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LONG TERM PREVENTION OF ACID MINE DRAINAGE

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INTRODUCTION

The long term prevention or abatement of acid mine drainage depends on the continued effectiveness of the control measures. These measures may involve covers of various types including soil, water or synthetic membranes, drainage or infiltration controls, base addition or long term drainage collection and treatment in chemical plants or wetlands. Such control measures are subjected to both extreme disruptive forces such as storms, floods, fires and earthquakes, as well as the lesser but perpetual action of weathering and chemical change, erosion, frost and root action and the burrowing activities of animals and man. Under these forces there is a deterioration which eventually leads to failure of the control measures. Failure can be prevented by an adequate program of monitoring and maintenance.

The period to failure and the nature of the failure mechanism determines the risk of environmental impact, the required monitoring, and frequency and cost of maintenance. Different control measures have different inherent stabilities (resistance to failure). The selection and application of the most appropriate may result in minimal visual monitoring (every few years) with inexpensive minimal maintenance only every few decades, with extremely low risks of environmental impact. Inappropriate controls may require continuous monitoring and maintenance at high cost with a high risk of environmental impact.

A MODEL FOR THE VISUALIZATION OF LONG TERM AMD

The author has found it useful, in his visualization of acid generation and drainage, to develop the analogy illustrated in Figure 1. A description of this analogy follows.

Factors Controlling Acid Generation

Acid generation occurs in a **sulphide reactor**. This reactor contains a finite load of sulphide. The rate at which the reaction proceeds is dependant on:

i) The nature of the reactive sulphides; with some oxidizing much more rapidly than others, EPA, 1977. The form of the sulphide is also important with disseminated framboidal pyrite oxidizing more rapidly than large cubical crystal forms.

ii) The rate at which the other fuels:
- oxygen and
- water,

are introduced into the reactor.

iii) The initiation of bacterial oxidation may increase the rates of oxidation from 50 to 1 million times, Lundgren, 1971. Both the chemical and biological oxidation rates are substantially dependant on the pH in the reactor as illustrated in Figure 2 (Knapp, 1987). Typically the reactor starts up slowly with local slow chemical oxidation, and increases rapidly as biological oxidation starts after the pH has dropped below 5. On a single lump of waste rock, as illustrated in the inset in Figure 1, individual crystals of pyrite may develop a surface coating of low pH adhered water, providing the conditions for rapid bacteriological oxidation long before similar conditions develop on other surfaces of the otherwise naturally alkaline host rock.

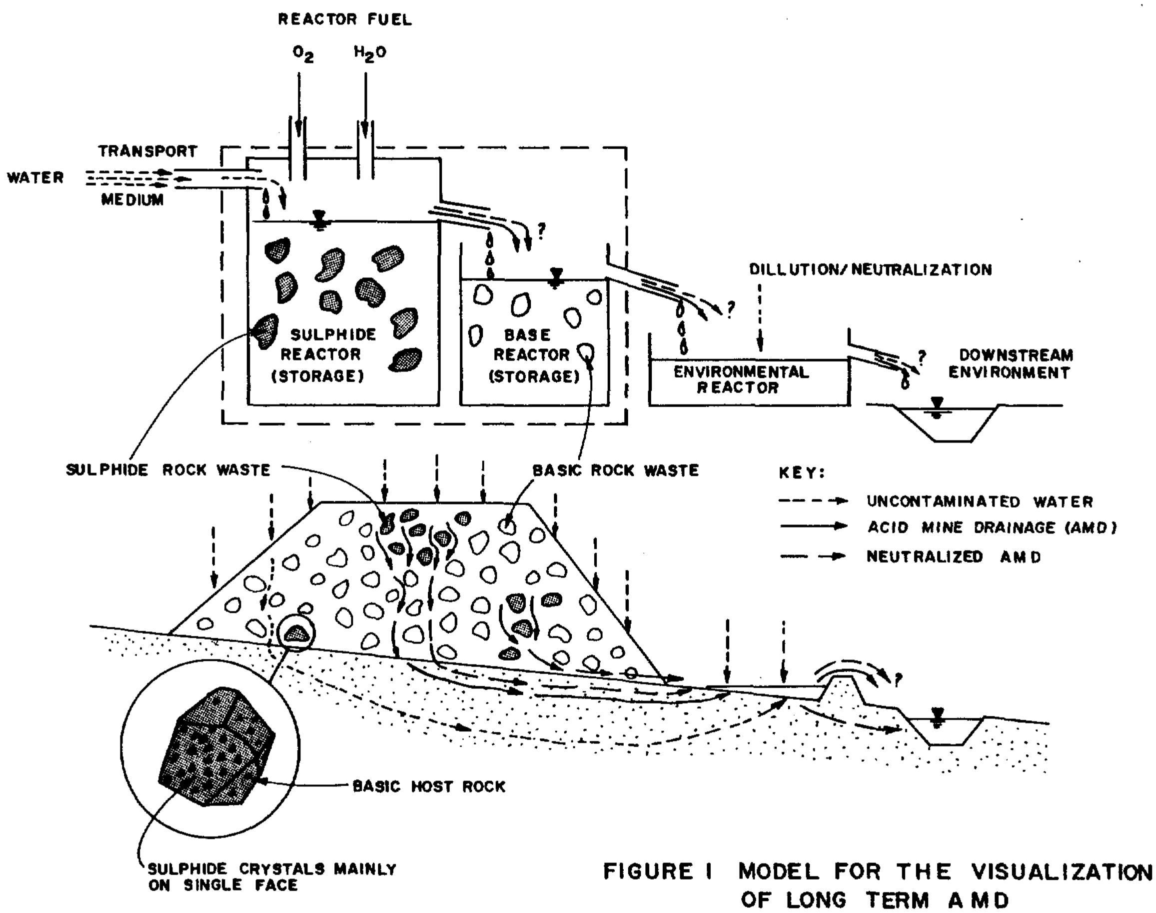


FIGURE I MODEL FOR THE VISUALIZATION OF LONG TERM AMD

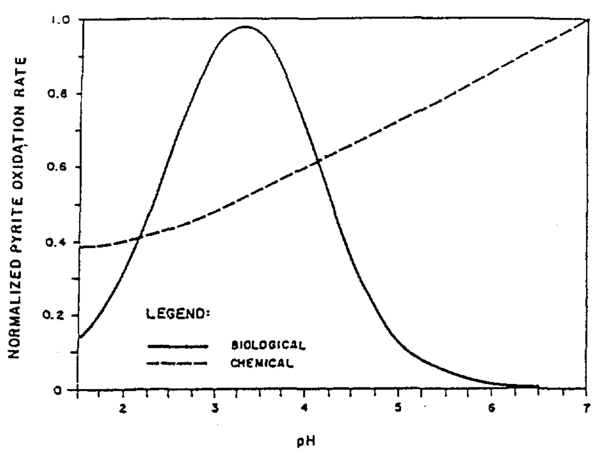


FIGURE 2 : EFFECT OF pH ON BIOLOGICAL AND CHEMICAL OXIDATION RATES (AFTER KNAPP, 1987)

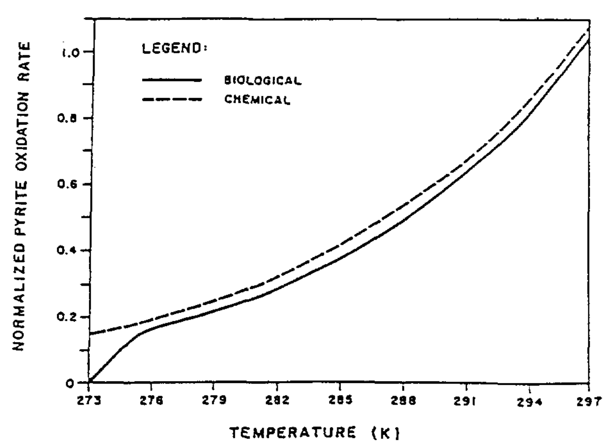


FIGURE 3: EFFECT OF TEMPERATURE ON BIOLOGICAL AND CHEMICAL OXIDATION RATES (AFTER KNAPP, 1987)

iv) Oxidation rates increase as the temperature increases as illustrated in Figure 3 (Knapp, 1987).

Acid is produced as a result of the oxidation reactions and stored in the vicinity of the site of generation, unless transported away from the site by diffusion or advective water flow. In the absence of flowing water the movement rate is extremely slow, and the acid products accumulate (are stored) in the vicinity of the sulphides and inhibit further oxidation. Movement of acid from the sulphide reactor site is therefore dependant on the presence of water as a **transport medium**. Removal of the acid products allows the oxidation reactions to continue. Metals and other products are dissolved in the acidic water. Flow or discharge from the sulphide reactor is therefore an acidic water flow containing dissolved metals commonly referred to as Acid Mine Drainage or simply AMD.

Factors Controlling Natural Neutralization

AMD is discharged into the **base reactor** in which it is neutralized. If the reaction rate in the base reactor is slower than the rate at which AMD is delivered to it then only partial neutralization occurs. There may still be acidic drainage while a net base potential remains. In practice this may occur on a lump of rock waste where the sulphide is on the exposed "joint" surfaces and oxidizing rapidly and the base material is contained in the interior of the waste lump from which it is released more slowly.

The base reactor has a finite quantity of base material and after this is consumed no further neutralization occurs. Depending on the amount of base material contained in the base reactor, and the rate at which AMD is introduced to it, the effective period of neutralization will vary. Thus if AMD generation or transport from the sulphide reactor is slow (as may occur in a dry climate or if a low permeability cover is installed) then the neutralization may be effective for a very long time, but the end result of acidic drainage may be the same. Some of the dissolved metals in AMD, including zinc, are not adequately precipitated on neutralization and such drainage may still be detrimental to the receiving aquatic environment.

The acid/base accounting method of AMD potential testing measures the total quantities of acid and base generating potential but does not take into account the rates at which the two reactors work. Hence the need for kinematic tests, particularly when the acid and base potential are nearly equal.

Factors Controlling AMD and Environmental Impact

AMD draining from the waste deposit passes through or over soils which have a neutralization capacity. AMD is also mixed with surface and groundwater streams which both neutralize and dilute the AMD. The **environmental reactor** results in some improvement of the AMD. As the store of basic materials close to the deposit is consumed the AMD plume migrates further from the deposit, resulting in an ever increasing impact zone. At some point the volume of dilution and neutralization streams with which it merges is sufficient that the effect of AMD is abated.

Some environments have an extremely high load of basic materials in the soils, surface and ground waters. This is the case in many of the old deeply weathered landscapes with well developed old soils. In Canada and Norway, where recent glaciation has stripped off all old soils, only relative fresh rocks and new, unweathered soils are exposed. These conditions generally yield soils, ground and surface waters which are low in neutralizing capacity. Thus the potential for extensive impact on the surface and groundwaters downstream from the deposit are large.

For all waste deposits there is a level of AMD release which can be sustained by the environment without significant damage. It is the objective of AMD abatement measures to reduce AMD releases to below this level.

ROCK WASTES DUMPS AND TAILINGS DEPOSITS AS REACTORS

Waste Rock Dumps

A waste dump can be visualized as a series of sulphide and base reactors on both a micro and macro scale. On each piece of rock waste there may be zones which are either acid generating (and acidic) or base yielding (and basic). The most reactive lump produces acid which allows the pH to depress, initiating rapid biological oxidation. Drainage from this acid lump onto lumps below it rapidly consumes excess base allowing a zone of high reaction rates to spread along the drainage path.

Zones of predominantly acid rock waste will yield AMD and zones having a net base potential will neutralize AMD flowing into them. The pH of the seepage from such a dump is dependant on the flow path which the transporting water has followed and may be either basic or acidic as illustrated in Figure 1. It is common to have both basic and acidic seeps from the same dump during the early stages of AMD development.

Neutralized AMD will contain some of the dissolved metals taken up in the acid flow zones and not deposited on neutralization. Zinc is often a persistent metal in this respect. Thus the evolution of AMD from the dump is cronologically as follows:

i) All seepage characteristic of unoxidized leaching of the waste rock.

ii) Some seeps develop characteristics of neutralized AMD (Lundgren et al, 1972). This stage may be evident within weeks or months of waste placement but may take years.

iii) Some seeps begin to exhibit depressed pH and characteristics of AMD. The stage may develop within months of placement but a number of Western Canadian examples exist of it taking 10 to 20 years for the <u>first</u> such seeps to develop.

iv) pH depression develops in all seeps from AMD generating zones of the dump. For many mines this may be the entire waste dump. Documentary evidence exists of highly reactive dumps that have developed to the maximum rate of AMD within a few years of construction. Our understanding is not complete for the time rate of increase for the much slower developing reactors. Based on the observations for (iii) above it may take tens to hundreds of years.

v) The quality of seepage improves as the sulphides are consumed and that in the faster of the sulphide reactors is exhausted. Slow reactors (such as sulphides in the interior of large hard rock lumps) can last for a very long time. This phase is observed to last for hundreds of years for large waste dumps.

Seepage flows through waste dumps are usually partially saturated, and flow tends to follow preferred flow channels. Some of the waste lumps are regularly flushed by infiltrating water while the majority are seldom wetted by flowing water. Acid products accumulate on the seldom flushed lumps with the result that acid products accumulate. During periods of high flushing (spring run-off or high precipitation periods) some of these products are flushed out resulting in high flows with very high contaminant concentrations. Because hydraulic conductivities are usually high in the dump, the period between infiltration and seepage is short, resulting in rapid flushing and seepage responses to precipitation.

The air conductivity of dumps are also extremely high. The tendency for coarse waste with large air voids to accumulate at the base of the dumps usually provides an easy passage for air into the base of the dump. Thermal gradients develop due to natural temperature ranges in the ambient air as well as due to the exothermic reactions of oxidation in the waste dump. Such thermal gradients result in a 'chimney effect' in the dump with the result that oxygen is drawn into the dump and is readily available to fuel sulphide reactions. Changes in the barometric pressure causes the dumps to 'breath'. This 'lung effect' results in air flowing in along the more conductive channels deep into the dump. The entire dump therefore serves as a reactor with an ample supply of oxygen and water for sulphide oxidation.

In hard rock dumps which are resistant to weathering the amount of sulphides exposed and available for oxidation is limited, limiting the rate of reaction. The mass of sulphides exposed to oxidation conditions are almost directly proportional to the surface area of dump material which increases approximately as the inverse of the cube of the average lump or particle mass in the dump. Where the rocks slake (break down with time) rapidly, increasing the surface area of exposed sulphides, the rate of sulphide oxidation may increase rapidly. Fortunately the slaking effect, if it reduces the rock to soil size particles, may also reduce the dump conductivity to both air and water sufficiently to result in reduced reactions.

Tailings Impoundments

The factors controlling acid production and AMD from tailings impoundments differs significantly from those operative in waste dumps. These differences are summarized in Table 1.

The sulphide content in tailings is often much greater than in the mine wastes from the same ore deposit, resulting in a potential for much larger acid production.

Because of the fine grind, a high percentage of the sulphides are exposed and available for oxidation. If only these two conditions controlled reaction rates, then tailings would be expected to be much greater acid producers than rock wastes.

The fine grind and mixing that occurs in the milling process results in a much more even distribution of the sulphides and base materials in the deposit. The tailings are also generally mainly in water or in a high moisture state, particularly during the operating life of the impoundment. The combination of intimate mixing of sulphides and base materials and the ample water to transfer acid and base ions over the small distances separating grains results in a hugely reduced potential for the development of 'trigger' or 'hot spots', and hence the initiation of fast reactions due to biological leaching. Conditions suitable for acid generation usually only develop after tailings placement is discontinued. Thus the initiation of acid generation in a tailings dam usually starts long after the same initiation in waste dumps at the same mine.

In contrast to dumps, infiltration and flow of air and water is restricted by the relatively low conductivity of the tailings. This flow restriction results in the development of zones of oxidation (sulphide reactor zones), neutralization (neutralization reactor zones) and contaminant migration as illustrated in Figure 4. These zones have been described and discussed by Robertson, 1987.

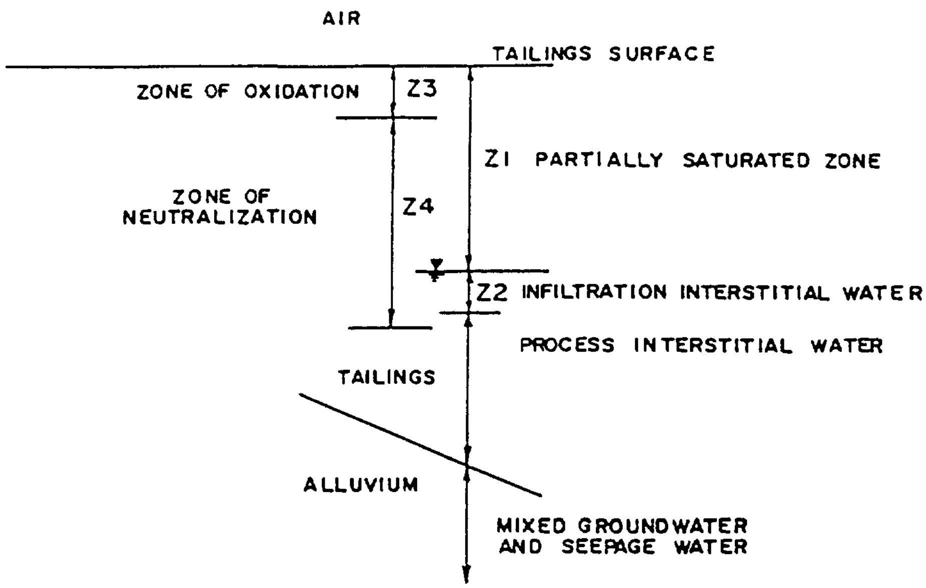


FIGURE 4(a) WATER QUALITY MODEL FOR TAILINGS COLUMN

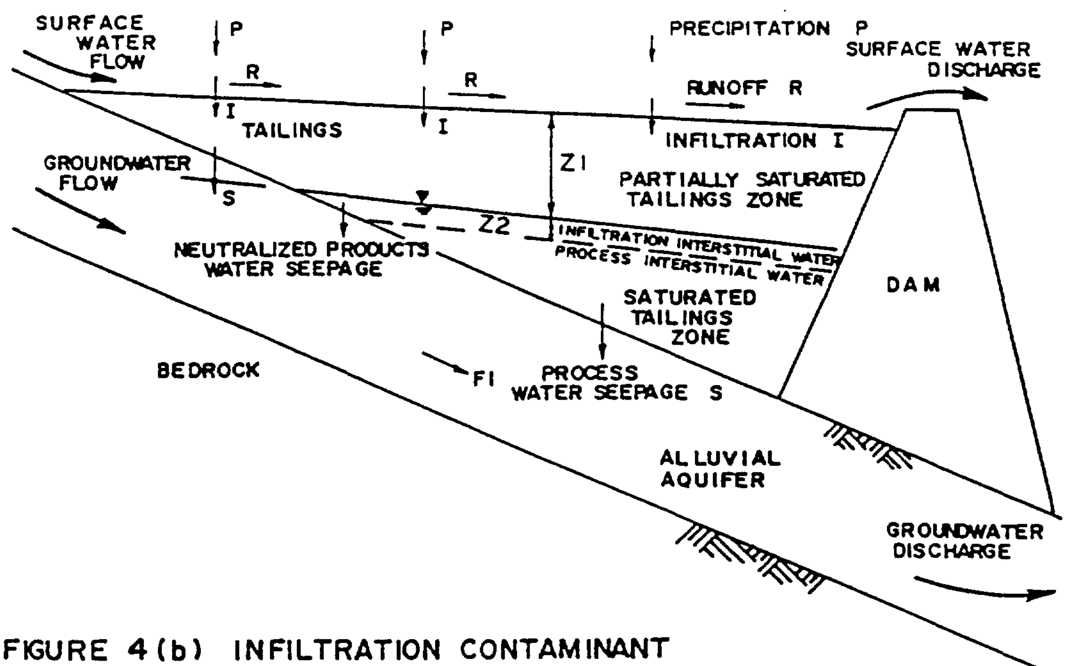


FIGURE 4(b) INFILTRATION CONTAMINANT SEEPAGE MODEL

TABLE 1

COMPARISON OF ACID MINE DRAINAGE FACTORS IN WASTE DUMPS AND TAILINGS IMPOUNDMENTS

A. ACID GENERATION	WASTE DUMPS	TAILINGS IMPOUNDMENTS
i) Sulphide source	- Variable in concentration and location - Conditions may vary from sulphide rich to basic over short distances	- Conditions uniform often with very high sulphide content.
ii) pH variation	- Highly variable conditions over short distances	- Fairly uniform conditions with a few major horizontal zones
iii) Initiation of Rapid Oxidation	- Usually starts immediately after first wastes are placed (in "trigger" spots)	- Usually starts after tailings placement ceases
iv) Oxygen Entry	- Enters freely along highly conductive flow paths at base of dump and large open void spaces. 'Chimney' and 'lung' effects.	- Restricted by water in the tailings void spaces and the lower conductivity of the partially saturated void spaces
v) Seepage	- Seepage rapid along preferential flow paths	- Seepage slow and uniform
vi) AMD Releases	- Large infiltration resulting in large seepage from toe and to groundwater - Rapid release following generation, sometimes with both neutralized and acid AMD seeps.	- Large early surface AMD run-off - Lower infiltration - Gradual transition in seeps from process water, to neutralized AMD, to AMD.

After tailings placement is discontinued, oxidation usually initiates fairly quickly at the surface of the tailings impoundment where tailings are exposed above water and where oxygen has free access to the tailings. Surface drainage from the tailings impoundment turns acid fairly quickly. The downward movement of the AMD is extremely slow because of the generally low permeability of the tailings and foundation soils. Flow is relatively uniform and there is not a route for rapid preferential seepage as in dumps. The period for the immergence of the first AMD contaminated groundwater may be extremely long (tens, possibly hundreds of years).

After impoundment closure, there is often a slow lowering of the water table in the impoundment as drainage takes place. The partially saturated zone, in which oxidation can occur, increases. Figure 5 illustrates the rapid increase in the gaseous difusivity of tailings or soil as the moisture content reduces. Drying of the upper surface of the tailings impoundment also results in dessication cracking of the fine tailings. This increases the conductivity to both air and water. If sandy zones are located in the deposit the cracks connect with the pore spaces in the sandy zones and the lung effect results in oxygen transmission to these zones. Thus we often observe yellow, oxidized sand zones interlayered with gray unoxidized slimes layers near the surface if the tailings impoundment.

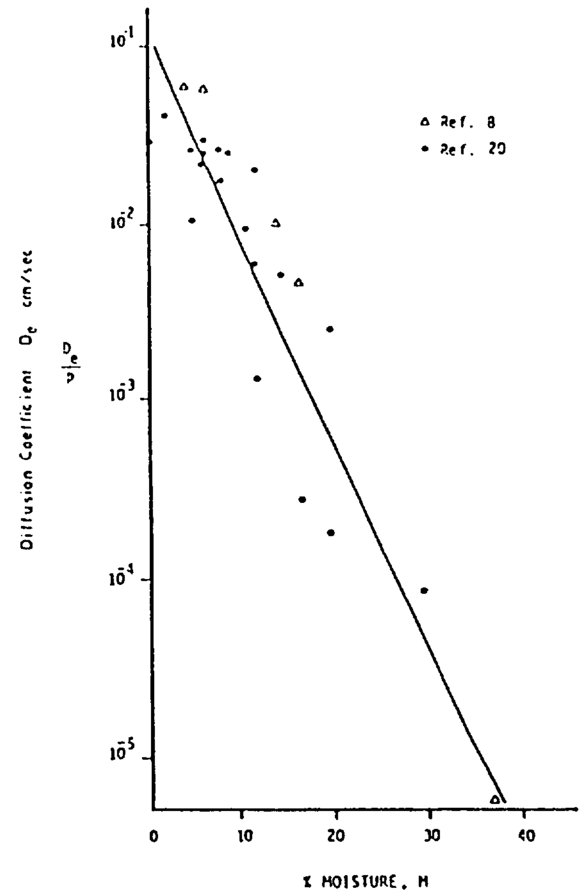


FIGURE 5 : MOISTURE DEPENDENCE OF THE DIFFUSION COEFFICIENT (ROGERS AND NIELSON, 1981)

ALTERNATIVE AMD CONTROL TECHNOLOGIES

AMD control technology is conveniently divided into three broad classifications.

- Prevention of acid generation
- Prevention of AMD migration
- AMD collection and treatment

Prevention Of Acid Generation

Prevention of acid generation in the first place is usually the most desirable of the control technologies. If generation does not occur, then there is no risk of its transportation into the environment.

This may be achieved by:

i) Removal of the pyrite source

Methods of pyrite removal have been reviewed by Hester and Associates, 1984. Removal of a portion of the sulphides from tailings, by flotation for example, may make the difference between

ii) Rendering acid generation minerals inactive by the development of surface coatings

Hester and Associates, 1984, demonstrate that while these approaches hold promise they do not as yet represent applicable technology.

iii) Exclusion of water

Exclusion of water to the extent that acid generation could not occur is not considered practical (Robertson, 1987).

iv) Control of biological oxidation

Bacterial action control by the application of bactericides have been discussed by Sobek, 1987. Periods of effective control for admixed bactericides do not exceed 5 years and surface spraying has been found to be not effective. This measure provides no control of chemical oxidation.

v) Temperature control

If freezing conditions can be achieved, acid generation can be prevented. This control has application in regions of permafrost, with adequate precautions being taken to prevent seasonal surface thawing. Elsewhere surface covers have the effect of reducing the maximum surface temperatures, and therefore oxidation rates, but do not provide adequate control for abatement.

vi) Exclusion of oxygen

The exclusion of oxygen to the extent that acid generation is reduced to acceptably low levels requires the placement of a cover with an acceptably low level of oxygen diffusion.

- Water covers. Such covers have been found to be effective in the control of acid generating materials placed below water. Both the cover and the water in the interstices help to prevent the oxygen transfer to the sulphides. It may be necessary to place a fine grained cover layer over submerged coarse rock waste to prevent oxygen transfer by convection of the pore water. Care must be exercised in the placement of old wastes below water to ensure that the solution of contained acid products is allowed for.

- Soil covers. Gaseous diffusion through soil covers differs little from that for tailings (Halbert et al, 1983, Silker and Kalkwarf, 1983). The effectiveness of the soil cover reduces rapidly as the moisture content of the cover reduces (Figure 5). Long term disruptions of the soil cover may occur as a result of erosion, cracking, frost action, root action, and burrowing animals. Current modelling techniques do not adequately allow for such disruptions. The comparative reduction in oxygen entry would be greatest for covers over very coarse waste dumps where 'chimney' and 'lung effects' would be greatest. There is considerable doubt that shallow soil covers will provide sufficient oxygen transfer control to abate acid generation. They reduce the infiltration of water and hence reduce the acid transport mechanism as discussed in the next section. Mathematical models and computer codes (such as the RATAP model, (SENES et al, 1986.) have been developed to evaluate the effect of soil covers on acid generation rates.

  Bog covers are a combination of water and soil covers, involving a layer of non acid generation soil placed over the acid generation waste together with shallow flooding, such that a layer of the soil cover is always saturated. The bog vegetation and saturated soil provides the barrier to the oxygen transfer (Steffen, Robertson and Kirsten, 1986a).

Complex covers are layered covers primarily for the purpose of infiltration control and are discussed in the next section.

- Synthetic covers. A number of synthetic covers have been proposed.

Synthetic membrane covers such as polyvinyl chloride (PVC), high density polyethelene (HDPE) etc. have been applied with some success (Caruccio and Geidel, 1983, and 1986,). The extremely low conductivity of such membranes to air offers the potential for oxygen exclusion. Main causes of failure would be holes due to imperfection in manufacturing and installation and formed after installation due to dump deformations and puncturing. The long term degradation and loss of plasticity and ultimate cracking limits the long term effectiveness of such thin membranes. In combination with low conductivity bedding materials or cover layers, the effects of such cracking can be considerably reduced. To entirely prevent oxygen entry it may be necessary to entirely encapsulate the waste in such a membrane.

Other synthetic membranes such as geopolymers, asphalts, and cements suffer from cracking and disruption. The potential for cracking increases with:

- reduced tensile strengths
- reduced plasticity and ductility
- increased dimensional instability due to humidity or temperature changes
- degradation with aging.

Because of their dimensional instability, bentonite covers have displayed a tendency to crack on dessication (Geidel and Caruccio, 1985). A cover material currently being evaluated which shows promise is high volume polypropylene fibre reinforced sulphate resistant gunite. The corrosion resistant fibres provide tensile strength and flexibility and spread out any cracking which occurs. It has the considerable advantage that it can be applied to steeply sloping surfaces and areas inaccessible to large mechanical equipment. Cracking generally would result in sufficient oxygen entry for acid generation to continue, though at a reduced rate. The costs of such synthetic covers are often prohibitively high.

vii) Addition of Base

Base addition can take a number of different forms:

- Blending of net acid producing and net acid consuming wastes to achieve a net acid consuming mixture. This is what is effectively practiced in the coal strip mines of the eastern USA (Skousen et al, 1987). Its effectiveness for hard rock mines has not been demonstrated. The flat horizontal layering of the sedimentary overburden over the coal seams and the strip mining method are well suited to achieving consistent and intimate blending of the overburden. The distribution of waste rock types and the mining sequence in hard rock mines is considerably more variable and consistent blending more difficult and costly to achieve. Where poor blending has been done, acid generation may still continue in localized zones resulting in neutralized AMD seepage of a quality which is still of concern to the downstream environment.

- Base addition and blending can be practiced to allow consistent control throughout the waste. The base material must be sufficiently fine and uniformly distributed that the rate of base neutralization is sufficient to prevent AMD development. Large isolated lumps of limestone would be inadequate even though the acid/base account may indicate a reserve of base. Coarsely ground limestone or calcarious rock is desirable. The rate of solution (hence depletion) and pH resulting from the addition of large quantities of slaked lime may be unsuitable for both short and long term AMD control.

- Surface applications are not considered effective for long term control.

Prevention Of AMD Migration

Where acid generation is not prevented, it is necessary to resort to prevention of acid and acid product migration. Since water is the mode of transport, the control technology relies on the prevention of water <u>entry</u> to the waste pile. Control of water <u>exit</u> from the pile is of little value since in the long term all water entering the pile must exit, long term storage being neglectable. The control requirements are as follows:

- diversion of all surface water flowing towards the pile
- interception or isolation of groundwater flow towards the pile
- prevention of infiltration of precipitation into the pile

Diversion facilities usually consist of ditches. Diversion of surface flows, while easily implemented are often difficult to maintain in the long term as discussed in the next section. The best long term solution to such surface flows is to select a disposal site which minimizes the need for diversion.

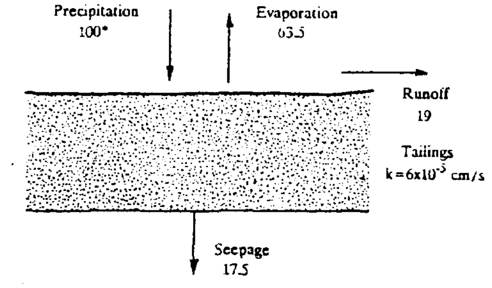
If the pile is located over a groundwater discharge area, interception and isolation of the groundwater is very difficult to achieve and maintain in the long term, While measures such as underdrains and sealing layers may be employed, their performance in the long term is questionable. The most effective solution is to select a site which is not located on a groundwater discharge area.

The secure prevention of infiltration, over the long term, is the most difficult to achieve. Covers of different types may be considered.

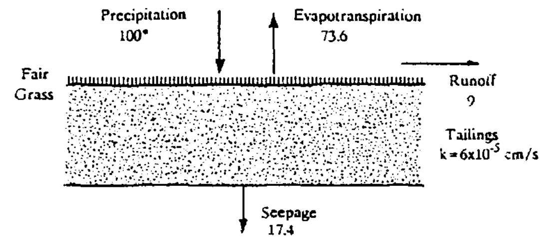
- Soil covers all have a variable but finite permeability. Depending on the nature of the cover, cover slope and precipitation pattern the percentage runoff varies dramatically. Surface slopes which permit ponding considerably increases infiltration. Vegetation increases evapotranspiration but inhibits runoff and may or may not result in a net reduction in infiltration.

  Complex covers (layers of high and low permeability) may be employed to promote drainage, reduce infiltration, facilitate vegetation growth, reduce erosion or resist frost action. Alternative cover designs and their long term stability are reviewed by Steffen, Robertson & Kirsten, 1986a. Some examples are shown in Figure 6.

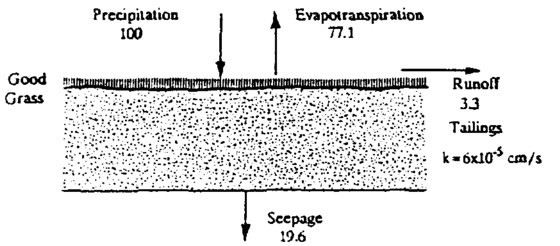
  The Hydrologic Evaluation of Landfill Performance (HELP) program may be used to estimate surface runoff, sub-surface drainage, and seepage that may be expected from a wide variety of cover designs. The results from a number of examples for the acid generating uranium tailings at Elliot Lake, Canada, are illustrated in Figure 6 (Steffen, Robertson and Kirsten, 1987). These examples demonstrate that covers which function as designed would considerably reduce infiltration but that infiltration remains significant for all soil only covers. The HELP model assumes saturated hydraulic conductivity in the various soil layers. Adequate models, to account for partially saturated flow in the layers, have not as yet been developed. The model also makes no allowances for the long term disruption of the covers resulting in local increases in infiltration.



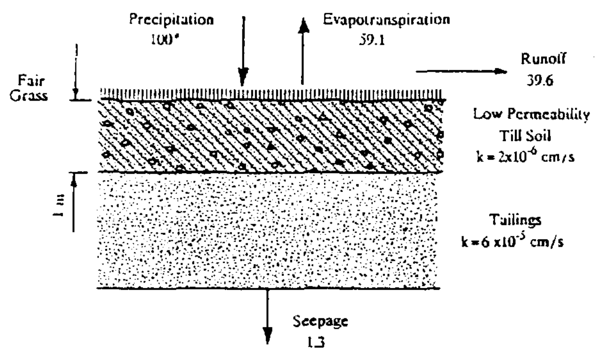
A) No Cover



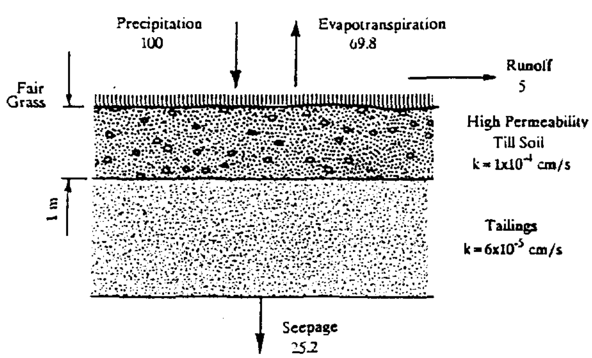
B) Moderate Vegetation Cover



C) Good Vegetation Cover

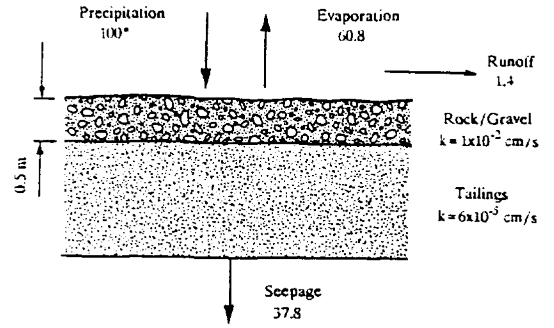


D) Low Permeability Till Soil Cover

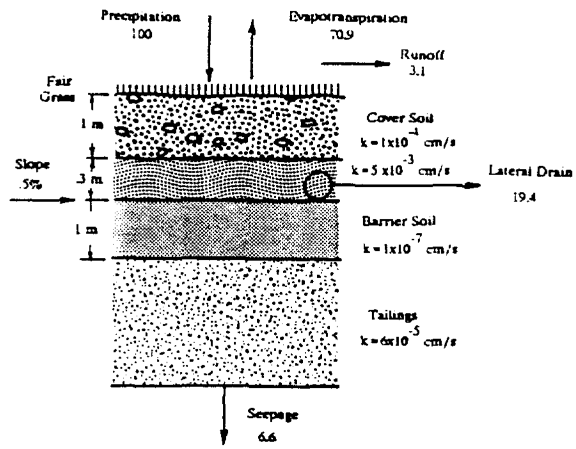


E) High Permeability Till Soil Cover

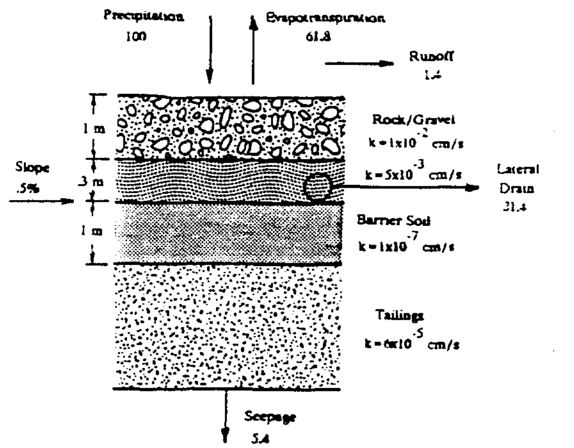
Note: (*) Numbers are percent of total annual precipitation.



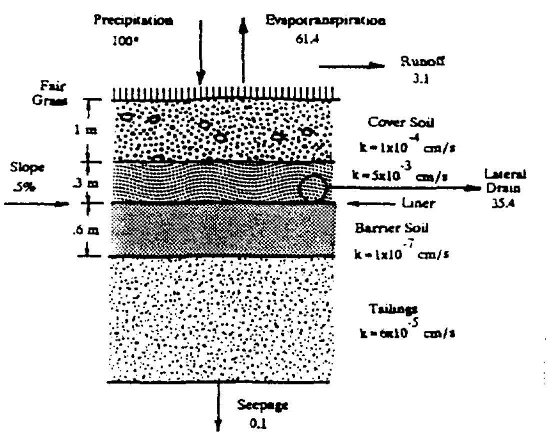
F) Riprap Erosion Resistant Cover



G) Soil Barrier with Lateral Drain and Soil Cover



H) Soil Barrier with Lateral Drain and Riprap Cover



I) Soil Barrier with Synthetic Membrane Liner, Lateral Drain and Soil Cover

Figure 6 Infiltration Barriers for Engineered Cap - Elliot Lake

- Synthetic membrane liner covers, in combination with soil layers can provide extremely effective infiltration controls. This is demonstrated in Figure 6(l) where infiltration is reduced to 0.1% of precipitation.

  The other synthetic covers discussed in the previous section would all serve to achieve substantial reductions in infiltration.

Reductions in infiltration do not necessarily mean equivalent reductions in contaminant loadings in AMD, since the concentrations may increase in the reduced flows. A 75% percent reduction in infiltration may only result in a marginal reduction in contaminant loading. On the other hand the placement of a cover also has other abatement effects due to reductions in air entry and thermal variation control. Reliance on covers for infiltration control requires their continued effective operation, in the long term, as discussed in the next section.

AMD Collection And Treatment

Collection and treatment provides the last defence in AMD abatement. It involves technology which is well established, and is working effectively at a large number of mines. Its main drawback is that collection and treatment must be continued for a very long period in time, while AMD continues.

The risk of failure of any form of treatment system is large. Extreme events such as flooding and fires can prevent treatment operations. Mechanical failure, labour disputes, power loss, reagent supply failure all represent large risks to continued treatment.

Alternative chemical treatment methods are reviewed by Skousen et al, 1987. The primary treatment method currently involves treatment with lime to produce a sludge. The mass of sludge produced exceeds by many times the mass of the sulphides responsible for acid generation. In the long term the volume of sludges may exceed the initial volume of the wastes producing the acid. Disposal of these sludges are an increasing problem. Long term dissolution of these sludges may represent an environmental hazard as great as the initial acid producing waste. Chemical treatment, while it offers a secure short term method of achieving environmental protection, may not offer long term affordable solutions.

Treatment of AMD by wetlands has been demonstrated by a number of workers to be effective (McHerron, 1986, Huntsman, 1985 & 1986, Pesavento and Stark, 1986). For northern climates, concerns exist regarding both the short term continuous effectiveness and the long term maintenance requirements. Biological activity reduces in the winter and water flow in winter is canalized by ice formation. Unless adequate treatment can be maintained all year round it will be necessary to store winter flows for treatment in the summer. The long term fate of metals accumulated in the organic deposits have not been determined. Where feasible, wetlands should be considered as the final polishing step in the treatment of residual AMD, after the implementation of other primary abatement measures.

LONG TERM STABILITY OF CONTROL MEASURES

Waste facilities can usually be designed to adequately achieve the design and abandonment plan objectives at the time of close-out. However, in the long term, the waste deposit and its control structures are subject to two classes of disruptive forces.

1) Short duration extreme events such as floods, fires, earthquakes and tornadoes which apply forces to the structures in excess of values for which they were originally designed.

2) The slow but perpetual action of forces which bring about deterioration, such as water and wind erosion, frost action, the weathering and chemical change of wastes, cover liners or structural materials, and intrusion by roots, animals and man.

Under the action of these forces, failure is inevitable within geologic time. Periodic maintenance can serve to repair the ravages of many of the perpetual forces. For a well designed facility the required interval between maintenance may be decades or centuries, imposing minimal cost on future generations. Remedial measures may be required after extreme events. The level of periodic maintenance and risk of remedial action which may be appropriate to pass on to future generations must be balanced by the present value to society of the resource.

During their evaluation of the long term stability of uranium tailings structures and surfaces, Steffen Robertson and Kirsten (1986a, 1986b), developed a summary of potential causes and associated risk of long term instability of 'generic' Canadian tailings impoundments. The conclusions from these evaluations are summarized in Robertson & Clifton, 1987.

Extreme Events

Because of the long period of interest, the likelihood of extreme events is proportionately large. This likelihood is determined from probability:frequency relationships based on the historical record of events.

The period of record is for an interval in which a particular climate applied. Evidence suggests (McInnis, 1985), that climatic cycles occur regularly, varying from relatively minor 30 year cycles to major glacial and inter glacial cycles of tens to hundreds of thousands of years. The weather in several years, or a few centuries from now is unknown (Hare and Thomas, 1974). While it is questionable whether man has altered world climate to date, the potential for material alteration increases and his influence may rival or overrule natural climatic changes in the early twenty-first century or sooner. While the nature of the changes are unknown, it is certain that the extremes to which the impoundments will be subjected will be greater than that predicted from existing records.

High Precipitation and Floods

Large precipitation events represent one of the most likely causes of waste impoundment failure. Failure during such events are also likely to result in large losses of tailings or waste fines to the environment.

Methods for the estimation of high precipitation events, and for the calculation of the resulting flood flows are well developed for dam design purposes. Current practice is usually to design operating facilities to withstand the one in two hundred year precipitation event. Design for the Probable Maximum Precipitation (PMP) is probably more appropriate for long term conditions.

Earthquakes

Dynamic loads, due to earthquakes, may result in the liquefaction of low density saturated tailings or uncompacted, saturated portions of granular embankments or embankment foundation materials. Failure of the El Cobre tailings dam in Chile, (Dobry and Alvarez, 1967) and Mochi Koshi tailings dam in Japan, (Okusa and Anma, 1980), are ample demonstration. New dams can be designed to appropriate standards. In populated areas, it may be appropriate to design for the long term to cope with the maximum credible earthquake. Methods of earthquake loading probability estimation is well developed for dam design.

Numerous older tailings impoundments have been constructed in a manner which make their embankments susceptible to liquefaction during extreme earthquake events. Abandoned impoundments of this type, if located in an earthquake potential area, may require remedial works to render them stable in the long term.

High Winds and Tornadoes

Tornadoes, tropical cyclones and low pressure systems are sources of high winds. Risk of failure from the last two sources is associated more with the precipitation that accompanies them than from the high winds themselves. Tornadoes, though the most destructive of all winds, are of such a short duration at an impoundment site that they do not have a significant potential of effecting the stability (Kolousek, 1984).

Forest Fires

Forest fires are expected to occur several times in the period of interest. Of themselves, they do not pose a significant threat to waste impoundment stability. However, loss of vegetation cover may lead to accelerated erosion by wind and water.

Perpetual Disruptive Forces

Erosion

Erosion may occur as a result of either wind or water action. Both are potentially severe causes of instability of surfaces and covers.

- Wind Erosion

Wind erosion has been observed to be a major release mechanisms at some existing waste impoundments. Control of this mechanism, for the long term, depends on the successful establishment and maintenance of a wind erosion resistant cover, such as vegetation, waste rock or surface crusting. Methods for the determination of the wind erosion potential and release rates of a particular cover type are reviewed by Steffen Robertson and Kirsten (1986a). They conclude:

1) Unacceptably high wind erosion rates occur on tailings surfaces and soil covers (without gravel) unless a well developed vegetation cover is established. Loss of vegetative cover (due to forest fires, flooding, or salt migration) could result in unacceptably high rates of wind erosion releases.

2) till, with a substantial gravel percentage, and rock waste will form effective wind erosion resistant layers when placed in thin (600 mm) cover layers.

- Water Erosion

This is probably the single most severe cause of impoundment instability. Erosion can take the form of food erosion of the diversion works, or sheet and gully erosion of the impoundment surface and embankment slopes.

i) flood erosion

A substantial portion of total erosion occurs during extreme precipitation and flood events. The probability of failure will depend on the criteria used to design the structure, and the degree of scour, sedimentation and/or blockage which has occurred. Sedimentation, ice, vegetation growth and debris blockage are extremely difficult to avoid in the long term; though easily and inexpensively cleared through maintenance.

Methods for the evaluation of erosion risk, and appropriate methods of design are reviewed in Steffen Robertson and Kirsten (1986a, 1986b). Appropriate control structure design would involve:

1) Design and construction of diversion structures to accommodate the Probable Maximum Flood (PMF) with ample width and size to allow for partial blockage or sedimentation.

2) use of heavy riprap (or waste rock) armouring along flow channels and on adjacent slopes. Methods for erosion protection design are provided in Walters and Skaggs (1984).

ii) sheet and gully erosion

The most suitable methods for the prediction of sheet and rill erosion are the Unified Soil Loss Equation (Wischmeier and Smith, 1978), and Modified Universal Soil Loss Equation (Williams,s 1975). After using these methods for erosion rate estimation, Steffen Robertson dn Kirsten (1986a) concluded that:

1) Tailings and bare soil would result in excessive sheet and rill erosion unless the soil contained a high percentage of coarse gravel.

2) Good grass cover does much to control this type of erosion which becomes insignificant with continuous forest cover.

3) Rock waste and cobble riprap are effective controls.

4) Discontinuous cover or periodic cover loss will result in unacceptable erosion rates.

iii) gully erosion

Gully erosion has been observed to be a major cause of instability of tailings surfaces and embankments. The only available method of gully erosion estimation is that proposed by Falk et al (1985). This method is based on limited data for American climatic conditions, does not account for vegetation cover and is considered invalid for long period estimation. Nevertheless, it has been used to demonstrate that the only effective gully erosion control for gravel free embankments and tailings slopes is riprap. This conclusion is in in agreement with field experience.

- Biotic Activity

i) root penetration

In general root action is considered to have an overall beneficial effect on covers, embankments and other structures in providing a binding effect and resistance to soil erosion, as well as minimizing infiltration. Two possible destabilizing effects have been observed:

1) Roots may penetrate low permeability layers and, on decomposing, provide seepage channels which increases infiltration through covers, or piping in embankments.

2) extensive root development in moist, permeable drains or drainage layers may ultimately result in clogging of the drains, in a manner similar to that experienced with residential drains.

Methods to reduce the potential for drain blockage include ensuring that the drains operate in a flooded condition and use of large drains with surplus drainage void space.

ii) burrowing intrusion

Burrowing intrusion by insects and animals have the potential, in the long term, of significantly altering the permeability of low permeability capping layers.

Intrusion by man, principally to obtain tailings for use in construction, has proved to be a material transport mechanism at some acid generating waste sites. Vehicle and large animal traffic can also be a major cause of erosion. The prevention of intrusion by man, in the long term, can only be achieved through institutional control and enforcement.

- Frost action

Recent studies and experience regarding frost action in tailings impoundments (Knight and Piesold, 1986; Geocon, 1986; Steffen Robertson and Kirsten, 1987), have demonstrated that the effects of frost on the engineering properties of tailings and their containment structures can be large. In those areas where continuous or discontinuous permafrost develops, and in areas of severe winter cold, frost action may be a major cause of long term instability.

The effects of freezing temperatures on tailings impoundment stability can be divided into two broad groups.

i) annual ice accumulation

Water flow in channels or drains may freeze in successive layers resulting in large accumulations of ice in a single winter, ice accumulations may result in blockage of the diversion structures or outlet works, with a consequential risk of erosion along the displaced flow channel during the early spring melt. Freezing of drains may result in a build up of pore pressures in embankments resulting in slope failure.

Ice accumulation can and does occur during tailings placement, where tailings are placed onto beaches.

Large consolidation settlements may occur after close-out. Such settlement will affect the drainage pattern on the surface of the impoundment and may result in cracking of any cover layers placed on the tailing.

ii) seasonal frost penetration

Knight and Piesold (1986) found that the effect of freezing low density tailings is to create a lattice work of ice crystal with consolidated tailings in between. The effect on the engineering properties of the tailings, (Robertson, 1987a), is to increase the permeability of the tailings at the same time as increasing the density. Seepage and consolidation rates (after thawing) are therefore increased. Frost susceptible cover materials subjected to freezing will develop ice lenses and a fissured structure which, on thawing, increases the impermeability of the cover. Where the cover is designed to limit infiltration this represents a severe failure mechanism. Frost penetration may also block subsurface drains, preventing drainage and causing pore pressure increases.

With annual accumulations of ice, there is an associate desegregational frost heave. Conditions have been identified where up to 200 mm of heave can occur annually. Steffen Robertson and Kirsten (1987). This seasonal heave is uneven, depending on surface and deposit conditions. Heave, with its consequential effects on drainage, wind and water erosion and cover disturbance, further affects differntial frost heave conditions. The end result is a hummocky, irregular surface with greatly disrupted drainage and cover layers. Small variations in seasonal temperature, snow cover and vegetation cover conditions will materially effect rates of aggradation and degradation of the frost. Frost induced creep (solifluction) also occurs on steeper surfaces such as embankment slopes.

CONTROL TECHNOLOGY FOR PHYSICAL STABILIZATION

Control technology for the physical stabilization of waste facilities control structures and covers are reviewed in Robertson and Clifton, 1987, and described in Steffen, Robertson and Kirsten, 1986a & b and 1987.

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