ALTERNATIVE ACID MINE DRAINAGE ABATEMENT MEASURES

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INTRODUCTION

Acid mine drainage (AMD) is recognized as potentially the single largest cause of detrimental environmental impact resulting from the mining of ores. There are currently over 2 billion tons of potentially acid generating tailings in Canada (John, 1987). If the cost of abatement measures were $1.00 per ton, an approximate figure which appears to apply in many cases, this represents an industry liability of at least 2 billion dollars. This figure does not provide for any consequential costs for environmental damage nor does it allow for abatement of AMD from mine wastes other than tailings.

AMD from abandoned and operating mines in the USA has resulted in a large number of these properties coming under mandatory Federal clean-up and abatement as a consequence of the US Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and Superfund Amendments and Re-Authorization Act of 1986 (SARA). Under these acts Federal Authorities are empowered and required to investigate sources of environmental impact, implement remedial actions, compensate those who have suffered significant damage and recover the costs of these actions from those responsible for causing the environmental damage. Natural resource damage, resulting from AMD, and related remedial costs suits under this legislation currently totals many billions of dollars.

The US experience serves to demonstrate the level of public concern (as reflected in US legislation) and the responsibility and liability that the US public has attributed to the US mining industry. Canadian industry should anticipate similar responsibility and liability.

Both mining industry concerns and public concerns have developed as a consequence of increasing environmental awareness and relatively recent realization of the long-term detrimental impact of AMD. The industry finds itself with a liability which it neither anticipated nor fully understands. Industry has not had sufficient time, or financial resources, to develop a complete understanding of the processes of AMD and has, as yet, not been able to develop a secure, cost effective control technology. It is necessary that the mining industry, together with the public that benefits from it, and the regulatory authorities responsible for its promotion and control, work together to find and implement control technology that will
provide adequate abatement of existing AMD and permit the continued recovery of natural resources from mineral deposits with potential for AMD.

This paper presents a brief review of available and alternative AMD abatement technology. It considers primarily the technology relevant to mine waste and tailings, though some of the techniques may also be applicable to exposed pit walls and drainage from underground workings.

Technology for AMD abatement is most extensively developed for the coal fields of the eastern United States. This technology is valuable, particularly as regards AMD collection and treatment. There are a number of fundamental differences between typical AMD from hard rock waste dumps and local overburden spoil piles. For example, coal overburden in the eastern US usually contains a high percentage of slaking mudstones or shales. Large changes in permeability of these materials, with time, results in substantial natural reductions in infiltration and oxygen penetration. Hard rock waste dumps remain highly permeable to both water and air for a long time and similar reductions in AMD do not occur as rapidly. There are also differences in the nature of the soluble metals. Transfer of this technology must be done with due caution.

A distinction must be drawn between existing deposits and new deposits. The technical options available for AMD abatement are considerably greater at new deposits than at existing deposits. At existing deposits, abatement measures are limited by the site specific and deposit conditions. Further, the operator of an existing deposit is limited by the economic constraints which have developed as a result of planning that may not have included provision for AMD abatement. The necessity now to include provision for abatement may demonstrate that the cost of such abatement cannot be supported by the remaining resource value. This is amply demonstrated by the lack of funds available to abate AMD at abandoned mine properties. Under these circumstances, the always important factor of 'cost of abatement' becomes a crucial factor, which may eliminate some of the otherwise more appropriate alternatives.

KINETICS OF ACID GENERATION

An understanding of oxidation and acid generation is essential in the development of abatement measures.

The process of acid generation in mine wastes has been described by numerous workers including Knapp, 1987; Paine, 1987; Errington and Ferguson, 1987. It is a time dependent process controlled primarily by:
the presence and nature of reactive sulphides.
- availability of water.
- availability of oxygen (convection and diffusion)
- bacterial action
- temperature
- pH or presence of base alkaline reactants

If a base source is present (and available) in the waste in sufficient quantities, the acid products are immediately neutralized and additional acid generation is inhibited. This effectively abates AMD. Most mine wastes contain at least some base potential. Unfortunately this base is sometimes not all available for acid neutralization, or it becomes available at a rate which is insufficient to neutralize the acid at the rate at which it is generated. Figure 1 illustrates, diagrammatically, the availability with time of base and acid in two hypothetical materials. Both materials have a net acid generating potential. Material type A does not produce sufficient acid for all the base to be consumed, and AMD does not occur in the time period of interest. pH controls may prevent material type A from ever producing AMD. Material type B produces sufficient acid that, after a period represented by of, it becomes acidic, and thereafter acid generation rates increase as a result of bacterial action and other pH dependent reactions and AMD becomes severe. Thus AMD is dependent not only on the acid/base potential of the material, but also on the total quantities of acid or base that are available with time.

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**Figure 1: Relationship between Acid Generation and Base Neutralization Potential with Time for Two Different Waste Types**
Acid generation prediction techniques are described by Ferguson and Erickson, 1987. Both static and kinetic tests are used in an attempt to determine the long-term behaviour of the wastes. Concern exists that the conditions imposed during some testing, to accelerate the time dependent reactions, result in unrealistically conservative results.

For coarse waste materials spiked (acidulated) tests may be more appropriate. Waste is not mixed or blended to the same degree as tailings. A single small quantity of highly acid generating waste may be mined and placed, without intermixing, in the waste pile. This small quantity of rock waste may become acid generating, long before the remainder of the waste in the pile, and act as a seed or natural spike for the remainder of the pile. Thus the initiation of AMD in waste rock dumps may be triggered by such natural seed quantities and not by the more typical average conditions.

The extrapolation of laboratory or field acid generation test results to estimates of AMD from a field deposit requires that the field deposit be modelled. Such modelling is extremely complex. The most comprehensive modelling program developed to date (RATAP or Reactive Acid Tailings Assessment) was developed for acid generating tailings and has been calibrated against the Elliot Lake uranium tailings (SENES and Beak), 1986. This model requires calibration for application to other tailings and must be further developed for application to waste rock. This model must be linked to other such modelling programs to evaluate the full pathway for any AMD before it impacts surface waters. The current state of the art is such that the predictive accuracy of long-term modelling of new tailings or mine waste deposits is extremely uncertain. Thus it is also very difficult to evaluate the absolute effects of alternative abatement measures in the long-term. Modelling does permit an effective evaluation of the comparative effects of different abatement measures.

ALTERNATIVE ABATEMENT APPROACHES

Alternative approaches to AMD abatement are reviewed in this section, while the effectiveness of specific abatement measures are evaluated in the section entitled 'Alternative Abatement Measures'.

AMD abatement may be divided into three broad approaches: control of acid generation; control of acid migration; and collection and treatment of AMD.
CONTROL OF ACID GENERATION

Acid generation control implies the prevention of acid formation. This requires one or more of the following:

i) Removal of acid generating minerals. Methods of pyrite removal have been evaluated by Hester and Associates, 1984 and it has been concluded that the economics cannot generally support this alternative.

ii) Rendering acid generating minerals inactive by developing chemical coatings. Hester and Associates, 1984, demonstrate that while these approaches hold promise they do not as yet represent applicable technology.

iii) Exclusion of water. This would require dry placement and the exclusion of any infiltration. Such conditions could only be achieved with a synthetic membrane cover. Clay or other low permeability soil covers have been evaluated by Steffen Robertson and Kirsten (1986a) in the context of covers for uranium tailings. It is concluded that long-term degradational effects would result in sufficient water penetrating the cover to enable acid generation to continue.

iv) Exclusion of oxygen. Entry of oxygen into the reactive waste is controlled by:

   a) the convection of air into the waste. Convection plays an important role in coarse waste piles. Daily and seasonal variations in barometric pressure result in the pile 'breathing', almost like a lung. Temperature differentials between the interior of the pile and the ambient air, particularly in instances where the heat of oxidation has elevated temperatures, result in thermal convection.

   b) the diffusion of oxygen through the cover or into the water. The diffusivity of typical dry tailings is about 2.0 x 10^{-2} cm/sec (Halbert et al, 1983). At this value, unacceptably high rates of oxidation and acid generation are being experienced in the reactive tailings at Elliot Lake and many other tailings deposits. Diffusion rates into coarser waste must be considerably greater. Tailings therefore are not considered a suitable candidate material for the elimination of acid generation, by either placing as a cover or by injection into the waste. Studies of diffusion through uranium tailings (Silker and Kalkwarf, 1983) have demonstrated
that similar diffusivity values are obtained for typical soils, including clayey soils, if they are dry or only partially saturated. Thus dry soil or clay cover layers are also probably inadequate as oxygen excluders, although they may play another, more effective, role as inhibitors of the water transport medium, as discussed in the next section. The diffusivity of oxygen through water is about \(2.0 \times 10^{-6}\) cm/sec (Klohn Leonoff, 1981), i.e., about four orders of magnitude less than that for typical dry tailings.

Water covers have been demonstrated to be effective for tailings, reducing acid generation to very low levels. Figure 2 shows the correlation between the diffusion

![Figure 2: Moisture Dependence of the Diffusion Coefficient (Rogers and Nielsen, 1981)](image-url)
v) Control of bacterial action. Once the pH in a waste pile drops below about 4.5 bacterial action increases the rate of acid generation by five fold or more. This bacterial action cannot be controlled by spraying or mixing the waste with bactéricides (Sobek, 1987). Only biological acid generation is controlled in this manner, and the period of effectiveness of the bactéricide must be taken into account.

vi) Temperature control. The rate of acid generation depends on temperature as illustrated in Figure 3 (Knapp, 1987). The coefficient for a gas and the moisture content of tailings as determined by Rogers and Nielson, 1981. This figure demonstrates that a high degree of saturation is required to reduce diffusion to values approaching that of water cover. If a saturated layer can be developed above the tailings this would provide an effective oxygen barrier. Maintenance of saturation is important, requiring either the establishment of permanent bog conditions, or the design of a complex layered cover to trap precipitation and inhibit evaporation as has been proposed for the Faro Mine tailings in the Yukon (Steffen Robertson and Kirsten, 1986b).
**Figure 3: Effect of Temperature on Biological and Chemical Oxidation Rates** (After Knapp, 1987)
vii) pH control. The effects of pH on biological and chemical oxidation rates are illustrated in Figure 4 (Knapp, 1987). Control of pH can be used to reduce both the chemical and biological oxidation rates. Control is achieved by adding limestone or lime (or other alkaline materials) to the waste or spreading it on the surface of the pile. Again, acid generation is not eliminated, and the effective period of the pH control must be considered. The addition of an alkaline material, however, has the advantage that acids are neutralized as they are produced, reducing the potential for low pH water to dissolve and transport metal contaminants from the piles. The neutralized acid products remain in the piles. Many of these products are more readily soluble in acid drainage, and regeneration of AMD would result in an increased environmental impact. Redevelopment of AMD must therefore be prevented.

CONTROL OF ACID MIGRATION

Acid migrates as a flow of low pH water from the waste pile into the environment. Because of differences in permeability, coarse waste dumps and tailings deposits do not behave the same, and abatement measures have different effects.
Coarse Waste Dumps

Coarse waste dumps have a very high permeability to both air and water. Oxygen and water are available almost throughout the dump, allowing acid generation and reaction products to be distributed anywhere within the mass. Precipitation and surface flows onto the dump infiltrate rapidly. Runoff is often low. Flow through the dump tends to follow preferred channels along which the acid products are regularly flushed out. There are zones in the dump that are seldom flushed by running water but receive moisture as a result of water vapour migration and condensation. These condensates may become highly acidic and trickle down to join the less acidic flows. The combined flow exits the toe of the dump, or enters the foundation soils to form a subsurface contaminant plume. Flow through the dump is rapid and rainfall often produce increased flow from the dump toe.

FIGURE 4: EFFECT OF pH ON BIOLOGICAL AND CHEMICAL OXIDATION RATES (AFTER KNAPP, 1987)
within minutes or hours of the start of the rain. The dump acts as a store of acid products, which are partially flushed out from time to time. Concentrations of contaminants in the toe seepage may reflect the flushing history. During periods of intense flushing, the concentration of contaminants in the AMD may reduce. Conversely, after a period of low infiltration and flushing the first significant rainfall may result in both high concentrations and large AMD loadings. Figure 5 illustrates diagrammatically the flow rate, concentration and loading variations that have been experienced at a typical small sized hard rock waste pile in British Columbia at a location where high rates of infiltration are experienced in June and October (Steffen Robertson and Kirsten, 1987).

Sulphide oxidation commences as soon as the first coarse waste is placed in the dump. Thus AMD from the toe of the dump can sometimes be detected within a few months of waste placement, depending only on the time required for part of the dump to become acid generating (refer Figure 1).

Tailings Impoundments

In contrast to dumps, infiltration and flow of air and water through tailings impoundments is restricted by the relatively low permeability of the tailings. This flow restriction results in the development of zones of oxidation and contaminant migration within the tailings, as illustrated in Figure 6a.

Water infiltrating through the tailings surface enters a zone of partial saturation, Z1. After passing through this zone it joins the water below the water table in the tailings. Infiltration water accumulates in this layer, Z2, and displaces the original process interstitial water downwards into underlying soils (in this case alluvium) where it mixes with the groundwater. Oxygen entering the tailings is consumed within the zone of oxidation, Z3, which limits the depth in which acid generation occurs to this zone. Water infiltrating through the tailings surface becomes acidic in this zone, Z3, and then flows downwards into a zone, Z4, in which the acidic waters react with the alkalies in the tailings and are neutralized. Depending on the rate of reactions and the elapsed time, the base of Z4 could be above or below the base of Z2. As the sulphides are consumed in the oxidation zone the depth to which oxygen can penetrate increases, and Z3 increases. As the alkalies are consumed in the tailings, the depth of zone Z4 also increases and the acid contaminated seepage and other dissolved products progress deeper into the tailings. After a period of time, zone Z4 penetrates the foundation soils and the groundwater becomes contaminated.
FIGURE 5(a) TEMPORAL VARIATION IN FLOWS AT SEEPS 3 & 5

FIGURE 5(b) TEMPORAL VARIATION IN COPPER LEVELS AT SEEPS 3 & 5
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Groundwater contamination is expected to occur first near the edges of the tailings impoundment where the depth of tailings is least and Z4 reaches the foundation soils first (refer Figure 6b). This contaminant load increases as Z4 increases and a larger portion of the impoundment contributes to groundwater contamination. The initial acidic flows reaching the foundation soils are neutralized by the base capacity of the foundation soils, which can be very large.

Acid generation in the tailings generally only commences after the last of the tailings have been discharged to the surface of the impoundment. Prior to this, acid generation is prevented by the neutralization which occurs each time a new layer of tailings is deposited (effectively alkaline control). Once acid generation starts it may be years (possibly tens of years) before the acid product front passes through the tailings and foundation soils to reach a surface discharge location. Surface flows across the tailings, on the other hand, may produce AMD shortly after tailings discharge stops, depending again on the time period for the tailings on the surface of the impoundment to become acid generating.

Initially it may appear that there are two approaches to the control of acid migration: (i) control of seepage entry to the waste using diversion ditches, and low permeability covers and (ii) control of seepage away from the waste using liners or cutoff walls. Interception systems consisting of wells or trenches are not migration barriers but collection systems and are reviewed in the next section. In practice approach (ii) cannot function in the long-term since infiltrating water which enters the waste and becomes acidic, and which can not escape via seepage, must accumulate until the available storage is filled and then discharge over the lip of the liner or cutoff wall. Thus the only effective long-term abatement is infiltration control and the prevention of groundwater entry to the waste.
Groundwater leaching can be very difficult to prevent if the site has not been selected to avoid it. Cutoff walls may be considered. Surface infiltration can be reduced considerably by diversion of surface flows, surface contouring to promote runoff, and placing low permeability covers. Almost complete elimination of infiltration can be achieved by a synthetic membrane cover, though provision would have to be made for its long-term replacement. Low infiltration rates (sufficient to achieve large AMD reductions) can be achieved by placing clay or other low permeability covers. Such covers may be subject to degradation with time, due to erosion, frost action and roots.

ACID DRAINAGE COLLECTION AND TREATMENT

The collection and chemical treatment of AMD has been the most widely applied abatement measure to date. A large number of papers are available on the topic (Vachon, et al, 1987). Collection of surface flows is usually fairly readily achieved. The collection of subsurface flows requires the installation of collection trenches, or wells, or cutoff walls to force the groundwater flow to the surface, where it can be collected.

Chemical treatment involves the addition of alkaline materials (usually lime or quick lime), and the settling of the resulting sludges in a settling pond. Major concerns relating to this abatement measure are the need for long-term treatment, the quantities of sludges produced and the requirement for the long-term stabilization of the sludges.

AMD can generally be expected to continue for many decades if not centuries. Treatment must be maintained therefore during these long periods. If there is a breakdown of the treatment plant, the AMD is essentially unabated for the period of the breakdown. During this period substantial damage may result to aquatic resources in receiving waters. Thus it is essential that such a treatment plant be built with adequate reliability and redundancy to minimize the risk of breakdown. This contrasts with most other abatement measures, which fail progressively allowing corrective measures to be implemented before the Impact becomes excessive.

Each tonne of pyrite in the waste has the capacity to produce approximately 3 tonnes of acid, which, when neutralized, produces about 7 tonnes of dry sludge. These sludges are extraordinarily difficult to densify in a settling pond. Steps taken to improve the density (thickening, underdrainage, evaporative drying, etc.) typically result in settled sludge densities of 10 to 15 percent solids by weight. Thus one tonne of sulphides may produce 70 tonnes of wet sludge.
Thus a waste pile containing 2% sulphides has the potential of producing a volume of sludge that exceeds the volume of the original waste.

Often these sludges are readily leachable by moderately low pH waters and are a potential long-term source of contaminants. They in turn must be carefully stored and protected. In the long-term, the containment of the sludge may be a considerably more difficult task than the alternative methods of AMD abatement.

Passive methods of treatment have and are being investigated. These include:

i) Passing AMD through limestone trenches or channels. The large volumes of sludge produced result in rapid coating of the alkaline materials and filling of the voids between them. Thus the trenches have a short effective life and cannot be considered in the long-term.

ii) The effectiveness of wetlands for the biological treatment of AMD has been well demonstrated (Kalin and Van Everdingen, 1987). A number of difficulties and uncertainties, however, still limit the general application of this abatement measure.

ALTERNATIVE ABATEMENT MEASURES

This section provides a brief review of the effectiveness of some abatement measures. Many of the measures are not by themselves sufficient to control AMD from any given site. Used in combination with other measures they may yield the most cost effective means to achieve the desired short and long-term abatement.

DIVERSION OF SURFACE WATER

Diversion of surface waters is almost always an inexpensive effective abatement measure. Diversion also reduces the potential for erosion of the other measures. Unfortunately, diversion works are themselves highly vulnerable to long-term disruptive forces, such as sedimentation, debris and ice blockage, erosion, etc., and maintenance is usually necessary at fairly frequent intervals.

Diversion of groundwater, by installing cutoff walls, etc., may also be considered where this can prevent leaching of the wastes.
CONDITIONING OF TAILINGS

Some improvements in AMD can be achieved by placing tailings in a condition that is more favourable for AMD abatement. Placement of tailings or wastes entirely under water (subaqueous deposition, i.e., providing a water cover) effectively prevents oxidation and therefore AMD.

Placing tailings in a systematic managed manner, to achieve a uniform deposit with maximum density and minimum segregation results in the minimum permeability to both air and water. Layered tailings placement, with minimized pool areas and maximized discharge densities is the most suitable placement method. This technique is often referred to as ‘sub-aerial’ (Knight and Haile, 1983) or ‘semi-dry’ placement. Reduction in acid generation due to oxygen exclusion is negligible. Reduction in infiltration (due to reduced surface permeability) is significant but still comparatively small. Where underdrainage is maintained this may increase the rate of both oxygen entry and AMD. Thus the direct beneficial effect of layered tailings, on AMD abatement is small, and, in some instances, may be detrimental. Of greater importance is the improved consolidation characteristics and surface trafficability which permits easier cover placement.

The relatively poor control of AMD provided by layered or sub-aerial deposition is graphically demonstrated by the experience with South African gold tailings, where layered tailings deposition is practiced extensively. Oxidation and acid generation has penetrated many meters, in some cases tens of meters, into these tailings.

COVERS

Covers offer one of the best means for long-term abatement of acid generation.

(i) Vegetation

It is desirable to establish vegetation on the waste pile in order to return the surface to a state similar to the surrounding environment. Vegetation also serves the very useful purpose of reducing erosion and therefore the frequency of maintenance work (Feldhuizen, Sewek and Blowes, 1987). There is also some evidence that vegetation may produce a marginal reduction in acid generation in the long-term. Root penetrations will result in permeability increases in any clay or low permeability soil layers installed as cover seals. Vegetation has a significant effect on the rate of infiltration.
through the cover; this may be either an increase or decrease depending on the precipitation pattern and cover properties.

(ii) Soil, till or clay

Soil covers act:

- to shed surface flows
- as a poor inhibitor of oxygen entry
- as a moderate inhibitor of infiltration
- as a temperature insulator
- to provide a medium for vegetative growth
- as a sacrificial erosion layer

Infiltration of air and water through the cover depends on the permeability of the material used as well as the cracks and holes that may develop over time. Erosion, dessication cracking, frost action, settlement cracking, piping into coarse waste, root penetration and burrowing by biota are all severe long-term disruptive forces, which tend to increase the rate of infiltration and oxygen entry. A recent study of the long-term integrity of such covers (Steffen Robertson and Kirsten, 1986a) has demonstrated that they are vulnerable to these disruptive forces. Their primary effect is the reduction of infiltration and under marginal AMD circumstances this may be sufficient to achieve the desired amount of abatement. Modelling programs are available for the determination of infiltration rates through simple and composite covers. The HELP program (Hydrologie Evaluation of Landfill Performance, Schroeder et al, 1984) is an example. Unfortunately these programs are as yet crude compared with actual field conditions, and they are useful only for comparison of the effectiveness of alternative covers and not for determination of absolute infiltration rates. In a recent study, Infiltration estimates were made for a large variety of simple and composite covers (Steffen Robertson and Kirsten, 1987). These indicate that in a high precipitation environment, such as the British Columbia coast, infiltration through a clay cap would still be a significant percentage of the annual precipitation.

(iii) Synthetic membrane liners

Because of their vulnerability to puncture, membrane liners must be installed with adequate bedding preparation and surface protective covers. They are of low permeability and offer the potential of acting both as oxygen and infiltration barriers. Thick (2 mm) high density polyethylene (HOPE) membranes are less susceptible to the disruptive forces effecting soil
liners, except for the likelihood of tearing under differential settlement and long-term weathering. To allow for long-term degradation it will probably be necessary to provide for liner replacement in 50 to 100 years.

(iv) Water

Water cover is currently the most secure oxygen inhibiting technique. It is therefore the most secure AMD abatement measure. There are, however, a number of limitations and disadvantages associated with a water cover. These include:

- It may not be possible to achieve water covers on some of the existing deposits.
- Water covers generally imply water retention dams. Such structures have the potential for catastrophic failure and require more secure construction and maintenance.
- Water covers provide driving force resulting in increased flushing of the wastes. If there are other soluble deliterious products in the wastes this may result in increased contaminant loadings to the environment.
- For existing piles, removal to an underwater disposal site may not be feasible because of the loading of oxidation products that have accumulated since the waste was placed.
- Reliable water sources must be available to ensure a continuous cover of sufficient depth to avoid erosion due to wave action or water flow.
- Placement of the wastes in natural water bodies may have other environmental impacts.

Despite these limitations, disposal of acid generating wastes in lakes appears to offer a large number of advantages. The lakes are usually stable basins with an assured water supply, and adequate capacity and depth to insure substantial depths of water coverage. Costs are usually low.

(v) Saturated soil or bog

The effectiveness of a saturated soil layer, for the exclusion of oxygen has been demonstrated.
Bog conditions can be achieved by a combination of a shallow soil cover with a shallow water cover provided for by a water retaining structure. Under these circumstances the tailings will be effectively under water. The soil helps to prevent total loss of coverage when the water depth reduces during dry periods, and it also prevents convective currents and wave action. Vegetative accumulation is also believed to have a marginal but beneficial effect on AMD abatement.

It is also possible to develop a shallow saturated layer of soil as a perched water table on the tailings as illustrated in Figure 7. In this cover a layer of tailings slimes are used to seal the upper surface of the tailings. A layer of till serves as a reservoir to hold water above the slimes. This is covered by a layer of coarse waste rock (non-acid generating) which serves to induce infiltration and retard evaporation. The need to construct a large water retaining embankment is eliminated. The long-term stability and effectiveness of such a cover remains to be evaluated.

BASE ADDITION

(i) Mixing with waste

If low cost sources of base materials, such as limestone, are available the option of mixing them with the waste to render it non-acid generating should be considered.

(ii) Surface application

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 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 method has been found to be ineffective.

ALKALINE TRENCHES

(i) Upstream of waste

The alkaline charge can be increased by concentrating surface water flows and directing them through trenches filled with large quantities of limestone and other alkaline materials before deliberately introducing the flows into the waste piles
FIGURE 7  COVER PROFILE TO DEVELOP SATURATED ZONE
(Caruccio and Geidel, 1987). While this method is an improvement on surface applications, and may have some application to marginal acid producing coarse rock waste, its long-term effectiveness and application to tailings is questionable, because of its rapid consumption and blinding.

(ii) Downstream of waste

Alkaline materials placed in trenches constructed downstream of the waste pile are quickly coated, blinded and clogged and have been found to be ineffective in the medium or long-term.

BACTERICIDE

(i) Mixing with waste

Bactericides serve only to control acid generation that occurs as a result of bacterial activity. The reduction in AMD is unlikely to reduce contaminant concentrations to levels required for abatement. The current state of the art is such that bactericides mixed with wastes during placement may be effective for up to 5 years (Sobek, 1987). Because of their partial and short term effectiveness they are applicable in only limited circumstances where other forms of control become the primary abatement measures.

(ii) Surface applications

Repeated surface applications of sprays are considered ineffective due to selective infiltration and the very short period for which the sprayed bactericides are effective.

COLLECTION AND TREATMENT

(i) Chemical treatment

AMD collection and chemical treatment is currently the most widely practiced AMD abatement measure. It represents mature and known technology, and it is functioning to successfully abate AMD impacts on the environment. The degree of abatement depends largely on the percentage of the surface and groundwater AMD that can be intercepted and collected. This measure is most successful where groundwater conditions are such that seepage releases are naturally concentrated and guided to a surface discharge.

Accumulation of sludge, its storage and long-term stable containment, is the primary concern associated with this
measure. Treatment costs often increase with time as the maximum acid generating potential of the waste pile develops and as the natural buffering capacity along the seepage path is exhausted. Treatment costs are high. Failure of the treatment plant for relatively short periods can result in large contaminant releases, requiring secure operating facilities.

Collection and treatment may be considered as an interim measure until a more secure cost effective set of abatement measures can be implemented. It may also be required as a final polishing step to improve the discharge water qualities achieved by other less costly, more reliable but less effective abatement measures.

(ii) Peat and woodwaste treatment

Alternative treatment methods using peat have been demonstrated by Sridhar et al, 1974, Kadlec and Rathbun, 1983, and Dissanoyake and Weerassoriya, 1981. While large percentage improvements can be obtained, such treatment requires large quantities of peat or woodwaste. Concerns regarding methods of channeling AMD flows to achieve efficient material consumption, the fate of the metals when the organic materials decompose, as well as the environmental impact resulting from the decomposition of the organic products render these treatment methods as experimental, at best.

WETLAND TREATMENT

Wetland treatment offers much promise as a long-term passive treatment system at those locations where wetlands can be established and maintained. Biological activity reduces in the winter and water flows through the wetland are canalized by ice formation. This considerably reduces the effectiveness of the biological activity during the winter period. Unless adequate treatment can be maintained all year round it will be necessary to store winter flows for treatment in the summer. This generally requires a large storage and treatment area. The rate of accumulation of sludges, metals and organic matter is large. This will require the periodic maintenance of the wetland. The long-term fate of the metals accumulated in the organic deposits so formed have not been determined. These deposits may themselves become the source of contaminant releases in the long-term as organic matter decomposes. Where feasible, wetlands should be considered as a final polishing step in the treatment of residual AMD following the implementation of other abatement measures. Considerable research and field trials are required to demonstrate the long-term effectiveness of this abatement measure and the long-term fate of the metals accumulated in the organic wetland deposits.
EVALUATION METHODOLOGY

The lack of reliable, accurate technology for the prediction of acid generation, the effectiveness of abatement measures and the long-term changes, makes the evaluation and selection of the most advantageous measures difficult. Much of the assessment methodology is necessarily based on judgement rather than deterministic analysis. In a recent study for the abatement of AMD from a waste dump (Steffen Robertson and Kirsten, 1987) an assessment method was used which involved consideration of each of the following factors:

- Practicality of implementing the measured
- Durability (life expectancy) of the measure
- Security/risk of failure
- Environmental impacts of constructing the measure
- Construction complexity and duration
- Inspection and maintenance requirements
- Effectiveness in reducing AMD

For each alternative abatement measure a point score was assigned for each of the above factors using a five point scale. The scale values are illustrated by an example from this evaluation in Table 1. The point score for each factor was weighted according to the importance of the factor and the total points counted. This point count was used to rank the various alternatives. The resulting ranking is shown on Table 2. A cost estimate was prepared for each measure which included the capital and operating costs for 50 years. By dividing the cost by the ranking points a measure of the cost benefit is achieved. The cost/benefit values determined for this project are also shown on Table 2. They demonstrate that some of the abatement measures, such as diversion ditches, have a comparatively large benefit at low cost, even though they are individually not capable of reducing AMD to low levels. Such measures are of particular benefit where funds available for abatement are very limited, and they should be considered as part of any AMD abatement plan.

The ranking procedure was used for the selection of the most advantageous alternatives, which were then investigated and evaluated in greater detail.

LONG-TERM MONITORING AND MAINTENANCE

It should be the objective of all AMD abatement plans to reduce monitoring and maintenance to a minimum commensurate with the available technology and long-term costs. The current state of the art of long-term AMD abatement is that a condition of no monitoring and no maintenance may not be achievable, even at very high cost, for
some of the existing waste deposits. The perpetual forces of erosion, weathering, root action, frost action and burrowing activities of biota (insects, animals and man), as well as a host of lesser effects, will result in disruption of abatement measures with time (refer Steffen Robertson and Kirsten, 1986a). To avoid the detrimental effect of these disruptions it is considerably more cost effective to provide for a measure of maintenance, rather than to attempt to construct structures that will operate without maintenance, in perpetuity.
TABLE I ABATEMENT OPTION: SYNTHETIC LINER OPTION

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Description</th>
<th>Scale</th>
<th>Weighting Factor</th>
<th>Point Total</th>
<th>Cost/Effect Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Practicality</td>
<td>Technical feasibility</td>
<td>Low (1) 2</td>
<td>Medium (3) 4</td>
<td>High (5) x4</td>
<td>20</td>
</tr>
<tr>
<td>2. Durability</td>
<td>Life expectancy</td>
<td>years</td>
<td>1 10 50 100 &gt;100</td>
<td>x2</td>
<td>10</td>
</tr>
<tr>
<td>3. Security/Risk</td>
<td>Risk of failure</td>
<td>High (1) 2</td>
<td>Medium (3) 4</td>
<td>Low (5) x4</td>
<td>12</td>
</tr>
<tr>
<td>4. Environmental Impacts</td>
<td>Adverse impacts due to construction or operation</td>
<td>High (1) 2</td>
<td>Medium (3) 4</td>
<td>Low (5) x1</td>
<td>4</td>
</tr>
<tr>
<td>5. Construction</td>
<td>a) Complexity, magnitude</td>
<td>Maximum</td>
<td>1 2 3</td>
<td>6</td>
<td>x2 6</td>
</tr>
<tr>
<td>6. Inspection and Maintenance</td>
<td>a) Frequency of inspection</td>
<td>Weekly</td>
<td>1 2 3</td>
<td>5</td>
<td>x1 4</td>
</tr>
<tr>
<td>7. Effectiveness</td>
<td>Reduction of contamination</td>
<td>&lt;75 75-90 90-95 95-100</td>
<td>x5 20</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**TOTAL RANKING POINTS**

Cost/Benefit = \( \text{ Preliminary Total Estimate } - 5820,000 \times \text{ Preliminary Total Points} \)
### TABLE 2

OPTION RANKING ACCORDING TO TOTAL OF RANKING POINTS

<table>
<thead>
<tr>
<th>Rank Points</th>
<th>Options</th>
<th>Cost/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>HIGH PROBABILITY OF SUCCESS (＞95% REDUCTION)</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>124 Synthetic Liner</td>
<td>6,612</td>
</tr>
<tr>
<td>2</td>
<td>97 Chemical Treatment</td>
<td>11,948</td>
</tr>
<tr>
<td></td>
<td><strong>MODERATE PROBABILITY OF SUCCESS (75-95% REDUCTION)</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>103 Compacted Till Cover</td>
<td>2,720</td>
</tr>
<tr>
<td>2</td>
<td>87 Removal of Pyritic Waste to Lakes</td>
<td>13,655</td>
</tr>
<tr>
<td>3</td>
<td>82 Alkaline Trenches</td>
<td>10,609</td>
</tr>
<tr>
<td>4</td>
<td>79 Waste Removal and Mixing</td>
<td>17,632</td>
</tr>
<tr>
<td></td>
<td><strong>LOW PROBABILITY OF SUCCESS (&lt;75% REDUCTION)</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>75 Diversion Ditches</td>
<td>367</td>
</tr>
<tr>
<td>2</td>
<td>73 In-Situ Seep Neutralization</td>
<td>1,643</td>
</tr>
<tr>
<td>3</td>
<td>70 Surface Application of Limestone</td>
<td>12,471</td>
</tr>
<tr>
<td>4</td>
<td>62 Limestone Barriers</td>
<td>6,532</td>
</tr>
<tr>
<td>5</td>
<td>57 Topsoil and Revegetation</td>
<td>4,052</td>
</tr>
<tr>
<td>6</td>
<td>56 Wetland</td>
<td>8,503</td>
</tr>
<tr>
<td>7</td>
<td>40 Peat</td>
<td>6,562</td>
</tr>
<tr>
<td>8</td>
<td>36 Woodwaste</td>
<td>12,471</td>
</tr>
<tr>
<td>9</td>
<td>34 Bactericides</td>
<td>21,617</td>
</tr>
</tbody>
</table>

Further it is noted that the present value of maintenance to be undertaken in 50 to 100 years time is small. Thus it is justifiable, by conventional economic principles, to provide for such very, long-term monitoring and maintenance with relatively low levels of present funding. Acceptance of this principle allows for the provision of maintenance in the design of AMD abatement measures. Under these circumstances some of the alternative abatement measures, which might otherwise be rejected as being of too short a duration, become more advantageous. An example is the use of synthetic liners to cover waste. A thick (2 mm) HOPE membrane liner, appropriately installed as part of a composite cover, may be expected to last for 50 to 100 years or more. The cost of establishing a fund for the replacement of the membrane at intervals of 50 to 100 years is relatively small.
ABANDONMENT PLAN DEVELOPMENT PROGRAMS

A current trend in regulatory control is to require that abandonment plans include adequate AMD abatement measures, in order to preclude AMD impact on the environment in the long-term. It may also be required that the abatement measures should be secure and maintenance free (in perpetuity). Given the present state of knowledge and analytical tools, both requirements may not be achievable.

However, with provision for maintenance and contingent treatment, the preclusion of AMD impacts are possible for the very long periods of interest. Many of the currently proposed abatement measures may turn out to provide adequate long-term abatement, but it may not be possible to demonstrate this conclusively with current technology.

The development and testing of AMD abatement measures is a rapidly evolving technology. It will be spurred by the research proposed in programs such as the Canadian Reactive Acid Tailings Studies (RATS) program (Ferguson, 1987). To allow appropriate new development and technology to be included in future abandonment plans, it is recommended that regulatory authorities should not insist on rigidly specified abandonment plans written into operating permits, but that they adopt a more flexible approach of requiring the implementation of appropriate abandonment plan development programs with defined objectives. Such programs should provide for field trials to demonstrate the effectiveness of AMD abatement measures, prior to their being incorporated in abandonment plans. This approach to regulation is now likely to ensure that the funds provided for abandonment measures are spent in the most cost effective manner.

The recommended approach is not unusual when compared to other fields of geotechnical engineering. In the field of earth dam engineering, for example, it has long been the practice to build to a flexible design that is monitored by instrumentation. The details of the design may be changed during construction should conditions in the field turn out different from what was anticipated during early design stages. This is known as the Observational Method (Peck, 1969). When applied to AMD it is likely to be a more pragmatic and successful approach, rather than trying to proscribe for contaminant control.

Specifying performance criteria (or end-product specifications) in terms of certain numbers to be met by law may be unrealistic. It may be simply unworkable because our understanding of the problem in the long-term is as yet too imprecise. It is better to require the mining industry to work to specific design criteria and regulate at this point, rather than be faced with the frustration of a fait accompli that does not meet up to performance specifications set out
in statutes. In practical terms this alternative approach means working to design criteria aimed at limiting or eliminating acid generation (Smith and Van Zyl, 1983). These criteria are exclusion or limitation of oxygen availability, water ingress/infiltration and bacterial activity. Methods of achieving these criteria are described in their paper together with case histories.
REFERENCES

Caruccio, F.T. and Geidel, G., 1987. 'The In-Situ Mitigation of Acidic Drainages', Management of Hydro-Geochemical Factors'. Department of Geology, University of South Carolina, Columbia, SC.


