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ACID MINE DRAINAGE PREVENTION AND CONTROL OPTIONS

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ABSTRACT

Acid mine drainage (AMD) is one of most significant environmental challenges facing the mining industry worldwide. It occurs as a result of natural oxidation of sulphide minerals contained in mining wastes at operating and closed/decommissioned mine sites. AMD may adversely impact the surface water and groundwater quality and land use due to its typical low pH, high acidity and elevated concentrations of metals and sulphate content. Once it develops at a mine, its control can be difficult and expensive. If generation of AMD cannot be prevented, it must be collected and treated. Treatment of AMD usually costs more than control of AMD, which could be practiced at the early stage of the mining and may be required for many years after mining activities have ceased.

Although prevention of AMD is the most desirable option, a cost-effective prevention method is not yet available. The most effective method to minimize penetration of air and water through the waste pile is to use a cover, either wet (water) or dry (soil) which is placed over the waste pile. Despite their high cost, these covers cannot always completely stop the oxidation process and generation of AMD.

Initial diagnosis of the problem, identification and implementation of appropriate prevention and control measures reduce the potential risk of AMD generation and associated high cost of mitigation. AMD prevention and control measures broadly include: source control to minimize the oxidation process, migration control and treatment. This paper provides an overview of AMD prevention and control options applicable for developing and operating mines as well as options for closure, rehabilitation or remediation of existing mines.

INTRODUCTION

AMD generation

Safe disposal and storage of large quantities of mine wastes which include waste rock, tailings, heap leach pads, etc. is an important issue for the mining industry worldwide. This is especially a problem if the waste materials contain sulphide minerals such as pyrite (FeS_2) or pyrrhotite (FeS). Sulphide minerals can become oxidised from contact with the atmosphere (air and rain), and can generate dilute sulphuric acid and cause liberation of the metals when they are not properly stored (Ritcey, 1989; MEND, 1991). The water infiltrating through the waste pile becomes acidic and metal rich and is referred to as Acid Mine (or Rock) Drainage (AMD or ARD). AMD occurs naturally at operating and decommissioned mines and is unavoidable unless oxidation of the wastes is prevented. Due to its low pH (i.e., as low as pH 2) and high levels of sulphate (SO_4) and metals (e.g., Fe; Zn; Cu; Ni; As; Cd), AMD causes a detrimental impact on the surrounding ecosystems and may harm human health.

The steps involved in the AMD generation process, using pyrite as the example, can be represented by the following reactions:

$$FeS_2(s) + 7/2\, O_2(g) + H_2O \rightarrow Fe^{2+} + 2\, SO_4^{2-}(l) + 2\, H^+ \qquad [1]$$

$$Fe^{2+} + 1/4\, O_2(g) + H^+ \rightarrow Fe^{3+} + {}^1/_2\, H_2O \qquad [2]$$

$$FeS_2(s) + 14\, Fe^{3+} + 8\, H_2O \rightarrow 15\, Fe^{2+} + 2\, SO_4^{2-}(l) + 16\, H^+ \qquad [3]$$

$$Fe^{3+} + 3\, H_2O \rightarrow Fe(OH)_3(s) + 3\, H^+ \qquad [4]$$

The overall sulphide to sulphate oxidation is summarized as follows:

$$FeS_2(s) + 15/4\ O_2(g) + 7/2\ H_2O \rightarrow$$
$$Fe(OH)_3(s) + 2\ SO_4^{2-}(aq.) + 4\ H^+ \qquad [5]$$

The principle ingredients in the formation of AMD are: (i) wastes containing reactive sulphides, including sulphide minerals (S^{2-} or S_2^{2-}), elemental sulphur (S^0) and various sulphur intermediates (e.g., thiosalts, $S_2O_3^{2-}$); (ii) molecular oxygen; and (iii) water as shown in Equations 1 and 2. Other factors influencing the rate of acid generation include bacterial activity, temperature, pH, presence of alternate oxidants (e.g., Fe^{3+} and Mn^{3+} or Mn^{4+}) as illustrated by Equation 3, and presence of buffer or alkaline minerals (e.g., calcite and silicates). The hydrolysis of ferric iron and precipitation of ferric hydroxide also produce acid as shown in Equation 4. Chemical oxidation of sulphides by ferric iron or manganese and hydrolysis reactions can take place under anoxic conditions. The Equations 1 and 2 could occur as a result of both abiotic and microbially catalyzed chemical reactions (Nicholson, 1994). Microbial oxidation reactions also require oxygen. The concept of ARD generation and bacterial oxidation of pyrite by direct and indirect pathways are illustrated in Figure 1.

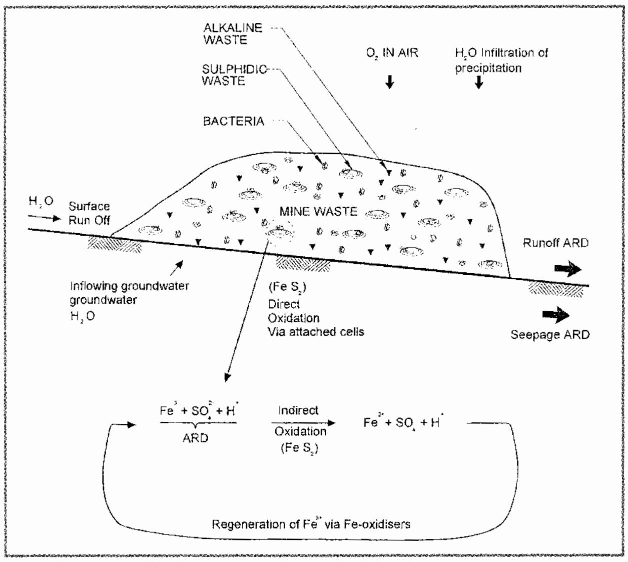

Figure 1. Conceptual presentation of AMD generation (British Columbia AMD Task Force, 1989; Johnson. 1995).

Once AMD has developed at a mine, controlling its growth and migration into the environment can be difficult and costly. It should be contained and treated using various chemical processes (e.g., lime neutralization (most common) and sulphide precipitation) or biological methods (e.g., wetlands and sulphate reducing bacteria) to detoxify the AMD (Kuyucak, 1995). Both these methods are cost intensive and tend to generate large volumes of sludge that will also require disposal, storage and monitoring. AMD treatment options are beyond the scope of the present communication; thus they will not be discussed here.

Before the development of AMD control measures, possible options such as dry cover, water cover, AMD collection and treatment are evaluated for technical and economical feasibility. The total cost for each option including capital and net present value (NPV) operating cost is calculated and is tabulated for comparison. The decision is made primarily based on the total cost of the option and the effect of option on the generation of AMD and its life span. In the case where AMD has already developed, the treatment may be the most feasible method. The use of high density sludge (HDS) lime neutralization method has recently become a preferred method for the treatment of AMD, because of its capability to generate a smaller quantity of sludge with improved chemical and physical properties.

Sources of AMD

The problem of AMD occurs in mine waste rock dumps, mine tailings impoundments, heap leach pads, mine adits, open-cuts, pit walls and other areas. In addition to waste rock and tailings, the sources of AMD from mining operations may include: underground mines, open pit mines, spoil piles and stock pile and spent heap-leach piles (MEND, 1996). The development of AMD is time dependent and, at some sites, may evolve over a period of many years. It may start along with mining activities.

Effect of physical properties of tailings and waste rock on AMD generation

Particle size, porosity, surface area of sulphide minerals and the homogeneous distribution of sulphide and alkaline mineral content differ for tailings and waste rock. These differences affect the rate of potential oxidation and neutralization processes, and hence the quality of ARD. As the mean particle size diameter in the waste rock environment is typically greater than 20 cm, tailings material is much finer, generally less than 0.2 mm (Nicholson, 1994; Broughton and Robertson, 1992). The finer particle size is associated with a larger surface area for sulphide minerals and this enhances the rate of oxidation. On the other hand, the finer and more homogeneous material that facilitates the neutralization process within the tailings impoundment, allows the alkaline materials to be in close proximity to the acid generating sulphide minerals.

DEVELOPMENT OF AMD CONTROL MEASURES

The general approach is to eliminate or reduce one or more of the essential components, or control the environment at the waste source in order to reduce the rate of acid generation to an insignificant level. The control of acid generation requires one or more of the following removal/isolation of sulphide; reduced supply of oxygen, reduced supply of water; temperature control; pH control; or control of bacterial action (BC

AMD Task Force, 1989; MEND, 1990). However, since air and water are considered to be the key ingredients of AMD, control methods usually aim to reduce the flux of air or water through isolating the waste material.

The steps involved in selection and design of appropriate control options include: material characterization and physical quantification; siting; assessment of options and site conditions; prediction of performance; economic evaluation; and implementation, monitoring and maintenance.

Material characterization and quantification

Waste material characterization and quantification is the first step for the design and implementation of AMD control measures. Geochemical characterization identifies the threshold conditions (e.g., percent sulphide (S) and alkalinity content) found in the material with respect to acid generation and metal mobilization potential (MEND, 1993; MEND 1995; Miller, 1995). Understanding of relative quantities of sulphide and alkaline materials and their mineralogy is essential in predicting the occurrence of AMD. For new and operating mines, the acid generation potential of waste materials and the schedule of production could dictate the need and design criteria for a waste storage impoundment. If geochemical characterization and material quantification work precedes the startup of mining, cost-effective AMD mitigation methods can be incorporated in design and development of a mine.

Siting

The sensitivity of background site conditions to impact, or beneficial uses of these conditions, are assessed and incorporated in defining suitable sites and selection of appropriate design standards for a waste rock dump and/or tailings impoundment area (Watson, 1995). Understanding of the site topography and water balance is critical to the control surface water and the diversion of flows away from waste rock and tailings facilities. If possible, it is best to choose sites for waste rock disposal that are high and dry, because waste rock piles need to be protected from surface water runoff and groundwater seepage before, during and after closure. Tailings impoundments are often sited in valley bottoms or low areas for various engineering reasons, because a large volume of tailings can be contained in natural topographic “bowls” with minimum embankment construction. However, in these areas, long-term stream diversion and liner systems are likely to be necessary to protect the dam and materials from erosion and from infiltration by oxidizing surface waters and groundwaters, even if sub-aqueous tailings closure plans are being considered.

Assessment of control options and site conditions

Suitable control options and potential interactions between the facility and the site are identified. Required performance standards or criteria are established and the tolerance of each option to site conditions is assessed for its benefits in terms of not exceeding some adopted environmental standards.

Prediction of performance

The performance of the designed or selected option(s) compared to the adopted standards is predicted by applying appropriate engineering techniques (e.g., computer modelling). Key engineering considerations would include seepage generation quantities, water quality and stability.

Economic evaluation – Cost-Benefit analysis

Following completion of design of the facility or works, an economic evaluation of the proposed solution would be appropriate. This costing would likely take place during the project feasibility assessment. Certainly, closure costs should also be estimated at this stage so that a life cycle cost for the mine can be considered.

Techniques to minimize overall cost would integrate the use of existing mining materials (e.g., run-of-mine wastes) for the construction work. The project should be designed and operated with closure in mind. Staged implementation of control measures to the site may also reduce the large capital outlay at the completion of the project.

Implementation, monitoring and maintenance

It is beneficial to implement control measures at the site as early as the exploration stage and throughout the mining operational stage. Full implementation would occur in the final decommissioning and closure of the containment or impoundment area.

Monitoring and maintenance would be part of both the implementation and post-closure care plan. Monitoring would be used to gauge actual performance against the predicted performance and adopted performance criteria. Maintenance would be necessary to ensure on-going performance through the phases of implementation and post-closure care.

AMD CONTROL MEASURES AND PREVENTION OPTIONS

Control and prevention methods aim to eliminate the process of sulphide oxidation. This can be achieved either by preventing air and/or water coming into contact with the sulphide-bearing material or by separating sulphide minerals from the waste. Development and implementation of source control methods are particularly important for new operating mines, since it may prevent acid generation before it develops. Mine operators need to plan ahead to use source control measures. The control and prevention methods include: control of water migration, separation and blending wastes with alkaline materials, and the use of dry and water covers (US EPA, 1995; Filipek et al., 1996; MEND, 1996; MEND, 1993; MEND, 1990). Depending on the site conditions (e.g., climate, topography and hydrology) and nature of the waste, suitable methods are identified and implemented at a given site. Table 1 presents an overview of AMD control and prevention methods applicable for the disposal of waste rock and tailings containing reactive sulphide minerals. Each option is discussed below.

Objective of Control	**Control/Prevention Method**
Water migration	Diversion ditches, grout curtains, slurry walls
Reduction of water inflow	Encapsulation, capping and sealing
	e.g., dry (soil) covers, liners or coating or permafrost
Exclusion of oxygen	Water covers (flooding) and sub-aqueous deposition
	Encapsulation, capping and sealing or permafrost
pH control	Waste segregation and blending
	Alkaline additives
Sulphide removal and isolation	Conditioning of tailings and waste rock
Control of bacterial action	Bactericide

Table 1. AMD prevention methods based on control objectives (British Columbia AMD Task Force, 1989).

Control of water migration

Migration control restricts the amount of water moving through potentially acid generating waste. Clean water flows including surface water and groundwater can be intercepted and diverted away to prevent them from passing through the waste materials with the potential to form AMD and become contaminated with release of metals and acidity (Watson, 1996). With the help of properly designed ditches, movement of contaminated (e.g., AMD seepage) or clean waters can be controlled. In theory, groundwater migration could be controlled using some type of interceptor structure such as grout curtains and slurry walls, as well as diversion ditches.

Rain falling directly on a waste dump surface is partitioned into interception, infiltration and runoff depending on the texture, grading and topography of the dump surface. Infiltration water migrates downward through the dump with a proportion appearing as leachate at the toe of the dump (Figure 1). Diversion can also be used to collect contaminated leachate and runoff (i.e., AMD) from waste storage sites and to facilitate the treatment of AMD. Diversion ditches may include liners or armours to minimize potential infiltration into the underlying materials or erosion.

Implementation of a strategy for the management of runoff is especially important for operating mines. Usually, large storage dams are needed to collect flows from catchments originating from open waste dumps and ore stockpiles at the site. In front of advancing dumps, runoff control sumps are placed to transfer runoff coming from the waste dump to a runoff control dam. If contaminated, water is treated using an appropriate method (e.g., lime addition). The treated water may be used as process water or stored in the water storage dam or discharged to the environment.

Appropriately designed slopes and regrading of waste piles minimize infiltration of water into the mining waste and allow placement of a soil layer for establishing vegetation that is required for the ultimate reclamation of the site. The use of proper slopes and steps in regrading also reduces the potential for erosion (Filipek et al., 1996).

Separation and blending

During the operation of a mine, waste rock containing a high percentage of sulphide minerals can be separated and be disposed to a specifically designed and prepared storage area. AMD generation potential of a reactive mine waste can be reduced further by reducing the net acid producing potential or by increasing the net neutralization potential of the waste. In addition, encapsulation with an alkaline material such as limestone or benign waste or non-acid producing material can inhibit AMD generation.

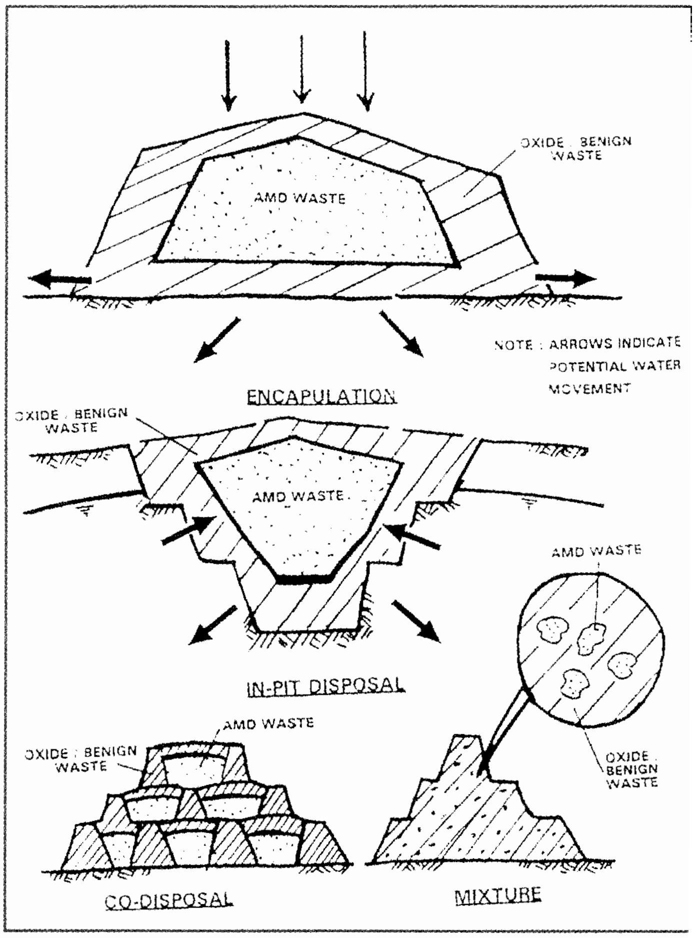

Figure 2. Separation and blending of sulphide bearing wastes.

Disposal options for separation and blending of wastes are illustrated in Figure 2 (see next page). The waste material can be mixed and/or co-disposed with a benign material. Co-disposal of waste rock with tailings, (i.e., co-disposal of coarse material with fine particle material), is sometimes practised. It is believed that filling the large pores of waste rock with fine tailings reduces oxygen penetration into the waste materials, thereby curtailing the oxidation process. Encapsulation comprises the development of small cells for placement of problematic wastes. To be cost-effective, these cells would be formed from enign waste or other suitable borrow materials readily available at the site. Blending would be the mixture of both the benign and problematic waste streams. Blending would rely on the neutralization capacity of the benign material, and it has been found that complete mixing of the two materials was more effective than placing them separately in layers.

Desulphurization of tailings has been investigated and used for the separation of sulphide compounds from tailings (MEND, 1996). A simple floatation process has been used to remove the residual sulphides and produce a small quantity of concentrate that would require proper disposal and storage. It has been reported that the separation method is more effective for pyrrhotite type sulphide minerals rather than pyrite. Developments in this area are underway.

Coating of certain mine wastes has been also investigated as an alternative method to prevent pyrite oxidation. The mechanism of coating involves the leaching of mining waste with a phosphate solution containing hydrogen peroxide. When this solution reaches pyrite surfaces, hydrogen peroxide oxidizes the surface portion of the pyrite and releases iron oxides so that phosphate precipitation forms a passive surface coating. A recent study has been testing the use of sodium or calcium silicate instead of phosphate. However, coating processes are still under development.

The use of anionic surfactants as bactericide has also been examined to inhibit bacterial activity and, subsequently, prevent acid generation. Bactericide is effective after the acid generation starts, because bacterially catalyzed oxidation becomes important when the pH in the media reduces to less than 3.5. Its effectiveness is time limited, thus requiring periodic applications. Bactericide may result in better performance if its use is combined with the addition of neutralizing materials and natural organic fertilizers that can stimulate the growth of vegetation and benign microorganisms (Filipek et al., 1996).

Dry covers, soil covers and liners

Covers, caps and seals can be used to isolate or encapsulate sulphide-bearing waste and to limit the access of either oxygen or water, or both. Exclusion of oxygen from waste materials is a very effective means of preventing sulphide oxidation, but it may be more difficult to achieve than excluding water. Capping materials that have a low coefficient of oxygen diffusion include water, amended and compacted soils and geomembranes. The effectiveness of a dry "soil" cover system basically relies on the presence of a low hydraulic conductivity and high moisture retaining layer (MEND, 1992; MEND, 1993; MEND, 1994).

A low-permeability soil cover containing a layer of compacted clay can be constructed as a single-layer or multilayered system over either tailings or waste rock dumps (Yanful and Nicholson, 1991). An ideal soil cover consists of a sufficiently thick soil layer and appropriately regraded slopes that can induce runoff, resist erosion and retain water. The top layer can be vegetated to maximize evapo-transpiration of water to decrease infiltration and resistance to erosion. The efficiency of a revegetated soil cover can be further increased by placing a layer of coarse rock beneath the cover to form a capillary break and decrease percolation.

In semi-arid conditions, simple single layer soil covers can be effective in controlling percolation of water into the waste dump. Multilayered soil covers are often used in high rainfall areas (e.g., >50 cm). Two or more layers can be used in a design including from top to bottom: a revegetated soil layer to retain moisture; a coarse layer to provide lateral drainage of infiltration; a compacted clay layer to prevent oxygen penetration; and compacted alkaline layer to facilitate cap construction and minimize reaction of water in the waste with the clay layer. Conceptual options for multilayered soil covers and the effect of cover and material type on infiltration rate are illustrated in Figure 3. In some cases, instead of revegetation, a layer of coarse material is placed for erosion control. To be effective, clay or other low-permeability soil must be kept saturated with water to limit oxygen

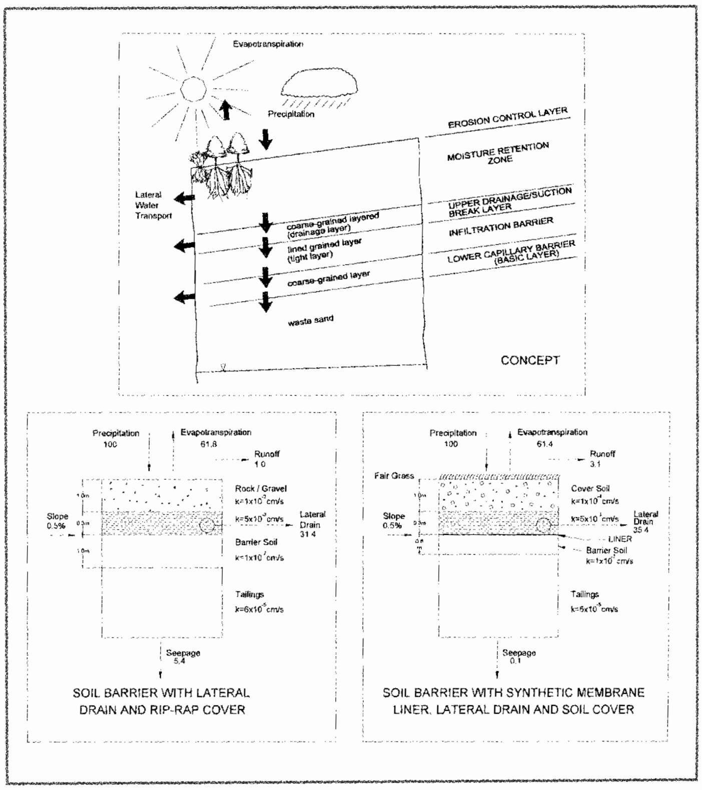

Figure 3. Conceptual multilayered cover design and effect of cover type on infiltration rate.

penetration and prevent cracking. Modelling can predict the performance for a given cover design followed by cost-benefit analyses. Depending on the results, the design can be modified to obtain the optimal number of soil layers, selection of soil materials, thickness of each layer and construction methods.

Despite their effectiveness, multilayered soil covers have been found to be costly to install in many areas. Materials including wastes or by-products from other industries have been investigated through laboratory and pilot scale tests for their potential as low cost alternatives for re-use as moisture retaining and oxygen consuming barriers. These materials include: inorganic and organic compounds such as sulphide-free tailings, shotcrete, fly ash mixtures, cementitious materials, peat, municipal solid waste compost, lime-stabilized sewage sludge and wood chips and bark (Cabral, 1997). Except for concrete fly ash materials, all materials tested have shown potential benefits by depleting oxygen.

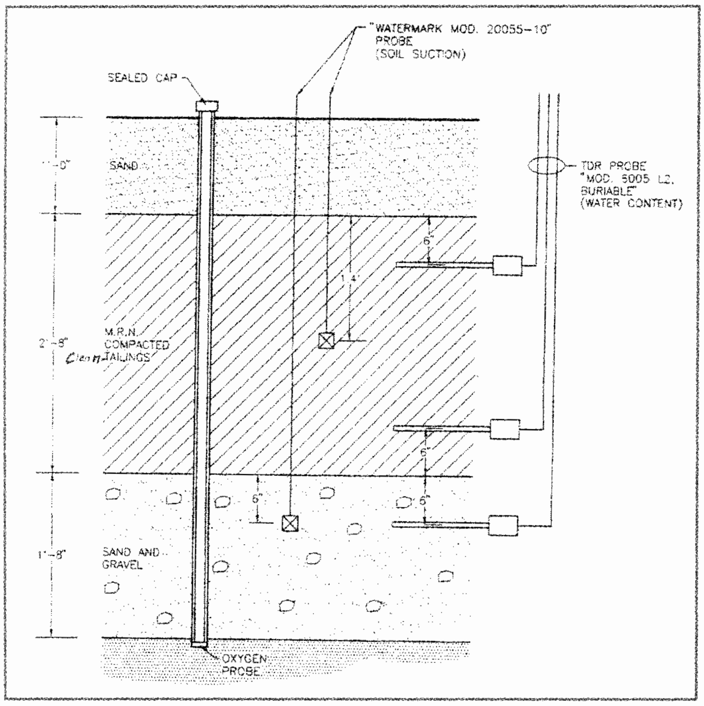

Figure 4. The use of sulphide-free tailings in instrumentation to monitor the performance of a multilayered cover system.

Golder Associates has designed a multilayered dry cover containing sulphide-free tailings for a decommissioned mine site in Quebec, Canada (Figure 4). In this application, it has been observed that a layer of tailings sandwiched between two sand layers could reduce oxygen flux by a factor of about 1000 or more (Ricard et al., 1997; MEND, 1996).

Availability of suitable material for cover construction is the key issue in terms of the cost and implementation of soil covers. At the sites where clay reserves are limited, in-situ compaction of waste rock dumps to form a low permeability seal has been tested (Orr, 1995). It was found that, with the help of an impact roller machine, the surface of waste rock dumps could be compacted to obtain a hydraulic conductivity of 10-7 to 10-8 m/s, which could act as an infiltration barrier. The concept has been implemented at the Mt. Leyson gold mine site in Australia.

Geomembranes such as polyvinyl chloride (PVC) and high density polyethylene (HDPE) have currently been examined for both top and bottom liners due to their low permeability that can limit the entry of water and oxygen into the waste materials. They must be handled with care to prevent possible punctures. The use of polyurethane and polyurea spray materials has also been investigated to form a membrane-like cover over tailings for AMD mitigation (MEND, 1996).

Permafrost option has been practised in cold climates as an AMD control method. In this option, tailings are kept frozen all year-round (MEND, 1996a). Application of this method primarily depends on the site climate.

Water cover "sub-aqueous disposal"

Water covers have been shown to be an economical alternative to dry covers, because oxygen has a very low solubility and a diffusion rate through water almost four orders of magnitude less than in air. Therefore, the oxidation of reactive wastes can be minimized and water covers can be an effective long-term control method for acid generation. However, the application of water covers is limited by site conditions. Site conditions with respect to hydrology, topography and the presence of a water source in the vicinity should be suitable for the water cover application (Dave, 1992; St-Germain and Kuyucak, 1998). Sub-aqueous or wet covers appear to be the most feasible option for controlling AMD generation, especially in higher rainfall areas.

Sub-aqueous deposition of tailings or waste rock can encompass many forms, including back-filling of mine pits and allowing the pit to flood, placement in man-made lakes or impoundments, or placement in flooded underground workings. The most common application of the sub-aqueous method is to deposit the waste in man-made (engineered) impoundments or to flood the existing tailings pond by designing and constructing appropriate dykes and dams. Golder Associates undertook a demonstration project in collaboration with Rio Algom Ltd. for the establishment of a shallow water cover over the Quirke mine waste management area in Elliot Lake, Ontario, Canada. In this

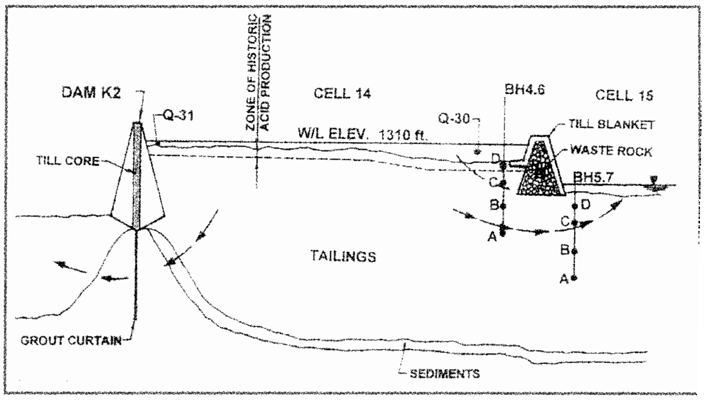

Figure 5. Schematic presentation of Quirke Mine tailing pond flooding (Karn et al., 1997).

work, following the construction of various internal dykes and dams, the tailings pond was flooded (Kam et al., 1997). A schematic presentation of flooding of the tailings pond is given in Figure 5. It has been reported that the water quality in the tailings pond was significantly improved after the implementation of the method and has remained excellent for pH, alkalinity, Ra-226, Zn, Fe and SO_4 concentrations.

Disposal in lakes and marine environments is also effective in controlling acid production, but it may create turbidity and cause the release of metals into the watercourse. Back-filling requires double handling of materials and may leave excess material, which cannot fit, back into the mine openings.

Although water covers can significantly reduce acid generation, a slow-release of some metals may still occur to the water column resulting in an increase in some metal concentrations which may exceed regulated water standards (Aube et al., 1995). Thus, the water would require treatment before its discharge to the environment.

The use of an organic layer at the tailings/water interface has been found to be effective to further improve the effectiveness of water covers (St-Germain and Kuyucak, 1998; Beckett et al., 1998; St-Germain et al., 1997). The organic layer could be built up by growing aquatic plants in situ and the concept is called a "Biologically Supported Water Cover". Aquatic plants could consist of emergent, floating and submerged species. The organic layer at the tailings/water interface could act as a barrier for oxygen and metal release. Oxygen would be consumed in the organic material through bacterial activity and thus oxygen diffusion from the surface water to the tailings pore water would be prevented. Upward metal fluxes from the tailings to the water cover would be prevented due to formation and precipitation of metal sulphide complexes through the activity of anaerobic sulphate reducing bacteria (SRB). The organic material degrades to lower molecular organic compounds during the consumption of oxygen by aerobic microorganisms and anaerobic conditions at the interface could form. The presence of lower molecular organic compounds and the anaerobic conditions enhance the growth of SRB. Additionally, metals form complexes with organic compounds, and biosorption and bioaccumulation phenomena occur in the system. These processes further help to retain metals at the tailings/water interface. Furthermore, the presence of plants in the tailings impoundment, especially emergent plants growing at the edges, improves the physical stability of the tailings through their roots. The concept of Biologically Supported Water Cover is shown in Figure 6.

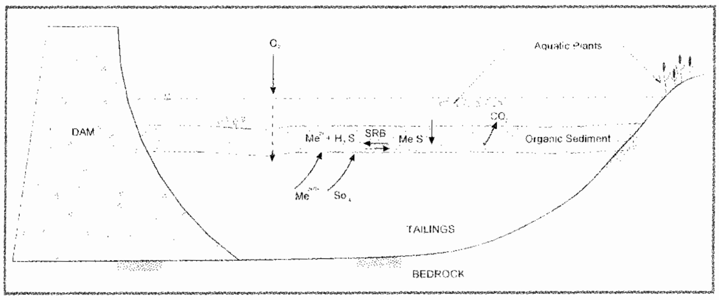

Figure 6. Biologically supported water cover to mitigate AMD generation (Kuyucak and St-Germain, 1998).

In-Pit disposal

Pits are often considered as geotechnically and geochemically stable environments for disposal of wastes, an aesthetic focal point in rehabilitation plans, and potential habitat for both terrestrial and aquatic plants and animals. (MEND, 1995). Mined-out pits have been employed for storing wastes originating from different activities around the world for a long time. The types of wastes include industrial process residues, municipal refuse and excavation spoils. The use of pits for mine waste disposal has become well-accepted practice in many countries, particularly in many jurisdictions in Canada. Environmental agencies in certain locations such as Saskatchewan, Canada encourage mining industries to evaluate the use of the mined out open pit as a potential disposal option. In addition, mine operators have recently proposed excavating pits for the sole purpose of uranium mine waste disposal.

A recent study conducted by MEND (1995) found out that over 40 sites around the world including Canada, the United States of America (USA), Australia and Germany have been using open pits for storing mine wastes. Types of wastes include tailings, waste rock, overburden, sludge and acid mine drainage. A wet, dry or combined wet-dry cover is placed on the pit when the mining activities are ceased and the site is closed. If site conditions are suitable, placement of a water (wet) cover is preferred over the placement of a dry cover because of the ability of water to prevent oxidation of wastes.

In-pit tailings disposal facilities which are flooded at closure often rely on a concept which is variously referred to as a 'porous envelope', a 'hydraulic cage' or a 'pervious surround' to limit post-closure effects on regional groundwater. If the hydraulic conductivity of the material surrounding the pit (e.g. naturally pervious rock or soil or a constructed high permeability zone) is more than two orders of magnitude greater than that of the tailings itself, the advective transport of contaminants from the waste into the regional groundwater will be minimal. Contaminant transport will be controlled by the much slower process of molecular diffusion (Donald et al, 1997).

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