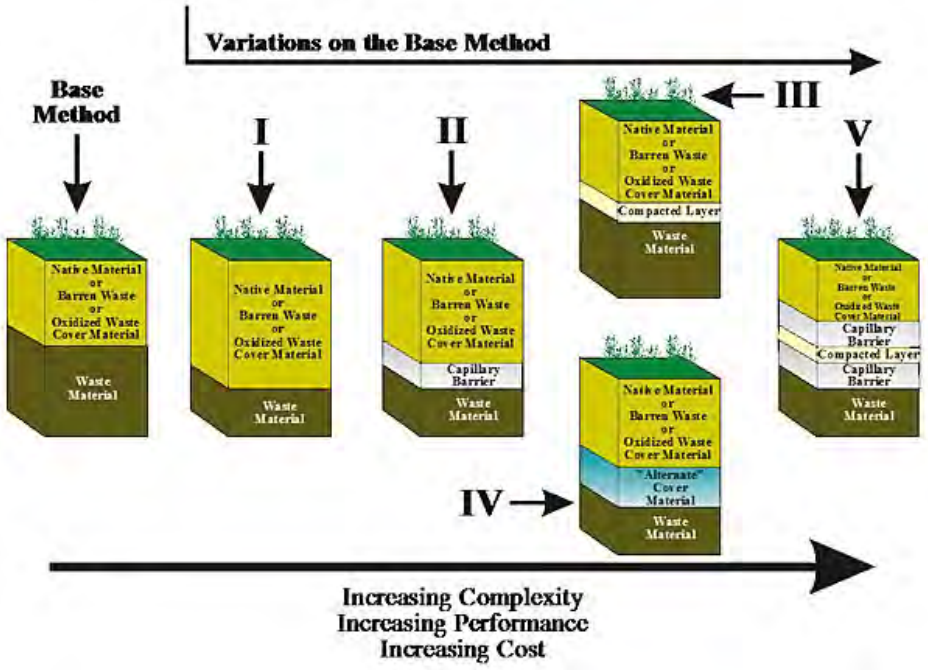


Table 6-4: Considerations and Limitations of Soil Covers

Considerations	Limitations
▪ Climate – wetting, drying, freezing, thawing ▪ Type and performance of waste (such as surface settlement), reactivity of wastes	▪ Soil covers do not stop infiltration and may not stop acid drainage. ▪ Permeability of water infiltration barriers may increase with time

▪ Surface water flow and erosion ▪ Topography ▪ Hydrogeological setting and basal flow ▪ Availability of cover materials ▪ Construction quality control and maintenance ▪ Design of landforms - final land use	when subjected to climate and vegetation. ▪ Oxygen barrier covers are especially vulnerable to relatively small imperfections in the cover – such as differential settlement, holes caused by animal burrows, desiccation cracking, – that effectively render permeable an otherwise sealed area. ▪ Soil covers may be prone to erosion and long-term maintenance requirements ▪ Soil covers may be vulnerable to vegetation, animal, and human activity including vehicle traffic

6.6.6.2.2 Alkaline Covers

The addition of alkaline materials to mine wastes has been described in Section 6.6.4.2. This section addresses alkaline covers. Alkaline cover materials, such as limestone, placed over PAG materials can increase alkalinity of infiltration, thereby providing pH control (see Section 6.8.3.6 and Section 6.8.4.2). Alkaline infiltration may react with and generate a surface coating on sulphide bearing materials that isolates sulphide minerals (Miller et al., 2003) and form a hardpan (i.e., "chemical barrier") at the contact between the alkaline material and the reactive mine waste. Use of the method must consider climate, availability of alkaline materials, geometry and reactivity of alkaline materials, and time of consumption. Infiltration through a limestone cover may transport sufficient alkalinity to neutralize the uppermost portion of the underlying waste and thus increase the effective cover thickness and slow the oxygen flux to reactive sulphides deeper in the profile. An example of the use of alkaline material in a cover is provided in the **Benambra Case Study**.

6.6.6.2.3 Organic Covers

The addition of organic matter to mine waste has been addressed in Section 6.6.4.3. Organic materials can also be used to cover PAG wastes to provide some or all of following:

- A saturated layer that serves as a physical barrier to oxygen
- An oxygen consuming layer – (Decomposition of organic material may create a large biological oxygen demand [note: may need replenishment])
- Chemical inhibition – (Decomposition products and compounds within the organic material may inhibit the growth and metabolism of acidifying bacteria)
- Chemical amelioration – (Organic compounds may create conditions that support the reductive dissolution of iron oxides and subsequent precipitation in the form of sulphides thus reducing acid production by ferric iron [see Chapter 2])
- A carbon source for sulphate reducing bacteria
- Limitation of water infiltration by lowering hydraulic conductivity

Organic materials have included pulp and paper residues, sewage sludge, bark, sawdust, sanding dust, fiberboard, pulpwood, deinking residues, peat, compost and carbonaceous matter, or waste rock rich in organic matter.

Organic covers have been shown to reduce acidity but without stopping ARD **(Case Study Organic Covers)**. Limitations to the process include availability of organic materials for cover, longevity (organic materials will become resistant to decomposition with time), and climate (humid climates may be required to maintain anaerobic conditions in the organic medium). Another example of the use of organic matter in a cover is provided in the **Benambra Case Study**.

6.6.6.2.4 Covers of Sulphide-bearing but Net Neutralizing Materials

Mineral wastes that contain sulphides, but which have an excess of neutralizing potential, can be used for covers that will consume oxygen but not contribute to ARD generation. For further information see Section 6.6.3.3 on the use of depyritized tailing covers.

6.6.6.2.5 Synthetic Covers

Use of synthetic materials to cover wastes can dramatically reduce infiltration. Synthetics include different types of plastics (polyethylene (PE), high density polyethylene (HDPE), chlorinated polyethylene (CPE), chlorosulphonated polyethylene (DuPont trade mark HYPALON), polyvinyl chloride (PVC), linear low-density polyethylene (LLDPE), geosynthetic clay liners (GCLs), and geomembranes impregnated with bitumen. A review of many types of synthetic covers is presented in MEND (2002). Synthetics are often subject to degradation by sunlight and must be protected with an earthen cover material. GCLs consist of a ~1 cm layer of sodium bentonite sandwiched between two geotextiles or glued to a geomembrane. Prior to selecting a GCL product, chemical compatibility with the overlying cover soil must be confirmed to prevent cation exchange with the bentonite layer, which can lead to substantial increases in the hydraulic conductivity of the GCL (Meer and Benson, 2007). A suitable bedding material layer (for example sand) must be laid in advance of application of the synthetic layer to prevent puncturing by underlying rock. Similarly, the synthetic layer must be carefully covered with a protective overlying layer before adding the final growth substrate or rock mulch layer. A slope stability analysis is recommended when a synthetic layer is incorporated in a multi-layer soil cover placed on relatively steep slopes. Sample configurations of synthetics in soil covers are illustrated in Figure 6-12. Benefits and disadvantages of synthetic covers are listed in Table 6-5.

At the Upshur Mining Complex in West Virginia, Meek (1994) reported covering a 20-per hectare(ha) spoil pile with a 39-mil PVC liner. This treatment

reduced acid loads by 70%.

One of the earliest HDPE covers was installed on a 46-ha tailings facility at the Poirier Mine **(Poirier Case Study)** site in Northwest Quebec, Canada in 2000 (Lewis et al., 2000). The cover has reduced acidity and metal loadings and decreased seepage from the tailings. A similar size cover system was installed on the Normetal **(Normetal Case Study)** reactive tailings in Northern Quebec, Canada. (Hofton and Schwenger, 2010).

Construction of a bitumen cover on mine rocks piles and over a partially backfilled, shallow pit at a former copper mine at Mount Washington, British Columbia, Canada was initiated in 2009 (Murphy, 2010). The historic mine operation was abandoned in the mid-1960s and copper loadings to the downstream environment were considered to have affected salmon spawning. The bitumen membrane was covered by 1 m of local till for protection. The four-hectare cover was estimated to cost about $4M CND (in 2007 $).

A GCL cover system was constructed over tailings at the Kam Kotia, abandoned copper zinc mine site (near Timmins, Ontario, Canada) over the period of 2006 to 08 (Hamblin, 2010). Mining occurred between 1943 and 1944 and again between 1961 and 1972, resulting in the deposition of almost 7 M tonnes of acid generating tailings over 500 ha, much of which did not represent an engineered impoundment. The 80 ha GCL multi-layer cover was estimated to cost $16.5 M Cdn (2008) or about $200,000 per ha. The cover system consisted of a GCL membrane over the existing granular material on the tailings and in order, overlain by 0.15 m of clay, 0.6 m of granular fill with a 0.15 m layer of topsoil at surface.

Figure 6-12: Sample Configurations of Synthetics in Soil Covers

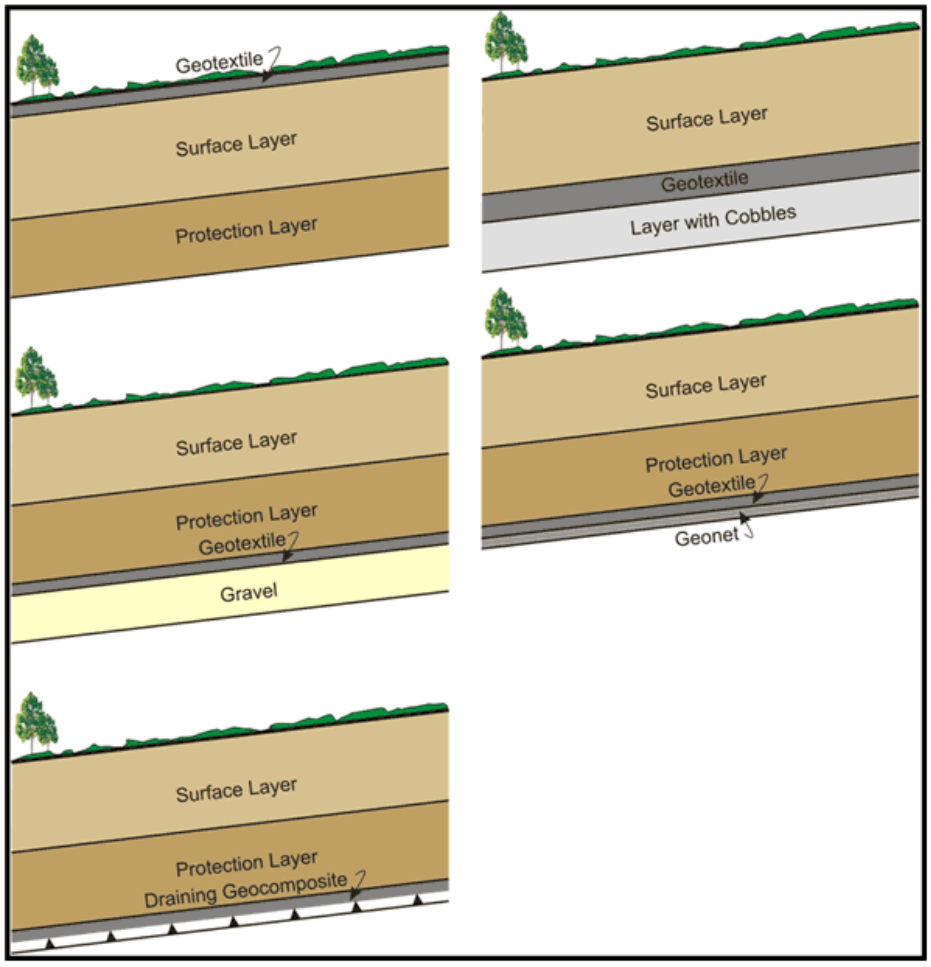


Table 6-5: Benefits and Disadvantages of Synthetic Covers

Benefits	Disadvantages
▪ Low permeability ▪ Easy to install ▪ Resistant to chemical and bacterial attack	▪ High cost ▪ Costly depending on distance between site and the product supplier ▪ Possible limited design life - on the order of 50 to 100 years ▪ Requires proper bedding and protective cover ▪ Geotechnical stability concerns for steep slope applications ▪ Vulnerabilities include: ▪ Sun light ▪ Puncture by surface traffic ▪ Cracking and creasing

	▪ Difficulties in seaming ▪ Uplift pressure from contained fluid or gases ▪ Degradation due to low acidity conditions / cation exchange for GCLs ▪ Differential settlement of underlying materials ▪ Thermal expansion and contraction (high thermal coefficient)

6.6.6.2.6 Gas Barriers

Flooding of underground mine workings with deoxygenated air (e.g., nitrogen) could prevent ARD, but applications are relatively rare. Mine ventilation is controlled during operation and any post-closure investigations must consider safe work procedures for confined spaces. For example, atmospheric levels of radon may increase (e.g., Lisheen Mine, Ireland). See Chapter 8 for reference to the extreme safety hazards posed by deoxygenated air as illustrated by fatalities in a sampling shed at the Sullivan Mine in British Columbia, Canada.

6.6.6.2.7 Vegetation

Establishment of vegetation is often included as a criterion for closure. The purpose of the vegetative cover may include erosion control, enhancement of evapotranspiration as part of a store and release cover system, re-establishment of sustainable ecosystems, and satisfaction of requirements for post-closure land use, including regulatory requirements and visual appeal. Depending on leaf area index, vegetation may increase the evapotranspiration rate up to a maximum equal to the potential evaporation rate provided an unlimited supply of soil water is available to the plant roots. The function of vegetation for store and release covers is important as it can substantially reduce the net percolation of meteoric waters to the underlying waste compared to a bare surface condition. The overall performance of the vegetation cover is dependent on the cover density, the species composition, and the available rooting depth. Generally, a diverse vegetative community that mimics or replicates the existing native communities in the surrounding area will provide the best long-term cover performance. A cover that is too thin will not only limit the volume of water that can be stored during wet periods, but will also limit the types of vegetation that can become established.

Effects of vegetation must be considered in engineered soil cover design with respect to ARD. Vegetation may physically alter cover systems by way of holes because of roots, tree throw, or blow down, and may uptake and transport contaminants from below the soil cover. Root penetration of cover systems may effectively bypass capillary break layers and provide a pathway to the surface ecosystem. Root exudates and decomposition products create soil structure that increases the permeability of clays. This may have undesirable consequences for water penetration and gas exchange. In many cases, however, an underlying barrier cover layer can be protected provided the growth medium or protective cover layer is thick enough to provide sufficient available water for plant growth. A properly designed growth medium (thickness and moisture retention characteristics) is more important to the long-term integrity of an underlying low permeability layer, than the properties and characteristics of the low permeability layer itself. One of the most common reasons for failure of a low permeability layer (i.e. eventual increase in permeability) is an inadequate growth medium layer, where inadequate generally implies insufficient thickness.

Long-term maintenance requirements must consider effects of vegetation. Vegetation growth will increase organic content of the cover, and its decay will consume oxygen (see Section 6.8.6.3).

Many jurisdictions encourage the use of local or native species to ensure ecological continuity with surrounding areas and minimize care and maintenance. However, seed of native species may not be readily available or they may be costly. Also, native species may be difficult to establish and lack the grazing resistance and erosion control properties of agronomic species.

6.6.6.2.8 Landform Design

The long-term integrity of dry cover systems must consider the effects of climate and extreme climatic events, hydrology, animals, vegetation, and bio-geochemistry. The closure landform will evolve or develop into a condition that is in steady-state harmony with its surroundings. The rate of evolution and the desired end point must be included as goals for reclamation. Cover systems that shed water might increase the potential for erosion and therefore the specified physical design parameters (e.g., slope angle and length) must take into account the variability of the local climate (MEND, 2007a). Some ongoing maintenance may be required for at least a period of time after closure.

6.6.6.2.9 Performance Monitoring of Dry Cover Systems

Historically, dry cover system performance was evaluated by water quality analyses of seepage discharged from the waste storage facility. This approach empirically describes a waste storage facility through monitoring of its cumulative effect at the base (Morin and Hutt, 1994). In addition, for sites actively generating ARD, monitoring gaseous oxygen and temperature profiles can also serve as a tool for the evaluation of cover system performance because the profiles indicate the internal behaviour of the a waste storage facility (Harries and Ritchie, 1987). Although these monitoring techniques have their merits, it may take tens of years before a considerable change is measured inside or downstream of the waste storage facility due to the drain-down effect and complete oxidation of sulphidic minerals.

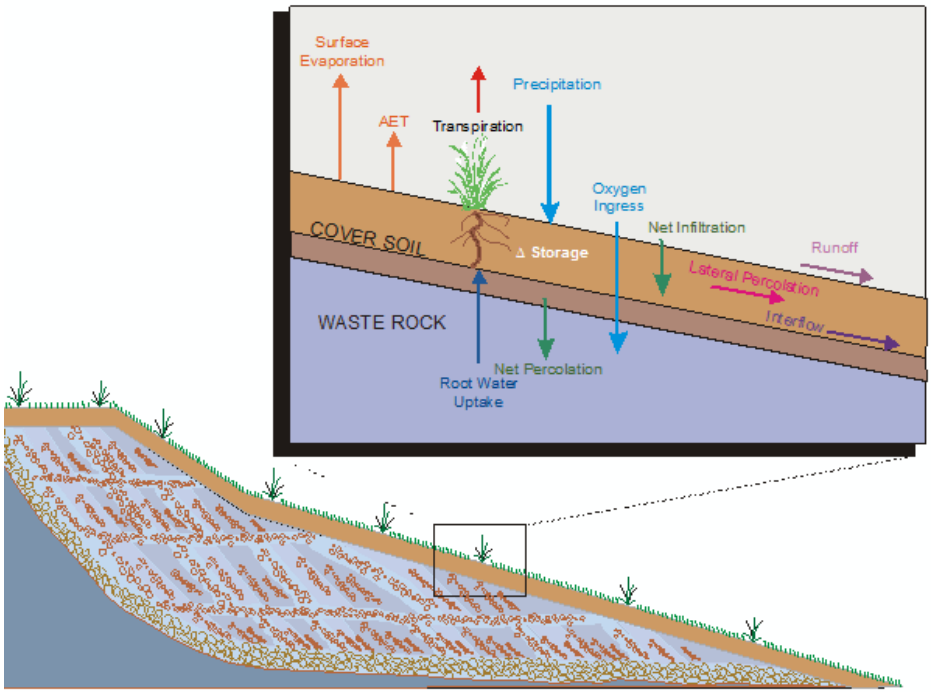
Direct measurement of field performance is the state-of-the-art methodology for measuring performance of a cover system. Field performance monitoring can be implemented during the design stage with test cover plots (e.g., MEND, 2007a; Aubertin et al., 1997; O'Kane et al., 1998a), or following

construction of the full-scale cover (e.g., O'Kane et al., 1998b; Ayres et al., 2007). Direct measurement of field performance of a cover system is the best method for demonstrating that the cover system will perform as designed. The main objectives of field performance monitoring are to (MEND, 2004a):

- Obtain a water balance for the site
- Obtain an accurate set of field data to calibrate a numerical model
- Develop confidence with all stakeholders with respect to cover system performance
- Develop an understanding for key characteristics and processes that control performance

In terms of a field test plot trial scale, cover system field performance monitoring systems should be designed to measure most of the components of the water balance as well as oxygen ingress rates, as shown schematically in Figure 6-13. This includes meteorological monitoring, monitoring of moisture storage changes, and monitoring of net percolation, surface runoff, erosion, and vegetation (MEND, 2004a). For field performance monitoring for a full-scale cover system, a recommended minimum level of monitoring would include meteorological monitoring (i.e. determination of potential evaporation rates), site-specific precipitation, cover material moisture storage changes, watershed or catchment area surface runoff, vegetation, and erosion (MEND, 2004a).

Figure 6-13: Conceptual Schematic of the Components of a Field Performance Monitoring System (from MEND, 2004a)



6.6.7 Water Cover Methods

Disposal of acid generating materials below a water cover is one of the most effective methods for limiting ARD generation. In water, the maximum concentration of dissolved oxygen is approximately 30 times less than in the atmosphere. More importantly, the transport of oxygen through water by advection and diffusion is severely limited relative to transport in air. For example, the diffusive transfer of oxygen in water is on the order of 10,000 times slower than diffusive transfer in air. Results of field and laboratory testing have confirmed that submergence of ARD generating materials is one of the best available methods for limiting ARD generation over the long term (MEND, 2001). Other mechanisms associated with water covers include sulphide reduction by bacteria, metal hydroxide precipitation, and development of sediment layers, which inhibit interaction between tailings and overlying waters.

Water covers can be attained in various ways. There are examples of sulphide materials deposited in natural water bodies to take advantage of physically stable, depositional environments. Mined out pits are also being used for under water deposition and storage of sulphide tailings (MEND, 1995). In other cases, engineered structures are used to raise or control water levels. Water covers can be developed at closure as discussed for the uranium mines in the Elliot Lake district of Canada (Section 6.6.5.4) or deposition under water can be achieved during operation such as that at the Louvicourt Mine in Quebec, Canada (MEND, 2007b) and at the Voisey's Bay Nickel Mine in Labrador, Canada. Some operations have comprehensive programs for long-term subaqueous deposition of sulphide tailings. Vale's Thompson tailings basin has been in operation since 1955 with underwater disposal of tailings and plans for raising the water levels in the basin as required to an expected closure in 2030 (Cochrane, 2012).

6.6.7.1 Subaqueous Disposal

Water covers limit the exposure of PAG materials to oxygen. Example configurations for subaqueous tailings disposal are shown in Figure 6-14. Generally, sufficient depth of water over the PAG material must be provided to account for mixing of the water column and to prevent resuspension of wastes by

wind or wave action. Water covers may not be suitable for material that has already appreciably oxidized. The "cut off" point at which this distinction is made will be mine-waste specific. General processes for water covers are illustrated in Figure 6-15. Sediment layers can help isolate subaqueous wastes and adjustment of water cover chemistry is also possible.

Figure 6-14: Subaqueous Tailings Disposal

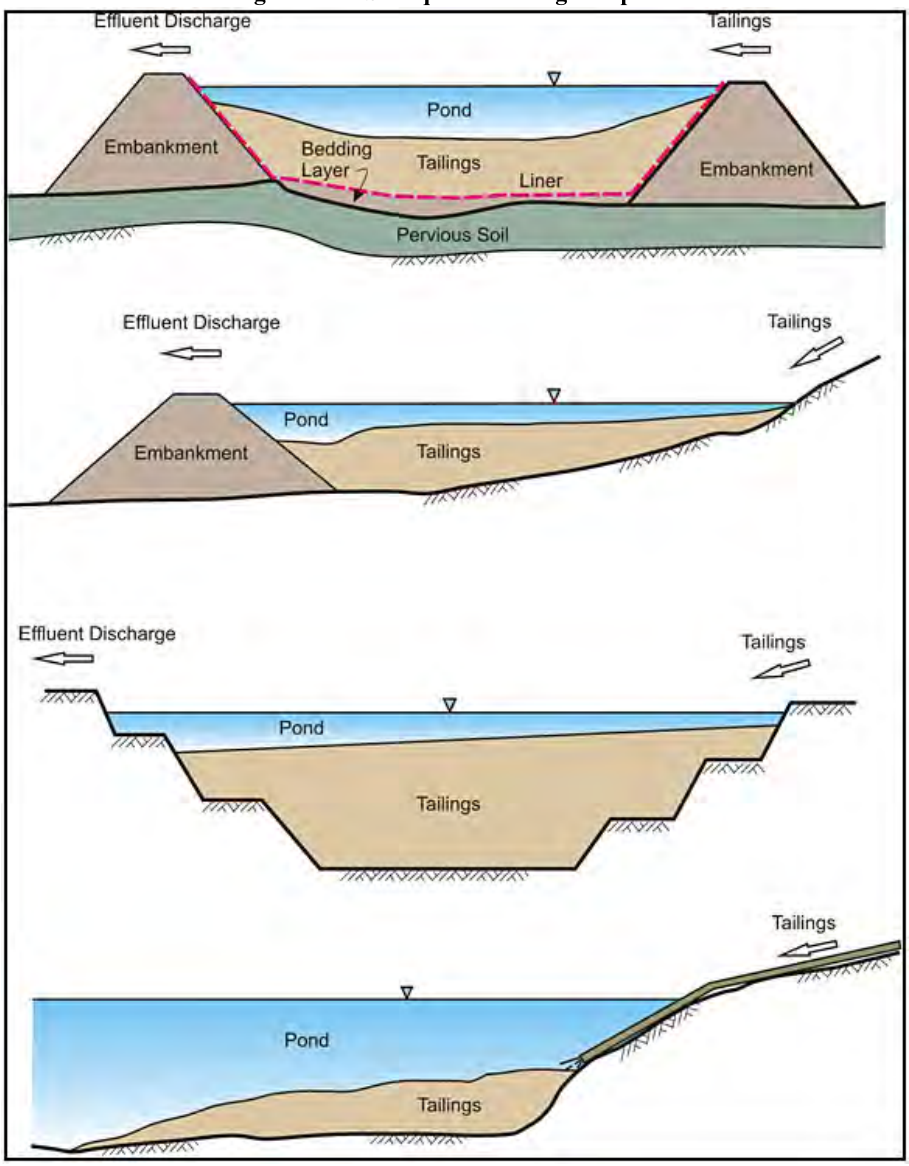
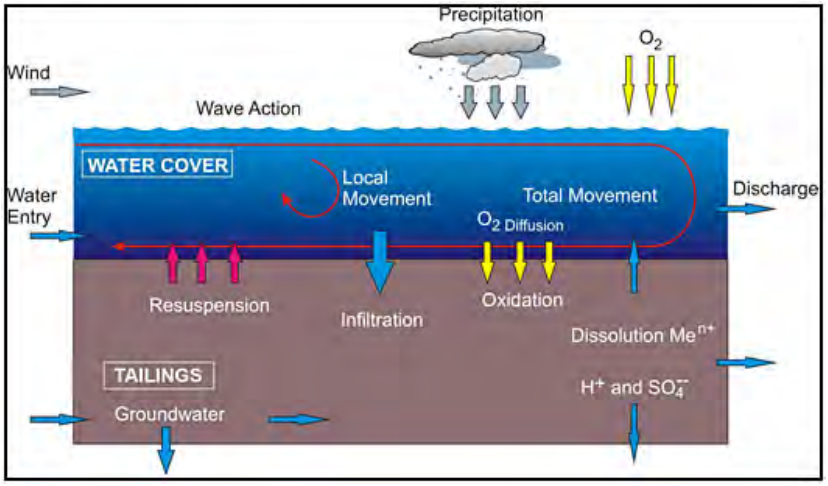


Figure 6-15: Water Cover Processes



Requirements for a water cover include a climate with a positive water balance, long-term physical stability of containment facilities and outlet structures (with sufficient capacity to handle extreme events), and water depth sufficient to prevent resuspension by wind and wave action. Designs must consider the potential for periods of extended drought and exposure of previously saturated material. The considerations for a water cover are summarized in Table 6-6. While only shallow water covers are needed to effectively prevent oxygen diffusion, a thicker cover (typically from 1 to 3 metres deep) is needed if preventing resuspension of fine tailings due to wave action is a consideration. MEND (1998b) provides a thorough guide for the design of subaqueous impoundments. An example of a permanent water cover, augmented by alkaline amendment and organic matter, is provided in the **Benambra Case Study**.

A distinction is made between use of natural water bodies or flooded mining voids and engineered tailings dams and manmade lakes. Table 6-6 presents a high-level overview of possible factors that could be considered in the evaluation of subaqueous disposal; this overview is not meant to be comprehensive. The proposed use of natural water bodies in particular may require extensive studies of baseline conditions and potential impacts, as well as legislative action. For example, in Canada special amendment to a regulation is required to use "fish-bearing water bodies" for storage of mine wastes.

Table 6-6: Some Considerations for Subaqueous Disposal

Considerations for Use of Natural Water Bodies (lakes or oceans)	Considerations for Engineered Water Retaining Structures (dikes and dams, pits, underground workings)
Proximity to Mine ▪ Water level ▪ Tides and currents ▪ Other lake uses ▪ Regulatory environment ▪ Potential toxicity of wastes including metal leaching, reagents and metals from the milling process ▪ Residue from blasting processes as a potential nutrient source ▪ Potential increase in turbidity ▪ Potential effects on local flora and fauna including commercial and recreational fisheries ▪ Potential loss of habitat ▪ Natural mixing processes ▪ Lake water chemistry	**Dams and Dikes** ▪ Detailed design of embankment and spillway required ▪ Measures required to control seepage ▪ Geotechnical, maintenance, and inspection requirements of dikes, dams, and hydraulic structures required to maintain a water cover ▪ Hydrogeology and hydrology, - a reliable water source is required to maintain flooded conditions, even during drought ▪ Potential risks to downstream receptors of catastrophic failure and release of retained water and/or wastes **Pits and underground workings** ▪ Potential mobilization of stored oxidation products upon flooding ▪ Potential leaching of metals from flooded materials ▪ Resulting pit lake chemistry ▪ Potential oxidation of materials above the water line ▪ Continuity with other underground workings

6.6.7.2 Partial Water Cover

The partial water cover concept involves an elevated water table that maintains saturation throughout the bulk of the tailings profile (Bussière, 2007; Ouangrawa et al., 2006). A surface pond does not extend to the embankment or dykes along the perimeter of the tailings impoundment, but a small pond may be maintained in the centre to maintain an elevated water table over the entire region of the tailings impoundment.

The objective of the partial water cover is to minimize the higher risk of structural failure associated with having a water cover and pond adjacent to the embankment wall, while maintaining saturation through enough of the waste to limit the maximum extent of oxidation that will occur. The partial water cover

method is well suited for operations where two types of tailings are being generated: the high sulphur concentrate produced by desulphurization (see Section 6.6.3.3) that is stored at depth and the non-acid generating tailings that are used as cover above the level of the pond (Sjoberg-Dobchuk et al., 2003). A partial water cover is also well suited to the case where the underlying non-oxidized tailings have sufficient neutralizing capacity to assimilate the entire acid load that is produced from the overlying rind of unsaturated tailings. A key design consideration is to raise the water table above the acid generating material by placing non-acid generating material as a cover, controlling the water level by the pond spillway elevation, or both placing non-acid generating material and controlling the water level.

Use of the partial water-cover method must consider climate, topography, hydrology and hydrogeology, the residual neutralizing capacity of unoxidized tailings, and the water characteristic retention curve of the tailings material. A case study is provided for the Lupin Mine in Nunavut, Canada **(Lupin Case Study)**.

6.6.7.3 Wetland Covers

A wetland or bog cover includes soil, vegetation, and water overlying acid generating wastes. Soil ameliorates extreme climatic drying events and vegetation helps prevents erosion. Water limits oxygen ingress and plants offer passive treatment opportunities (ERMITE, 2003). The most critical operational aspect of using wetlands and bogs as covers is that oxygen depleted and reducing conditions are maintained at the base of the cover profile, thus not only protecting underlying unoxidized material but also creating the potential for precipitation of existing ARD products as sulphides. MEND (1993) provides a comprehensive case study of wetland covers.

6.6.7.4 Attenuation

Attenuation measures are discussed in Chapter 7.

6.6.7.5 Streamflow Regulation

Control of surface water flow and drainages that discharge to adjacent receiving water bodies must satisfy compliancy criteria established by regulatory agencies and internal corporate standards. In most cases, criteria are defined in terms of concentrations for specified parameters (e.g., pH, acidity, alkalinity, metals, sulphate, and major ions), streamflows, and environmental loadings. Concentrations may also be defined based on periods for high flow and low flow.

Assessment of mine drainage often involves development of a comprehensive water balance (i.e., both surface and groundwater) combined with mass loadings. Key components of a surface water balance include precipitation (both daily and hourly), evapotranspiration, runoff, infiltration, and drainage rates from surface structures (i.e., waste rock). Surface water management is controlled most strongly by precipitation, which is highly responsive within short time periods and can be easily monitored with instruments and flow gauges. Contamination of groundwater resources and the migration of plumes to surface water streams are frequently overlooked and can only be evaluated based on an understanding of groundwater hydrogeology and chemical analyses (see Chapter 8).

Stormwater management associated with extreme climatic events is often the most important issue for peak flow prediction, design of impoundment storage capacity, freeboard, spillways, flow concentrations, and diversion channels. Design inadequacies and failure of surface water management systems generally occur during extreme events so designs are based on storm return periods and hydrologic assessments. In many cases, it is better to use multi-staged designs based on operational flow rates supported with bypass spillways and diversion channels to handle extreme high-flow conditions. Criteria for bypass flow must be established based on risk, peak loadings, and downstream dispersion and dilution. Designs need to minimize the risk of severe erosion and structural stability of major containment facilities, especially after closure.

6.6.7.6 Water Recycle and Reuse

Minimization of water use and water losses is a critical objective, especially in arid climates. Key design options include minimizing process water discharged to tailings (i.e., thickening), use of low permeability liners and barriers, recycling of process waters along with any contaminated discharges and seepage to the mill, and the use of surface water retention ponds for evaporation (climate permitting). Treatment sludges are also frequently discharged to tailings impoundments and may be sent to voids for deep disposal in pit lakes for long-term management.

Salt budgets may also be critical at arid sites for pit lakes and surface impoundments where a negative water balance because of low precipitation and high evaporation can cause evapoconcentratio or yper saline conditions to develop with time.

6.6.8 Drained / Sub-Aerial Tailings Deposition Methods

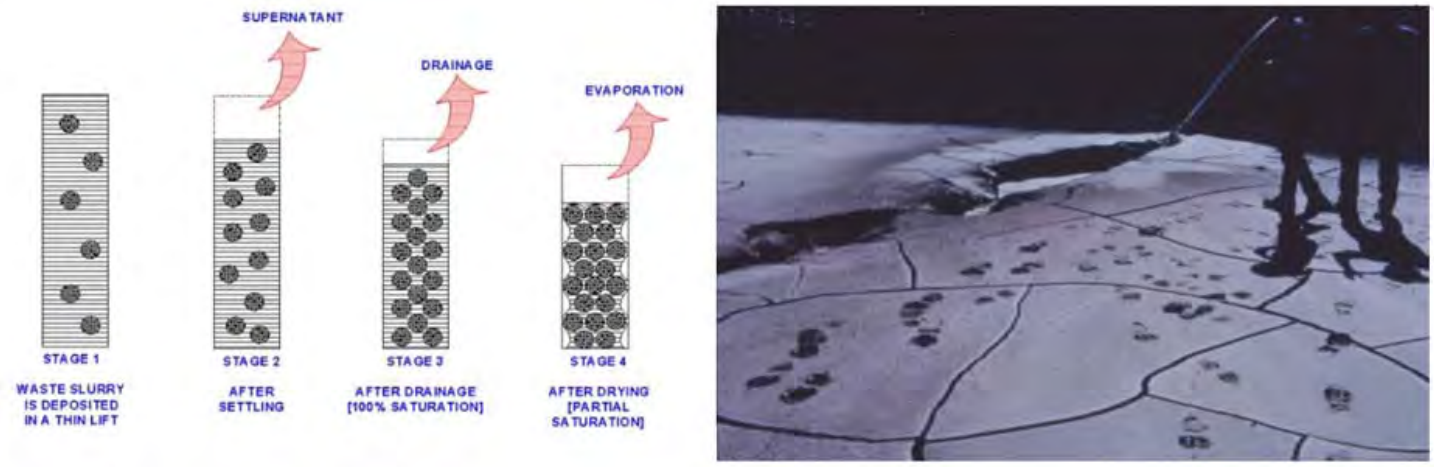
Two legs of the “ARD Tetrahedron” (air and water) can be disrupted if fine-grained pyritic tailings can be dewatered and consolidated. Creating a low-water content paste is one method of tailings management that has been used to accomplish this goal as well as to maximize the amount of solids that can be stored in a given tailings storage facility. However, the energy and machinery involved in paste tailings production and placement is expensive and a certain amount of water must remain in the tailings to allow pipeline transport. De-watering tailings passively with little additional equipment is an attractive alternative.

Sub-aerial tailings deposition (more specifically, thin-layer sub-aerial deposition) is a methodology for mineral waste management which has proven successful in a number of sites in environmentally sensitive areas of the western U.S.A., Canada and in the Pacific Rim. Since about 1990, the method has been used to place tens of millions of cubic meters of tailings in an environmentally acceptable manner. The method involves the sequential deposition of

tailings slurry in thin layers around the perimeter of the tailings facility. As each layer is deposited, particle settlement, desiccation, and consolidation occur in four distinct stages as detailed below and in Figure 1:

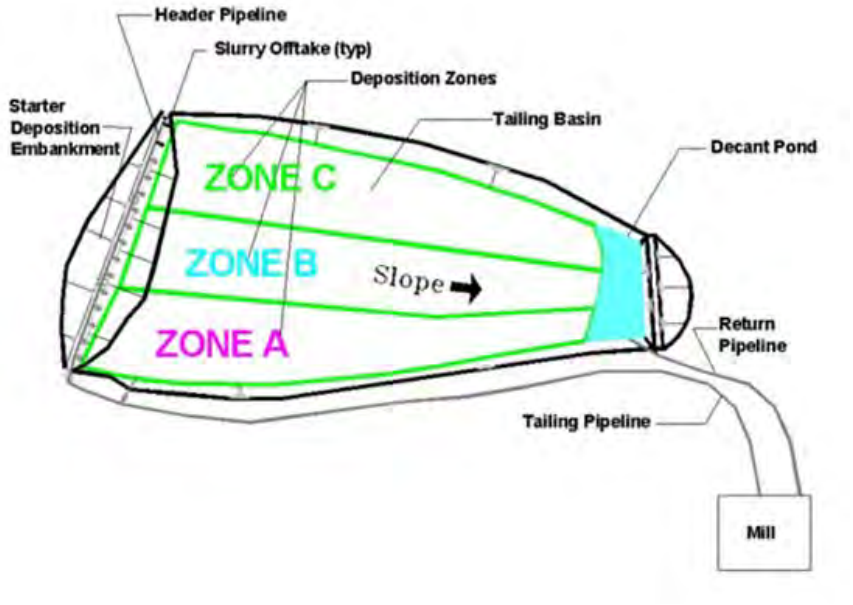
- In Stage 1, the slurry is in a super-saturated condition with solid particles completely suspended in the fluid. There is minimal intergranular contact and a hydrostatic pore pressure distribution is present, resulting in an unstable condition which requires agitation for particles to remain in suspension.
- Stage 2 begins where the slurry has been initially deposited in a super-saturated plastic condition under water. As the solid particles settle, low intergranular contact is established and bleeding of surface water has started, with further release of liquid induced by drainage and/or evaporation. Loading of the settled deposit will result in formation of excess pore pressures which will slowly dissipate with seepage.
- Stage 3 is characterized by increased in-place density by means of application of underdrainage, which causes further consolidation and dissipation of positive pore pressures.
- Stage 4 develops as the drained deposit is allowed to air-dry and consolidate. This consolidation can be quite significant and results from the development of negative or suction pressures in the deposit as air is entrained within the soil structure. The resultant layer of air-dried waste is a stable, partially-saturated mass which has a lower permeability and greatly increased resistance to liquefaction under seismic loading. The most significant attribute of the slurry's transformation from Stage 1 to Stage 4 is the increase in the dry density of solids. For example, a gold tailings slurry initially at a solids content of 42% increases in dry solid density from approximately 0.83 kg/L (52 pounds per cubic foot [pcf]) to nearly 1.6 kg/L (100 pcf) merely by allowing settlement, drainage and air-drying in relatively thin layers prior to deposition of a fresh layer of tailings.

Figure 6-16: State of Solids during Deposition and Consolidation (L); Stage 4 Photo (R)



As the drying process continues and the moisture content has been reduced to approximately 20%, the dry density shows little increase with continued drying. In practice, once this point has been reached, a new layer of tailings is added and the cycle begins again.

Figure 6-17: Schematic Plan View, TSF with Three Depositional Zones



In order to achieve Stage 4 conditions, air-drying of the thinly-deposited (100 to 150 mm) layer of tailings is typically facilitated through a systematic rotational waste discharge strategy. Note that even though the tailings material in Figure 1 (R) is probably finer than 74 microns (<200 mesh), foot traffic is possible within several weeks of cessation of deposition. Vehicular traffic to conduct closure activities (e.g., placement of cover soils, liners, or soil amendments for revegetation) is also possible shortly after Stage 4 conditions are observed on the tailings surface (Reisinger et al., 2001).

If the tailings are very fine grained, thin-layer sub-aerial deposition techniques can create a tailings mass that is relatively impermeable with little entrained moisture. In fact, it can be demonstrated that the low permeability of the consolidated tailings materials in the initial lifts could allow regulating agencies to consider the tailings themselves as a "liner" in a double-liner configuration. A drainage blanket beneath the tailings would be included in the design as a leach collection and detection system. Consequently, the design should require only one geosynthetic liner (beneath the drainage blanket) to satisfy a double-liner requirement.

If the tailings contain significant concentrations of reactive sulfides, the relative impermeability of the tailings mass created with sub-aerial placement techniques should also suppress ARD formation, either in the toe seepage (which should be minimized) or runoff from the revegetated surface. Retrofitting existing tailings impoundments that have been designed as sub-aqueous facilities is also possible (Filas and Zmudzinski, 1993). Inserting wick drains or implementing other passive methods that relieve the pore pressure in saturated tailings has also been considered (Brown and Greenway, undated).

In summary, the thin-layer sub-aerial tailings deposition method may provide a cost-effective minimum energy and equipment tailings management technology. Advantages of the technology include:

- increased stored densities
- reduced seepage losses
- reduced ARD generation
- increased ease of surface reclamation at closure and
- improved embankment stability.

More economical upstream construction may be feasible with sub-aerial deposited tailings. In short, this technology fully embraces the concept of storing solids, not water, and in doing so, can better avoid ARD problems during operation and post closure.

6.7 Selection and Evaluation of Alternatives

No universal solution exists for the prevention, control, and mitigation of ARD, NMD, and SD. While submergence is clearly the most geochemically-stable approach, subaqueous disposal of tailings and waste in natural water bodies, such as lakes or marine environments, can be contentious. The applicability of technologies to ARD sources and phase of mining is shown in Figure 6-18.

Specific evaluation of methods for prevention and mitigation of ARD requires a clear definition of objectives and defined purpose. The specific environmental technologies and options that will work best will be site specific, often governed by climatic considerations. The applicability of several methods described in the preceding sections is summarized in Table 6-7. Some methods have been demonstrated to be effective at sites around the world while others have had limited demonstration. This is a simple summary only in order to broadly categorize the technology. Some technologies may have been demonstrated in a few climate type but could be applicable to others. As discussed throughout this Guide, site-specific considerations must be

assessed during the evaluation of any ARD prevention technology.

Water covers are a proven technology from a geochemical perspective but are sustainable only in climates with a positive water balance (i.e., precipitation > evaporation). In climates with a suitable water balance, geotechnical and long-term hazards with respect to stability, extreme storms and floods, spillways, erosion, and other natural hazards such as seismic events must be considered.

Figure 6-18: Prevention and Mitigation Evaluation of Alternatives

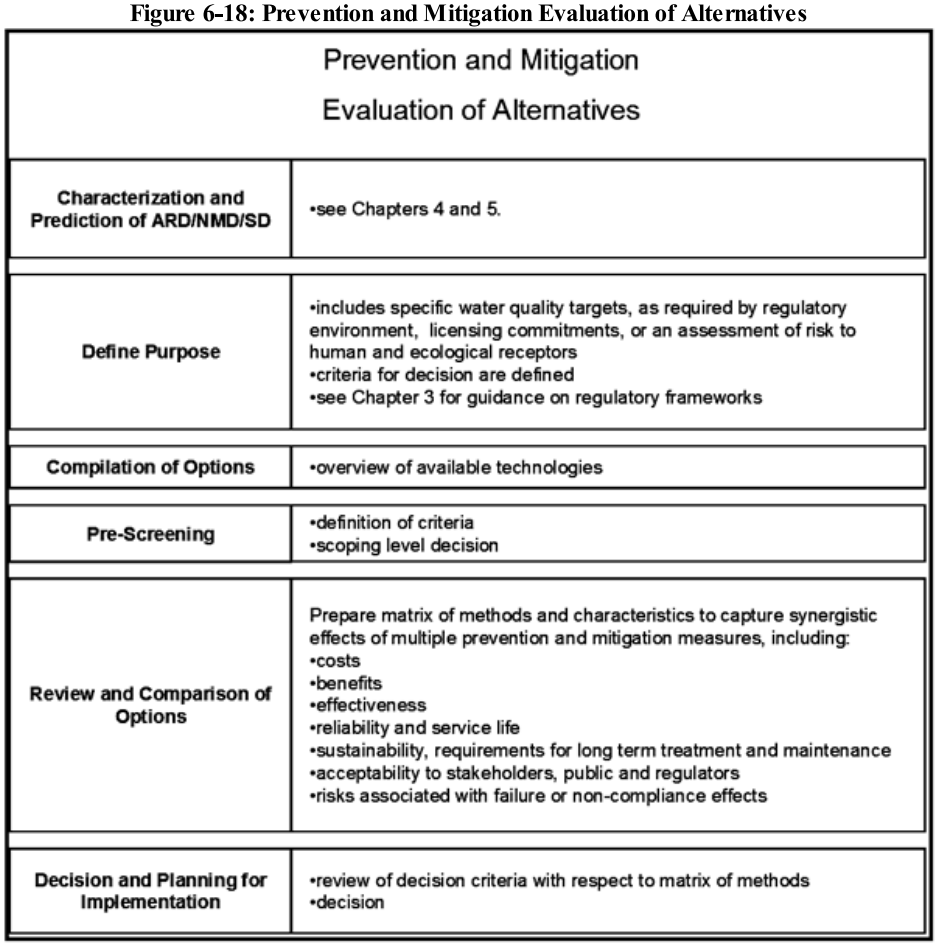


Table 6-7: Summary of Prevention and Mitigative Measures and Climate Considerations

Oxygen Limiting	
Widely Demonstrated	**Limited Demonstration**
▪ Submergence (all climates except B) ▪ Water covers (A, C, D) ▪ In-pit disposal (all climates) ▪ Elevated water table (A,C, D) ▪ Mine backfilling (all climates) ▪ Membrane covers (all climates)	▪ Oxygen consuming cover (all climates) ▪ Saturated soil cover (A, C, D)
Water Limiting	
Widely Demonstrated	**Limited Demonstration**
▪ Diversion (all climates) ▪ Store and release covers (B)	▪ Low permeability covers in wet climates (A, C, D)

▪ Membrane covers (all climates)	▪ Paste Tailings (C,D)
Geochemical	
Widely Demonstrated	**Limited Demonstration**
▪ Segregation (all climates) ▪ Avoidance (all climates) ▪ Tailings desulphurization (C) ▪ Encapsulation (coal) (C)	▪ Alkaline covers (all climates) ▪ Passivation (all climates) ▪ Blending (all climates) ▪ Encapsulation (metal) (A,C)

LEGEND: (Climate Classification by Köppen system)

(A) Tropical humid
(B) Dry
(C) Temperate mild mid-latitude
(D) Continental severe mid-latitude
(E) Polar
(H) Highland

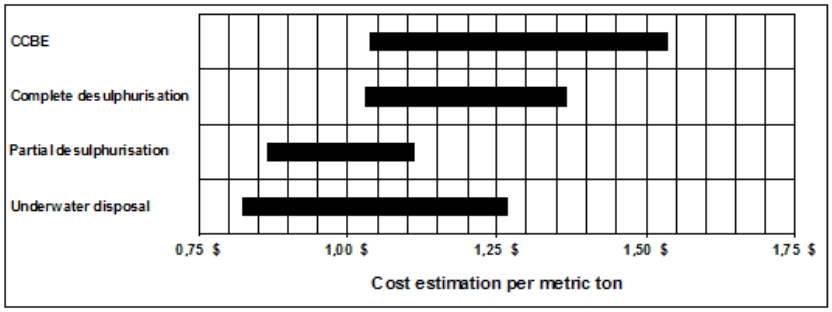
In-pit disposal and mine backfill might be preferred in some situations, but this method of disposal usually only becomes available after or well into the mine operating phase.

In many cases, more than one approach or method will be required. For example, sulphide separation combined with water covers, elevated water table, and barrier covers may prove to be the best combined system for a given tailings impoundment.

Cost and economic viability must be evaluated similar to the other criteria for environmental and social settings. Cost estimates are almost always site-specific. Standard engineering approaches are used to develop capital and operating cost estimates to evaluate options and to assist in selecting a technology. Detailed design of an ARD prevention or mitigation technology involves preparing a detailed cost estimate. The specific approaches and methods used to cost ARD prevention and mitigation technologies are beyond the scope of the GARD Guide, but are described in standard engineering text books. Site-specific pre-construction cost estimates and actual as-built construction costs may be found in the proceedings from the major ARD conferences and other sources.

However, in general, cover systems for tailings and waste rock deposits are often costly. Although costs vary widely, soil covers costs can range from about $25,000 to $100,000 (USD) per hectare (ha); heavily dependent upon the proximity of borrow sources for the soil cover material. The application of synthetic and complex multi-layer covers can easily double this cost and therefore those technologies are usually applied at smaller sites. Figure 6-19 as an example, summarizes relative costs of a few technologies for a particular site: capillary barrier cover (i.e., covers with capillary barrier effects (CCBE)), desulphurization covers, and water covers. As shown here, desulphurization may be the most attractive alternative of the three options for this particular site depending upon the consideration of other factors (e.g., ease of application and environmental and social requirements).

Figure 6-19: Comparative Costs for Capillary Barrier Cover (CCBE), Complete and Partial Desulphurization and Water Cover (Bussiere and Wilson, 2006)



Data requirements for detailed design of prevention and mitigation strategies include detailed site characterization, such as topography and physical setting, geology, hydrogeology and hydrology, climate, materials availability and mine development sequence, and detailed characterization of source materials, including type, geochemistry, volume, and reactivity. Evaluation of alternatives as part of the preparation of the overall ARD management plan is discussed further in Chapter 9.

6.8 Design and Construction Considerations

Design of prevention and mitigation measures will likely require some analytical or numerical modeling (or both analytical and numerical modeling) to predict both geochemical and physical performance (see Chapter 5). The time frame and scheduling of the implementation of control measures becomes

important when PAG materials have a limited time to the onset of ARD production.

Construction must consider site location and transportation logistics, use and availability of local material types, quality control and quality assurance, including as-built inspection and reporting, and ongoing monitoring, maintenance, and reporting requirements. Construction quality control programs are critical to the success of any prevention and mitigation measure.

6.9 Maintenance and Monitoring Considerations

Effective maintenance and monitoring programs must follow selection and implementation of any technical method for prevention or mitigation. Monitoring demonstrates achievement of objectives and maintenance ensures engineering integrity of the design. Monitoring is discussed in more detail in Chapter 8.

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Case Studies Chapter 6

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1. Pamour Tailings – Encapsulation

A historic gold tailings impoundment in the Timmins area, Ontario, Canada is sulphide bearing with moderate to high carbonate contents. Expansion of an open pit required relocation of a tailings stack (T1). During milling, the tailings were separated into a sulphide concentrate and a carbonate-rich flotation tailings and were placed in different locations within the T1 stack. The sulphide concentrate tailings were on surface and exposed to the atmosphere for decades and therefore had developed acidic pore water within the near-surface tailings. Relocation planning included investigations to mitigate existing acidic pore water as well as ongoing acid generation. The selected option included the relocation and deposition of the acidic sulphide concentrate tailings onto a nearby high-carbonate tailings stack (T2) followed by a cover composed of the remaining high-carbonate tailings from the relocated T1 stack. This encapsulation approach was investigated extensively to minimize the risk of acidic leachate. An investigation was also completed to evaluate the quality of pore water that would evolve when acidic waters migrated down through the high-carbonate tailings and the results were presented in MEND Report 2.46.1 (2010).

The tailings in both the T1 and T2 stacks were characterized in the field during the options investigation. Samples of the sulphide concentrate and carbonate-rich T1 tailings were collected from multiple depths and at several locations. The solids and soluble (pore water) products were analyzed in all samples. Acid base accounting (ABA) was complemented by total sulphur and sulphide-sulphur analyses as well as carbonate contents to illustrate AP/NP values for the carbonate-rich tailings and to quantify available NP in the stack below the sulphide concentrate layer.

The acidity in the existing pore water represented only a small portion of the AP. The AP/NP balance clearly showed that there was adequate NP to consume all acidity in low-pH pore water as well as all AP that could be generated in the sulphide concentrate layer if all of the remaining sulphide reacted to form sulphuric acid.

The investigation of mitigated water quality was completed in two phases. The initial phase included batch studies that added acidic tailings to neutral carbonate-rich tailings, after which pore water was extracted and analyzed. The second phase included column studies involving acidic tailings overlying neutral tailings, which were completed over a one-year period with field-like infiltration rates. Samples of pore water were collected within the neutral tailings and column drainage was collected at the base of the column and analyzed. The results showed that concentrations of most soluble constituents in the neutralized pore water were attenuated or mitigated to low values as waters migrated through the neutral tailings. Field monitoring was conducted to follow the performance of the encapsulated tailings.

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Mine Environment Neutral Drainage Program (MEND), 2010. Evaluation of the Water Quality Benefits from Encapsulation of Acid-Generating Tailings by Acid-Consuming Tailings – December.

2. Lupin Tailings – Elevated Water Table Covers for Reactive Tailings

The Lupin former gold mine in Nunavut, about 400 km NE of Yellowknife, NT, Canada operated from 1982 and closed in the mid-2000s. The tailings were potentially acid generating. Tailings were deposited over a 600-ha area in multiple shallow cells that were originally small lakes and were contained by multiple small dams. The closure concept for the tailings included construction of "dry covers" between 0.6 to 1.6 m thick with the added design feature that the final water table in each tailings cell would occur within the cover layer as described in MEND (2004). With the water table above the tailings surface, the raised water table provides an "effective" water cover to prevent sulphide oxidation. The cover design therefore was a hybrid system that represented a dry cover with no standing water within the tailings cells while maintaining submerged conditions for the sulphide tailings. Although this concept was implemented at a mine site in permafrost terrain, permafrost was not a necessary aspect of the design and adaptation is possible at other sites with an appropriate water balance and topography.

Deposition of tailings in cells provided an opportunity for progressive reclamation that started in 1995. The cover material consisted of esker sands. There was no need for low-permeability materials to prevent infiltration of water or ingress of oxygen. The elevated water table above the tailings represented the design feature that prevented oxidation and generation of ARD. The cover system, however, included a second feature to complement and maintain the raised water table. The surface layer was composed of coarse granular material that reduces evaporation and promotes infiltration to maintain an elevated water table.

While it is commonly accepted that a water cover in a pond, for example, should have a thickness of 1 to 3 m in order avoid physical resuspension of tailings, the depth below the water table can be minimal because any water cover thickness is effective at limiting oxygen access and there is no potential for mixing within a porous medium. Therefore, the design criteria for a raised water table above the tailings surface can include a minimum depth below the water table and the thickness of the cover in constrained only by the preference to avoid free water over the cover layer surface.

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Mine Environment Neutral Drainage Program (MEND), 2004. Covers for Reactive Tailings Located in Permafrost Regions Review. Report 1.61.4, Natural Resources Canada

3. Strathcona Tailings – De-Sulphurized Tailings Cover

The Strathcona tailings facility, near Sudbury, Ontario, Canada has an active area of 100 ha and has been operating since 1968. For the first two decades, the nickel tailings with a sulphur content of 15% S, mainly as pyrrhotite, were discharged as an unsegregated slurry in cells within an impoundment. When tailings were exposed to the atmosphere with no further addition of fresh tailings slurry, the surface material oxidized rapidly, producing acidity, soluble metals and a visible crust, or hard pan, of iron hydroxide. Tailings management alternatives were considered in the early 1990s and the preferred option was to use the scavenger tailings with a sulphur content of less than 1% to cover the high-sulphur tailings. Lime kiln dust or reject material from lime production was also added to the low-sulphur tailings to increase the carbonate NP as well as the NP/AP ratio. The high-sulphur tailings fraction with 30% S was deposited underwater in the Oxidation Pond that is also an integral part of the water treatment system for the mining complex in the Onaping area. The low-sulphur cover placement was initiated in 1995.

The low-sulphur tailings cover is produced as the cyclone overflow from the scavenger flotation units that generate a sandy material for mine backfill. The overflow contains the fine-grained fraction referred to as slimes and therefore has the value-added property of moisture retention capacity. The high-moisture retention acts to reduce oxygen ingress due to low values for the gas diffusion coefficient.

The low-sulphur tailings slimes cover was evaluated through modelling to determine the appropriate thickness required to protect the underlying high-sulphur tailings from oxidation. A minimum cover thickness of 1.5 m was selected as being

adequate as an oxygen barrier based on the degree of moisture retention or saturation anticipated in the lower zone of the cover layer. The desulphurized tailings cover was almost completed by the summer of 2011.

Interim assessment of the cover layer has shown that the sulphur content is consistently less than 1% S and that the NP/AP ratios ranged between 1.4 and 12. The lime demand for water treatment in the adjacent oxidation pond has decreased substantially since the cover construction was initiated. The lime demand in the pond, however, represents other possible sources of acidity and therefore does not directly reflect the performance of the desulphurized tailings cover.

4. Poirier Tailings – HDPE Synthetic Cover

The Poirier Mine was an underground copper-zinc operation that opened in 1965 and closed in 1975, producing about 5 million tonnes of tailings containing between 6 and 20%S. A reclamation options assessment was initiated in 1996 for the surface oxidized and acid generating tailings. The preferred option that was accepted by the regulators was the construction of a HDPE membrane over the 46-ha tailings impoundment with a protective earth materials cover over the membrane. The objective of the cover was to reduce long-term loadings of acidity and metals from the tailings to the adjacent environment by limiting infiltration into the tailings that contained substantial loads of soluble oxidation products as a result of more than 20 years of exposure since the mine closed.

A follow-up study with four years of performance data showed that the loadings of acidity and metals from the tailings impoundment were reduced to small percentages of pre-reclamation values (Maurice and Wiber, 2004). The water table in the tailings had declined to elevations near the base of the tailings as a result of limited infiltration to recharge the subsurface water. The outflow from the tailings had also declined in response to the decrease in the water table.

Reference

Mauric, A. and Lottermoser, B.G. Phosphate amendment of metalliferous waste rocks, Century Pb-Zn mine, Australia: Laboratory and field trials. Applied Geochemistry, 26 (2011), 45-46. P. 45-56.

5. Normetal Tailings – HDPE Membrane Cover

The underground Normetal Mine operated from 1937 to 1975, producing more than 10 million tonnes of sulphide-bearing tailings that were deposited over a 60-ha area. An HDPE membrane was placed over 56 ha of the tailings in 2005-06. The objective of the membrane cover system was to reduce oxygen and water infiltration into the tailings, thereby reducing acidity and metal loadings to the environment.

The cover system included 0.3 m of clay till on membrane slopes and 0.5 m of clay on flatter membrane surfaces. Rip-rap was also placed on slopes as added protection and for stabilization. Toe drains were installed at the base of tailings slopes below the membrane to collect and divert tailings seepage to desired locations. Surface drainage networks were constructed to collect and divert non-contact waters. The exposed clay cover layer was re-vegetated. Construction was completed in September 2006.

In the first two years after construction, the water table decreased an average of about 6 cm per month resulting in a reduction of tailings seepage flow from 150 to 103 L/min. The downstream conditions improved over that time, showing increases in pH and decreases in concentrations of acidity and metals. The pH increased from 3.0 before reclamation to 6.8 in 2009. Concentrations of iron decreased from a high of 300 mg/L to values near 10 mg/L and zinc declined from a high near 7 mg/L to values near 0.2 mg/L over the same period. The overall cover performance was considered to be successful to 2009 with plans to complete detailed monitoring to 2011. One technical issue noted was partial blockage of seepage drain pipes by iron precipitates and organic “slime” thought to have resulted from iron-oxidizing bacteria. Mitigation of the precipitate formation was being considered.

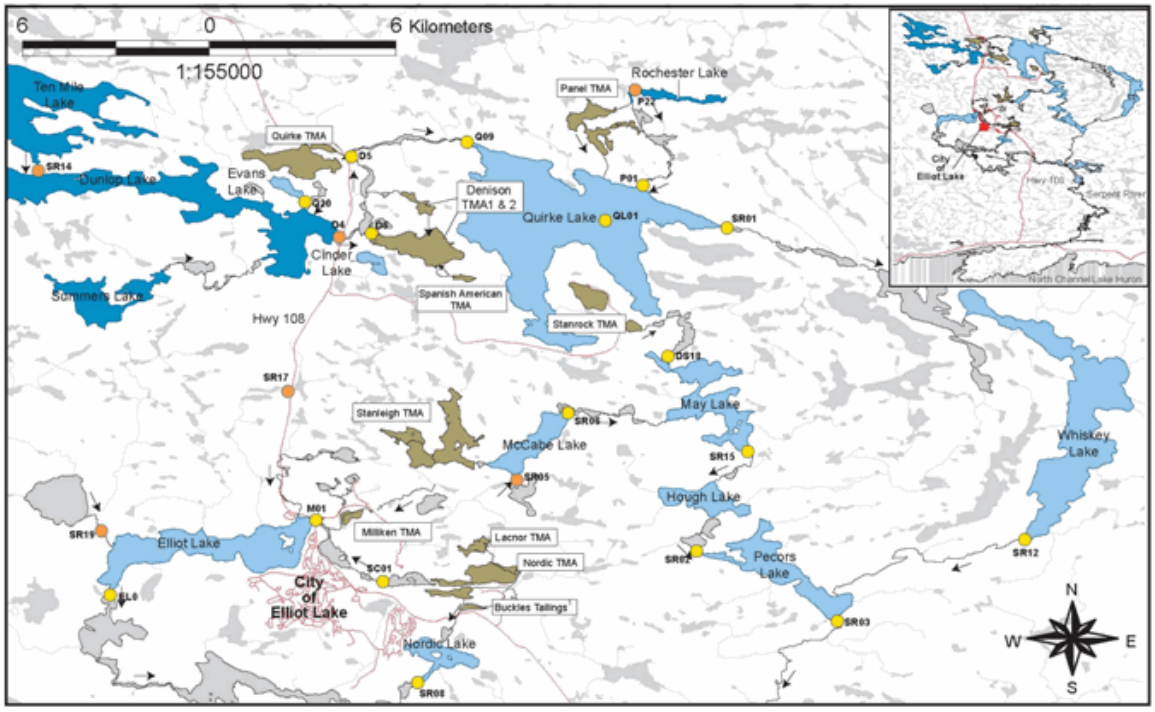
6. Denison Tailings – Reclamation by Flooding Post Closure

The Elliot Lake Uranium Mining District in Ontario was one of several early sources of uranium in Canada. Many of the Elliot Lake mines ceased operation in the early 1960s. Some mines, however, operated until the early 1990s producing almost 200 million tonnes of tailings before closure. The Denison Mine operated from 1957 to 1992, producing about 60 million tonnes of tailings that were stored in two tailings management areas (TMA).

Description of Denison Mine TMA

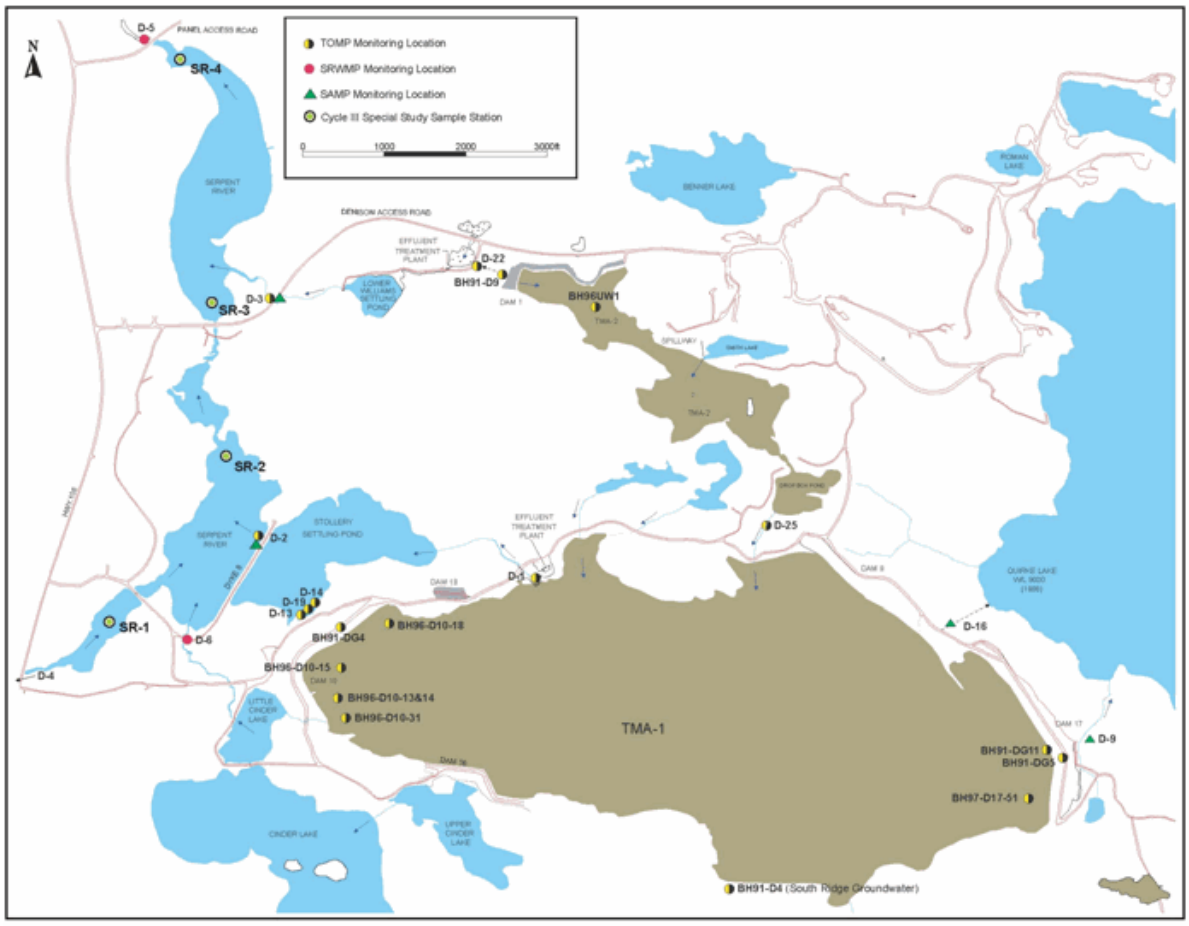
Elliot Lake is 30 km north of Lake Huron and 130 km west of Sudbury on the Canadian Shield, a region of exposed Precambrian rock that mantles a large area across Canada. The Denison property is located about 11 km north of Elliot Lake and is within the Serpent River watershed that drains to Lake Huron (Figure 1). The underground mine began operation in 1957 and continued production until 1992. The mill was located on site and the original production rate of 5,000 tonnes per day was increased to 6,350 tonnes per day in 1977 and 13,600 tonnes per day in 1982. More than 60 million tonnes of ore were processed over the life of mine and the tailings were stored in two tailings management areas (TMAs), TMA1 and TMA2 (Figure 2). The combined area of the TMAs is 280 ha.

Figure 1: Location of the Denison Mine



The TMAs were originally lakes that had dams constructed at lower sections of the perimeters in order to increase capacity. Tailings deposition was typical with low density slurry delivery to the impoundments. Spigotting resulted in the development of long beach areas near the spigot and ponds where fines settled near the dams.

Figure 2: Configuration of the Denison Tailings Management Area



The Denison tailings were typical of those from the Elliot Lake ore body. The ore was a Precambrian conglomerate similar to the gold deposits in South Africa. The uranium grade was on the order of 0.2% U. Pyrite was an accessory mineral with typical sulphide contents in the range of 5 to 10 % S. The ore was milled with a sulphuric acid leach process that removed any potential carbonate or other neutralizing minerals. The only neutralization potential (NP) in the tailings originated from residual traces of carbonate minerals in the lime that was used to neutralize the tailings prior to deposition in the TMAs. Studies of other tailings deposits in the region suggested that the NP of Elliot Lake tailings was less than 0.1% CaCO3 or 1 kg CaCO3/t (Dubrovsky et al., 1985).

Acidic water in the Denison tailings was recognized in the 1980s and water treatment plants were constructed to manage the effluents from each of the TMAs separately. The treatment systems were designed for pH control as well as for the removal of radium-226, a daughter isotope of uranium that has a prescribed effluent release limit of 0.37 Bq/L (10ρCi/L).

The Decommissioning Concept

The proposed decommissioning plan for the TMAs was based on the concept of mitigation to lessen the need for active management in the long term, in accordance with the principles developed by the federal nuclear regulatory agency. While the decommissioning plan considered all mine facilities and infrastructure, the tailings represented the main focus for water quality effects, and therefore, is the focus of this discussion.

Pyrite oxidation and ongoing acid generation in exposed on-land tailings was identified as the key concern with the need to develop chemical stability for the protection of water quality in the long term. Therefore, flooding and permanent underwater storage of the existing tailings was selected as the preferred closure option at Denison, as well as several other TMAs at Elliot Lake. Although dams were in place to contain tailings in TMA1 and 2, they were generally not suited to raise water levels sufficiently to flood the beached tailings. Flooding was achieved through a combination of modest dam

raises and upgrades to hold water at appropriate elevations, as well as the relocation of some beached tailings to lower elevations. Some beached tailings in TMA2 were relocated to TMA1 and some were sent underground. Some drainage redirection in the watershed was also required to have a positive water balance and to maintain a water cover on TMA1.

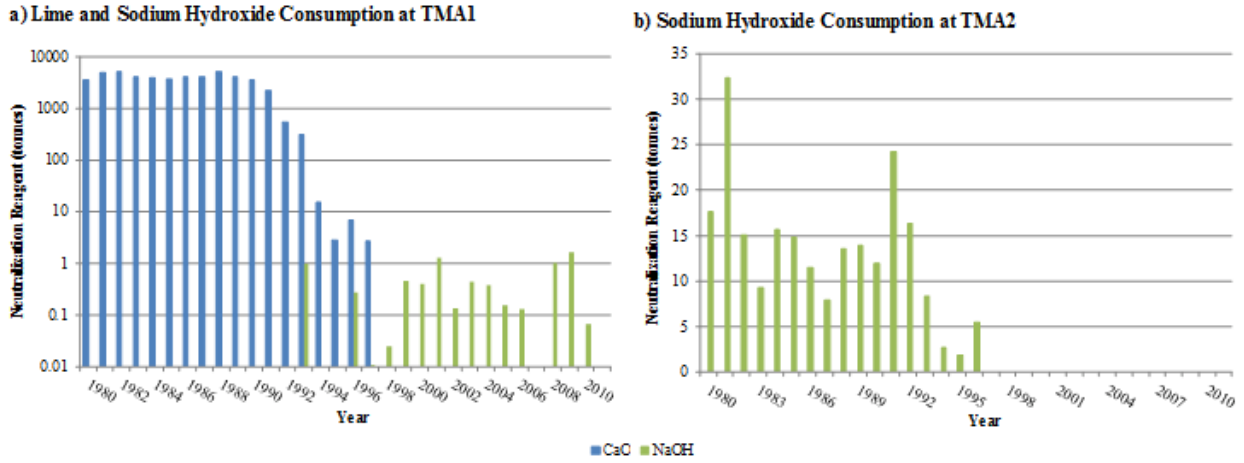
A cornerstone of the decommissioning plan for Denison, and for other TMAs at Elliot Lake, was the follow-up monitoring plan that consisted of three tiers of surveillance. These included a range of physical scales from the footprint of the tailings facility to the greater watershed that receives water from most of the TMAs.

Water Quality Before And After

Acidic conditions had developed in the beached tailings in TMA1 and TMA2. The acid conditions were observed in the effluent from the Denison tailings. More detailed investigations at other Elliot Lake TMAs showed that the shallow tailings pore waters were commonly characterized by pH values less than 3 with elevated sulphate and acidity, iron and other metals (Dubrovsky et al., 1985). In fine-grained tailings, the acidic zones were generally limited to the top few metres of tailings while in coarser and well-drained tailings acid zones had developed to depths of 10m. At Denison, about 1.7Mm3 of the most acidic tailings in TMA2 were relocated during decommissioning with about 50% sent to underground workings and 50% to TMA1. During relocation, lime was added to the acidic tailings to raise the pH.

The acidity loads generated in the TMAs can be estimated from the quantities of lime and/or sodium hydroxide used in the treatment plants that receive runoff and seepage from the tailings. Prior to flooding TMA1, typical lime consumption was on the order of 4,000 tonnes of CaO per year (Figure 3a). Lime consumption declined dramatically during the decommissioning process by three orders of magnitude (99.9%). Similarly in TMA2, sodium hydroxide consumption prior to decommissioning was on the order to 1.5 t/a, which declined to zero post decommissioning (Figure 3b).

Figure 3: Lime and Sodium Hydroxide Consumption at TMA1 and TMA2 at the Denison Mine



Water quality of the influent to the water treatment plant reflects the effects of flooding to some extent as shown for sulphate, acidity and iron concentrations in Figure 4. All parameters that were elevated prior to flooding exhibit decreases after flooding. The differences do not appear as dramatic as those for lime use, primarily because the chemistry of the tailings basin water was altered by in-situ lime addition prior to reporting to the treatment plant. Part of the overall trend in pyrite oxidation at TMA1 is exhibited by the concentrations of sulphate in the treated water, as shown in Figure 5, that were typically in the 1,500 to 2,000 mg/L range prior to decommissioning and declined to the 20 to 100 mg/L range after flooding. The lower concentrations of sulphate are expected to persist for an extended period because of the presence of gypsum ($CaSO4 \cdot 2H2O$) in the tailings that dissolves and releases sulphate to pore water. Subsequently, sulphate in the pore water is released to the overlying water as a result of diffusion at the water-tailings interface. In the tailings at the Denison site, gypsum originated from two sources: it formed when the sulphuric acid ($H2SO4$) in the leach solution was neutralized with lime (CaO) and in the oxidized tailings when sulphuric acid was produced by pyrite oxidation and reacted

with available calcium.

The effects of decommissioning are also observed in the Serpent River, immediately downstream of the Denison effluent discharge as shown in Figure 6. While the pH values have become more consistently in the range of 6.5 to 7.5, the sulphate, acidity and iron concentrations have all declined to low levels. For example, prior to 1994, sulphate concentrations as high as 1,000 mg/L were commonly measured in the river while the average value from 2010 to 2011 is less than 20 mg/L.

Quirke Lake is the largest water body immediately downstream of the Denison TMAs in the Serpent River chain of lakes with a volume of 803.0Mm3 and an annual average outflow of 183Mm3/a. Quirke Lake also receives treated effluent from the other TMAs that were also decommissioned and flooded at about the same time as the Denison TMAs. In the 1960s, Quirke Lake had pH values near 4 as a result of early milling practices that did not include complete neutralization of mill process water prior to tailings discharge. Neutralization of tailings was implemented in the 1970s and the pH in Quirke Lake increased. The water quality at the outlet of Quirke Lake from the late 1980s to 2011 is summarized in Figure 7. The pH was typically in the range of 5 to 6 in the early 1990s and has since increased to values consistently near 7. The concentrations of sulphate have declined from about 200 mg/L in 1991 to less than 50 mg/L in 2011. Similarly, concentrations of acidity and iron have declined since decommissioning of the Denison and other upstream TMAs.

Figure 4: Water Quality in the Influent to the TMA1 Treatment Plant

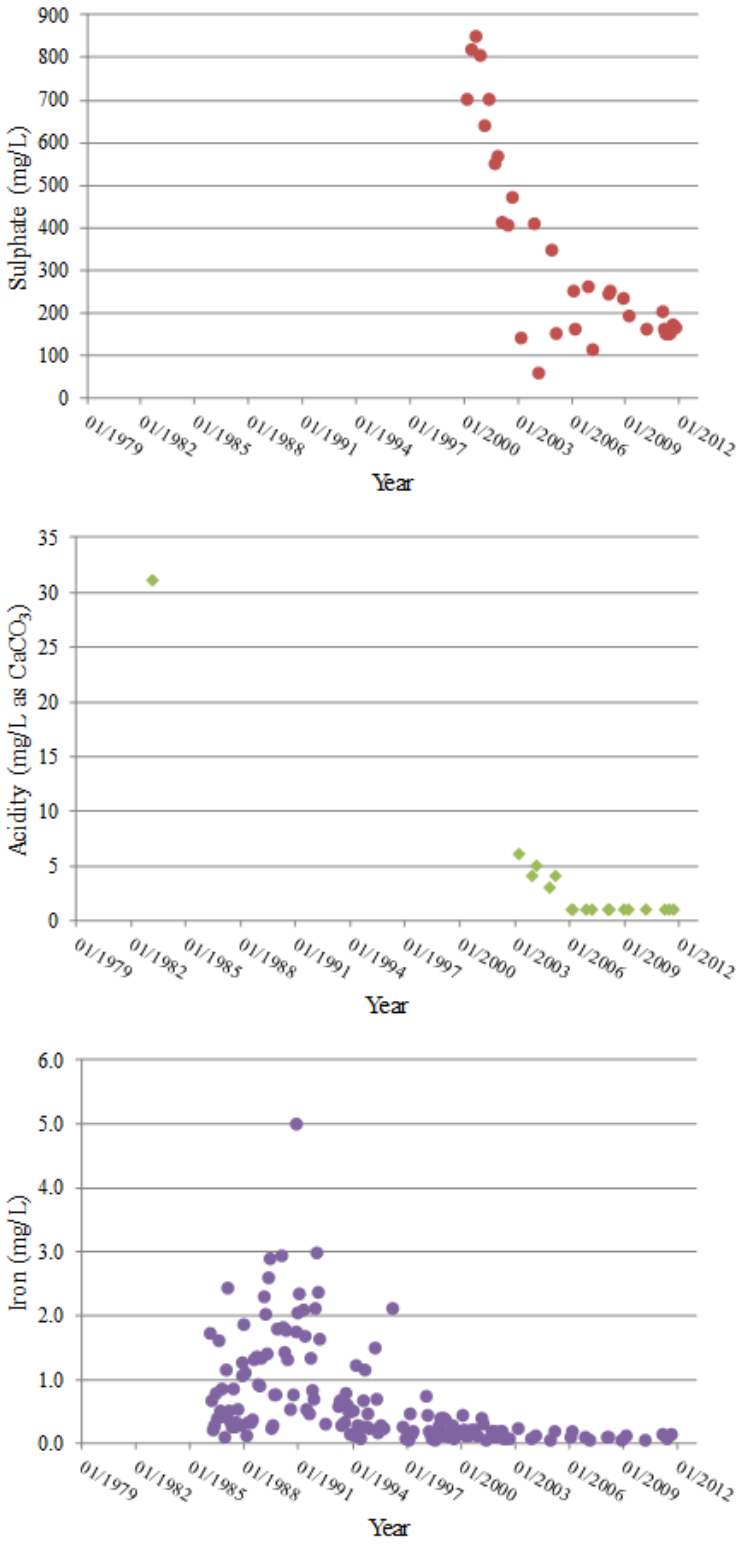


Figure 5: Sulphate Concentrations in Effluent from the TMA1 Treatment Plant

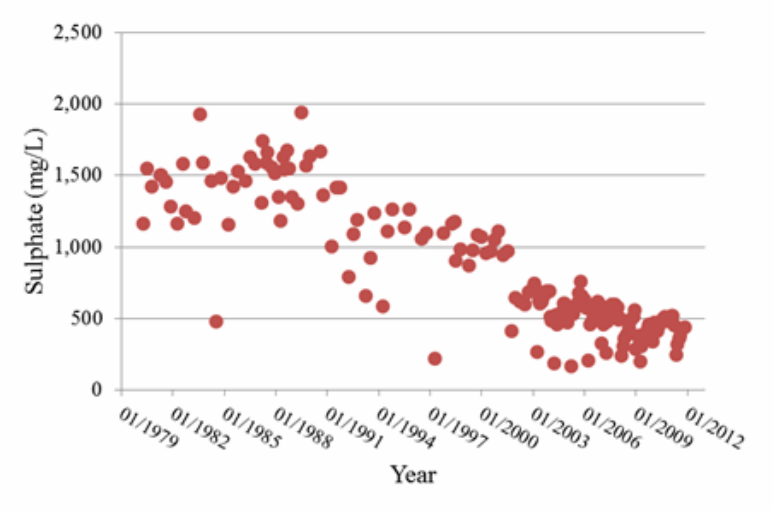


Figure 6: Water Quality in the Serpent River Downstream from the Denison Effluent Discharge

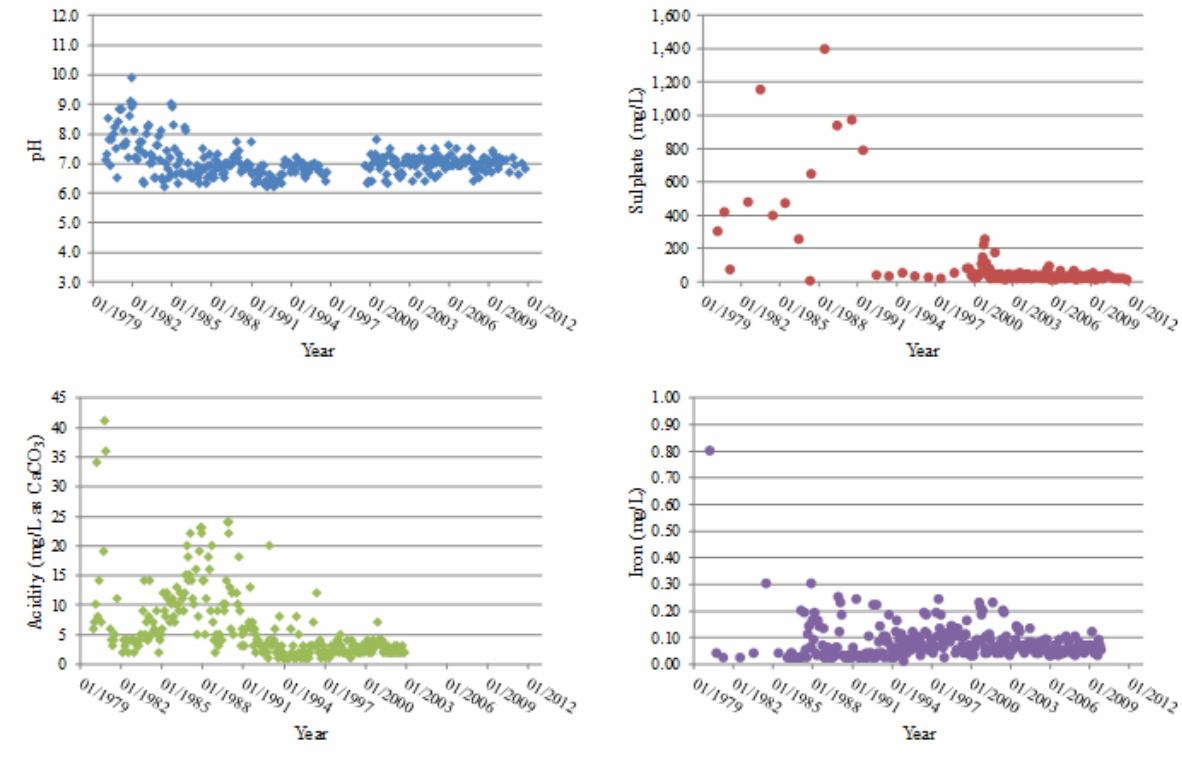
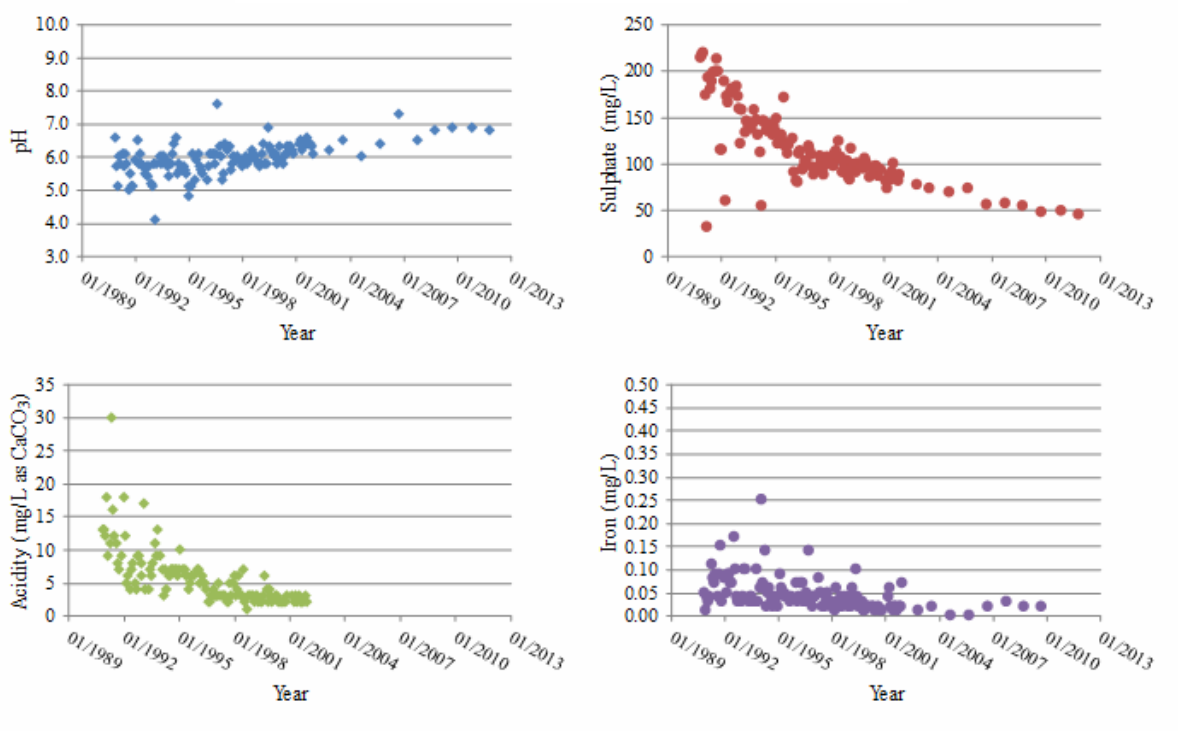


Figure 7: Water Quality in Quirke Lake Outflow



Conclusion

The uranium mines in Elliot Lake were developed and operated over decades at a time when environmental effects from sulphide oxidation and acid generation on water quality were not clearly understood. Planning for decommissioning and mitigation of acid generation was therefore only considered in the late stages of operation, prior to mine closure. During closure planning, sulphide oxidation and tailings acidification were recognized as the most important influences on future water quality and ecological health of the watershed. The implementation of effective mitigation strategies for potentially acid generating tailings produced excellent results for water quality improvement at the individual TMAs and in the watershed, overall. The case study of the Denison TMA and results for other flooded TMAs in the Serpent River Watershed represent excellent examples of the reversibility of environmental effects from mining operations that were not initially designed to mitigate acid generation. The commitment by Denison Mines Inc. and other former uranium mine operators at Elliot Lake has clearly demonstrated that historic mines need not represent a negative environmental legacy for future generations.

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7. East Sullivan mine site – Organic Covers

A mixture of organic materials (sawdust and sewage sludge) was emplaced into a mine spoil backfill to stimulate microbial growth and generate an anoxic environment through sulphate reduction (Rose et al., 1996). The results of the organic matter injection process caused no change in water pH, about a 20% decrease in acidity and a similar decrease in Fe, Mn, and Al. The results indicate that the process works, but improvements in organic material injection and the establishment of a reliable saturated zone in the backfill are needed for maximum development.

The nature of the organic material used to prevent the oxidation of sulfidic mine tailings is varied. Forestry wastes have been laid down since 1984 at the East Sullivan mine site in north-western Québec (Germain et al., 2003).

The wood waste cover on the East Sullivan mine tailings serves several functions. The cover is considered to act as a prevention method for potential ARD production. The organic matter consumes oxygen and therefore acts as an oxygen barrier. The wood waste also promotes higher infiltration rates and therefore maintains a higher water table in the tailings than would occur without the cover. The higher water table is considered to be protective of the reactive tailings if oxygen does migrate through the cover. In addition, the cover has had a role in water treatment. Water collected in perimeter ponds is pumped onto the wood waste cover with the intent of removing soluble sulphide oxidation products, such as iron and other metals, and to neutralize the water with alkalinity produced by decomposition of the organic matter (Germain, et al., 2010).

A field-scale experiment was conducted at the Greens Creek Mine on Admiralty Island, Juneau, Alaska, USA to evaluate various organic carbon sources (peat, spent-brewing grain, municipal biosolids) as amendments for passive treatment of tailings in pore water (Lindsay et al., 2011). The field experiment proved that the technique can effectively limit the transport of sulphide mineral oxidation products in mine tailings impoundments. The experiment reported that the amendments containing a large proportion of labile organic carbon compounds should be used sparingly, as rapid development of reducing conditions can lead to enhanced mobilization of iron and associated trace elements.

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8. Benambra Mine Site - Alkaline Covers

Rehabilitation and Post-Closure Monitoring and Performance at the Benambra Base Metal Mine Site in Australia

A Closure and Rehabilitation case study prepared by Earth Systems Pty. Ltd.

Site History

The Benambra Mine Site in south-eastern Australia was operated as an underground base metal mine from 1992 to 1996. During operations, 927,000 tonnes of ore was processed on site to produce copper and zinc concentrate, and nearly 700,000 tonnes of sulfidic tailings from the process plant was delivered by pipeline to a nearby tailings dam. The tailings are dominated by pyrite (65 wt.%), with lesser amounts of quartz (13 wt.%) sphalerite (1-8 wt.%), dolomite (4-5 wt.%) and chalcopyrite (1-2 wt.%).

The mining company was liquidated in 1996 and the site is now managed by the state government of Victoria, Australia. A detailed rehabilitation strategy was developed for the tailings dam, process plant site, geological core storage facility and road network. The rehabilitation strategy aimed to restore the environment to as near pre-mining conditions as possible, in accordance with industry best practice and stakeholder, community and legislative requirements. The key environmental risk was the potential for ARD generation from the tailings dam (Earth Systems, 2003) which is therefore the focus of this case study.

Description

The tailings dam was engineered as a competent water-retaining structure. Prior to rehabilitation, the dam contained about 160 ML of supernatant water, with near-neutral pH and elevated concentrations of dissolved metals (zinc, arsenic, copper, lead, and manganese) and sulfate. Due to the irregular bathymetry of the tailings surface, the supernatant water depth varied from 0 to 8 m. Prior to rehabilitation, the supernatant water was treated with hydrated lime (calcium hydroxide; Ca(OH)2) on several occasions as required to achieve suitable water quality for off site discharge. The residual metal hydroxide precipitates arising from these treatment activities remained in the tailings dam but progressively began to dissolve, with acidic catchment inputs releasing metals back into the water column, over subsequent months after treatment. Seepage from the dam wall, flowing at around 1 L/s, was also affected by ARD. This water was characterised by slightly acidic pH, elevated zinc, manganese, copper, lead and arsenic, and high sulfate concentrations. The source of this ARD was attributed to the presence of sulfidic rocks in the dam wall rather than the tailings. This is based on the water chemistry and low flow rates observed, and effectively saturated condition of the tailings.

Rehabilitation

The primary objective of site rehabilitation was to manage ARD in the tailings dam by creating a permanent water cover over the tailings, with a minimum 2 m depth, and utilising passive treatment systems for long-term water quality control, as follows:

- Diversion channels around the tailings dam were removed and original creek alignments were reinstated in the upstream catchment, to direct water back into the tailings dam to maintain the permanent water cover.
- A spillway was constructed to allow controlled overflow and ensure long term stability of the dam wall. Long term climate and water balance modelling was conducted to determine the required spillway elevation to maintain the

Plate 1. Aerial view of the Benambra tailings dam at completion of rehabilitation works.



permanent water cover of at least 2 m.

- The tailings were redistributed to remove irregularities in the bathymetry and ensure a consistent water cover across the tailings surface.
- The levelled tailings were then covered with a layer of limestone sand to minimise wave-based re-suspension of tailings in the water column and therefore minimise the potential for oxidation of sulfidic material near the water surface.
- Organic matter layers (jute matting and sawdust) were installed above the limestone sand to promote sulfate reducing bacterial activity, in order to convert existing metal hydroxide precipitates into relatively stable metal sulfide complexes and lower sulfate concentrations in the supernatant water. Furthermore, the organic matter was intended to further minimise the potential for sulfide oxidation by inhibiting the migration of dissolved oxygen from the water column into the tailings.
- The tailings dam perimeter was revegetated to permit a constant supply of organic inputs to the tailings dam via leaf litter. This was aimed to promote ongoing sulfate reducing bacterial activity, to convert any residual metal hydroxides to sulfides and further reduce sulfate concentrations, in the long term.
- Passive alkalinity addition systems were installed in the upstream catchment to raise the naturally acidic pH of creek water to near-neutral levels prior to entering the tailings dam, to minimise acidity addition to the tailings dam water.
- The dam wall was strengthened by creating a 4:1 (H:V) downstream batter slope to maintain geotechnical stability in the event of a “maximum credible earthquake”.
- An anaerobic vertical upflow wetland was installed to passively treat seepage from the base of the dam wall. The wetland has a design life of 20-30 years, after which maintenance will be required if ARD-affected seepage continues to emanate from the dam wall.

Monitoring

The water monitoring program during rehabilitation involved the collection of in-situ water quality data and samples for laboratory analysis. At the completion of rehabilitation, a remote monitoring system was installed at the tailings dam to continuously monitor rainfall, surface water level and key water quality indicators (pH, temperature and electrical conductivity), in order to monitor the effectiveness of rehabilitation and provide early warning of potential water quality issues. Results from the monitoring system were compared with field results collected manually during the first 12 months post rehabilitation, to confirm the reliability of the system. Sensor calibrations are checked quarterly (rainfall gauge six monthly) or as required. Seepage water quality and flow rate has also been monitored (manually) on a regular basis to verify the performance of the constructed wetland system.

Results

Key findings from the surface water monitoring before and after rehabilitation were:

- A minimum water cover of

Plate 2. View of the vertical upflow anaerobic wetland that was constructed for passive treatment



2 m over the tailings material has been maintained.

- The pH was elevated at around 8.5-9.0 due to water treatment during rehabilitation, but has subsequently stabilised at near-neutral to slightly alkaline values.
- Dissolved metal concentrations have decreased by around 85-95% following rehabilitation. For example, copper concentrations decreased from 2.4 mg/L to 0.03 mg/L, lead decreased from 1.95 mg/L to 0.001 mg/L, manganese decreased from 1.3 to around 0.1-0.2 mg/L, zinc decreased from above 1 mg/L to around 0.1-0.2 mg/L, and arsenic decreased from 0.068 mg/L to 0.001 mg/L.
- Similarly, there has been an 80-90% reduction in sulfate concentrations, from 1600 mg/L to less than 200 mg/L following rehabilitation. Trends in salinity have been similar to those observed for sulfate.
- Detailed review of the sulfate data, taking into account the effects of dilution and evaporation in the dam, indicates no evidence of sulfate addition associated with ARD generation.

Key findings from the seepage water monitoring before and after rehabilitation were:

- There has been no apparent increase in seepage flow rates from the dam wall.
- The pH has increased from slightly acidic (5.6-6.0) values to near-neutral values (6.3-7.1) and salinity has a progressively decreased following wetland installation.
- A comparison of dissolved metal concentrations before and after wetland installation indicates a decrease of around 85-95% for copper, lead, zinc and arsenic (generally below detection limits). These metals are effectively converting to stable metal sulfide precipitates in the wetland.
- Unlike copper, lead, zinc and arsenic, the precipitation of manganese requires oxidising conditions. This is effectively occurring in the receiving creek line, within 1 km of the wetland overflow, where dissolved manganese drops from around 10 mg/L to less than 0.5 mg/L.

Conclusions

- There has been substantial improvement in surface water quality in the tailings dam post rehabilitation.
- The permanent minimum water cover of 2 m over the tailings is providing an effective long-term solution to water quality control in the tailings dam.
- Passive alkalinity addition systems, including a limestone sand layer over the levelled tailings, have maintained near-neutral to slightly alkaline pH in the dam.
- Addition of organic matter to the dam has promoted sulfate reducing bacterial activity and generated at least a 75% reduction in its soluble sulfate load since the completion of rehabilitation activities. This sulfate reduction is improving water quality by promoting metal sulfide precipitation, and concomitantly contributing alkalinity to the surface water.
- Decreasing soluble copper concentrations have gradually permitted algal growth which has in turn

encouraged water birds to the dam. Faeces from water birds is introducing new organic matter and phosphorus to the system, which is further encouraging sulfate reducing bacterial activity and probably metal phosphate precipitation, ultimately improving water quality.

- Continued vegetation growth around the dam perimeter will promote a self-sustaining biological remediation system within the dam (via passive carbon addition) and ensure long-term passive water treatment through natural biological processes.
- The anaerobic wetland and downstream oxidation processes are combining to effectively treat ARD seepage from the dam wall.

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