EVALUATION
OF
PASSIVE PROCESS WATER TREATMENT

For
Kennecott Corporation
PLANT PROJECTS GROUP

CONTRACT NO.: DC-46

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EXECUTIVE SUMMARY

The scope of work for this study, as defined by Kennecott's Plant Projects Group and M. Kalin of Boojum Research Limited, focuses on evaluating passive treatment of process water, storm water runoff, and emerging groundwater with elevated sulfate and metal contents. The feasibility of using phosphate rock and other materials as pretreatment to passive systems and as a means to generate protective precipitates on the surface or inside waste rock dumps was also to be assessed.

Water treatment processes, either conventional chemical, or biologically-mediated, passive "wetland" treatment systems, have to be based on an understanding of the chemistry of the waters to be treated. Kennecott's process water streams are dominated by aluminium. Its hydrolysis results in the low pH, which is in contrast to most other acid mine drainage, where the hydrolysis of ferric iron causes acidic conditions. Iron is removed from acid mine drainage through natural precipitation of "yellowboy", ferric hydroxide. Precipitation of iron, or, in the case of Kennecott's process waters, aluminium, is required as a first step, prior to microbially-mediated "wetland" treatment. Therefore, a low-maintenance solution to precipitate aluminium has to be found. Aluminium precipitation occurs naturally in the Old Bingham Tunnel, where it is caused by mixing of two water streams of different quality, i.e. leach water is mixing with alkalinity-bearing ground water. However, the required mixing ratio of ground to leach water (appr. 9 : 1) makes this approach impractical for use as pretreatment to passive systems on a larger scale. Nevertheless, it does suggest that some form of precipitation is feasible.

Aluminium can be precipitated either as $Al_2(SO_4)_3$, $Al(OH)SO_4$, $KAl(SO_4)_2$ or $Al(OH)_3$. Calculations of the concentration products of these compounds indicate that aluminium in process water is controlled by the equilibrium between $Al(OH)SO_4$ and both, the sulphate content and pH of the water. Solubility products, calculated for $Al(OH)_3$ between pH 2.5 and 6.5 at various concentrations of Al, representing leach water and Old Bingham Tunnel waters, suggest that, in many of the waters, $Al(OH)_3$ will precipitate out of the supersaturated solutions.

Attached algal biomass growing in the outflow of the Old Bingham Tunnel contains up to 10 % aluminium. Such biomass can be used as biological polishing agent, relegating aluminium to the sediment in a polishing pond. In this contaminant removal process, algal growth mediates water quality improvement through adsorption, absorption and coprecipitation.

Based on the limited data available, there appears to be an inverse relationship between potassium and aluminium concentrations in the process water. It is recommended that this relationship be further explored and, possibly, fly ash with appropriate characteristics could be considered as a precipitation agent.

Phosphate might be used as a precipitation agent. Preliminary geochemical simulations indicate that precipitation reactions can be anticipated with the use of phosphate rock. An experiment, where process water and phosphate rock were mixed at different ratios, is in progress. The usage of phosphate rock to inhibit leaching of wasterock requires detailed information on the wasterock types. From a preliminary review of Kennecott's wasterock types, it is evident that some wasterock contains significant amounts of chlorite and carbonate, and would thus not be acid-generating. If the wasterock has been leached, much of the pyrite has likely been dissolved with the leaching process. Microbial activity in the corrosion pits on the rock surface could be inhibited due to bacterial coprecipitation with surface-charged colloidal aluminium. The design of a respective test on larger scale goes beyond the scope of this report.

A literature review on passive treatment systems is included in this report, describing anoxic limestone drains, constructed wetlands, reed beds, biosorption and microbially-driven "wetland" processes. With respect to the issue of how passive water treatment techniques could be implemented if they prove to be successful and cost effective, some conceptual plans were prepared jointly with the Plant Projects Group for four target areas: the Midas/Congor drainage; the Mixed Tails area; the Saints' Rest drainage; the Lark seep area.

The Midas/Congor canyon has been considered as a developmental area where aluminium precipitation as well as wetland systems can be tested in field trials. Various drainages in this area are barren and will not accept traditional revegetative efforts due to the poor water quality of locally occurring seepages. Several small earth dams are proposed to be constructed to retain water in > 6 ft deep ponds for ARUM (Acid Reduction Using Microbiology) treatment. Shallow ponds for biological polishing would follow, with the principle target of reducing aluminium concentrations. A simple model, developed by Boojum Research Limited, could be used to evaluate the expected performance of the process, once the chemical and hydrological characteristics of the proposed ponds are known.

The Mixed Tails area is located just east of the Large Reservoir dam. The concept of a "wetland" treatment system for this area comprises a sequence of cells which operate in parallel and receive water from mixing-precipitation cells. Floating cattail mats will assist the development of reducing conditions in the water column over a microbially-active sediment, consisting of organic material. It is concluded that the Mixed Tails area could become a good demonstration project because it would provide the capability for easy control of some of the major parameters like feed water quality and retention time. However, a low-maintenance approach for aluminium removal has to be developed in order to prevent the "wetland system" from being rendered ineffective within a short period of time, due to accumulation of aluminium precipitates in the biomass and over the sediments. Further development of the wetland concept for this area was deferred pending the results from the Midas/Congor canyon.

The evaluation of treatment options for Saints' Rest and Lark waters shows that these waters are circumneutral and contain mainly calcium and magnesium sulphates. A biological polishing process is suggested for the removal of these substances, using rooted populations of the algal family Characeae, commonly known as "Stoneworts". Some species of Stoneworts colonize magnesium sulphate-rich waters or brines. Boojum Research Limited has worked with this algal group for many years. Field applications are well-advanced using these algae to remove ^{226}Ra in waters from a uranium mine. Using population density measurements and growth rates of the algae from that project, it is estimated that a 1 ha underwater meadow of the algae could treat 100,000 m^3 of Lark or Saints' Rest water per year for magnesium, and 50,000 m^3 for sulphate.

The conclusions resulting from the assessment of the applicability of passive "wetland" treatment systems for Kennecott's process and storm waters are:

1) Passive wetland systems appear to be a promising option for treatment of Kennecott's process and storm waters. However, due to the unique chemical characteristics of these waters, low-maintenance solutions to aluminium precipitation have to be established prior to applying biologically-driven treatment processes in the Midas and Mixed Tails areas. For Lark and Saints' Rest such precipitation steps will not be required.

2) Phosphate rock can be used for process water pretreatment as well as for reduction of meteoric water penetration into waste rock dumps. Most likely precipitates resulting from such treatment are $Al(OH)SO_4$ and $AlPO_4$. Both applications require further research and pilot field tests. The tests concerning sealing of the waste dumps need to be designed and carried out under consideration of the heterogeneous nature and other characteristics of these dumps as described in this report.

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0.0 INTRODUCTION

After a brief site visit to Bingham Canyon by M. Kalin, guided by the Kennecott Plant Projects group, a scope of services was developed through consultation with the group and finalization of details with Helmar Bayer.

The objective of the work is to advise on and evaluate the feasibility of designing a pilot passive water treatment system for the Kennecott process (LEAWA) and storm water. Passive treatment systems are also evaluated for the water in the Lark and Saint's Rest canyons, as well as for the Midas and Mixed Tailings areas.

The focus of the evaluation is the development of constructed wetlands for process and storm water treatment, with consideration of eventual post-closure operations.

Scope of Services: The Scope of Services and the specific problem areas to be addressed are outlined in Contract No. DC-46 as follows:

1) Evaluate, based on the chemistry of the Kennecott process water and effluent characteristics, as provided by the leach water and other analyses:

    1a) The feasibility to use phosphate rock as a precipitation agent as pretreatment to a passive system, such as ARUM or biological polishing.
    1b) The feasibility to use phosphate rock as a means to inhibit leaching of waste rock, through formation of corrosion protective precipitates within the waste rock pile and on pyrite material surfaces.
    1c) Design experimental approach to evaluate feasibility of these and other Company specified and Contractor agreed approaches to reduce meteoric and leachate infiltration.

2) Assess the potential of the Mixed Tails Area for development into a treatment wetland/biological polishing system, which has treatment capacity for storm water with elevated sulphate and metal contents.

   2a) Wetland Hydrological requirements - water balance - evapotranspiration acreage requirement.
   2b) Ecological Requirements - indigenous species - succession etc.
   2c) Contamination removal/mobilization conditions/pathways.
   2d) Maintenance requirements short-term/long-term.
   2e) Potential environment impacts and or benefits.

3) Utilize the configuration of the Midas Area to design a passive treatment system for storm water with elevated sulphate and metals contents.

   3a) Assess field data and integrate into objective 3.

4) Interpret data collected and measures taken at Saints' Rest and Lark and provide recommendations for improvements.

Data acquisition and information available: Boojum Research has provided instructions for sample collection in the Midas, Lark and Saints Rest canyons with respect to water and algae material to Helmar Bayer and Ivan Weber. Some water analyses were carried out during the project, and other information was supplied on request. All information received is given in Appendix A, consisting mainly of chemical analyses provided by Kennecott's analytical services.

In addition to the chemical analyses, portions of reports or complete reports were provided by Kennecott Plant Projects Group on sludge analysis from the Bingham Tunnel, as well as a report describing the surficial stratigraphy of the area and characteristics of waste rock. These reports are listed as references in Appendix A.

Through discussion with the Plant Projects Group, it became evident that a "wetland" treatment system for the Kennecott waters was under consideration.

In conventional water treatment systems, chemical additions induce chemical precipitation processes, whereupon precipitates are collected in settling ponds. In passive systems, also referred to as "wetland" treatment systems, the precipitation reactions are mediated by those bacteria which utilise some of the water constituents as energy sources. For example, one group of bacteria convert sulphate to hydrogen sulphide. The various bacterial activities alter the chemical conditions of the water. Specific bacterially-mediated changes in the water result in the precipitation of contaminants such as heavy metals.

Once the contaminant precipitates have formed, these suspended particles can be filtered from the water using biological polishing agents such as algae. Through settling of particle-laden algal biomass in the treatment ponds, contaminants are accumulated in the sediments.

The assessment, presented in the following sections, focuses upon the potential usage of passive treatment systems for the Kennecott leach and storm water. Conditions which are required for contaminant removal have to be based upon a reasonable understanding of the chemical characteristics of the water to be treated. The objective is, therefore, to evaluate the water chemistry of the Kennecott process and storm water, and identify possible low-maintenance or passive treatment processes which could feasibly treat this particular water.

As the Kennecott leach and storm waters are dominated by high aluminum concentrations, a brief literature review of aluminum chemistry was completed. Preliminary geochemical simulations were performed for identification of precipitates potentially formed upon addition of phosphate sand to the leach solution. These simulations overall assist the stepwise approach to developing a water quality improvement strategy.

During this feasibility study, the magnitude of the treatment problem, with respect to the Kennecott situation, was elaborated. Boojum Research Ltd. is not very familiar with the site conditions. This feasibility study should be considered as a "paper" evaluation of the chemical conditions of the process water. It should only be used for identification of those critical parameters requiring detailed evaluation, prior to commitment to large-scale passive treatment systems.

1.0 LEAWA WATER CHEMISTRY AND PHOSPHATE USAGE

During characterization of a mining process water, the history of the waste material from which the effluent emerges is typically summarized, and weathering or leaching processes can usually be identified from the mineralogy. However, given the long history of the Kennecott Copper facility and the size of the operation, completion of this approach's components is either not possible, or outside the scope of this contract.

As an alternative, a pragmatic approach to the feasibility evaluations has to be adopted, using the information provided. The evaluation is based on the chemistry of the Kennecott process water and effluent characteristics, as provided by the very limited number of chemical analyses. Examination of seasonal or long-term trends is not possible. Knowledge of such trends is essential with respect to predicting the long-term water quality.

Current LEAWA Water Chemistry

A large quantity of sludge has accumulated in the Old Bingham Tunnel. Conditions which facilitate the natural formation of sludge must therefore prevail in the tunnel. The available chemical analyses of water and sludge samples collected by Kennecott were used to explore natural precipitation mechanisms which would not require the addition of lime.

Sludge Formation in Bingham Tunnel

The analytical results of water and sludge samples, collected from the deep portions of the tunnel at given distances away from the portal, were provided in the Kennecott November 1992 report. These data were used to determine the key factors which result in natural precipitation and sludge formation.

The ratios of major elements' concentrations in water emerging from the Old Bingham Tunnel portal (except OBT1675) are very similar to the mean values of 12 LEAWA waters, as reported in September 1992 analyses (Figure 1). Both types of waters contain high concentrations of SO_4, Al and Mg ions, with lower concentrations of Ca and even lower concentrations of other elements.

The major difference between the two water types is the iron concentration. In most leachate water, iron concentrations range from 400 to 2200 $mg.L^{-1}$, while the iron concentration in the Old Bingham Tunnel water is less than 10 $mg.L^{-1}$.

In samples collected in the Bingham Tunnel, the iron concentrations in sludges from the deeper portions of the *tunnel* (*1675R, 1005S, and 840S*, Report 1 *cited in* Appendix A) are higher than in sludge samples collected near the tunnel portal (samples 500S-200S, 435S1-375S1-275S1, from Report 1).

The events underlying the precipitation process in the Bingham Tunnel may be as follows; ground water with a higher pH and some alkalinity, and leach water from the waste rock pile containing dissolved ferric iron, are both entering the tunnel. Upon mixing, ferric iron borne in the leach water is precipitated as ferric hydroxide. Following ferric iron precipitation, the pH of the mixture is still between 4.5 and 6.5, values adequately high for aluminum hydroxide precipitation (Figure 2).

The acidity in Bingham Tunnel and the LEAWA water is attributable to elevated aluminum, copper, manganese and zinc concentrations. If the concentrations of these elements in the available data are plotted with pH, it becomes evident that, with the rise of pH, the concentrations of the elements decrease (Figure 2).

If *Bingham Tunnel or* LEAWA *water were diverted to a wetland setting without prior* precipitation of elements, massive precipitation of cations in the wetland would blanket the wetland, hindering both flow of water and normal functioning of biologically-

Fig.1: Tunnel & Leach Water Comparison

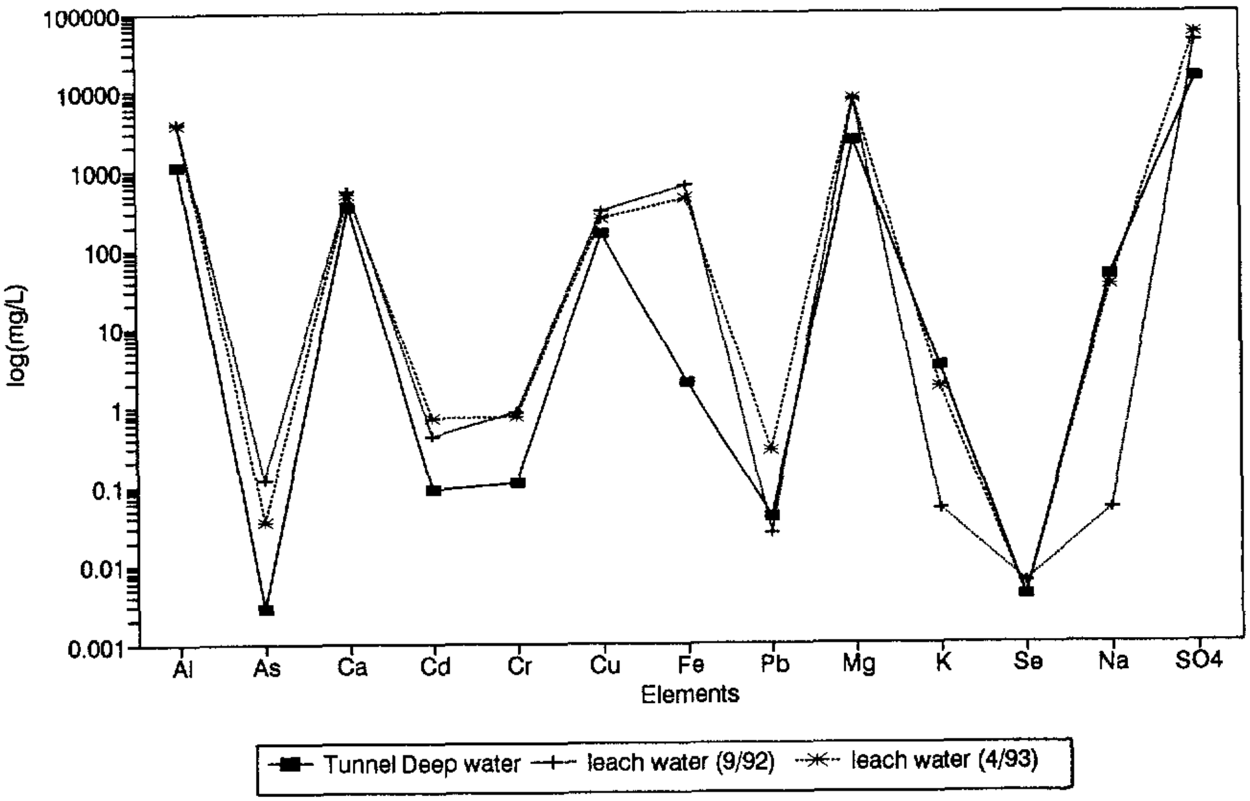
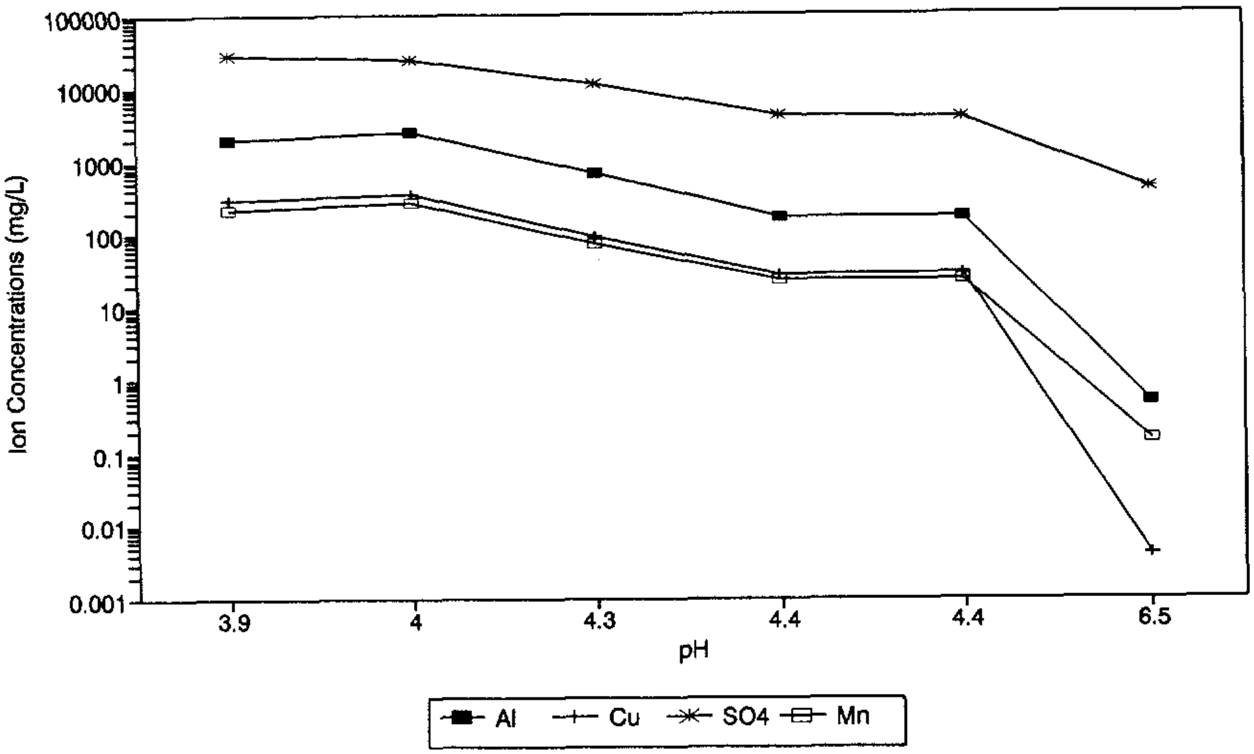


Fig.2: Ion Concentration Change with pH
Bingham Tunnel Water

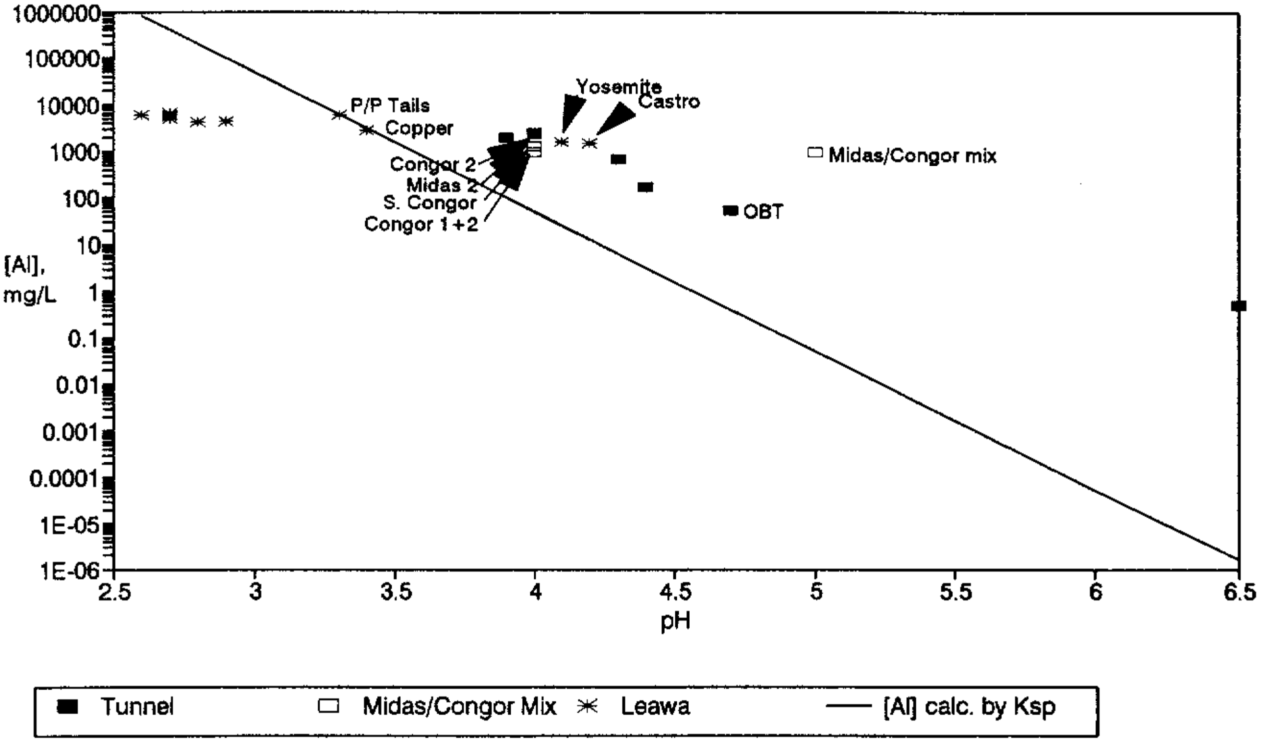


mediated water treatment processes. The minor increase in pH required to induce precipitation of large quantities of cations presents an potential means to passively enhance the natural precipitation process. When precipitates form naturally, the sludge volume is generally lower than when precipitation is induced by additions of chemicals. For instance, given the characteristics of the Kennecott process water, a storm event (neutral pH rain water unaffected by smelter fall-out) could theoretically induce precipitate formation in the leach water.

LEAWA Water Characteristics

Calculations of solubility products, using the LEAWA water and the Old Bingham Tunnel water chemistry, can be used to identify the aluminum species present in the solutions (Figure 3). The line in Figure 3 represents the calculated solubility product for $Al(OH)_3$ at various concentrations at pHs ranging from 2.5 to 6.5. The Kennecott waters can now be examined with respect to the aluminum species which dominate a particular solution.

Fig. 3: Actual [Al], Compared With Calculated [Al] from Ksp of Al(OH)3



For Bingham Tunnel water and some of the LEAWA (25 Yosemite and 24 Castro) water, as well as Midas and Congor, the concentrations lie above the calculated line. This means that the water is supersaturated with $Al(OH)_3$. The Al concentration in the Bingham Tunnel water is about 100 times higher than the calculated values. Values above the line indicate that, in these waters, aluminium hydroxide will precipitate.

Aluminum hydrolysation and precipitation is described by Huang and Keller (1972), Yariv and Cross (1979), and Stumm and Morgan (1981), and is given below with the associated equilibrium constants for each reaction.

(1) $Al^{+3} + H_2O = Al(OH)^{+2} + H^+$ $pK_1 = 4.89$
(2) $Al(OH)^{+2} + H_2O = Al(OH)_2^+ + H^+$ $pK_2 = 10.32$
(3) $Al(OH)_2^+ + H_2O = Al(OH)_3 + H^+$ $pK_3 = 16.28$
(4) $Al(OH)_3 + H_2O = Al(OH)_4^- + H^+$ $pK_4 = 23$

In the equilibrium reactions above, only products of step (3) do not dissolve in water. Reactions (1), (2), and (4) all result in water-soluble species. As aluminum hydrolyses, as in the case of the LEAWA waters, the pH of the solution drops.

The pH is characteristically low in Kennecott water as a result of the hydrolysis of Al^{+3}. The characteristics of the water indicate that, in contrast to most examples of AMD chemistry where the pH decrease is brought about by the hydrolysis of reduced iron, that Kennecott process water has a low pH, due to the hydrolysis of aluminium. Water entering a passive treatment system must contain completely hydrolysed aluminium hydroxide, as otherwise the pH can be expected to change.

Aluminium Concentrations and Phosphate Interactions

The chemical characteristics of the process water, with emphasis on the aluminium concentrations, are discussed in this section. Kennecott process waters represent an unusual dimension to any precipitation process as aluminum hydroxide is amphoteric in nature (behaves as both acid and base).

Aluminium concentration: When the pH of a acid solution containing aluminum is raised, $Al(OH)_3 \cdot nH_2O$ precipitates are formed. As the pH is further increased, the precipitates are redissolved, forming a complexed aluminum anion. Therefore, during operation of a treatment system, it is important to consider the consequences resulting from pH changes at any point in the treatment train, where aluminum hydroxide precipitates are present.

Aluminum is an ion which very readily hydrolyses. During its hydrolysis, two or more Al ions can share one OH^- group and become dimerized or polymerized particles. In natural water, aluminum not only exists as monomers (Al^{+3}) but also as dimers and polymers in the form of bidimensional ionic sheets and tridimensional ionic particles.

Hem (1968) studied the polymerization process of hydrated Al ions and found that it involves the following steps:

(a) hydrolysis of the monomer and dimerization.
(b) further hydrolysis and condensation of the orientation of Al species into a two dimensional polymeric ionic sheet which is referred to as a gibbsite sheet.
(c) condensation by the parallel orientation of the sheets into perpendicular axes and formation of a three dimensional particle or a tactoid.
(d) aggregation of the various Al species and formation of amorphous particles.

The polymerization process is determined by the ratio, g = $[OH^-]/[Al^{+3}]$, where g is the ratio of hydroxyl concentration to the Al^{+3} concentration. When g = 1, Al is present in the solution mainly as a monomer or dimer, as expressed in reactions (1) and (2). When g $\geq$ 3, aluminum precipitates as $Al(OH)_3$, as outlined in reaction (3). An evaluation of the LEAWA water indicates that g is low, given the low pH. It is therefore reasonable to suggest that LEAWA waters are dominated by aluminium monomers. It follows, then, that through the addition of hydroxyls, it is possible to form a precipitate.

Hem (1968) stated that Al in natural water is not always in the monomeric form, but also in a polymeric state. Polymerization of Al forms relatively large particles in water, but since $Al(OH)^{+2}$ and $Al(OH)_2^+$ are both positively charged, the aggregation is difficult. Aluminum, therefore, often forms colloid particles in nature.

These surface-charged colloidal aluminum precipitates can present a problem to bacterial populations, as the bacteria become inactivated through adhesion of aluminum colloids onto their cell surfaces. These bacteria-aluminium colloid interactions could also be employed to inhibit bacterial leaching activity in waste rock.

In tailings rich in clays, oxidizing bacteria are inhibited due to surface binding (McCready, l984 & l985). Ferris et al. (l987) reports that aluminium hydroxides which accumulate in sediments have been found to co-precipitate bacteria. Practically, it is important to recognize that microbial activity could be reduced in solutions with high aluminum concentrations and in various precipitates of aluminum.

Aluminum can be precipitated either as $Al_2(SO_4)_3$, $Al(OH)SO_4$, $KAl(SO_4)_2$ or $Al(OH)_3$. All of these compounds' concentration products in LEAWA water were calculated and are presented in Figure 4. The concentration products of $Al_2(SO_4)_3$ and $Al(OH)_3$ are greatly variable in the different LEAWA waters. While the concentration product of $KAl(SO_4)_2$ changes slightly in all the waters, the concentration product of $Al(OH)SO_4$

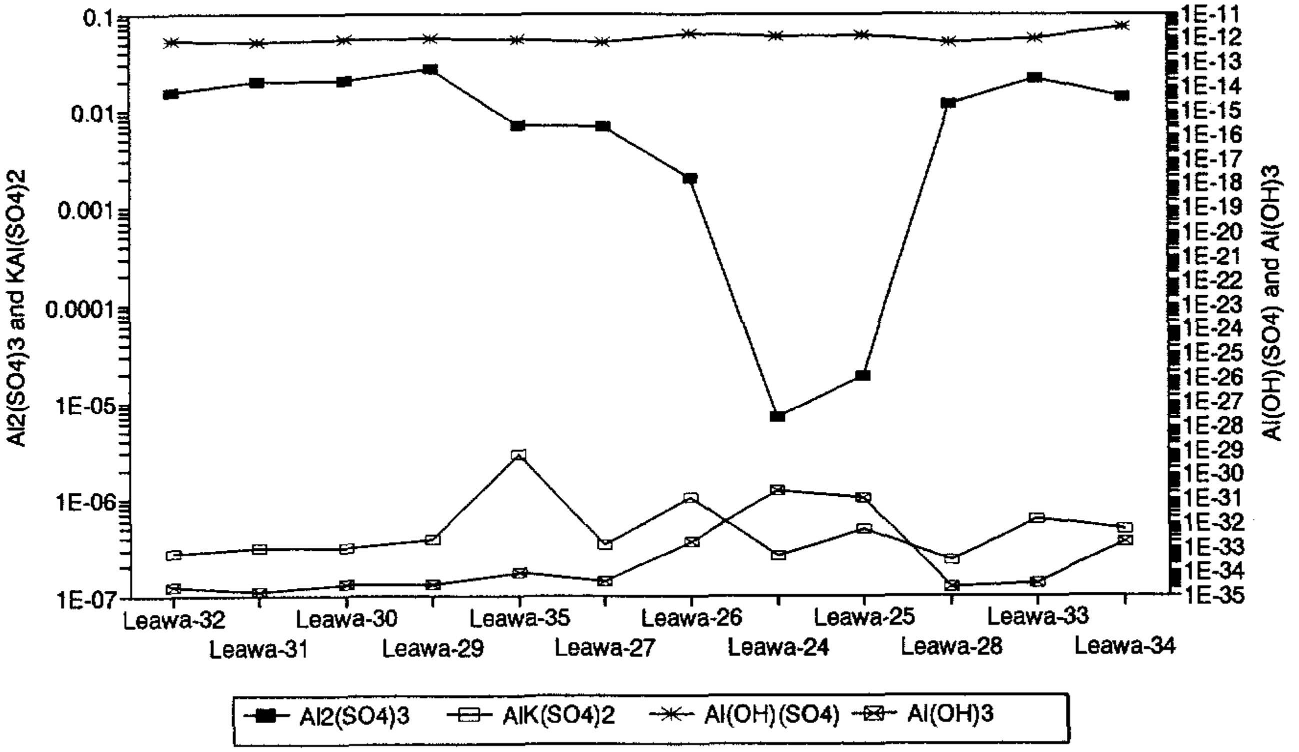


Fig.4: Concentration Product of Al Compounds, Leawa Water Analysis

remains virtually constant in all waters. This indicates that Al concentrations in LEAWA process water are mainly controlled by the equilibrium between $Al(OH)SO_4$ and both the $[SO_4^{-2}]$ and water pH.

This is consistent with the thermodynamic studies of Sullivan et al. (1988) examining aluminum solubility in acid mine drainage. The concentration products of $KAl(SO_4)_2$ in LEAWA water further indicate that the concentration of K may also affect $[Al^{+3}]$. Unfortunately, the analytical results for K and Na concentrations in the LEAWA samples are very inconsistent, and the potential relationship between K and the precipitation process cannot be explored at this time.

Al can also form $Al(SO_4)^+$ and $Al(SO_4)_2^-$ complex ions. In the LEAWA waters, the ratio of $[OH^-]/[Al^{+3}]$ is low, due to the low pH, but the ratio of $[SO_4^{-2}]/[Al^{+3}]$ is about 2 to 5. Considering no other cations apart from SO_4^{-2} ions (albeit an oversimplification in light of the complexity of the solutions), it is reasonable to suggest that Al in LEAWA water is likely to be present in the complex form of $Al(SO_4)_2^-$, a negatively-charged complex.

Phosphate considerations: Agents which reduce the surface charges on the precipitates should be considered, for these compounds may facilitate the precipitation of aluminium species, since supersaturated Al ions are mainly present in the monomeric form, or complexed as $Al(SO_4)_2^-$. Hsu (l979) studied the effect of phosphate and silicate on the crystallization of gibbsite ($Al(OH)_3$) from OH-Al solutions. Hsu reports that, with the addition of silica or phosphate, precipitates form.

Hsu (1968 and 1979) studied reactions between solutions of $AlCl_3$ and NaH_2PO_4 in different conditions. He found that Al monomers (in solutions of about pH 3) and hydrolysed Al polymers (in pH 4 to 5) reacted with phosphate differently. Monomers tended to form soluble complexes with phosphate, whereas the polymers could be precipitated by phosphate easily. Precipitates obtained from a monomer solution are compact, resistant to acid, and contain some crystal structures. Precipitates from polymer solutions are amorphous and easily redissolve in acid. However, aging may change the precipitates formed at higher pHs into a more stable form.

The literature review, and the evaluation of the Kennecott process waters, indicate that aluminium reactions with phosphate and other ions, forming precipitates, are functions of several parameters. The specific aluminum species in solution, the temperature of the solution, the rate of precipitation reagent mixing, the Al/P ratio (in the case of phosphate addition), as well as the presence of other cations in the solution, are all important parameters.

1.1 PHOSPHATE ROCK USAGE

1.1a The feasibility to use phosphate rock as a precipitation agent as pretreatment to a passive system, such as ARUM or biological polishing.

From the considerations derived from the literature review on aluminium chemistry and the chemical characteristics of the LEAWA water, it appears that two different types of precipitates are likely to be formed upon addition of phosphate. It is recommended that, before large-scale phosphate rock application plans are made, simple bench-scale experiments be carried out with the different types of LEAWA water to determine the type of precipitate formed via direct chemical analysis of the resultant precipitate.

The complexity of the precipitation process is evident from the results of the preliminary geochemical simulations using PHREEQE. Details are given in Appendix B3. The simulations suggest two key aspects with respect to phosphate as a precipitation agent.

First, an experiment using relatively high phosphate sand:leach water ratios would likely result in significant changes in solution composition. Once the upper limit of application rate is established, and its effectiveness in removing aluminium from the process water is known, then lower application rates can be tested with flow-through conditions.

Second, the preliminary geochemical simulation (PHREEQE) output suggested that, after aluminum precipitation has taken place, some sulphate will remain in solution. This is important, as a microbially-driven sulphate reduction treatment option is being considered for operation downstream of the phosphate precipitation phase. If most sulphate precipitated prior to entry of water into a passive wetland treatment area, sulphate would not be available for the key microbial processes.

Phosphate rock and process water reaction trials:

As the results from the geochemical simulation (PHREEQE) emerged and considerations of chemistry were under way (as discussed under "Aluminum Concentrations and Phosphate Interactions", page 10), Boojum suggested that performance of a simple phosphate sand-process water reaction experiment may provide useful information.

Unfortunately, Boojum did not provide sufficient detail concerning the experimental design, and some shortcomings can be noted in experiment's dataset. Boojum was provided with two sets of experimental data, pH and Eh measurements. This information is used to outline those experiments required to arrive at design criteria for a precipitation pond.

The experimental set-up included agitated and non-agitated treatments, in which different volumes of process water were mixed with a series of different weights of phosphate sand. Two replicate treatments were in the ratio of 100 mL of process solution to 1 gram of phosphate sand (100 $mL.g^{-1}$) and of 50 $mL.g^{-1}$. Single tests were set up at 500 $mL.g^{-1}$, 250 $mL.g^{-1}$, 25 $mL.g^{-1}$, 20 $mL.g^{-1}$ and 10 $mL.g^{-1}$.

Process Plant Discharge (11/10/93) solution was treated by Code 30 phosphate sand (12.8 % P grade), supplied by Texasgulf, Glennwood, North Carolina. The material description sheet is available in Appendix A, Document 11.

The experiment was run at room temperature. Gentle agitation was provided using a sample shaker apparatus. The various treatments were contained in closed (capped) bottles during the experiment. The same pH and Eh probes and meters was used throughout the experiment.

The data were provided by Kennecott on floppy disc. Although the dataset is limited, the following components can be examined:

- Ratio of water volume(mL)/PS(g)(Phosphate Sand)
- Eh and pH changes
- Agitation

Ratio of water volume (mL) / PS (g): The ratios of water volume (mL) per gram of phosphate sand of the experiment are presented in Table 1. The highest ratio is 500 mL.g^{-1} of phosphate sand, provided in the 500 mL.1 g^{-1} treatments. The lowest ratio is 10 mL.g^{-1}, in the 100 mL.10 g^{-1} treatments.

Table 1: Ratios of Water Volume to Phosphate Sand

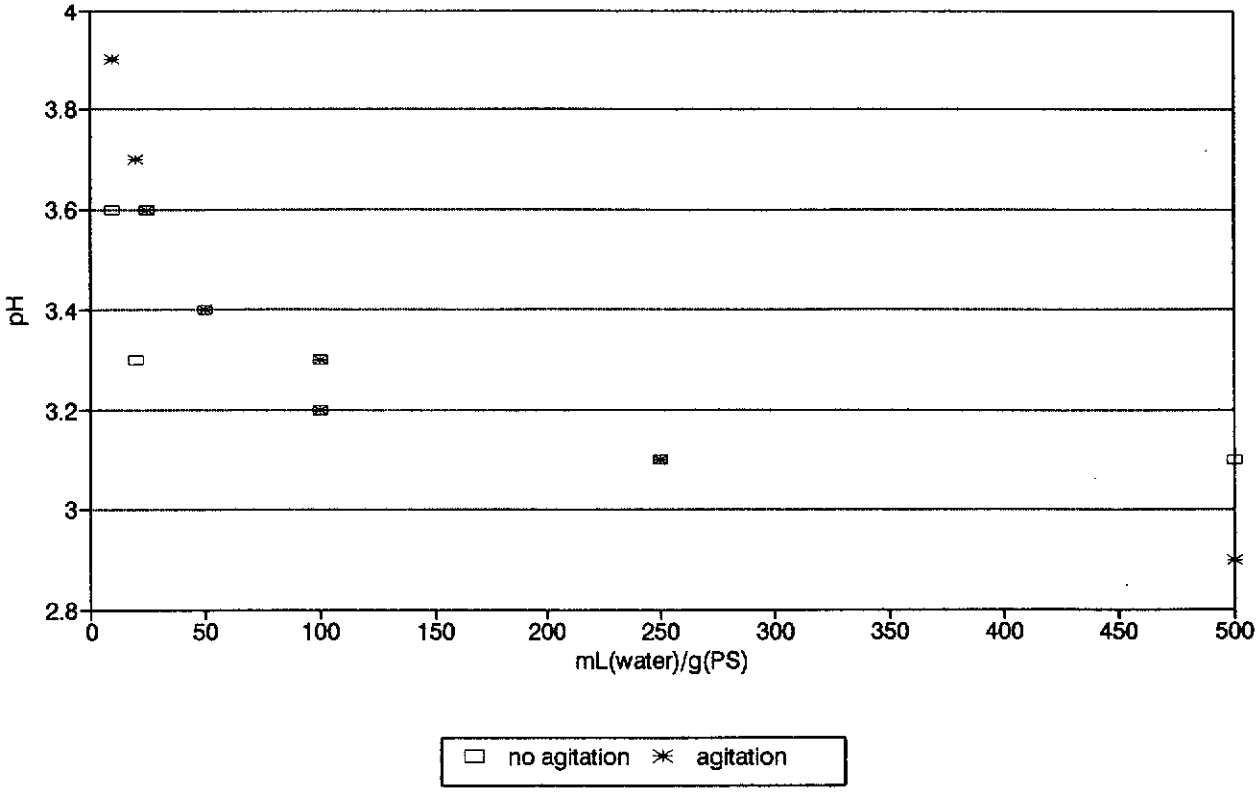
Experiment	100mL/1g	100mL/5g	100mL/10g
ratio(mL/g)	100	20	10
Experiment	250mL/1g	250mL/5g	250mL/10g
ratio(mL/g)	250	50	25
Experiment	500mL/1g	500mL/5g	500mL/10g
ratio(mL/g)	500	100	50

The data shown in Table 2 suggest that, when a small volume of process water is combined with phosphate sand (low volume:weight ratio), the pH of the mixture is increased, and the Eh reduced, compared to treatments where a large volume of process water was combined with phosphate sand (high volume:weight ratio). This is also evident in Figure 5, where the greatest pH increases occurred in treatments where the process water volume: phosphate sand weight ratios were less than 50.

Table 2: Eh and pH Values for the High and Low Ratio

Ratio mL/g	Eh		pH	
	agitated	not agitated	agitated	not agitated
500	445	450	2.9	3.1
10	390	385	3.9	3.6

Fig.5: Phosphate Experiment Summary-pH



The Eh measurements recorded during the experiment are presented in Figures 6a to 6d, and the pH measurements are presented in Figures 7a to 7d. The Eh values from the last day of the 26 day experiment are plotted against the process water: phosphate rock ratios in Figure 8.

If, for example, Copper process water (pH 3.4; [Al^{+3}] 2900 mg.L^{-1}) were to be treated in field conditions and the results of this experiment are used, at least 26 g of phosphate sand would be required to precipitate all the aluminum in one litre water, equivalent to a process water volume:phosphate sand of 38.5 mL.g^{-1}.

In a scaled-up experiment using, for example, 50 to 100 L of process water, the water volume to phosphate sand weight ratio should be smaller, in light of the limited surface area of phosphate sand, relative to the reaction rate. It should be noted that, in some of the treatments where low ratios were used, the final pH values at the end of the experiment were lower than the original pH at the beginning of the experiment.

Fig.6a: Phosphate Sand Experiment - Eh
with agitation

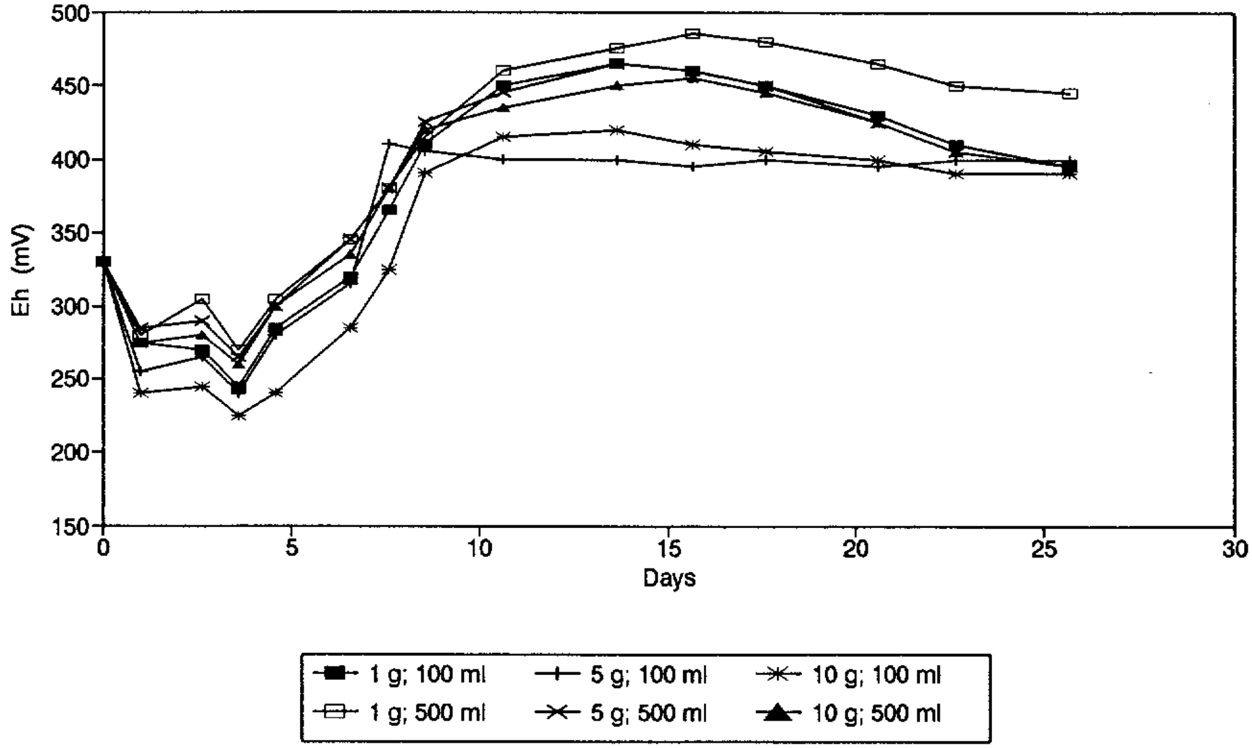


Fig.6b: Phosphate Sand Experiment - Eh
with agitation

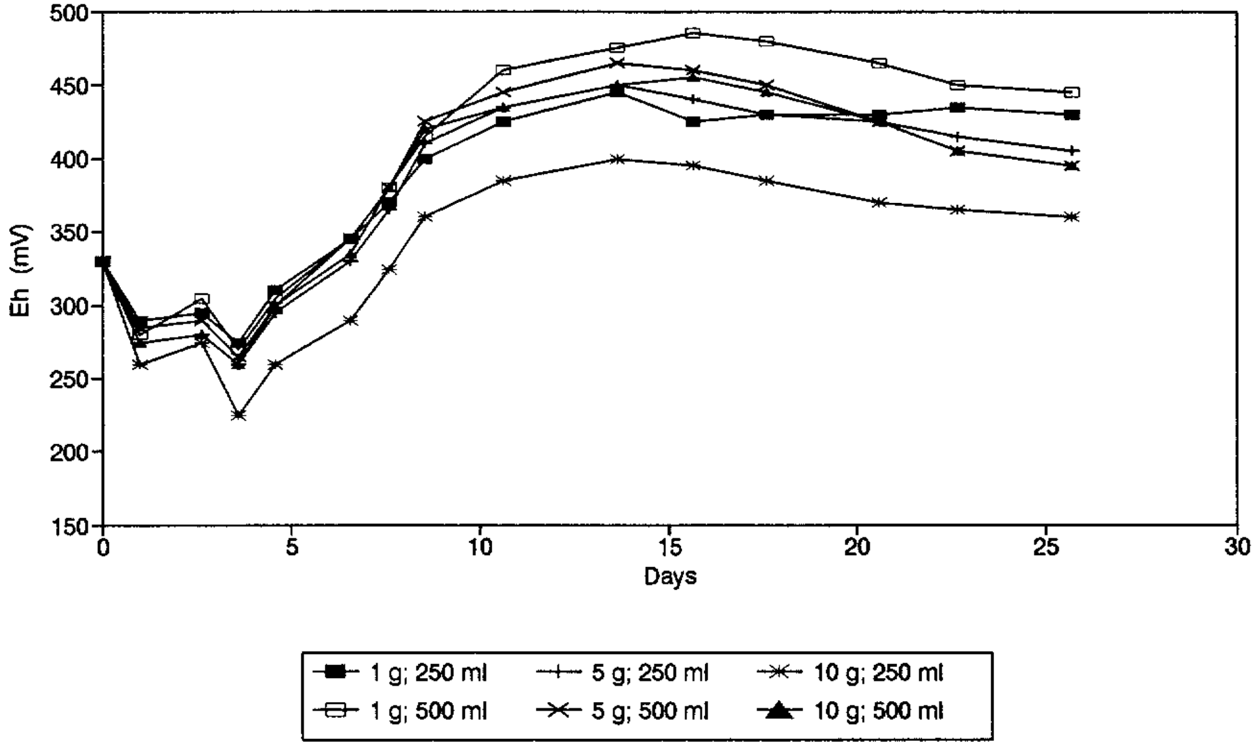


Fig.6c: Phosphate Sand Experiment - Eh
without agitation

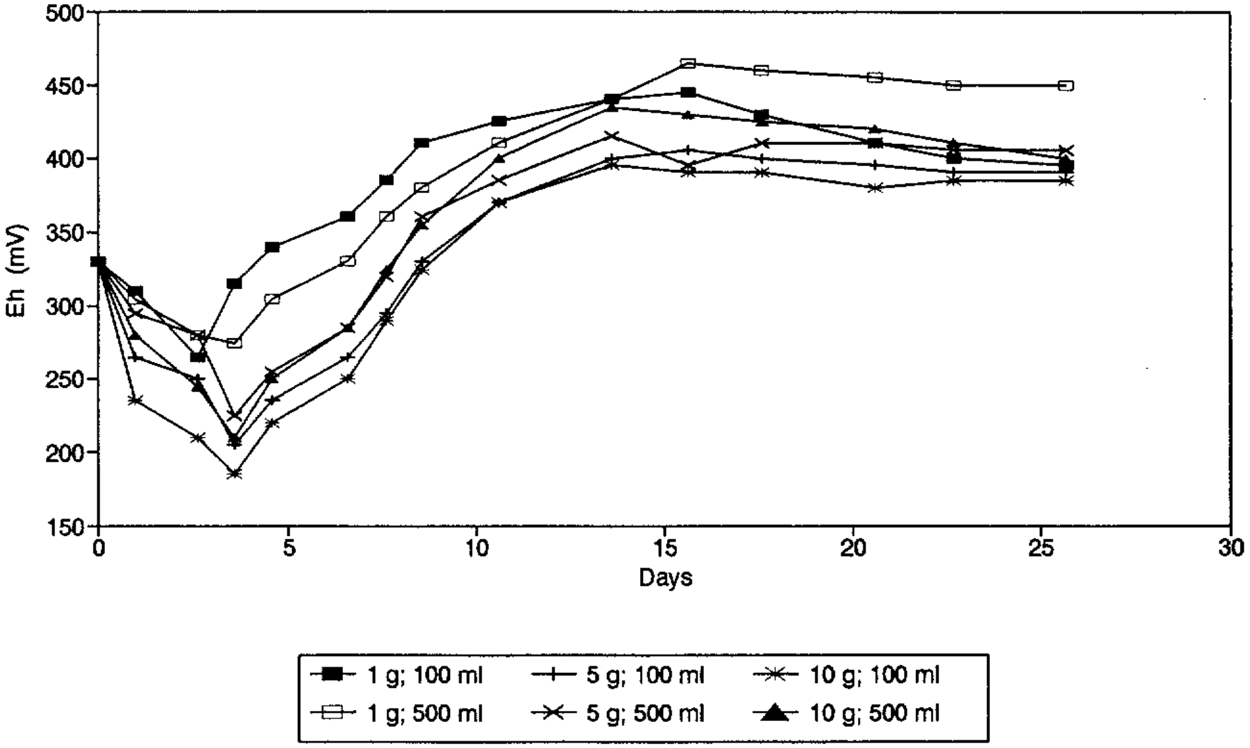


Fig.6d: Phosphate Sand Experiment - Eh
without agitation

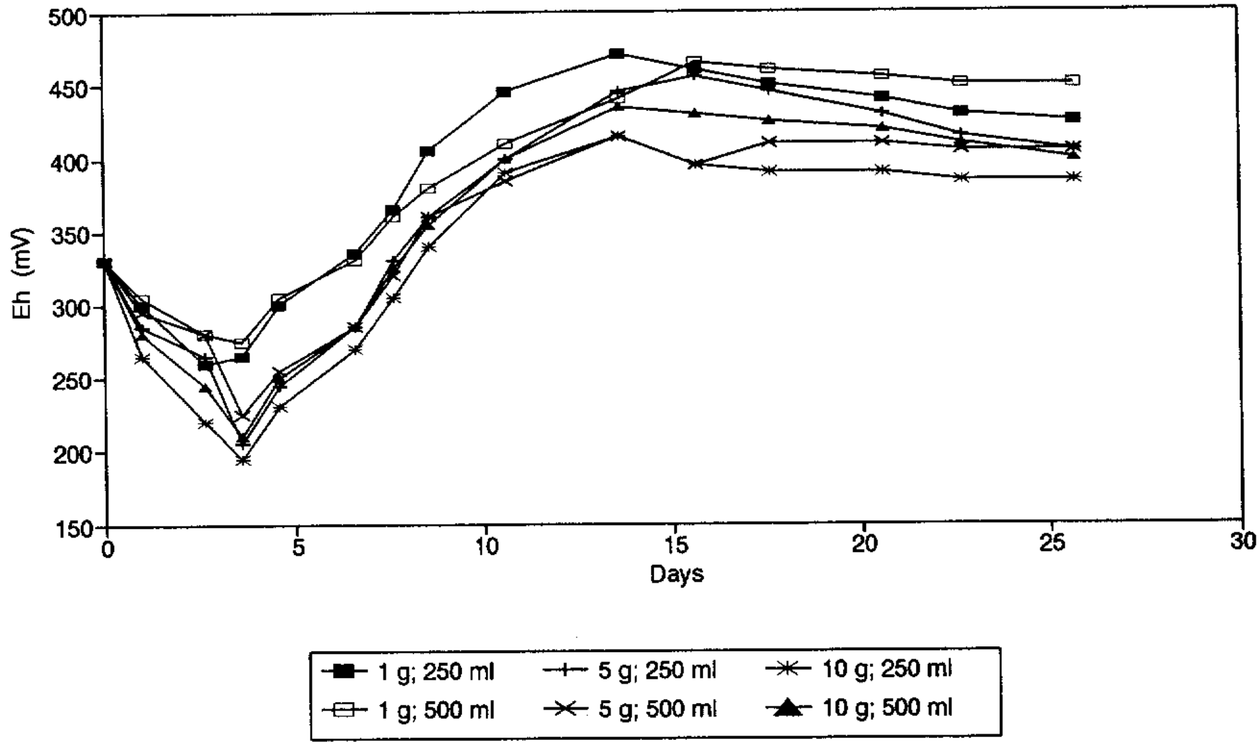


Fig.7a: Phosphate Sand Experiment - pH with agitation

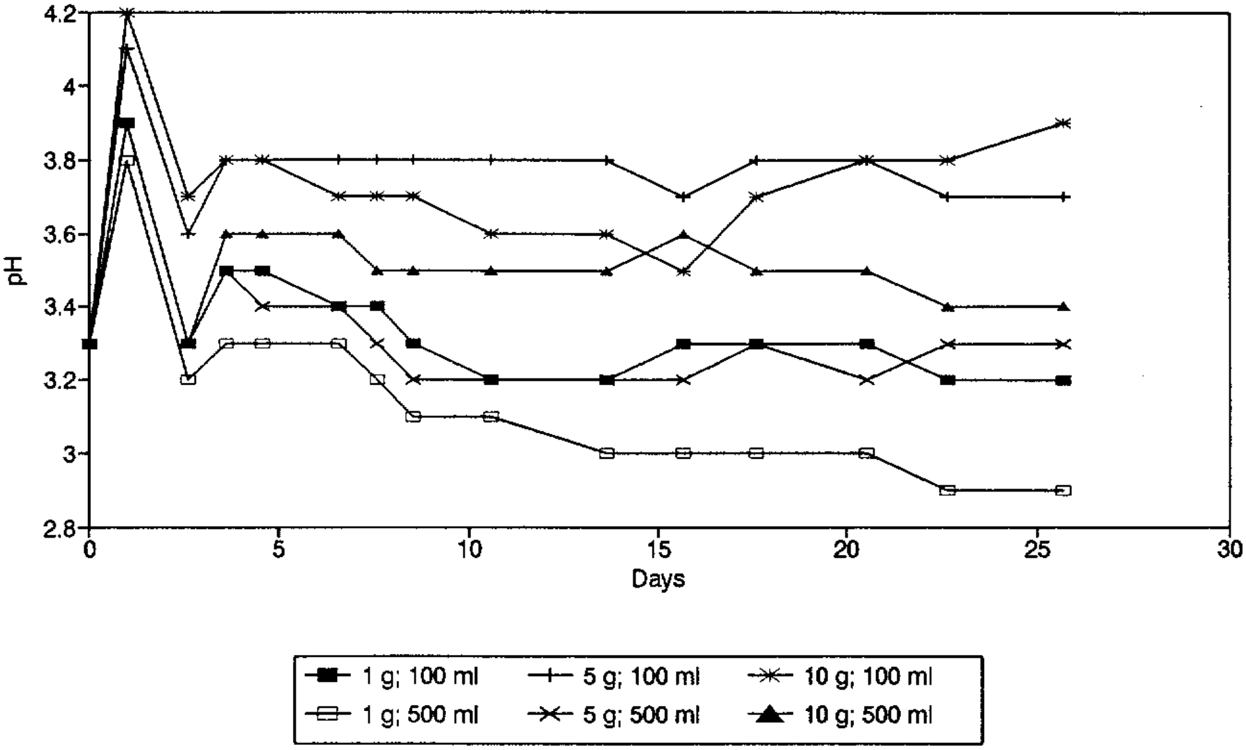


Fig.7b: Phosphate Sand Experiment - pH with agitation

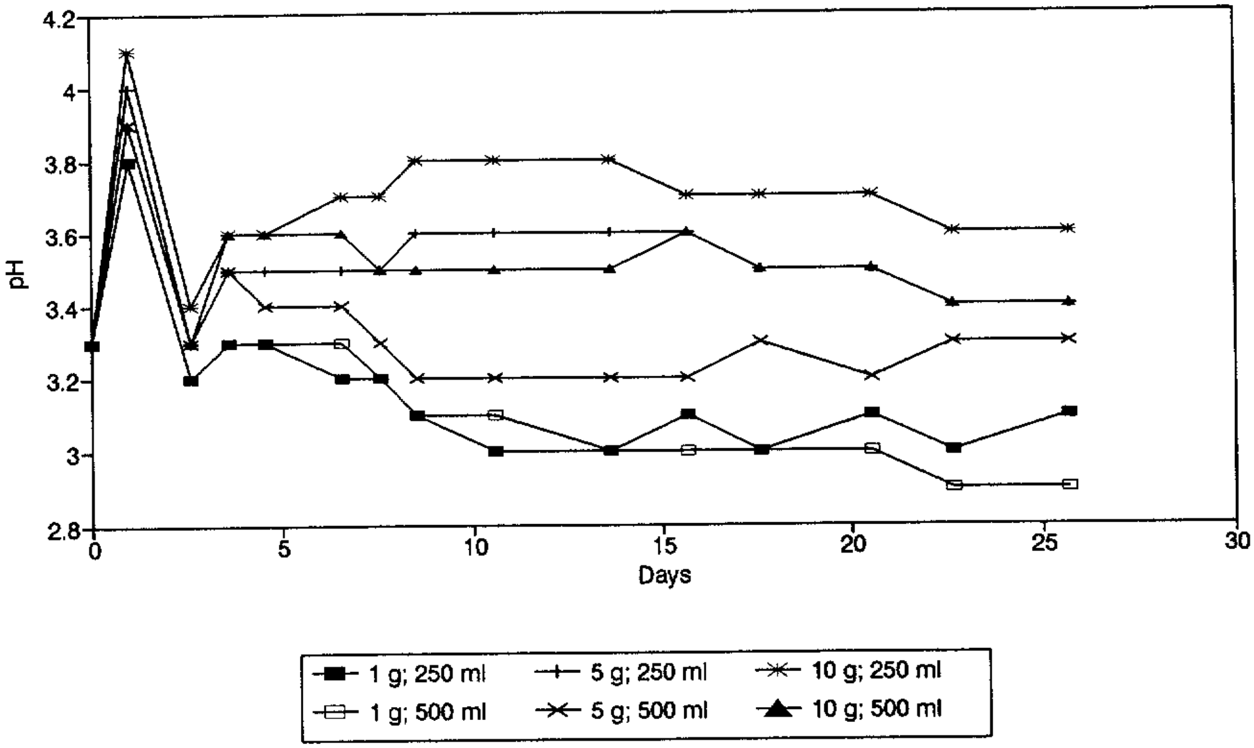


Fig.7c: Phosphate Sand Experiment - pH without agitation

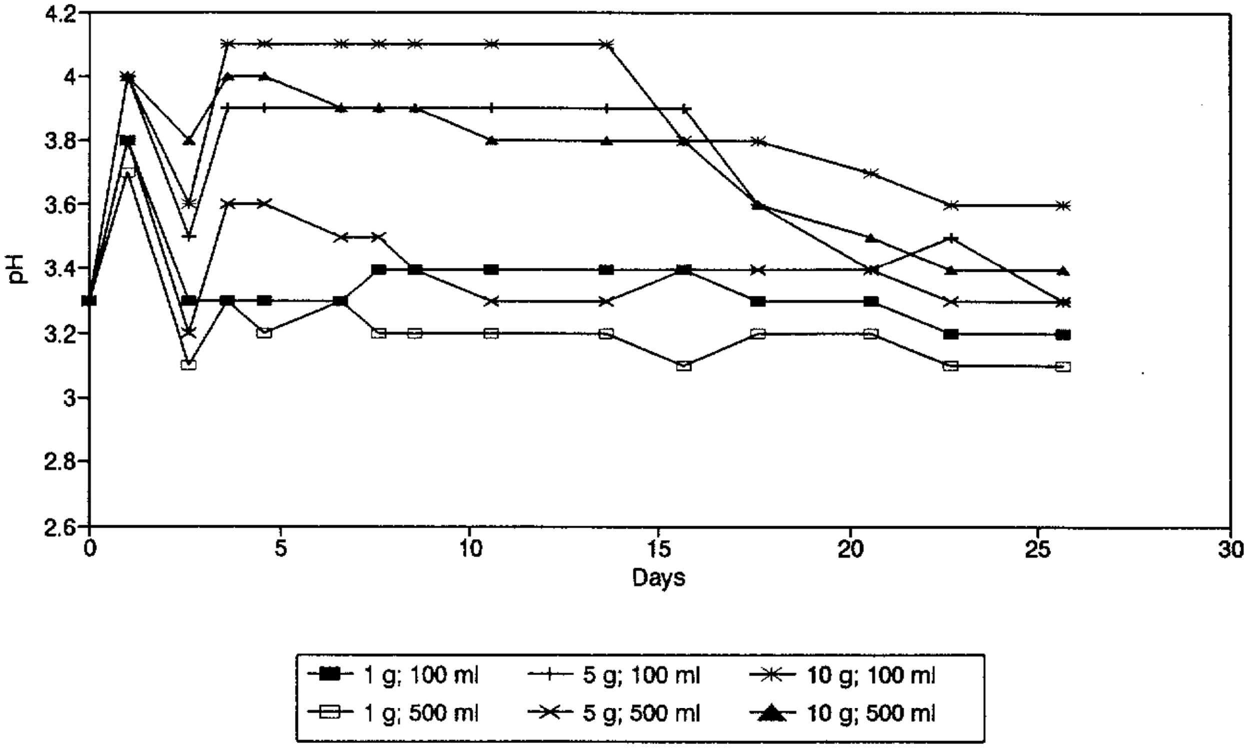


Fig.7d: Phosphate Sand Experiment - pH without agitation

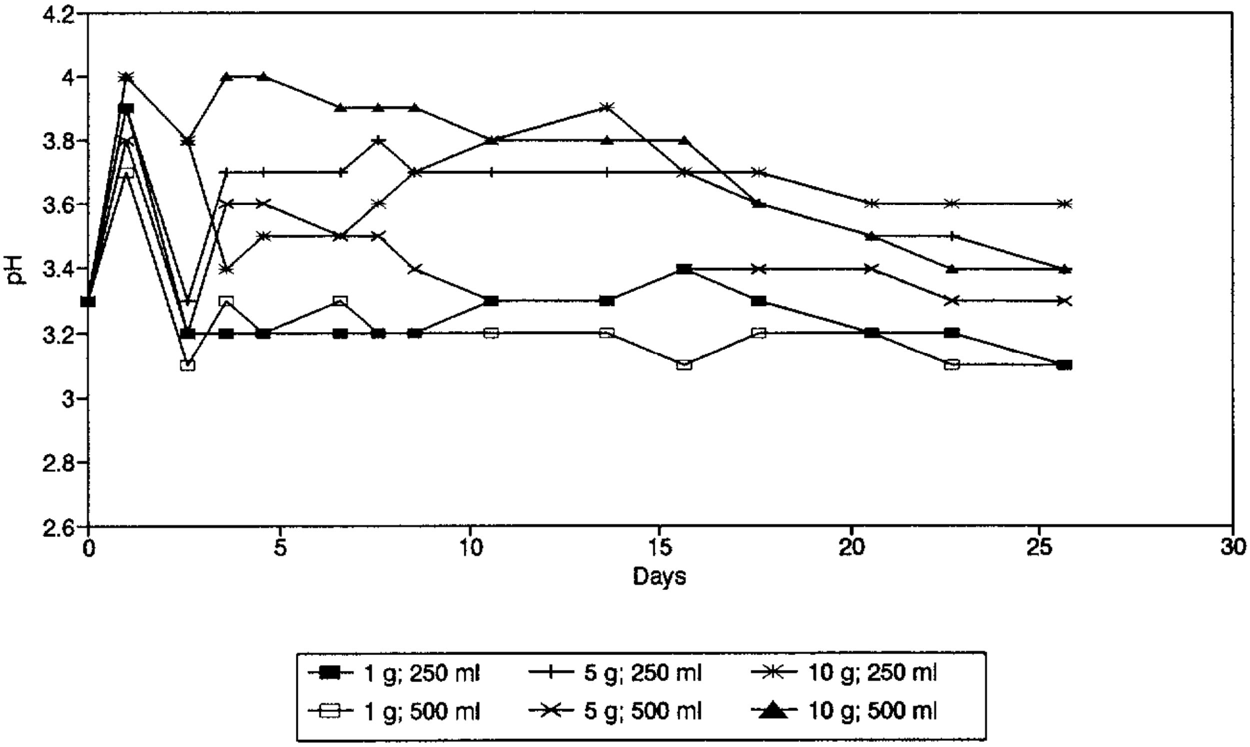
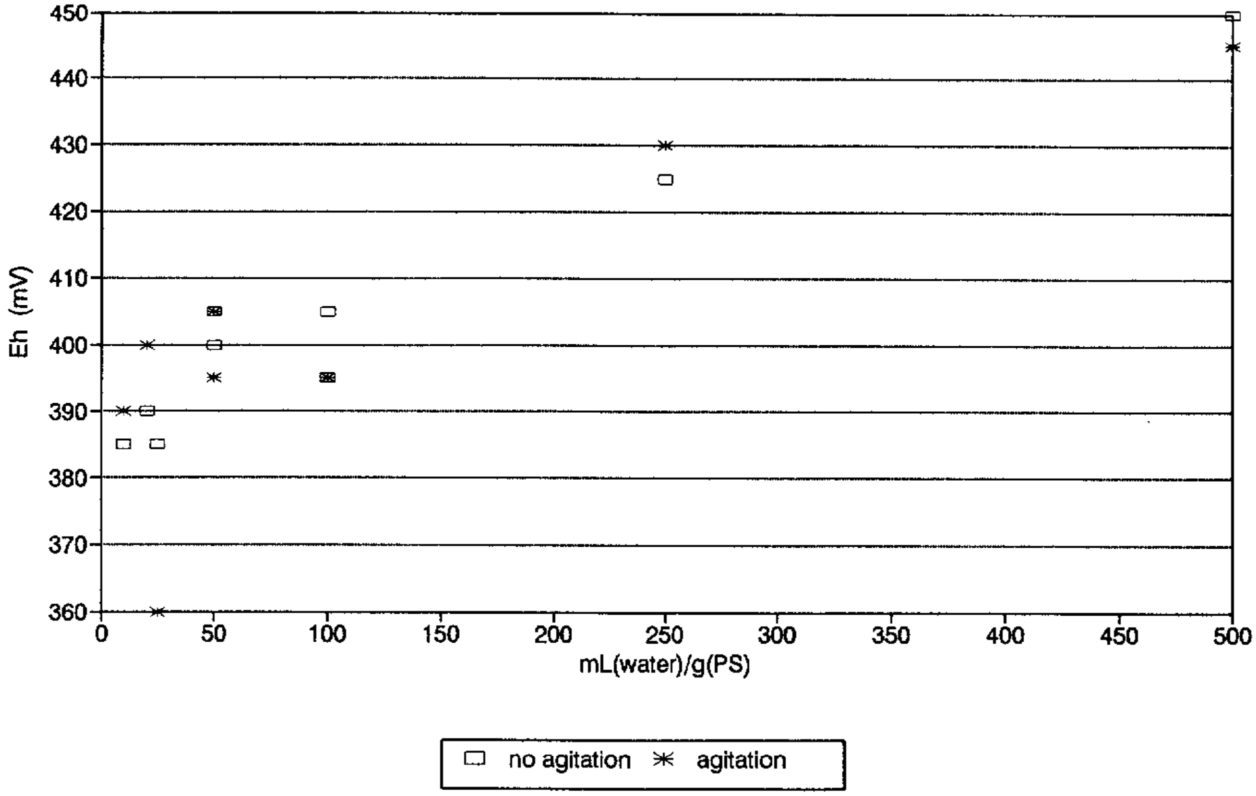


Fig.8: Phosphate Experiment Summary-Eh



Unfortunately, no control, i.e. treatments with no phosphate sand added, was included in the experimental set-up. However, since the decrease in pH is more pronounced in the agitated treatments than in the non-agitated treatments, it is suggested that the process water from the plant discharge used in the experiment was not completely oxidized at the start of the experiment. Over the course of the experiment, further hydrolysis of either iron and aluminium may have taken place, such that the full effect of phosphate sand addition is not evident from the measurements.

Eh and pH Changes: Within the first two days of the experiment, the pH increased in all treatments, while the Eh decreased in all treatments over the first four days. However, pH decreased by day 2 or 3 of the experiment and, in some treatments, dropped to values lower than the original measurement. In contrast, Eh began to gradually increase, starting on day 3 or 4, over the next 10 days reaching values much higher than at the start of the experiment. These Eh and pH trends have not been observed in any of the phosphate sand experiments carried out by Boojum to date. However, the results of the PHREEQE runs, simulating precipitate formation, suggest that pH changes may take place resembling the results obtained in the experiment.

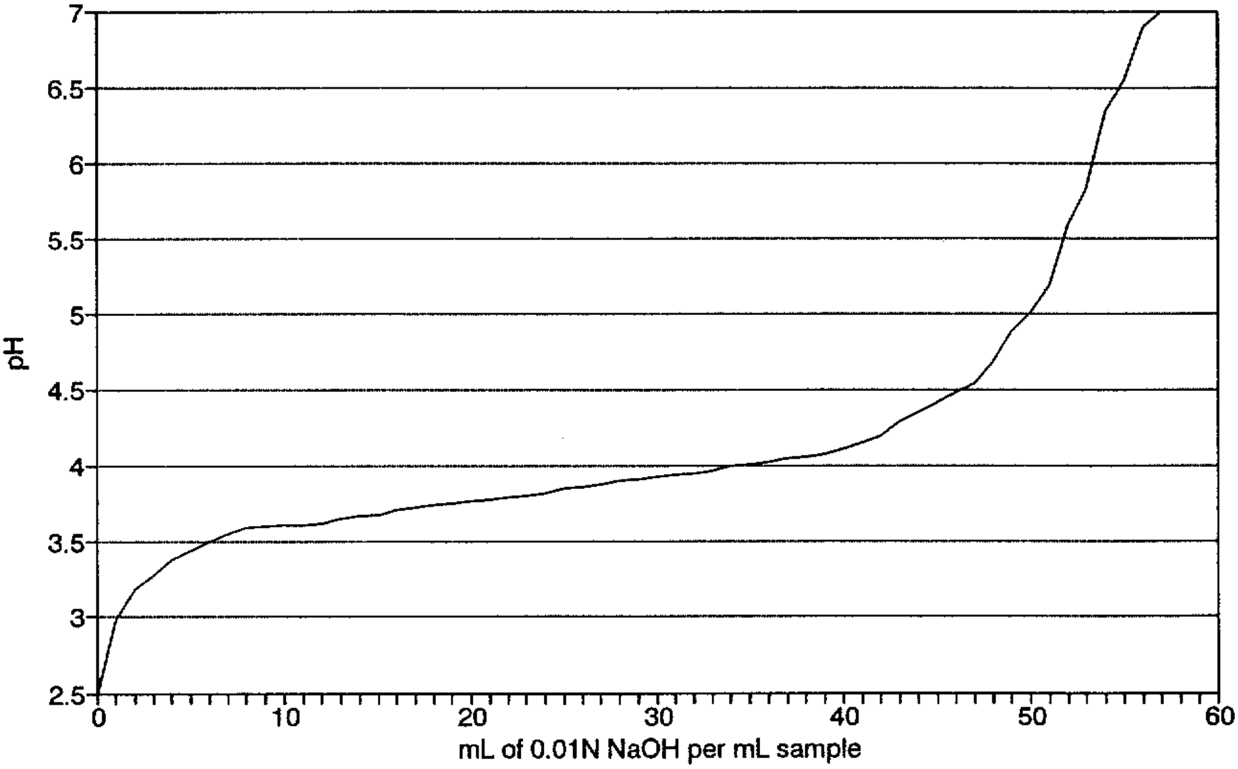
The observed pH decreases in some treatments, and the increase in Eh in all treatments suggest that plant process water was reactive at the start of the experiment, and that reactions other than those due to addition of phosphate sand were occurring. As no control was set up, clear differentiation of the two origins of pH and Eh changes cannot be performed.

Agitation: Eh and pH values for agitated treatment were similar to non-agitated treatments. The final pH of the 10 $mL.g^{-1}$ treatment is slightly higher (pH = 3.9), and the 500 $mL.g^{-1}$ treatment is slightly lower (pH = 2.9) in the agitated set-up than in the non- agitated set-up (Figure 7). With agitation, more surface area of the phosphate rock is exposed to solution, promoting dissolution of phosphate. In non-agitated treatments, the decreasing pH trend is more gradual than in the agitated treatments. However, it is still difficult to explain the dramatic rise and fall of pH values in the first days of experiment. The overall higher Eh values in the agitated solutions is likely due to better oxygenation, and subsequently more complete oxidation of compounds in the process water.

Conclusions: The experimental results, although limited to pH and Eh, overall indicate significant changes took place in the solutions. The process water:phosphate sand ratios in the set-up could have induced precipitation of a significant portion of the aluminium, the original intent of adding phosphate sand. It is suggested that titrations of the supernatant in the treatments are performed. The shape of the titration curves will indicate whether chemical analyses are warranted for, at least, the elements Al, Fe and P.

The wet volume, dry weight and wet density of sludge produced in each treatment should be determined, along with the settling characteristics of the sludge. This wet density can be compared to sludges generated by lime addition, in order to determine whether phosphate sand induces formation of denser sludge. A titration of process water with 0.25 N NaOH (Figure 9), performed by Kennecott staff, yielded 670 mL of sludge per litre of water. Given this high sludge volume per litre of process water, storage/disposal of the sludges volume will be overall problematic, especially when the volume of water to be treated is large.

Fig.9: Eastside Collection Reservoir Acidity Titration (Kennecott data)



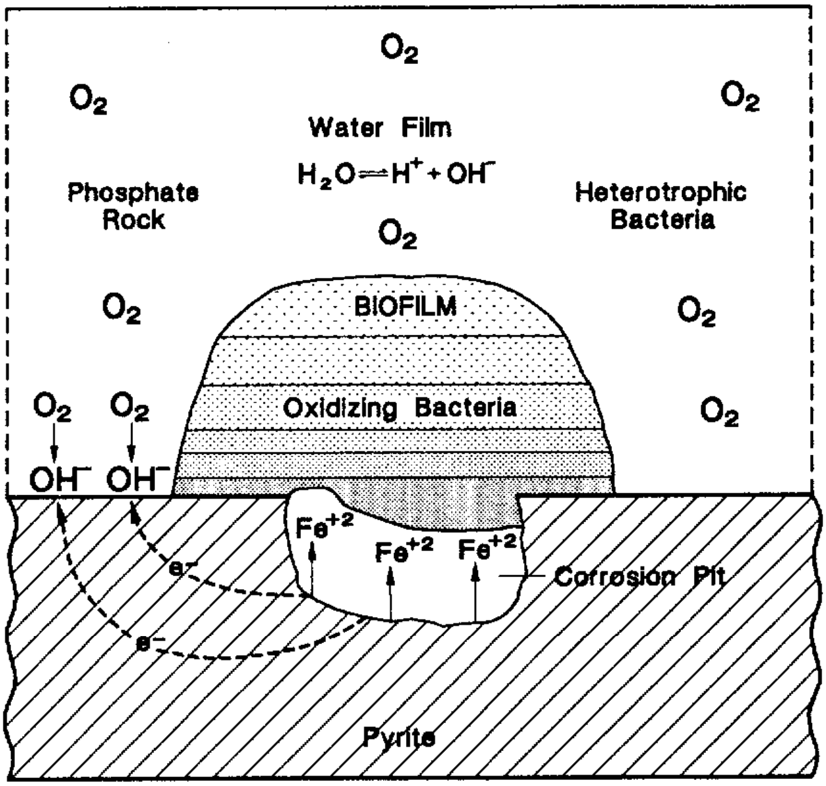
It is suspected that the sludge volume per litre of water treated by phosphate sand might be more reasonable than that induced by lime. It is recommended that a flow-through experiment is set up, from which design parameters for precipitation formation and precipitation ponds can be derived. In Appendix B1, details are given for such an experiment, which has been used successfully for the same purpose with other examples of acid mine drainage. If Kennecott process water is treated with phosphate sand utilizing the same methodology, the results obtained will have a broader basis from which they can be interpreted.

1.1.b The feasibility to use phosphate rock as a means to inhibit leaching of waste rock, through formation of corrosion protective precipitates within the waste rock pile and on pyrite material surfaces.

Leaching of waste rock for the recovery of metals is brought about by both microbially and chemically-catalyzed reactions. Once a waste rock pile no longer produces leach solutions with economic values of metals, then the acidic leach water, containing contaminants and requiring treatment, becomes an environmental problem.

Decommissioning waste rock piles which have previously served to generate leachates of economic value requires the reversal of a natural process. In Schematic 1, the conditions at the pyrite surface are depicted. Acid is generated in corrosion pits initially created by weathering, which then provide a habitat for oxidizing bacteria. Oxidizing bacteria require molecular oxygen dissolved in water or present in air. It has been proposed that inhibition of the acid generation in the corrosion pit can only be brought about if conditions in the pits are altered, such as by accumulation of secondary precipitates with subsequent reduction in oxygen transport to the pit.

Waste rock leach piles have been reported to stop producing acid. One example is the Gibraltar waste rock pile in British Columbia, Canada. Rocks from within the pile were recovered and found to be encrusted with secondary precipitates. Experiments at



Modified after: Little, B.J., P.A. Wagner, W.G. Characklis, W. Lee (1990). Microbial Corrosion. In: W.G. Characklis and K.C. Marshall (eds) Biofilms. John Wiley & Sons, N.Y., page 655.

Schematic 1: Chemical and microbial conditions at pyrite surface during oxidation.

Boojum have been run for 12 months where rocks of different ages are exposed to weathering with different applications of phosphate sand. The results obtained to date are given in Appendix B2. In the seventy-litre drums, the phosphate sand additions have shown to be effective in reducing the amount of acid generated.

Findings from other experiments, where phosphate sand has been applied to coal waste, indicate that phosphate sand inhibits acid generation, and that the inhibitory action is a function of the surface area of the waste material to be treated.

Before design of a experiment can be recommended, the characteristics of the Kennecott waste rock has to be reviewed. The objective of this review is to identify and quantify, as accurately as possible, minerals in the rock which might be subject to dissolution, due to deliberate or natural leaching in the waste rock pile.

In all likelihood, expertise resides within the Kennecott operation which could provide this information in more detail. However, it was not available to Boojum for the experimental design. Instead, the waste rock characteristics will be described based on published information and one internal report provided by Kennecott, listed in Appendix A. A brief review of the information on the waste rock is provided in Appendix B4.

From the information at hand, the waste rock inventory in the Kennecott operation is comprised of at least 5 different types of waste rock. It can be expected that sedimentary rock, rock with insignificant mineralisation, or rock which has been heap-leached, would all likely react differently to phosphate sand applications. Leachable waste rock is considered to correspond generally to the moderate or weak mineralization zones. The concentration of carbonate in these moderate or weak mineralization zones is reported at 0.9 % to 2.3 %. Carbonate provides some natural acid neutralization capacity. In addition to carbonates in the waste rock, chlorite can be considered as a further acid consuming mineral. Igneous rock is reported by Peters (1966) to contain about 4.7 % to 6.5 % chlorite, which is highly reactive and would naturally inhibit acid generation.

Hence, it is suspected that the phosphate sand requirement by the waste rock piles is heterogeneous, depending on the specific areas within the piles and that, in some regions, no phosphate sand is required.

The pyrite content is generally not very high, with only 3% to 4 %. Most of the pyrite may have already leached and therefore, the waste rock material might no longer be acid-generating. The water characteristics of Lark and Saints Rest, neutral waters containing only calcium, magnesium and sulphate at high concentrations may be evidence of low acid generation rates.

The feasibility of using phosphate rock to inhibit leaching in Kennecott waste rock material requires specific information regarding the waste rock types for which this application is considered. It is recommended that samples of this material are collected for investigation, using SEM and EDX, of the nature of the corrosion pits.

1.1.c Design experimental approach to evaluate feasibility of these and other approaches to reducing meteoric and leachate infiltration.

From the basic mineralogical considerations, the design of a suitable phosphate rock experiment using Kennecott waste rock would be augmented with more site-specific information at hand. Since this experiment should be carried out in the field, and should be designed such that the experimental results are potentially applicable during scale-up to the waste rock pile, considerably more input from Kennecott is required during experimental design.

Some design considerations are presented for discussion. These considerations are related to scale-up of the proposed experiment, as well as to connection of the ongoing experiment with base metal waste rock at the Boojum Research Limited facility to a potential design.

The experimental design of the base metal waste rock experiment at the Boojum facility was based on the following considerations for scale-up of the experimental results to actual application of phosphate sand over an acid-generating waste rock pile:

- The very top of each lift is compacted due to heavy hauling. This will keep most of phosphate sand on the surface.
- A 5 cm-thick layer of phosphate sand would be placed on top of each lift during built-up. This will ameliorate AMD from above and prevent AMD generation in the lifts below. AMD will not be generated under the secondary minerals formed on the surface of rocks.

- The thicknesses of lifts are around 4 m, and the void spaces occupy approximately 40% of bulk waste rock volume.

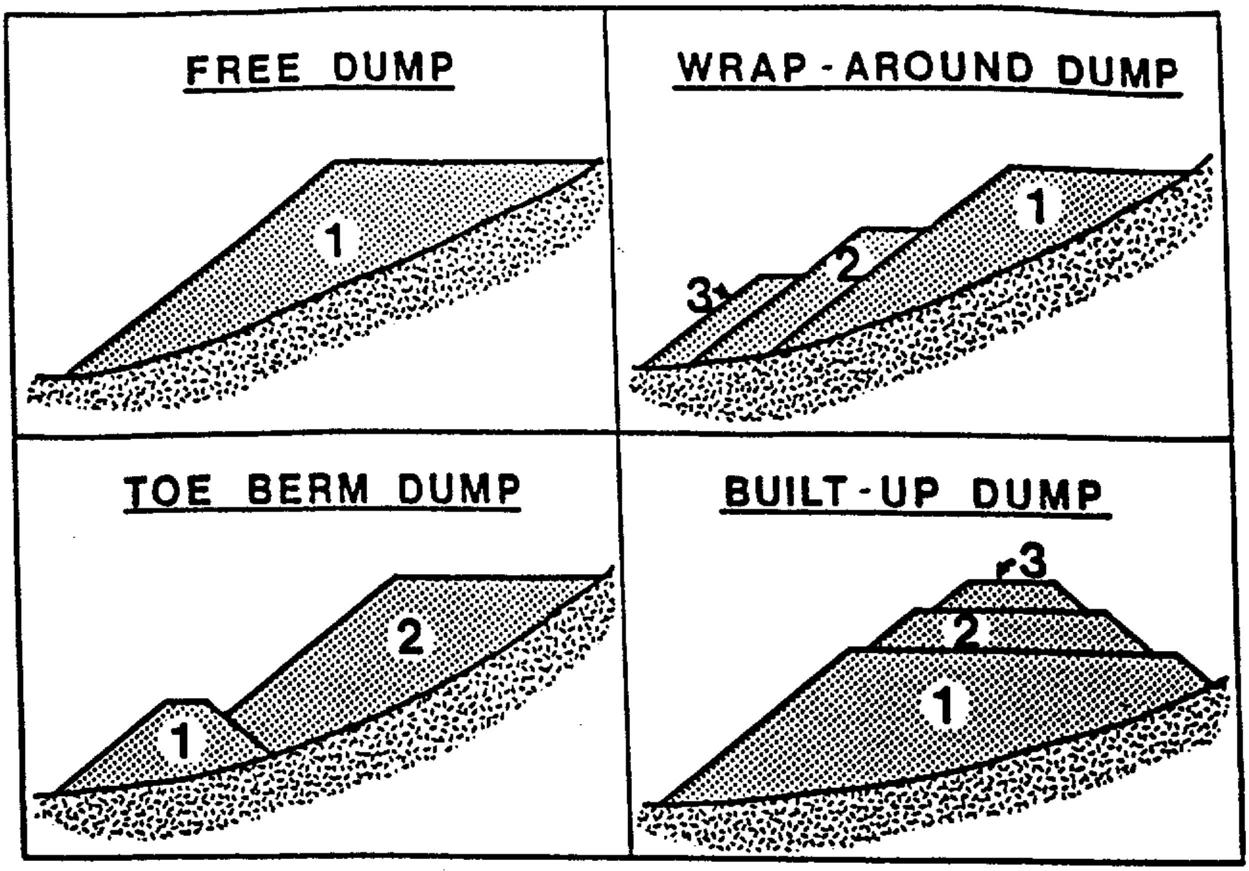
This configuration is being tested on the Boojum premises in the waste rock experiment. Although the phosphate sand application rate in the experiment is considered high, the overall objective was to test whether it is possible to create conditions necessary for the formation of secondary minerals.

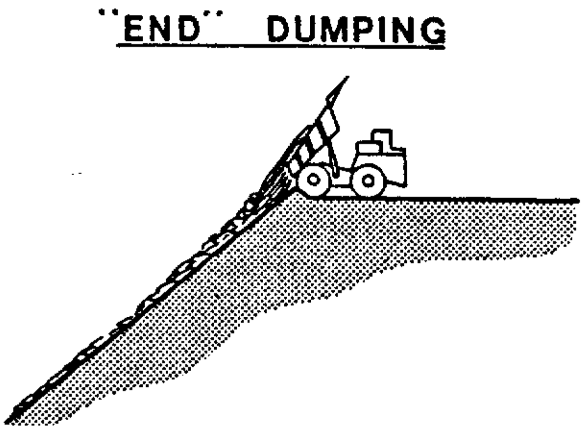
The experimental application rate translates to 3.6 L of phosphate sand per drum, or 1.25% of phosphate sand per bulk volume of waste rock. It is suggested to test, in a complementary field trial, the rate of 0.75% phosphate per bulk volume of waste rock.

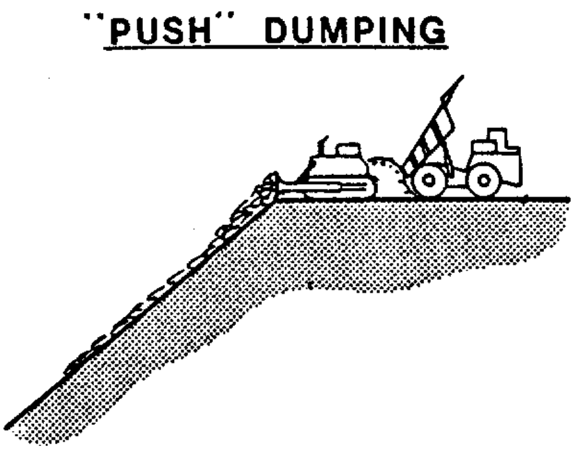
Typical dumping practices

Four basic dump types can be constructed on valley slopes that generally range from 10 to 30 degrees: free dump; wrap-around dump; toe-berm dump; and formed or "built-up dump" (See Schematic 2 for numbers indicating sequence of construction). Two dumping procedures used in dump construction are end dumping and push dumping. The former ensures rock segregation down the dump face, because the momentum developed by the rocks sliding down the truck box carries the largest pieces to the dump bottom. In the later method, large rocks can become "hung-up" within the finer material at the top of the dump.

For purposes of phosphate sand applications, it is proposed to build three test dumps: the wrap-around dump, the toe-berm dump, and the built-up dump, and to test both dumping techniques: end and push dumping. Between dump sections, the phosphate sand layers would be inserted at a rate of 0.75% of underlying rocks volume.







Schematic 2: Four basic dump types can be constructed on valley slopes that generally range from 10 to 30 degrees.

The major form of phosphate in phosphate sand is $Ca_3(PO_4)_2$. When phosphate is added to Kennecott waste rock and process water is used in the experiment, it is suggested that, in principal, two reactions may take place:

(1) phosphate ions dissolve into the water, and hydrolyses as:

$$PO_4^{-3} + H_2O = HPO_4^{-2} + OH^-$$
$$HPO_4^{-2} + H_2O = H_2PO_4^- + OH^-$$
$$H_2PO_4^- + H_2O = H_3PO_4 + OH^-$$

The increased OH^- ion concentration in the solution might substitute SO_4^{-2} ions in the complex. Should this be the case, the $Al(OH)SO_4$ complex charge would become neutral and would result in an Al precipitate as $Al(OH)SO_4$.

(2) PO_4^{-3}, HPO_4^{-2} or $H_2PO_4^-$ ions may compete with SO_4^{-2} ion, to form a complex with Al, which in turn will finally precipitate as aluminium phosphate.

Solubility of both $Al(OH)SO_4$ and $AlPO_4$ drops when pH increases. Since in high pH solutions $[OH^-]$ and ionized $[PO_4^{-3}]$ increase, the solubility of $Al(OH)SO_4$ and $AlPO_4$ will be reduced. Values of $[Al^{+3}]$, calculated from the equilibrium value of $Al(OH)SO_4$ and mean concentration of $[SO_4^{-2}]$ in LEAWA water (56 g/L), are 810 g/L at pH 2.7, 10 g/L at pH 3.6, 29 g/L at pH 4.1 and 0.4 g/L at pH 6. Aluminum phosphate, $AlPO_4$, is much less soluble than the hydroxysulphate. Values of $[Al^{+3}]$ calculated with 0.5 g/L $Ca_3(PO_4)_2$ in solution are 0.027 g/L at pH 2.7, 3.3×10^{-4} g/L at pH 3.6, 2.8×10^{-5} g/L at pH 4.1 and $3.3 \times 1O^{-10}$ g.L at pH 6 (activity effect is not considered in the calculations).

Given the differences which can be expected, due to the different mineralization of the waste rock, its history and, fundamentally, two different types of process waters, the design for the phosphate rock experiment has to be selected for the appropriate waste rock as well as the process water to be used in the experiment. It has to be applicable to Kennecott operations and waste rock management plans, which are unknown to Boojum. This is important since, depending on the type of process water used in the experiment, differentiated with respect to its position of the solubility constant line for aluminium (demonstrated in Figure 3), different precipitates may be formed.

In addition to the type of waste rock and process water to be used, the detailed design of the experiment should consider, for the general applicability of the results, the waste rock site topography and a overall water balance of the waste rock pile. Selection of the most suitable placement method must be made based on the cost of placement, technical feasibility and the expected impact on the dump slope stability. In addition, waste rock properties, such as 1) rock gradation, which control the hydraulic conductivity of the waste, 2) void ratio, 3) extent of homogeneity and presence of relatively fine gradation zones, 4) extent of water ponding inside the dump, and 5) water turnover in existing dumps, would be very useful, and at least require consideration prior to detailed design of a test.

2.0 ASSESS THE POTENTIAL OF THE MIXED TAILINGS AREA FOR DEVELOPMENT INTO A TREATMENT WETLAND/BIOLOGICAL POLISHING SYSTEM WHICH HAS TREATMENT CAPACITY FOR STORM WATER WITH ELEVATED SULPHATE AND METAL CONTENTS

The Mixed Tailings Area is comprised of approximately 22 acres of dry land, which is considered suitable for the development of a wetland system. A conceptual design was provided by the Kennecott Plant Projects Group (enclosed in the map pocket of the report).

To assist the assessment, the following assumptions were defined by Kennecott as follows:

1) Construction will follow the natural grade as much as possible, and will be in compliance with the dam safety regulations.

2) Water supply is engineered from various possible sources, i.e. quantity and quality of water are controlled. There is no danger of flooding.

3) Water supply and discharge will be seasonal to a large extent; main inflow will be contaminated storm water (snow melt from February through the end of May); main outflow will be used for agricultural irrigation (April through October). There is potential to store storm water and treated water in additional reservoirs in order to provide sufficient retention time for water treatment in the wetland system.

Along with these assumptions, ten more questions specific to the design of such a system were posed. These are given in the Appendix A (Document 10). It was evident from these questions that the perception of the capacity of wetlands as treatment system is more advanced than the actual current state of the art of this technology.

"Wetland" water treatment or passive treatment systems: A literature review on passive treatment systems carried out by Boojum Research is included in Appendix C. The "wetland" water treatment processes are briefly summarized below.

Passive waste water treatment utilizes natural purification processes which, when maintained in a natural balance, produce reusable water. In passive treatment, the major chemical forces which assist in purification are oxidation, reduction, coagulation, adsorption, absorption and precipitation.

Biological forces, dominated by microbial activity, mediate many chemical water purification actions. Physical forces of water purification are gravity, light, aeration, dilution and wind-driven turnover. Wetlands and lakes represent ecosystems in which these processes take place.

Water treatment plants for the removal of specific contaminants are designed to treat a certain quantity of contaminant loading. The treatment process requires that chemical reactions take place at defined rates, and physical forces are used to remove the resultant precipitate.

Energy, as light, is required to drive the passive treatment process, and is converted to a form available to organisms via photosynthesis.

In a wetland, the plants and sediment provide the physical structure of the treatment system. The sediment provides the "vessel" in which the microbes mediate the chemical reactions. The reactions change the form of the contaminant such that it may leave the wetland as a gas, or form particulate matter which will settle to the sediment. Contaminants may be removed from water by ion-exchange, complexation or precipitation on algal/plant/bacterial surfaces (biosorption) or by uptake into these organisms.

Within sediments, precipitates of metals may be transformed to less soluble forms through biomineralization, a process where microbes assist in the formation of minerals such as pyrite.

The forms of inorganic pollutants are changed in the sediment through oxidation/ reduction reactions, which are mediated by microbes. Micro-organisms utilize sulphate and convert it through reduction to sulphide using the organic acids which are produced by the decomposition of plant or organic matter. The purification step for inorganic contaminants is therefore the microbially-mediated change in the chemical form which then, depending on the chemical conditions of the water, either escapes as a gas (bog gas) or precipitates as a metal sulphide.

Organic pollutants can be used as a food source in microbial decomposition, which may result in the generation of organic acids. These act as flocculants, coagulants or complexing reagents. They assist in forming particulate matter, which either settles to the sediment or adheres to surfaces of the wetland plants.

The rates at which these microbial and chemical water purification processes take place in the wetland determine the contaminant loading which can effectively be treated. Therefore, to determine the design parameter for a pilot system, which resembles a wetland, the microbial reaction rates and the chemical conditions under which they take place, and are sustained, are the essential components of the design of any system.

The Mixed Tails Area: Considerations, given in the previous sections, regarding the chemistry of the leach or storm water to be treated, and the precipitation steps required, suggest that, at this stage, it would be premature to design a passive system, since insufficient design criteria specific to the Kennecott water are available.

However, there is clearly the potential for such a passive treatment system in the Mixed Tails Area. Such a system should be implemented in steps, after preliminary work is carried out to derive specific design criteria for the Kennecott leach and storm water.

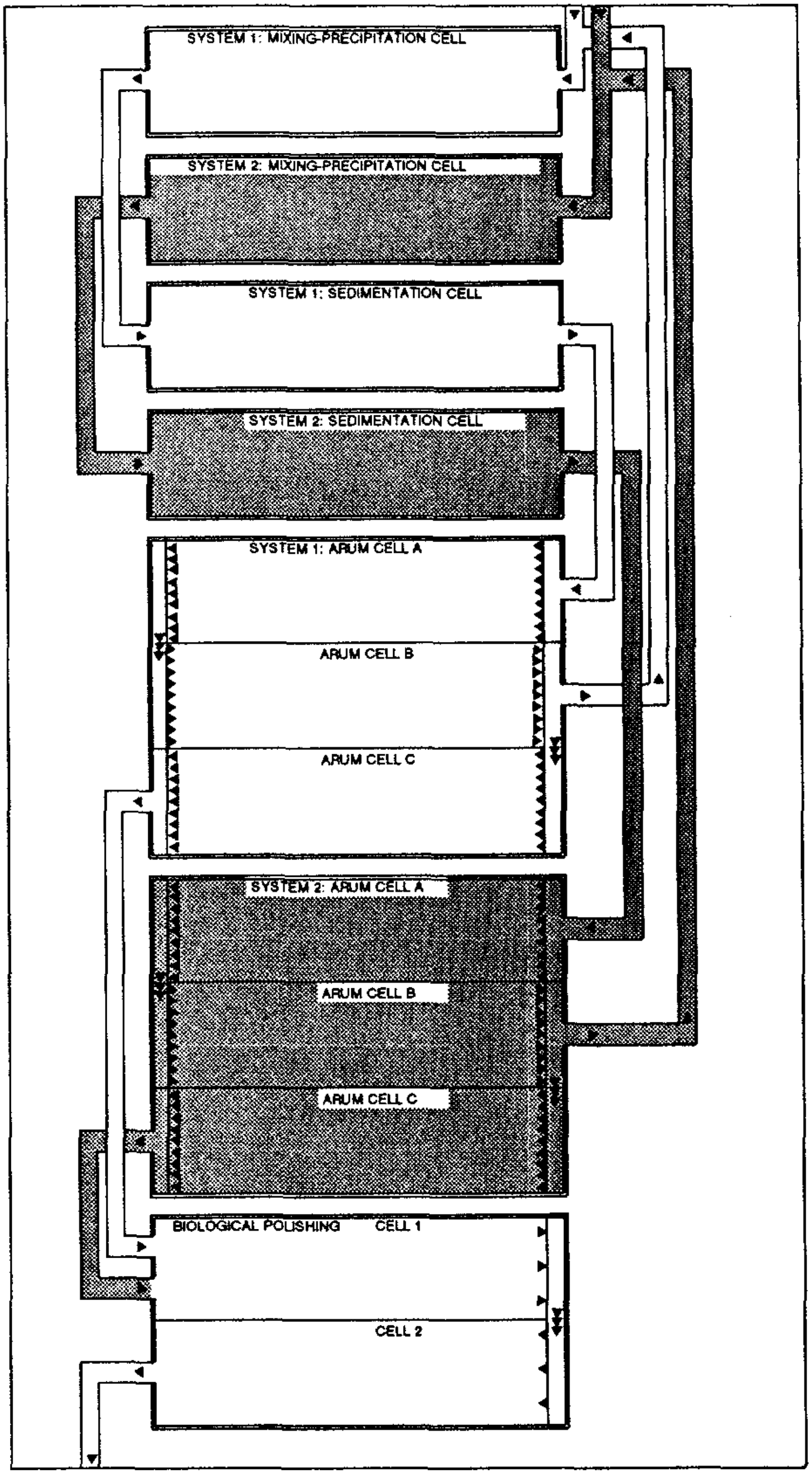
Design considerations: The waste water treatment train is envisaged as outlined in Schematic 3, derived from the dimensions given by the conceptual map from Kennecott (see Map Pocket).

Currently, the design of microbially-based treatment systems for AMD range from cost-intensive, process-controlled industrial bioreactors, to simply diverting AMD into natural wetlands. Industrial bioreactors are proving to work, while the minimal-design approach, such as AMD diversion to natural wetlands, anoxic limestone drains and constructed wetlands have had mixed results, as detailed in the literature review.

The ARUM (Acid Reduction Using Microbiology) has been developed by Boojum for the treatment of acid mine drainage. Through appropriate organic substrate additions to a sediment, or constructing a sediment anew, sediment-bound microbial ecosystems are encouraged to establish and subsequently function as the passive treatment system. The process is generally considered for decommissioning of mine sites, when natural hydrological conditions exist. A detailed summary report on a four year project on ARUM was provided earlier during this contract to Kennecott under separate cover.

Although the ARUM process has been designed to operate passively in a decommissioning scenario, with some flow control and the option to recycle or retreat, the process might be used as a flow-through system, as would be required for the Mixed Tails Area.

Schematic 3: System Layout



Uncontrollable parameters in a passive field system include (as opposed to [*aot*] bioreactor process control):

- ambient temperature and light (*aot* heating, cooling in chamber).
- dilution by precipitation/concentration by evapotranspiration (*aot* closed system).
- ecosystem-controlled concentrations of specific organic substrates (*aot* monitored and metered organic chemical addition).
- micro-environment and concentration gradient development (*aot* stirred/raked/agitated reactors).

The design of a biological treatment system which can operate with some process control should be designed to take the following parameters into account:

- Fixed length, width, depth and volume of cells comprising system.
- Fixed water levels.
- Defined range of inflow and outflow volumes.
- Defined range of input AMD water chemistry.
- Some selectivity in AMD strength through dilution and solution recycle.
- Defined range of retention times.
- Defined range of organic carbon production by aquatic macrophytes.
- Defined range of microbially-mediated process rates.

Conceptual overview of the system: Presently, two systems, comprised of Stages 1 through 3 operating in parallel, are envisaged as indicated by the shaded areas in Schematic 3. A single system for the fourth stage, Biological Polishing, will serve both parallel systems.

Each system will be operated on a six month flow-through, six month batch schedule in alternating six month periods. For instance, while System 1 is operating in flow-through mode for six months between May 1 and November 1 (ice-free season), System 2 will be operating over this same period in a batch mode. Between November 1 and May 1, System 1 is operating in batch mode, while System 2 is in flow-through mode.

System 1 will have been in batch mode for 6 months by May 1 each year. The cells will contain water, treated over the six month period and ready for discharge. Higher rates of bacterial alkalinity generation and sulphate reduction, two major components of the water quality improvement process, can be expected during the growing (ice-free) season, compared to winter months. System 1 will begin discharging treated water, and will receive raw AMD on a flow-through basis during the ice free months.

During these six months, the volume of System 1 will be refilled with raw AMD at least once. By fall, with decreasing temperatures, System 1's performance will steeply decline. The system is then switched to batch mode, and the volume of System 1 is treated at a slower rate over the six winter months.

Meanwhile, System 2 has been in batch mode for 6 months over the ice-free season. By November 1, System 2 will contained a batch of treated water. Raw AMD will enter System 2, displacing the batch of treated water over the winter period. By spring, System 2's volume of treated water has been replaced by a volume of new AMD. On May 1, System 2 switches to batch mode, and over the summer months, the ARUM system can recover and treat the batch of AMD.

It is possible that System 1 will typically treat more AMD than System 2, since System 1 receives fresh AMD during summer months, the period when the microbial population is more active, and hence more resilient.

The proposed design and operation of two parallel systems hold several advantages over operation of a single system, as outlined below:

a) The treatment system can be operated in a continuous mode, while both Systems 1 and 2 can both be operated in alternating batch and flow through modes.

b) The batch mode provides a period for the ARUM microbial community to recover between periods of introducing new AMD.

c) The performance of the overall system will be determined in the first year(s) of operation. During this time, the possibility exists that one of the ARUM systems may be inadvertently overloaded with acidity, and the ARUM microbial population damaged and de-activated. A parallel system design would allow for this system to recover, while testing using the second system continues.

d) With refinement of Stage 1 and Stage 2 processes, with subsequent improved raw AMD water quality entering the ARUM stage, it may be possible to operate both Systems 1 and 2 at higher flow-through, thereby increasing the overall system's treatment capacity.

Passive treatment stages: Conceptually, four treatment steps or stages are envisaged. Because process water will, in all likelihood, contain high concentrations of dissolved aluminum, the first stage must be the precipitation of a large fraction of this aluminum in an area upstream from the microbial treatment stage, using a passive technique if possible. In the second stage, these precipitates will be sedimented in settling ponds. Otherwise, upon addition of alkalinity to this solution in the microbial stage, large quantities of sludge containing aluminum (Figure 9) will form, coating the ARUM sediments and reducing ARUM treatment effectiveness in Stage 3. The final stage is Biological Polishing and filtration of suspended solids.

In the event that the process water-phosphate sand experiment solutions are analyzed, and that adequate aluminum removal is evident from the results, it would then be sensible to proceed with further work on the chemistry and reaction rates for the phosphate sand-induced precipitation process. It should be realized that, while the bulk of aluminium has to be removed prior to the microbial treatment, complete removal is not required.

The four treatment stages are briefly described as follows:

STAGE 1: Precipitation by Phosphate Sand or Through Mixing AMD With Alkalinity-Generating Water

The acid mine drainage entering the system will likely contain very high concentrations of dissolved aluminum and sulphate. The aluminum has to be precipitated in Stage 1 Mixing Cells by the addition of alkalinity, either by treatment with phosphate sand or by addition of alkalinity-containing water.

The bulk of aluminum precipitation should be completed upstream of the ARUM stage. Treatment with phosphate sand, dilution of AMD with fresh water containing some alkalinity in the Stage 1 Mixing Cell, and/or by recycling a fraction of partially treated water from the ARUM Cells to the Stage 1 Mixing Cell, the bulk of aluminum sludge volume could be formed prior to AMD entry into the ARUM. The depth of a Mixing Cell should be 7 ft (2.1 m). Depending on the precipitation rates, it may be possible to achieve removal of aluminum sludge by sedimentation in the Stage 1 Mixing Cell.

STAGE 2: Sedimentation of Aluminum Sludge Precipitates

Following the mixing and satisfactory precipitation of the aluminum as hydroxide, phosphate and/or complex hydroxysulphate, the Stage 2 Cell has to provide the retention time and surface area for the settlement of sludge. The surface decant system will deliver process water with a low suspended solids concentration to Stage

3, the ARUM system.

The dimensions of the Sedimentation Cells will likely be similar to the Mixing Cells. Baffles will likely be required in the Sedimentation Cell in order to minimize short-circuiting and reduce wind-driven circulation of the water column to the cell bottom, and subsequent re-suspension of settled solids. By setting the cell at a fixed water level, the discharge flow rate will closely equal the inflow rate. The depth of a Sedimentation Cell should be 7 ft (2.1 m).

STAGE 3: ARUM Microbial Treatment

The third stage, ARUM microbial treatment, will employ anaerobic, microbially-mediated processes, including alkalinity generation and sulphate reduction, in order to remove acidity and precipitate metals as high-density sulphide sludges.

Each System will have three ARUM cells. The area of the cells will be similar to the Stage 1 and Stage 2 cells. However, the ARUM cells should be deep deeper (9 ft, or 2.74 m) than the Mixing or Sedimentation Cells, in order to increase the retention time in these cells on a per unit area basis.

The purpose of the ARUM stage is to provide suitable physical, bio/chemical and hydraulic conditions for maintenance of an active anaerobic microbial community in the cells' sediments. Simultaneously, the cell must be designed such that exchange of dissolved compounds between the AMD/mixture solution and the microbially-active sediments can occur. Overall, this exchange is determined by horizontal and vertical concentration gradients established in the cell.

Practically, horizontal and vertical concentration gradients in the cell are controlled by:

a) The pattern of water movement, the pattern of circulation, and the retention time of water in the cell, in conjunction with:

b) Microbially-mediated dissolution and precipitation reactions, directly affecting the form and concentration of compounds in the sediment pore water and, subsequently (via diffusion and bulk movement of solutes and gases) the form and concentrations of compounds in open solution.

The key ARUM microbial processes, including sulphate reduction, are anaerobic. Atmospheric oxygen supply to the ARUM cell should be minimized, else microbial activity will be dominated by higher Redox reactions using oxygen, nitrate, nitrite, manganese and iron. Atmospheric oxygen diffusing into the cell can be limited by installation of a floating vegetation mat, dominated by cattail, over the entire ARUM cell. The mat will both physically block oxygen transport into cell, and consume oxygen in the upper floating sediment layer.

Since ARUM microbial processes are sediment-based, the available sediment surface area should be as large as possible. By covering the ARUM cell with a floating cattail population, the effective sediment surface area can be nearly doubled.

Maintenance of an unobstructed, wide and deep path for water movement through the cell will minimize the water velocity at the upper and lower boundaries of the open water layer interfacing with the upper and lower sediment layers. The cattail cover will eliminate wind and wave-induced water circulation patterns, limiting water movement patterns to unidirectional laminar flow through the system.

Organic carbon, available nitrogen and phosphate are required for ARUM microbial activity. An initial supply of these compounds will be supplied using suitable waste organic materials. Waste organic material and easily degradable organic carbon such as potato waste should be placed on the cell bottom to stimulate growth of the ARUM microbial community. In the long term, cattail leaf, root and rhizome detritus will supply these compounds to the sediment.

A floating cattail mat should be installed over the whole ARUM Cell area. By filling the cell with fresh water during the first year, the cattail population can be established from seed directly on soil or peat covering the floating structures installed over the pond.

AMD entering the ARUM Cell should not be from a point discharge, since this would promote the formation of stagnant areas in the cell at some locations, and short-circuiting along other paths. AMD should be discharged to the upstream end of the ARUM Cell into a zone running the width of the ARUM Cell and separated from the ARUM Cell at large by a permeable baffle. This baffle will extend from the surface to bottom of the cell over the width of the ARUM Cell. Water will enter the ARUM Cell at large through a horizontal series of holes at the mid-depth horizon, such that AMD is distributed uniformly along the width of the cell at a uniform depth and flow.

Similarly, ARUM-treated solution leaving the ARUM Cell will pass through a horizontal series of holes in a baffle at the mid-depth horizon, such that ARUM solution is being uniformly drawn out of the cell along the width of the cell at a uniform depth.

Since the ARUM Cell is based upon an active microbial population and a healthy floating cattail population, the physical, bio/chemical and hydraulic conditions should remain as stable as possible. This includes constant water level, low water velocity through the system, and low variation in input water quality.

Dilution of AMD with fresh water may be required as a means to decrease concentrations of compounds to levels which can be handled by the ARUM microbial community. If this fresh water contains some alkalinity, precipitation of aluminum sludges can be expected. A fraction of water leaving the ARUM cell could be recycled to Stage 1, whereupon further precipitation of aluminum sludges will occur.

Since density differences, due to temperature and dissolved solids concentrations, may exist between solutions, all incoming solutions should be pre-mixed prior to entry into the ARUM cell.

In summary, the ARUM Cell is comprised of the following components:

a) A large pond will be constructed from low-permeability material.

b) Baffles will be installed across inflow and outflow ends of cell such that water enters and exits as a horizontal sheet 1 m above sediment and 1 m below the surface.

c) A floating cattail mat will cover the pond.

d) Waste organic material will form the sediment.

STAGE 4: Biological Polishing

Following treatment with ARUM, an anaerobic solution with circumneutral pH, and low acidity and metal concentrations is anticipated. A fourth stage, Biological Polishing, will utilize attached algal and aquatic macrophyte population for filtration of suspended solids and adsorption of remaining metals in solution.

The water will likely be anoxic and contain some dissolved nutrients. Upon release from the ARUM cell and oxygenation of the water, residual iron, aluminum and other metals will precipitate.

Filamentous algal populations can serve as suspended solids filtration systems and dissolved metal scavengers. Aquatic macrophyte populations (e.g. bottom-bound cattails) can, in turn, serve as coarse filters for screening and sedimenting detached filamentous algal biomass.

The Biological Polishing Cell should be shallow, relative to the cells upstream. By restricting the depth to 0.6 to 1.2 m, the volume will be low, and water velocity is relatively high. Areas with depth of 1.2 m will provide suitable flow conditions for filamentous algal population growth. Shallower intervening areas (0.6 m) should be incorporated for growth of cattail populations for screening large solids.

By maintaining very low water levels in the Biological Polishing Cell in the first year, cattail populations can be established in the shallow sections. Inoculation of the deeper sections with filamentous algae will not likely be required, since these algae are pandemic.

The water quality in the discharge from the ARUM cells, and the intended use of final effluent will determine whether Biological Polishing Cells are required.

2.a Wetland Hydrological Requirements - Water Balance - Evapotranspiration Acreage Requirement

The cells will be 2 acres (0.93 ha) in area, with volumes of approximately 20,000 m^3. The walls and floors should be constructed from low-permeability material. Inflow of AMD, fresh water and ARUM recycle water will be controlled. If the pond level and the outflow weir level are at fixed elevations, the outflow will be determined by the rate of inflow.

It is almost unavoidable that the proposed system will be located on either a groundwater discharge or recharge area (or span both types of areas) unless the system is lined with an impermeable liner, or is built on high integrity bedrock.

Currently, the system is envisaged as a series of cells built on a natural decline using local materials. Cells may or may not be lined with impermeable liners. The walls and floors of these cells should be lined, or constructed using appropriate materials and in a manner such that they are relatively water-tight, in order to minimize uncontrolled subsurface water flow from beneath one cell into the next cell.

If unlined, four additional measures can be taken in order that the system hydrology and overall system performance can be defined.

First, the locations of seepages from the floors of the cells must be recorded, indicating those cells positioned in a groundwater discharge area. This information will be required during later assessments of system hydrology, once the system is operational.

Second, during filling of the ponds, the inflow versus cumulative volume of water in the cells should be recorded.

Third, once the cells are filled, a period of water level monitoring should be completed for differentiating water loss due to evaporation from leakage water loss due to leakage in those cells positioned in a groundwater recharge area. Finally, simple, but accurate flow monitoring stations (weirs) should be installed at the inflow and outflow of each cell during system construction.

Other considerations with respect to meteorological data, maximum rain events for the region are given in Appendix B-3.

2.b Ecological Requirements- Indigenous Species - Succession

Floristically, Utah lies in the Great Basin province of North America (Gleason and Cronquist, 1964). Wetlands in this area will be distinct in their floral composition from wetlands in other floristic provinces on the continent. Floristic provinces are associated with specific faunas which have to be considered in a wetland design. For example in northern regions, beavers and muskrats will alter or interfere with the water flow of wetlands and may have to be controlled when wetland systems are used to treat water.

At this stage of the considerations regarding the development of a passive treatment system in the Mixed Tails Area, detailed floristic and ecological evaluations are not called for. They can be derived relatively easily, once area-specific soil, vegetation, and faunistic data are made available from a local sources or provided by Kennecott.

From the type of vegetation, the soil formations, the climatological regime and other ecological characteristics, the succession, or in other words, the changes which might be expected when wetland ecosystems are introduced at the foot of the Kennecott waste rock pile, can be derived.

2.c Contaminant Removal

A computer spreadsheet has to be used to estimate the potential system treatment capacity. These estimates are based on system dimensions and volumes, as shown in Table 3.

In Table 4, system settings and outputs are presented, based on flow rates of AMD, fresh water and ARUM recycle water. The system settings are for the ice-free season, when System 1 is in flow-through mode while System 2 is in batch mode.

Table 3: System Dimensions and Volumes

	L, ft	L,m	W, ft	W,m	Avg D, ft	D,m	Vol,m3
SYSTEM 1 Mixing,Precipitation	500	152.4	200	60.96	7	2.134	19,822
SYSTEM 2 Mixing,Precipitation	500	152.4	200	60.96	7	2.134	19,822
SYSTEM 1 Sedimentation	500	152.4	200	60.96	7	2.134	19,822
SYSTEM 2 Sedimentation	500	152.4	200	60.96	7	2.134	19,822
ARUM 1A	500	152.4	200	60.96	9	2.743	25,485
ARUM 1B	500	152.4	200	60.96	9	2.743	25,485
ARUM 1C	500	152.4	200	60.96	9	2.743	25,485
ARUM 2A	500	152.4	200	60.96	9	2.743	25,485
ARUM 2B	500	152.4	200	60.96	9	2.743	25,485
ARUM 2C	500	152.4	200	60.96	9	2.743	25,485
Biological Polishing 1	500	152.4	200	60.96	3	0.914	8,495
Biological Polishing 2	500	152.4	200	60.96	3	0.914	8,495
							249,188 m3

Table 4: System Settings and Output

SETTINGS

SET INPUT AMD FLOW RATE VALVE AT	200	m3/day
SET INPUT FRESH WATER INPUT RATE AT	200	m3/day
SET PERCENT ARUM RECYCLE	50	Percent
SET MIX-PRECIP SYSTEM, 1 OR 2: SYSTEM	1	SIX MONTHS ON
SET SULPHATE CONCENTRATION IN AMD	3587	mg/L
SET ESTIMATED SULPHATE REDUCTION RATE	500	mg/m3/day

OUTPUT, OPERATION OVER ONE YEAR

ARUM SYSTEM RETENTION TIME	381	Days
[SO4] IN AMD MIXING CELL, WITH FRESH MIX	1,794	mg/L
[SO4] IN AMD WITH ARUM RECYCLE MIX	1,477	mg/L
SULPHATE CONCENTRATION IN DISCHARGE	956	mg/L
SYSTEM DISCHARGE RATE	400	m3/day
AMD - FRESH MIXING RATIO	50%	% AMD

The input settings are presented in Table 4, including the flow rates (AMD, fresh water and recycle), the System which in flow-through mode, the AMD sulphate concentration and the estimate sulphate reduction rate, in mg.m^{-2}.day^{-1}.

Using these settings, combined with the various cells' volumes and the flow paths, the retention time of water in System 1 (flow-through mode), the expected sulphate concentration following fresh water, then ARUM water, dilution, and the final sulphate concentration at discharge following treatment by ARUM, are given in the output box.

At the settings presented in Table 4, 200 m^3.day^{-1} of AMD containing 3587 mg.L^{-1} enters Stage 1 and is mixed with an equal flow of fresh water. The diluted sulphate concentration is 1,794 mg.L^{-1}. The sulphate concentration in this water, following mixing with ARUM recycle water (956 mg.L^{-1} sulphate) at a flow of 200 m^3.day^{-1}, is further diluted to 1,477 mg.L^{-1}. After passing through System 1, the sulphate concentration is reduced to 956 mg.L^{-1} due to sulphate reduction in Stage 3, ARUM, where sulphate reducing bacteria are converting 500 mg sulphate per m^3 per day to sulphide.

In this spreadsheet format, the calculations do not, among many other considerations, incorporate sulphate loss from solution by precipitation in Stages 1 and 2, due to alkalinity contained in the ARUM recycle water.

These calculations represent likely grossly underestimated microbiological performance, due to the many unknowns since no design criteria have been derived specifically for Kennecott water. These calculations are intended only as a "first cut" at describing the system.

2.d Maintenance Requirements

Given the characteristics of the Kennecott water it is unlikely that a completely maintenance-free system can be established. The concept proposed for the Mixed Tails Area can be expected, once flow control has been achieved, to operate as a low-maintenance system. It can be expected that it will take some time to achieve flow control in the system.

Depending on the characteristics of the precipitate formed in the mixing precipitation pond, the settling ponds will require periodic de-sludging.

It can be expected that, in the first 5 years, some fertilizer and easily degradable carbon additions are required. The time frame of 5 years is derived from productivity measurements on floating cattails (Kalin and Smith, 1992).

2.e Potential Environment Impacts

The environmental impact of a low-maintenance passive system, in comparison to a conventional water treatment system, could be considered lower. On a "per volume" basis, the passive system is expected to produce less secondary wastes which need to be handled. If the precipitation step at the head of the Mixed Tails Area can be optimized, then the water treatment can be considered to be more environmentally friendly, as naturally stable precipitates will accumulate in the wetland sediment.

If the Mixed Tails Area were transformed to a passive wetland, this would validate concepts of using this system for the treatment of other leachates, as may come from the landfill site below it. These leachates would be a nutrient source for the microbial treatment.

Environmentally acceptable solutions have to be found to the water management problems of the Kennecott waste rock piles. Given the history of the operation, Kennecott Corporate environmental objectives should be stated, within which it would be possible to comment on environmental impacts.

If all, or a percentage of, the discharge from the treatment system is required to pass irrigation water standards, then the Mixed Tails Area would be considered as a benefit to the system as a whole, rather than an environmental impact. Irrigation water considerations are given in Appendix D.

3.0 UTILIZE THE CONFIGURATION OF THE MIDAS AREA TO DESIGN A PASSIVE TREATMENT SYSTEM FOR STORM WATER WITH ELEVATED SULPHATE AND METAL CONTENTS

A passive treatment system for the Midas Area, to treat storm water with high sulphate and metal content, requires a run-off retention system in order regulate flow despite possible heavy rain storms.

Additions of phosphate rock or fly ash as a convenient source of alkali or lime may have to be used upstream from a pond system incorporating algae or floating vegetation, configured for precipitate collection. The proposed configuration, the installation of as many dikes as possible to increase the retention time, for test work in the Midas/Congor area suggested by Kennecott, and included in the map pocket, is appropriate. Within this series of many small cells, a sequence of precipitation ponds and particulate settling areas, followed by biological polishing ponds could be set up in order to handle the estimated 25 usgpm average flow.

However, until the precipitation reactions are clarified, through bench-scale tests, it is not possible to give further suggestions with respect to pond design.

3.a Field Data Assessment to be Integrated into the above

The analytical data for water samples collected in October l993 in the Midas/Congor Area are provided in Appendix A. These chemical analyses were used to evaluate the required mixing ratios of leach water to alkalinity-carrying ground water in order to arrive at the measured water quality arriving at the portal of the Old Bingham Tunnel (Table 5). Such aluminium concentrations ranging from 55 to 180 $mg.L^{-1}$ are reasonable and could be further improved with passive treatment.

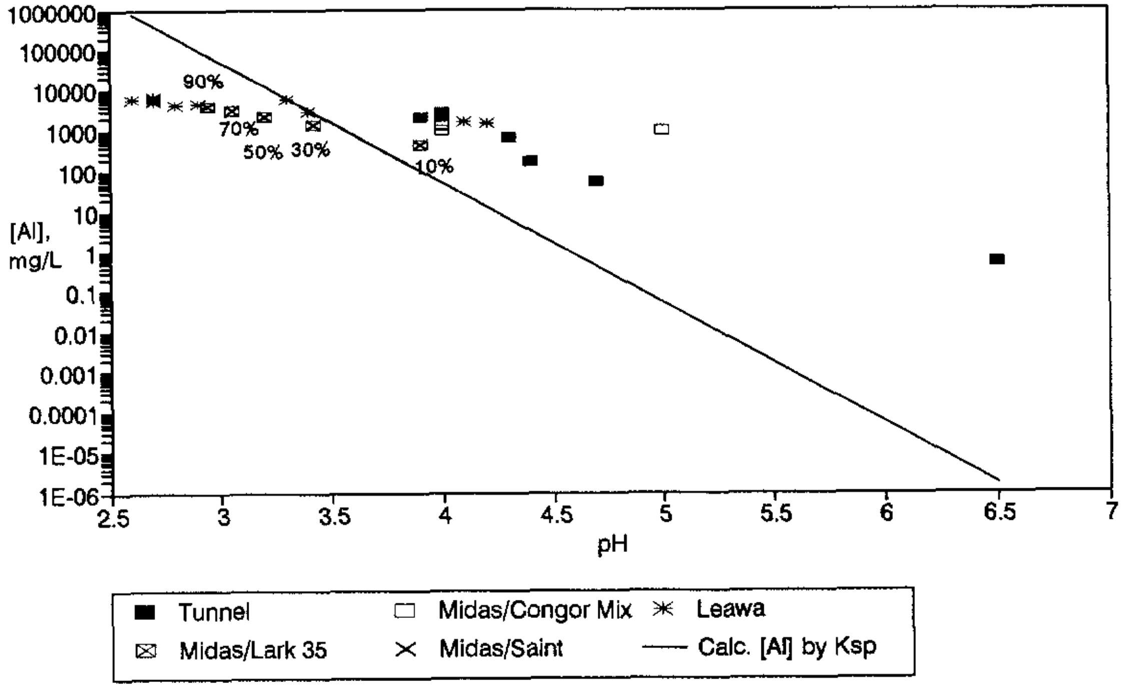
Table 5: Bingham Tunnel Water Comparison

Date	10/20/93 OBT	9/17/92 OBT 210	9/23/92 OBT 500
pH	4.7	4.4	4.4
TDS	4660	6200	6000
TSS	314	310	300
Cond.	4480	4900	4900
ACIDITY	420	12000	13000
Al	55	190	180
As	0.01	0	0
Ca	474	390	390
Cd	0.2	<0.004	<0.004
Cr	<.004	<0.01	<0.01
Cu	19	36	36
Fe	0.08	<0.01	<0.01
Pb	0	<0.05	<0.05
Mg	392	570	550
K	4.6	<0.1	<0.1
Se	0	<0.05	<0.05
Na	99	70	69
SO4	2760	4100	3900
Si	-	9.4	9.5
Mn	16.1	29	27
Zn	4.9	-	-
Cl	319	-	-

Using the characteristics of Lark or Saints' Rest waters as examples of groundwater to be mixed with Midas water, the percentages of the mixtures are plotted in Figure 10. They can be compared with respect to their position of aluminium saturation to the other LEAWA waters, as Figure 10 incorporates the data from Figure 3.

Although the pH of both Lark and Saints' Rest are relatively high, a mixture of leachwater and groundwater could contain 10 % Midas water and 90 % Lark or Saints

Fig. 10: Actual [Al] Compared with Calculated [Al] from Ksp



Rest water. Only with these significant additions of ground water could an increase in pH be expected to be sufficient to produce aluminium hydroxide precipitates. The concept of diluting the Midas water nine times it volume with the other waters is not realistic.

However, biological polishing steps appear an avenue to be considered, since the algal samples collected at the outflow of the Old Bingham Tunnel and in the Saints Rest ponds contained concentrations of aluminium of 10 % and 1 % respectively (Appendix A, Document 7). The sulphate concentrations in the algae are also high, with 5.4 % and 2.1 % in the algal biomass.

A biological polishing model is being refined by Boojum in l993/l994 which could be used to assess the removal capacity of algal biomass, with growth rates derived from acid and circumneutral mine waste water. Algal populations were, in fact, noted during the site visit in one of the ponds containing storm water in the Midas/Congor system. This process, given the concentrations in the biomass, has definite promise for the Midas area.

In Figures 11a and 11b, the characteristics of Midas water are plotted. Although the drainage basin contains a variety of seepages, the seepages are generally acidic, with some improvement as Midas and Congor mixes. The relative high pH value of 5 of the Midas/Congor mix sample is likely related to contact with limestone or carbonate stone.

The water sample was clearly still reacting at collection, as the measurement in the field was pH 4.1, but pH 5.0 later in the laboratory. Precipitation reactions are indicated from the unstable Eh readings (see data in Appendix A).

In conclusion, the Midas / Congor area should be used as a experimental area where the design parameters for passive removal of aluminium from the water are determined.

Figure 11a: MIDAS Water Analysis
Sept.- Oct. 1993

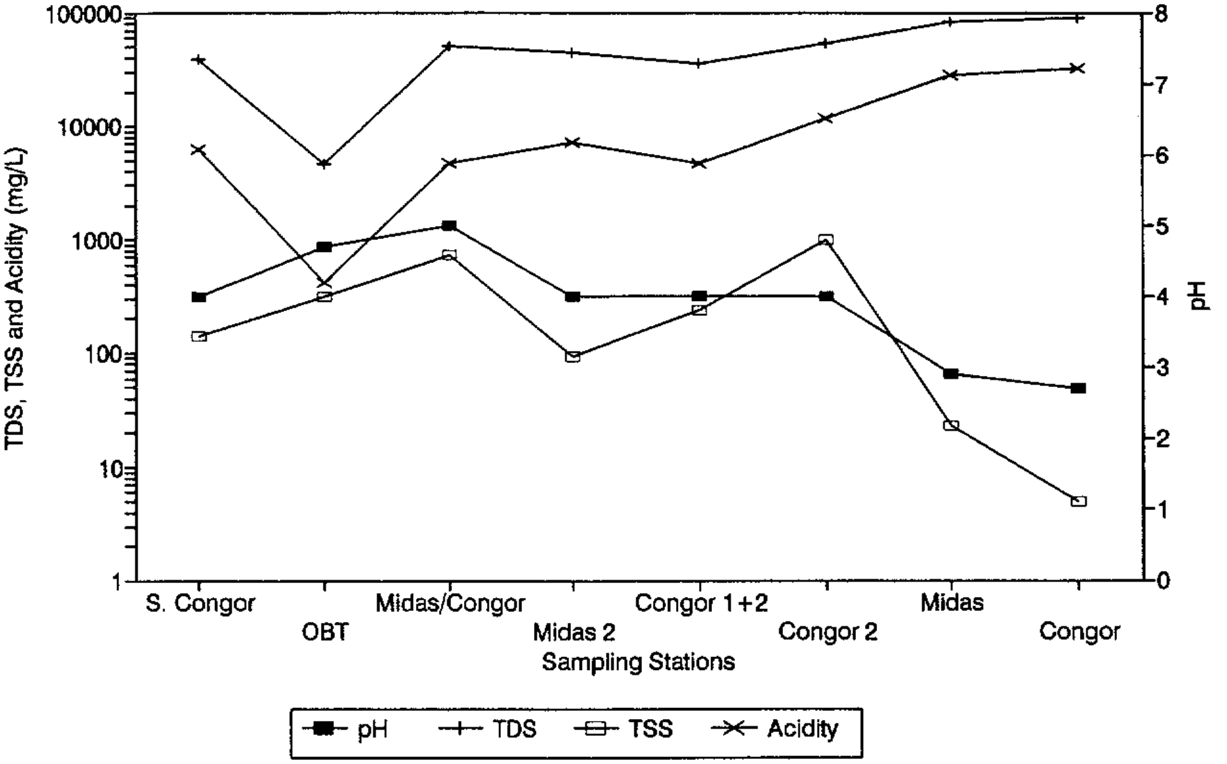
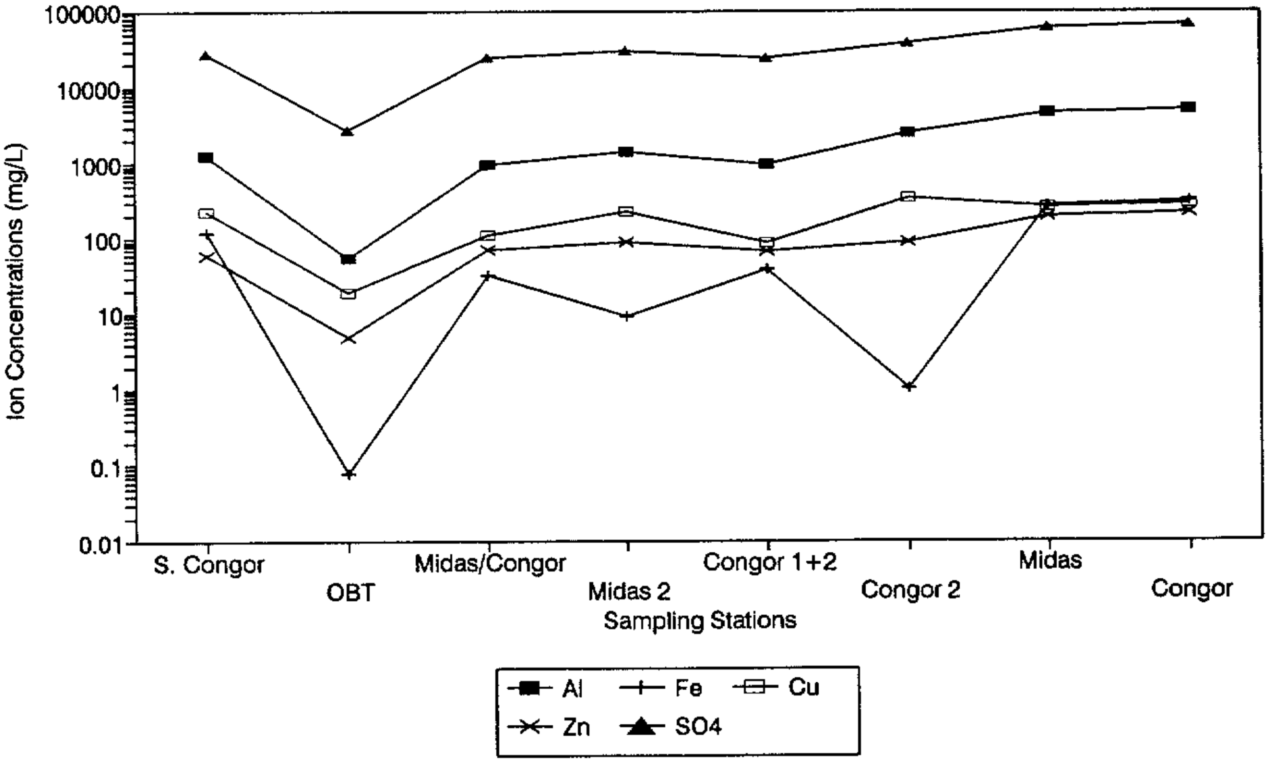


Figure 11b: MIDAS Water Analysis
Sept.- Oct. 1993



4.0 LARK AND SAINTS' REST EXISTING CONSTRUCTED WETLANDS

4.a Interpretation of data collected and of measures taken at Saints' Rest and Lark with recommendations for improvements.

Waters entering the Lark and the Saints' Rest Wetlands contain sulphate at concentrations which may exceed limits for agricultural and livestock applications. The waters are not acidic and do not contain exceptionally high concentrations of heavy metals (Table 6).

Table 6: Comparison of chemical composition of Stonewort (Characean algae) media, sea water and the Lark and Saint's Rest wetland waters.

Sampling Date		Toronto Tap Water (C. vulgaris)	Artificial Waldsea L. Water (C. buckellii)	Sea Water (Marine Algae)	Lark Wetland Inlet Water 22-Oct-93	Saint's Rest Wetland Water(at float) 22-Oct-93
Sodium	mg/L	19	3,070	10,561	394	101
Magnesium	mg/L	9	2,670	1,272	204	221
Calcium	mg/L	43	320	400	850	457
Potassium	mg/L	6	310	380	5	6
Manganese	mg/L	< 0.01	N.A. *	0.01	0.387	0.042
Sulphate	mg/L	36	11,600	2,652	1,830	1,830
Chloride	mg/L	27	4,400	18,980	1,100	131
Bi/Carbonate	mg/L	103	480	28	N.A.	N.A.
Phosphate	mg/L	< 0.01	N.A.	< 0.1	N.A.	N.A.
Zinc	mg/L	< 0.01	N.A.	0.01	0.03	0.04
Copper	mg/L	< 0.01	N.A.	0.09	0.04	< 0.03
Aluminum	mg/L	0.2	N.A.	1.9	< 0.2	< 0.2
Iron	mg/L	< 0.01	N.A.	< 0.01	< 0.04	< 0.04
pH	units	8.2	8.3	8 - 9	7.5	7.7
Conductivity	uS/cm	350	20,000	48,000	5,450	3,110

* N.A., Not Analysed

In Table 7, the anions and cations are reported in millimoles, the equilibrium concentrations of $CaSO_4$ and $MgSO_4$ indicate that the water is essentially in equilibrium for these two substances. As both sulphate species cannot be removed through increases in pH, the sulphate removal in these waters would conventionally require lime additions, reverse osmosis or ion exchange treatment. These three methods are economically unrealistic treatment options.

Table 7: Equilibrium Concentrations of Saints' Rest and Lark Water

	SO4(mM)	Ca(mM)	Mg(mM)	Na(mM)	Cl(mM)	cation	anion
Lark Inlet	19.06	21.25	8.50	17.13	30.99	69.11	76.63
Outlet	18.85	18.00	7.58	15.48	29.58	67.29	66.64
Saint Well	12.08	8.55	6.04	3.28	3.38	27.55	32.46
float	19.06	11.43	9.21	4.39	3.69	41.82	45.66
outlet	17.29	10.13	8.58	4.05	3.52	38.10	41.47

It is proposed that the Chara Process is considered as a self-regenerating static treatment (Appendix E). The Chara Process is a biological polishing treatment for alkaline waters, which has been developed by Boojum for uranium, ^{226}Ra and TSS removal. It should be possible that healthy aquatic/semi-aquatic ecosystems can establish in these wetlands. Ideally, this ecosystem should contain aquatic plant species which will reduce the cation and sulphate concentrations upon passage through the wetland.

The Characeae are the best candidate plant family for this application, given the broad spectrum of salinity in which these species, collectively, thrive (Table 8). To date, the species *Chara buckellii*, known to populate four magnesium sulphate-rich water bodies in North and South America, is probably the most appropriate species to test, because of its documented ability to osmoregulate, a physiological feature permitting it to survive in widely fluctuating osmotic pressure (Hoffman & Bisson, 1986).

Table 8: Composition of two species of Stoneworts (Characean algae) following culture in natural and mine wastewater solutions.

Stonewort Species	*Chara buckellii*		MgSO4 Lakes		*Chara vulgaris*		Freshwater Lakes	
Assayer No.	1660	1661	1665	1667	1662	1663	1664	1666
Culture Solution	Toronto Tap Water	AWW* (MgSO4 Sol'n)	X-23 Mine Wastewater	AWW (MgSO4 Sol'n)	X-23 Mine Wastewater	Toronto Tap Water	X-22 Mine Wastewater	X-23 Mine Wastewater
Growth Substrate	Sediment	Sediment	Sediment	Sand	Sediment	Sediment	Sediment	Sand
Al, ug/g	742	530	424	318	530	530	1007	53
Fe, ug/g	1890	1260	1330	490	700	2450	2730	1890
Mn, ug/g	154	693	2926	77	3696	847	693	6468
Pb, ug/g	10	23	53	12	27	304	47	1473
Zn, ug/g	38	27	3260	14	4467	34	347	9146
Ba, ug/g	283	245	160	38	183	290	875	135
K,ug/g	166	36520	166	7553	415	83	83	83
Na, ug/g	222	31080	518	22940	888	222	296	74
P, ug/g	880	1320	572	308	572	836	1364	396
Sr, ug/g	182	108	170	45	210	180	189	132
Combustable Content, %	62.6	56.9	39.3	52.3	53.9	58.4	61.2	46.2
Ash residue, %	37.4	43.1	60.7	47.8	46.1	41.6	38.8	53.8
SO4, %	1.5	8.1	2.7	9.9	2.1	1.5	1.8	2.1
CaCO3 Equiv., %	15.6	7.8	17.4	4.1	17.4	27.7	27.8	8.0
MgCO3 Equiv., %	2.3	7.7	2.1	8.7	1.9	1.5	1.7	1.1
Total Dolomite Equiv., %	17.9	15.5	19.5	12.8	19.2	29.1	29.5	9.1
Metals as Hydroxides, %	0.6	0.5	1.4	0.2	1.7	0.8	1.0	3.2
Non-Combustibles Accounted For, %	20.2	31.1	23.8	26.0	23.3	31.6	32.6	14.5
Remainder, as Chloride, Silicate, %	17.2	12.1	36.9	21.7	22.9	10.0	6.2	39.3

*AWW, Artifical Waldsea Lake (Saskatchewan) Water

All Samples: Ag<=5.1, As<=54, B<100, Be<10, Bi<=13, Cd <=20, Ce<10, Co<=94, Cr<=22, Cu<=105, Hg<10, La<10, Mo<=11, Nb<=23, Ni<=123, Sb<10, Se<=19, Sn<=17, Te<=28, Th<10, Ti<86, U<=20, V<10, W<=130, Y<10, Zr <10

In Table 8, it can be seen than *C. buckellii* thrives in solutions with much higher concentrations of cations and sulphate (Waldsea Lake, Saskatchewan) than present in the Lark and Saints' Rest Wetlands. Laboratory studies have shown that this species continues to survive and grow if the osmotic pressure ($\approx$ salinity) in the medium is gradually reduced, as may occur in a wetland receiving variable salinity influent (Smith, 1990).

In a separate laboratory study performed for Curraugh Resources' Faro operation (Yukon), cultures of *C. buckellii* and *C. vulgaris* were grown in tap water, artificial Waldsea L. Water or waste water from a Pb-Zn mine in the Yukon. Following culture, plant biomass as dried and analyzed by ICP.

From the results, presented in Table 8, it can be seen that living biomass of both species accumulated large amounts of Ca, as $CaCO_3$ (4 to 28 %), Mg, likely as $MgCO_3$ (1.1 to 8.7 %) and sulphate (1.5 to 9.9 %). This ability of Characean living biomass to accumulate carbonates and sulphate from solution may be applicable to the Lark and Saints' Rest wetlands.

An estimate of how much Mg and SO_4 could be removed by a *C. buckellii* population has been derived in Table 9, using the relationships between concentrations in solution and concentrations accumulated by *Chara* biomass in the laboratory culture experiment, shown in Figure 12.

If the calcium, magnesium and sulphate concentrations in the October 22, 1993 water collected from sampling stations "Lark Inlet" and "Saints' Rest at float" are considered (Figure 12), then a *C. buckellii* population might contain 30% $CaCO_3$, 2 % $MgCO_3$ and 3 % SO_4.

The following calculations assume that the standing biomass will be 200 g dry weight.m^{-2}, and the population will replace this biomass twice a year.

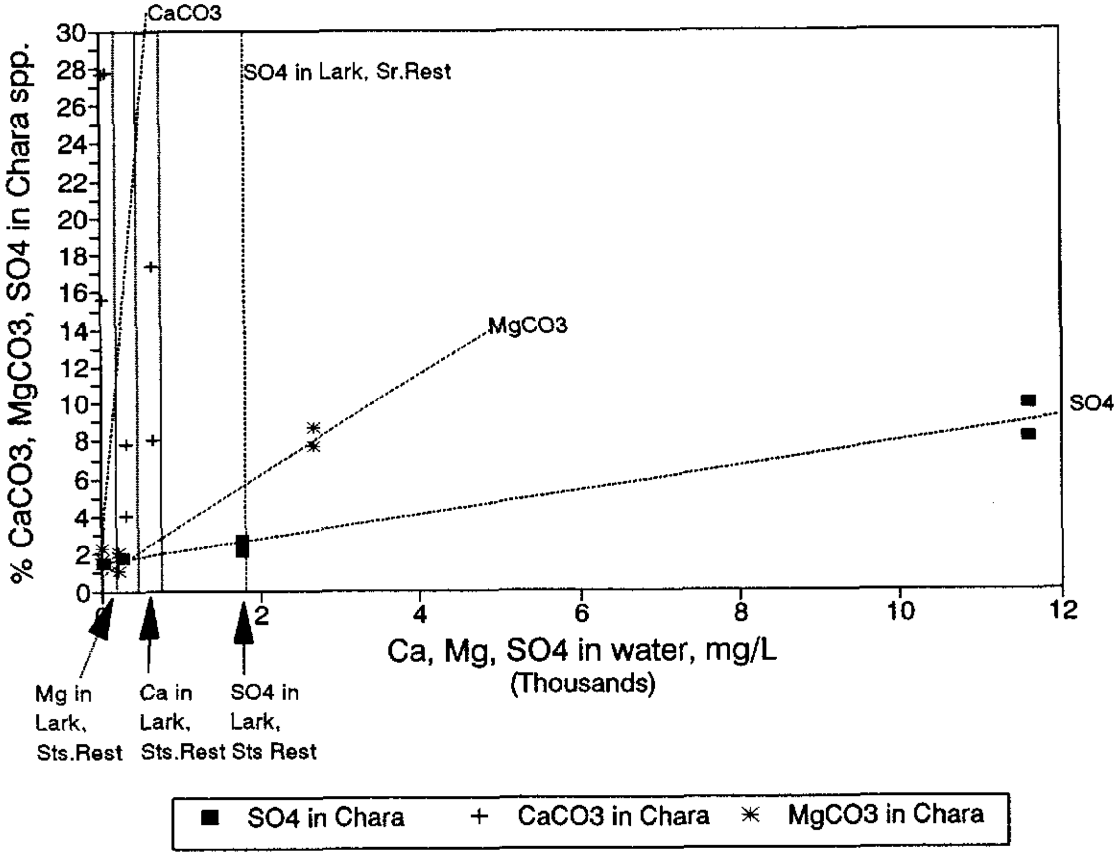
The amount of magnesium which will crystallize on the algal biomass and join the sediment per hectare will be equivalent to 109,714 m^3 of influent water per hectare per year. The amount of sulphate will be equivalent to 54,645 m^3 of influent water per hectare per year.

These volumes which could be treated are based on estimates derived from growth rates and population densities in other Boojum projects (e.g. Smith & Kalin, 1989). The feasibility of using this algae for the removal of sulphate and magnesium has to be properly assessed via specific laboratory and field tests addressing this concept.

Table 9: Estimated magnesium and sulphate removal by a *Chara buckellii* population in Lark or Saints' Rest wetlands.

Chara population standing biomass	200	g dry weight/m2
Chara population annual turnover	2	times per year
New biomass each year	4,000	kg/ha/year
Expected CaCO3 in biomass	30	%, from graph
Expected MgCO3 in biomass	2	%, from graph
Expected SO4 in biomass	3	%, from graph
Mg removal from water	23	kg/ha/year
SO4 removal from water	100	kg/ha/year
Equivalent complete treatment for Mg	109,714	m3 influent/ha/year
Equivalent complete treatment for SO4	54,645	m3 influent/ha/year

Fig.12: CaCO3, MgCO3, SO4 in Chara spp. versus Ca, Mg and SO4 in Medium



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APPENDICES

APPENDIX A CHEMICAL ANALYSES DOCUMENTS AND LIST OF CITED REPORTS PROVIDED BY KENNECOTT AND OTHERS

REPORT 1 Technical Report 76-16 Chemical, Mineralogical, and Physical Characteristics of as-mined UCD and CMMD waste rock. Project No. R5059 - July 1976; Jorgason, Jackson and Schlitt. Research Center, Metal Mining Division.

REPORT 2 Geology of the Bingham Canyon Porphyry Copper Deposit, Utah. Peters, James and Field.

REPORT 3 Kennecott Utah Copper Modernization pays off. Eng. and Mining Journal. January 1990.

REPORT 4 Analysis of Sludge/Sediment and Water Samples from the Old Bingham Tunnel. Kennecott Plant Projects Group, November 3, 1992.

Document 1 Leach Water Analyses: 9/92, 4/93

LEACH WATER ANALYSIS

9/92

Sample#		Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	K	Se	Na	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal. %
LEAWA-1	Bw 1	5300	0.08	590	0.31	1.1	380	410	0.025	10000	0.05	0.0025	0.05	460000	200	36000	2.8	45000	94000	100	21.7%
LEAWA-2	Bw 2	4800	0.069	510	0.38	1.2	230	800	0.025	8000	0.05	0.0025	0.05	490000	200	35000	2.7	47000	99000	120	12.0%
LEAWA-3	Bw 2	4500	0.047	490	0.34	1	210	770	0.025	7200	0.05	0.0025	0.05	490000	200	38000	2.6	47000	102000	150	7.8%
LEAWA-4	Bw 3	4300	0.046	460	0.32	0.93	280	450	0.025	7700	0.05	0.0025	0.05	510000	210	39000	2.5	49000	103000	140	6.0%
LEAWA-5	BW 3	6100	0.074	650	0.39	1.1	340	530	0.025	11000	0.05	0.0025	0.05	480000	210	39000	2.6	50000	45000	240	22.1%
LEAWA-6	Midas	4800	0.061	500	0.37	1	200	470	0.025	8100	0.05	0.0025	0.05	460000	200	37000	2.8	47000	95000	4100	11.9%
LEAWA-7	Keystone	3500	0.042	530	0.91	0.72	370	93	0.025	6000	0.05	0.017	0.05	340000	210	35000	2.9	44000	98000	100	8.1%
LEAWA-8	Copper	3300	0.17	460	0.62	0.8	400	1600	0.025	7200	0.05	0.0025	0.05	350000	270	33000	3.5	42000	80000	140	8.5%
LEAWA-9	Castro	190	0.0025	460	0.34	0.02	160	5.4	0.025	2700	0.05	0.02	0.05	70000	140	10000	3.9	12000	19000	38	2.9%
LEAWA-10	Yosemite	160	0.0025	520	0.13	0.04	81	1.6	0.025	3700	0.05	0.011	0.05	39000	370	13000	4.7	14000	22000	61	7.7%
LEAWA-11	Conger	5100	0.075	580	0.39	0.67	240	290	0.025	7200	0.05	0.0025	0.05	390000	200	27000	3.4	48000	95000	210	9.1%
LEAWA-12	P/Plant	5900	0.79	660	0.65	1.7	99	2200	0.025	9000	0.05	0.0025	0.05	400000	100	27000	3.7	49000	98000	370	19.4%
Min		160	0.0025	460	0.13	0.02	81	1.6	0.025	2700	0.05	0.0025	0.05	39000	100	10000	2.5	12000	19000	38	2.9%
Max		6100	0.79	660	0.91	1.7	400	2200	0.025	11000	0.05	0.020	0.05	510000	370	39000	4.7	50000	103000	4100	22.1%
Mean		3996	0.12	526	0.43	0.87	249	635	0.025	7483	0.05	0.006	0.05	373250	209	31000	3.2	41167	79000	461	11.4%

4/93

Sample#		Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	K	Se	Na	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal. %
LEAWA23	Bw 1	5382	0.017	445	0.7	0.93	385	288	0.025	9820	0.05	0.0025	2.1	39500	287	26280	2.8	70710	112400	923	−1.1%
LEAWA21	Bw 2	5654	0.034	517	0.78	0.99	196	544	0.025	9954	0.05	0.0025	2.7	40500	276	29460	2.6	66860	106600	783	3.5%
LEAWA19	Bw 3	6135	0.05	565	0.82	1.1	406	625	0.025	11720	0.05	0.0025	1.4	39250	397	27960	2.5	74230	115300	823	4.6%
LEAWA20	Bw 3	5710 ✓	0.029	537	0.77	0.93	227	425	0.025	10490	0.05	0.0025	3.3	44250	282	25200	2.6	68010	103100	861	4.2%
LEAWA18	Midas	3794	0.053	432	0.64	0.74	240	246	0.025	6370	0.05	0.0025	75	30000	374	24000	3.1	59950	94470	723	−4.4%
LEAWA13	Keystone	3251	0.019	451	0.9	0.44	257	171	0.6	8394	0.05	0.005	23	41200	284	28350	3.0	54020	79040	234	−1.9%
LEAWA14	Copper	1672	0.074	514	0.96	0.8	449	806	1.1	4500	0.8	0.0025	39	35900	358	24070	3.5	53080	76840	229	−28.8%
LEAWA15	Castro	101	0.0025	390	0.28	0.13	88	0.73	0.61	1901	8.7	0.016	48	2400	199	9841	4.5	20640	13230	79	−38.7%
LEAWA16	Yosemite	302	0.0025	441	0.33	0.17	105	1.1	0.47	2755	8.4	0.0025	162	3500	480	12960	4.1	13990	19680	75	−2.1%
LEAWA17	Conger	5576	0.051	536	0.74	0.87	291	371	0.025	11140	0.05	0.0025	6.1	35750	77	27240	2.8	22450	103300	1196	54.3%
LEAWA22	P/Plant	4756	0.048	457	0.85	1.1	36	1174	0.025	8730	0.05	0.0025	8.5	36250	272	20280	3.5	64530	106000	918	−1.2%
Min		101	0.0025	390	0.28	0.13	36	0.73	0.025	1901	0.05	0.0025	1.4	2400	77	9841	2.5	13990	13230	75	−38.7%
Max		6135	0.074	565	0.96	1.1	449	1174	1.1	11720	8.7	0.016	162	44250	480	29460	4.5	74230	115300	1196	54.3%
Mean		3848	0.035	480	0.71	0.76	243	423	0.27	7979	1.7	0.004	34	31682	299	23240	3.2	51670	84724	622	−1.0%

LEACHW

LEACH WATER ANALYSES (EAST SIDE COLLECTION SYSTEM)

10/14/93

9/93 Sample #	Location	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal
LEAWA-32	BW 1	5100	0.0025	530	0.85	0.56	310	205	0.1	10800	250	0.1	0.25	4	149	36400	288	36300	2.7	72512	96800	2.9	−2.3
LEAWA-31	BW 2	6000	0.0025	550	0.39	0.71	192	810	0.1	10000	360	0.1	0.25	5	205	39400	258	37900	2.6	71071	93550	5.1	1.7
LEAWA-30	BW 3(P)	5600	0.0025	560	0.40	0.60	300	470	0.1	11100	360	0.1	0.25	5	216	36900	309	39000	2.7	72685	97850	4.2	2.6
LEAWA-29	BW 3(CB)	5900	0.0025	540	0.42	0.65	300	480	0.1	11200	390	0.1	0.25	0.6	218	36900	314	39000	2.7	73401	96630	3.6	2.7
LEAWA-35	Mides	4500	0.0025	580	0.48	0.69	260	270	0.1	9700	410	1.7	0.25	55	194	28700	334	35800	2.9	60962	82880	23.0	2.7
LEAWA-27	Keystone	4400	0.0025	470	0.33	0.26	106	210	0.1	8800	380	0.2	0.25	16	208	30200	258	34800	2.8	60990	80150	3.7	−2.0
LEAWA-26	Copper	2900	0.0025	530	0.44	0.36	72	1170	0.1	8400	43	1.2	1.80	54	180	25600	375	34100	3.4	53536	96690	4.6	−1.9
LEAWA-24	Castro	1500	0.0025	420	0.30	0.08	139	0.7	0.4	1240	43	10.5	0.25	61	59	1204	167	12410	4.2	12600	20510	2.6	4.6
LEAWA-25	Yosemite	1600	0.0025	480	0.15	nd	78	1.6	0.1	1450	43	10.5	0.25	270	23	1101	739	16540	4.1	16800	28050	2.6	−5.3
LEAWA-28	Congor	5100	0.0025	590	0.48	0.41	290	810	0.1	10900	420	0.1	0.25	8	215	32300	577	36100	2.7	66149	88980	5.0	8.8
LEAWA-27	Duplicate	4600	0.0025	460	0.40	0.25	116	204	0.1	8500	380	0.2	0.25	16	200	30400	260	34200	2.8	61000	80850	3.3	−1.4
LEAWA-30	Duplicate	5900	0.0025	590	0.57	nd	300	480	0.1	10400	370	0.1	0.25	6	215	36400	315	39000	2.7	72978	97960	4.6	0.9
Min		1500	0.0025	420	0.15	nd	72	0.7	0.1	1240	43	0.1	0.25	0.6	23	1101	167	12410	2.6	12600	20510	2.6	
Max		6000	0.0025	590	0.57	0.71	310	1170	0.4	11200	420	10.5	1.80	270	218	39400	739	39000	4.2	73401	96690	23.0	
Mean		4442	0.0025	518	0.39	0.38	205	366	0.13	8483	287	2.06	0.38	42	173	27959	349	33246	3.0	57840	80258	6.5	
LEAWA-33	ESC Res.*	7000	0.0025	720	0.08	nd	170	440	0.1	12300	370	0.2	0.25	10	206	34300	278	37000	2.7	65968	95460	17.0	14.3
LEAWA-34	P/P Tails**	5900	0.0025	610	0.39	nd	40	900	0.1	10400	390	0.2	0.25	10	202	38900	263	36100	3.3	63660	99960	4.8	6.0

Note : * = East Side Reservoir and ** = Precip. plant return water (Thickener overflow).

MIDAS WATER ANALYSES

11/01/93

Sampling Date: 10/20/93

Location	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal
S. Congor	1270	0.012	532	0.19	0.04	221	121.00	< 0.05	4990	188.0	10.4	< 0.002	187	58.4	6220	464	20400	4.0	27800	38800	142	1.6%
OBT	55	0.010	474	0.02	< 0.004	19	0.08	< 0.05	392	16.1	4.6	< 0.002	99	4.9	420	319	4480	4.7	2760	4660	314	1.2%
Midas/Congor Mix 1)	952	0.004	494	0.26	0.02	111	31.90	0.09	4790	219.0	18.2	< 0.002	153	70.8	4710	591	20300	5.0	24700	51100	736	2.1%
Midas 2	1390	< 0.003	458	0.32	0.03	228	9.18	0.09	5290	291.0	12.8	< 0.002	220	90.0	7160	793	23100	4.0	29800	43900	92	0.5%
Congor 1+2	954	< 0.003	461	0.23	0.02	86	38.10	0.14	4580	205.0	19.0	< 0.002	161	68.8	4780	621	19700	4.0	24200	36100	238	1.3%
Congor 2	2480	0.015	448	0.32	0.04	349	1.06	0.12	5410	309.0	13.2	< 0.002	62	89.5	11800	499	24300	4.0	37300	53200	1000	−1.1%
Min	55	< 0.003	448	0.02	< 0.004	19	0.08	< 0.05	392	16.1	4.6	< 0.002	62	4.86	420	319	4480	4.0	2760	4660	92	−1.1%
Max	2480	0.015	532	0.32	0.04	349	121	0.14	5410	309	19	< 0.002	220	90	11800	793	24300	5.0	37300	53200	1000	2.1%
Mean	1184	0.007	478	0.22	0.03	169	34	0.07	4242	205	13	< 0.002	147	64	5848	548	18713	4.3	24427	37960	420	0.9%

Comparison of Duplicates:

Location	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal.
Congor 2	2480	0.015	448	0.32	0.04	349	1.06	0.12	5410	309	13.2	< 0.002	62.2	89.5	11800	499	24300	4.0	37300	53200	1000.0	−1.1%
C2TX	2020	0.012	448	0.34	0.04	351	1.00	0.13	5420	291	11.8	0.005	67.0	79.7	13000	460	24300	4.0	36700	52800	445.0	−3.6%
RPD	20%	22%	0%	5%	7%	1%	6%	8%	0%	6%	11%	200%	7%	12%	10%	8%	0%	0%	2%	1%	77%	

Field Measurements:

Location	pH	Cond	Eh	Estimated Flow *(gpm)*
S. Congor	4.0	13300	360	10
OBT	4.8	4000	325	25
Midas/Congor Mix 1)	4.1	14000	1)	2
Midas 2	4.0	16400	370	1
Congor 1+2	4.2	15000	325	1
Congor 2	4.3	15100	320	1

Notes : 1) High suspended solids content; brownish appearance; no stable Eh reading.
2) Max range of field conductivity meter was 19.9 mmhos/cm.

SAINTS' REST WETLAND: WATER ANALYSES

11/03/93

Sampling Date: 10/22/93

Location	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal
SR at well	< 0.2	0.005	342	< 0.004	< 0.004	0.07	< 0.04	< 0.05	145	< 0.02	6.6	0.004	75.4	1.48	16	120	2390	7.8	1160	2190	4	8.4%
SR at float	< 0.2	0.004	457	< 0.004	< 0.004	< 0.03	< 0.04	< 0.05	221	0.042	5.6	0.003	101	0.04	12	131	3110	7.7	1830	3080	122	4.5%
SR L.Pond outlet	< 0.2	0.005	417	< 0.004	< 0.004	< 0.03	< 0.04	< 0.05	206	0.037	6.2	0.003	93.2	0.02	6	125	2860	7.8	1660	2870	94	5.1%
Min	< 0.2	0.004	342	< 0.004	< 0.004	< 0.03	< 0.04	< 0.05	145	< 0.02	5.6	0.003	75.4	0.02	6	120	2390	7.7	1160	2190	4	4.5%
Max	< 0.2	0.005	457	< 0.004	< 0.004	0.07	< 0.04	< 0.05	221	0.042	6.6	0.004	101	1.48	16	131	3110	7.8	1830	3080	122	8.4%
Mean	< 0.2	0.005	405	< 0.004	< 0.004	0.02	< 0.04	< 0.05	191	0.026	6.1	0.003	90	0.51	11	125	2787	7.8	1550	2713	73	6.0%

Comparison of Duplicates:

Sample #	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal.
SR at well	< 0.2	0.005	342	< 0.004	< 0.004	0.07	< 0.04	< 0.05	145	< 0.02	6.6	0.004	75.4	1.48	16	120	2390	7.8	1160	2190	4.0	8.4%
Dp-1	< 0.2	0.004	337	< 0.004	< 0.004	0.06	< 0.04	< 0.05	138	< 0.02	< 3.8	0.004	69.2	1.48	20	121	2380	7.7	1160	2180	< 1.0	8.4%
RPD	0%	22%	1%	0%	0%	15%	0%	0%	5%	0%	200%	0%	9%	0%	22%	1%	0%	1%	0%	0%	200%	

SAINTS' REST WATER ANALYSES - DISSOLVED SPECIES

Sample ID	Loc.[1]	Al	As	Ba	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	Ni	K	Se	Si	Ag	Na	Acid.	Alk.	Cl	Cond.	NO3	NO2	pH	SO4	Ion Bal.	Field Measurements pH	Field Measurements Cond.
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l CaCO3		mg/l	umhos/cm	mg/l	mg/l		mg/l	%		umhos/cm
SRW-2	0'	< 0.05	0.011	0.068	525	< 0.004	0.06	< 0.030	< 0.04	< 0.05	259	< 0.020	< 0.03	< 3.2	0.003	21.9	< 0.01	110	< 1.0	339	150	3230	1.12	< 0.01	7.0	1750	6.4%	6.7	3200
SRW-1	100'							< 0.030	0.09																	1840		6.6	3250
SRW-3	250'							< 0.030	0.24																	1710		6.7	3350
SRW-4	350'							< 0.030	0.13																	1740		7.0	3300
SRW-5	450'							< 0.030	0.38																	1730		7.0	3300
SRW-6	525'	< 0.05	0.014	0.061	479	< 0.004	0.068	< 0.030	< 0.04	< 0.05	251	< 0.020	< 0.03	< 3.2	< 0.002	21.0	< 0.01	106	< 1.0	257	157	2880	0.67	< 0.01	7.8	1830	2.9%	7.2	3200
Duplicates																													
SRW-2	0'	< 0.05	0.011	0.068	525	< 0.004	0.06	< 0.030	< 0.04	< 0.05	259	< 0.020	< 0.03	< 3.2	0.003	21.9	< 0.01	110	< 1.0	339	150	3230	1.12	< 0.01	7.0	1750	6.4%	6.7	3200
SRW-A7	0'	< 0.05	0.012	0.059	519	< 0.004	< 0.004	< 0.030	< 0.04	< 0.05	256	< 0.020	< 0.03	< 3.2	< 0.002	23.6	< 0.01	106	< 1.0	336	161	3260	1.19	< 0.01	6.9	1870	2.6%	6.8	
Diff.			0.001	0.009	6						3					1.7		5		1	11	30	0.01		0.1	120		0.1	
Mean			0.011	0.063	522						257.5					22.7		108		336.5	155.5	3245	1.12		6.95	1810		6.75	
RPD			9%	14%	1%						1%					7%		5%		0%	7%	1%	1%		1%	7%		1%	

\Wat\SRW

Notes:
1) Location: Distance (feet) from well.
2) Sampling Date: 07/29/93

Table No. 2.1 : LARK WETLAND WATER ANALYSES – DISSOLVED SPECIES

09/12/93

Sample Loc. 1) No.		Al mg/l	As mg/l	Ba mg/l	Ca mg/l	Cd mg/l	Cr mg/l	Cu mg/l	Fe mg/l	Pb mg/l	Mg mg/l	Mn mg/l	Ni mg/l	K mg/l	Se mg/l	Si mg/l	Ag mg/l	Na mg/l	Acid. mg/l CaCO3	Alk.	Cl mg/l	NO3 mg/l	NO2 mg/l	SO4 mg/l	Ion Bal. %	pH	Cond. umhos/cm
																											Field Measurements
LW 1	a)	9.06	0.437	0.068	1050	< 0.004	0.024	20.9	51.8	0.21	229	0.34	< 0.03	11.9	< 0.2	85.2	< 0.01	509	< 1.0	287	1150	0.67	< 0.01	1820	13.2%	7.2	6200
LW 2	b)	13.3	0.317	0.132	1040	0.005	0.022	14.4	61.1	0.43	243	0.66	< 0.03	16.1	< 0.2	182	< 0.01	504	< 1.0	213	1200	0.69	< 0.01	1970	11.8%	6.9	6400
																											Lab Measurements
W–1	c)	< 0.05	0.019	0.122	866	< 0.003	< 0.004	0.1	< 0.04	0.03	219	0.88	< 0.03	5.6	0.003	29	0.03	446	10	265	1240	5.17	0.02	2050	–0.6%	7.0	6280
W–A	c)	< 0.05	0.016	0.063	892	< 0.003	< 0.004	0.1	< 0.04	0.03	215	0.88	< 0.03	5.6	< 0.002	27.1	< 0.01	462	12	273	1220	5.14	< 0.01	1930	2.2%	7.0	6300
RPD			17%	64%	3%			0%		0%	2%	0%		0%		7%		4%	18%	3%	2%	1%		6%		0%	0%
W–2	d)	< 0.05	0.011	0.049	917	< 0.003	< 0.004	0.16	< 0.04	0.03	211	0.19	< 0.03	5.2	0.003	36.1	0.02	428	13	297	1170	5.96	< 0.01	1980	1.6%	7.2	6400
W–B	d)	< 0.05	0.010	0.090	897	< 0.003	< 0.004	0.09	< 0.04	< 0.03	207	0.21	< 0.03	5.6	0.003	31.6	< 0.01	426	12	281	1180	5.92	< 0.01	2050	0.6%	7.2	6320
RPD			10%	59%	2%			56%			2%	10%		7%	0%	13%		0%	8%	6%	2%	1%		3%		0%	1%
W–3	e)	< 0.05	0.009	0.062	907	< 0.003	< 0.004	0.1	< 0.04	0.03	213	0.21	< 0.03	4.6	0.004	34.7	< 0.01	432	9	276	1180	6.04	< 0.01	1940	2.3%	7.4	6350
W–C	e)	< 0.05	0.012	0.031	899	< 0.003	< 0.004	0.16	< 0.04	< 0.03	210	0.18	< 0.03	6.2	< 0.003	32.6	0.02	427	10	302	1180	6.04	< 0.01	2070	–0.2%	7.4	6340
RPD			29%	67%	1%			46%			1%	15%		30%		6%		1%	11%	9%	0%	0%		6%		0%	0%
Difference 3)		–100%	–97%	–37%	–14%	–100%	–100%	–99%	–100%	–94%	–10%	–17%		–64%		–73%		–14%		13%	1%	740%		6%		2%	1%
LW 3	f)	< 0.12	0.016		853	< 0.004	< 0.004	< 0.03	< 0.04	< 0.003	210	0.06	< 0.03	9.37	0.003	30.4	< 0.01	432		329	1260	3.38	0.16	2000	–2.2%	7.6	6310
Difference 4)		–100%	–96%		–18%	–100%	–100%	–100%	–100%	–100%	–11%	–84%		–36%		–74%		–15%		32%	7%	397%		6%		8%	0%
Difference 5)			25%		–5%			–100%			–1%	–81%		71%		–8%		–1%		16%	6%	–41%	5300%	–0%		6%	–0%

Notes:
1) Location: a) 100' WSW of concrete structure; b) south end of concrete structure; c) West; d) East; e) Middle; f) West Pond.
2) Sampling Dates: LW 1&2 08/02/93 (before removal of tailings); W 08/20/93 (during removal of tailings); LW 3 09/01/93.
3) Difference: 100 x (Avg W – Avg LW 1&2) / Avg LW 1&2 4) Difference: 100 x (LW 3 – Avg LW 1&2) / Avg LW 1&2
5) Difference: 100 x (Avg W – LW 3) / LW 3

Table No. 2.2 : SEEPS IN LARK WETLAND AREA – DISSOLVED SPECIES

Sample Loc. 1) No.		Al mg/l	As mg/l	Ba mg/l	Ca mg/l	Cd mg/l	Cr mg/l	Cu mg/l	Fe mg/l	Pb mg/l	Mg mg/l	Mn mg/l	Ni mg/l	K mg/l	Se mg/l	Si mg/l	Ag mg/l	Na mg/l	Acid. mg/l CaCO3	Alk.	Cl mg/l	NO3 mg/l	NO2 mg/l	SO4 mg/l	Ion Bal. %	pH	Cond. umhos/cm
Seep #1	a)		< 0.005		752			0.3	0.43	< 0.05	187							458		290	777			1368		7.9	5756
Seep #2	b)		< 0.005		936			0.47	15.46	< 0.05	203							501		340	827			1450		7.6	5632

Field Measurements

SO4 mg/l	Eh	pH	Cond. umhos/cm
1250	370	6.8	4400
1000	510	6.5	3500

\Wet\LW

Notes:
1) Location: a) N 2493; E 20033; b) N 2519; E 19684.
2) Sampling Date: 02/09/93

LARK WETLAND: WATER ANALYSES

11/03/93

Sampling Date: 10/22/93

Location	Al	As	Ca	Cd	Cr	Cu	Fe	Pb	Mg	Mn	K	Se	Na	Zn	Acidity	Cl	Cond.	pH	SO4	TDS	TSS	Ion Bal
Lark Inlet	< 0.2	0.006	650	< 0.004	< 0.004	0.04	< 0.04	< 0.05	204	0.367	5.0	0.004	394	0.03	20	1100	5450	7.5	1630	4700	74	5.2%
Lark Outlet	< 0.2	0.005	720	< 0.004	< 0.004	0.05	< 0.04	< 0.05	162	0.451	6.4	0.004	356	0.02	8	1050	5240	7.7	1810	4430	52	−0.4%

Document 6 Phosphate Rock Experiment 12/11/93

With Agitation:

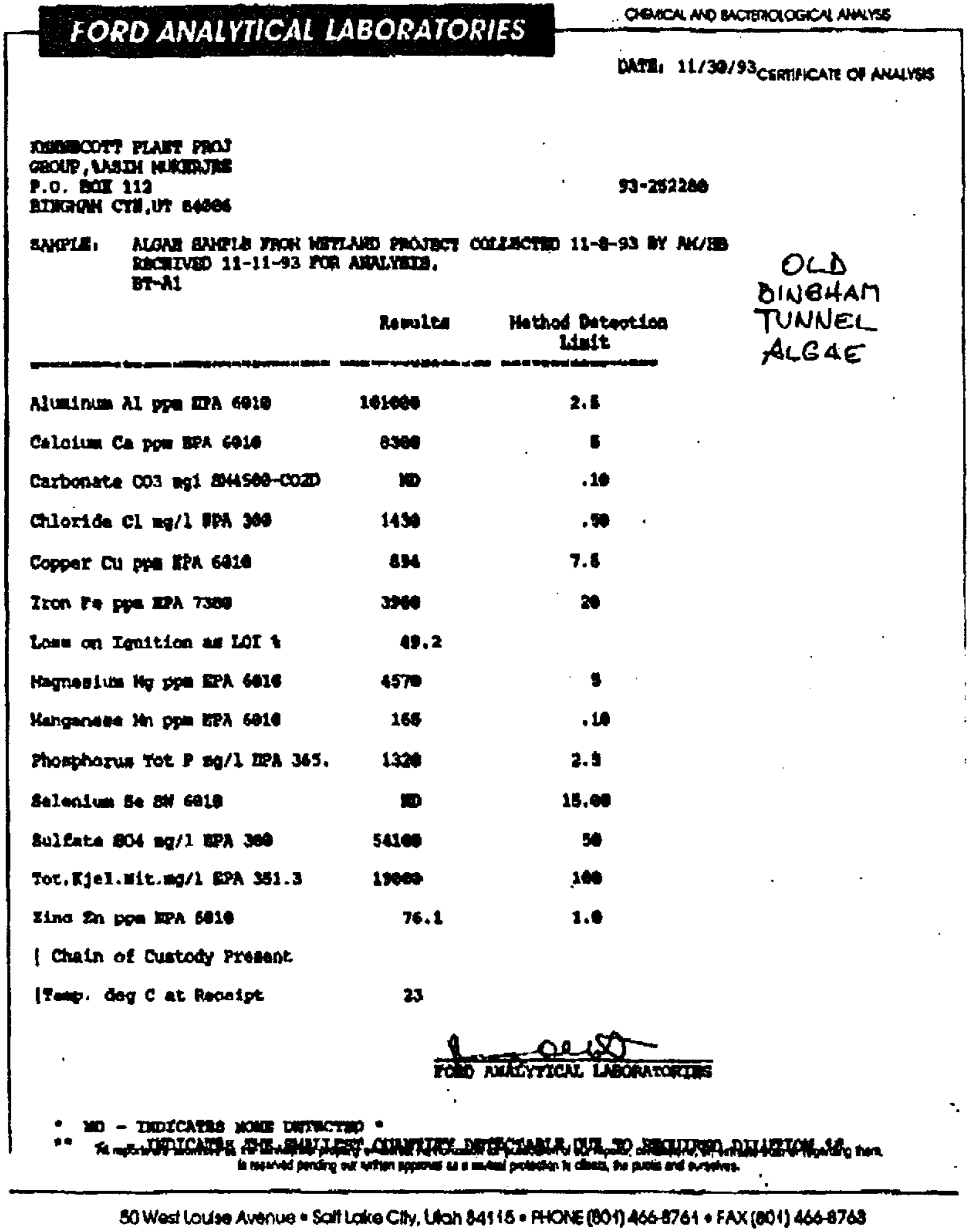
			100 ml Leachwater						250 ml Leachwater						500 ml Leachwater					
			1 g		5 g		10 g		1 g		5 g		10 g		1 g		5 g		10 g	
Date	Time	Day	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH
11/15/93	17:30	0	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3
11/16/93	17:30	1	275	3.9	255	4.1	240	4.2	290	3.8	275	4.0	260	4.1	280	3.8	285	3.9	275	3.9
11/18/93	08:00	3	270	3.3	265	3.6	245	3.7	295	3.2	280	3.3	275	3.4	305	3.2	290	3.3	280	3.3
11/19/93	07:45	4	245	3.5	240	3.8	225	3.8	275	3.3	260	3.5	225	3.6	270	3.3	265	3.5	260	3.6
11/20/93	07:15	5	285	3.5	280	3.8	240	3.8	310	3.3	295	3.5	260	3.6	305	3.3	300	3.4	300	3.6
11/22/93	07:20	7	320	3.4	315	3.8	285	3.7	345	3.2	330	3.5	290	3.7	345	3.3	345	3.4	335	3.6
11/23/93	07:50	8	365	3.4	410	3.8	325	3.7	370	3.2	365	3.5	325	3.7	380	3.2	380	3.3	380	3.5
11/24/93	07:05	9	410	3.3	405	3.8	390	3.7	400	3.1	410	3.6	360	3.8	415	3.1	425	3.2	420	3.5
11/26/93	08:00	11	450	3.2	400	3.8	415	3.6	425	3.0	435	3.6	385	3.8	460	3.1	445	3.2	435	3.5
11/29/93	08:45	14	465	3.2	400	3.8	420	3.6	445	3.0	450	3.6	400	3.8	475	3.0	465	3.2	450	3.5
12/01/93	09:45	16	460	3.3	395	3.7	410	3.5	425	3.1	440	3.6	395	3.7	485	3.0	460	3.2	455	3.6
12/03/93	08:30	18	450	3.3	400	3.8	405	3.7	430	3.0	430	3.5	385	3.7	480	3.0	450	3.3	445	3.5
12/06/93	07:15	21	430	3.3	395	3.8	400	3.8	430	3.1	425	3.5	370	3.7	465	3.0	425	3.2	425	3.5
12/08/93	09:30	23	410	3.2	400	3.7	390	3.8	435	3.0	415	3.4	365	3.6	450	2.9	405	3.3	405	3.4
12/11/93	10:00	26	395	3.2	400	3.7	390	3.9	430	3.1	405	3.4	360	3.6	445	2.9	395	3.3	395	3.4

Without Agitation:

			100 ml Leachwater						250 ml Leachwater						500 ml Leachwater					
			1 g		5 g		10 g		1 g		5 g		10 g		1 g		5 g		10 g	
Date	Time	Day	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH	Eh	pH
11/15/93	17:30	0	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3	330	3.3
11/16/93	17:30	1	310	3.8	265	4.0	235	4.0	300	3.9	285	3.9	265	4.0	305	3.7	295	3.8	280	4.0
11/18/93	08:00	3	265	3.3	250	3.5	210	3.6	260	3.2	265	3.3	220	3.8	280	3.1	280	3.2	245	3.8
11/19/93	07:45	4	315	3.3	205	3.9	185	4.1	265	3.2	205	3.7	195	3.4	275	3.3	225	3.6	210	4.0
11/20/93	07:15	5	340	3.3	235	3.9	220	4.1	300	3.2	245	3.7	230	3.5	305	3.2	255	3.6	250	4.0
11/22/93	07:20	7	360	3.3	265	3.9	250	4.1	335	3.2	285	3.7	270	3.5	330	3.3	285	3.5	285	3.9
11/23/93	07:50	8	385	3.4	295	3.9	290	4.1	365	3.2	330	3.8	305	3.6	360	3.2	320	3.5	325	3.9
11/24/93	07:05	9	410	3.4	330	3.9	325	4.1	405	3.2	360	3.7	340	3.7	380	3.2	360	3.4	355	3.9
11/26/93	08:00	11	425	3.4	370	3.9	370	4.1	445	3.3	400	3.7	390	3.8	410	3.2	385	3.3	400	3.8
11/29/93	08:45	14	440	3.4	400	3.9	395	4.1	470	3.3	445	3.7	415	3.9	440	3.2	415	3.3	435	3.8
12/01/93	09:45	16	445	3.4	405	3.9	390	3.8	460	3.4	455	3.7	395	3.7	465	3.1	395	3.4	430	3.8
12/03/93	08:30	18	430	3.3	400	3.6	390	3.8	450	3.3	445	3.6	390	3.7	460	3.2	410	3.4	425	3.6
12/06/93	07:15	21	410	3.3	395	3.4	380	3.7	440	3.2	430	3.5	390	3.6	455	3.2	410	3.4	420	3.5
12/08/93	09:30	23	400	3.2	390	3.5	385	3.6	430	3.2	415	3.5	385	3.6	450	3.1	405	3.3	410	3.4
12/11/93	10:00	26	395	3.2	390	3.3	385	3.6	425	3.1	405	3.4	385	3.6	450	3.1	405	3.3	400	3.4

Leachwater from Process Plant Discharge, collected 11/10/93
Phosphate Sand,Ca10(F2)(PO4)6 . nCaCO3; Code 30 from Texasgulf Inc., Glennwood, North Carolina.

Document 7 Algae, Old Bingham Tunnel 11/30/93



FORD ANALYTICAL LABORATORIES

CHEMICAL AND BACTERIOLOGICAL ANALYSIS

DATE: 11/30/93 CERTIFICATE OF ANALYSIS

KENNECOTT PLANT PROJ
GROUP,VASIM MUKERJEE
P.O. BOX 112
BINGHAM CYN,UT 84006

93-252280

SAMPLE: ALGAE SAMPLE FROM WETLAND PROJECT COLLECTED 11-8-93 BY AK/HB
RECEIVED 11-11-93 FOR ANALYSIS.
BT-A1

OLD
BINGHAM
TUNNEL
ALGAE

	Results	Method Detection Limit
Aluminum Al ppm EPA 6010	101000	2.5
Calcium Ca ppm EPA 6010	8300	5
Carbonate CO3 mgl SM4500-CO2D	ND	.10
Chloride Cl mg/l EPA 300	1430	.50
Copper Cu ppm EPA 6010	894	7.5
Iron Fe ppm EPA 7380	3900	20
Loss on Ignition as LOI %	49.2	
Magnesium Mg ppm EPA 6010	4570	5
Manganese Mn ppm EPA 6010	165	.10
Phosphorus Tot P mg/l EPA 365.	1320	2.5
Selenium Se SW 6010	ND	15.00
Sulfate SO4 mg/l EPA 300	54100	50
Tot.Kjel.Nit.mg/l EPA 351.3	19000	100
Zinc Zn ppm EPA 6010	76.1	1.0
| Chain of Custody Present		
|Temp. deg C at Receipt	23	

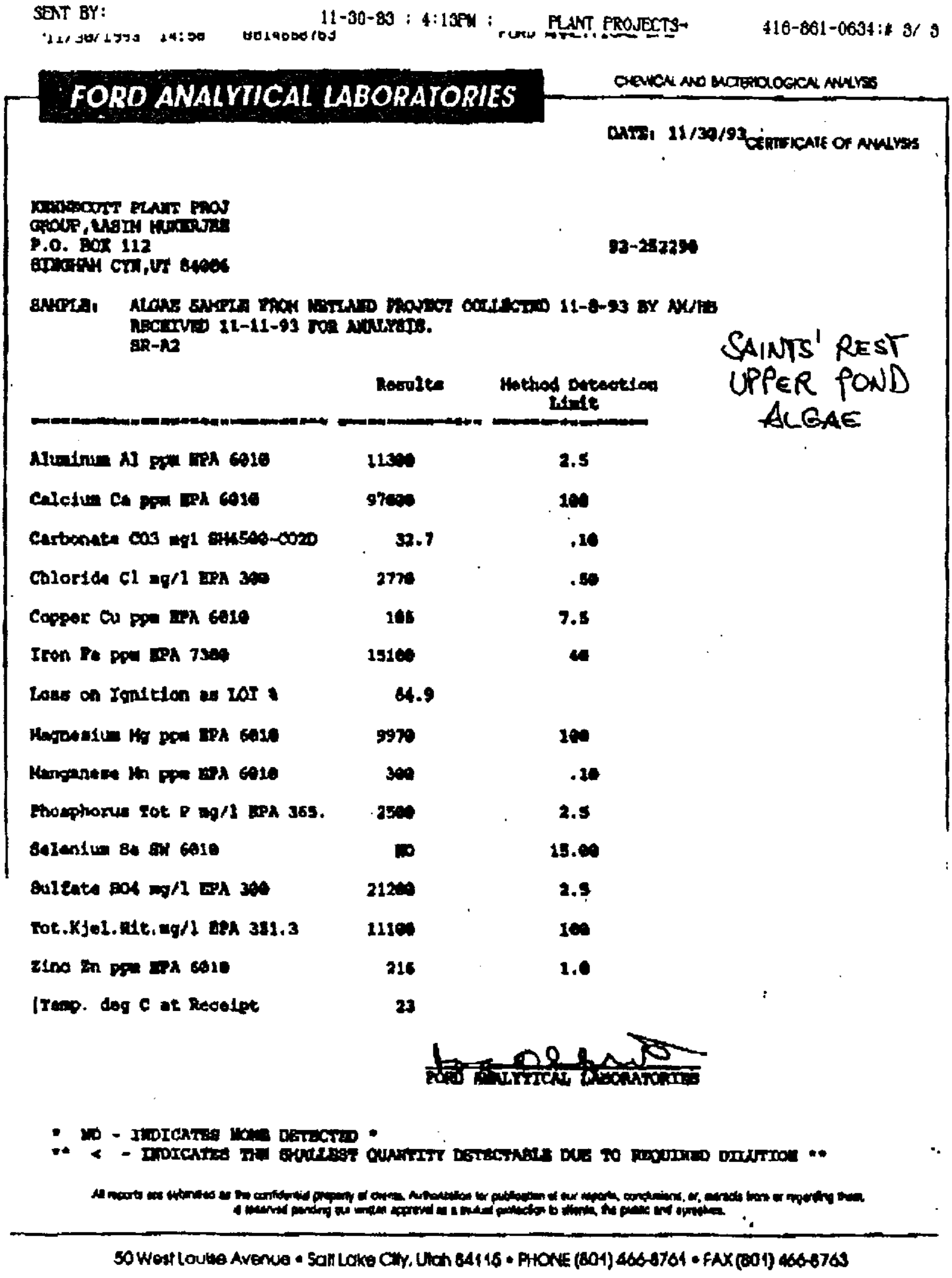
FORD ANALYTICAL LABORATORIES

* ND - INDICATES NONE DETECTED *

** INDICATES THE SMALLEST QUANTITY DETECTABLE DUE TO REQUIRED DILUTION 10

[illegible] regarding them, is reserved pending our written approval as a mutual protection to clients, the public and ourselves.

50 West Louise Avenue • Salt Lake City, Utah 84115 • PHONE (801) 466-8761 • FAX (801) 466-8763



SENT BY: 11-30-93 ; 4:13PM ; PLANT PROJECTS→ 416-861-0634;# 3/ 5

11/30/1993 14:58 8014666763

FORD ANALYTICAL LABORATORIES

CHEMICAL AND BACTERIOLOGICAL ANALYSIS

DATE: 11/30/93 CERTIFICATE OF ANALYSIS

KENNECOTT PLANT PROJ
GROUP,NASIM MUKERJEE
P.O. BOX 112
BINGHAM CYN,UT 84006

93-252250

SAMPLE: ALGAE SAMPLE FROM WETLAND PROJECT COLLECTED 11-8-93 BY AM/HB
RECEIVED 11-11-93 FOR ANALYSIS.
SR-A2

SAINTS' REST
UPPER POND
ALGAE

	Results	Method Detection Limit
Aluminum Al ppm EPA 6010	11300	2.5
Calcium Ca ppm EPA 6010	97600	100
Carbonate CO3 mgl SM4500-CO2D	32.7	.10
Chloride Cl mg/l EPA 300	2770	.50
Copper Cu ppm EPA 6010	105	7.5
Iron Fe ppm EPA 7380	15100	40
Loss on Ignition as LOI %	64.9	
Magnesium Mg ppm EPA 6010	9970	100
Manganese Mn ppm EPA 6010	300	.10
Phosphorus Tot P mg/l EPA 365.	2500	2.5
Selenium Se SW 6010	ND	15.00
Sulfate SO4 mg/l EPA 300	21200	2.5
Tot.Kjel.Nit.mg/l EPA 351.3	11100	100
Zinc Zn ppm EPA 6010	216	1.0
[Temp. deg C at Receipt	23	

FORD ANALYTICAL LABORATORIES

* ND - INDICATES NONE DETECTED *
** < - INDICATES THE SMALLEST QUANTITY DETECTABLE DUE TO REQUIRED DILUTION **

50 West Louise Avenue • Salt Lake City, Utah 84115 • PHONE (801) 466-8761 • FAX (801) 466-8763

WELL REPORT

ABC-04

KENNECOTT COPPER CORPORATION
SALT LAKE COUNTY, UTAH

Prepared by

Adrian Brown Consultants, Inc.
155 South Madison Street
Suite 302
Denver, Colorado 80209

October, 1990

6.0 GEOLOGY

6.1 Stratigraphic Summary

The drilling results indicate that alluvium in this portion of Bingham Canyon is at least 990 feet thick. The dominant clast lithology of the alluvium is sedimentary sandstone and quartzite from the surface to 190 feet. Volcanics become the dominant clast lithology from 190 feet to 980 feet. Several thin brown clay zones are interbedded with the alluvial sediments.

A green clay, not seen before at this location, was encountered at 980 feet along with the brown clay. This changed rapidly to a dull green clay mottled with black and brown at 990 feet (possibly a weathered volcanic). From 997 to 1000 feet, the clay changed to a white to light gray, non-plastic material with clasts, possibly a volcanic ash. Underlying the clay is an unweathered massive quartzite, extending from 1000 to 1007 feet (1007 feet was the maximum possible depth with the available drill rods). Based on regional geology, the quartzite may either represent a large boulder zone within or near local volcanic bedrock, or a large quartzite fragment within the alluvial section.

6.2 Lithologic Log

The following are lithologic details of the intervals drilled:

DEPTH (ft)	DESCRIPTIONS
0-20	SAND mostly quartzite surface fill

DEPTH (ft)	DESCRIPTIONS
20-75	SILTY SAND and GRAVELLY SAND alluvial material being 95% sedimentary brown and light tan sandstone and light gray quartzite, angular to subangular; moderately to poorly sorted; containing some silt; 5% gray/black matrix porphyry volcanics
75-115	SANDY CLAY appearance of brown clay, still dominantly sedimentary SS/qtzite
115-125	GRAVELLY SAND dominantly SS/qtzite alluvial material as above
125-128	SANDY CLAY as above
128-187	GRAVELLY SAND mostly SS/qtzite alluvial material
187-190	CLAY light brown
190-283	GRAVELLY SAND and CLAY alluvial material changing to dominantly purple and black matrix volcanic porphyry and lesser amounts of SS/qtzite sedimentary material as above; thin interbedded brown clay zones at 225 to 228 and 280 to 283
283-388	GRAVELLY SAND and CLAY less massive sequence of gravelly sand volcanic alluvial material and some minor percentages of sedimentary alluvial material as above; more frequent appearance of thin brown clay zones at 300 to 302, 315 to 317, 328 to 330, 358 to 360, and 383 to 388
388-468	SANDY CLAY and CLAY clay becoming dominant lithology modified with some black and gray matrix porphyry volcanics and lesser amounts of sandstone and quartzite; brown clay zone at 464 to 468
468-555	GRAVELLY SAND and CLAY more massive sequence of 80% volcanics and 20% SS/qtzite alluvial sands interbedded with thin brown clay zones at 494 to 503 and 552 to 555
555-605	GRAVELLY SAND and CLAY less massive sequence of alluvial volcanic sands and lesser amounts of SS/qtzite, interbedded with brown clay zones at 575 to 580 and 600 to 605

DEPTH (ft)	DESCRIPTIONS
605-860	GRAVELLY SAND and CLAYEY SAND much more massive sequence of 80% volcanic alluvial material and 20% sedimentary SS/qtzite material; thin interbedded alluvial sands modified with brown clay at 695 to 700 and 735 to 740
860-870	CLAY brown clay zone
870-900	CLAYEY SAND alluvial material, mostly volcanics as above with brown clay
900-925	GRAVELLY SAND alluvial material, mostly volcanics as above, no clay
925-975	CLAYEY SAND alluvial material, mostly volcanics as above with brown clay
975-980	GRAVELLY SAND thin alluvial sand as above, no clay
980-990	CLAYEY SAND alluvial sand as above with brown clay and additional green clay
990-997	CLAY dull green clay mottled with brown and black specks and streaks
997-1000	CLAY white to light gray non-plastic clay containing sparse poorly sorted volcanic clasts, moderately friable with applied pressure; volcanic ash appearance
1000-1007	QUARTZITE hard, competent, white to light gray quartzite zone; angular, even size distribution of cuttings; much slower drilling rate

TD1007

Document 9 Waste Rock Analyses 1970/1980

FAX HEADER PAGE

KENNECOTT CORPORATION
PLANT PROJECTS GROUP
10200 SOUTH 8400 WEST
P.O. BOX 112
BINGHAM CANYON, UTAH 84006-0112

FAX NUMBER: (801) 569-6854
CONFIRMATION NUMBER: (801) 569-6810 - SUSAN

TIME: 11:00 DATE: 10/20/93

TO: MARGARETE KALIN

LOCATION: BOOJUM RESEARCH (416) 861-0634

FROM: HELMAR G. BAYER (801) 569-7301

LOCATION: SLC

NUMBER OF PAGES (INCLUDING HEADER PAGE): 1

SPECIAL INSTRUCTIONS:

The analysis of waste rock does not seem to be a routine activity in Kennecott. However, we will receive reports from the 1970s and 1980s with detailed analyses. We will fax them to you as soon as they arrive. In the meantime, we give you a few sentences from a report we found:

Typical low-grade sulfide mine waste runs from less than 0.1 to 0.3 % Cu, mostly in form of chalcopyrite or secondary copper sulfides disseminated in quartzite or intrusive host rock. The principal sulfide species is pyrite, generally 5 to 50 times more prevalent than the copper sulfides.
Half the waste contains 2 to 4 % pyrite and the other half, 1 to 2 % (exclusive of ore and metalimestone zones). The waste also contains 0.13 % copper as sulfides, giving a pyrite-to-copper sulfide ratio of 17.5 : 1.

Regards,
Helmar

MIXED TAILS AREA - WATER TREATMENT WETLAND

Assumptions:

1) Construction will follow natural grade as much as possible and will be in compliance with the dam safety regulations.
2) Water supply is engineered from various possible sources, i.e. quantity and quality of water are controlled. There is no danger of flooding.
3) Water supply and discharge will be seasonal to a large extent: main inflow will be contaminated storm water (snow melt February through end of May); main outflow will be used for agricultutral irrigation (April through October). The possibility exists to store storm water and treated water in additional reservoirs in order to provide sufficient retention time for water treatment in the wetland system.

Questions:

1) What is the desired ratio of areas of polishing ponds to ARUM ponds?
2) What are desired depths of polishing ponds and ARUM ponds?
3) What should the transitions from one pond to the next be (aerated or not)?
4) Can the batching pond, which functions as feed water preparation pond, be an ARUM pond at the same time?
5) What water quality and quantity can this project handle? (Water discharge quality must meet agricultural irrigation requirements).
6) What design improvements can you suggest? What impact will these improvements have on process capacities?
7) What are the operating requirements and costs for this system?
8) How many cattail floats do we need? What are optimal design parameters and costs (materials, dimensions, anchoring, etc.)?
9) What range of water level control do we need?
10) What are the comparable water treatment costs (investment and operating costs) by conventional methods?

Document 11 Phosphate Rock analysis. Letters from Texasgulf Export Corporation

Texasgulf Export Corporation
an elf aquitaine company

3101 Glenwood Avenue
P.O. Box 30321
Raleigh, NC 27622-0321

Ronald C. Knutson
President
Office (919) 881-2851
Telex 802516 TG INT SLS RAL
Fax (919) 881-2995

June 2, 1992

Fax: 9-1-416-861-0634

Ms. Margarete Kalin
President
Boojum Research Limited
468 Queen St. E., Suite 400
Toronto, Ontario M5A 1T7

Dear Ms. Kalin:

As promised, following is the analytical information for your review:

A) Phosphate by product 2106

	Sample I	Sample II
Cd	7 ppm	6 ppm
As	3 ppm	3 ppm
Cu	11 ppm	6 ppm
Mn	17 ppm	26 ppm
Ni	14 ppm	14 ppm
Cr	88 ppm	96 ppm
H_2O	8.72%	8.59%
Zn	77 ppm	70 ppm
Pb (Total)	11.5 µg/gram	12.1 µg/gram
U (Total)	28 µg/gram	22 µg/gram
Th (Total)	<50 µg/gram	<50 µg/gram
Ra^{226}	27.9 ± 1.6 pCi/gram	20.0 ± 1.4 pCi/gram

B) Phosphate Sand (Code 30 - presumably similar for Code 31)

Pb (Total	13.6 µg/gram
U (Total)	155 µg/gram
Th (Total)	<50 µg/gram
Ra^{226}	28.7 ± 1.2 pCi/gram
H_2O	0.87%

Sincerely,

Ronald C. Knutson
President
Texasgulf Export Corporation

RCK/jss

MATERIAL SAFETY DATA SHEET

PHOSPHATE ROCK, 67% BPL

AVOID BREATHING DUST-CAN CAUSE
RESPIRATORY IRRITATION

Texasgulf Inc.
Glenwood at Glen Eden
P.O. Box 30321
Raleigh, North Carolina 27622-0321 (919)881-2700
TRANSPORTATION EMERGENCIES. CALL (800) 424-9300 (CHEMTREC)
HEALTH EMERGENCIES. CONTACT YOUR LOCAL POISON CENTER

PRODUCT INFORMATION

CHEMICAL NAME AND SYNONYMS Fluorapatite, Calcium Fluorphosphate

TRADE NAME AND SYNONYMS Phosphate Rock, 67% BPL

CHEMICAL FAMILY Mineral

FORMULA $Ca_{10}(F_2)(PO_4)_6 \cdot XCaCO_3$

CAS NUMBER 65996-94-3

LISTED IN: ____ OSHA SUBPART Z ____ ACGIH TLV LISTS; ____ NTP LIST;

____ IARC MONOGRAPH; __X__ NONE OF THE ABOVE

TYPICAL COMPOSITION	%
Calcium, as CaO	48
Phosphate, as P_2O_5	30
Fluoride, as F	3.7

PHYSICAL DATA

BOILING POINT (°F) N/A

MELTING POINT (°F) N/A

VAPOR PRESSURE (mm Hg.) N/A

SPECIFIC GRAVITY (H_2O=1) 2.9 to 3.1

VAPOR DENSITY (AIR=1) N/A

PERCENT, VOLATILE BY VOLUME (%) N/A

SOLUBILITY IN WATER Negligible

EVAPORATION RATE (______ =1) N/A

APPEARANCE AND ODOR Brownish black, granular solid.

pH N/A

OTHER 90 pounds per cubic foot loose
100 pounds per cubic foot tamped

FIRE AND EXPLOSION HAZARD INFORMATION

FLASH POINT (Method Used) Not combustible

FLAMMABLE LIMITS LEL N/A UEL N/A

EXTINGUISHING MEDIA N/A

SPECIAL FIRE FIGHTING PROCEDURES Wear self contained breathing apparatus and full protective clothing when entering enclosed area.

UNUSUAL FIRE AND EXPLOSION HAZARDS Temperatures above 1800°F may cause release of irritating or toxic phosphorus oxides and fluoride gases, SiF_4 and HF.

HEALTH INFORMATION

THRESHOLD LIMIT VALUE None established. OSHA dust limit of 15/mg/m^3 and the ACGIH nuisance dust TLV of 10/mg/m^3 for the eight hour time weighted average applies..

EFFECTS OF OVEREXPOSURE EYE-Irritant. SKIN-May be slightly irritating. INHALATION-Discomfort in breathing, respiratory irritation. INGESTION-Large amounts (over 1/2 pound) could cause (due to fluorides)nausea, vomiting, diarrhea, stomach and abdominal pain, cramps and fluorosis.

(N/A = Not Applicable)

12/28/88

Document 12 Letter from M.A. Williamson to H.G. Bayer re. ROVERS Report, December 9, 1993

MEMORANDUM

TO: Helmer G. Bayer File: 1212T

FROM: Mark A. Williamson

RE: ROVERS Geochemical Report

DATE: December 9, 1993 1:09 pm

Per your request, I contacted Robert Van Everdingen regarding the ROVERS research report of their PHREEQE model for leachwater-phosphate reaction. I found Dr. Van Everdingen to be quite pleasant and willing to answer my concerns.

As you and I have discussed, there are several noticeable inconsistencies in the ROVERS report. However, in all fairness to Robert Van Everdingen, he was not provided sufficient information (e.g. temperature and redox potential of leach solutions) or time to produce a well thought out product.

Some noteworthy items from my discussion with Van Everdingen:

- He reports hematite (Fe_2O_3) as the principle iron precipitate because it is what PHREEQE reports as the most thermodynamically oversaturated phase for iron. He did agree with me, however, that other phases like ferrihydrite or jarosite are kinetically favored and more likely to form. He stated that allowing hematite to form in the computer simulations would not affect other calculations of saturation indices, but I suspect that he is incorrect in that assumption. Ferrihydrite or jarosite would either one allow higher equilibrium concentrations of ferric iron, which may facilitate the formation of other iron-bearing solids (e.g. strengite, $FePO_4 \cdot 2H_2O$)

- His model provided phosphate to solution for reaction with dissolved components in the leachwater by simply adding dissolved PO_4^{3-} (counterbalanced with calcium to maintain electro-neutrality). This approach may have compromised the result he obtained, because the formation of phosphate-bearing solids with low solubilities (e.g. zinc phosphate) could easily have kept PO_4 concentrations in solution low enough to never reach the concentrations listed at the top of his table.

- He had no clear indication of why the molecular weight for phosphate was shown as 135 gm/mol. It was probably an error. Note also that in the bottom portion of his model output the molecular weight listed for gypsum is really the molecular weight of anhydrite (anhydrite is $CaSO_4$ compared to $CaSO_4 \cdot 2H_2O$ for gypsum).

- The PHREEQE model results suggest no formation of iron or aluminum phosphates, which is very inconsistent with advertised claims of the utility of phosphate treatment, which can precipitate ferric iron, limiting acid production by minimizing hydrolysis reaction and reducing any unwanted oxidation of residual sulfide minerals in waste rock piles.

My conclusion is consistent with what I related to you earlier: I do not believe that the reported PHREEQE exercise provides any real insight into the utility of phosphate treatment of leachwater.

APPENDIX B PHOSPHATE ROCK EXPERIMENTS AND CHARACTERISTICS OF THE GENERAL GEOLOGY OF KENNECOTT

B.1 Laboratory Bench Scale Systems for Testing AMD Iron and Aluminum Precipitation Induced by Natural Phosphate Rock.

B.1.1 Introduction

A laboratory bench scale system has been designed for quantitatively assessing the effectiveness of natural phosphate rock (NPR) for precipitating iron and aluminum in copper-zinc AMD and high sulphur coal AMD.

B.1.2 Design

The laboratory experimental system design is shown in Schematic 1.

A total of 4.1 kg (3 litres) of NPR, sized 3-5 mm, is packed as three alternate layers into the inner column "H", separated by equal 6 cm layers of styrofoam packing material, sized 2.2 - 2.5 cm. The inner column has a diameter of 15 cm and a height of 42 cm.

This prevents the phosphate rock from forming hardened, concreted layers. With accumulating precipitate, precipitates can settle into the large void spaces in the styrofoam layers.

The column is suspended in an acrylic Plexiglass outer sleeve. Water level is controlled by the overflow port in the outer sleeve. The water level is fixed at a level just above the upper NPR layer in the column.

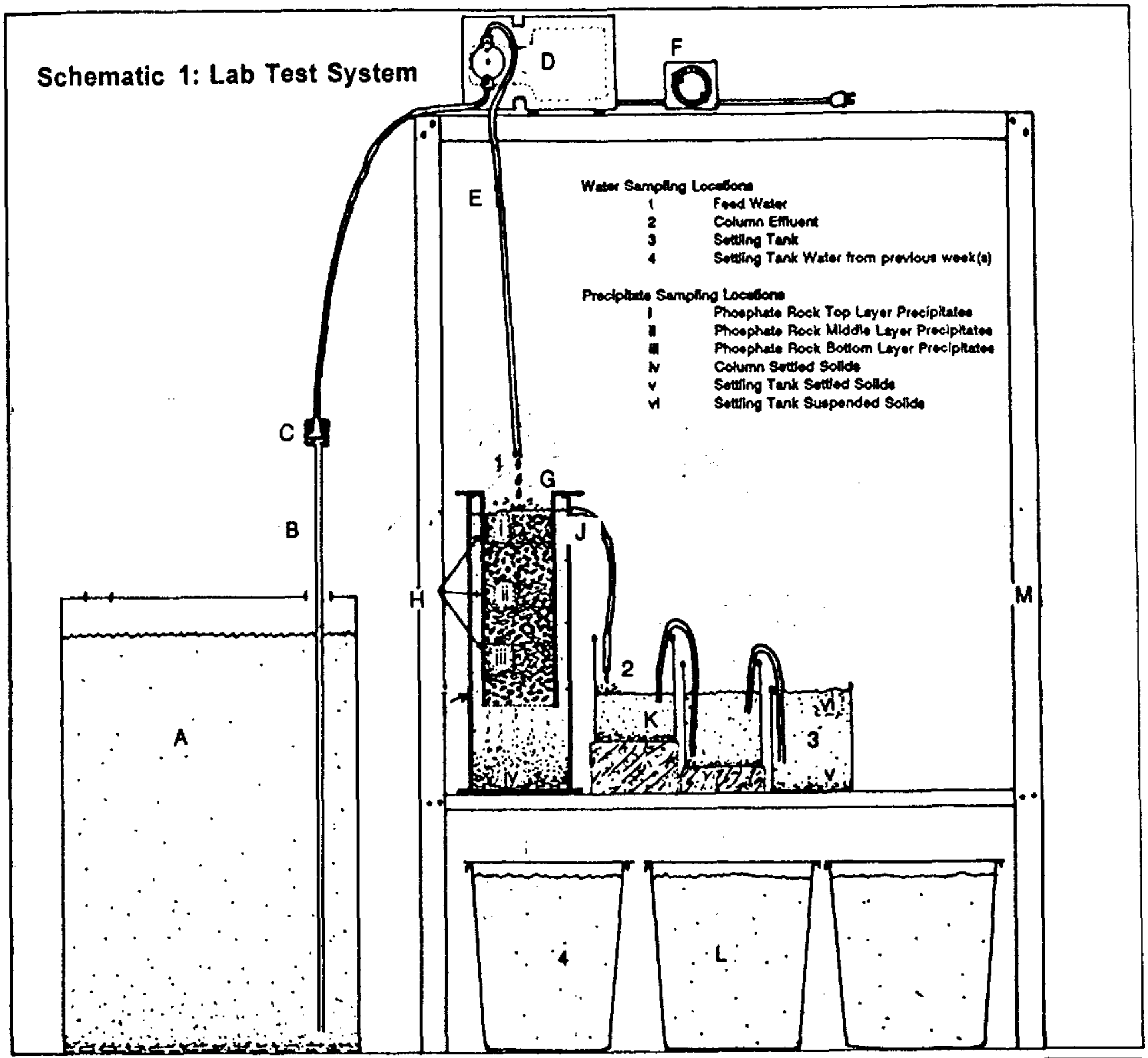
Water passing through the NPR-styrofoam layers in the inner column has a residence time of 0.8 days. Water flows from the inner column into the outer sleeve through a bottom sieve.

The combined residence time of water in the inner column and outer sleeve is 6.8 days. Water overflows from the outer sleeve through the overflow port "J" into a series of settling containers "K".

B.1.3 Operation

AMD water is fed from Feed Tank A into the column "H", by a pump set at 50 mL/min, which operates for two 30 minute periods each day. Therefore, three litres of AMD is treated per day. The experiment is run for as long as the AMD supply lasts.

Schematic 1: Lab Test System



Water Sampling Locations

1	Feed Water
2	Column Effluent
3	Settling Tank
4	Settling Tank Water from previous week(s)

Precipitate Sampling Locations

i	Phosphate Rock Top Layer Precipitates
ii	Phosphate Rock Middle Layer Precipitates
iii	Phosphate Rock Bottom Layer Precipitates
iv	Column Settled Solids
v	Settling Tank Settled Solids
vi	Settling Tank Suspended Solids

Lab System Components

A	200 L Plastic Feed Tank
B	Feed Line, 4 mm I.D. rubber tube
C	One-way valve
D	Plastic Piston Pump, adjusted to 50 mL/min. Operates twice daily for 30 min. 3 L/day.
E	Pump Outlet Line, 4 mm I.D. rubber tube
F	Electrical Timer, set 30 min on twice daily
G	Acrylic Packing Chamber 15 cm diam., 42 cm tall. 6 L capacity. Perforated bottom.
H	Column packing. Three 1 L phosphate rock layers, alternating with three 1 L styrofoam packing chunks (cheezies). Fibreglass window screen disc placed at phosphate rock- cheezie interface.
I	Acrylic Outer Sleeve, 20 cm diam x 57 cm tall. 18 L capacity.
J	Overflow port, 6 mm I.D. polyethylene tubing.
K	Glass aquarium 20 cm tall, 15 cm wide, 30 cm long, 9 L capacity. Three in series connected by siphons.
L	Plastic Pails, 35 cm tall 26 cm diameter, 21 L capacity, one filled per week of operation.
M	Steel Support Frame.

B.1.4 Results

In the experiment using Cu-Zn AMD, most of the iron precipitates, formed during the NPR treatment, settled in the NPR and styrofoam layers (i - iii), or at the bottom of the outer sleeve (iv).

Some suspended precipitates, or precipitates formed later in the settling container "K", settled in the settling containers. Precipitates floating on the surface of the settling containers (top, vi) were collected separately from the bottom (v) precipitates.

Each week, the inner column was dismantled, and precipitates collected from the NPR and styrofoam layers. The washed NPR was then repacked into the column.

The wet, hydrated precipitate volumes were determined and dry weights of precipitates were measured. The precipitates collected after the first week of operation were sent for ICP analysis. These precipitates contained mainly iron, phosphorus, aluminum and gypsum, along with some copper and zinc.

From Schematic 1, the samples at (i) ,(ii) and (iii) contained 15%, 13% and 15% Fe, were 0.9%, 1.1% and 1.6% aluminum, and 0.5%, 0.7% and 1.2% copper. Samples from the top and bottom of the settlers assayed 1.1% and 1.0% iron, 2.1% and 1.4% aluminum, and surprisingly 25.6% and 9.8% copper.

The water was sampled at the same time. At the feed tank it contained 682 mg/L iron, 103 mg/L aluminum and 151 mg/L copper, and at the settling tank it contained 0.02 mg/L of iron, 0.29 mg/L aluminum and 10.9 mg/L copper. Elements such as calcium, cadmium, magnesium, manganese, sodium and zinc were not extracted from the solution at this sampling date.

The system receiving Cu-Zn AMD did not plug over the seven week experimental period, using the weekly wash. Only moderate agitation, together with flow, would seem to be necessary to prevent plugging of the NPR layers.

During the experimental run with coal AMD (60 - 100 mg/L Al), although the inner column was never dismantled and cleaned over the 14 week period, the system did not plug.

The pH of the water was consistently higher following passage through the NPR in both the Cu-Zn and coal AMD experiments in the first weeks of the experiment. Even when the pH did not significantly increase towards the end of the run, acidity was still being reduced from, for example, 3250 to 1610 mg/L $CaCO_3$. On average, the acidity was reduced by 67% over the run. Ferrous and ferric iron removal was nearly 100% completely removed.

B.1.5 Current Application

Acidity in the AMD solutions tested to date were primarily caused by high ferrous and ferric iron concentrations.

Differences in NPR performance will likely be observed when AMD, with acidity dominated by dissolved aluminum concentrations, is passed through the test system. The short and medium-term reactivity of the phosphate rock with aluminum acidity, and the quantity and characteristics of aluminum precipitates formed during the reaction, should be measured.

The test, using this system, should be operated for two to three months. Therefore, four hundred litres of test water will be required.

B.2 Phosphate Rock/Waste Rock - Drum Experiment

B.2.1 Introduction

The object is to test the effect of phosphate rock on the generation of ARD by waste rock in different configurations in 70 L test drums.

Waste rock dumps are important sources of acid, generated by the oxidation of sulphides, particularly pyrite within the discarded material. Rocks from a failing heap leach (Gibraltar) are covered with secondary minerals. It is therefore hypothesised that, if secondary minerals can be formed on the rock surfaces, acid generation may be inhibited.

An experiment was set-up at Boojum on a balcony exposed to ambient meteorological conditions. This objectives of this experiment are to:

- Quantify waste rock oxidation
- Determine if NPR inhibits acid generation
- Identify the nature and role of secondary minerals in any inhibition

Waste rock piles are comprised of lifts. It is proposed to place NPR during pile construction on each lift prior to placement of the next lift. As the surface of each lift is compressed (due to truck traffic), it is envisaged that NPR can remain as a discrete layer if placed on top of the lift. The experiment was designed to measure effects of phosphate rock with and without direct contact with the waste rock.

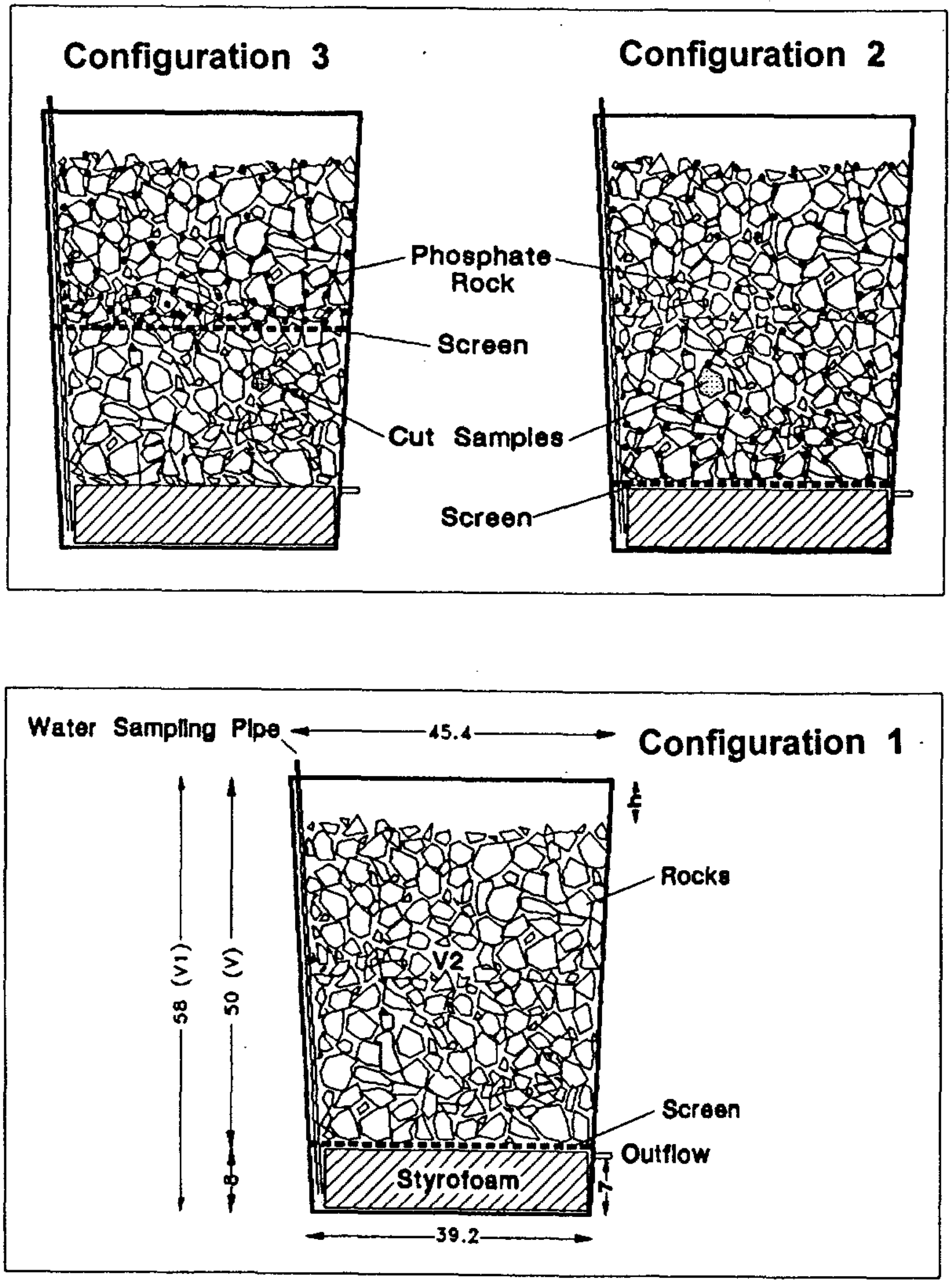
The waste rock samples were collected from the waste rock pile of a lead/zinc mine in Quebec. A variety of types were picked, based on visual estimates of pyrite content and known periods of exposure in the pile.

Five rock types were tested:

A	Low-pyrite, fresh (< 1 year exposure in waste rock pile) rock
B	High-pyrite, fresh
C	Low pyrite, high dacite tuff, weathered > 4 years
D	Dacite tuff, fresh mixed with type C to give a sample representative of what comes out of the pit
E	High pyrite, weathered > 4 years exposure in waste rock pile

The drums were set up as shown in the Schematic 2. Phosphate rock (NPR, 3.6 L) was held above a screen half-way up the drum (drums A3-E3), or mixed throughout the rock column (drums A2-E2), in order to determine the necessity for direct contact for inhibition of acid generation. The drums were left open and received only rain water. Water leaving the bottom of the drums therefore is rain water which has percolated through the rock column, picking up dissolved ions and particles en route.

Schematic 2: Phosphate Rock/Waste Rock - Drum Experiment Set-up.



Overflow through the bottom port was quantified to determine total volumes of 'seepage' leaving the drums. Samples for determination of acidity were syphoned from the top of the water sampling pipe (Schematic) and stored at 4°C prior to analysis (generally less than 24 h). Titrations were carried out on a Metrohm Titrino autotitrator. Water samples were titrated against NaOH to determine acidity (end point pH 8.3). Alkalinity titrations with H_2SO_4 were also carried out (data not shown).

B.2.2 Results

The drums were set up in September 1992. Acidity generated through the first 421 days of operation has been monitored and is reported in Table 1.

The accumulated acidity by the drums are shown in Figures 1 through 5.

The low pyrite waste rock (A1 and C1) generated as much or more acidity than the comparable high pyrite samples (B1 and E1). Throughout the period of observations, there was no consistent relationship between the degree of weathering of the rock and the rate of acid generation. The seasonal patterns of accumulated acidity are similar for the four rock types and the mixture.

There was a striking seasonal pattern of acid generation. During the first three months, acid accumulation was greater than in the subsequent six months. This is attributable to the higher temperatures in the late summer and fall following set up. If the oxidation is carried out by bacteria, rates of oxidation would be expected to be relatively low during the winter months as was observed.

Some of the early acid generation may also be due to dissolution of materials from the waste rock surfaces accumulated in the field prior to collection. From June (275 days after set up), there was a marked acceleration in rate of acidity accumulation in all the drums. This is attributed to rising temperatures and the consequent increase in the activity of pyrite-oxidising bacteria.

Titration curves after 421 days incubation are shown in Figures 6 - 9. The curves for the low-pyrite, 'fresh' rock (Figure 6) indicate an almost complete inhibition of net acidity generation by the phosphate rock whether placed in the top half or throughout the rock-column.

The pattern of the control curve indicates the chemical composition of the acid rock drainage leaving the drum. The flat part of the curve at pH 3.5 is due to the presence of ferric iron which precipitates at this pH as more NaOH is added. The slight flattening around pH 5 is attributable to aluminum. The major flat zone around pH 7 is due to ferrous iron and zinc which are clearly the major contributory factors to acidity in this water.

Fig.1: Cumulative Acidity
Drums A1-E1

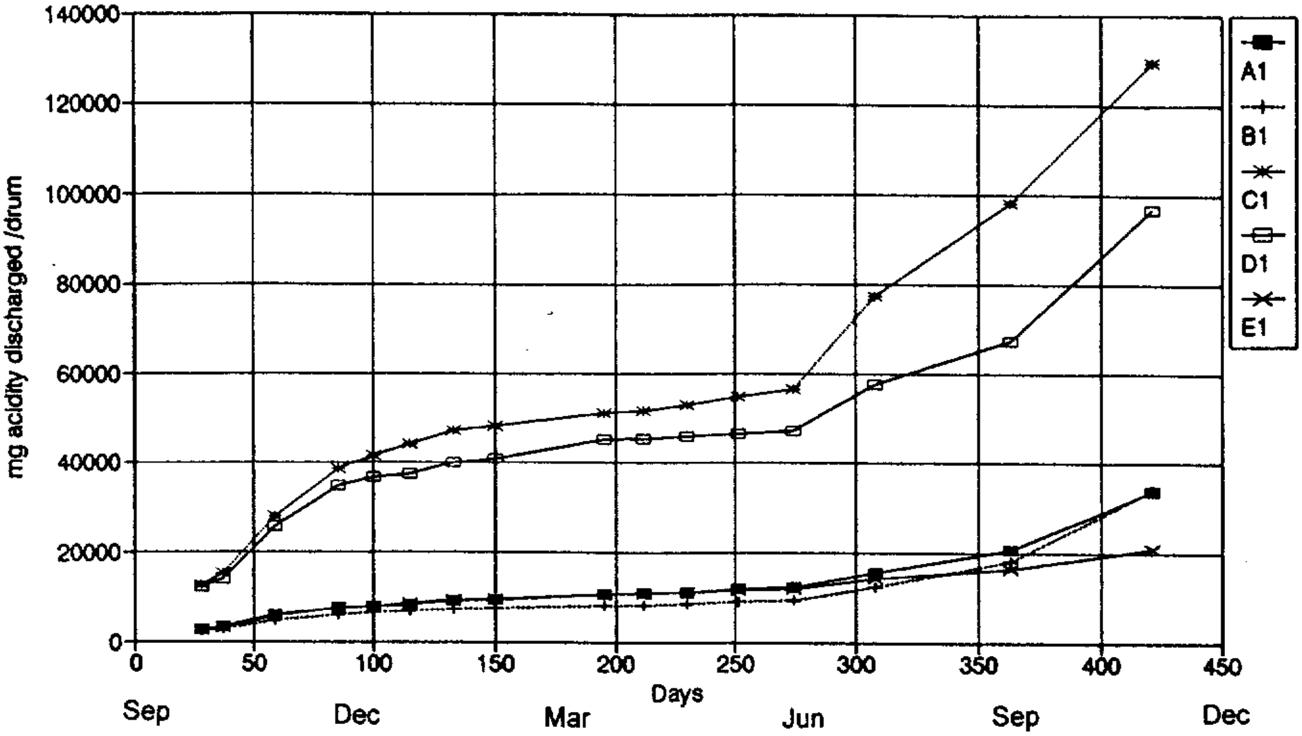


Fig.2: Cumulative Acidity
Drums A1-A3

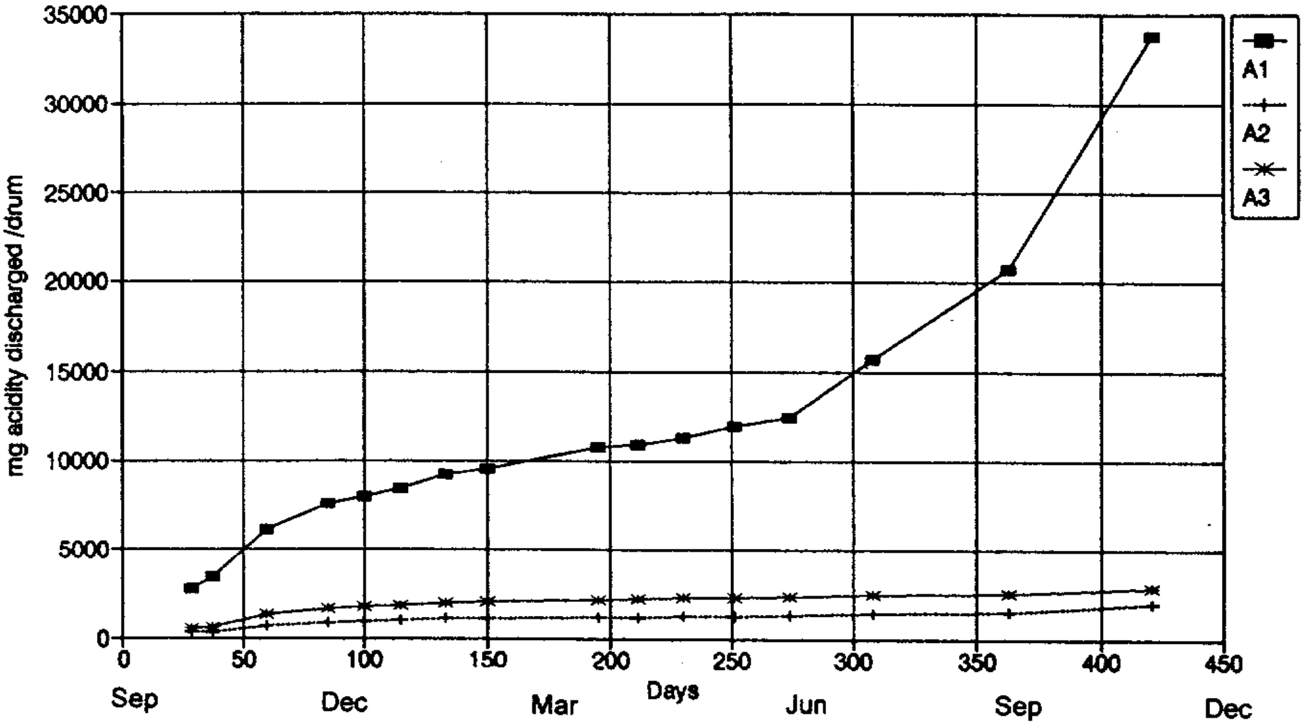


Fig.3: Cumulative Acidity
Drums B1-B3

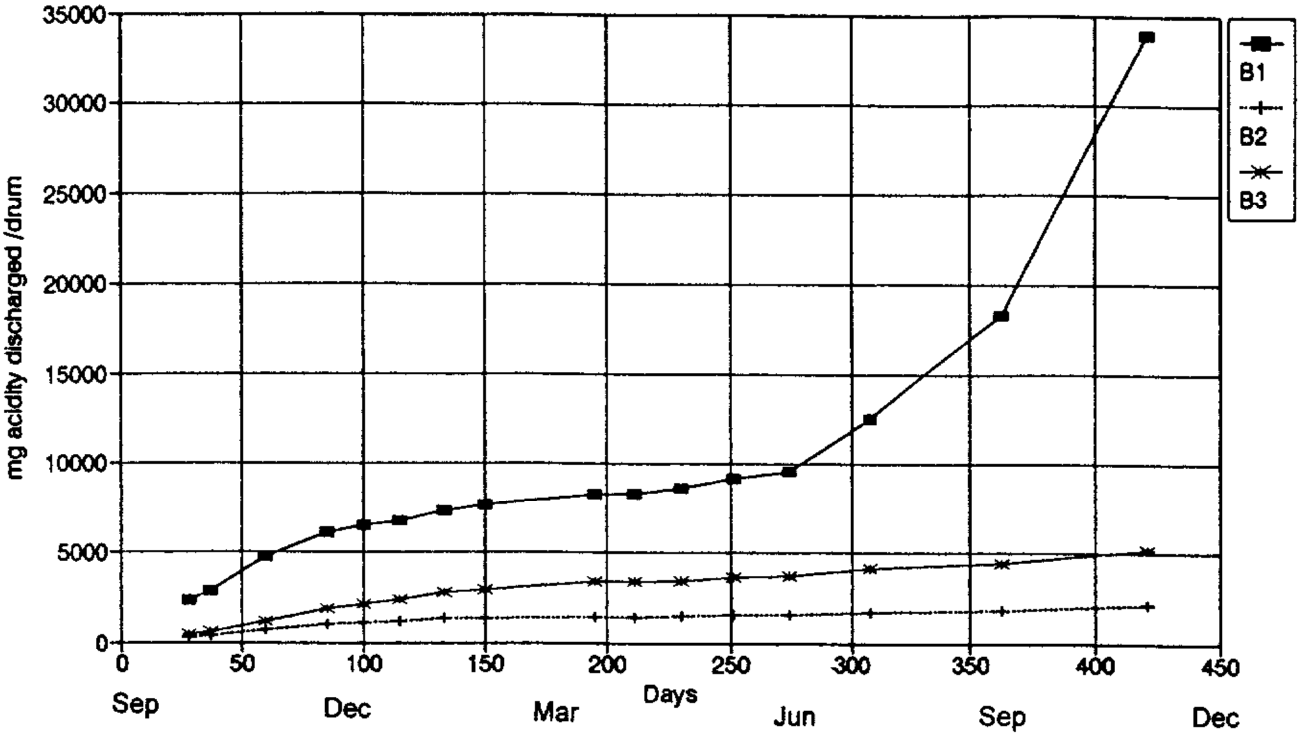


Fig.4: Cumulative Acidity
Drums C1-C3

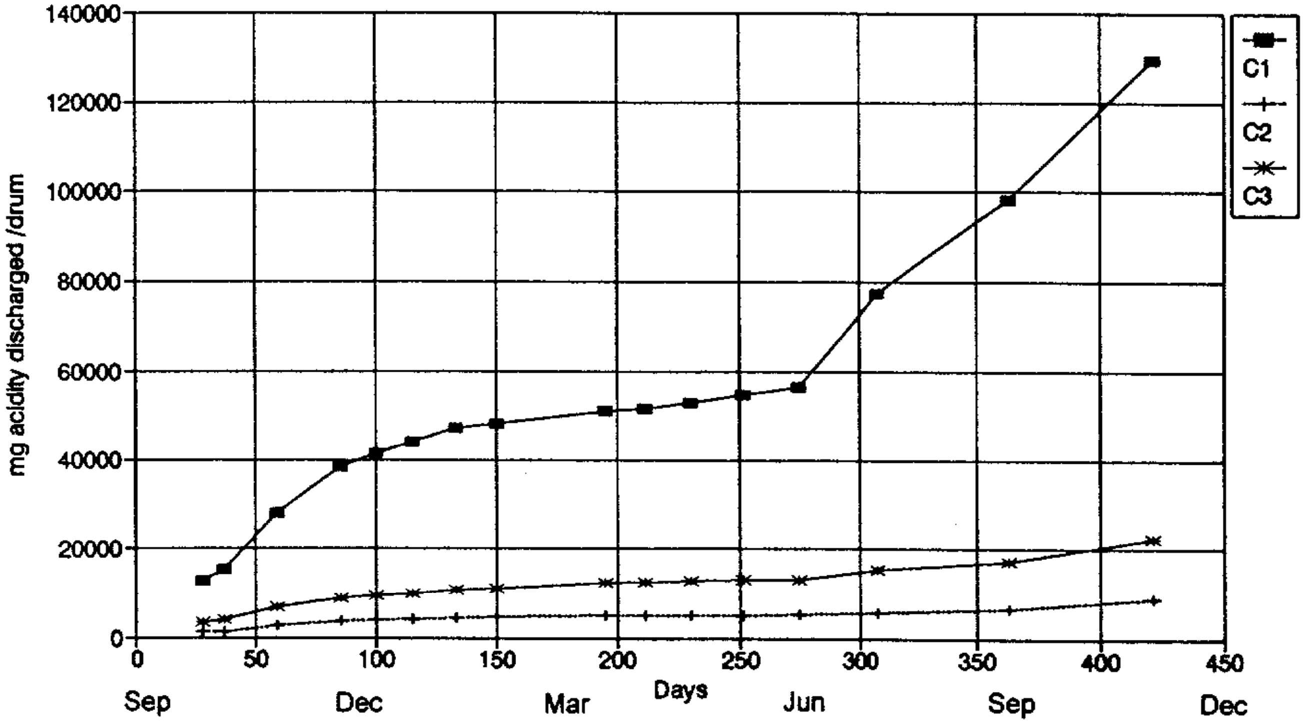


Fig.5: Cumulative Acidity
Drums E1-E3

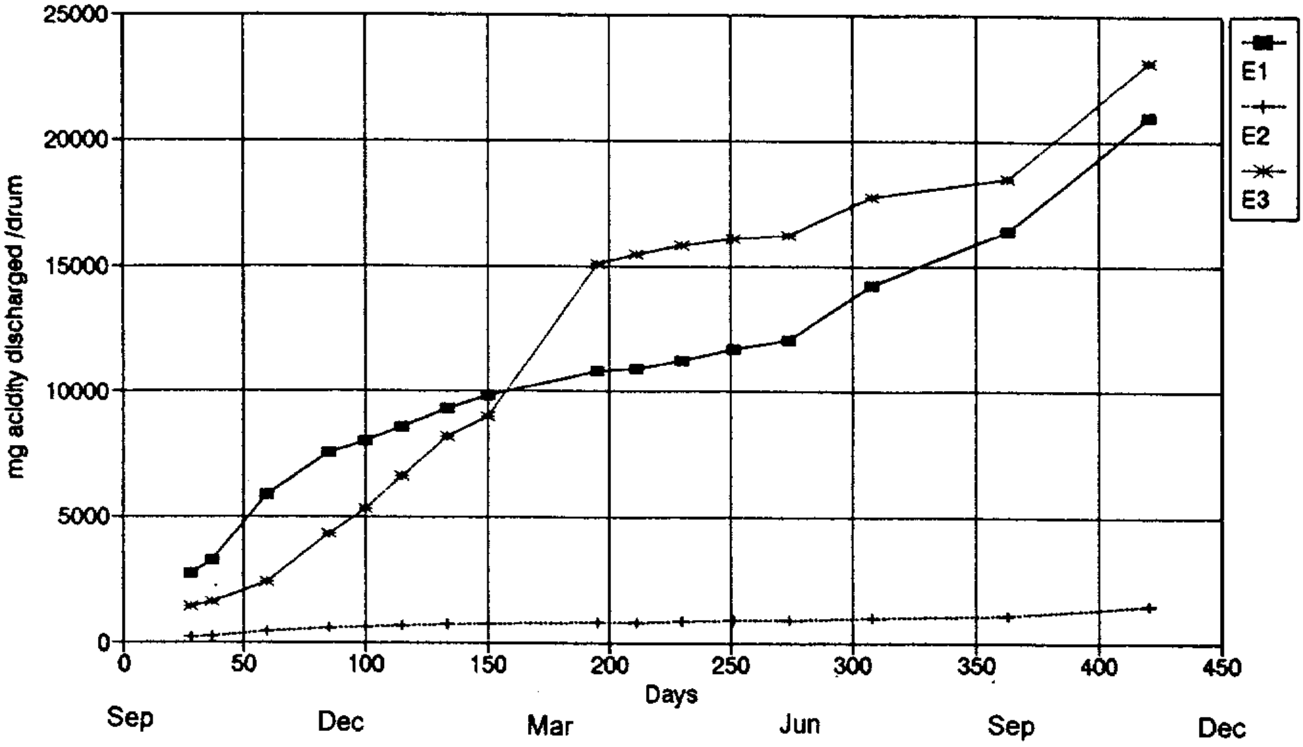


Fig.6: Waste Rock Drums
A, Low Pyrite, Fresh-October 20, 1993

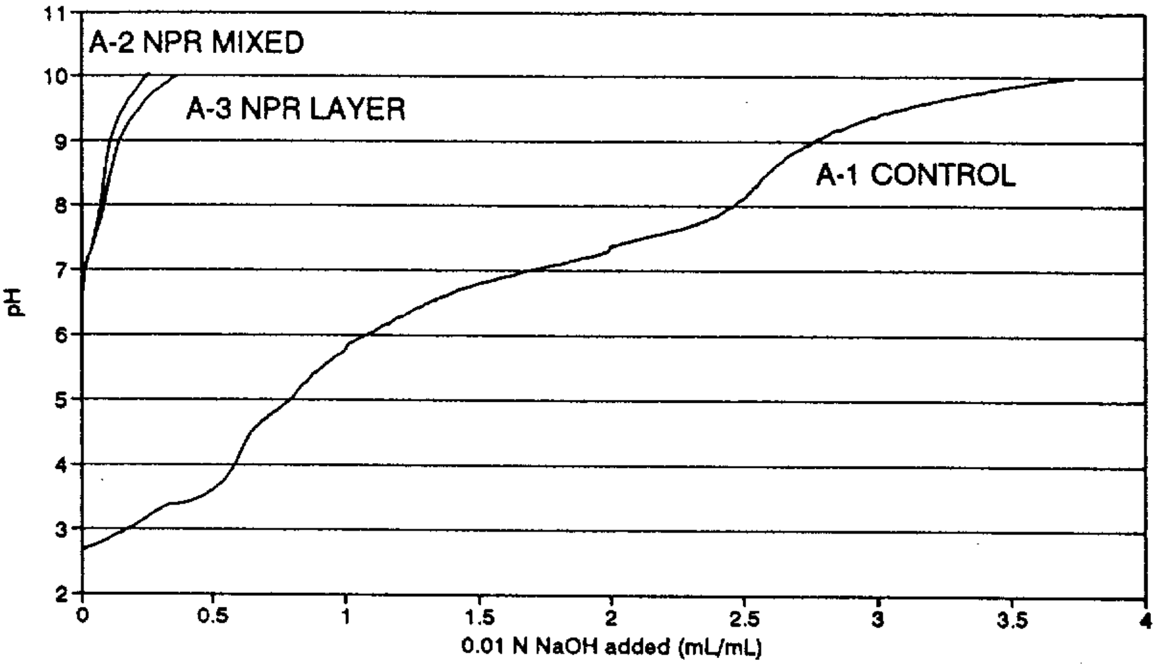


Fig.7: Waste Rock Drums
B, High Pyrite, Fresh-October 20, 1993

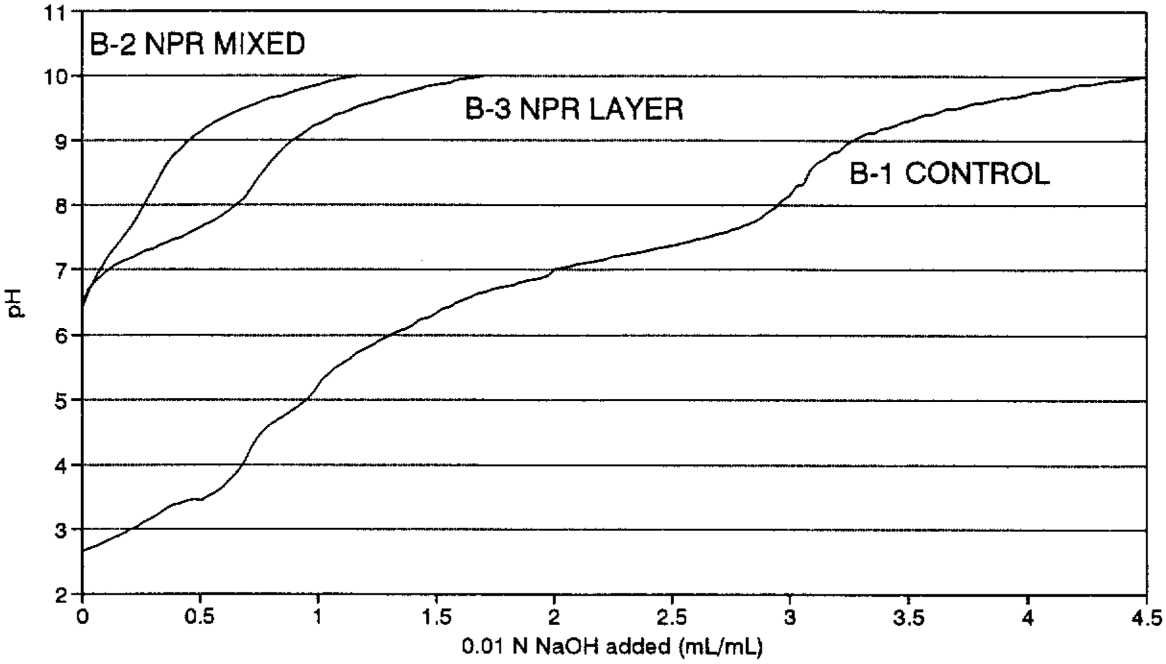


Fig.8: Waste Rock Drums
C,Low Pyrite, Weathered-October 20,1993

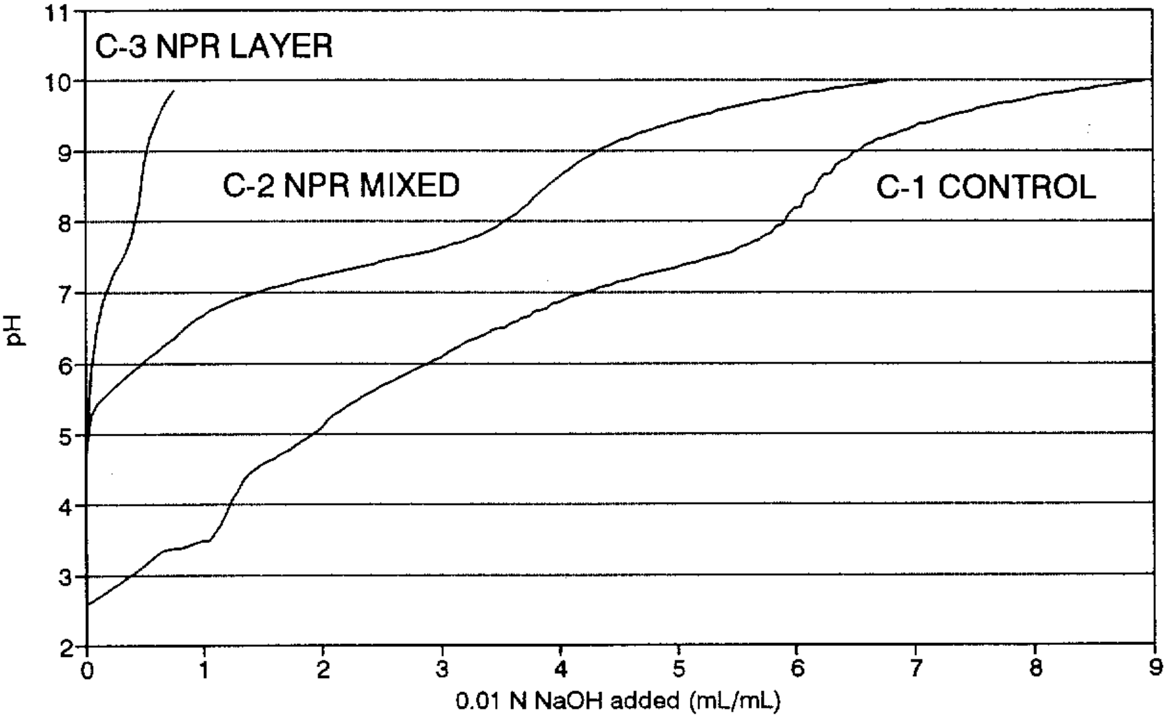
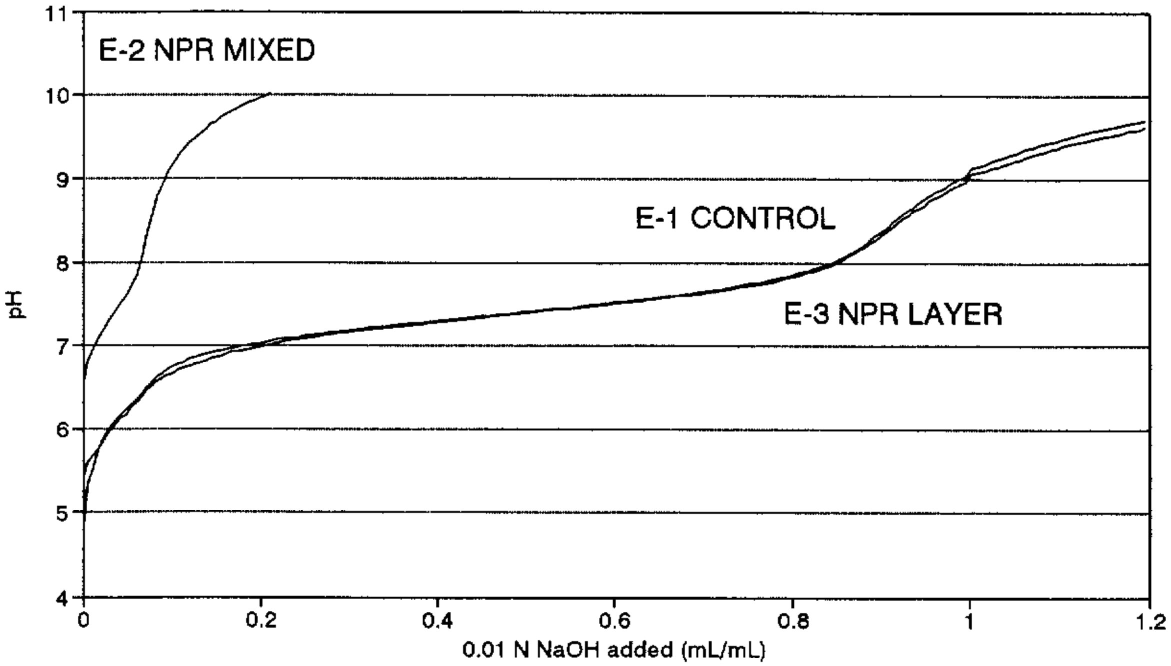


Fig.9: Waste Rock Drums
E,High Pyrite,Weathered-October 20,1993



In the presence of phosphate rock, the initial pH of the water is near neutral (pH 7) and the three flat parts of the curve are absent, indicating that either these elements have not been released into solution, or that they have precipitated within the rock-column.

The curves for the high-pyrite, 'fresh' rock (Figure 7) show a very similar pattern to those of the low-pyrite, 'fresh' rock (Figure 6).

The shape of the curves for the controls are remarkably similar in shape, the only difference being that the flat zone around pH 7 for zinc is a little longer in the high-pyrite rock. The curve for the drum with phosphate rock confined to the top half of the rock column indicates the presence of some zinc and/or ferrous iron in the water.

The curves for the low-pyrite, 'weathered' rocks (Figure 8) exhibit a similar pattern to the 'fresh' rocks. However, the total acidity is much greater in the former case. Also, there was much more acidity apparent in the presence of phosphate rock, mainly due to zinc and/or ferrous iron. In the high pyrite 'weathered' rock drums (Figure 9), the acidity was lower in the controls than with the other rock types. It is possible that most of the acid-generating potential of this rock had been exhausted while exposed in the field.

Table 1 summarises the effects of phosphate rock both on accumulated acidity and on acidity of the samples collected on October 20, 1993 (after 421 days). This data clearly indicates that the phosphate rock, as applied here, was generally able to prevent the release of > 90 % of the acidity generated by the control columns.

The phosphate rock was more effective in controlling acidity generation with the 'fresh' than with the 'weathered' material, suggesting that, where oxidation of pyrite and sphalerite surfaces is well established, the NPR is unable to form an effective preventive barrier, or an alkaline solution completely inhibitory, to the oxidation process. In 'fresh' material, the chemistry changes induced by the NPR are sufficient to substantially inhibit, though not entirely prevent, acid generation.

Golder Associates (1990) published data on analyses of a lead/zinc mine's waste rocks and estimated their acid generating potential. The lowest S content they found was 2.17 % and the highest, 7.76 %. They estimated an acid generating potential of 66.4 kg/T and 237.4 kg/T, respectively, for these materials.

Assuming that the low pyrite rock used in the drums had the same S content (2.17 %) as Golder's low S sample, the acid generating potential of the estimated 77.5 kg of rock in the drums is 5.15 kg.

The cumulated acid generated in 421 days by drum A1 was 33.8 g (Table 1). At this rate of acid generation, the waste rock will continue to generate acid for 180 years.

A similar calculation, using B1 as the high pyrite rock and assuming an S content of 7.76 % (highest Golder estimated value), the drum would generate acidity at the present rate for 640 years. The NPR added to the drums has an approximate phosphate content (as P_2O_5) of 23 % or 8.4 g.mol (260 g) of P. This could precipitate approximately 470 g of Fe.

This represents approximately 16 % of the pyrite iron in low pyrite rock, or 4.5 % of the pyrite iron in the high pyrite rock. This is equivalent to 19 years of acid generation at present rates. However if the $FePO_4$ precipitates coat the surfaces, the potential is there to completely inhibit acid generation forever.

Future studies will determine how long the phosphate rock remains effective and also identify the processes by which the NPR acts. In particular, the quantity, composition and location of precipitates will be determined and, hence, the long-term benefits and optimal rates and mode of NPR application for this particular waste rock type will be determined.

B.2.3 Conclusion

Phosphate rock (NPR) has remained extremely effective in preventing acid generation from both low and high pyrite waste rock in 70 L drums. These results are very promising for the development of a new technique for the inhibition of ARD generation from pyrite-rich waste rock piles.

Table 1: Effect of NPR on acid generation by Selbaie waste rock drums, October 20, 1993

Drum	Rock type	Exposure year	NPR	pH	Acidity (sample of Oct 20) mg/L	Inhibition %	Accumulate acidity (421 days) mg/L	Inhibition %
A-1	Low pyrite	<1	-	2.67	1270		33834	
A-2			mixed	6.43	42	97	1976	94
A-3			layer	6.59	31	98	2888	91
B-1	High pyrite	<1	-	2.65	1514		33914	
B-2			mixed	6.42	31	98	2153	94
B-3			layer	6.46	73	95	5185	85
C-1	Low pyrite	>4	-	2.57	3038		129399	
C-2			mixed	4.7	227	93	8916	93
C-3			layer	4.64	503	83	22492	83
D-1	Mixture		-	2.93	2871		97027	
E-1	High pyrite	>4	-	4.82	445		20969	
E-2			mixed	6.55	36	92	1438	93
E-3			layer	5.43	448	+1	23130	+10

B.3 Kennecott Utah Copper Facility - Preliminary Geophysical and Hydrological Considerations

B.3.1 Introduction

The purpose of this study was to evaluate the feasibility of using phosphate rock to pretreat acid waste water from the facility, and to reduce or stop the leaching of metal-sulphides from the waste rock pile. Final discharge quality would have to be suitable for use as irrigation water.

PHREEQE, the geochemical simulation program employed, requires very complete chemical analysis as input parameters. These are very difficult to obtain in waste waters which show high reactivity, such as the Kennecott process water. Thus, due to these shortcomings in the representativeness and completeness of the chemical data available for the feasibility study, the results of the evaluation can only be regarded as very preliminary, from the point of view of both geochemistry and hydrology.

B.3.2 Geochemistry

Many of the analyses provided showed significant ion-balance errors. The analysis for water from the Bingham Tunnel did not contain data on [Cl] and [Zn]; 9/92 and 4/93 analysis for the LEAWA samples did not contain data on [Cl], [Mn] and [Zn]; none of the LEAWA sample analysis contained data on SiO_2^+. None of the analysis provided data on water temperatures or redox potentials. Table 1 gives the analysis as a combined print out. The analysis with the highest overall concentrations and a reasonable ion-balance error was chosen as a representative (LEAWA-29 BW 3(OB) collected September 93).

Values for water temperature and redox potential were assumed. Water temperature was set at 9 °C (48.2 °F), reflecting the mean annual temperature for Bingham Canyon, Utah, as provided by Kennecott using climate normals 1947 to 1968 (given in Table 3). A value of Eh=+450 millivolts was assumed to reflect the likely aeration of the waste water. Eh values for the Midas seepages were reported later, measured on the 10/20/1993, which were indeed only slightly lower than those assumed for the simulation, with values of up to 370. Eh values, as measured in the phosphate sand experiment, ranged between 340 and 440 mV and, thus, the assumed value of 450 mV is reasonably representative of the waste water conditions. Although the process water is likely to be somewhat warmer, due to the high temperatures of the waste rock pile, the assumed temperature setting of 9°C would represent, potentially, winter conditions based on the mean annual temperature for the Bingham Canyon Utah data.

TABLE 1. KENNECOTT WATER CHEMISTRY

Date	9/92	4/93	9/93	9/92	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93
Source	Bw 1	Bw 1	Bw 1	Bw 2	Bw 2	Bw 2	Bw 2	Bw 3	Bw 3(P)	Bw 3(P)	BW 3	BW 3(C	BW 3(C	Midas	Midas	Midas	Keystone	Keystone	Keystone
pH	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.7	2.6	2.6	2.7	2.8	3.1	2.9	2.9	3	2.8
Al	5300	5382	5100	4800	4500	5654	6000	4300	6135	5800	6100	5710	5900	4800	3794	4500	3500	3251	4400
As	0.08	0.017	0.0025	0.069	0.047	0.034	0.0025	0.046	0.05	0.0025	0.074	0.029	0.0025	0.061	0.053	0.0025	0.042	0.019	0.0025
Ca	590	445	530	510	490	517	550	460	565	560	550	537	540	500	432	530	530	451	470
Cd	0.31	0.7	0.35	0.38	0.34	0.78	0.3	0.32	0.82	0.4	0.39	0.77	0.42	0.37	0.64	0.48	0.91	0.9	0.33
Cr	1.1	0.93	0.56	1.2	1	0.99	0.71	0.93	1.1	0.6	1.1	0.93	0.53	1	0.74	0.69	0.72	0.44	0.25
Cu	380	385	310	230	210	196	192	280	405	300	340	227	300	200	240	260	370	257	106
Fe	410	288	205	800	770	544	610	450	625	470	530	425	480	470	246	270	93	171	210
K	0.05	0.05	0.1	0.05	0.05	0.05	0.1	0.05	0.05	0.1	0.05	0.05	0.1	0.05	0.05	1.7	0.05	0.05	0.2
Mg	10000	9820	10300	8000	7200	9954	10000	7700	11720	11100	11000	10490	11200	8100	8370	9700	8000	8394	8800
Mn			250				350			360			390			410			380
Na	0.05	2.1	4	0.05	0.05	2.7	5	0.05	1.4	5	0.05	3.3	0.6	0.05	75	55	0.05	23	16
Pb	0.025	0.025	0.1	0.025	0.025	0.025	0.1	0.025	0.025	0.1	0.025	0.025	0.1	0.025	0.025	0.1	0.025	0.6	0.1
Se	22	0.0025	0.25	0.0025	0.0025	0.0025	0.25	0.0025	0.0025	0.25	0.0025	0.0025	0.25	0.0025	0.0025	0.25	0.017	0.005	0.25
SO4	45000	70710	72512	47000	47000	66860	71071	49000	74230	72685	50000	68010	73401	47000	59950	60362	44000	54020	60990
Zn			149				205			216			213			194			208
Cl	200	287	283	200	200	276	258	210	397	309	210	282	314	200	374	384	210	284	258
TDS	61904	87321	89644	61542	60372	84006	89242	62401	94080	91806	68732	85686	92740	61272	73483	76668	56705	66853	75839

Date	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93	9/92	4/93	9/93	9/93	9/93	9/93
Source	Copper	Copper	Copper	Castro	Castro	Castro	Yosemite	Yosemite	Yosemite	Conger	Conger	Conger	P/Plant	P/Plant	Ret.wate	Duplic.	Duplic.	EsideRe
pH	3.5	3.5	3.4	3.9	4.5	4.2	4.7	4.1	4.1	3.4	2.8	2.7	3.7	3.5	3.3	2.8	2.7	2.7
Al	3300	1672	2900	190	101	1500	160	302	1600	5100	5576	5100	5900	4756	5900	4600	5900	7000
As	0.17	0.074	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.075	0.051	0.0025	0.79	0.048	0.0025	0.0025	0.0025	0.0025
Ca	460	514	530	460	390	420	520	441	480	580	536	590	660	457	510	480	530	720
Cd	0.62	0.98	0.44	0.34	0.28	0.3	0.13	0.33	0.15	0.39	0.74	0.48	0.65	0.85	0.39	0.4	0.57	0.03
Cr	0.8	0.8	0.38	0.02	0.13	0.03	0.04	0.17		0.87	0.87	0.41	1.7	1.1		0.25		
Cu	400	449	72	160	88	139	81	105	73	240	291	290	99	35	40	116	300	170
Fe	1600	806	1170	5.4	0.73	0.7	1.6	1.1	1.5	290	371	310	2200	1174	900	204	450	440
K	0.05	0.8	1.2	0.05	8.7	10.5	0.05	8.4	10.5	0.05	0.05	0.1	0.05	0.05	0.2	0.2	0.1	0.2
Mg	7200	4500	8400	2700	1901	1240	3700	2755	1450	7200	11140	10900	9000	8730	10400	8500	10400	12300
Mn			43			43			43			420			390	380	370	370
Na	0.05	39	54	0.05	48	61	0.05	162	270	0.05	6.1	8	0.05	8.5	10	16	8	10
Pb	0.025	1.1	0.1	0.025	0.61	0.4	0.025	0.47	0.1	0.025	0.025	0.1	0.025	0.025	0.1	0.1	0.1	0.1
Se	0.0025	0.0025	1.8	0.02	0.0016	0.25	0.011	0.0025	0.25	0.0025	0.0025	0.25	0.0025	0.0025	0.25	0.25	0.25	0.25
SO4	42000	53080	53536	12000	20540	12600	14000	13990	16800	48000	22450	66149	49000	64530	63850	61000	72978	65968
Zn			150			59			23			215			202	200	215	205
Cl	270	358	375	140	199	167	370	480	739	200	77	577	100	272	253	280	315	278
TDS	55232	61422	67234	15656	23277	16241	18833	18245	21491	61611	40449	84560	66962	79965	82456	75777	91467	87462

Table 2: Bingham Geochemistry

BINGHAM LEAWA Bw-3(OB) - 9/93 PHREEQE test with Calcium Phosphate

							mol.wt(g)
Ca3(PO4)2, M/L	0.00	0.05	0.10	0.15	0.20	0.25	310.08
Ca3(PO4)2, g/L	0.00	15.50	31.01	46.51	62.02	77.52	
Concentration, gram\L							
Al	6.502542	1.948064	0.936258	0.098213	8.88E-06	1.22E-05	26.9815
Cu	0.330439	0.000762	0.000595	0.000254	2.92E-06	6.22E-07	63.546
Fe	0.528871	0.000461	0.000228	1.74E-05	3.74E-11	9.55E-13	55.847
Mn	0.429615	1.99E-06	1.26E-06	4.66E-07	6.54E-09	2.06E-09	54.938
SO4	80.88252	61.4784	46.20486	31.12344	17.09868	4.870242	96.06
Zn	0.234678				0.006092	0.000843	65.3699
pH	2.7	3.61	3.74	4.14	6.04	6.65	
Log[IAP/KT]							
Al(OH)SO4	1.82	2.23	2.02	1.42	-1.57	-2.84	
Al4(OH)10SO4	-7.27	0	0	0	0	0	
Cuprousferrite	2.85	0	0	0	0	0	
Hematite	2.32	0	0	0	0	0	
MnHPO4		0	0	0	0	0	
MnSO4	-7.74	-13.1	-13.3	-13.8	-15.8	-16.7	
Zn3(PO4)2					0	0	
ZnSO4	-4.86	-3.12	-3.37	-3.95	-6.61	-7.77	
Precipitates, gram/L							
Al4(OH)10SO4		-15.7823	-20.8311	-22.1775	-22.5365	-22.5365	373.9876
Gypsum		-21.7282	-42.0678	-62.489	-82.3657	-99.5195	136.1416
CuFeO2		-0.87983	-0.87983	-0.88067	-0.88152	-0.88152	169.393
Fe2O3		-0.34175	-0.34175	-0.34111	-0.34095	-0.34095	159.694
MnHPO4		-1.18011	-1.18011	-1.18011	-1.18011	-1.18011	150.9094
Zn3(PO4)2					-0.45052	-0.46056	386.0525

Total Precipitate: -124.919 gram/L

Table 3: Bingham Canyon, Utah, Climate Data

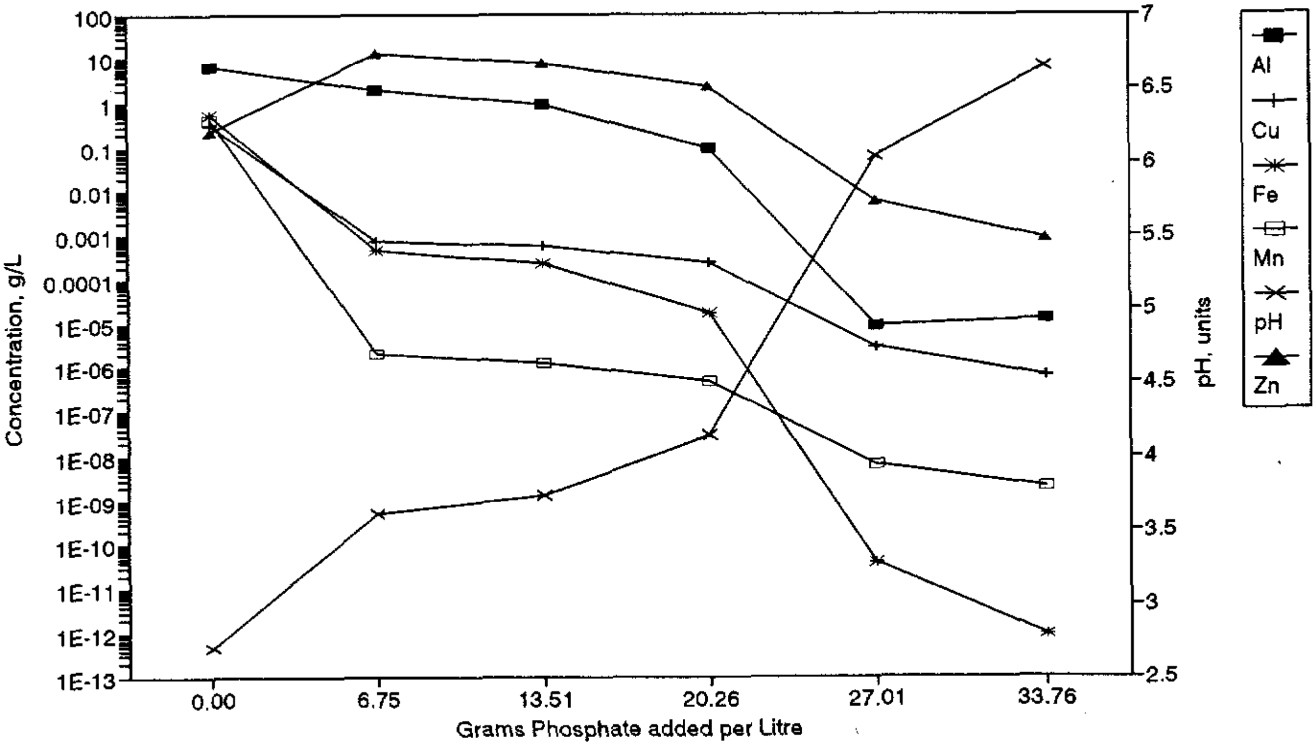
CLIMATE MEANS 1947-1968

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Precipitation, rain and snow in inches													
HIGH	4.52	3.89	4.58	4.75	4.88	4.61	4.52	4.50	5.24	3.65	4.62	3.14	52.90
LOW	0	0.11	0.32	0	0.68	0.58	0.72	0.1	0.01	0.02	0.01	0.03	2.58
AVERAGE	1.94	1.89	2.29	2.53	2.17	1.87	1.05	1.45	0.92	1.39	1.66	2.05	21.21
Mean Temperatures in degree F													
DAILY MAX.	34.2	38.5	44.0	54.0	64.2	72.4	82.0	79.9	71.8	60.9	44.9	36.2	56.9
DAILY MIN.	20.4	23.2	27.0	35.2	44.6	51.7	62.0	65.4	52.3	43.4	30.3	24.0	40.0
DAILY MEAN	27.4	30.7	35.6	44.6	53.8	61.4	71.4	69.2	61.6	51.6	38.5	31.7	48.1
(Max+Min)/2	27.3	30.9	35.5	44.6	54.4	62.1	72.0	72.7	62.1	52.2	37.6	30.1	

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Precipitation, rain and snow in mm													
HIGH	114.8	98.8	116.3	120.7	124.0	117.1	114.8	114.3	133.1	92.7	117.3	79.8	1344
LOW	0.0	2.8	8.1	0.0	17.3	14.7	18.3	2.5	0.3	0.5	0.3	0.8	66
AVERAGE	49.3	48.0	58.2	64.3	55.1	47.5	26.7	36.8	23.4	35.3	42.2	52.1	539
Mean Temperatures in degree C													
DAILY MAX.	1.2	3.6	6.7	12.2	17.9	22.4	27.8	26.6	22.1	16.1	7.2	2.3	13.8
DAILY MIN.	-6.4	-4.9	-2.8	1.8	7.0	10.9	16.7	18.6	11.3	6.3	-0.9	-4.4	
DAILY MEAN	-2.6	-0.7	2.0	7.0	12.1	16.3	21.9	20.7	16.4	10.9	3.6	-0.2	9.0

Mean Annual Precipitation		539	mm
Mean Annual Lake Evaporation		?	mm
Mean Annual Evapotranspiration		?	mm
Mean Annual Runoff	(A)		mm
	(B)		mm

Fig.1: Bingham LEAWA Bw-3(OB)
Phosphate Addition



The geochemical simulation program PHREEQE was used to:

(1) determine ion speciation in the LEAWA water;

(2) determine degrees of saturation with respect to various potential precipitate minerals; and,

(3) evaluate the effects of addition of phosphate rock, $Ca_3(PO_4)_2$, on potential precipitate formation and dissolved metal concentrations.

It required a large number of simulation runs until reasonable results were obtained. The results are summarized in Table 2.

In the top part of the table, the concentrations of the BW-3(OB) water are given in $g.L^{-1}$ with no phosphate additions in the first column of the table. The input concentrations used by PHREEQE are molalities, which are calculated by the program with densities which are also derived within the program. Therefore, the concentrations used as input are converted back to $gram.L^{-1}$ for ease of reference, but are no longer the same as in the original chemical analysis.

In subsequent columns, the results of phosphate additions, in moles of $Ca_3(P0_4)_2$, are given with increasingly higher concentrations of phosphate. Each time the program is run, the characteristics of the simulated solution are maintained for the next additions of the phosphate rock. The resultant changes in the concentrations of the process water are listed in the table. The concentrations of all elements considered are generally decreasing consistently.

To make interpretation easier, the results were converted from molalities and moles per litre (as produced by the computer program) to grams.L^{-1}. This assumes that the solution densities are equal to one; as the highly concentrated solutions undoubtedly have densities higher than one, the conversion will have introduced potentially some differences with respect to the actual solution.

The analysis shows some supersaturation (positive Log[IAP/KT] values) with respect to some Al, Fe, and Cu minerals, and gypsum (given in the middle part of Table 2). The very preliminary simulation did not allow to run for all possible and most likely precipitates under each conditions. Thus, in Table 2, only a few precipitates are indicated, but the preliminary runs indicated that also Melanterite, Diaspore and Basaluminite are potential precipitates.

B.3.3 Conclusion

The main conclusion which is of relevance, with respect to the objective of evaluating the potential of using phosphate rock, is the fact that, indeed, a great number of precipitates can form, and that phosphate rock will likely be a useful agent to induce precipitation.

Addition of progressively larger amounts of phosphate, from 0.05 moles to 0.25 moles per litre of solution, reduced the metal concentrations by producing increasing amounts of several potential precipitate minerals.

Although the quantities of dissolved phosphate added are theoretical, the simulation runs indicate that addition of 15.5 g calcium phosphate per litre should reduce [Cu], [Fe] and [Mn] to values below the maximum irrigation water guidelines. Addition of 62 g calcium phosphate per litre should reduce [Al] sufficiently, and addition of about 70 g calcium phosphate should adequately reduce [Zn] (Figure 1 and Table 2).

As phosphate is added, pH changes can be noted. Very slight changes in pH produce rather drastic changes in the composition of the waste water. With the first addition of phosphate, it is estimated that about 15.7 g of $Al_4(OH)_{10}$ sulphate and 21.7 g of gypsum are precipitated from the solution. This suggests that, potentially, a relatively small increase in pH, even if brought about by other neutralizing capacities, could significantly improve the waste water with respect to sulphur and aluminium concentrations.

It is therefore recommended that a trial experiment is run with phosphate sand and process water.

B.4 Review of Kennecott Reports - The General Geology and the Characteristics of Its Waste Rock

B.4.1 Introduction

Information was collected from Kennecott's "Geology of the Bingham Canyon Porphyry Copper Deposit" by Peters, James and Field, and the report 76-16 on the "Chemical, Mineralogical and Physical Characteristics of As-Mined UCD and CMD Waste Rock" by Yorgason, Jackson and Schlitt.

Some of these rock types have been considered for leaching to recover copper.

This information was used to identify and quantify, as far as possible, the minerals that might be subject to dissolution due to deliberate or natural leaching in various waste zones.

B.4.2 Geology and Mineralogy

The porphyry copper orebody at Bingham Canyon is associated with a mile-square "stock" of a granite or monozite formation. It was formed by intrusion of the molten rock, magma, into a layer of siliceous sediments.

The intrusive rocks, consisting of quartz, feldspars and biotite mica, have been partially altered by metamorphic agents into secondary minerals, including clays, sericite, chlorite, talc, iron oxides and secondary copper minerals.

Most of the copper ore occurs as disseminations in the intrusive zone, although significant copper mineralization extends into the sediments. Chalcopyrite is the principal copper-bearing sulphide.

Pyrite is least abundant in the centre of the ore body, which is enveloped by a halo of pyrite. Pyrite occurs mainly in veinlets and on fracture surfaces.

Molybdenite occurs in the ore zone amounting 0.02% in the rock.

Enargite-famatinite, galena, sphalerite and tetrahedrite are present locally in veinlets in sediments on the periphery of the ore body.

Encircling most of the Bingham stock are fissure and replacement bodies of lead and zinc, at distances ranging from 1,000 to 10,000 ft. from it. The deposits are localized in the sediments and some are associated with carbonates.

Underground mining commenced on these deposits as early as the 1870's and is still going on today.

B.4.3 Types of Waste Rock

There are a variety of waste rock types, including the following:

1. Low-grade copper ore from the sedimentary zone, suitable for heap leaching to recover copper.
2. Low-grade copper ore from the intrusive zone, suitable for heap leaching to recover copper.
3. Wastes similar to (1) and (2) but too low in copper to be leached economically.
4. Low-grade waste from areas of lead-zinc mineralization, if the pit extends into these areas.
5. Sedimentary and other rocks with insignificant or no mineralization.

There is no quantitative mineralogical data in the reports reviewed for the various wastes except for the first two types.

The Kennecott report describes chemical, mineralogical and physical investigations on three samples each of the first two types of waste referred to above, identified as UCD waste. A seventh sample, identified as CMD intrusive, was described as "not typical of the major waste type to be shipped at Santa Rita during the next few years".

Mineralogical studies by Kennecott included identification of the major gangue and metallic minerals in each sample. Quantitative studies were confined to micrometric analyses of pyrite and copper sulphide minerals, and chemical analyses for copper and sulphur.

Results of these studies are shown in Table 4 of the Kennecott report. Average sulphides and sulphur analyses from these tests are as follows:

Sample	Pyrite Wt.%	Copper Sulphides Total Wt.%	S Wt.%
UCD Quartzite (3)	3.21	0.24	1.80
UCD Intrusive (3)	4.04	0.32	2.66

These tests indicated that pyrite is by far the most abundant sulphide in the waste rock, and the studies showed that the pyrite occurs mostly in veins and on fracture fillings and is, therefore, largely exposed to leaching.

Copper is disseminated and, therefore, may leach slowly and incompletely. It occurs primarily as chalcopyrite, but acid-soluble copper in the six samples (probably carbonates or hydroxides) averaged 16% by weight of the total copper.

An indication of the principal minerals comprising the leachable wastes can be found in Table 1, taken from the Peters report. Principal minerals from zones of differing mineralization intensity are shown for igneous (intrusive) and sedimentary zones. It is reasonable to assume that the leachable waste rocks correspond generally to the moderate or weak mineralization zones.

The igneous rocks consist primarily of quartz, feldspars and secondary silicates. Carbonate content is negligible.

The sedimentary zone is highly siliceous, but does not contain significant concentrations of secondary silicates. Carbonate amounts to 0.9% and 2.3% by weight in the moderate and weak mineralization zones, respectively.

B 4.4 Dissolved Solids in Leach Solutions and Waste Rock Drainage

Potential sulphuric acid producers in the waste rocks include pyrite and other sulphide minerals. Potential acid consumers are secondary siliceous minerals such as chlorite and carbonates.

Since pyrite occurs in veinlets and on fracture surfaces, most of it should leach fairly readily by bacterial action. The copper minerals are mostly disseminated and, therefore, may leach slowly and incompletely.

Chlorite will dissolve in sulphuric acid. However, there is no leaching data in the Kennecott report to indicate how reactive it is in dilute acid, nor how much of it may be exposed to leach solution.

The three samples of sedimentary waste investigated by Kennecott averages 1.8% by weight sulphur. This is equivalent to 110 lb sulphuric acid per ton of rock. The Peters report indicates that the moderately and weakly mineralized sediments contain significant amounts of chlorite, which should neutralize some of the acid produced and precipitate some of the sulphate as gypsum (Table 1). Metals in the leach liquor will include iron and copper from the sulphides and aluminum from sericite.

The intrusive waste samples averaged 2.66% sulphur, equivalent to 163 lb. sulphuric acid per ton of rock. Referring again to Table 1, the igneous rock contains a comparatively high concentration (6.5%, 4.7%) of chlorite and negligible carbonate. If the chlorite is very reactive, it may be necessary to add sulphuric acid to start and maintain the leaching process. As a result of the higher sulphur contents and the probable addition of acid to the leach solution, leach liquors from the intrusive rock likely contain higher concentrations of dissolved solids than is the case for the siliceous waste. The major metals will be the same.

There is insufficient information to predict the quality of drainage water from other waste rock outside the zone of commercial copper ore. The pit may well be extended in some places into areas of copper and zinc mineralization, but there may be enough carbonate in these areas to inhibit bacterial leaching.

In addition to iron and copper, leach liquors and drainage may contain lead, zinc, antimony, arsenic and mercury.

TABLE 1

AVERAGE VALUES FOR PRINCIPAL MINERALS COMPRISING IGNEOUS (BINGHAM STOCK AND NEARBY INTRUSIVES) AND SEDIMENTARY ROCKS FROM ZONES OF DIFFERING MINERALIZATION INTENSITY (BASED ON THIN-SECTION DATA AND INFRARED AND X-RAY DIFFRACTION ANALYSES)

Rock type	Igneous			Sedimentary		
Mineralisation intensity	Strong	Moderate	Weak	Strong	Moderate	Weak
Number of samples	23	6	12	6	27	71
Mineral (percent)						
Quartz	20.7	19.8	19.3	73.8	89.3	89.5
Potash feldspar	31.7	25.3	9.0	3.2	1.7	1.4
Plagioclase feldspar	7.3	9.5	36.4	—	—	—
Amphibole	—	2.0	.5	.5	.5	1.2
Pyroxene	—	—	4.0	13.7	.3	trace
Biotite	21.0	15.8	7.2	4.7	trace	—
Sericite	7.4	10.7	8.8	1.5	1.3	1.1
Chlorite	2.3	6.5	4.7	—	2.5	.8
Talc	—	—	—	—	1.5	.4
Montmorillonite	trace	2.3	3.5	—	trace	.6
Kaolinite	.9	1.0	.2	.3	1.3	.4
Carbonate	—	—	.2	.2	.9	2.3
Epidote	—	.3	1.0	1.5	.1	trace
Garnet	—	—	—	present	present	—
Magnetite	trace	.3	1.3	present	present	—

B.4.5 Geological Terms and Mineral Formulae

A stock is formed when a mass of molten rock (magma) intrudes into the upper region of the earth's crust and solidifies there.

Porphyry is a rock in which distinct crystals occur in a fine groundmass.

Granite is a medium-grained, light-coloured rock consisting of feldspar and quartz with a minor amount of ferromagnesian silicates (mica). The predominant feldspar is orthoclase.

Quartz monzonite is similar to granite, except that plagioclase is the predominant feldspar.

Sulphides and Oxide Metallic Minerals

Bornite	Cu_5FeS_4
Chalcocite	Cu_2S
Chalcopyrite	$CuFeS_2$
Covellite	CuS
Diginite	Copper sulphide
Enargite - famatinite	$3Cu_2S$, Sb_2S_5
Galena	PbS
Limonite	$2Fe_2O_3 \cdot 3H_2O$ soluble in acids
Magnetite	Fe_3O_4
Molybdenite	MoS_2
Pyrite	FeS_2
Sphalerite	ZnS with some FeS (isomorphous)
Tetrahedrite	$3Cu_2S \cdot Sb_2S_3$

Silicate and carbonate minerals
Formulae from Rutley's Mineralogy

Actinolite	$Ca(Mg,Fe)_5(Si_8O_{22}(OH)_2$ an amphibole
Biotite (mica)	$K(Mg,Fe)_3(Al,Si_3)O_{10}(OH,F)_2$
Calcite	$CaCO_3$
Chlorite	$(Mg,Fe)_5Al(Al,Si_3)O_{10}(OH)_8$
Epidote	$Ca_2(Al,Fe)_3(SiO_4)_3(OH)$
Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Montmorillonite	$(Na,Ca)(Mg,Al)_4Si_8O_{20}(OH)_4.nH_2O$
Orthoclase	$KAlSi_3O_8$
Plagioclase	$NaAlSi_3O_8$ range to $CaAl_2Si_2O_8$
Pyroxene	$(Ca,Mg,Fe,Al)(Al,Si)_2O_6$, Mn and Zn is sometimes present
Quartz	SiO_2
Sericite	a variety of muscovite mica, $KAl_2(AlSi_3)O_{10}(OH,F)_2$
Talc	$Mg_3Si_4O_{10}(OH)_2$

APPENDIX C PASSIVE TREATMENT SYSTEMS
- A Literature Review

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1.0 INTRODUCTION

Passive ecological waste water treatment and utilizaion systems for the treatment of sewage and agricultural effluents has been utilized by mankind for at least 2000 years (212). However, only since the early 1980's has the ability of ecosystems to remove contaminants from waste waters been exploited in the western world (215,216). Experimentation utilizing wetlands for the amelioration of Acid Mine Drainage (AMD) has been ongoing since the early 1980's in North America, as it was observed that coal seepages passing through natural wetlands emerge with a significant improvement in their characteristics (160).

A study of natural wetlands associated with 6 base metal mines in eastern Canada suggested that none of the wetlands reduced downstream metal or acidity loadings. However, high metal concentrations in the wetland sediments indicated that wetlands had removed metals from AMD passing through them (222). The ecological approach to the utilization of wetland processes to ameliorate acid mine drainage in mining waste management systems is described in 1988 (221).

Passive waste water treatment utilizes natural purification processes which, when maintained in a natural balance, produce reusable water. In passive treatment, the major chemical forces which assist in purification are oxidation, reduction, coagulation, adsorption, absorption and precipitation. Biological forces, dominated by microbial activity, mediate many chemical water purification actions. Physical forces of water purification are gravity, light, aeration, dilution and wind-driven turnover (213). Wetlands and lakes represent ecosystems in which these processes take place.

Water treatment plants for the removal of specific contaminants are designed to treat a certain quantity of contaminant loading. The treatment process requires that chemical reactions take place at defined rates, and physical forces are used to remove the resultant precipitate. Energy is required to support the treatment process.

In a wetland, the plants and sediment provide the physical structure of the treatment system. The sediment provides the vessel in which the microbes mediate the chemical reactions. The reactions change the form of the contaminant such that it may leave the wetland as a gas, or form particulate matter which will settle to the sediment.

Contaminants may be removed from water by ion-exchange, complexation or precipitation on algal/plant/bacterial surfaces (biosorption) or by uptake by these organisms. Within sediments, precipitates of metals may be transformed to less soluble forms through biomineralization, a process where microbes assist in the formation of minerals such as pyrite.

The forms of inorganic pollutants are changed in the sediment through oxidation / reduction reactions, which are mediated by microbes. Microorganisms utilize sulphate and convert it through reduction to sulphide using the organic acids which are produced by the decomposition of plant or organic matter. The purification step for inorganic contaminants is therefore the microbially-mediated change in chemical form which then, depending on the chemical conditions of the water, either escapes as a gas (bog gas) or precipitates as a metal sulphide.

Organic pollutants can be used as a food source in microbial decomposition, which may result in the generation of organic acids. These act as flocculants, coagulants or complexing reagents. They assist in forming particulate matter, which either settles to the sediment or adheres to surfaces of the wetland plants.

The rates at which these microbial and chemical water purification processes take place in the wetland determine the contaminant loading which can effectively be treated. Therefore, to determine the design parameter for a pilot system, which resembles a wetland, the microbial reaction rates and the chemical conditions under which they take place and are sustained are the essential components of the design.

2.0 METHODOLOGY AND APPROACH

2.1 The Bibliography

A bibliography on wetlands and passive treatment systems was compiled in a spreadsheet table. The papers are referred to by a number, stating the author (i.e. the reference) with abbreviated titles. Some information about the paper is entered into the bibliography which describes its contents using keywords.

The type of water which is treated is referenced and the wetland type is described. A total of 223 papers from the reference collection at Boojum Research, and those supplied by additional sources, were entered into the bibliography. A computer search with the key words "mine drainage," "sulphide," "pyrite," "iron" and "tailings" was updated from I984. Relevant abstracts will be utilized in the design work.

The papers in the bibliography are categorized broadly by the type of passive treatment which is described in the paper. Four treatment system types are identified with all the wetland papers grouped together, as some are difficult to classify. These categories are: anoxic limestone drains; wetlands (aerobic wetlands, reed beds, compost wetlands); microbial systems; and finally, systems which utilize biosorption. For each system category, written summaries are presented in the next section.

3.0 PASSIVE SYSTEMS REVIEW

3.1 Anoxic Limestone Drains

Anoxic limestone drains utilize limestone to release alkalinity under anoxic conditions. Carruccio and Geidel (47) first used this principle for emerging seepages which, after contact with limestone, returned into the tailings pile. Drains were subsequently used as a pretreatment to wetlands, notably in coal mines in the TVA region.

The Impoundment 4 system at Fabius, Alabama, described by Brodie et al.(192), was constructed to treat a coal drainage prior to its passage through a constructed wetland. It worked well for 6 months with a precipitous drop in Fe and Mn concentrations in the effluent. Acid mine drainage may contain both ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron which precipitate around pH 5.5 to 6.5 and pH 3 to 4 respectively. If the pH in the drain is low, $Fe(OH)_3$ precipitates will be produced which can rapidly reduce the hydraulic conductivity of the limestone and render the system useless. Replenishment of the limestone would require extensive excavation. In the Impoundment 4 drain, such a buildup of $Fe(OH)_3$ precipitates took place which eventually blocked the flow.

The drains described by Nairn, Hedin and Watzlaf (131,153, 154) set up in 1990 in the southern Appalachians (Morrison and Shade) were effective in providing alkalinity. The seepage in the Morrison system gained an average of 255 mg/L $CaCO_3$ equivalent alkalinity for the 12 months following construction. The water leaving the drain passed through a wetland where more than 99 % of the iron and 60 % of the manganese were removed. This system worked effectively for the reported period. The water entering the drain had low concentrations of Fe^{3+} and other metals (Table 2a).

At Shade, excellent alkalinity generation was observed. In this system, however, the drain reduced Al concentration considerably. Aluminum hydroxide precipitates at pH > 3.5 to 4.5 and thus may build up in the drain in the long term. All anoxic limestone drains are expected to eventually become ineffective due to precipitate clogging or through dissolution of the limestone. To date, the literature gives no reasonable estimates of the expected effective life of these systems.

3.2 Aerobic Wetlands

Cattails survive in iron hydroxide sludge, which accumulates when AMD passes through wetlands. Wetlands were therefore specifically constructed to optimize the removal of iron from AMD. The performance of constructed wetland systems in the TVA area was used to derive guidelines for the construction of wetlands (7). The sizing of wetlands is based on the estimated area to remove a quantity of iron. The guidelines for the required size have changed several times reflecting new data which have been generated (133). Many wetlands have been built to treat AMD (46).

Brodie et al (7, 194) describe the design of wetlands to treat coal AMD in the TVA area to meet compliance for Fe and Mn concentrations as well as pH. Local materials (soil, gravel, fly-ash, etc.) are used in the construction, and cattails are transplanted by hand. The substrates often have low permeabilities and therefore the AMD is mainly treated in surface water flow. This promotes oxidation and hydrolysis of iron, leading to the buildup of ferric hydroxide. AMD is prone to channel-flow through the wetland. Therefore, low retention times result and only a small part of the wetland is utilized in AMD treatment.

Nine of the 14 TVA constructed systems have been operating well for several years. These wetlands treat AMD with relatively low Fe concentrations (0.7 to 69 mg/L, loading 0.03 to 6.13 g/day/m^2) and low net inflow alkalinity (35-300 mg/L equiv. $CaCO_3$). Effective removal of iron takes place, and to a lesser extent, manganese. Data on the hydrological characteristics of the wetlands required to assess the potential effects of ground water contributions, evapotranspiration, and precipitation are frequently not available. Four of the TVA systems, characterized by low or zero input alkalinity and high Fe loadings (40-170 mg/L, 5-41 g/day/m^2), have failed to meet discharge requirements (Table 2b). Sphagnum bogs have also been tested for their ability to treat AMD (161) but their performance has not been promising.

Wetlands have been constructed for a wide variety of waste waters in addition to AMD. Two publications from 1989 (215) and 1990 (216) summarize a large number of studies on these projects. The largest number of wetlands have been constructed to treat domestic waste water. The EPA has reviewed some 150 of such systems (60). The reviews suggest that for the pretreatment of agricultural and domestic sewage, the wetlands are reasonably effective in removing BOD-5 (biological oxygen demand for 5 days) but less effective at removing nitrogen (generally NH_4-N) and particularly phosphorus.

A few wetlands have been constructed recently for the treatment of landfill leachate. This is a particularly complex effluent since the water quality varies in the short term and over the years. 'Young' leachate is characterized by high BOD-5 and COD (chemical oxygen demand), a low BOD-5/COD ratio, and relatively low NH_4-N. 'Old' leachate is characterized by lower BOD-5 and COD, a high BOD-5/COD ratio and high concentrations of NH_4-N. Landfill leachate carries a wide variety of organics and often heavy metals which require removal. Wetlands have only been described to treat low strength leachate. For example, Birkbeck et al (96) constructed a wetland system in British Colombia to treat leachate with a BOD-5 of 21 mg/L, COD 176 mg/L, NH_4-N 32.3 mg/L and Fe 11.2 mg/L. Six wetlands with different substrates and planted species removed most of the Fe but only a small part of the BOD-5, and little of the COD and NH_4-N. The size and retention times of the wetlands (1.0 to 2.6 days) were probably inadequate for removal of NH_4-N by denitrification.

2.3 Reed Bed Wetlands

Reed bed wetlands are sub-surface flow wetlands, usually planted with *Phragmites* (Reeds). The concept was developed in Germany by Kickuth in the early seventies (219) for treatment of domestic waste water. Hundreds of systems utilizing this concept have been constructed in Europe. Design parameters based on hydraulic conductivity of the reed bed substrate for removal of BOD-5 have been developed (217). Three examples are summarized in Table 2c (62, 68, 107).

The performance of the Valleyfield system in Scotland (107) gives an indication of a typical situation where such wetlands are used, and indicates some of the problems associated with these systems. In the first monitoring period, the 5 months following construction (summer-autumn), removal of BOD-5 (mean of 76 % of 236 mg/L) and phosphorus (mean 82 % of 12.7 mg/L) was effective, but N removal (mean 31% of 29.5 mg/L) was poor. Two years later, BOD-5 removal (83 %) remained effective but little N (8 %) or P (21 %) was removed. The following winter, there was a net gain in N. Four different substrate materials (two particle sizes of fuel ash and two sizes of gravel) have been tested in the Valleyfield study. They all behave in a similar fashion. Hydraulic conductivities were reduced to near zero in all four substrates, which resulted in surface flow and short retention times. The poor winter performance is attributable to reduction in biological activity with lower winter temperatures.

Haberl and Perfler (68) described the performance of the Mannersdorf system in Austria. Three years after establishment of flow, the system was removing an average of 95 % of the BOD-5 (mean 93 mg/L) and 86 % of the COD (mean 316 mg/L) from raw sewage. The system also removed 38 % of the N and 69 % of the P.

Brix and Schierup have summarized reed bed performance in Denmark (62). Most systems remove 70-90 % of the BOD-5, 25-50 % of the nitrogen and 20-40 % of the P. The poor removal of N and P was attributed to surface flow (poor permeability of substrate) and excessive loading rates (Table 2c).

Overall, reed beds provide an effective means of removing BOD-5, but are generally inadequate for removing nitrogen and phosphorus. The role of the plants in increasing substrate permeability and releasing oxygen into the rhizosphere (to stimulate aerobic microbial activity) has not been clearly established. Some studies have shown (218) that such systems perform as well without any vegetation present.

2.4 Compost Wetlands

Wetlands constructed for AMD with higher acidity and iron loadings generally incorporate a biodegradable compost with added limestone to generate alkalinity and increase the rate of microbial decomposition. Limestone has been incorporated into many constructed wetlands. The Tracy wetlands in Montana (50) were constructed with a substrate of limestone and soil with a peat cover. Over the first year of operation, both wetland systems failed to improve the quality of two coal acid mine drainages. This was attributed to inadequate retention times.

The Simco #4 wetland (54) was successful. This system had a substrate of 15 cm of crushed limestone overlain with 45 cm of spent mushroom compost. These conditions are similar to an anoxic limestone drain. Following construction, the effectiveness of the system improved over two years. Performance was then variable (negatively correlated with flow) but showed a clear improvement after the placement of hay bale dikes which reduced water short- circuiting (Table 2d).

The Big Five Tunnel system in Colorado (193) treats a seepage which has an average pH of around 3, Cu 1 mg/L, Fe 35 mg/L, Mn 30 mg/L and Zn 10 mg/L. The wetlands are relatively small, comprising five different treatment cells. The substrates used in the cells are various mixtures of mushroom compost, peat, manure and woodshavings overlying 15 cm of limestone. These materials have a neutralizing capacity and play a role in the adsorption of metals.

Performance of the system was very variable during the summer months with a poorer performance during the winter months for all measured parameters. The nutrient-rich organic material would definitely encourage microbial activity of sulphate and iron-reducers, but this treatment process can not be differentiated from the effect of the limestone and mushroom compost added to the cells.

The work of Wieder (223) is the best-documented wetlands application to treat AMD. Five wetlands in Kentucky were constructed with 5 different substrates and operated for 111 weeks with weekly monitoring of effluent parameters. The mushroom compost wetland (containing limestone) gave the best performance, while the peat wetland performed the worst.

The wetlands did not improve the effluent in the winter and failed to recover after the second winter. During the two summers, titratable alkalinity was generated in the mushroom compost and straw/manure wetlands. The alkalinity generated is attributable directly to dissolution of limestone. The reduction of sulphate in 4 of the 5 wetlands indicates that microbial sulphate reduction may also account for pH improvement and alkalinity generation. Towards the end of the study the acidity loading from the seepage overwhelmed the ability of all wetlands to generate alkalinity and remove metals.

Wieder studied in some detail the form of sulphur, iron and other metals in the wetlands. The wetlands retained iron as exchangeable, organically-bound carbonate hydroxide and sulphide iron. Carbonates and sulphides were abundant in the mushroom compost and straw/manure wetlands.

Hedin and Nairn (133) have suggested criteria for selection of wetland type (aerobic or compost) and sizing based on data from a variety of constructed wetlands for mine drainage treatment. Where the water is net-alkaline, passive systems with aerobic wetlands are recommended with sizing based on 20 $gm^{-2}d^{-1}$ Fe or 0.5 $gm^{-2}d^{-1}$ Mn. For net-acidic waters, systems with compost wetlands are recommended with sizing based on 5 $gm^{-2}d^{-1}$ acidity or 0.5 $gm^{-2}d^{-1}$ Mn.

3.5 Microbial Systems-Bioreactors, ARUM

Reactor systems have been set up to test the ability of sulphate reducing bacteria to generate alkalinity and precipitate metals from AMD. Small-scale flow-through (43) and large-scale (200 L or more) batch reactors (163, 208) have established that metal removal and alkalinity generation can occur (Table 2e). In the Kuyucak (43) and Dvorak (163) systems, limestone was added which makes quantification of the relative roles of bacterial sulphate reduction and limestone dissolution difficult. Kalin et al (208) established that in the presence of organic amendment (flax straw) but in the absence of added limestone, substantial amounts of alkalinity and 99% removal of Ni (60 mg/L) and Fe (200 mg/L) could be achieved in 200 L reactors (208).

These results suggest that batch treatment with long retention times are required to optimize conditions for sulphate reduction and other microbial alkalinity generating processes. These reactors are simulating the conditions of anaerobic sediments where the alkalinity generating processes occur in nature. Thus, Kalin (208) tested the use of a floating cattail mat as part of the ARUM (acid reduction using microbiology) process to extend sediment conditions through the water column of a field test cell system treating AMD at Sudbury, Ontario. The final configuration of the system - a microbially-active sediment with a floating cattail cover - produced, with a calculated retention time of 131 days, a removal of 80 - 87 % of the nickel loading, 77 - 98 % of the copper loading, 10 to 20 % of the sulphur loading as well as 47 - 73 % of the acidity loading. Removal rates of microbial systems with ARUM at several locations in Canada are summarized in Table 3 (208).

3.6 Bioabsorption Systems-Bio-Fix, Biopolishing

A number of studies have established that a variety of organisms, both alive and dead, can very effectively remove metal ions from solution through biosorption, a term which encompasses ion exchange, complexation and local precipitation. Volesky (211) provided a detailed review of biosorption processes and applications.

Peat, present in most constructed wetlands, is very effective at removing Cu by cation exchange (Chen et al 175, 202). Wieder (223) has established that metals can displace H^+ on the surfaces of peat.

The ability of peat to remove ions led to the development of Bio-Fix beads, finely ground peat in a matrix of polysulphone. Beads of this material expose a large surface area of peat. These Bio-Fix beads have been tested in laboratory columns and in field systems for their ability to remove heavy metal ions from AMD (40). Bags of beads were placed in trenches in two field experiments. The beads effectively removed Cu and Fe from an AMD with a pH of 5.5. Removal of Zn was variable and of Mn negligible (Table 2f). Although they are very effective the beads require frequent eluting and recharging.

Biological Polishing utilizes live algae for collection of metal precipitates. The loaded biomass is relegated to the sediments. The maintenance of algal populations requires addition of fertilizer when not available in the waste water. Slow-release formulations of fertilizer allow for additives once a year. Performance during the winter months is reduced but not eliminated. Kepler (52) combined algal ponds with constructed wetlands in a treatment system. The system was reasonably effective in treating the water but it is not possible to quantify the role of algae in the process. Periphyton in a series of polishing ponds effectively removed Zn from an AMD seepage in Newfoundland (210).

4.0 DESIGN CRITERIA FOR PASSIVE SYSTEMS

Passive treatment systems are perceived as systems with no power supply other than sunlight, and requiring minimal ongoing additions to assist the water treatment process. These systems are perceived as self-sustaining and require low maintenance throughout the year. Although the experimental systems represent the passive treatment approach, their performance is available only for few years, and chemical additions of neutralizing agents (limestone or mushroom compost) were made during construction. This does not allow a separation of chemical and biological processes which are effective in improving AMD.

The review revealed that for each system, the published data are limited. Emphasis is placed on the removal of selected elements. The pollutant concentration of influent and effluent parameters are reported. Few studies report data which would allow assessment of loadings which would lend themselves to derive reliable design criteria.

Anoxic limestone drains can initially release much alkalinity but in the presence of heavy metals they are likely to become clogged up. Iron present in the ferrous state may pass through the system without precipitation until the system nears a neutral pH.

Biosorption processes are very effective in removing heavy metals. Non-living materials such as Bio-Fix beads are unsuitable because of the necessity for frequent 'recharging' of the biosorbant material. Living algae can remove metals (and remaining N and P) through biopolishing. This process could be used as a final treatment step to remove remaining pollutants before water discharge.

Removal of ammonium-N can be achieved in wetlands but is not reliable. Nitrification in aerobic ponds is undoubtedly the best way of removing this pollutant. Wetlands can be effective in removal of heavy metals, nitrogen and BOD-5 (organics). Many systems fail due to short circuiting flow either due to inadequate substrate permeability in subsurface flow wetlands (reed beds) or to channel building in surface flow wetlands. Removal of N, P and heavy metals can be achieved by ensuring adequate effective retention time and contact with the substrate. Microbial pollutant removal processes will generally be enhanced through an increase in pH.

In all systems where metals are removed through precipitation, precipitates (sludges) will accumulate and eventually require removal. Sludges alter the hydrologic characteristics of the wetlands and cover surfaces of organic materials rendering them unavailable both for biosorption processes or as substrates for decomposing microorganisms, which are required for sulphate reduction. In the ARUM configuration for the tailings seepage rich in iron, a iron hydroxide precipitation cell was installed, preceding the ARUM treatment cells.

Most passive treatment systems described in the literature have been operating for two or three years or less and, with the exception of anoxic limestone drains, sludge build-up has not been quantified.

In Table 4, a summary is provided for all types of wetland reviewed and ratings are given by the parameter(s) which needs to be addressed for a mixture of AMD and wood wastes.

5.0 SUMMARY

Seven categories of passive treatment system were considered:

- Anoxic limestone drains
- Settling ponds
- Aerobic wetlands
- Reed beds
- Compost wetlands
- Microbiology based systems
- Biosorption systems

For each category, the published literature was examined and a small number of papers selected for detailed review. The data presented was summarized and the overall role and efficacy of the treatment assessed.

Anoxic limestone drains have been constructed in the U.S., principally to add alkalinity and increase pH to the acid mine drainage water prior to passage through a wetland. These systems comprise a buried trench of high grade limestone chips over an impervious liner and buried under a clay layer. They are designed for passage of water in an anoxic state. This is in order to maintain the iron (the concentration of which is generally high in all acid mine drainages) in the reduced or ferrous state. If the iron is exposed to oxygen, it will oxidise and precipitate as ferric hydroxide if the pH exceeds 3.5. The three systems examined were only running for a short period. One system failed due to ferric hydroxide clogging. The longevity of the other systems has to be determined. These systems are effective for short periods in attaining the goal of adding alkalinity and raising pH but in the long-term will require limestone replacement.

Aerobic wetlands have been extensively planted in the U.S. to treat AMD. Essentially their role is to precipitate iron and manganese in oxidising conditions. The effectiveness of these systems is very variable and generally only work well where the pH of the water is initially high. Failure may be attributed to inadequate hydrological conditions (channelling, short retention times, leakage). Over a period of years these iron precipitation will result in build-up of sludges which will require removal for continued operation of the wetland. Such build up has not been well documented and most papers discuss the performance of wetlands three years old or less.

Reed beds comprise a bed of substrate (usually gravel, sand or soil), planted with reeds (Phragmites australis L.) designed for sub-surface flow of wastewater. These are generally for the secondary or tertiary treatment of domestic waste-water. However, they are considered since they are consistently effective in removal of BOD5 and suspended solids. Overall these systems have not performed as anticipated, particularly in relation to N and P. This is attributed to low substrate permeability and consequent surface flow and reduced retention time.

Compost wetlands evolved from aerobic wetlands to treat acidic mine drainages. These were conceived to promote the activity of sulphate reducing bacteria which can both generate alkalinity, raise the pH and result in the precipitation of heavy metals as sulphides. These have a smaller volume than ferric hydroxide. These wetlands generally use a substrate of spent mushroom compost with limestone added. This limestone raises the pH and generates alkalinity which makes it very difficult to quantify the role of sulphate reduction.

Microbiology systems like the compost wetlands are designed to exploit the ability of anaerobic microbial processes such as sulphate reduction to generate alkalinity, raise the pH and precipitate metals as sulphides. These systems unlike the compost wetlands are designed to extend optimum conditions for the bacteria through the system. These systems may or may not have added limestone. It has been established that such systems can function without added limestone to treat acid mine drainages with a low pH (<3). Therefore there is no absolute requirement to replenish limestone. However a continued source of nutrients for the bacteria is required. This could be achieved through regular (annual) addition of suitable, biodegradable materials or in the long term through establishment of plant covers, the breakdown of which provides the microbial food.

Biosorption systems are very effective in removing metal ions from waste water through ion-exchange, complexation or local precipitation. Dead or living biomass is utilised. Bio-Fix beads, finely ground peat in a high surface area inert matrix exploit the ability of peat to remove protons and heavy metal ions by ion exchange. Such systems are very effective but require replenishing every few days. Biopolishing with growing algae can exploit biosorption processes, particularly local precipitation, without the need for replenishment. However, high algal productivity may require the addition of fertilizers.

To summarise, all passive treatment systems require some ongoing maintenance for continued effective water treatment. The benefits of such systems depend on the cost savings both in plant construction and maintenance.

Table 1: Bibliography

No.	Author	Year	Title	Source	Page	System	Water	Avail
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43	Kuyucak, N, Lyew, D., St. Germain, P.,	1991	In situ treatment of AMD in open pits	Montreal Conf. on Abatement of Acidic Drainage, Vol.	335	Bioreactors	AMD	Y
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188	Duggan, L.A., Wildeman, T.R., and Upd	1992	The aerobic removal of manganese from mine dr	ASSMR, Duluth, Minn., June 14-18		Biopol	AMD	Y
110	Gerber, D.W., Burris, J.E., and STone, R	1985	Removal of dissolved iron and manganese ions	Proc. Penn State U. Conf., Pittsburgh	365	Fe, Mn	AMD	Y
167	Jennett, J.C., Hassett, J.M., and Smith,	1979	Control of heavy metals in the environment usin	London Int. Conf. on Heavy MEtals in the Envt.		Algae	AMD	Y
184	Kalin, M.	1990	Ecological engineering applied to base metal mi	Acid Mine Drainage Designing for Closure (Gadsby,	407	South Bay	AMD	Y

210	Kalin, M.	1993	Biological Polishing in Acid Mine Drainage: Final	CANMET Contract 23440-2-9216, Doc 015SQ.23440-2		Biopolishing	AMD	Y
206	Kalin, M., and Wheeler, W.N.	1992	Periphyton growth and zinc sequestration	BIOMINET, Edmonton, 1992			AMD	Y
52	Kepler, D.A.	1988	An overview of the role of algae in the treatment	USBM Circular 9183, Pittsburgh Conf.	286		AMD	Y
53	Lapakko, K., and Eger, P.	1988	Trace metal removal from stockpile drainage by	USBM Circular 9183, Pittsburgh Conf.	291		AMD	Y
201	Pettersson, C., Hakansson, K., Karlsson	1993	Metal speciation in a humic surface water syste	Wat. Res., 27	863	Cu ion exchange	AMD	Y
140	Smith, M.P., and Kalin, M.	1989	Biological polishing of mining waste waters: Bioa	Biohydrometallurgy, Jackson Hole, WY	659		AMD	Y
170	Spisak, J.F.	?	Metallurgical effluents-Growing challenges for se	Symp.:Biological recovery of metals from waste water	249		AMD	Y
56	Spratt, A.K., and Weider, R.K.	1988	Growth responses and iron uptake in Sphagnum	USBM Circular 9183, Pittsburgh Conf.	279	Fe	AMD	Y
83	Stevens, S.E>, Dionis, K., and Stark, L.	1989	Manganese and iron ensrustation on green alga	Hammer "Constructed wetlands.."	767	Biopolishing	AMD	Y
211	Velosky, B.	1990	Biosorption of heavy metals	CRC Press Inc.		Review		N
86	Vymazal, J.	1989	Use of periphyton for nutrient removal from wate	Hammer "Constructed wetlands.."	558	Biopolishing	DWO	Y
159	Wieder, R.K.	1990	Metal cation binding to Sphagnum peat and saw	Water, Air and Soil Pollution, 53	391	Ion exchange	AMD	Y
203	Xue, H-B., and Sigg, L.	1990	Binding of Cu(II) to algae in a metal buffer	Wat. Res., 24	1129	Cu binding to algae		Y
183	Kalin, M., Fyson, A., and Smith, M.P.	1993	ARUM-Acid reduction Using Microbiology	Biohydrometallurgy, Jackson Hole		Buchans, INCo, Deni	AMD	Y
14	DeBusk, T.A., Langston, M.A., Peterson,	1991	A performance comparison of duckweed and hy	Constructed wetlands... Pensacola	23		DWO	A
13	Hancock, S.J., and Buddhavarapu, L.R.	1991	Advanced wastewater treatment with Lemna tec	Constructed wetlands... Pensacola	21		DWO	A
182	Kalin, M.	1991	Decommissioning OPen Pits with ecological eng	AGM CMP, Ottawa, Jan 21-23		Buchans, limnocorral	AMD	Y
137	Kalin, M.	1989	Ecological engineering applied tobase metal an	Biohydrometallurgy, Jackson Hole, WY	363		AMD	Y
146	Kalin, M.	1990	Ecological engineering applied to base metal mi	Proc. 7th. AGM of BIOMINET, Mississauga	3		AMD	Y
	WETLANDS							
1	ASSMR	1990	Constructing wetlands on mined lands (1985-19			Review	AMD	Y
60	Bastian, R.K., Shanaghan, P.E. and Tho	1989	Use of wetlands for municipal wastewater treatm	Hammer "Constructed wetlands.."	265		DWW	Y
59	Batal, W., Laudon, L.S., Wildeman, T.R.,	1989	Bacteriological tests from the constructed wetlan	Hammer "Constructed wetlands.."	550	Big-Five Tunnel	AMD	Y
20	Best, G.R.	1991	Creation of multifunctional wetland ecosystems f	Constructed wetlands... Pensacola	50	Review of Florida wet	WW	A
96	Birkbeck, A.E., Reil, D., and Hunter, R.	1990	Application of natural and engineered wetlands f	CWWPC, Cambridge	411		LL	Y
191	Bolis, J.L., Wildeman, T.R., and Cohen,	1991	The use of bench scale permeameters for prelim	ASSMR, Durango, CO, May 14-17		National and Quartz	AMD	Y
189	Bolis, J.L., Wildeman, T.R., and Dawson	1992	Hydraulic conductivity of substrates used for pa	ASSMR, Duluth, Minn., June 14-18		Hydrology	AMD	Y
174	Breen, P.F.	1990	A mass balance method for assessing the poten	Wat. Res. 24	689	Microcosms	DWO	Y
10	Britt, C.R., Taylor, J., Brodie, G.A. and T	1991	Raising pH of constructed wetlands effluent usin	Constructed wetlands... Pensacola	8	TVA/PEC	CAMD	A
97	Britt, C.R., and BRodie, G.A.	1990	Wetland issues of the Flat Woods coal lease and	CWWPC, Cambridge	547	Flat Woods	CAMD	Y
62	Brix, H., and Scheirup, H.	1989	Management of domestic and mucicipal wastew	Hammer "Constructed wetlands.."	565	Review	DWW	Y
61	Brodie, G.A.	1989	Selection and evaluation of sites for constructed	Hammer "Constructed wetlands.."	307	Design	GEN	Y
98	Brodie, G.A.	1990	Constructed wetlands for treating acid drainage	CWWPC, Cambridge	461	TVA, review	CAMD	Y
7	Brodie, G.A.	1991	Staged, aerobic, constructed wetlands: Impoun	Constructed wetlands... Pensacola	5	TVA, review	CAMD	A
194	Brodie, G.A.	1993	Staged, aerobic, wetlands-based acid drainage t	Wetland Design for Mining Operations, Brodie, Wilde		TVA review	AMD	Y
58	Brodie, G.A., Hammer, D.A., and Tomlja	1988	Constructed wetlands for drainage control in the	USBM # 9183	325	TVA,review	CAMD	Y
63	Brodie, G.A., Hammer, D.A., and Tomlja	1989	Treatment of acid drainage with a constructed w	Hammer "Constructed wetlands.."	201	950 Coal Mine	CAMD	Y
64	Brodie, G.A>, Hammer, D.A>, and Tom	1989	Constructed wetlands for treatment of ash pond	Hammer "Constructed wetlands.."	211	TVA wetlands	CAMD	Y
3	Brooks, R.P.	1984	Optimal designs for restored wetlands	Contribution #264, Dept. of Biol., PSU			AMD	N
31	Brooks, R.P.	1985	Wetlands and water management of mined land	Proc. Penn State U. Conf., Pittsburgh		Proceedings	AMD	Y
21	Burgoon, P.S., Reddy, R.K., and DeBus	1991	Design considerations for secondary and advan	Constructed wetlands... Pensacola	59	REview of FAM and V	DWO	A
22	Butler, J.E., and Deweder, A.	1991	Gravel bed hyderoponic sewage treatment	Constructed wetlands... Pensacola	66	Portsmouth, U.K., Is	DWO	A
130	Calabrese, J.P., Bhumbla, D.K., Sexsto	1990	Simulated Typha wetlands applied to removal of	Proc. 11th. Ann. WVSMDTFS, Charleston	351	Fe, Mn, lab. wetland	AMD	A
33	Calabrese, J.P., Sexstone, A.J., Bhumbl	1991	Application of constructed cattail wetlands for th	Montreal Conf. on Abatement of Acidic Drainage, Vol.	559		AMD	Y
114	Chen, G., Li, L., and Lan, C.	1992	Typha beds constructed wetland Pb-Zn wastewa	Global Wetlands, Columbus, Ohio		Pb, Zn	AMD	A
26	Choate, K.D., Watson, J.T., and Steiner,	1991	Consructed wetland treatment systems	Constructed wetlands... Pensacola	79	TVA review	DWO	A
217	Cooper, F.P.	1990	European design and operation guidelines for re	EC/EWPCA EHTSECG, Report UI 17			DWO	Y
216	Cooper, P.F., and Findlater, B.C.	1990	Constructed wetlands in water pollution control	IAWPRC, Cambridge				Y
94	Cooper, P.F., and Hobson, J.A.	1989	Sewage treatment by reed bed systems: The pre	Hammer "Constructed wetlands.."	153	MD	DWO	Y
24	Crites, R.W., Beggs, R.A., and Lekven,	1991	Subsurface flow constructed wetlands at Mequit	Constructed wetlands... Pensacola	69	Mesquite, Nevada	DWO	A
11	Crumpton, W.G.	1991	Transformation and fate of nitrate in wetlands rec	Constructed wetlands... Pensacola	10	Non-point source, rev	ARO	A
200	Dollhopf, D.J., Goering, J.D., Rennick,	1988	Hydrological, vegetational and microbiological e	MSU/MDI, RRU 8804			AMD	Y
66	Dornbush, J.N.	1989	Natural renovation of leahcate-degraeded groun	Hammer "Constructed wetlands.."	743	Brookings, SK	LL	Y
27	Dornbush, J.N.	1991	Constructed wastewater wetlands: The answer in	Constructed wetlands... Pensacola	87	South Dakota review	DWO	A

214	EPA	1991	Report on the use of wetlands for municipal wast	EPA report 430/09-88 005 US EPA Office of Municipal		Review	DWO	N
6	Eger, P., Melchert, G., Antonson, D., an	1991	The use of wetland treatment to remove trace m	Constructed wetlands... Pensacola	4	Minnesota	AMD	A
49	Eger, P., and Lapakko, K.	1988	Nickel and copper removal from mine drainage	USBM Circular 9183, Pittsburgh Conf.	301	Cu, Ni	AMD	Y
67	Eger, P., and Lapakko, K.	1989	Use of wetlands to remove nickel and copper fro	Hammer "Constructed wetlands.."	780	CU, Ni, Dunka, Minne	AMD	Y
93	Faulkner, S.P., and Richardson, C.J.	1989	Physical and chemical characteristics of freshwa	Hammer "Constructed wetlands.."	41	Wetland chemistry		Y
99	Faulkner, S.P., and Richardson, C.J.	1990	Iron and manganese fractionation in constructed	CWWPC, Cambridge	441	Fe, Mn	AMD	Y
187	Filas, B.A>, Wildeman, T.R.	1992	The use of wetlands for improving water quality t	Navada MA Ann. Rec. C., Sparks		Review	AMD	Y
4	Frostman, T.M.	1991	System-wide approach to acidic mine drainage t	Constructed wetlands... Pensacola	1	Minnesota-Taconite	AMD	A
196	Gallinger, R., Gormely, L., Kistritz, R., an	1991	Constructed wetland experiment for treating AM	16th. AGM CLRA, Kamloops, BC, June 24-28	276	Bell Copper	CAMD	Y
69	Girts, M.A., and Knight, R.L.	1989	Operations optimization	Hammer "Constructed wetlands.."	417	Review, monitoring		Y
100	Gray, K.R., Biddlestone, A.J., Job, G., a	1990	The use of reed beds for the treatment of agricul	CWWPC, Cambridge	333	High N, limestone	ARO	Y
68	Haberl, R., and Perfler, R.	1989	Root-zone system: Mannersdorf-New Results	Hammer "Constructed wetlands.."	606	Reed-Bed performan	DWO	Y
215	Hammer, D.A.	1989	Constructed wetlands for wastewater treatment	Lewis Publishers, Chelsea Michigan				Y
15	Hammer, D.A., Pullin, B.P., McCaskey,	1991	Treating livestock wastewaters with constructed	Constructed wetlands... Pensacola	31	Sand Mountain AES,	ARO	A
166	Hammer, D.E., and Kadlec, R.H.	1985	Design principles for wetland treatment systems	EPA No. PB-83-188-722		Design		N
141	Hedin, R.S.	1989	Treatment of coal mine drainage with constructe	Majumder et al, Wetlands Ecology and Conservation:	349		CAMD	Y
51	Hedin, R.S., Hyman, D.M., and Hamma	1988	Implications of sulfate reduction and pyrite form	USBM Circular 9183, Pittsburgh Conf.	382	SR	AMD	Y
70	Hedin, R.S., Hyman, D.M., and Hamma	1989	Potential importance of sulphate reduction proce	Hammer "Constructed wetlands.."	508		AMD	Y
122	Hedin, R.S., and Nairn, R.W.	1990	Sizing and performance of constructed wetlands	Proc. 11th. Ann. WVSMDTFS, Charleston	385		CAMD	Y
133	Hedin, R.S., and Nairn, R.W.	1992	Designing and sizing passive mine drainage trea	Proc. 13th. Ann. WVSMDTFS, Morgantown			CAMD	Y
135	Hellier, W.W.	1989	Constructed wetlands in Pennsylvania. An overvi	Biohydrometallurgy, Jackson Hole, WY	599	Review		Y
143	Hellier, W.W., and Hedin, R.S.	1993	The mechanism of iron removal from mine disch	?		Fe	CAMD	Y
35	Hendricks, A.C.	1991	The use of an artificial wetland to treat acid mine	Montreal Conf. on Abatement of Acidic Drainage, Vol.	549		AMD	Y
71	Henrot, J., Weider, R.K., HEston, K.P., a	1989	Wetland treatment of coal mine drainage: Contro	Hammer "Constructed wetlands.."	793		CAMD	Y
144	Henrot, J., and Wieder, R.K.	1990	Processes of iron and manganese retention in la	J. Environ. Quality 19	312	Fe, Mn	AMD	Y
72	Hicks, D.B., and Stober, Q.J.	1989	Monitoring of constructed wetlands for wastewat	Hammer "Constructed wetlands.."	447	Monitoring-review		Y
50	Hiel, M.T., and Kerins, F.J.	1988	The Tracy wetlands: A case study of two passive	USBM Circular 9183, Pittsburgh Conf.	352		CAMD	Y
16	Higgins, M.J., Wengrzynek, R.J., and R	1991	The use of constructed wetlands in treating agric	Constructed wetlands... Pensacola	35	USDA, Maine	ARO	A
19	Hilton, B.L.	1991	Wastewater treatment in a CELSS unit employin	Constructed wetlands... Pensacola	47		DWO	A
73	Hobson, J.A.	1989	Hydraulic considerations and the design of reed	Hammer "Constructed wetlands.."	628		DWO	Y
74	Howard, J., Emerick, J.C., and Wildema	1989	Design and construction of a research site for pa	Hammer "Constructed wetlands.."	774	Big Five Tunnel	AMD	Y
121	Huntsman, B.E.	1986	Sphagnum dominated man-made wetlands use	Proc. 7th. Ann. WVSMDTFS, Morgantown		Sphagnum wetlands	CAMD	Y
111	Huntsman, B.E., Kleinmann, M.C., and	1985	Hydrologic and geochemical considerations in	Proc. Penn State U. Conf., Pittsburgh	375		AMD	Y
132	Jamison, E., and Rauch, H.W.	1990	Impacts of voluntary cattail wetlands on drainag	Proc. 11th. Ann. WVSMDTFS, Charleston	350	Volunteer wetlands	CAMD	A
115	Jenssen, P.D., Maehlum, T., and Krogst	1992	Adopting constructed wetlands for wastewater tr	Global Wetlands, Columbus, Ohio		northern climate		A
92	Kadlec, R.H.	1989	Hydrologic factors in wetland water treatment	Hammer "Constructed wetlands.."	21	Hydrology		Y
75	Kadlec, R.H.	1989	Dynamics of inorganic and organic materials in	Hammer "Constructed wetlands.."	459	Decomposition		Y
116	Kadlec, R.H.	1992	Wetlands for municipal wastewater polishing	Global Wetlands, Columbus, Ohio			DWO	A
25	Kadlec, R.H., and Watson, J.T.	1991	Hydraulics and solids accumulation in a gravel b	Constructed wetlands... Pensacola	72	Benton, KY	DWO	A
178	Kalin, M., Cairns, J., and McCready, R.	1991	Ecological engineering methods for acid mine dr	Resources, Conservation and Recycling, 5	265	Victoria Junction	CAMD	Y
147	Kalin, M., Scribailo, R.W., and Wheeler,	1990	Acid mine drainage amelioration in natural bog s	Proc. 7th. AGM of BIOMINET, Mississauga	61		CAMD	Y
205	Kalin, M., and Smith, M.P.	1992	The development of floating Typha mats	WSWPC, Sydney, Aust., Nov 30-Dec 2		Typha establishment	AMD	Y
44	Karathanasis, A.D., and Thompson, Y.L.	1991	Metal speciation and retention patterns in a high	Montreal Conf. on Abatement of Acidic Drainage, Vol.	485		AMD	Y
125	Kepler, D.A.	1990	Wetland sizing, design, and treatment effectiven	Proc. 11th. Ann. WVSMDTFS, Charleston	403	USBM,PA	CAMD	Y
219	Kickuth, R.	1976	Degradation and incorporation from reed	EEC document EUR5672e, Utilization of manure by la			DWO	N
150	Kleinmann, R.L.P.	1983	A low cost, low maintenance system for acid min	Lexington, KY, Symp. on Surface Mining, Hydrology,			AMD	Y
138	Kleinmann, R.L.P.	1989	Biological treatment of mineral processing waste	Biohydrometallurgy, Jackson Hole, WY	593		AMD	Y
46	Kleinmann, R.L.P., Edenborn, H.M., and	1991	Biological treatment of mine water-an overview	Montreal Conf. on Abatement of Acidic Drainage, Vol.	27	Review	AMD	Y
76	Kolbash, R.L., and Romanoski, T.L.	1989	Windsor Coal Company wetland: An overview	Hammer "Constructed wetlands.."	788	Windsor Coal	CAMD	Y
101	Lan, C., Chen, G., Li, L., and Wong, M.	1990	Purification of wastewater from a Pb/Zn mine usi	CWWPC, Cambridge	419	Zn, Pb	AMD	Y
222	Lane, P. and Associates	1990	Assesment of existing wetlands affected by low	Mend Project 3.12.1 Final Report			AMD	Y
102	Litchfield, D.K.	1990	Constructed wetlands for wastewater treatment a	CWWPC, Cambridge	399	Amoco Oil, Mandan	OW	Y
77	Litchfield, D.K., and Schatz, D.D.	1989	Constructed wetlands for wastewater treatment a	Hammer "Constructed wetlands.."	233	Amoco Oil Mandan,	OW	Y
195	Machemer, S.D., and Wildeman, T.R.	1991	Organic complexation compared with sulfide pre	J. Contaminant Hydrology, 9	115	Big Five Tunnel,SR, c	AMD	Y

112	McHerron, L.E.	1985	The seasonal effectiveness of a phagnum wetl	Proc. Penn State U. Conf., Pittsburgh	385	Fe, Mn, Grampian, P	AMD	A
151	McHerron, L.E.	1986	Removal of iron and manganese from mine drain	Masters Thesis, PennState U., Biology Department		Fe, Mn	AMD	N
152	McIntire, P.E., Edenborn, H.M., and Ha	1990	Incorporation of bacterial sulfate reduction into c	Proc. Nat. Symp. Mining, Knoxville, Tenn.	207	SR	AMD	Y
139	McIntire, P.E., and Edenborn, H.M.	1989	Application of anaerobic processes in constructe	Biohydrometallurgy, Jackson Hole, WY	627	SR	AMD	Y
78	Miller, G.	1989	Use of artificial cattail marches to treat sewage in	Hammer "Constructed wetlands.."	636	Listowel, Cobalt	DWO	Y
79	Mingee, T.J., and Crites, R.W.	1989	Constructed wetlands for secondary treatment	Hammer "Constructed wetlands.."	622	Gustine, CA	DWO	Y
179	Mitsch, W.J.	1993	Ecological engineering-a cooperative role with th	Environ. Sci. Technol., 27	438	Review		Y
109	Mitsch, W.J., Cardarone, M.A., and Tayl	1985	Wetlands and water quality management in the	Proc. Penn State U. Conf., Pittsburgh	121	Review	AMD	Y
153	Nairn, R.W., and Hedin, R.S.	1993	Designing wetlands for the treatment of polluted	?			CAMD	Y
129	Nawrot, J.R., and Klimstra, W.B.	1990	Biochemical treatment of mine drainage through	Proc. 11th. Ann. WVSMDTFS, Charleston	353	Nat. wetland	AMD	Y
181	Nichols, D.S.	1983	Capacity of natural wetlands to remove nutrients	Journal WPCF, 55	495	Natural wetlands, revi	DWO	Y
148	Pett, R.J., MacKinnon, D.S., and Lane,	1990	Natural wetlands fail to ameliorate acid mine drai	Proc. 7th. AGM of BIOMINET, Mississauga	101	Seasonal	AMD	Y
168	Phragmitech Inc.	1991	Root Zone Process, the natural method of waste	Brochure				Y
117	Pu-Gen, L.	1992	The influence of copper mine developing and w	Global Wetlands, Columbus, Ohio		Cu	AMD	A
29	Radoux, M.	1989	Epuration des eaux usees par hydrosere reconst	Tribune de l'eau, 42, #450	62	Review of wetland ty	DWO	Y
30	Radoux, M., and Kemp, D	1988	Epuration comparee des eaux usees domestiqu	Acta OEcologica, 9	25		DWO	Y
156	Reed, S.C., and Brown, D.S.	1992	Constructed wetland design-the first generation	Water. Environ. Res. 64	776	Review		Y
171	Reynolds, J.S., Bolis, J.L., Machemer, S	1991	Sulfate reduction in a constructed wetland	ACS,Div. ENv. Chem.,Atlanta		SR, Big Five Tunnel	AMD	Y
190	Reynolds, J.S., Machemer, S.D., Wilde	1991	Determination of the rate of sulfide production in	ASSMR, Durango, CO, May 14-17		Big Five Tunnel, SR	AMD	Y
103	Schierup, H., Brix, H., and Lorenzen, B.	1990	Wastewater treatment in constructed wetlands in	CWWPC, Cambridge	495	Review	DWO	Y
118	Stark, L.R.	1992	Assessing the longevity of a constructed wetlan	Global Wetlands, Columbus, Ohio		Longevity	CAMD	A
54	Stark, L.R., Kolbash, R.L., Webster, H.J.	1988	The Simco #4 wetland: Biological patterns and	USBM Circular 9183, Pittsburgh Conf.	332		AMD	Y
124	Stark, L.R., Stevens, S.E., Webster, H.J.	1990	Iron loading, efficiency and sizing in a construct	Proc. 11th. Ann. WVSMDTFS, Charleston	393	Simco #4	CAMD	Y
45	Stark, L.R., Wenerick, W.R., Wuest, P.J.,	1991	Adding a carbon supplement to stimulated treat	Montreal Conf. on Abatement of Acidic Drainage, Vol.	465		AMD	Y
80	Staubitz, W.W., Surface, J.M., Steenhuis	1989	Potential use of constructed wetlands to treat lan	Hammer "Constructed wetlands.."	735	Tompkins, Allegany	LL	Y
81	Steiner, G.R., and Freeman, R.J.	1989	Configuration and substrate design consideratio	Hammer "Constructed wetlands.."	363		DWO	Y
82	Stengel, E., and Schultz-Hock, R.	1989	Denitrification in artificial wetlands	Hammer "Constructed wetlands.."	484	Denitrification	DWO	Y
57	Stillings, L.L., Gryta, J.J., and Ronning,	1988	Iron and manganese removal in a Typha domina	USBM Circular 9183, Pittsburgh Conf.	317	Fe, Mn	AMD	Y
28	Surface, J.M., Peverly, J.H., Steenhuis,	1991	Constructed wetlands for landfill leachate treatm	Constructed wetlands... Pensacola	99	Tompkins County, N	LL	A
119	Surface, J.M., Peverly, J.S., Steenhuis,	1992	Landfill leachate treatment by means of a constr	Global Wetlands, Columbus, Ohio			LL	A
104	Swindell, C.E., and Jackson, J.A.	1990	Constructed wetlands design and operation to	CWWPC, Cambridge	107		DWO	Y
37	Taddeo, F.J., and Wieder, R.K.	1991	Accumulation of iron sulfides in wetlands constr	Montreal Conf. on Abatement of Acidic Drainage, Vol.	529		AMD	Y
105	Tarutis, W.J., and Unz, R.F.	1990	Chemical diagenesis of iron and manganese in c	CWWPC, Cambridge	429	Fe, Mn	AMD	Y
9	Taylor, H.N., and Choate, K.D.	1991	Storm event effects on constructed wetl;ands di	Constructed wetlands... Pensacola	7	Fabius Mines	CAMD	A
17	Tettleton, R., Howell, F., and Reaves, R.	1991	Performance of a constructed marsh in the tertia	Constructed wetlands... Pensacola	40	Leaf River Pulp, New	PME	A
84	Thut, R.N.	1989	Utilization of artificial marshes for treatment of pu	Hammer "Constructed wetlands.."	239	NSTL, Mississippi	PME	Y
18	Thut, R.N.	1991	Large scale pilot study of the feasability of treati	Constructed wetlands... Pensacola	42		PME	A
91	Tomljanovich, D.A., and Perez, O.	1989	Constructing the wastewater treatment wetland-s	Hammer "Constructed wetlands.."	399			Y
85	Trautmann, N.M., Martin, J.H., Porter, K.	1989	Use of artificial wetlands for treatment of municip	Hammer "Constructed wetlands.."	245	Fenton, NY	LL	Y
158	Vile, M.A., and Wieder, R.K.	1993	Alkalinity generation by Fe(III) reduction versus s	Water, Air and Soil Pollution		IR, SR	AMD	Y
106	Vymazal, J.	1990	Use of reed-bed systems for the treatment of co	CWWPC, Cambridge	347		ARO	Y
23	Vymazal, J.	1991	The use of reed bed systems for wastewater trea	Constructed wetlands... Pensacola	68	Prague Central Wast	DWO	A
88	Watson, J.T., Reed, S.C., Kadlec, R.H.,	1989	Performance expectations and loading rates for	Hammer "Constructed wetlands.."	319			Y
12	Watson, J.T., and Danzig, A.J.	1991	Pilot scale nitrification studies using vertical flow	Constructed wetlands... Pensacola	16	Benton, KY	DWO	A
87	Watson, J.T., and Hobson, J.A.	1989	Hydraulic design considerations and control stru	Hammer "Constructed wetlands.."	379			Y
113	Weider, R.K., Lang, G.E., and Whitehou	1985	Metal removal in a Sphagnum dominated wetlan	Proc. Penn State U. Conf., Pittsburgh	353	Fe	AMD	Y
197	Whitehead, A.J., Malick, J.G., Kelso, B.	1991	Performance of a pilot scale wetland for nitrogen	16th. AGM CLRA, Kamloops, BC, June 24-28	290	N, winter, Quinsum M	CAMD	Y
38	Wieder, R.K.	1991	Spatial and temporal patterns in surface and sub	Montreal Conf. on Abatement of Acidic Drainage, Vol.	507		CAMD	Y
120	Wieder, R.K.	1992	Wetlands for mine drainage treatment	Global Wetlands, Columbus, Ohio		Data review	AMD	A
223	Wieder, R.K.	1992	The Kentucky WetlandsProject: A field study to	Final report, Coop Agreement GR-896422 between th			CAMD	Y
162	Wieder, R.K., Lang, G.E., and Whitehou	1984	Destruction of a wetland ecosystem by inputs of	Graves ed., 1985SMHSR, Lexington, KY	433	Wetland destruction	CAMD	N
177	Wieder, R.K., Linton, M.N., and Heston,	1990	Laboratory mesocosm studies of Fe, Al, Mn, Ca	Water, Air and Soil Pollution, 51	181	Metal removal mecha	CAMD	Y
89	Wieder, R.K., Tchobanoglous, G., and T	1989	Preliminary considerations regarding constructe	Hammer "Constructed wetlands.."	297			Y
160	Wieder, R.K., and Lang, G.E.	1984	Influence of wetlands and coal mining on stream	Water, Air and Soil Pollution, 23	381		AMD	Y

161	Wieder, R.K., and Lang, G.E.	1986	Fe, Al, Mn and S chemistry of Sphagnum peat in	Water, Air and Soil Pollution, 29	309		AMD	N
90	Wildeman, C.T., and Laudon, L.S.	1989	Use of wetlands for treatment of environmental p	Hammer "Constructed wetlands.."	221	Big Five Tunnel	AMD	Y
193	Wildeman, T.R.	1993	Handbook for constructed wetlands receiving ac	Wetland Design for Mining Operations, Brodie, Wilde		Big five Tunnel + revi	AMD	Y
185	Wildeman, T.R., Brodie, G.A>, and Gus	1993	Wetland design for mining operations			Big Five Tunnel	AMD	Y
186	Wildeman, T.R., Duggan, L.A>, Bolis, J.	1992	Constructed wetlands that emphasise sulfate re	24th. CIM AGM, Ottawa, Paper #32		Big Five Tunnel	AMD	Y
172	Wildeman, T.R., Klusman, R., Updegraff	1990	Big Five Tunnel Pilot Wetland	Proc. 16th. RREL HWRS< EPA/600/9-90037	104	Big Five Tunnel	AMD	Y
173	Wildeman, T.R., Machemer, S.D., Cohe	1990	Passive treatment for heavy metals removal by c	ACS,Div. Env. Chem., Washington, D.C.		Big Five Tunnel	AMD	Y
126	Wildeman, T.R., Machemer, S.D., Klus	1990	Metal removal efficiencies from acid mine draina	Proc. 11th. Ann. WVSMDTFS, Charleston	417	Big Five Tunnel	AMD	Y
108	Willadson, C.T., Riger-Kusk, O., and Qvi	1990	Removal of nutritive salts from two Danish root z	CWWPC, Cambridge	115		DWO	Y
198	Winter, M., and Kickuth, R.	1989	Elimination of sulphur compounds from wastewa	Wat. Res., 23	535		DWO	Y
199	Winter, M., and Kickuth, R.	1989	Elimination of sulphur compounds from wastewa	Wat. Res., 23	547		DWO	Y
218	Wittgen, H.B., and Sundblad, K.	1990	Removal of wastewater nitrogen in an infiltration	CWWPC, Cambridge	115		DWO	Y
8	Witthar, S.R.	1991	Wetland water treatment systems [ABSTRACT O	Constructed wetlands... Pensacola	6	Roberts/Indian Creek	AMD	A
107	Wolstenholme, R., and Bayes, C.D.	1990	An evaluation of nutrient removal by the reed be	CWWPC, Cambridge	139		DWO	Y
95	Wood, A., and Hensman, L.C.	1989	Research to develop engineering guidelines for i	Hammer "Constructed wetlands.."	581	South Africa review	DWO	Y

Water type: DWO Domestic wastewater; LL Landfill leachate; ARO Agricultural runoff
Gen General; OW Oil processing wastewater; AMD Acid mine drainage; CAMD Coal waste drainage

Table 2a: Performance data for passive treatment systems

ANOXIC LIMESTONE DRAINS

Author	Nairn et al			Nairn et al			Brodie et al		
Abst. #	154			131			192		
System	Morrison			Shade			IMP 4		
Water	Coal drainage			Coal drainage			Coal drainage		
Size (m3)	30			130			450		
Flow (L/min)	7.5			15			130		
Retention time (days)	0.83			1.81					
Age (months)	0-13			0-12					
Substrate									
Plants									
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)	15	255	+1700	0	103	+inf	40	100	+250
Acidity (mg/L)	438	83	-81	194	0	-100	380	0	-100
pH	4.7	6.2		3.4	6.6		3.1	6.3	
BOD (mg/L)									
COD (mg/L)									
SS (mg/L)									
NH4-N (mg/L)									
NO3-N (mg/L)									
SO4 (mg/L)	1332	1168	-12	943	1300	+38			
P (mg/L)									
Al (mg/L)	0.6	0.2	-67	22	5	-77			
Cu (mg/L)									
Fe (mg/L)	208	168	-19	4	1	-75	6	1	-90
Mn (mg/L)	44	46	+5	35	36	+3	1.6	0.2	-88
Zn (mg/L)									
Cd (mg/L)									
Ni (mg/L)									

Table 2b:

AEROBIC WETLANDS

Author	Brodie			Hiel & Kerins			Hiel & Kerins			Birkbeck		
Abst. #	7			50			50			96		
System	IMP 1			Tracy-large			Tracy-small			Richmond		
Water	Coal drainage			Coal drainage			Coal drainage			Landfill leachate		
Size (m2)	5700			420			108			45		
Flow (L/min)	73			30-57			23-30					
Retention time (days)				3.8-7.5			1.88-2.47			1.0-2.6		
Age (months)	0-72			0-12			0-12			6-12		
Substrate							Limestone/Peat					
Plants	Typha			Typha			Typha/Carex			Typha/Juncus		
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)												
Acidity (mg/L)												
pH	6.1	6.7		2.7	2.58		3.1	2.8				
BOD (mg/L)										21	17	-19
COD (mg/L)										176	159	-10
SS (mg/L)												
NH4-N (mg/L)										32.3	27.9	-14
NO3-N (mg/L)										0.2	1.9	+950
SO4 (mg/L)				2618	2683	+2.5	1560	1551	-0.6			
P (mg/L)										0.45	0.29	-36
Al (mg/L)				178	180	+1	46.7	45.7	-2			
Cu (mg/L)												
Fe (mg/L)	69	0.9	-99	284	271	-5	149	94	-37			
Mn (mg/L)	9.3	1.8	-80	1.51	1.67	+11	1.2	1.3	+8			
Zn (mg/L)												
Cd (mg/L)												
Ni (mg/L)												

Table 2c:

REED BEDS

Author	Wolstenholme			Wolstenholme			Wolstenholme			Brix & Shierup			Haberl & Perfler		
Abst. #	107			107			107			62			68		
System	Valleyfield			Valleyfield			Valleyfield			Denmark			Mannersdorf		
Water	Domestic wastewater			Domestic wastewater			Domestic wastewater			Domestic wastewater			Domestic wastewater		
Size (m2)	50			50			50			<4000			150		
Flow (L/min)													3.1-5.2		
Retention time (days)	0.8-2.5			0.8-2.5			0.8-2.5								
Age (months)	0-4(summer)			24-29(summer)			29-36(winter)						40		
Substrate															
Plants	Phragmites			Phragmites			Phragmites			Phragmites			Phragmites		
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)															
Acidity (mg/L)															
pH															
BOD (mg/L)	236	54	-76	218	37	-83	186	25	-87	20-550	25-50	-70--90	93	5	-95
COD (mg/L)													316	44	-86
SS (mg/L)															
NH4-N (mg/L)	29.5	20.3	-31	36.7	34	-8	19.8	29.6	+50	10-130	5-35	-25--50	29	18	-38
NO3-N (mg/L)															
SO4 (mg/L)															
P (mg/L)	12.7	2.3	-82	9.1	7.2	-21	6	4.6	-23	2-39	1.5-11	-20--40	5.4	1.8	-69
Al (mg/L)															
Cu (mg/L)															
Fe (mg/L)															
Mn (mg/L)															
Zn (mg/L)															
Cd (mg/L)															
Ni (mg/L)															

Table 2d:

COMPOST WETLANDS

Author	Stark			Wieder			Wieder			Wildeman			Wildeman		
Abst. #	54			223			223			193			193		
System	Simco #4			Kentucky			Kentucky			Big Five Tl			Big Five Tl		
Water	Coal drainage			Coal drainage			Coal drainage			AMD			AMD		
Size (m2)	2623			180			180			18.3			18.3		
Flow (L/min)	328			5.9			5.9			3.8			3.8		
Retention time (days)	4.2			5.1			5.1			3.4			3.4		
Age (months)	0-48			0-25.6			0-25.6			0-36			0-24		
Substrate	limestone/mush compost			Peat			mushroom compost			mushroom compost			peat/manure/sawdust		
Plants	Typha			Typha			Typha			5 species			5 species		
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)	87	26	-80	0	0	(0)									
Acidity (mg/L)	123	32	-40	557	559	+6	557	189	-67						
pH	6.5	6.4		2.89	2.79	+23	2.89	3.38	-61	3	4.6		3	3.6	
BOD (mg/L)															
COD (mg/L)															
SS (mg/L)	40	50	+25												
NH4-N (mg/L)															
NO3-N (mg/L)															
SO4 (mg/L)	1146	1067	-7	3132	3169	+2	3132	2644	-16						
P (mg/L)															
Al (mg/L)				26.5	30.8	+28	26.5	11.1	-56						
Cu (mg/L)										0.74	0.23	-73	0.83	0.6	-46
Fe (mg/L)	111	42	-56	119.1	93.3	-35	119	27	-81	40	25	-36	38	21	-40
Mn (mg/L)				19.3	21.7	+15	19.3	14.6	-23	30	31	+3	29	30	+6
Zn (mg/L)										9.1	4.9	-38	9.2	7.2	-32
Cd (mg/L)															
Ni (mg/L)															

Table 2e:

MICROBIOLOGY

Author	Dvorak			Dvorak			Kuyucak			Kalin			Kalin		
Abst. #	163			163			43			208			208		
System	Pittsburgh reactors			Palmerton			Mattabi			Makela ARUMators			Makela Test Cells		
Water	Coal drainage			AMD			AMD			AMD			AMD		
Size	0.6			4.5			0.0015			0.2			188		
Flow (L/min)	0.055			0.07			0.0001			0			1		
Retention time (days)	5			17			7						131		
Age (months)	1-12			1-5			0-1			8-20			36-37		
Substrate	Mushroom compost			Mushroom compost			limestone/Na pyruvate			flax straw			flax		
Plants													Typha		
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)	0	349	+inf	17	1583	+9311				146	3035	+2078			
Acidity (mg/L)	201	15	-93	520	1	-100				1197	301	-75	330	138	-58
pH	3.2	6.4		6.2	7.1		3.34	6.23		5.37	7		3	4.4	
BOD (mg/L)															
COD (mg/L)															
SS (mg/L)															
NH4-N (mg/L)															
NO3-N (mg/L)															
SO4 (mg/L)							4000	2275	-43	3663	567	-85	1905	1620	-15
P (mg/L)															
Al (mg/L)							131	117	-11	1.37	3.47	+253	21.6	0.85	-96
Cu (mg/L)							0.2	0.2	0	0.017	0.18	+1050	4.9	0.57	-88
Fe (mg/L)	53	8	-85				133	91	-30	281	1.15	-99	13	20.7	+59
Mn (mg/L)				26	0.5	-98				11.1	15.8	+42	4.4	7.5	+70
Zn (mg/L)				317	0.3	-99.9									
Cd (mg/L)				0.3	0.00	-99	2.4	0.06	-97						
Ni (mg/L)				0.9	0.02	-98				60.6	0.6	-99	40.9	6.9	-83

Table 2f:

BIOSORPTION

Author	Kepler			Bennett			Bennett			Kalin		
Abst. #	52			40			40			210		
System	Richland			Gold Waste			Gold Waste			Buchans		
Water	Coal drainage			AMD			AMD			AMD		
Size	183			0.26			0.26			243		
Flow (L/min)				1.9			4.4			7.3		
Retention time (days)				0.1			0.04			23		
Age (months)	0-4											
Substrate	manure			Bio-Fix bags			Bio-Fix bags			Alder trees		
Plants	Typha									Periphyton		
Location	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)	In	Out	Change(%)
Alkalinity (mg/L)												
Acidity (mg/L)	400	250	-38									
pH				5.5			5.5					
BOD (mg/L)												
COD (mg/L)												
SS (mg/L)												
NH4-N (mg/L)												
NO3-N (mg/L)												
SO4 (mg/L)												
P (mg/L)												
Al (mg/L)												
Cu (mg/L)				1	0.05	-95	1	0.2	-80			
Fe (mg/L)	125	65	-48	40	0.5	-98	40	9.8	-75			
Mn (mg/L)	70	64	-9	3	1.6	-47	3	2.9	-3			
Zn (mg/L)				37	8.4	-77	37	33	-11	167 kg/ye	89 kg/yr	-54
Cd (mg/L)												
Ni (mg/L)												

Data for wetland after biopolishing pond

Table 3: ARUM performance

Location	System	Period/ return time days	Volume m3	Acidity removed mg/m3/min	Volume for acidity removal mg/m3/min	Alkalinity gained mg/m3/min	SO4 removed mg/m3/min	Fe removed mg/m3/min	Metals removed mg/m3/min
MAKELA	ARUMator 1	65	0.17	6.54	0.153	9.43	6.25	0.95	0.37 (Ni)
	ARUMator 2	120	0.17	4.52	0.221	8.26	9.26	1.55	0.32 (Ni)
	*Cell 3&4	116	188	1.05	0.95		0.34		0.21 (Ni)
DENISON	ARUMator A	104	0.17	4.22	0.237	1.26	5.65	1.98	
	ARUMator B	104	0.17	3.13	0.32	1.03	0.134	4.81	
VICTORIA JUNCTION	Old Bog Cells	454	0.6	0.178	5.6		0.322	0.011	0.066 (Al)
SELMINCO	ARUM Enclosure	55	40	7.09	0.141		22.2	0.29	
BUCHANS	LC1	51	34						0.33 (Zn)
	LC2	122	36						0.18 (Zn)
	Ponds 7-9	3.56	53	2.94	0.34		1.22		1.36 (Zn)
SELBAIE	DONUT	482	0.018	5.52	0.181		2.72	0.472	0.82 (Zn)

* - based on a July 1992 flow rate of 1.13 L/min

Table 4 Overall assessment of the capacity of passive treatment systems to remove contaminants from waste waters

Parameter	Anoxic limestone drain	Phosphate rock	Settling pond	Aerobic wetland	Reed bed	Compost wetland	ARUM Pond	Biopolishing Pond
Suspended solids	+	+	++	++	++	++	++	++
BOD5	-	-	++	+	++	++	++	-
Organics	-	-	++	+	++	++	++	-
Nitrogen	-	-	NH4	NH4	+	+	+	+
Heavy metals	+	+	Fe/Mn	Fe/Mn	-	++	++	++
Acidity	++	++	-	-	-	+	+	-
Low pH	+	+	-	-	-	+	+	-
Limitations	Plugging Maintenance O2 presence	Placement technique	Aeration (O2 conc)	Plugging Channelling	Plugging Chanelling Maintenance	Chanelling Maintenance Bacterial nutrients	Bacterial nutrients	Algal nutrients Geochemistry

++ effective
+ moderately effective
- ineffective

APPENDIX D HYDROLOGICAL CONSIDERATIONS AND IRRIGATION WATER REQUIREMENTS

HYDROLOGY

For the design of a treatment system using wetlands, it is extremely important to have adequate values for long-term maximum and minimum flow rates. The biological portion of the treatment system may be damaged by extreme high flow velocities long before the integrity of any hydraulic structures (dams and channels) is endangered. Inadequate treatment may also result before any actual damage is done. Extreme low flows, on the other hand, may kill the biota in the wetlands.

The only meteorological data available so far for the area are the 1947-1968 climate 'normals' for precipitation and temperature at Bingham Canyon, Utah. In view of long-term changes in temperature and precipitation patterns observed in North America, it would be useful to obtain climate normals for the most recent 20-year period, as well as actual data for the last few years.

The available climate data are reproduced, with precipitation in inches and temperatures in °F, in the upper portion of Table 3 in Appendix B3; and converted to precipitation in mm and temperatures in °C, in the lower portion of this table. Although there is apparently a period of three months with mean daily temperatures below freezing, the available precipitation data does not indicate the possible extent of the snow cover.

The total quantity of wastewater mentioned was 120,000 acre-feet in the system at any time. This is equivalent to 148×10^6 m^3.

IRRIGATION WATER REQUIREMENTS

The information for this section was derived from the Canadian Water Quality Guidelines (Council of Canadian Resource and Environment Ministers, no date, Chapter 4).

The suitability of any water for irrigation is determined by the concentrations of dissolved salts, trace substances, and pathogens. The most common problems resulting from the use of poor quality water for irrigation are accumulation of salts in the root zone, loss of permeability of the soil because of excess sodium or leaching of calcium, and toxicity of ions, trace elements or pesticides.

Three important factors should be considered in applying guidelines for irrigation water quality:

1 - Quantity of water: Evapotranspiration determines the frequency of irrigation required; the potential for substances from the irrigation water to reach toxic levels in the soil is higher when more frequent irrigation is required.

2 - Type of crop: Crops vary widely in their sensitivity (or tolerance) to toxic substances.

3 - Type of soil: Sandy soils generally have higher permeability than clay-based soils; structure and permeabiliity of clay-based soils can be adversely affected by high sodium concentrations.

The guidelines, presented in Tables 1 to 4, are set to protect the most sensitive crops from toxic concentrations of dissolved ions and other constituents in the irrigation water. These guidelines are based on an assumed application rate of 1000 mm of irrigation water per year, which is quite common in California. The protection provided against buildup of toxic elements in soils should be greater than 100 years.

These guidelines may not protect crops grown hydroponically in greenhouses, without the use of soil, because many of the recommendations are dependent on the capacity of soils to deactivate toxic substances.

Table 1 Summary - Guidelines for Irrigation Water Quality. Table taken from CCREM (no date), Chapter 4.

	Guideline ($mg.L^{-1}$)	
Parameter	All soils[1]	Neutral to alkaline soils[2]
Major Ions		
Bicarbonate[3]	-	-
Chloride	100-700 (see Table 2)	-
Sodium	Soils: Determine sodium adsorption ratio Crops: see Table 3	
Total dissolved solids (salinity)	500-3500 (may not protect some sensitive crops)	-
Heavy Metals and Trace Ions[4]		
Aluminum	5.0	20.0
Arsenic	0.1	2.0
Beryllium	0.1	0.5
Boron	0.5-6.0 (see Table 4)	-
Cadmium	0.01	-
Chromium	0.1	-
Cobalt	0.05	5.0
Copper	0.2 (sensitive crops) 1.0(tolerant crops)	5.0
Fluoride	1.0	15.0
Iron	5.0	20.0
Lead[5]	0.2	2.0
Lithium	2.5	-
Manganese	0.2	10.0
Mercury[3]	-	-
Molybdenum	0.01 (0.05, intermittent for acidic soils)	0.05
Nickel	0.2	2.0
Selenium	0.02 (0.05, intermittent)	-
Uranium[5]	0.01	0.1
Vanadium	0.1	1.0
Zinc	1.0 (soil pH<6.5)	-
	5.0 (soil pH>6.5)	-
Pesticides	Insecticides[3]: -	
Biological Parameters		
Plant pathogens[3]	-	
Human and animal pathogens[5]	100 fecal coliforms per 100mL; 1000 total coliforms per 100 mL	

---

[1] Assumes continuous irrigation unless otherwise noted.

[2] Maximum period of irrigation with water containing high concentrations of heavy metals and trace ions is 20 years on neatral to alkaline fine-textured soils.

[3] No guideline recommended at this time.

[4] Guidelines expressed as total concentration (dissolved + suspended).

[5] Tentative guideline.

Table 2 Sodium or Chloride Concentrations in Irrigation Water Causing Foliar Damage. Table taken from CCREM (no date), Chapter 4.

	Ion Concentration ($mg.L^{-1}$)		
Sensitivity	Cl	Na	Affected Crops
Sensitive	<178	<115	Almond, apricot, plum
Moderately sensitive	178-355	115-230	Grape, pepper, tomato, potato
Moderately tolerant	355-710	230-460	**Alfalfa**, barley, **corn**, cucumber
Tolerant	>710	>460	Cauliflower, cotton, safflower, sesame, **sorghum**, sugar beet, sunflower

Source: Westcot and Ayers, 1984

Table 3 Tolerance of Crops to Sodium. Table take from CCREM (no date), Chapter 4.

Tolerance	SAR of irrigation water	Crop	Conditions
Very sensitive	2-8	Deciduous fruits	Leaf tip burn, leaf scorch
Sensitive	8-18	Beans	Stunted growth
Moderately tolerant	18-46	Clover, oats tall fescue	Stunted because of nutrition and soil structure
Tolerant	46-102	Wheat, lucerne, barley, tomatoes, beets, wheatgrass crested wheatgrass	Stunted because of soil structure

Source: Hart, 1974

Table 4 Relative Tolerance of Agricultural Crops to Boron. Table adapted from CCREM (no date), Chapter 4.

Tolerance[1]	Concentration of boron in soil water[2]	Agricultural Crops
Very sensitive	<0.5	Blackberry
Sensitive	0.5-1.0	Deciduous fruits, onion, garlic, sweet potato, wheat, barley, beans, sunflower, sesame, lupin, Jerusalem artichoke
Moderately sensitive	1.0-2.0	Red pepper, carrot, pea, radish, potato, cucumber
Moderately tolerant	2.0-4.0	Lettuce, cabbage, celery, turnip, Kentucky blue grass, oat, **corn**, artichoke, tobacco, mustard, **clover**, squash, mush melon
Tolerant	4.0-6.0	**Sorghum**, tomato, **alfalfa**, purple vetch, parsley, red beet, sugar beet
Very tolerant	6.0-15.0	Asperagus

[1] Tolerances will vary with climate, soil conditions, and crop varieties; values are to be used only as a guideline.

[2] Maximum concentrations tolerated in irrigation water without reductions in yield or vegetative growth are approximately equal to soil water values or slightly less.

Source: Westcot and Ayers, 1984

APPENDIX E THE CHARA PROCESS

Introduction

The Characeae are a family of large (1 m tall), highly specialized macrophytic algae which form dense underwater meadows in circumneutral pH water, with salinities ranging from extremely fresh to euryhaline, in wetlands, streams, rivers, lakes and estuaries. There are more than 300 species, found on every continent except Antarctica (Chapman & Chapman, 1973). In North America, the major genera are *Chara*, *Nitella*, *Nitellopsis* and *Tolypella* spp.

These algae are commonly called Stoneworts because of their sometimes stone-like appearance. Up to 40 % of plant biomass dry weight can be comprised of a calcium-magnesium carbonate encrustation. Hydroxides, silicates and sulphates also likely accumulate on the surface.

Mechanism

The possible mechanism(s) responsible for carbonate precipitation on Characean cell walls has been intensively studied. Spear et al. (1969) suggest that Characean cells maintain both alkaline and acid regions at the cell wall. The alkaline regions can have pH higher than pH 10, and whereupon carbonates precipitate and form crystals. Spatial variation in cell surface pH is believed by some to serve as a CO_2 acquisition mechanism in waters with pH 8.3 or higher, where inorganic carbon is in the form of bicarbonate (Lucas et al., 1983). Hydrogen ions are pumped out of the cells in the acid regions for co-transport of bicarbonate into the cell. However, hydroxyl ions must also be pumped out, creating the alkaline regions.

Boojum Research Limited has been examining Stoneworts as Biological Polishing agents for mine waste water, based on numerous reports of their exceptional capacity to accumulate metals and radionuclides (e.g., Mudroch & Capobianco, 1978; Dusauskene & Polikarpov, 1978; Harding & Whitton, 1978). Currently, Boojum is developing a biological polishing system using *Nitella flexilis*, a species of the Characeae, for decommissioning a drainage basin receiving run-off from uranium waste rock piles (Smith & Kalin, 1989). A population has been introduced specifically for removal of trace quantities of ^{226}Ra in lake water.

Final Report Data 37.1
Kennecott

```
PC Shell Version 6                Directory Print                   ID =  None
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   Name      Ext       Size #Clu   Date     Time  Attributes
   A-A-DOC6 WQS      43815   86 12/31/93 11:38a     A
   A-B2-F1  WQS      17423   35 12/30/93  3:04p     A
   A-B2-F2  WQS      11972   24 12/30/93  3:01p     A
   A-B2-F3  WQS      11959   24 12/30/93  3:08p     A
   A-B2-F4  WQS      11954   24 12/30/93  3:11p     A
   A-B2-F5  WQS      11976   24 12/30/93  3:15p     A
   A-B2-F69 WQS     110054  215 12/30/93  3:47p     A
   A-B2-T1  WQS       5634   12 12/30/93  3:58p     A
   A-B3-T1  WQS      81473  160 12/30/93  4:11p     A
   A-B3-T3  WQS      12658   25 12/30/93  4:26p     A
   A-B3T2F1 WQS      21637   43 12/30/93  4:46p     A
   A-C1-T1  WQS      82573  162 12/30/93  5:05p     A
   A-C1-T2  WQS      42489   83  8/18/93  4:57p     A
   A-C1-T3  WQS       6264   13  8/18/93  5:31p     A
   A-C1-T4  WQS       6151   13  8/18/93  4:59p     A
   FIG-10   WQS       8194   17  1/01/94  4:59p     A
   FIG-11   WQS      17837   35  1/01/94  5:04p     A
   FIG-3    WQS      10135   20 12/30/93  1:19p     A
   FIG-4    WQS      21280   42 12/30/93  1:23p     A
   FIG-9    WQS       8057   16 12/30/93  2:32p     A
   FIG1-2   WQS      28868   57 12/30/93  1:13p     A
   FIG6-7   WQS      44586   88 12/30/93  1:59p     A
   SCHEM-3  WQS      16873   33 12/31/93  4:01p     A
   T12-F58  WQS      11464   23 12/30/93  2:20p     A
   TAB-3    WQS       7223   15 12/31/93  3:18p     A
   TAB-4    WQS       4655   10 12/31/93  4:05p     A
   TAB-5    WQS      12375   25  1/01/94  4:56p     A
   TAB-6    WQS       7350   15  1/01/94  5:07p     A
   TAB-7    WQS       3959    8  1/01/94  5:09p     A
   TAB-8    WQS      10570   21  1/01/94  5:14p     A
   TB9-FG12 WQS      12657   25  1/01/94  5:22p     A

   31 files LISTed       704,115 bytes  31 files in sub-dir =    704,115 bytes
   0  files SELECTed           0 bytes  Available on volume =    265,728 bytes
```