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COLUMN LEACH STUDY III: EFFECTS OF SAMPLING LOCATION, SAMPLING METHODS, AND CHEMICAL ABATEMENT TREATMENTS ON THE DISSOLUTION OF METALS IN GOLD-COPPER MINE TAILINGS*

by
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ABSTRACT

Metal dissolution from tailings collected at a gold-copper mine mill site was examined by researchers from the U.S. Bureau of Mines using column leaching procedures and on-site field monitoring wells. The 3-year laboratory study reviewed effects of column waste depths, dry cycles, waste sampling locations, and metal dissolution abatement techniques. Results of the laboratory testing indicated that the concentrations of metals in the leachate gradually decreased with each leaching and that metal release from unsaturated tailings was enhanced in most, but not all, samples. Sulphide-rich tailings produced leachates with a pH in the range of 2 to 4, sulphate concentrations as high as 40,000 mg/L, and copper concentrations in the range of 0.2 to 2,400 mg/L. The effects of abatement treatments using phosphate, lime, and sodium lauryl sulphate were also examined, but the treatments were demonstrated to be of only marginal value. The interaction between tailings and wood chips, and tailings and a compost-peat moss mixture was also studied.

(Additional Key Words: Leaching, contamination, tailings, [illegible]

INTRODUCTION

For nearly 3 years, a field study has been conducted by U.S. Bureau of Mines researchers at a sulphide tailings impoundment in the Cascade Mountains (Williams et al. 1989; Stewart et al. 1990; Lambeth et al. 1991). This site contains mill tailings from an abandoned gold-copper mining operation. The objectives of the field study were to

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determine (1) the influence of the partially saturated zone on acid production, leaching, and transport of dissolved constituents from the tailings and (2) how site-specific geological, physical, and hydrochemical properties of the tailings and host -environment either maintained or attenuated transport of dissolved constituents in the ground water (Lambeth et al. 1991). At the same time, tailings from this site and tailings from many other sites were used in a series of laboratory tests set up to determine the boundary conditions on metal dissolution and transport within metal mine wastes.

The purpose of this specific paper is to draw together the results of various column leaching tests involving these gold-copper tailings, to characterize metal dissolution from the tailings, to study the effects of sample location and chemical abatement treatments, and to suggest reactivity and migration pathways within a tailings impoundment.

MATERIALS AND METHODS

Site and Waste Description

The waste material used in this laboratory study was obtained from the main tailings impoundment, which measures 200 by 46 m and has an average depth of 3.7 m (maximum depth of 6.1 m). Four composite samples of tailings were formulated from grab samples taken 30 to 100 cm below the surface in the main tailings containment area. Each composite was composed of samples from at least 2 locations. The major gangue constituent is quartz (SiO_2). The sulphide fraction consists of pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and trace amounts of chalcocite (Cu_2S). Pyrite is the most abundant sulphide mineral and generally occurs as liberated grains, but it is also found locked up with the quartz gangue. Grain size for the pyrite averages 10 to 20 micrometers (µm). Chalcopyrite is significantly finer grained (5-10 µm) than the pyrite and is almost always locked up with gangue quartz. In addition, trace amounts of sphalerite (ZnS) and galena (PbS) are also observed. Iron phases dominate the oxide fraction of the tailings and include magnetite (Fe_3O_4), haematite (Fe_2O_3), and goethite (FeO(OH)) (Doepker and O'Connor 1990). A partial listing of the results of the maximum leachability assay, a nondestructive, mixed HCl-HNO_3 assay (Kuryk et al. 1985), for the composite samples is given in Table 1.

Table 1. Maximum Leachability Assay

Composite	Element (mg/g waste)										
No	Al	Ca	Cu	Fe	K	Mg	Mn	Na	Pb	S	Zn
1	5.4	4.4	0.74	11.9	3.2	4.5	0.14	0.20	0.08	10.1	0.35
2	1.0	0.85	0.07	17.2	0.74	0.68	0.02	0.09	0.10	4.1	0.07
3	3.5	0.59	1.1	10.1	0.56	1.8	0.04	0.06	0.05	7.7	0.68
4	0.16	0.10	0.04	5.40	0.24	0.29	0.01	0.30	0.10	1.70	0.05
Soil Conditioner											
Peat moss	4.00	9.70	0.03	5.90	7.20	4.90	0.28	1.60	0.04	1.70	0.08
Wood chips	0.07	0.89	0.01	0.16	1.80	0.11	0.01	0.43	0.01	0.24	0.09

Column Test Equipment and Methods

Leaching columns were constructed from 61- or 122-cm lengths of 7.6-cm inside diameter (ID) polyvinyl chloride (PVC) pipe equipped with cemented couplings and bushings in which perforated Nalgene plates had been installed. A 9-cm borosilicate glass-fiber filter was placed on the perforated plate. The bushing was coated with silicone vacuum grease and inserted into the coupling. A similar set of columns was constructed out of 61-cm lengths of PVC pipe, except that the bottoms of the column walls were tapered so that they could be driven directly into the tailings to collect an "undisturbed" sample. The coupling and the bushing were greased with silicone vacuum grease before assembly. Other columns were constructed for 61- and 122-cm lengths of 7.6-cm outside-diameter (OD) acrylic tubing. A solid acrylic rod 7-cm OD was cut into 5.1-cm plugs, drilled, and tapped to accept a standard polyethylene tubes-to-pipe fitting. A 5-cm polyethylene perforated disk was recessed into the base plug in order to support a 7-cm glass microfiber filter. The acrylic plugs were then cemented into the base of the columns.

Table 2. Composition of Synthetic Rain

	mg/l	µmole/l
Ca $(NO_3)_2.4H_2O$	1.77	
NH_4Cl	0.45	
KNO_3	0.21	
HNO_3		5.40
H_2SO_4		12.50

Test series 1 involved tailings from 19 different mine sites. In this study, an air-dried sample of gold-copper mine tailings (composite 1) was distributed between 1 61-cm and 1 122-cm PVC column. In the short column, 1.75 kg of tailings was placed, while 7 kg of tailings was placed in the longer column. The columns were maintained under laboratory temperatures (20°C to 24°C) and humidity (35 to 45%). The pore volume was determined by leaching each column with a known volume of deionized water (leachate), collecting and determining the volume eluted (leachate), and calculating the difference between the leachant volume and leachate volume (the pore volume).[1] The depth of waste in the 2 columns was approximately 25 and 100 cm, respectively. The pore volume of the shorter column was determined to be 375 cm^3, while the pore volume of the longer column was 1,390 cm^3, nearly 4 times that of the shorter. In each subsequent leaching, 375 cm^3 of leachant was poured into each column. These 2 columns were leached monthly for 3 years with synthetic rain (see Table 2; Bainbridge et al. 1980) or 1 g/L aqueous sodium lauryl sulphate over a period in excess of 3 years.

Test series 2 involved tailings samples from 17 mine sites and was designed to test the effect of seasonal and daily temperature variations on metal dissolution. In this test series, 5.6 and 1.5 kg of air-dried composite 2 were added to 2 acrylic columns. Sample depths reached 24 and 92 cm, respectively. Leachings with synthetic rain were carried out as described in test series 1 above, except that the columns containing composite 2 tailings were placed in an insulated shed equipped with 3 150-W infrared heat lamps to prevent freezing. During the summer months, the day-to-night temperature differences within the shed ranged from 10°C to 18°C. In winter, the daily variation ranged from 5°C to 10°C.

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[1] Pore volume, as defined here, may also be termed field capacity.

A single air-dried grab sample obtained from the main tailings impoundment was used in a set of 3 5.1-cm OD acrylic columns in test series 3. This series was designed as an exploratory examination of the effect of phosphate on the dissolution of metal from these tailings. Eight hundred grams of tailings was added to each column and initially leached with deionized water. The pore volume in these columns was determined to be 215 cm^3. After 4 additional leachings with 120 mL of de-ionized water, the leachant was changed to 0.1 F disodium hydrogen phosphate. The pH of the leachant was 9.16 and conductivity was 13.68 mmho cm^{-1}.

A band of what was called "blue silt" appeared at a depth of approximately 60 cm below the surface of the tailings impoundment at 1 location, and a sample of this material was collected. A single column containing 800 g of this "blue silt" was added to test series 3 and leached with the same protocol as given above. The pore volume of this column of waste was found to be 360 cm^3.

Four 61-cm-long, 7.6-cm OD PVC columns were filled with 1.5 kg of composite 3 tailings as a part of test series 4, an investigation designed to examine enhanced metal release from unsaturated tailings. These columns were leached with 1 pore volume (350 mL) of synthetic rain weekly. Two of the columns were maintained at saturation over the complete course of the experiment, while the 2 others were allowed to undergo wet/dry cycles. Other leachants were introduced in the course of the experiment: 1 g/L aqueous sodium lauryl sulphate with a pH of 8.4, 0.1 F sodium bicarbonate with a pH of 8.7, and deionized water.

Table 3. Additives to Columns Containing 1 kg Tailings, Grams

Additive	Columns							
	1-4	5-8	9-12	13-16	17-20	21-14	25-28	29-32
CaO	5	-	-	-	-	-	5	5
$CaHPO_4$	-	-	5	-	-	-	-	-
Wood chips	-	-	-	40	-	-	-	40
Peat moss	-	-	-	-	80	-	80	80
$CH_3(CH_2)_{11}$-OSO_3Na	-	-	-	-	-	5	-	5

In test series 5, 32 61-cm-long, 7.6-cm ID PVC columns were used to make 8 sets of 4 columns each in order to examine different chemical treatment strategies. Two hundred grams of silica sand was first added to each column, after which 800 g of composite 4 tailings was added. An additional 200 g of tailings was mixed with a "treatment reagent" and added to the columns. A breakdown of these columns and treatment reagents is given in Table 3.

After determining the pore volume of each set of columns, each set was then leached biweekly with the equivalent of 1 pore volume of synthetic rain. After 8 leachings, columns were replenished with calcium oxide, calcium hydrogen phosphate, or sodium lauryl sulphate to the original levels.

At the field site, three 61-cm-long PVC columns with tapered walls were pushed into the tailings near a cluster of field monitoring wells in the main tailings impoundment to a depth of approximately 70 cm, while a second set of 3 columns was pushed into the tailings near a second cluster of wells. All 6 of these columns were then dug out of the tailings and carefully transferred to the laboratory as "undisturbed" tailings samples. The top 7 cm of waste was removed from each column to accommodate leaching solutions. Approximately onehalf of a pore volume of synthetic rain (pH 5.6) was used for each leaching. After a series of 14 leachings, the leachant was changed to a 0.01 F Na_2HPO_4 with a pH of 9.3 in order to examine further the effect of phosphate on metal dissolution. After 7 leachings with aqueous phosphate ending with a dry cycle of 29 days, the leaching solution was changed to deionized water.

Chemicals

All chemicals in this study were commercially available, analytical-grade reagents used without further purification. The deionized water was produced in the laboratory through distillation (Barnstead glass still) and then deionized with a Barnstead NANOpure II Demineralizer[2] (18.3 Mohm-cm).

Analytical Equipment

Electrical conductivity and pH were measured on each sample collected. The unfiltered samples were then split, with 1 portion acidified with nitric acid for metal analysis and the other for anion analysis. Metal analyses were carried out with the aid of a PerkinElmer Plasma II ICP spectrometer and anion analyses with a Dionex 4000i ion chromatograph.

RESULTS AND DISCUSSION

As a general rule, leachate metal concentrations obtained from leaching columns of air-dried metal mine tailings peak within 1 to 3 leachate pore volumes and then decrease with each subsequent leaching (Doepker and O'Connor 1990a, 1990b). This generality should be qualified in that the columns must be maintained at or near saturation. In the case of reactive sulphide tailings, a condition of unsaturation may lead to enhanced metal dissolution from the columns (Doepker 1988, 1990, 1991). This enhanced metal release is most pronounced for short columns. It has been further demonstrated (Doepker and O'Connor 1990a, 1990b) that leachate metal concentrations increase with increased waste column depth (for saturated columns) when identical leachant volumes are used. On the other hand, metal concentrations are almost independent of column depth when leachate concentrations are compared on a pore volume basis. These generalities appear to hold true in the study reported here (see Figure 1). (Note, Table 1A and 1C relates leachate concentrations (zinc and sulphate, respectively) as a function of total leachate volume used, while Figure 1B and 1D demonstrates the similarity of concentrations when total pore volumes are compared.)

Effect of Daily Temperature Fluctuations

The effect of daily temperature fluctuations on metal concentrations from columns of various depths was examined previously (Doepker 1991). In these earlier studies, it was observed that the leaching of longer columns (presumed to be maintained at nearsaturation) produced higher concentrations of metal leachate than shorter columns (determined to be maintained at near-saturation), even on a pore-volume basis, when using tailings that were sensitive to oxidation and enhanced metal release (dry-cycle effect). This finding appeared to be related to the fact that covered columns containing less than 25 cm of tailings remain nearly saturated even under free drip conditions. On the other hand, tailings in longer covered columns were found to be only partially

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[2] Reference to specific equipment or trade names does not imply endorsement by the Bureau of Mines.

saturated, thus more sensitive to oxidation in the unsaturated zones. For columns held at nearconstant temperatures, oxygen availability was diminished because of a stagnant environment in which diffusion was controlled. With daily temperature fluctuations of 10°C to 20°C or even higher, oxygen was pumped in and out of the column. Thus, it was found that oxydation in longer columns produced leachates with higher concentrations of metals than shorter, saturated columns even though both columns were covered to reduce evaporation of pore water; that is, the columns were maintained in such a manner as to reduce dry-cycle effects.

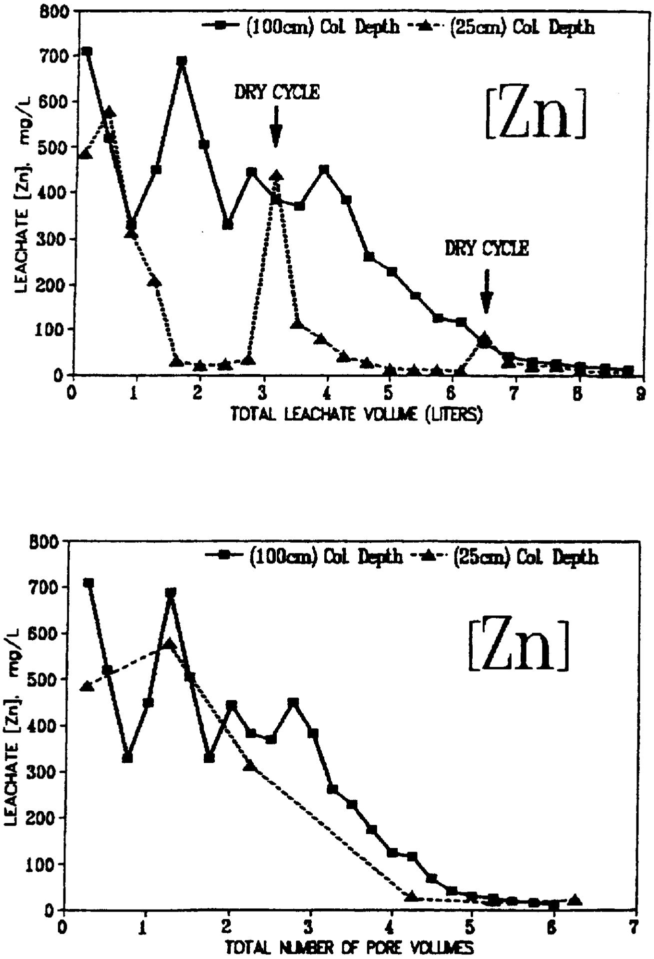
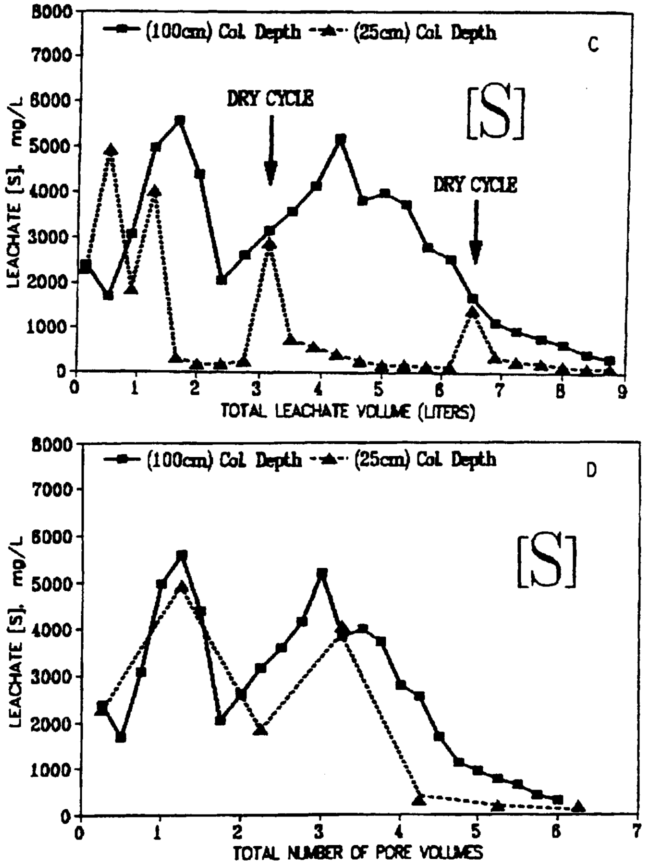


Figure 1. Leachate concentrations as a function of column depth: A, Zinc versus total leach volume; B, Zinc versus total number of leach pore volumes; C, Sulphur versus total leach volume; D, Sulphur versus total number of leach pore volumes.

Figure 1 continued



These effects were not as prominent for the gold-copper, composite 2 tailings studied here (see Figure 2). Unfortunately, composite 2 was found to be more completely oxidized than composite 1 (used in test series 1) and thus far less reactive.

It has been shown that certain sulphide tailings produce enhanced metal dissolution when leaching occurs after an extended drying period (Doepker 1988; Doepker and O'Connor 1990a, 1990b). In Figure 1A and 1C, it can be seen that columns containing tailings to a depth of 25 cm and kept open for 2 months show enhanced release of zinc and sulphur with the next leaching. In general, the sulphur yield from the ICP is nearly 1/3 the sulphate as determined by ion chromatography. On the other hand, enhanced metal release from columns containing tailings to a depth of 100 cm is either delayed or completely masked. The same effects with a drying cycle of 2 months can be observed to a lesser extent in Figure 1, even though thermal pumping could take place.

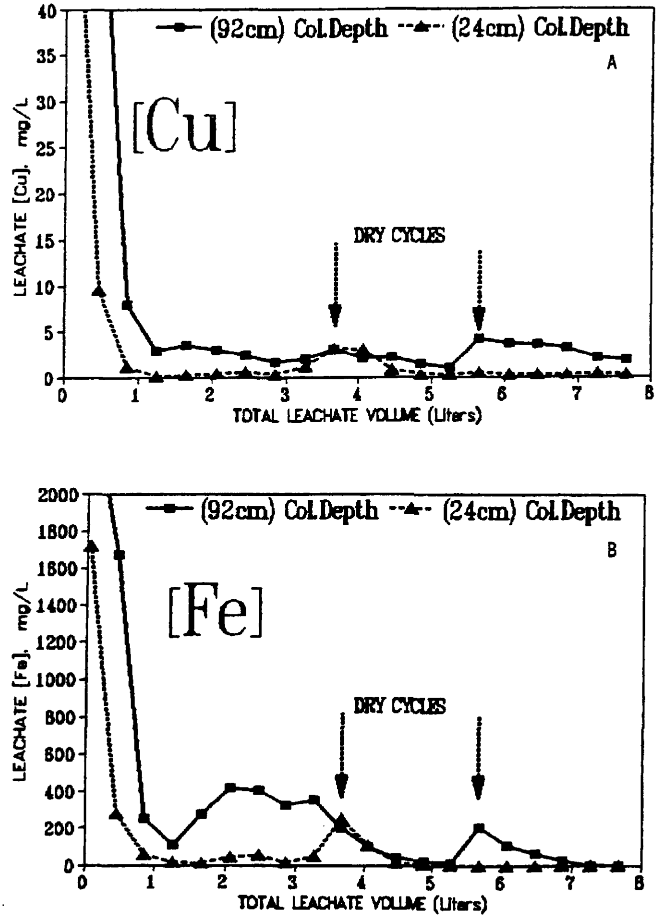
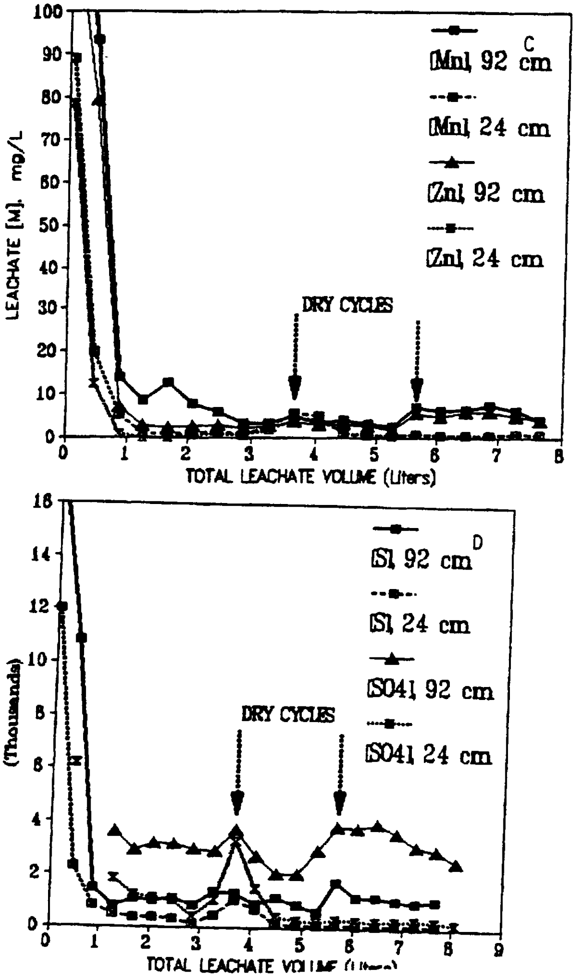


Figure 2. Effect of daily temperature fluctuations on leachate concentrations: A, Copper; B, Iron; C, Manganese and zinc; D, Sulphur and sulphate.

Figure 2 continued



Effect of Chemical Treatments

A series of experiments was carried out to examine the effect of different chemical treatments on concentrations of leachate constituents. A brief description of the results of these individual tests is given below.

Sodium lauryl sulphate. Rates of sulphide oxidation and acid generation are enhanced in some environments by microorganisms such as Thiobacillus ferrooxidans. Some laboratory and field experiments indicate that biocides reduce the rate of acid generation, as well as concentrations of certain metals (Kleinmann and Erickson 1983; Kleinmann 1981; Erickson et al. 1985; Rastogi and Sobek 1986; Watzlaf 1986, 1988; Sobek, 1987).

Four 7.6-cm OD columns containing 1.5 kg of composite 3 were leached with synthetic rain through 2 dry cycles, after which they were leached with 1 g/L aqueous sodium lauryl sulphate at a pH of 8.4 through 1 dry cycle. Table 6 reports leachate pH, copper, sulphur, and zinc concentrations for this test protocol. It can be seen that leachate pH was unaffected by the presence of sodium lauryl sulphate. Enhanced releases of copper, sulphur, or zinc following the dry cycle, which are indicative of oxidation in the unsaturated zone, were not observed after sodium lauryl sulphate treatment. Previous work seems to relate sulphate production to pore water loss (Doepker 1990, 1991). All 4 dry cycles (arrows on Figure 3), were 21 days long, but losses in pore

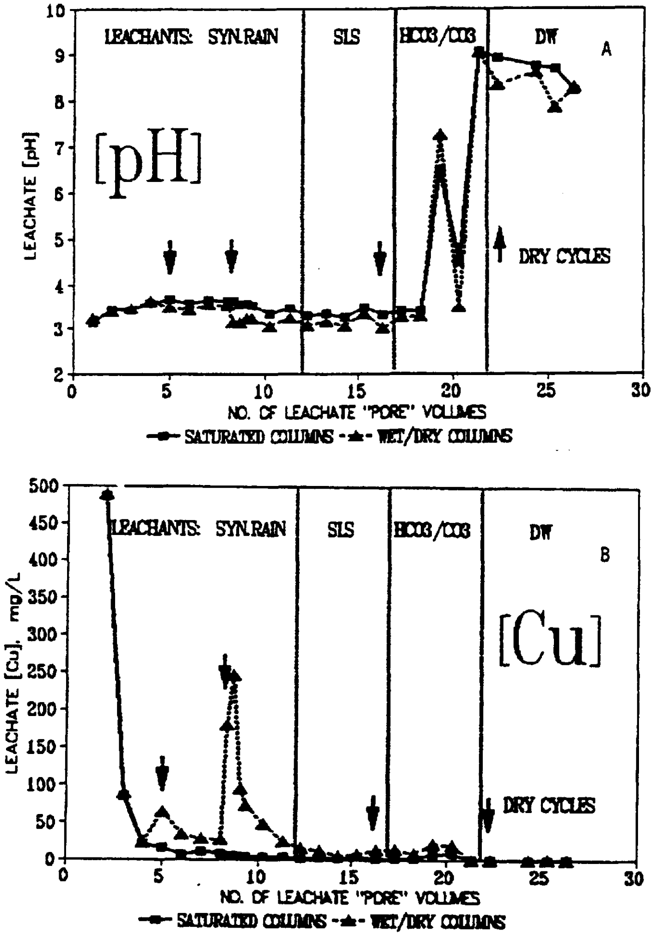
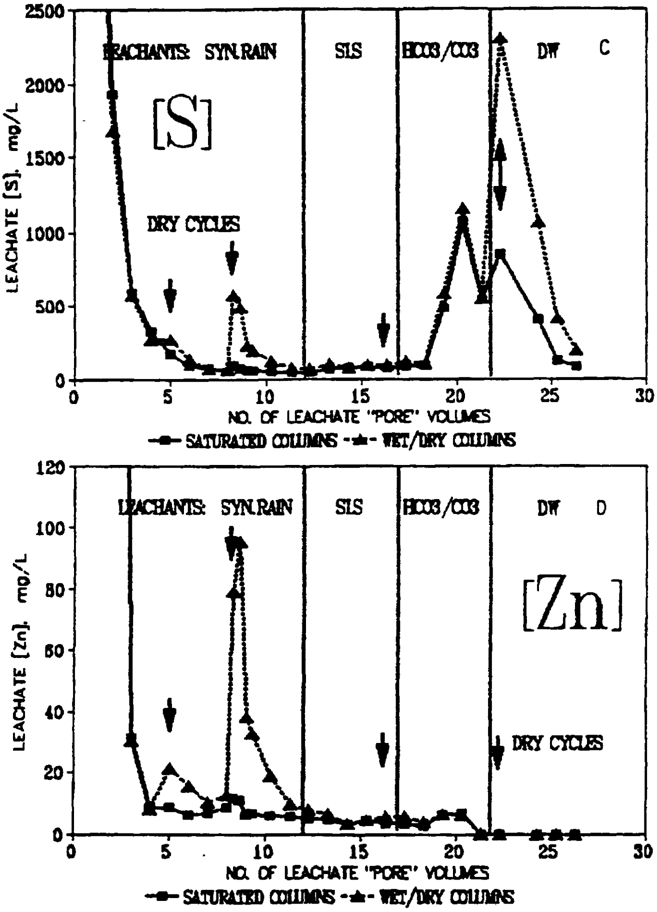


Figure 3. Influence of sodium lauryl sulphate on dry cycle effects: A, Leachate pH; B, Leachate copper; C, Leachate total sulphur; D, Leachate zinc.

Figure 3 continued



water, a necessary condition for enhanced sulphate production, were 20, 25, 15, and 30%, respectively.

A composite 1 test series was continued using 1 g/L sodium lauryl sulphate leachant. Figure 4 shows the effects of the treatment on leachate pH, copper, sulphate, and zinc in columns with depths of 100 and 25 cm. Note that the pH of the shorter column rose approximately 1 pH unit, while the longer column displayed no change. Because both columns were leached with the same volume of sodium lauryl sulphate each time, the short column was leached with 10 pore volumes of leachant, while the long column received only 2-1/2 pore volumes over the same 10-month period. Although the presence of the biocide did not appear to reduce concentrations of sulphate, it did appear to reduce copper and zinc by a factor of 2. As observed in previous tests, the enhanced metal release that normally occurs after a dry cycle was again reduced with sodium lauryl sulphate treatment. In this case, pore water losses for the 2 dry cycles shown in Figure 4 were 40 and 50%, respectively.

The evidence presented from these 2 studies suggests that biological activity (based on the observed effects of the biocide sodium lauryl sulphate) is an important reaction pathway for sulphate production and metal release from these unsaturated gold-copper mine tailings. However, it is difficult to ascertain the extent of this activity from this study, because companion studies suggest that biological activity may account for only a small fraction of the enhanced dissolution from metal-mine tailings observed during

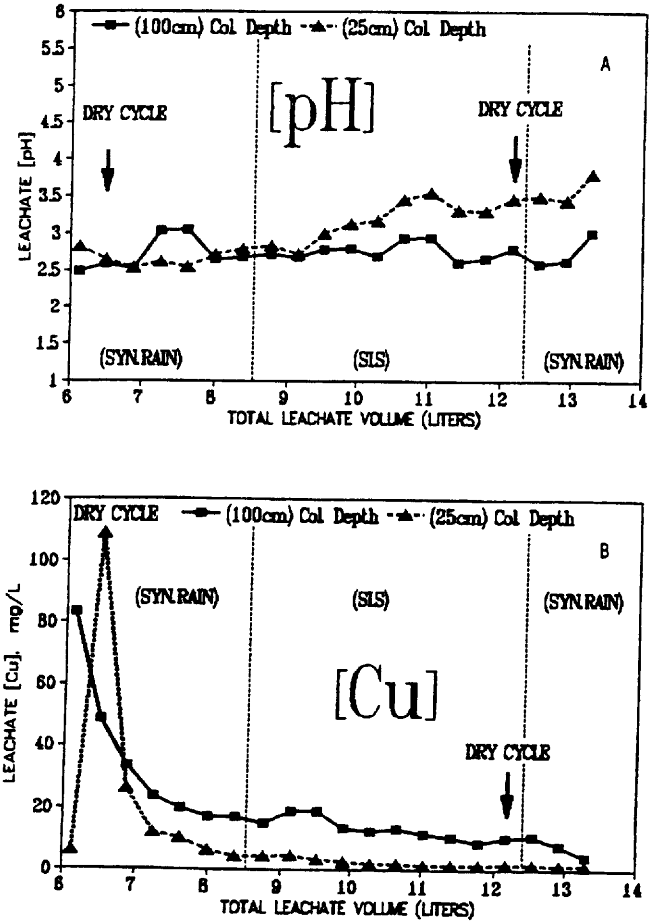
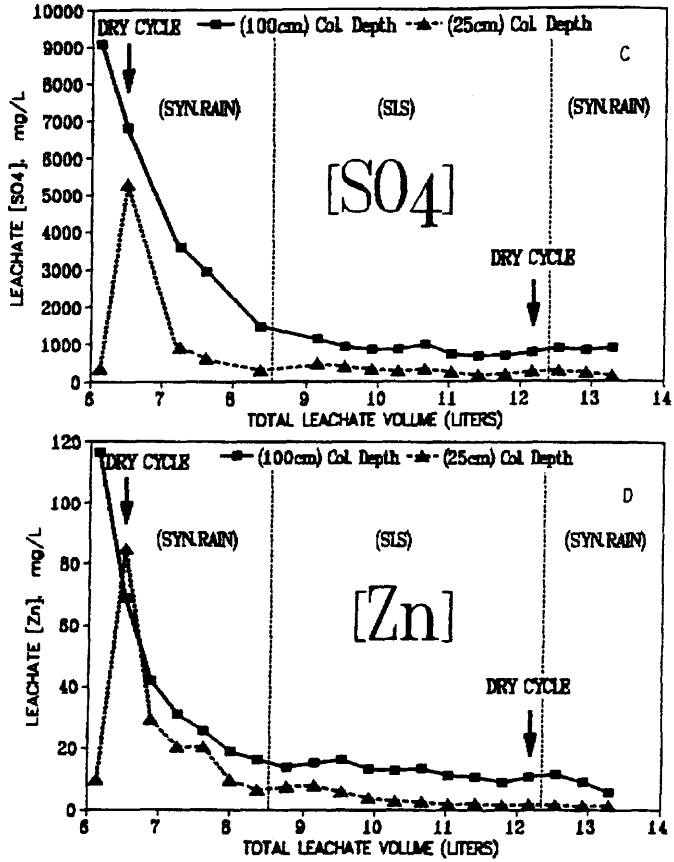


Figure 4. Effect of sodium lauryl sulphate on leachate concentrations: A, Leachate pH; B, Leachate copper; C, Leachate sulphate; D, Leachate zinc.

Figure 4 continued



dry cycles. Furthermore, since there is a natural decay of reactive sulphides, it is not possible to know to what extent a dry cycle may influence metal release from an untreated column. It should be emphasized that use of sodium lauryl sulphate to reduce acid production or metal mobility within these tailings would have very limited, if any, value.

Disodium Hydrogen Phosphate. The main pathways for pyrite oxidation are either through oxygen or iron(III) as the oxidizing agent. Above pH 4-5, the major reaction channel is through oxygen, while below pH 4, iron(III) becomes the predominant oxidizing agent. Backes, Pulford, and Duncan (1986, 1987, 1988) showed that the iron(III) oxidation pathway could be inhibited by the use of specific chemicals, such as sodium lauryl sulphate, to reduce the oxidation of iron(II) to iron(III), which is a low-pH biological pathway. Phosphates have been suggested by Renton, Stiller, and Rymer (1988) as a means of removing iron(III) by precipitation.

The effect of a hydrogen phosphate leachant on the dissolution of goldcopper mine tailings was examined in 2 different series of experiments. Three columns containing 800 g of a grab sample of gold-copper mine tailings were leached 5 times (approximately 2-1/2 pore volumes) with deionized water. After the initial leachings, the leachant was changed to 0.1 F disodium hydrogen phosphate. The results of this series are shown in Table 4. The concentrations of nearly all the species in the leachate increased after the second addition of the hydrogen phosphate leachant, reaching a maximum within 2 to 3 pore volumes. If plug flow is assumed, the first pore volume of disodium hydrogen phosphate should displace the interstitial pore water with little effect on the dissolved species. Major concentrations of sodium do not appear in the leachate until the addition of a third pore volume of aqueous disodium hydrogen phosphate leachant, and these concentrations correspond to the maximum metal concentrations observed in the leachate. These facts suggest that many cation species are being displaced by sodium ion (cation exchange). Similarly, it appears that some of the sulphate is also being displaced by the anion hydrogen phosphate (anion exchange). The concentrations observed after a prolonged period of hydrogen phosphate additions are low, but within an extrapolated value that might have been obtained with a deionized water leachant.

The columns of undisturbed tailings were also treated with a hydrogen phosphate leachant after an initial study using synthetic rain. The more significant test results are given in Figure 5. Leachate copper, sulphur, and zinc concentrations for the columns taken from 2 sampling locations responded in a similar manner following the introduction of a hydrogen phosphate leachant. Again, a strong ion exchange effect was observed, followed by a lowering of the metal concentrations in the leachate. Dry-cycle effects were small, but still apparent. It did not appear that treatment of these tailings with hydrogen phosphate had any major effect on dry cycle dissolution, but the treatment may have reduced normal metal concentrations and raised leachate pH (see Figure 5B).

Other Chemicals. Thirty-two columns containing composite 4 tailings were treated with calcium oxide (base treatment), calcium hydrogen phosphate [iron(III) precipitator], wood chips (soil conditioner), sodium lauryl sulphate (biocide), peat moss (soil conditioner), and combinations of calcium oxide and peat moss and calcium oxidepeat moss-wood chips-sodium lauryl sulphate (see Table 1). These columns were compared to 4 columns of untreated tailings. Figure 6 shows that treatment with sodium lauryl sulphate increased leachate pH to the greatest extent, although it must be emphasized that the low solubility of solid calcium oxide and calcium hydrogen phosphate greatly inhibits their effectiveness. Concentrations of sulphate in the leachates were not reduced below concentrations observed in untreated tailings for any of the treatments (see Figure 7). Calcium oxide reduced manganese mobility, while sodium lauryl sulphate greatly enhanced manganese mobility (see Figure 8). The effects on other elements found in the leachates were similar, with no 1 additive or combination of additives showing much promise as a general chemical control for metal dissolution.

Effect of Sampling Location

It can be easily seen from the assays shown in Table 1 and from the variations observed in leachate concentrations during different tests that very little homogeneity is to be found within this tailings impoundment. The differences between locations is especially displayed through the use of columns of undisturbed tailings. Figures 9 through 11 emphasize these differences.

After the tests with the undisturbed tailings were completed, the tailings in 1 column from each location were examined. The sample taken from location B1 appeared similar throughout the depth of the 60 cm column. Chemical assay results for a sample near the top (at a depth of approximately 5 cm) and 1 near the bottom (a depth of 58 cm) fell

Table 4. Effect of Phosphate Leachant on Dissolution from Gold-Copper Mine Tailings

Leachant	Element, mg/L												
	pH	Al	Ca	Cd	Cu	Fe	Mg	Mn	Na	Ni	P	S	Zn
DW	3.14	1480	401	8.12	1450	106	216	7.87	4.88	1.02	n.d.	3670	548
DW	3.05	1887	461	11	1890	101	283	10.7	6.64	1.36	n.d.	4330	1140
DW	3.11	1440	496	8.58	1640	72.2	225	8.18	6.24	1.10	330	3400	664
DW	3.14	276	571	1.86	385	30.2	49.3	2.47	3.67	.26	83.3	1030	151
DW	3.42	61.2	410	.3	86.3	10.4	7.81	.59	2.95	.04	15	465	28.8
Na_2HPO_4	3.39	13.3	191	.11	28.4	4.3	3.36	.37	2.92	.01	8.99	193	10.9
Na_2HPO_4	3.3	12.9	120	.14	32.5	8.2	4.33	.51	121	.02	7.2	217	13
Na_2HPO_4	3.61	36.5	147	.27	57.7	12.6	8.27	.91	1330	.05	13.8	985	24
Na_2HPO_4	6.13	11.2	18.6	.09	16.4	1.4	2.92	.17	1480	.01	306	465	6.57
Na_2HPO_4	7.18	.59	1.37	.13	.4	1.2	1.48	.01	3030	0	2250	157	.15
Na_2HPO_4	7.49	.6	.35	.08	.2	.7	2.11	.03	2180	0	2820	170	.05
Na_2HPO_4	7.73	.71	.63	.05	.1	.7	1.14	.01	1680	0	4750	214	.04
DW	7.63	.55	0	.08	.2	.61	.58	.02	2000	0	5800	579	.12
Assay, mg/g		3.84	0.919	0.0077	1.26	11.9	1.72	0.117	0.055	0.0059	0.336	7.25	0.446

n.d. Not determined.

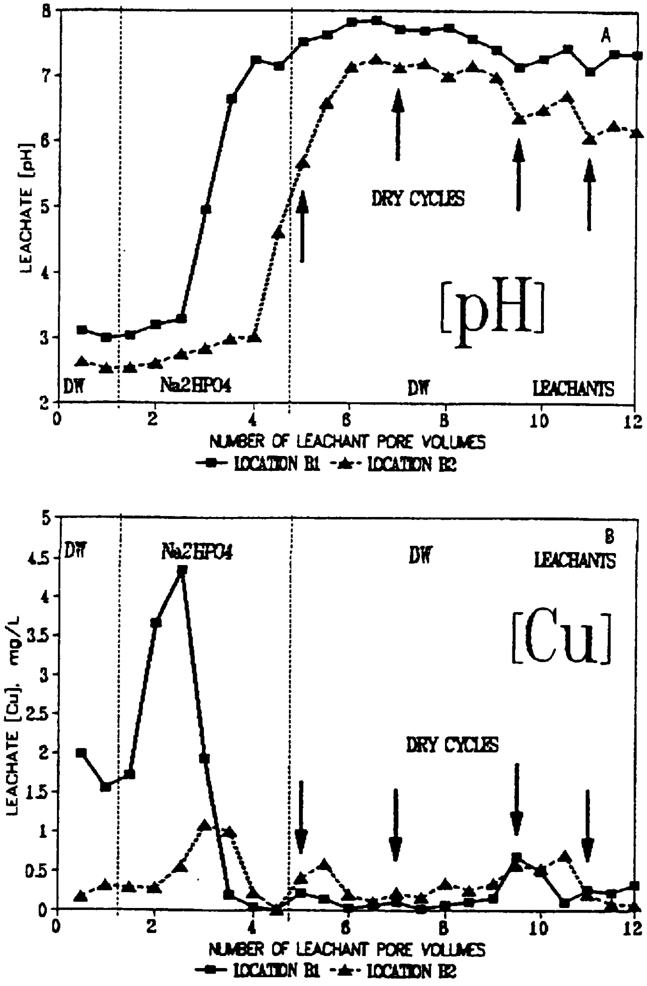


Figure 5. Effect of phosphate treatment on columns of undisturbed tailings: A, Leachate pH; B, Leachate copper; C, Leachate total sulphur; D, Leachate zinc.

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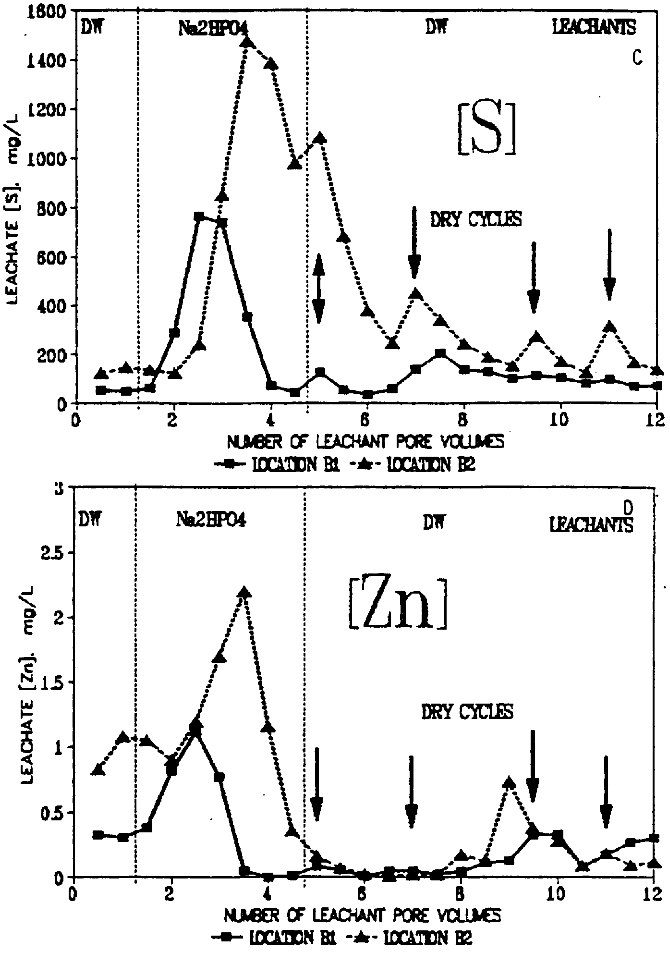
Figure 5 continued



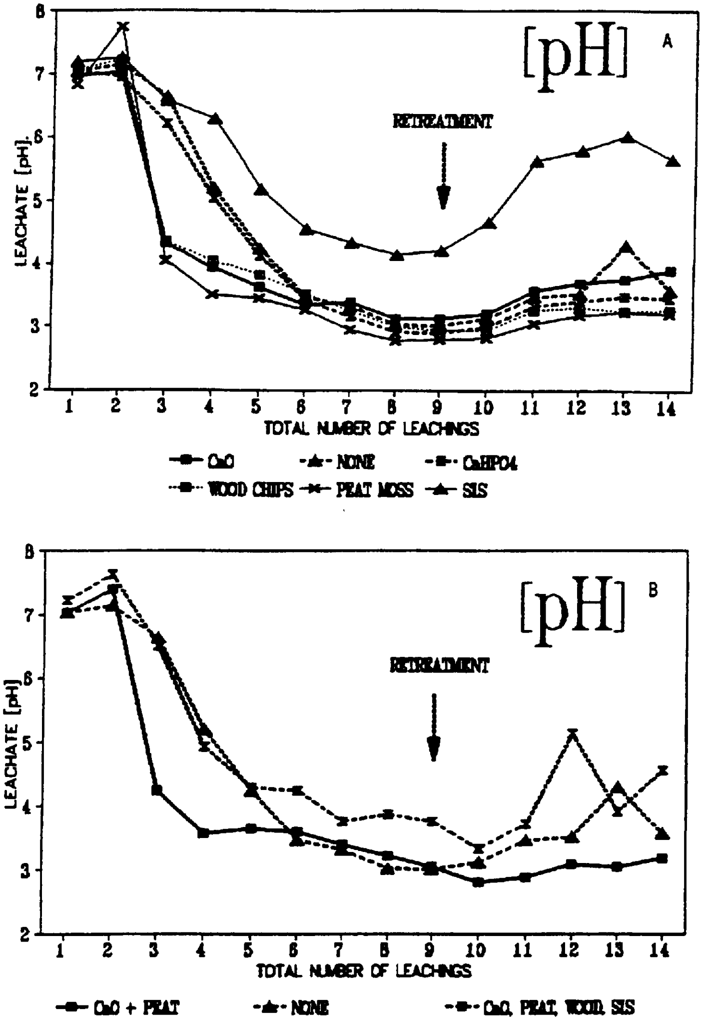


Figure 6. Effect of chemical treatments on leachate pH. A, Calcium oxide, calcium hydrogen phosphate, wood chips, peat moss, and Sodium lauryl sulphate compared to untreated tailings; B, Calcium oxide-peat moss and calcium oxide-peat moss-wood chips-sodium lauryl sulphate compared to untreated tailings.

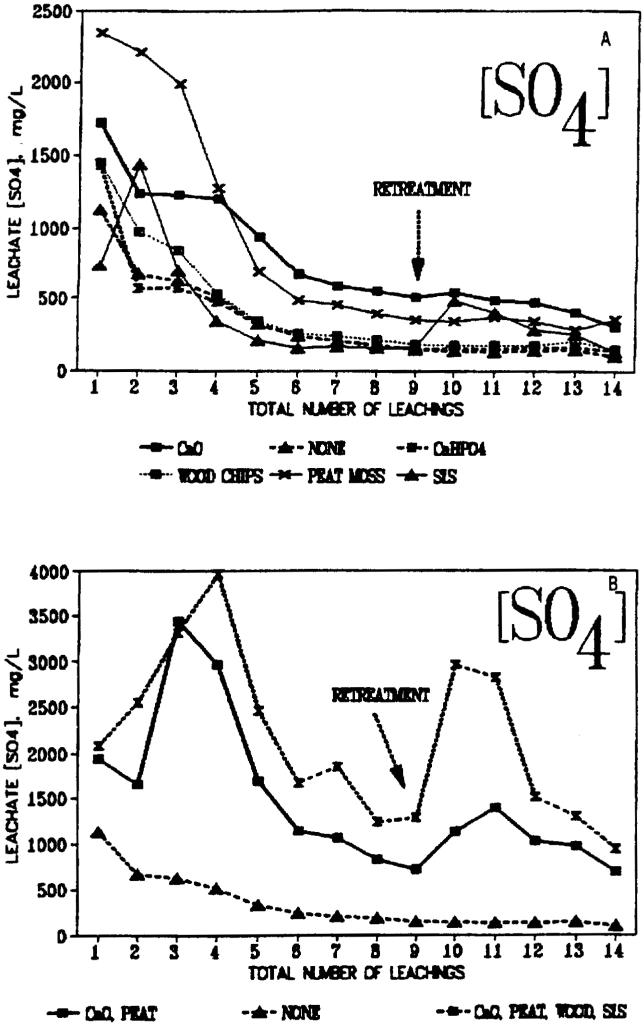


Figure 7. Effect of chemical treatments on leachate sulphate concentrations. A, Calcium oxide, calcium hydrogen phosphate, wood chips, peat moss, and sodium lauryl sulphate compared to untreated tailings; B, Calcium oxide-peat moss and calcium oxide-peat moss-wood chips-sodium lauryl sulphate co pared to untreated tailings.

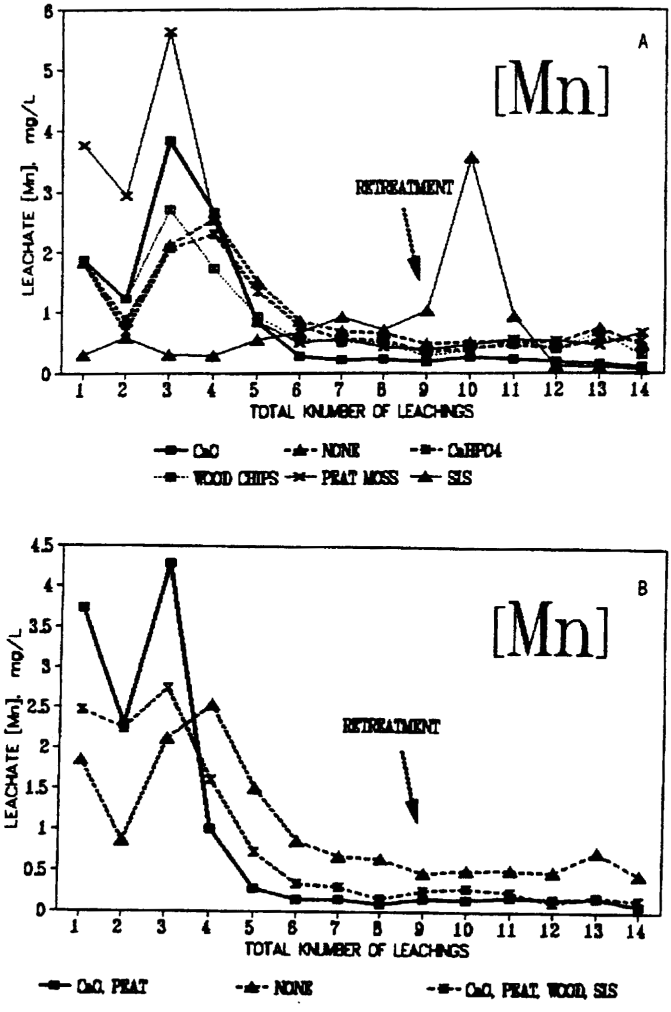


Figure 8. Effect of chemical treatments on leachate manganese concentrations. A, Calcium oxide, calcium hydrogen phoxphate, wood chips, peat moss, and sodium lauryl sulphate compared to untreated tailings; B, Calcium oxide-peat moss and calcium oxide-peat moss-wood chips-sodium lauryl sulphate compared to untreated tailings.

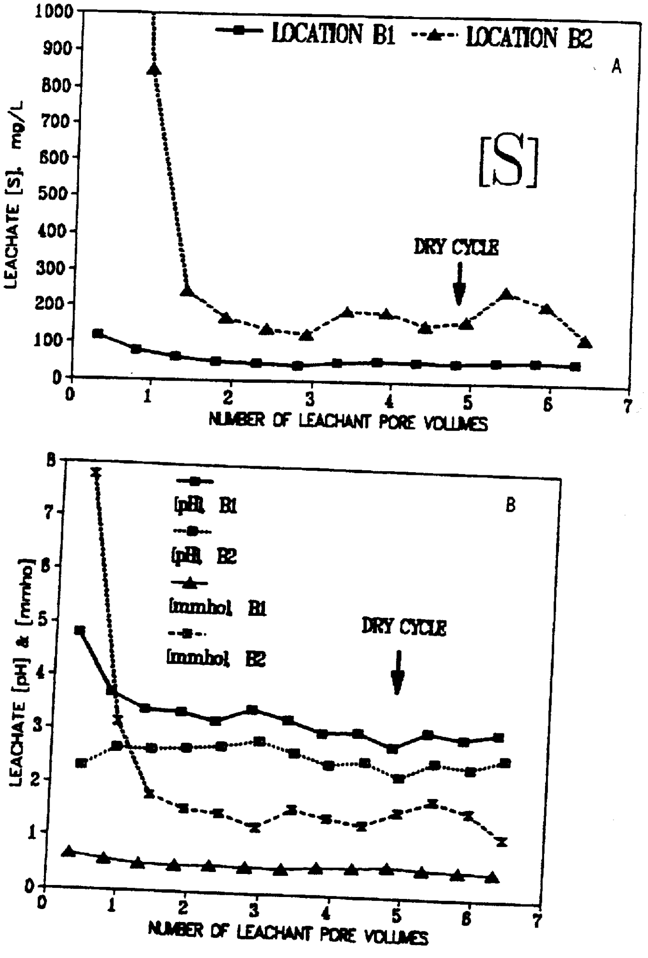
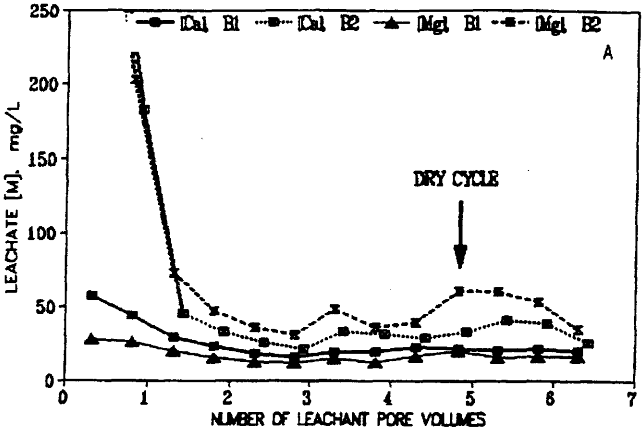


Figure 9. Effect of sampling location on leachate. A, Total sulphur for columns of undisturbed tailings; B, pH and conductivity.



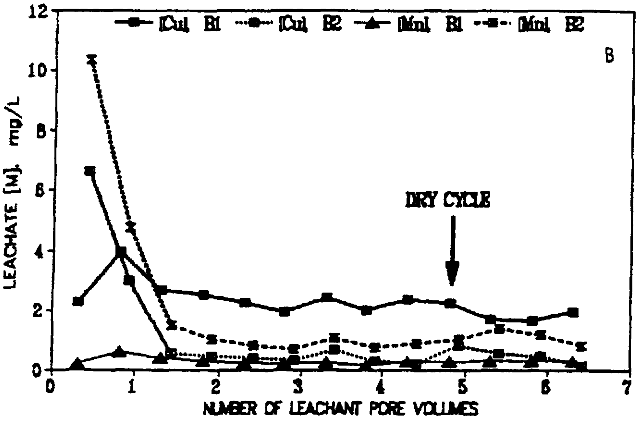


Figure10. Effect of sampling location on leachate. A, Calcium and Magnesium; B, copper and manganese for columns of undisturbed tailings.

within expected experimental variance. On the other hand, the sample of tailings from location B2 showed many layers, from sand-like tailings to gray and blue silts, and even some oxide material that could be classified as hardpan. The silt layers (1 found at a depth of 18 cm and a second at 48 cm) were found to be low in iron and other metals typically found in the bulk of the tailings, but were high in sulphur. The hardpan appeared in fractures within the silts and contained elevated amounts of iron, copper, zinc, and chromium. Elemental analyses of tailings samples directly above and below the low-permeability silt were similar to each other and to the bulk of the surrounding tailings.

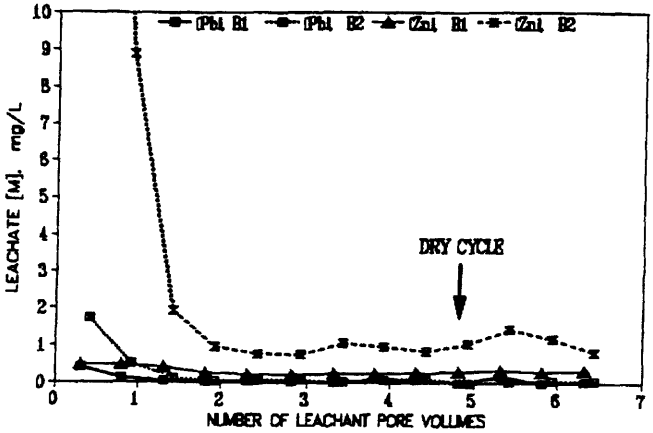


Figure 11. Effect of sampling location on leachate level and zinc for columns of undisturbed tailings.

SUMMARY AND CONCLUSIONS

Considering the variety of samples and tests conducted with tailings taken from a single gold-copper mill site, it should be possible to suggest the potential environmental impact of dissolution from the tailings and the impoundment. Unfortunately, because of the spatial variation of metal concentrations in the waste within this relatively small impoundment, only a few general statements can be made. These tailings are of low oxidative reactivity and should not show large dry-cycle effects. The oxygenreactivity of the remaining sulphides in the unsaturated zone should be low. The slow oxidative dissolution that does occur may be the result of iron(III) acting as the oxidizing agent, with possibly a biological pathway for added iron(III) formation. Vertical percolation of water may be slow in areas where there are silt lenses, while horizontal movement may predominate. Chemical treatment methods would appear to have very limited value in reducing metal mobility within these tailings. The use of soil conditioners around an impoundment, which are needed for revegetation, does not appear to affect metal dissolution and mobility.

LITERATURE CITED

Backes, C.A.; I.D. Pulford; and H.J. Duncan 1986. Studies on the Oxidation of Pyrite in Colliery Spoils I. The Oxidation Pathway and Inhibition of the Ferrous-Ferric Oxidation. Reclamation & Revegetation Research 4, p. 291-297.

Backes, C.A.; I.D. Pulford; and H.J. Duncan 1987. Studies on the Oxidation of Pyrite in Colliery Spoils II. Inhibition of the Oxidation by Amendment Treatment. Reclamation & Revegetation Research 6, p. 1-11.

Backes, C.A.; I.D. Pulford; and H.J. Duncan 1988. Treatment to Combat Pyrite Oxidation in Coal Mine Spoil. U.S. Bureau of Mines IC 9184, p. 91-96.

Bainbridge, K.L.; M.A. Wilkenson; and B.M. Mahar 1980. Evaluation of Lixiviation of Mine Waste, Final Report. U.S. Bureau of Mines OFR 73-81 (contract JO199057, Calspan Corp., Buffalo, NY), 240 p.

Doepker, R.D. 1988. The Interrelation of Factors Influencing the Dissolution of Metals in Columns of-Mine Tailings. In Mine Drainage and Surface Mine Reclamation, Vol. II: Mine Reclamation, Abandoned Mine Lands, and Policy Issues, U.S. Bureau of Mines IC 9183, pp. 210-219.

Doepker, R.D. 1990. Enhanced Heavy Metal Mobilization from Unsaturated Mine Tailings. Society of Mining Engineers, Inc., Transactions 1990.

Doepker, R.D. 1991. Column Leach Study IV: Factors Affecting the Dissolution of Metals from Sulfitic Metal-Mine Tailings. To be presented at the Second International Conference on the Abatement of Acidic Drainage, Sept. 16-18, 1991, Montreal, Canada, 22 p.

Doepker, R.D. and W.K. O'Connor 1990. Column Leach Study I: Heavy Metal Dissolution Characteristics from Selected Copper Mine Tailings. Proceedings of the Fifth Billings Symposium on Disturbed Land Rehabilitation, Vol. 1, Billings, MT, Mar. 25-30, 1990, p. 27-40.

Doepker, R.D. and W.K. O'Connor 1990. Column Leach Study II: Heavy Metal Dissolution Characteristics from Selected Lead-Zinc Mine Tailings. Proceedings of the Mining and Mineral Processing Wastes, Western Regional Symposium, University of California, Berkeley, May 30June 1, 1990, p. 69-80.

Erickson, P.M.; R.L.P. Kleinmann; and S.J. Onysko 1985. Control of Acid Mine Drainage by Application of Bactericidal Materials. In Control of Acid Mine Drainage, U.S. Bureau of Mines IC 9027, p. 35-40.

Kleinmann, R.L.P. 1981. Field Evaluation of a Bactericidal Treatment to Control Acid Drainage. Proceedings of the Symposium on Surface Mining Hydrology Sedimentology and Reclamation, Univ. of Kentucky, Lexington, Dec. 7-11, 1981.

Kleinmann, R.L.P. and P.M. Erickson 1983. U.S. Bureau of Mines RI 8847.

Kuryk, B.A.; I. Bodek; and C.J. Santhanam 1985. Leaching Studies on Utility Waste: Feasibility Experiments. EA-4215 (research project 2485-4), Arthur D. Little, Inc., Cambridge, MA, 316 p.

Lambeth, R.H.; B.M. Stewart; and B.C. Williams 1991. An Investigation of Hydrogeochemical Mechanisms in an Abandoned Sulphide Tailings Impoundment and Underlying Aquifer. To be presented at the 2nd International Conference on the Abatement of Acidic Drainage, Montreal, Canada, Sept.16-18, 1991, 22 p.

Rastogi, V. and A.A. Sobek 1986. Reclaiming Abandoned Mine Lands Using Controlled Release Bactericides: A Case Study. Proceedings of the Eight Annual Abandoned Lands Conference, Billings, MT, Aug. 10-25, 1986.

Renton, J.J.; A.H. Stiller; and T.E. Rymer 1988. The Use of Phosphate Materials as Ameliorants for Acid Mine Drainage. In Mine Drainage and Surface Mine Reclamation, Vol. I: Mine Water and Mine Waste, U.S. Bureau of Mines IC 9183, p. 67-75.

Sobek, A.A. 1987. The Use of Surfactants to Prevent AMD in Coal Refuse and Base Metal Tailings. Proceedings of the Acid Mine Drainage Seminar/ Workshop, Halifax, Nova Scotia, Mar. 23-26, 1987. Environment Canada Catalog No. EN 40-11-7/1987.

Stewart, B.M.; R.H. Lambeth; and B.C. Williams 1990. Effects of Pyritic Tailings in an Abandoned-Impoundment on Downgradient Groundwater Quality. Proceedings of the Mining and Mineral Processing Wastes, Western Regional Symposium, Univ. of California, Berkeley, May 30June 1, 1990, p. 133-142.

Watzlaf, G.R. 1986. Control of Acid Drainage from Mine Wastes Using Bacterial Inhibitors. Proceedings of the 1986 National Meeting of the American Society of Surface Mining and Reclamation, Jackson, MS, Mar. 17-20, 1986.

Watzlaf, G.R. 1988. Chemical Inhibition Williams, B.C.; R.H. Lambeth; and B.M. of Iron-Oxidizing Bacteria in Waste Rock and Sulphide Tailings and Effect on Water Quality. In Mine Drainage and Surface Mine Reclamation, Vol. I: Mine Water and Mine Waste, U.S. Bureau of Mines IC 9183, p. 109-116.

Stewart 1989. Determining Heavy Metal Leaching and Transport from Abandoned Mine Wastes. Presentation at the Society of Mining Engineers Annual Meeting, Las Vegas, NV, 10 p.