

DESIGN AND RECLAMATION OF MINE WASTE FACILITIES
TO CONTROL ACID MINE DRAINAGE¹

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Abstract. The economics of mine waste management are often greatly influenced by the potential of the waste to generate acid mine drainage (AMD). If mining operations result in the exposure of sulphide bearing rock which has the capacity to produce AMD, control measures are necessary to protect the environment. This is particularly important in the long term, after mining operations have ceased. Facilities such as tailings deposits, waste rock dumps and open pits in acid generating rock need to be designed to prevent AMD damaging the environment. Existing facilities need to be reclaimed such that AMD is reduced to insignificant levels. If AMD is not controlled, there is potential for considerable harm to the immediate aquatic environment.

A number of mines in British Columbia are either producing or have the potential to produce AMD. Considerable effort is being directed towards developing effective, economic control measures in this Province. This paper describes the currently available AMD control measures. Important lessons may be learned from sites where AMD is occurring and from those sites where reclamation plans, that are designed to control AMD, have been implemented. A recommended approach to the design and implementation of control measures is presented.

Introduction

Acid mine drainage (AMD) may be defined as contaminated drainage that occurs as a result of natural oxidation of sulphide minerals contained in rock which is exposed to air and water. Mining in

sulphide bearing rock is one activity which may lead to the generation and release of AMD, although not all operations that expose sulphide bearing rock will necessarily result in AMD. Acidic drainage will not occur if the sulphide minerals are non-reactive, nor if the rock contains sufficient base potential to neutralize the acid, nor if appropriate control measures are successfully implemented.

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In British Columbia (B.C.), AMD was first observed in 1928 at the Britannia Mine (Errington and Ferguson, 1987) where mining began in 1905, however the date of initial release of AMD is not known. Acid mine drainage has had some major detrimental effects on B.C.'s environment. Errington and Ferguson report that five abandoned mines are affecting streams. At

one mine site (Mt. Washington) they reported that AMD has contributed soluble metal loadings to a salmon river (the Tsolum) at a sufficient level to be partly responsible for the loss of fisheries resources in the river for 11 kilometres. Until recently, the potential for a new mine to generate AMD was often not adequately anticipated during the planning stages; due mainly to a lack of understanding of the problem. Some operating mines, such as Equity Silver, have had to institute very costly treatment measures to prevent severe damage to the environment (Wilkes, 1987).

AMD currently experienced from mining activities in B.C. and the Yukon occurs predominantly from waste rock facilities at hard rock metal mines. While AMD does occur from underground workings and tailings deposits, open pits and waste rock dumps are the major AMD sources. On the other hand, in Eastern Canada, AMD from tailings is of major concern particularly at the underground uranium, copper and nickel mines in Ontario and Quebec. This trend is probably due to a number of factors. In B.C. metal mining in sulphide ores tends to be open pit mining with resultant large quantities of waste rock. The waste rock, while not necessarily high sulphur content, has very low buffering capacity and is durable and hence permeable, allowing acid generation to occur and be realized rapidly. In Eastern Canada, underground mining is more predominant with lesser quantities of waste rock, and the waste rock that is produced tends to have a greater neutralization potential. AMD develops more rapidly from waste rock than tailings deposits. Thus the AMD from the relatively "young" B.C. and Yukon tailings deposits may not have developed to their maximum potential.

Available Control Measures

An approach to the prevention and abatement of AMD is described by Robertson and Barton-Bridges (1988). This approach applies control of AMD in three categories, or levels of control, as follows:

- 1) Control of acid generation.
- 2) Control of AMD migration.
- 3) Collection and treatment of AMD.

The control of AMD by preventing or inhibiting acid generation is the most preferable level of control. If acid generation is prevented there is no risk of the resultant contaminants entering the environment. The formation of acid at the source may be prevented by excluding one or more of the essential ingredients or by controlling the

environment around the sulphides. The essential ingredients in the acid generation process are; reactive sulphide minerals, oxygen and water. Criteria that influence acid generation, in terms of rate of production, include oxygen and water availability, nature of sulphides, bacterial activity, temperature, and pH.

The next level of control is to prevent or reduce the migration of AMD to the environment. Since water is the transport medium for contaminants, the control technology relies on the prevention of water entry to the AMD source. Control of water exit is of little value since in the long term all water entering the AMD source must exit, long term storage being negligible.

The third level of control, after control of acid generation and AMD migration, is to collect and treat contaminated drainage. The collection and treatment of AMD has been the most widely applied abatement measure to date. Treatment measures can be either active systems which require continuous operation, such as a chemical treatment plant, or passive systems which are intended to function without intervention by man, such as wetlands. Chemical treatment involves technology which is well established and is working effectively at a number of mines.

A number of control measures are available in each of the categories listed above. The suitability of individual measures depends on many factors including; site specific conditions, the length of time during which the control is to remain effective, and whether the control is for an existing or proposed waste facility. The currently available control measures in each of the three categories are listed in Table 1. These measures include both short and long term controls and each method will likely experience a different level of success, depending on the project and site specific conditions. The most effective control might be achieved by incorporating a combination of measures from each of the three categories of control. The methods listed in Table 1 will not be described in detail here, other than to mention the most effective long-term control measures and to discuss the geotechnical considerations in the design of soil covers, and the diversion or collection of surface and ground water.

Long-Term Control Methods

There are at present three control measures that have the potential to be successful in the long term depending on the application and site criteria. These measures are; water covers,

TABLE 1
Available AMD Control Measures

Control of Acid Generation

- . Conditioning of tailings or waste rock to remove or exclude sulphide minerals.
- . Covers and seals to exclude water.
- . Covers and seals to exclude oxygen (including water cover).
- . Waste segregation and blending to control pH.
- . Base additives to control pH.
- . Bactericides to control bacterial oxidation of sulphide minerals.

Control of AMD Migration

- . Covers and seals to exclude infiltration of precipitation.
- . Controlled placement of waste to minimize infiltration.
- . Diversion of surface water.
- . Interception of ground water.

Collection and Treatment of AMD

Surface and groundwater collection systems together with treatment as follows:

- . Active systems, e.g. chemical treatment plant.
- . Passive systems, e.g. treatment by wetlands.

soil covers, and collection and treatment of AMD. Each of these measures have clear advantages and disadvantages in terms of both effectiveness and cost.

The most secure long-term control measure currently available is to provide a water cover over the reactive waste. This generally serves to exclude oxygen to such an extent that the rate of acid generation is reduced to negligible levels. Water cover may be implemented by placing the waste

directly under water, by flooding the waste after placement and maintaining flooded conditions, or by means of saturated soil or bog covers. If designed correctly, this measure may offer protection with minimal long-term maintenance. Water cover is often only feasible for new mines due to the high costs of either re-handling existing waste or tailings deposits in order to place these under water, or of constructing structures to maintain flooded conditions in the long term. In the case of existing tailings deposits, it may be practical and feasible to maintain saturated conditions if the tailings are contained behind water retaining structures. An example of water cover to control AMD in B.C. is the Island Copper Mine on Vancouver Island where waste rock and tailings are placed under water in Rupert Inlet (Steffen Robertson and Kirsten, 1988).

Soil covers show promise as inhibitors of oxygen (particularly to coarse rock waste dumps) and, probably more importantly, as barriers to infiltration. The effectiveness of soil covers as oxygen barriers is influenced by the moisture content maintained in the cover. A cover that can be maintained in a saturated condition will be more effective, primarily due to the low solubility and diffusivity of oxygen in water and due to prevention of desiccation cracking. Soil covers have been used to abate AMD from existing wastes where water cover is not feasible. An example of the application of a soil cover to rock waste in B.C. is the abandoned Mount Washington mine on Vancouver Island (Healey and Robertson, 1989). The effectiveness of such covers is still to be determined by long term field testing, as is currently being done at a number of sites (NTDME, 1986; Steffen Robertson & Kirsten, 1986b; Healey and Robertson 1989). The geotechnical considerations in the design of soil covers are discussed in more detail below.

At some existing facilities, the only practical option available to control AMD is to collect and treat the contaminated drainage. Collection is only possible if surface and groundwater flows can be intercepted and stored to allow appropriate treatment. This is an exercise in geotechnics and geohydrology. The main disadvantage of chemical treatment is that it requires continuous operation and maintenance. There is a relatively high risk of equipment or power failure which makes back-up or contingency measures necessary, and a need to dispose of large volumes of sludge. Chemical treatment, while it offers a secure short-term method of achieving environmental protection, may not offer a cost effective long-term solution.

Geotechnical Considerations in the Design of Soil Covers

Simple Soil Covers

In the interest of minimizing cost; a simple, single layer, soil cover is preferred. A fine textured soil, such as clay or silt, is required to limit infiltration. To effectively limit oxygen transport it is necessary to maintain the layer at a high moisture content. A single soil layer, however, is limited in its effectiveness for the following reasons.

Without capillary barriers, a simple soil cover is prone to large seasonal variations in moisture content. This could result in desiccation cracking and hence an increase in permeability. In addition, decreasing the moisture content of the soil increases the rate of oxygen diffusion. These seasonal variations are greatest near the surface and are therefore greatest for thin covers. For single layer soil covers to be effective they need to be relatively thick to maintain a saturated zone during the dry season. The cover thickness required is probably a function of the climate but is likely to be of the order of 2 m for regions such as B.C.

The fine-grained soils required to limit infiltration may be frost susceptible. Ice segregation may result in degradation of the cover and increased permeability. Frost heave may also make the surface of the

cover irregular, allowing ponding and increased infiltration. Permeability changes may also result from root action and biotic activity.

A simple soil cover does not have the ability to prevent moisture being sucked up from underlying tailings (or vice-versa) by capillary action. In net evaporation regions, it does not limit the migration of salts from the tailings to the surface due to surface evaporation and transpiration.

A simple, single layer fine-grained soil cover may not be able to adequately withstand wind and water erosion or burrowing and root action. Some form of erosion protection, such as vegetation or rip-rap is normally required.

These limitations on the effectiveness of a single soil layer can be overcome by using complex covers, as described in the next section.

Complex Soil Covers

The effectiveness of soil cover is greatly improved by adopting a complex cover design consisting of several layers, each performing specific functions to improve water and oxygen exclusion and long-term stability. These layers and their specific functions are described below. A typical complex cover design is illustrated in Figure 1 (Rasmuson and Eriksson, 1987).

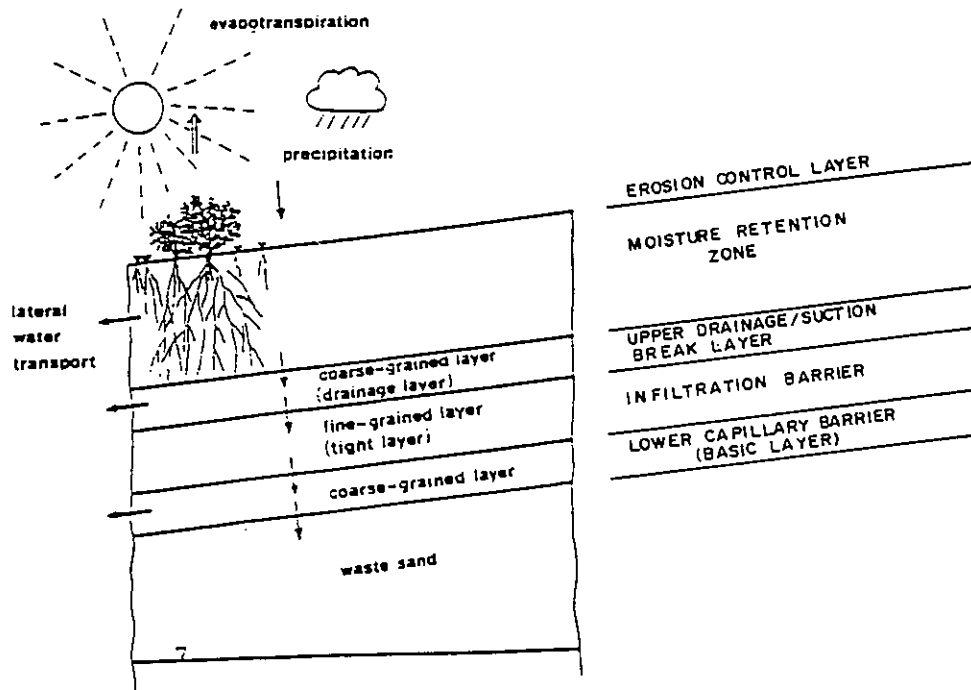


Figure 1 Concept for a Soil Cover for Reactive Tailings
(after Rasmuson and Eriksson, 1987)

Erosion Control Layer. Erosion protection can be provided by vegetation or by a layer of coarse gravel or rip-rap. The establishment of vegetation on the waste dumps is desirable for aesthetic and land use reasons. Therefore, revegetation is usually the most desirable method of providing erosion control. However, where revegetation is not practical or will not sufficiently control erosion coarse gravel or rip-rap may be required.

Studies for uranium tailings deposits in Canada (Steffen, Robertson and Kirsten, 1986a) indicated that forest cover would adequately control sheet and rill erosion, and wind erosion, but methods of analysis are not available to assess the effectiveness of vegetation to control gully erosion. A vegetation cover design guide has been prepared for U.S. uranium tailings deposits by Beedlow (1984). While this design guide illustrates and discusses many of the aspects relevant to vegetation cover design, it is not necessarily directly applicable to B.C. mine waste deposits. A similar guide for the design or rip-rap erosion protection has been prepared by Walters (1982).

A special study on vegetative covers was recently carried out as part of the Uranium Mill Tailings Remedial Action Project (UMTRAP) in the United States (U.S. Department of Energy, 1988). This study investigated the use of vegetation to stabilize uranium tailings, and specifically includes the use of vegetation to intercept infiltration. The principal finding of the study is that properly developed plant communities on complex soil covers can be effective in stabilizing covers and controlling infiltration on top slopes of waste piles. The study showed that the appropriate vegetative cover will adapt to climatic change, will repair itself after severe disturbances such as fires and droughts and will persist indefinitely with little or no maintenance. The plants were found to protect topslopes against sheetwash erosion, however, resistance to gully erosion depends more on the overall pile configuration rather than on the vegetation and soil.

Certain physical, chemical and vegetative stabilization methods have been evaluated for purposes of mine waste reclamation by the U.S. Bureau of Mines (Dean, et al, 1986). This study incorporated field testing of these different methods and costs for the various stabilization procedures.

Moisture Retention Zone. The purpose of the moisture retention zone is to provide a zone for moisture retention to limit desiccation of underlying layers. It also provides a growth medium to support vegetation. Moisture retention is therefore desirable for two reasons:

- i) It helps to keep the infiltration/oxygen barrier moist. This helps prevent desiccation cracking and reduces oxygen diffusion.
- ii) By retaining moisture after a precipitation event it supports vegetation and allows time for evapotranspiration to occur, thus reducing infiltration.

The soil used to construct the moisture retention zone would generally be a loam soil with a substantial sand fraction.

Upper Drainage/Suction Break Layer. The upper drainage/suction break layer serves two primary purposes:

- i) To drain water laterally from the surface of the infiltration barrier, preventing ponding.
- ii) To prevent moisture loss from the infiltration barrier due to upward capillary suction.

Prevention of ponding reduces infiltration. Keeping the infiltration barrier moist helps to reduce oxygen diffusion and prevents desiccation cracking. This layer can also be designed to prevent intrusion by burrowing animals if it incorporates large gravel. For drainage to be effective it must be constructed with a cross fall of 1% or greater.

The effectiveness of this layer would be expected to decrease with time as it becomes clogged with roots and organic debris and fines, and as the drainage slope is modified by long-term settlement of the underlying tailings or rock waste.

Infiltration Barrier. This is a low-permeability layer consisting of fine-grained soil or synthetic materials (or a combination of both). Its purpose is to prevent the downward infiltration of moisture and the diffusion of oxygen into the waste. The lower the permeability of this material, the more effective it is as a barrier to infiltration. The objective of this layer is to provide a sufficient barrier to enable the overlying coarse-grained layer to drain infiltration.

Lower Capillary Barrier. Rasmusson and Eriksson (1987) investigated the use of capillary barriers, beneath the infiltration barrier, to reduce infiltration. The principle is that, if negative pore-water pressure is maintained in the low

permeability material at the interface with the underlying coarse grained capillary barrier, infiltration into the lower layer would be prevented. They found that this would only be effective if ponding on the low-permeability layer does not occur, which would be difficult to achieve in practice. However, for soil covers over fine grained waste deposits such as tailings, a capillary barrier beneath the infiltration barrier may be useful in preventing suction of contaminated pore water from tailings up into the cover in dry periods.

The long-term performance of a complex soil cover could be greatly reduced if fine-grained materials are allowed to migrate into the coarse-grained layers. Filter layers should be considered.

Basic Layer. A basic layer could be incorporated into the design to reduce the pH of infiltrating water and therefore acid generation rates. Alkaline materials such as lime or limestone could be spread over the surface of the waste, before placing the cover, or mixed into the cover layers.

Limestone is commonly mixed with waste rock during placement at coal mines with great success and research is being done on the addition of phosphate rock (Chiado et al, 1988). It is also proposed for short-term acid generation control in the waste rock at the Cinola project (Robertson and Barton-Bridges, 1988). The potential for acid generation control by surface applications of alkaline materials is less attractive than mixing them with the waste. Limestone has a low solubility in near neutral water, and the resulting alkaline charge is therefore small and may be insufficient to control AMD. Surface inflows tend to be concentrated at isolated locations such as depressions, cracks, permeable zones, etc. At these locations the available alkaline materials are quickly exhausted. The addition of a basic layer would not significantly reduce acid mine drainage where unsaturated conditions predominate, such as in waste piles. It would be more beneficial in saturated tailings, and might be usefully employed in tailings impoundment covers.

Effectiveness of Soil Covers

Information on the relative effectiveness of soil covers in controlling acid mine drainage may be obtained from the results of mathematical model simulations of covers, and from the results of monitoring of actual covers. Figure 2, developed from results using the RATAP model (Senes and Beak, 1986) illustrates the effect of depth of a till cover on typical tailings from the Elliot Lake project for various depths of unsaturated tailings (Steffen Robertson and Kirsten et al, 1987).

Figure 3 shows the effects of various types of covers on infiltration rates as predicted by the HELP model for acid generating tailings at Elliot Lake (Steffen Robertson and Kirsten et al, 1987). The results show considerable benefit of a complex cover design over simple covers, and the benefit of adding a synthetic liner.

The results of the modelling indicate a range of infiltration (shown as "seepage" on Figure 3) from approximately 38% to 0.1% of precipitation, depending on the cover design. It is worth noting that single layer cover of rip-rap or high permeability soil serve to increase infiltration due to reduced runoff.

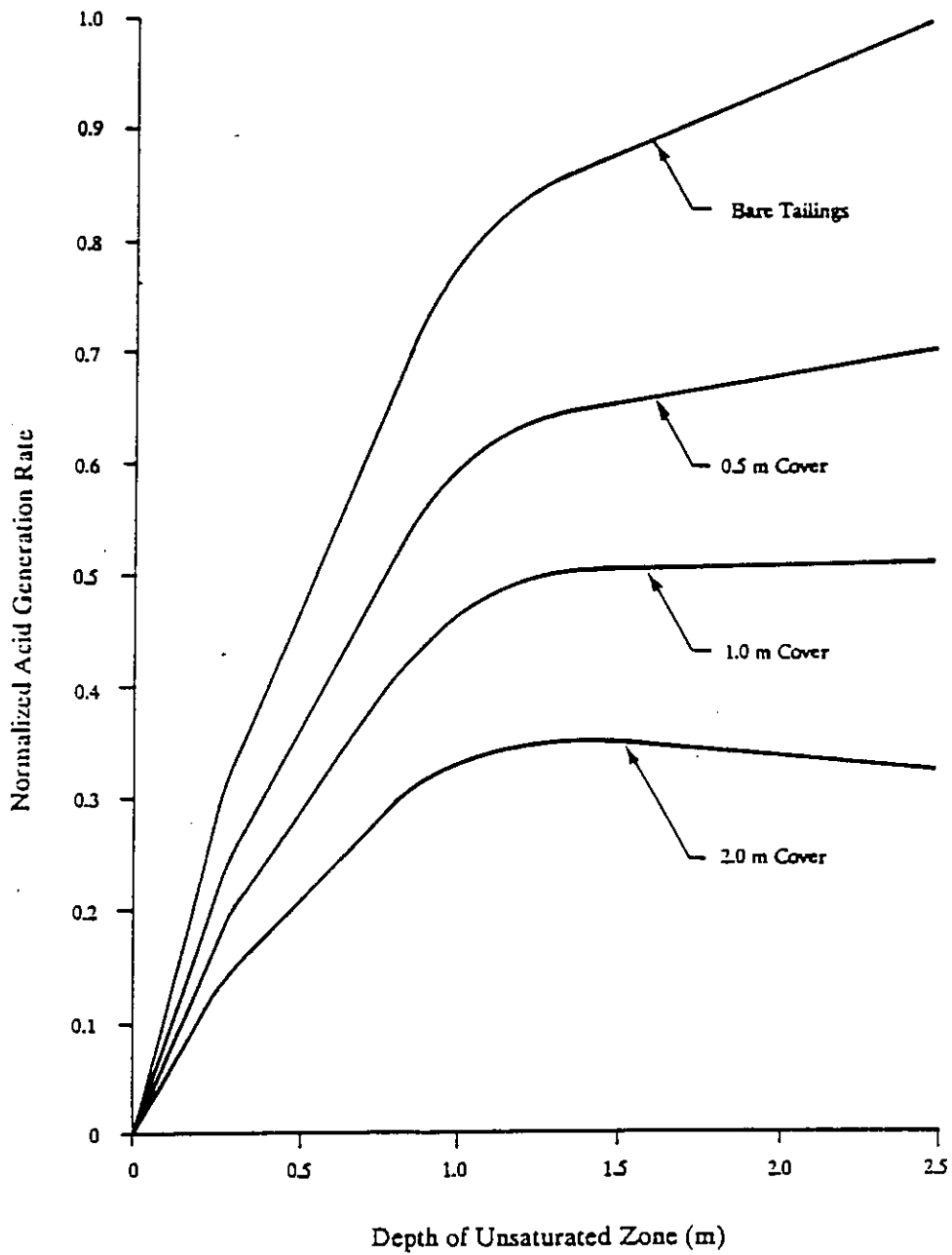
Evaluation and Design of AMD Control Measures

A step-by-step approach to the design and implementation of AMD control at either existing or proposed facilities is demonstrated by means of a flow-chart as shown in Figure 4.

The type of waste is an important initial consideration, due to the differences in physical properties of wastes and differences in suitability of the various control measures. The flow-chart first evaluates methods for controlling acid generation at the source, then considers AMD migration control measures, if required, and finally includes collection and treatment.

The development of a plan to control AMD should begin by evaluating the potential availability and feasibility of water cover, given that this is currently the most secure form of control. If underwater disposal is not possible or feasible, the remaining acid generation control measures should be evaluated. If one or a combination of the alternative measures can be shown to achieve the required control, there is no need to proceed further. The evaluation of the effectiveness of the control measures should be made with input from laboratory geochemical test results and possibly field tests, together with information from case histories.

If further control is required, methods to prevent or minimize the flow of water into the waste should be considered next. If this evaluation indicates that these measures, together with acid generation control, provide adequate control, no further measures are required. If the required control is still not achieved, collection and treatment of some form is required. The most cost efficient control may be provided by a combination of a number of methods from one or



**Figure 2 Effect of Till Cover Depth on Acid Generation Rate in Tailings
(After Steffen Robertson & Kirsten et al, 1987)**

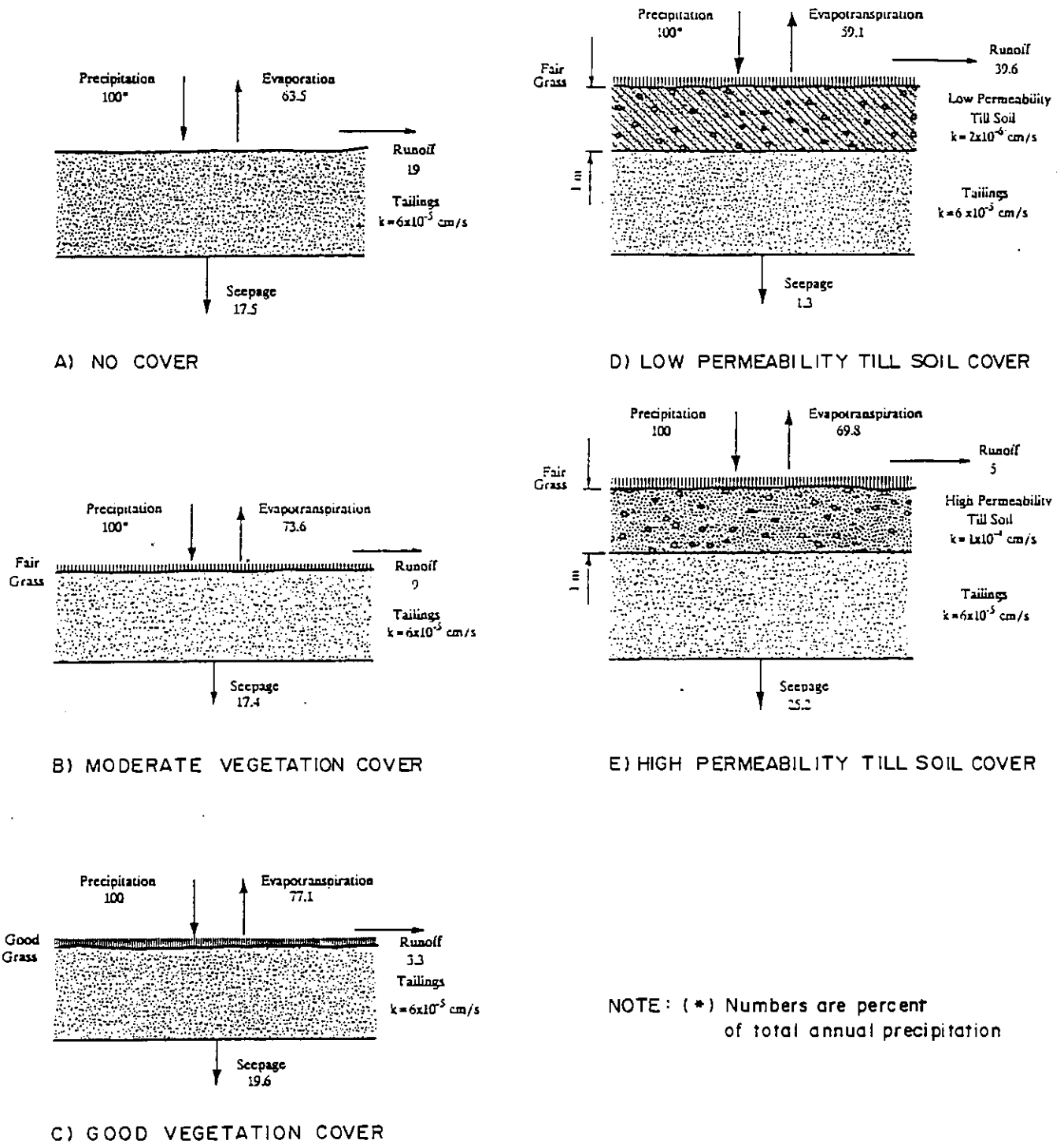
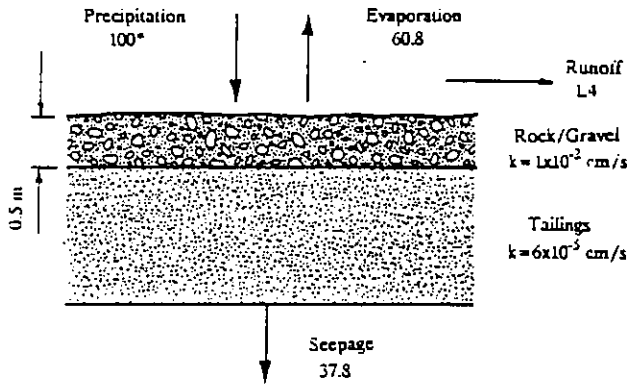
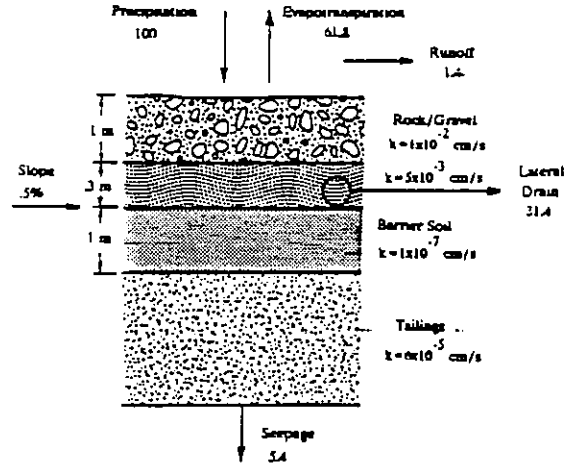


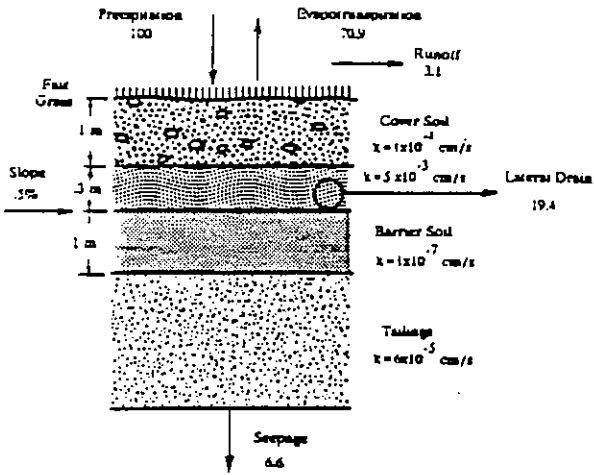
Figure 3 Effect of Cover Type on Infiltration Rate
(After Steffen Robertson & Kirsten et al, 1987)



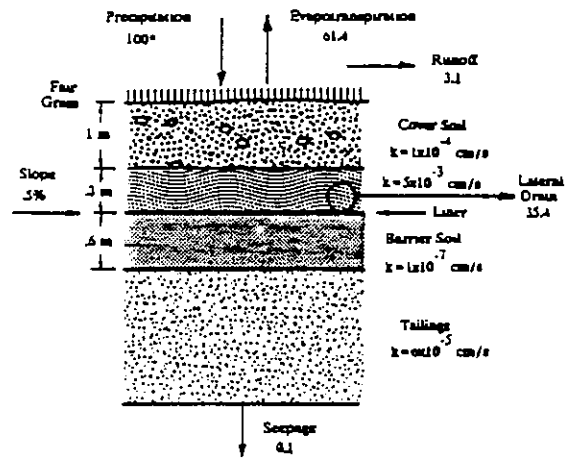
F) RIPRAP EROSION RESISTANT COVER



H) SOIL BARRIER WITH LATERAL DRAIN AND RIPRAP COVER



G) SOIL BARRIER WITH LATERAL DRAIN AND SOIL COVER



I) SOIL BARRIER WITH SYNTHETIC MEMBRANE LINER, LATERAL DRAIN AND SOIL COVER

Figure 3 (Cont'd) Effect of Cover Type on Infiltration Rate
(After Steffen Robertson & Kirsten et al, 1987)

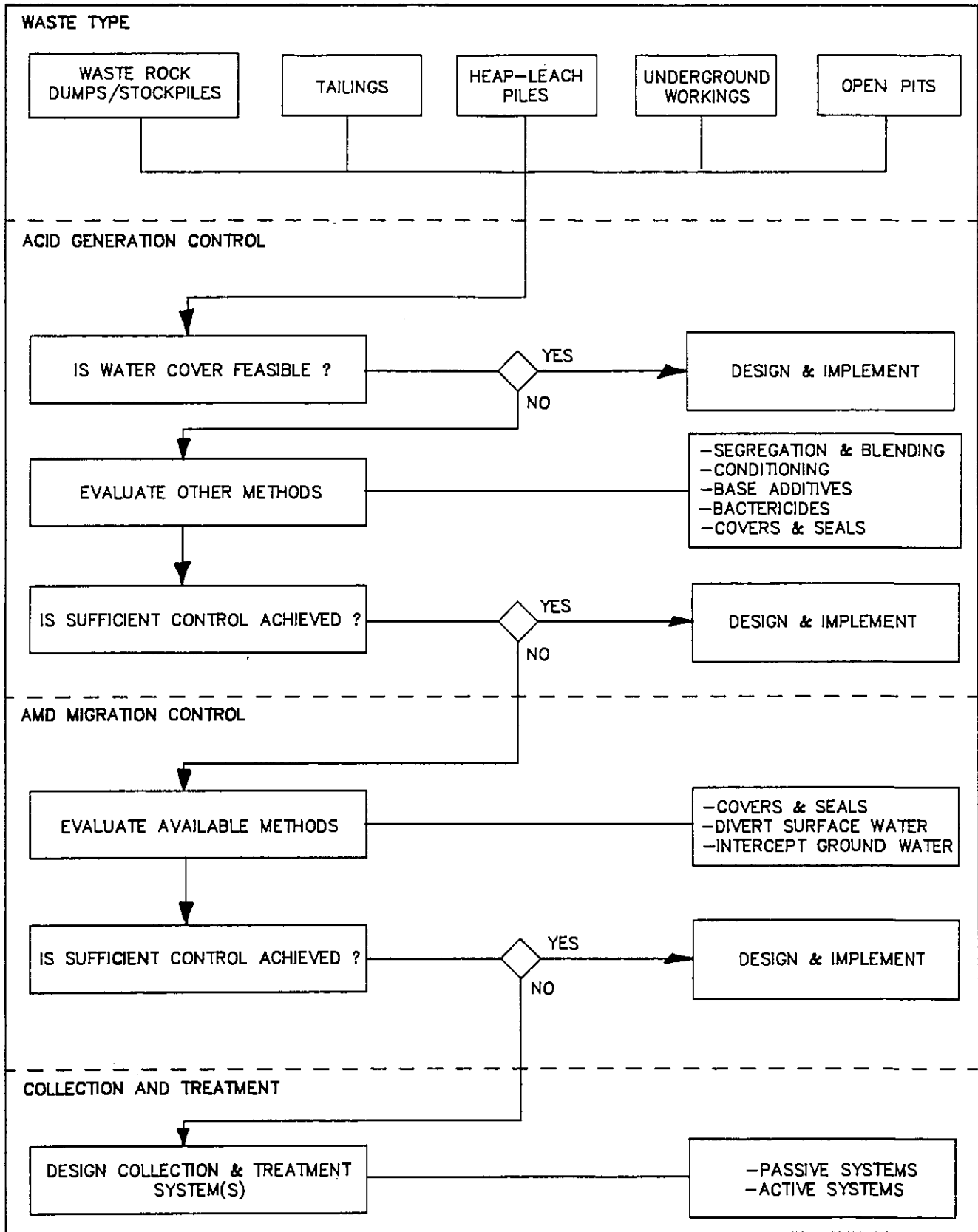


Figure 4 Flow Chart Showing Approach to A.M.D. Control

all of the control categories. The cost of the control measure(s) arrived at by working through the flow-chart must be compared to the cost of collection and treatment on its own to check that the most cost effective solution has been chosen.

Summary And Conclusions

Mining activity in sulphide bearing rock may produce waste that has the potential to generate acid mine drainage. If AMD is not controlled it poses a serious long-term threat to the environment due to the toxicity of dissolved heavy metals and other contaminants to aquatic life.

The impact of AMD may be minimized by controlling the acid generation reactions, by preventing the contaminants from entering the environment, or by collecting and treating the contaminated drainage. A number of control measures are available, some of which are better suited to short-term than to long-term control, and some measures are better suited to particular types of mine waste.

The most secure long-term control measure currently available is to provide a water cover over the reactive waste in order to exclude oxygen. The most obvious form of water cover is underwater disposal in natural water bodies or man-made impoundments. Disadvantages of this method include other potential environmental impacts associated with placing mine wastes in natural waters, and the high cost of its application to existing waste facilities.

Soil covers can be effective in inhibiting oxygen access to wastes, hence retarding the acid generation reactions, and as barriers to infiltration, hence controlling migration of contaminants to the environment. Current technology does not enable an accurate prediction to be made of the reduced rates of AMD resulting from covers and field scale tests are being performed at a number of locations, internationally. The effectiveness of soil covers as oxygen barriers is influenced by the moisture content maintained in the cover. The effectiveness of soil covers as barriers to infiltration depends on the ability of the cover; to resist erosion, to provide lateral drainage for run-off, to prevent moisture loss and resulting desiccation cracking, and to provide a low-permeability barrier to infiltration. Covers designed with multiple soil layers are more effective in meeting these objectives than single soil layers.

If the acid-generation reactions and the migration of contaminants to the environment are not controlled, the only remaining control is to collect

and treat the AMD. This is, at some existing facilities, the only available option.

The evaluation and design of AMD control should be approached in a step-by-step manner, first evaluating acid generation control measures then proceeding to AMD migration control and finally collection and treatment.

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