

**Evaluation of the Water Quality
Benefits from Encapsulation of
Acid-Generating Tailings by
Acid-Consuming Tailings**

MEND Report 2.46.1

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**EVALUATION OF THE WATER
QUALITY BENEFITS FROM
ENCAPSULATION OF ACID-
GENERATING TAILINGS BY ACID-
CONSUMING TAILINGS**

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EXECUTIVE SUMMARY

An investigation was completed to assess the benefits of encapsulation of acid generating tailings by acid-consuming tailings as a strategy for water quality mitigation, including acid neutralization. The focus of the investigation was a column test that assessed the effects of different source materials as well as different thicknesses utilized for the bottom layer of tailings. Geochemical modelling was performed to evaluate the attenuation of arsenic that was observed in the column studies. Pyrite oxidation modelling was also completed to provide guidance on the thickness of the overlying layer that was required to prevent further oxidation of the acidic high-sulphur tailings.

The column tests were designed to simulate the placement of low pH acidic tailings sandwiched between layers of neutral tailings with excess neutralizing potential under different arrangements and layer thicknesses. Water was added to the top of tailings and allowed to migrate through the tailings. Samples were collected from the drainage outlet at the bottom of the column as well as from suction lysimeters that were placed within the individual tailings layers to sample *in-situ* porewater.

The results of the test confirmed that the neutral layers could consume the existing acidity in the low pH tailings and prevent acidic and metal-laden drainage on a time and spatial scale that is appropriate for field conditions. It was shown that the thickness of the high NP-containing tailings is important in improving efficiency of the technique. Better efficiency was observed with a greater thickness of and longer residence time for pore water in the underlying neutral layer and this efficiency is expected to improve at the field scale. Acid and metal loadings were effectively decreased when the acid-consuming tailings were placed under the acidic tailings.

Modelling of arsenic attenuation showed that the effective removal of arsenic was very sensitive to the amount of ferric oxyhydroxide material in the bottom neutral tailings layer. Although arsenic is readily attenuated, there are conditions for which increasing arsenic concentrations in the effluent or seepage in the field may only be delayed rather than eliminated. However, with sufficient sorption capacity on the ferric oxyhydroxide solids, the elevated arsenic concentrations may be sufficiently reduced to levels below protective environmental guidelines. The modelling results provide guidance to develop a monitoring program for the field scale trial.

The results of pyrite oxidation modelling in the top neutral tailings layer suggest that the residual sulphide content of the tailings will act as an oxygen scavenger while the neutralization potential prevents acid generation in that layer. The combination of oxygen consumption in the top layer and the resistance to oxygen transport from moist tailings act to limit further oxidation in the underlying acidic high-sulphur layer. The modelling results suggest that a 3 m thick layer of the neutral tailings with a low sulphide content would be sufficient to prevent ongoing acid generation in the high sulphur layer. After the sulphide is depleted in the cover layer of T1F material, the oxygen consumption in the top layer will cease and that layer will only act as a diffusion barrier to oxygen. Once the sulphide is depleted, and perhaps before it is entirely depleted in the top cover layer, there will be a very small flux of oxygen into the high sulphide layer that will contribute to ongoing oxidation at a rate that is limited by the oxygen flux. This oxidation will contribute to the acid generating

reactions so there will be an ongoing source of weak acidic porewater infiltrating through the high sulphide layer and into the underlying neutral layer where the water will be neutralized.

This will be a process that will occur over centuries or millennia. Mass balance calculations suggest that there is sufficient carbonate NP in the underlying layer to consume all of the acid produced in the overlying layer.

The pyrite oxidation model also provides a framework for a monitoring strategy to assess the effectiveness of the low-sulphur neutral tailings cover layer.

RÉSUMÉ

On a réalisé une étude afin d'évaluer les bénéfices d'un encapsulage des résidus produisant de l'acide au moyen de résidus consommant de l'acide, dans la cadre d'une stratégie de mesures d'atténuation pour la qualité de l'eau, y compris la neutralisation de l'acide. L'étude a été centrée sur des tests sur colonne servant à évaluer les effets de matériaux provenant de différentes sources, ainsi que de différents niveaux pour les couches inférieures de résidus. On a réalisé une modélisation géochimique pour évaluer l'atténuation de l'arsenic observée lors des études sur colonne. On a aussi réalisé une modélisation de l'oxydation de la pyrite afin d'évaluer l'épaisseur de la couche sus-jacente requise pour prévenir une oxydation ultérieure des résidus acide riches en sulfure.

Les tests sur colonne ont été conçus pour simuler le placement de résidus acides à faible pH entre des couches de résidus neutres avec potentiel de neutralisation en excès pour différents arrangements et différentes épaisseurs des couches. De l'eau a été ajoutée sur le dessus des résidus, et on l'a laissé migrer au travers des résidus. On a collecté des échantillons de drainage au bas de la colonne, ainsi qu'au moyen de lysimètres à succion placés dans les différentes couches de résidus afin de prélever in situ de l'eau interstitielle.

Les résultats des tests ont confirmé que les couches neutres pourraient consommer l'acidité existante dans les résidus à faible pH et prévenir le drainage acide et le drainage chargé de métaux à une échelle spatiale et temporelle appropriée aux conditions sur le terrain. On a montré que l'épaisseur des résidus à fort potentiel de neutralisation est importante pour améliorer l'efficacité de la technique. On a observé une meilleure efficacité pour une plus grande épaisseur et un temps de séjour plus long de l'eau interstitielle dans la couche de résidus neutres sous-jacente, et on pense que l'efficacité sera plus grande à l'échelle du terrain. Les charges d'acide et de métaux ont effectivement diminué quand des résidus consommateurs d'acide ont été placés sous les résidus acides.

La modélisation de l'atténuation de l'arsenic a montré que l'élimination réelle de l'arsenic était très sensible à la quantité de matériau à base d'oxyde et hydroxyde ferrique présente dans la couche inférieure de résidus neutres. Bien que l'arsenic soit facilement atténué, il existe des conditions pour lesquelles une augmentation des concentrations d'arsenic dans les effluents ou le suintement sur le terrain peut seulement être retardée plutôt qu'éliminée. Toutefois, avec une capacité de sorption suffisante des solides à base d'oxyde et hydroxyde ferrique, les concentrations élevées d'arsenic peuvent être suffisamment réduites à des niveaux inférieurs aux directives pour la protection de l'environnement. Les résultats de la modélisation fournissent des renseignements pour le développement d'un programme de suivi sur le terrain.

Les résultats de la modélisation de l'oxydation de la pyrite dans la couche supérieure de résidus neutres suggèrent que la teneur en sulfure résiduel des résidus agira comme un piège à oxygène, alors que le potentiel de neutralisation permet de prévenir la production d'acide dans cette couche. La combinaison de la consommation d'oxygène dans la couche supérieure et de la résistance au transport de l'oxygène depuis les résidus humides conduit à limiter l'oxydation ultérieure dans la couche sous-jacente acide riche en sulfure. Les résultats

de la modélisation suggèrent qu'une couche de 3 m d'épaisseur de résidus neutres serait suffisante pour prévenir la production continue d'acide dans la couche riche en sulfure. Le modèle d'oxydation de la pyrite fournit également un cadre pour une stratégie de suivi pour évaluer l'efficacité de la couche de couverture de résidus neutres à faible teneur en sulfure.

Quand le sulfure sera disparu dans la couche supérieure de la couverture T1F, la consommation d'oxygène dans cette couche cessera et celle-ci ne servira que de barrière de diffusion pour l'oxygène. Après la disparition du sulfure, et peut-être même avant sa complète disparition dans la couche supérieure de la couverture, il y aura un très faible flux d'oxygène dans la couche à forte concentration de sulfure qui participera à l'oxydation continue à un taux limité par ce flux d'oxygène. Cette oxydation favorisera les réactions génératrices d'acide, de sorte qu'il y aura une infiltration continue d'eau interstitielle faiblement acide dans la couche à forte concentration de sulfure et dans la couche neutre sous-jacente où l'eau sera neutralisée. Ce processus durera des siècles ou même des millénaires. Des calculs du bilan massique portent à croire qu'il y a suffisamment de NP carbonaté dans la couche sous-jacente pour consommer la totalité de l'acide produit dans la couche sus-jacente.

Le modèle d'oxydation de la pyrite fournit également un cadre pour une stratégie de surveillance pour évaluer l'efficacité de la couche de couverture de résidus neutres à faible teneur en soufre.

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As always, any deficiencies in the report remain the responsibilities of the authors.

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1.0 INTRODUCTION

A planned expansion of the Pamour open pit mine in Timmins Ontario by the Porcupine Joint Venture (now Goldcorp Canada Ltd. - Porcupine Gold Mines) required the relocation of an historic tailings stack (T1). The T1 Tailings Facility was developed in the 1940s and contained tailings from gold ore processed by a combination of flotation and cyanide leach extraction. The flotation process produced two tailings streams; a sulphide concentrate and a low-sulphide flotation tailings.

The historic sulphide concentrate was subjected to a cyanide leach process and had sulphide acid generating potential (AP) that far exceeded the remaining carbonate-based neutralization potential (NP). The flotation tailings were characterized by very high carbonate NP values so that NP/AP ratios far exceeded a value of one. Commonly, the two tailings streams were combined in the mill prior to deposition but in some instances, the streams were deposited separately. This has resulted in the T1 tailings stack containing a surface layer of high sulphide leach tailings that has, over time, developed acidic conditions.

The planned relocation of the T1 leach tailings requires mitigation of the potential environmental effects caused by the acidic porewater. The need for managing the existing acidic water within the T1 leach tailings has led to the development of the concept of encapsulating the acidic tailings in neutral, acid-consuming tailings in an existing nearby tailings impoundment.

While some of the benefits of neutralizing acidic tailings porewater with carbonate minerals in neutral tailings are self evident, the overall effect on water quality is less certain. The acidic porewater in the weathered T1 leach tailings contains elevated concentrations of several metals including aluminum, cadmium, copper, iron, nickel and zinc, which are typically managed by pH adjustment in treatment systems. However, arsenic is also elevated in the tailings and porewater and is not commonly treated by pH control. In addition, neutralization by carbonate minerals may be expected to adjust pH values to near neutral (6.5 to 7.5) while many metals require higher pH values for effective removal. Therefore, there was a need to investigate the resulting chemistry of porewater from the T1 oxidized leach tailings after neutralization by contact with carbonate minerals in the high NP tailings.

The encapsulation concept includes the following components;

- Placement of the acidic, high-sulphur tailings layer above an existing neutral tailings with a high NP value in order to achieve;
 - Neutralization of existing acidic porewater as it infiltrates downward; and
 - Mitigation of water quality resulting from natural pH adjustment and other chemical processes in the neutral tailings layer;
- Placement of neutral, low-sulphur tailings above the acidic high-sulphur tailings in order to prevent further oxidation of the high sulphur tailings by;

- Acting as a resistant layer to oxygen transport; and
- Acting as an oxygen consuming layer as the residual sulphide minerals in the top low-sulphur layer oxidize.

The flotation tailings from T1 were proposed for use as a cover layer over the T1 oxidized leach tailings after relocation to the T2 tailings dam. Applying the flotation tailings as a cover is expected to mitigate ongoing oxidation of the leach tailings in two ways: as an oxygen barrier and an oxygen consuming layer. Over the long term, the flotation tailings should act as an oxygen barrier by retaining moisture and causing the overall effective diffusion coefficient for oxygen through the cover to remain low. The residual pyrite in the flotation tailings (about 1% S or less) should also scavenge oxygen, as pyrite oxidation occurring in the cover layer effectively removes the availability of oxygen for transport to the underlying leach tailings. Model calculations suggest that effective oxygen scavenging could occur within a layer of flotation tailings containing between 0.5 and 1% sulphide-sulphur. The thickness of the layer could be reduced if the sulphide content is greater and /or the moisture content in the cover layer is higher than that found for the flotation tailings.

1.1 Objectives

The objective of this investigation was to demonstrate the effectiveness of the encapsulation of acid-generating tailings by acid-consuming tailings as a strategy for acid neutralization and water quality mitigation. The laboratory scale test was carried out to determine if the neutral tailings layers could consume the existing acidity from the low pH tailings and prevent breakthrough or escape of acidic porewater. A secondary objective was to assess the attenuation of elevated concentrations of metals, specifically arsenic, which are associated with the acidic porewater existing in the weathered tailings. The objective of the pyrite oxidation modelling was to determine the probable depth of oxidation and flux of oxygen (rate of pyrite consumption) in the flotation tailings cover layer.

1.2 Scope of Investigation

The scope of the investigation was to perform experimental tests to assess the performance of the encapsulation technique to reduce acid and metal loadings from acidic tailings. Two types of acid-consuming tailings (T1-flotation, T2-flotation) and one acid-generating tailing (T1-leach) were obtained from historic tailings deposits at the Pamour open pit mine in Timmins, Ontario. The experiment design included four columns with different arrangements and thicknesses of tailings layers. The tailings were layered in each column with the low pH acidic tailings either above a neutral tailings layer or “sandwiched” between the two layers of neutralizing tailings. The tailings porewater and the column outflows were analyzed for water quality. The performance of each layer configuration was also assessed.

This investigation also included modelling exercises to determine the optimum thickness of the top layer of neutral tailings that would prevent further oxidation of the high sulphur tailings. The model was applied to determine the necessary thickness and to provide guidance for monitoring in the field since the thickness of the top layer could not be practically assessed in the laboratory. A computer model was also developed, using the PHREEQC code, to describe the attenuation of arsenic in the column test and to assess arsenic

attenuation at the field scale. Recommendations to set-up a monitoring program in the field are presented based on the arsenic attenuation modelling.

1.3 Background

Gold mine tailings in Canada and elsewhere often have small percentages of sulphide minerals in the presence of much higher percentages of carbonate minerals. Typically, these tailings can be net acid-consuming. However, at some mines, various mineral processing techniques have resulted in the production of separate tailings streams, some of which contain the sulphide concentrate and are net acid-generating, and others that have had sulphides removed and are strongly acid-consuming.

Some of the historic tailings deposits in the Timmins area contain high concentrations of sulphide minerals and are known to be acid-generating. Closure and reclamation planning for these deposits is being conducted by Porcupine Mines and various closure concepts are being considered. One concept that has undergone preliminary review is based on encapsulation of acid-generating tailings by acid-consuming tailings to mitigate acid loading from the acid-generating tailings. This concept had been used and considered by others in the past for waste rock piles with very limited to no demonstrated success to date. However, many of the conditions that appear to limit the effectiveness in waste rock are not present or do not apply to tailings. The potential success for tailings encapsulation is enhanced by several conditions and/or characteristics, including:

- almost complete availability of neutralization potential (NP) in fine-grained tailings;
- presence of calcium and magnesium carbonate minerals that represent the majority of the NP;
- presence of small quantities of sulphide minerals in the acid-consuming tailings that act as oxygen scavengers in the top layer or cover portion of the encapsulating tailings, while having adequate NP to maintain a net-neutral condition; and
- limitation of oxygen ingress by diffusion through the surface and sides of the deposit by reducing drying and evaporation to maintain higher degrees of saturation in the near surface tailings.

Porcupine Mines relocated one high-sulphide tailings deposit in late 2006 in preparation for the Pamour Pit expansion near Timmins. Preliminary assessment of the acid-generating tailings and a nearby deposit containing acid-consuming tailings suggests that these provide excellent material to evaluate the encapsulation strategy for mitigation. Chemical data were available on the solids from both deposits, including ABA (acid base accounting) and metals analyses (AMEC Report, 2005). Leach test data were also available to characterize porewater quality, including soluble loads of acidity and metals. Some previous results from mixing and percolation tests suggest that neutralization was rapid and complete when acidic leachate was added to acid-consuming tailings. The results also showed that attenuation of metals, specifically arsenic, occurred during neutralization.

A program to investigate encapsulation concept was proposed by EcoMetrix to MEND and supported by Goldcorp Canada Ltd. and the Porcupine Gold Mine operation. The project was proposed in two phases; Phase 1 included laboratory and modelling studies that focused on water quality issues for selected sub-options and Phase 2 included field measurements to monitor the overall effectiveness and to verify water quality at the trial field site. This report presents the results of Phase 1.

2.0 METHODS

A series of tests were conducted to assess the ability of encapsulation of acidic tailings to attenuate acidic drainage passing through neutral tailings layers. These tests included:

- characterization of solids by ABA testing and metal analyses,
- shake flask tests, to evaluate the soluble constituents associated with tailings porewater, and
- column leach tests that involved the percolation of acidic porewater from the acidic tailings (leach tailings) through layers of neutral tailings (flotation tailings).

The following sections describe the methods in details.

2.1 Sample Characterization

Tailings core samples were collected from the field in Timmins, Ontario. The tailings included two net neutral tailings originating in the T1 and T2 tailings stacks and referred to as T1-flotation tailings (T1F) and T2-flotation tailings (T2F) and one net acid tailings referred to as T1-leach (T1L). Five subsamples of each material were collected from different locations in the field and mixed thoroughly for better representation of field conditions.

The tailings solids were subjected to several characterization methods. The moisture contents of the original field samples were measured. Using the modified acid base accounting method, at room temperature for 24h, the solids were analyzed for ABA characteristics including paste pH, total and sulphide sulphurs, carbonate content (as CO₂), NP and AP (acid generating potential). The NP was measured using the modified Sobek procedure at room temperature for 24 hour digestion prior to the titration. The solid phase metal contents were also determined. Shake flask tests were completed on tailings samples using distilled water, with a water to solids ratio of 3:1. Shake flask leachates were analysed by ICP-MS for metals and metalloids as well as acidity and sulphate.

2.2 Column Tests

The test program included column studies. **Figure 2.1** presents a schematic of a column set-up and a photo of a constructed column illustrating the tailings layering. Clear acrylic columns with a height of 75 cm and a diameter 15 cm were used, and loaded with a combination of tailings arrangements. Suction lysimeters were installed within each layer for *in-situ* porewater collection. The effects of type and thickness of the tailings were studied by employing four column configurations as shown in **Figure 2.2**. The tailings were placed in the columns (left to right) with the following order from the top to the bottom of column. Values indicate layer thickness in centimeters.

- Column 1: T1F (20) – T1L (20) – T1F (20)
- Column 2: T1F (20) – T1L (20) – T2F (20)
- Column 3: T1F (20) – T1L (20) – T2F (30)
- Column 4: T1L (20) – T2F (30)

Effluent was collected at the bottom of the columns from drainage outlets. The collection flasks were maintained under anoxic conditions by purging with nitrogen gas in order to prevent oxidation of ferrous iron in the effluent. Before packing the columns with the tailings, the following components were placed in the bottom of the column: fine fibre screen, glass wool, coarser fibre screen, Ottawa sand and another coarse fibre screen. The columns were then packed by placing approximately 5 cm thick lifts of tailings, followed by compaction to minimize any air trapped in the tailing. Lysimeters were placed at desired locations and the packing of the tailings continued until the specified thickness of each tailings layer was attained. The next layer of tailings was then placed in a similar fashion and the lysimeters were positioned at the selected depths. The column was topped with a third layer of tailings to specified thicknesses. The lysimeters were located at the critical horizons to define the most important chemical changes from the top, middle and bottom layers

Distilled water was added to each column biweekly. The water added (0.88 L) was estimated to provide sufficient volumes to collect and analyse from the outflow at the base of the column as well as from the three suction lysimeters within the column. This rate of water addition was equivalent to about 1300 mm/a as net precipitation and therefore represented a value that was about three to four times the value expected in the field. The rate of water addition was expected to affect the residence time in the tailings. This was considered in the columns' design by having two thicknesses of the bottom layer: the thicker layer provided longer residence time than the thinner layer. The tops of the columns were loosely covered by films of plastic wrap to prevent excessive evaporation between additions of water without affecting the oxygen concentration above the tailings.

2.3 Suction Lysimeters

Suction lysimeters are sampling devices that are designed to collect water in porous media such as soils or other unconsolidated geologic materials in which water is held under tension or negative pressures. Suction lysimeters are required for water sampling above the water table while monitoring wells or piezometers are used to collect water samples below the water table or within zones in which the water is under positive pressure. A suction lysimeter is constructed as a tube with a porous ceramic cup at one end. The porous ceramic material has a high air-entry or bubbling pressure, meaning that once all the pores in the ceramic are filled with water or are saturated, a large pressure is required to displace the water by air. The water is held by capillary forces. Although the permeability of the saturated ceramic is not high, water can move through the porous ceramic material when there is a hydrostatic pressure differential across the wall of the ceramic cup. The ceramic must be in physical contact with the moisture in the porous medium that is being sampled.

A vacuum was therefore applied to the lysimeters and negative pressures were established on the inside of the porous ceramic cups in order to draw in samples from the tailings. Due to the permeability of the ceramic, the vacuum is held for about 24 hours to allow sufficient tailings porewater to enter the lysimeter for sampling. About 50 ml of water was required for the specified analyses and typically between 50 to 150 ml of water were retrieved from the lysimeters. The lysimeters were sampled on the day prior to addition of water to each column in order to ensure that the porewater had achieved chemical equilibrium and a stable moisture distribution prior to sampling.

2.4 Analysis of Water Samples

Water samples were analysed by a commercial laboratory. There were challenges related to data quality in this investigation. By nature of the lysimeter samples, sample volumes were relatively small compared to those typically required for routine laboratory processing. In addition, concentrations of many constituents were much higher than those typically encountered in environmental samples. Substantial dilution was required to prepare samples for analysis. For these reasons, the reported detection limits were commonly much higher than those typically reported for samples from natural waters. The analytical results were therefore reviewed and screened to remove values with reported detection limits that were too high to be of assistance with the interpretation of time trends. As a consequence, the data appear to have gaps over the course of the test that are not consistent for all analytes. The missing data were actually omitted to avoid confusion related to the higher than normal detection limits.

2.5 Arsenic Attenuation Modelling

The sorption of arsenic onto ferric oxyhydroxide surface has been previously geochemically characterized. Sorption models such as the double-layer model described by Dzombak and Morel (1990) have been used to quantify the attenuation of arsenic in geologic media. The double-layer sorption model is also included in the PHREEQC (Parkhurst and Appelo, 1999) model that is one of the modelling standards for geochemical applications. The PHREEQC model was applied to the results of the column tests in order to evaluate the potential for attenuation of arsenic that was observed and to provide some guidance for monitoring and assessment that may be required for the field-scale trial.

The double-layer sorption model is based on the two types of sorption sites with different binding capacities. The binding capacities are described as surface complexation reactions between the positive and neutral sites on the hydrous ferric oxide (HFO) solid and the species of interest in solution. The complexation coefficients for several metals and non-metals, including arsenic, are included in the WATEQ4F data base for the PHREEQC model. The model was used with the existing coefficients and only the weak binding sites were considered for this modelling exercise.

For laboratory-scale modelling the Column 3 characteristics were used including a 30 cm flotation tailings layer underlying a 20 cm leach tailings layer, and the corresponding porewater chemistry in each layer. The model combined two modules of PHREEQC; transport of acidic water through the flotation tailings and adsorption of arsenic on the HFO when acidic water migrates through the flotation tailings. Different parameters were involved in the model. While reasonable parameter values were used as input, sensitivity analysis was conducted to evaluate the effect of parameters on arsenic attenuation. The critical parameter was found to be the sorption sites present on HFO. This was then calculated in order to reproduce the results observed in the column 3 drainage.

For the field-scale modelling a 12 m thick acid-neutralizing tailings layer overlaid by a 4 m thick acid-generating tailings layer was used, together with the chemistry of Column 3 tailings

porewater. In this case the HFO adsorption sites were evaluated in order to attenuate drainage arsenic concentration to below a selected benchmark value.

2.6 Pyrite Oxidation Modelling

The pyrite oxidation model is a one-dimensional, single species diffusive transport model that contains a loss term for the constituent of interest. The model has been applied to the assessment of covers on sulphide tailings (Nicholson *et al.*, 1990). The differential equation that describes the transport and reaction is:

$$\partial C/\partial t = D_e \partial^2 C/\partial x^2 - KC^n/\theta_g$$

where: C = concentration of oxygen in the gas phase (mol/m³)
 t = time(s)
 D_e = effective diffusion coefficient for oxygen in moist tailings (m²/s)
 x = depth (m)
 K = pyrite oxidation rate constant (units)
 n = reaction rate order (-)
 θ_g = gas filled porosity (-)

The equation is solved for steady-state conditions (i.e., $\partial C/\partial t = 0$) and the boundary conditions, shown, respectively, as:

$$C = C_o \text{ at } X = 0$$

$$C = 0 \text{ at } X = \infty$$

The gas-filled porosity is equal to 1- θ_w, where θ_w is the volumetric water content. The pyrite oxidation rate constant is derived from the sulphide content and the tailings bulk density, together with the known oxidation rate of 2.2x10⁻⁹ mol-O₂ m⁻² s⁻¹ for standard conditions presented in Nicholson (1994) and Elberling *et al.* (1994b). The units for K depend on the rate order or value of n and should be consistent with the other terms in the rate equation.

The most important parameter in this model is the moisture content that controls the effective diffusion coefficient for oxygen in the tailings. The diffusion coefficient is calculated from an empirical relationship with moisture content or degree of saturation, in tailings, presented by Elberling *et al.* (1993). The effective diffusion coefficient (D_e) is shown as a function of saturation in **Figure 2.3**. This relationship shows that the diffusion coefficient, that controls the flux of oxygen, can vary over several orders of magnitude, from completely dry tailings (S=0%) to completely saturated tailings (S=100%). The diffusion coefficient decreases dramatically when saturation exceeds about 60%.

The measured moisture contents with depth in three test pits on the T1 tailings are shown in **Figure 2.4**. Although the degree of saturation may be as low as 10% in some samples, values greater than 50% dominate and values greater than 70% are common. The variations in moisture content are mainly attributed to differences in grain size of the tailings with higher values corresponding to finer grain size materials. Given these characteristics, and the understanding that a high moisture content layer will control the effective diffusion coefficient through the vertical profile, sensitivity calculations were completed for the saturation range of

50 to 70%. The other unknown that may control the uptake of oxygen is the sulphide content. The sulphide content of T1 flotation tailings will likely be in the range of 0.5 to 1% S, and these values were also used to bound the uncertainty for pyrite oxidation. The reaction order was set at 0.5 (half-order) that agrees well with experimental data. The depth of the oxidation zone, in any case, is not very sensitive to reaction order.

The flux of oxygen can also be calculated for the modelled conditions. The flux of oxygen at the surface can be approximated by:

$$F_{O_2} = C_o (K D_e \theta_g)^{1/2}$$

3.0 RESULTS

3.1 Characteristics of the Tailings Solids

Several investigations have been completed on the Pamour tailings in order to characterize the solids. The sulphide and carbonate mineral contents of the leach and flotation tailings from T1 were determined by the Minnesota Department of Natural Resources and reported in Knight and Piésold (2003). A summary of the mineralogy is presented in **Table 3.1**. The results showed that the sulphide minerals in the leach tailings represented almost 15%, by mass and were dominated by pyrite but included small quantities of other metal sulphides. The leach tailings also contain substantial quantities of carbonate minerals, dominated by dolomite. In contrast, the flotation tailings contained less than 1% sulphide minerals, most of which was represented by pyrite. The carbonate mineral content of the flotation tailings was similar to that of the leach tailings, again dominated by dolomite.

Detailed geochemical characterization of the T1 and T2 tailings was completed in the past (Knight and Piésold, 2003). The ABA characteristics of T1 and T2 tailings are summarized in **Table 3.2**. A summary of concentrations of selected constituents in the tailings solids is presented in **Table 3.3**.

The acid-generating tailings (T1L) had sulphide contents near 20% S and Net Neutralizing Potential (NNP) -500 kg CaCO₃/t. The neutral tailings (T1F and T2F) had considerable neutralizing potential and low sulphide contents. The NP values for the neutral tailings were on the order of 100 kg CaCO₃/t while for the acidic tailings, near surface, were negative because of the low pH of the tailings porewater. The metal contents of T1L were also elevated compared to those in the T1F and T2F samples.

The soluble metals and sulphate concentrations resulting from the shake flask tests on the samples used in the column tests are presented in **Table 3.4**. The T1L acidic tailings exhibited elevated levels of metals and sulphate as a result of historic oxidation in the field while the two neutral tailings samples had relatively low values for most metals. The sulphate concentrations in the T1F were also elevated and correspond to values reflecting sulphide mineral oxidation with subsequent neutralization.

3.2 Column Test Results

The column tests simulated water infiltration and downward percolation as would be expected to occur in the field. Although the rates of infiltration were higher than those expected under field conditions, downward displacement from the surface, through the different layers of tailings in the columns was similar to what would occur in the field with somewhat shorter residence times than those in nature. Results were monitored for the drainages that exited the bottom layers of the columns to evaluate the effect on water quality caused by contact with the entire neutral tailings layer. The resident porewater in each of the tailings layers was also monitored to understand the source concentrations in the initially acidic tailings as well as any attenuation caused by partial contact with the bottom layer and the source concentrations represented by the top neutral layer.

Chemical attenuation in column tests is commonly evaluated by determining the number of pore volumes of effluent that are collected before the constituent of interest arrives at a concentration representing a threshold. The arrival at this concentration is referred to as “breakthrough” indicating the significance of chemical release. The results are therefore presented and discussed in terms of the volumes of water collected from each column, expressed as pore volumes (PV) that were estimated for the bottom layer of each column and the chemistry of the effluent as well as samples collected from the lysimeters during the column tests. The PVs also showed that sufficient water was displaced in the columns to replace the resident volumes in the bottom layers and to verify that the acidic water in the overlying layer had also percolated through the bottom layer of tailings.

3.2.1 Pore Volumes Displaced

The PVs for the tailings layers were calculated from the drained moisture contents, porosities and layer volumes. The number of PVs of water discharged and collected from each column was monitored in order to ensure that the acidic water in the middle layer had migrated through the lower acid consuming layer. **Table 3.5** summarizes the number of PVs, corresponding to the bottom layer beneath the acid generating layer, that were collected in the drainage. For example, in Column 1, in which the thickness of the lowest layer is 20 cm, 40% of the porewater initially residing in the T1F (lowest layer) had been collected by day 6 of the test while after 400 days, about 1.9 PVs of water had been collected from Column 3 (in which the bottom layer was 30 cm).

3.2.2 Lysimeter Samples

Figure 3.1 shows plots of the pH values of the porewater within the layers of tailings as well as the pH of drainage from each of the columns for comparison. The plots show how the transition of T1L porewater through the underlying acid-consuming tailings has changed the drainage quality. Missing data points reflect malfunctioning of the lysimeters and inability to collect sufficient sample volumes for analyses during the test. Challenges associated with the lysimeter design and operations are discussed later in the report.

In general, the pH values of the middle or acidic tailings layers were between 3 and 6. The pH values were not consistently acidic in the lysimeter samples from all middle layers. However, the effect on the acidic water of migration through the bottom neutral layer is evident from the consistent increase in pH in porewater from the bottom lysimeter and in the drainage effluent from each column.

The pH of the porewater in the acidic layers also remained low even after more than one PV of water had passed through the middle layer. For example, 1 PV shown on the plot represents a pore volume for the bottom neutral layer but is also equal to 1 PV in the middle layer because both layers are the same thickness (0.2 m). Even after collection of more than 3 PV, the pH in the middle layer remained near a value of 4. This shows that the acidic water was not flushed out of the middle layer during the experiment by the neutral water displaced downward from the overlying tailings.

A volume of 1 PV in Column 3 represents about 1.5 PV in the middle acidic layer. Therefore, the pH of about 3 in the middle layer after about 1.5 PV in the plot of **Figure 3.1** indicates that

the low pH has persisted after flushing of approximately 3 PVs from the middle layer. Again, the low pH water was not flushed by the percolating neutral water from above.

In spite of the continuing low pH in the middle layers, the pH values within the lower layers as well as those in the drainage from the bottom of the columns remained neutral. In all cases, the pH values in the drainages were somewhat higher than those within the middle layers. This appears to suggest that neutralization was ongoing and not quite complete within the upper portions of the bottom layers compared to the degree of neutralization inferred by the higher pH values in the drainages. This is not unexpected for the short distances and residence times represented by the scale of this laboratory experiment. This suggests that the kinetics of dissolution of carbonate minerals may play a role at the spatial and temporal scale of the laboratory study. It is consistent with the dominance of dolomite ($\text{CaMg}(\text{CO}_3)_2$) as the carbonate mineral which is known to have slower dissolution kinetics than calcite (CaCO_3).

The pH values in drainage samples from columns 3 and 4 decreased one and two pH units, respectively over the last three sampling events of the test. Based on mass balance considerations, these lower pH values can not be related to depletion of carbonate minerals in the bottom layer. Both of these columns have 30 cm thick bottom layers designed to increase the residence times over those in Columns 1 and 2. Therefore, the lower pH values in Columns 3 and 4 would not appear to be related to smaller residence times in the bottom layers. Although the drainage from both columns exhibited pH decreases, the final pH values from Column 3 remained above 7 while those from Column 4 fell below 6. The only differences between Columns 3 and 4 were the absence of a cover layer on and the slightly larger number of pore volumes collected from Column 4. It is not evident how this lack of cover could have resulted in the low pH values in drainage from Column 4. And while the larger number of pore volumes could indicate a potential for breakthrough of migrating constituents, the number of PVs collected from column 1 were greater than those for Column 4 without an observed increase in pH. The pH of the final sample from Column 4 had increase by one-half of a pH unit from the previous sample but the test ended before being able to determine if this was an upward trend. Even at the scale of this experiment, however, it is evident that the neutralization by the bottom layer is effective for consuming the acid generated from the high sulphur tailings.

The specific conductance values in the lysimeter samples from each column are shown as a function of PVs in **Figure 3.2**. In general, the specific conductance, that is representative of the total dissolved solids (TDS), tends to be the highest in the bottom layer and in the drainage compared to samples from the middle and top layers. The trends exhibited by the specific conductance confirm that the resident waters with initially higher values in the bottom layer were flushed from the column during the experiment. The relative peak values in drain samples at 1 PV are consistent with an increase of TDS concentrations representing the neutralization of the initial acidic porewaters from the overlying layer. The increases in specific conductivity values in Columns 3 and 4 at the end of the test appear to correlate to the decreases in pH as well as to an increase in magnesium concentrations.

The elevated arsenic concentrations in porewater associated with the acidic high-sulphur tailings are common in weathered gold tailings and therefore, the potential for passive attenuation or removal of arsenic was a priority for assessment in the current investigation.

Figure 3.3 presents the trends of arsenic concentrations in the porewaters within the different layers and compares them with the drainage from each column. Missing data points in these plots represent a combination of; 1) samples that could not be collected from lysimeters, and 2) not plotting results for samples with high reported detection limits, as discussed previously.

The concentrations from the acidic layers (or top layer in Column 4) and in the drainage samples clearly show that attenuation of arsenic has occurred. The differences in concentrations between the porewaters in the acidic layer and those in the drainage are several orders of magnitude in some cases. It appears that arsenic was attenuated well beyond two PVs of displaced porewater containing elevated concentrations of arsenic. For example, the porewater in the middle layer of Column 1 (**Figure 3.3**) maintained an arsenic concentration of about 1 mg/L for more than 3PVs of flushing. The porewater from the middle layer would have initially arrived at the drain of the column after approximately 1 PV. After 1PV, however, the arsenic concentration in the drain samples decreased from about 0.05 mg/L to less than 0.001 mg/L until the completion of the test. The arsenic in the porewater was lost to the solids in the bottom layer of flotation tailings.

The results from Column 1 also show that the arsenic in the acidic tailings (middle layer) is not simply flushed out, but can represent a source that continues after more than two PVs have flushed through the middle layers. The continuation of elevated arsenic concentrations beyond 2 PVs is similar to the ongoing low pH trend observed for Column 1 in the middle layer as shown in **Figure 3.1**.

3.2.3 Drainage Samples

The following results are presented in terms of PV fractions displaced during the column test and the evolution of water quality discharged from the bottom layer of tailings.

Figure 3.4 shows the pH and specific conductivity (SC) values versus PV for water discharging from the base of the columns. The pH of drainage samples from all columns was generally in the range of 6 to 8.5. Two samples from Column 4 after 2 PV exhibited pH values close to 5.5 and as indicated earlier, the cause of these lower pH values is not clearly evident. Nonetheless, these overall results show that neutralization of the acidic porewater was effective. The fluctuations in pH values do not appear to be related to the arrival of the front of acidic water that was expected after 1 PV had been collected. The pH values from two columns exhibit relatively high values at 1 PV and those from the other two columns exhibit relative lows at 1 PV.

The SC values exhibited consistent trends for all columns. The SC increased from 0 to 1 PV and then declined. As shown in **Figure 3.2** and discussed above, the SC was dominated by the high SC of the initial arrival of the porewater from the acidic layer that had undergone neutralization. The trends therefore, appear to reflect the flushing of the porewater representing the reaction front as neutralized water from the middle layer arrived at the drain for each column.

Figure 3.5 presents the concentrations of calcium and magnesium, in the drainage effluents from all columns. Maximum calcium concentrations approached 1,000 mg/L in the effluent from Column 4 but were generally near 500 mg/L in other samples in porewater from the

middle oxidized layer. These concentrations are consistent with control by gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) that would be expected in carbonate bearing tailings that had experienced sulphide mineral oxidation with elevated levels of dissolved sulphate.

The concentrations of magnesium in the effluent samples from all but Column 4 generally decreased after 1 PV. Values before 1 PV were omitted because of detection limit issues. Maximum concentrations were as high as 7,000 mg/L at 1 PV in Column 1 and up to about 5,000 mg/L in the effluent from Column 3. The magnesium concentrations in Column 4 increased in concentrations after about 2 PVs to values near 5000 mg/L. The source of the magnesium is dolomite ($\text{CaMg}(\text{CO}_3)_2$), which dissolves when in contact with the acid in porewater from the middle oxidized layer. There are no effective solubility controls on magnesium concentrations at neutral pH and therefore the high concentrations that were observed were anticipated. Concentrations of magnesium in effluent from three of four columns exhibited declines after 1 PV indicating that less neutralization and consequently less dolomite dissolution occurred over time and with increasing pore volumes. The magnesium concentration increases in effluent from Column 4 near the end of the test coincided with a pH decrease that likely resulted in more dolomite dissolution.

Concentrations of selected minor or trace constituents as well as sulphate in the column effluents are presented in **Figures 3.6** and **3.7**. The concentrations of minor constituents did not appear to exhibit strong consistent trends with the number of PVs collected. In the case of some constituents with higher concentrations such as cobalt, iron and nickel, the concentration trends appear to be representative of classical breakthrough behaviour in column tests of this type. The concentrations increased to relative maximum values followed by declines to lower values. The timing or number of PVs that coincide with the relative maximum values depend on the chemical interactions and the degree of attenuation that occurs during transport of constituents from the acidic middle layer through the neutral bottom layer of the tailings. Although sulphate is considered to be a major constituent in these column tests, the trends in concentrations reflect more classic breakthrough curves with relative maximum concentrations near 1 PV before starting to decline to lower levels (**Figure 3.7d**). Sulphate concentrations were available up to day 41 only. The samples were analysed with a different protocol after day 41 and sulphur, representing sulphate, was not included on the new ICP scan. Therefore, no sulphate values were reported after day 41.

Arsenic concentrations were generally highest initially followed by declining values throughout the experiment. The maximum values were observed in the effluent from Column 2 to be near 0.1 mg/L. The concentrations in the effluent from all columns then declined to values of less than about 0.02 mg/L after 1 PV. The trends for arsenic suggest that no column exhibited breakthrough and that the arsenic had been, and continued to be, attenuated in the bottom layer during the course of the experiment. It also suggests that arsenic attenuation could be expected to continue over longer experimental durations. The arsenic concentrations in the column drainages reflected the initial concentrations in the bottom and top layers with values near or below 0.1 mg/L, in contrast to the concentrations observed in the acidic middle layer, which were in the range of 1 to 3 mg/L.

The maximum cadmium concentrations occurring in the effluent from all columns were generally at or below 0.001 mg/L with no consistent trends observed over the course of the experiment.

Cobalt concentrations in the effluent samples exhibited relative maximum concentrations between 1 and 2 PV in Columns 2 and 3 with concentrations as high as 12 and 0.7 mg/L, respectively. The effluent from Column 3 exhibited the lowest cobalt concentrations after 1.5 PV with concentrations between 0.06 and 0.2 mg/L. The concentrations of cobalt in Column 4 increased from about 0.1 mg/L initially to near 70 mg/L after 2 PV. Because of detection limit issues in earlier samples, the cobalt concentrations in the effluent from Column 1 were only available after 2 PV and those were near 1 mg/L. The increase in cobalt concentrations in effluent from Column 4 near the end of the test correlated with the decrease in pH in those samples.

Iron exhibited relative maximum concentrations from as high as 8,000 mg/L in Column 1 to as low as 2 mg/L in Column 4 at about 1 PV. The iron concentrations in the effluent samples from all columns then declined to near 1 mg/L after 2 PVs and to as low as 0.1 mg/L in the effluent from Column 3.

The concentration plots as a function of PVs for nickel, selenium, zinc and sulphate are presented in **Figure 3.7**. With the exception of Column 4, nickel exhibited relative maximum concentrations between 0.5 and 1.5 PVs. Maximum concentrations as high as about 900 mg/L were observed in effluent from Column 1 and as low as 7 mg/L in Column 3. Column 4 exhibited relative maximum concentrations of about 320 mg/L after about 2 PVs that coincided with a decrease in pH for those samples.

Selenium concentrations in the column effluent were initially as high as 0.4 mg/L in Column 1. Most of the effluent samples had selenium concentrations between 0.2 and 0.002 mg/L with no consistent trends related to the number of PVs collected.

The highest concentrations of zinc in effluent samples were observed for Column 1 with a value of 2.4 mg/L prior to 1 PV and in Column 4 with a value of 4.9 mg/L after 2 PVs that also corresponded to samples with lower pH values at the end of the test. Most other zinc concentrations ranged between 0.1 and 0.02 mg/L with no discernable trends related to PV values.

Sulphate concentrations in the column effluent samples were expected to exhibit trends similar to those for specific conductance because sulphate tends to dominate the SC values in neutral waters that have been affected by sulphide oxidation. Relative maximum values occurred at about 0.9 PV in Column 4 and about 1.3 PV in Column 1. Insufficient data prevented the determination of relative maximum values for the other columns. Initial sulphate concentrations ranged from 6,000 mg/L in Column 4 to about 3,000 mg/L in Columns 2 and 3. Maximum sulphate concentrations approached 40,000 mg/L between 1 and 2 PV in Columns 1 and 2.

One notable observation for the drainage chemistry was that Column 3 consistently exhibited lower concentrations of most constituents after 1 PV was displaced from the bottom layer than those from other columns. For example, the apparent attenuation in Column 3 resulted in orders-of-magnitude differences in concentrations from those in the other columns for iron and nickel. These results suggest that the thickness of, or residence times in, the lower layers play an important role in the chemical attenuation of individual constituents as the porewater migrates downward through the lower neutral tailings layer.

3.3 Modelling

Modelling exercises were completed to assess arsenic attenuation in the bottom neutralizing layer and pyrite oxidation in the overlying cover layer of neutral tailings. The results are presented in the following sections.

3.3.1 Arsenic Attenuation Modelling

The PHREEQC model was applied to assess the attenuation of arsenic in the bottom layer of the column test. The results from Column 3 were considered for modelling purposes because the results from that column were considered to be optimal in terms of overall quality of the effluent. The effluent quality results for Column 3 showed that arsenic had not exhibited breakthrough or release of the high concentrations observed in the middle acidic layer during the nearly 2 PVs of water collected in the column study. If an arsenic peak concentration had been observed in the drainage, the sorption model could be calibrated to quantify the absorption characteristics for arsenic in the column. Arsenic attenuation is commonly attributed to sorption onto or co-precipitation with ferric hydroxide solids. At neutral to acidic pH values, the negatively charged arsenate (As(V)) or arsenite (As(III)) ions can sorb onto the positively charged ferric hydroxide surfaces. Alternatively, dissolved arsenic species can react with ferric iron and can co-precipitate with the ferric hydroxide solids when conditions favor this reaction. The role of ferric iron in controlling arsenic concentrations has been recognized for decades (Krause and Ettel, 1985). Although precise mechanisms for arsenic removal are poorly defined, ferric iron precipitation has been used as an effective and practical means of controlling arsenic concentrations in water treatment plants as well as in milling processes.

When ferric iron oxides or hydroxides already exist in solids, arsenic sorption will occur during migration through the solids. A sorption model was proposed by Cherry et al (1985) for control of arsenic concentrations in groundwater at a gold mine operation. This model was based on the constant capacitance approach presented by Morel (1983) and that has been incorporated into the geochemical reaction code PHREEQC (Parkhurst and Appelo, 1999). The model contains the sorption reactions and equilibrium reaction constants for arsenic species onto ferric hydroxide. Ferric hydroxide solids are referred to as hydrous ferric oxides (HFO) in the model.

The model was first applied to the conditions and results for Column 3. The concentrations of arsenic in the porewater as a function of distance within the bottom layer of flotation tailings were then calculated at the end of the test for a range of HFO contents as a form of sensitivity analysis. The breakthrough of arsenic concentrations in the column effluent was then modelled for a range of HFO contents to illustrate the effect of attenuation in the bottom layer. The model was then modified to simulate field conditions with appropriate flow distances and tailings thickness in order to assess the potential effectiveness of arsenic attenuation in the T2 flotation tailings for full scale implementation of the encapsulation approach.

The physical scale of the field trial included an anticipated 4 m thick layer of acidic, high-sulphur tailings layer over a 12 m thick layer of neutral tailings that were tested in the Column 3 design. The HFO in the tailings required to prevent breakthrough of arsenic in the column

test was initially considered to model the arsenic adsorption within the 12 m thick neutral tailings in the field. The HFO content was then increased to assess the sensitivity of arsenic attenuation to HFO content in the neutral tailings.

The model calculations for arsenic transport and sorption in the bottom layer of Column 3 are summarized as concentration versus distance profiles in **Figure 3.8**. This plot shows several profiles that were calculated for a range of HFO contents from 0.018 to 0.050 moles of sites per kg of tailings. Because the HFO content could not be precisely estimated with the available data, a calibration approach was attempted.

The column results showed that arsenic breakthrough at concentrations greater than 0.01 mg/L had not yet occurred in Column 3 at the end of the test. In order for breakthrough to be prevented in that period, the HFO must have been greater than or equal to 0.025 moles/kg. Therefore the minimum HFO content of the T2 flotation tailings was assumed to be 0.025 moles/kg. The model was then rerun with different HFO contents as multiples of this minimum value in order to assess the sensitivity of the attenuation effects to the HFO content. The results of these sensitivity calculations are shown in **Figure 3.9**. This plot shows the predicted concentrations in the effluent as a function of pore volumes passed through the column. The concentrations of chloride are shown for reference to illustrate that a non-reactive tracer will exhibit a maximum concentration at 1 PV. The CCME Canadian Water Quality Guideline for the protection of aquatic life for arsenic (0.005 mg/L) is also shown for reference.

Breakthrough with a minimum HFO value of 0.025 moles/kg occurs at about 2 PVs, as expected, and the maximum arsenic concentration reaches a value of about 3 mg/L, almost equal to the modelled concentration of arsenic in the middle layer of Column 3. Therefore, at the minimum HFO content, the sorption of arsenic delays the breakthrough compared to that of a non reactive constituent but does not effectively attenuate the peak concentrations leaving the column. However, as the HFO content increases, not only is the arrival of arsenic at the base of the column delayed but the peak is also reduced. At a HFO value that is eight times the minimum value, the peak arsenic concentration declines to about 0.2 mg/L with breakthrough at about 15 PVs.

The PHREEQC model was revised to include the field dimensions and geochemical conditions. The results showing arsenic concentrations in porewater exiting the base of the T2-F tailings as a function of pore volumes are summarized in **Figure 3.10**. At a minimum HFO content of 0.001 moles/kg, there is only a small difference between breakthrough curves for chloride and arsenic. However, even with this low HFO value and 12 m of travel distance, the peak concentrations of arsenic are predicted to be a factor of 10 lower than those in the column results for a HFO content of 0.025 moles/kg and 0.3 m of travel distance (**Figure 3.9**). By increasing the HFO content incrementally, the number of PVs required for breakthrough increased and the peak concentrations decreased. A HFO content of 0.09 moles/kg was required to reduce the peak arsenic concentration to value of less than 0.005 mg/L with breakthrough at about 200 PVs.

The pore volume axis in **Figure 3.10** can be converted to time if the flow conditions can be estimated for field conditions at the T2 tailings site. For illustration purposes, an infiltration rate of 500 mm/a was assumed for the relatively permeable tailings impoundment that is

located in an area that receives about 800 mm/a of total precipitation. A volumetric moisture content of 20%, corresponding to a value near the average measured value measured at T1 and shown in **Figure 2.4**, was assumed for field conditions. The selected infiltration rate and moisture content result in a vertical infiltration velocity of 2.5 m/a. In a 12 m high tailings stack, this translates to a residence time of about 5 years to displace one PV. The resulting plot of arsenic concentrations exiting the base of the 12 m thick tailings over time is shown in **Figure 3.11**. As expected, the chloride breakthrough that occurs at one PV occur in about 5 years while the arsenic breakthrough curves occur at times corresponding to the pore volumes shown in **Figure 3.10** for the selected values of HFO, requiring almost 1000 years for a HFO value of 0.09 moles/kg.

The modelling results clearly show that arsenic can be attenuated to low concentrations given sufficient HFO content in net-neutral tailings. A major uncertainty in the model is the available HFO in the tailings. In the case of the underlying net-neutral tailings, there will be three potential sources of HFO. These include the existing HFO on tailings solids that has formed as a result of historic processes such as mill processing and oxidation of sulphide minerals during storage in the tailings facility. Other potential sources of HFO also include dissolved iron that exists in porewater within the acidic leach tailings as well as iron that will be generated in the future as a result of ongoing oxidation of residual sulphide minerals in the neutral tailings that will cover the acidic leach tailings layer. The iron produced during ongoing oxidation will not likely play an important role in attenuation of dissolved arsenic in the acidic leach tailings because that source of iron will originate in the cover layer and the water from that layer will be above the water containing the more elevated arsenic concentrations in the leach tailings pore water. The dissolved iron in the leach tailings pore water may be very important, however, because the pH of the pore water will increase as it migrates into the neutral tailings and contact with residual oxygen will likely result in oxidation of the iron to the ferric form and precipitation of HFO. Precipitation of the ferric hydroxide from the pore water containing elevated arsenic concentrations will likely represent a very effective additional removal mechanism for arsenic that was not considered in the model described above. Nonetheless, these considerations highlight the need to better understand the HFO content or the overall sorption characteristics of the neutral tailings solids in order to reduce the uncertainty in the predictions of arsenic attenuation for encapsulated acidic leach tailings.

3.3.2 Pyrite Oxidation Modelling

The results of the pyrite oxidation modelling calculations are summarized in **Figure 3.12**, which shows the oxygen concentration profiles with depth for the four sensitivity cases. The two topmost curves show the oxygen profiles for 70% saturation with small differences between the 1% S (upper) and 0.5% S (lower) curves. The pair of lower curves represents the 50% saturation condition with 1% and 0.5% S values. These calculations show that the degree of saturation has a much larger effect on the extent of the oxidation zone than does the sulphur content. The results indicate that the zone of oxidation (depth at which the oxygen concentration approaches zero) extends to about 3 m below surface for the worst case (low moisture and low sulphur content). In all other cases, the oxidation zone is less than 3 m deep.

These results show that a 3-metre thick cover of flotation tailings will prevent most, if not all, oxygen migration into the underlying leach tailings for the range of likely conditions. It should be noted that the degree of saturation in the tailings is expected to vary with depth. The moisture content or degree of saturation in the layers will control the diffusion of oxygen into the tailings. For example, tailings with a saturation of 80% will prevent oxygen penetration beyond 0.4 m if the sulphide content is between 0.5 and 1% S. This means that a layer of only 40 cm thickness can prevent downward oxygen migration if 80% saturation is present.

The initial oxygen flux at the surface will be approximately $47 \text{ mol-O}_2 \text{ m}^{-2} \text{ a}^{-1}$ for 70% saturation and 1% S. This translates to about $1.5 \text{ kg-FeS}_2 \text{ m}^{-2} \text{ a}^{-1}$ (pyrite oxidized per m^2 per year). If the bulk density of the tailings is $1,500 \text{ kg m}^{-3}$, then the depletion rate for pyrite will be about 0.1 m/a initially. The rate will decrease with time as the depletion zone thickens. Ultimately, when all sulphide is depleted in the cover, the flux of oxygen at the bottom of cover will be about $9 \text{ mol-O}_2 \text{ m}^{-2} \text{ a}^{-1}$ or less than 20% of the flux initially for an effective diffusion coefficient for oxygen (D_e) value with 70% saturation. Assuming the rate remains constant, the 3-metre cover would be depleted of pyrite in about 30 years. If a thin layer of tailings has a saturation value of 80% or higher, this time would increase to 100 years or more, because the flux changes by a factor of 3.2 for a change in the effective diffusion coefficient by a factor of 10.

4.0 DISCUSSION

4.1 Column Tests

The column test investigation was designed to assess water quality that could result from the passive treatment of acidic tailings porewater during migration through neutral tailings with excess neutralization potential. Although the scale of the column test is quite different from the field application for this mitigation strategy, the laboratory results provide insight into the benefits and potential challenges associated with implementation in the field.

The column test results clearly show that neutralization of acidic porewater will occur on a timescale and spatial scale that are applicable to field conditions. While the pH of effluent treated by T1 flotation tailings (Column 1) ranged between 6 and 7, treatment by the T2 tailings (Columns 2, 3, and 4) were generally better, with values between 7 and 8. The reason for the lower pH values associated with the T1 flotation tailings is likely related to the historic long-term exposure to the acidic porewater in the overlying T1 leach tailings; the sample of T1 flotation tailings was retrieved from a shallow depth immediately below the acidic T1 leach tailings, where exposure to acid had been ongoing over several decades. Other evidence for this historic exposure to acidic water includes the lower NP (76 kg-CaCO₃/t) and the increased levels of soluble sulphate in the T1 flotation tailings compared to those measured in the T2F tailings. Nonetheless, both neutral tailings samples provided effective neutralization in the short time frame of the column tests, proving that the NP in the tailings was readily available and not kinetically hindered during the experimental period.

The neutralization capacity or total effective acidity that can be treated by a mass of neutral tailings was not tested in this investigation. However, evaluation of the available NP in the T2F tailings shows that there will be excess NP compared to the present soluble acidity in the T1 leach tailings layer. In addition, the potential future acidity, represented by the sulphide content of the T1 leach tailings is also less than the available NP in the anticipated 12 m thick layer of T2F tailings underlying the T1L layer in the field setting and therefore all potential acidity can be neutralized. The effective depletion of NP in the underlying tailings may also be monitored by collecting core samples periodically after construction of the encapsulated tailings system. The depletion of NP will occur over decades so that there will be time to evaluate and update predictions as appropriate. A study by Jambour and Blowes (1991) of gold tailings similar to the T2F tailings in the Timmins area at the former Delnite mine, showed that the oxidation front had only migrated down about 0.6 m from the surface in more than 20 years of exposure with no cover or other mitigation strategies applied to the tailings. Although the Delnite tailings contained sulphide, the excess NP maintained neutral pH porewater with low concentrations of most metals.

In addition to neutralization, the mitigation of elevated concentrations of other soluble constituents is important to the success of this application. In general, the passive treatment and neutralization by the underlying flotation tailings results in attenuation or reduction of several dissolved constituents to varying degrees. The most effective apparent removal of metals was observed for Column 3 that included a 30 cm thick bottom layer of T2 flotation tailings underlying the acidic tailings layer. This treatment was likely more beneficial than that for T1 flotation tailings for two reasons. First, the T2F tailings had not been previously

exposed to acidic porewater, as had the shallow T1 flotation tailings. Secondly, the bottom layer of tailings was 50% thicker in Column 3 than that in Column 2, providing an increase in residence time and higher solids to water ratios for the kinetically influenced geochemical reactions to occur.

The results from Column 4 were similar to those from Column 3 with the exception of a lower pH effluent containing more elevated metal concentrations at the end of the test period. The only design difference between those columns was the absence of a neutral tailings cover layer in Column 4. One other difference that occurred as a result of drainage differences was a larger number of PVs for Column 4 than for Column 3 at day 400, representing the end of the test. While about 1.8 PVs had been collected from Column 3 during the test, 2.3 PVs had been collected from Column 4, a difference of 28%.

The potential influence of no cover layer in Column 4 is not clearly evident. While the neutral tailings cover would provide some dissolved alkalinity to the porewater entering the acidic leach tailings layer from above, this alkalinity would have only a very small affect on the pore water within the acidic tailings layer.

The larger number of PVs for Column 4 could have played a role in the pH depression at the end of the test. However, 3.1 PVs were collected from Column 1, exceeding the value from Column 4 by 35% while exhibiting neutral pH throughout the test. The cause of the pH depression in the effluent of Column 4 therefore remains uncertain. If the test had run longer, it would have been possible to observe whether or not the pH would have continued to rebound into the neutral range following the increase of one-half of a pH unit for the last sampling date as shown in **Figure 3.1d**.

The performance of the suction lysimeters was disappointing. These devices were constructed with 1.5 cm diameter ceramic cups that were glued to PVC tubing. This design had been used successfully in other projects but failed to collect samples consistently from the columns in this study. In future studies, it is recommended that an alternate design be considered in order to reduce the risk of instrument failure.

The breakthrough of different constituents occurs at different PVs. A breakthrough at one PV indicates migration of that constituent at the same rate as the porewater. Arrival at larger PV values indicates attenuation of a constituent with a migration rate that is the inverse of the PV number when breakthrough occurred. Hence, different constituents have varying degrees of attenuation as a result of migration through the neutral tailings layer that depend on how reactive each constituent is.

The results for all columns exhibited pulses for some constituents with relative maximums at about 1 PV indicating that the dissolved constituents, as indicated by the specific conductance, are moving at the same rate as the porewater with no attenuation. The specific conductance values reflect the total dissolved solids concentrations that are dominated by sulphate. Therefore, the breakthrough curves suggest that sulphate was not attenuated in the tests and moved at the same rate as the porewater. This is anticipated if sulphate does not precipitate as gypsum, for example, while migrating through the neutral tailings.

The breakthrough of iron is evident for Columns 1 and 2 but not for Columns 3 and 4 as shown in plots **Figure 3.6d**. In contrast, breakthrough of arsenic does not appear to have occurred in any of the columns as suggested by the plots in **Figure 3.6a**. This means that arsenic had been effectively removed from solution for the entire column test period. These observations suggest that some constituents may be delayed while migrating through the tailings while others may be removed by reactions between porewater and solids.

A crude mass balance for key constituents in Column 3 was completed to evaluate the effectiveness of mass removal by the neutral bottom layer of T2F tailings. The difference in mass for each constituent was calculated from estimates of the initial soluble mass in the acidic middle layer less the dissolved mass leaving the column in drainage. The soluble mass in the middle layer was calculated from the average concentrations in samples from the lysimeter in the subject layer multiplied by the estimated initial volume of porewater. The mass in the drainage was estimated by summing the concentrations multiplied by the volumes of each effluent sample collected. The results of the mass balance calculations are summarized in **Table 4.1**. The differences in mass are expressed as positive values for attenuation or transfer of mass to the solids and negative values for transfer from the solids to solution or release to the water from the bottom layer of tailings.

As anticipated, there was production of calcium and magnesium as a result of dissolution of carbonate minerals during neutralization of the acidic porewater as it migrated through the neutral tailings layer. The calcium mass in the effluent was almost 2 times higher than in the original porewater of the acidic tailings, and the mass of magnesium was about 10 times higher. The concentration of calcium was expected to be controlled by the solubility of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and therefore the calcium in the effluent may not be a true reflection of the calcium released during the neutralization of acidic porewater. However, magnesium, which originates from the dissolution of dolomite ($\text{CaMg}(\text{CO}_3)_2$) does not have any important solubility controls at neutral pH levels and therefore provides a better indication of the NP utilization when acid is neutralized. In contrast, many other constituents exhibited losses from solution ranging from about 41% for selenium to effectively 100% for cadmium, copper, iron and zinc. Almost all of the arsenic was removed from the porewater.

This mass balance is considered to be conservative in that the soluble mass in the middle layer of tailings was likely under-estimated. The assumption that the initial soluble mass was static is not precise. For example, review of **Figure 3.3** shows that the arsenic concentrations in the middle layer of Column 3 increased slightly from the start of the test to the time at which 1.5 PVs were collected from the column. This shows that initial arsenic mass was not simply flushed from the middle layer as was assumed in the mass balance calculation, but that the acidic tailings continued to be a source of arsenic for more than 1 PV and that arsenic continued to be removed by the underlying T2F tailings layer before discharge from the column. Therefore, the proportion of arsenic removed from the acidic porewater will likely be greater than that shown in **Table 4.1**.

It is probable that there are multiple mechanisms for removal of metals and non metals in this system. One mechanism that likely affects copper is the increase in pH to neutral values resulting in precipitation of oxide or hydroxide solids of copper. Another probable mechanism for other metals is sorption onto or co-precipitation with, ferric oxyhydroxide solids. The formation of ferric hydroxide phases are indicated by the loss of a substantial fraction of

dissolved iron as well as the visual observation of a reddish-brown zoning at the top of the T2F tailings layer, immediately below the interface between the layers as shown in **Figure 2.2** in the “after test” photo. The observation of the formation of the ferric hydroxide precipitates or HFO was also supported by the cementation of the brownish zone that was verified upon dismantling of the columns at the end of the test. Part of the cementation is also likely attributable to the precipitation of gypsum that forms when the sulphuric acid is neutralized by calcium carbonate minerals as shown by Jambour and Blowes (1991). However, the mass balance calculations suggest that about 3 g of iron (as Fe or 6 g as $\text{Fe}(\text{OH})_3$) were removed in the bottom layer, supporting the visual observation of substantial iron hydroxide precipitation at the top of the T2F tailings layer.

The results of the column tests do not provide definitive conclusions with respect to the long term behaviour of a tailings encapsulation system. However, the results show that neutralization of acidic porewater is practical and effective. In addition, there is substantial benefit to water quality in such a system and natural attenuation will almost certainly play a key role in mitigating the quality of acidic drainage from the high sulphur-low NP tailings. A field trial is now in progress and ongoing monitoring is planned over the next decade in order to confirm the benefits of this tailings management strategy.

4.2 Arsenic Modelling

4.2.1 Implication for the Field-scale Trial

The arsenic attenuation modelling showed that decreases to levels below the environmental guideline of 0.005 mg/L in the effluent are achievable with sufficient HFO in the underlying flotation tailings layer. With sufficient HFO, release of an arsenic concentration peak and breakthrough with less than 0.005 mg/L are delayed by hundreds of years. The model inputs may be revised when more refined data are obtained for field conditions at the tailings facility. The monitoring results can then be compared to updated model results to better understand the actual behaviour of the encapsulation technique.

4.2.2 Uncertainty in Sorption Parameters

The results of the arsenic attenuation model were presented as the magnitude and timing of arsenic breakthroughs. These results are most sensitive to the sorption model parameters. The key parameters in the sorption model are the concentration of HFO in the tailings, available binding sites, and the specific surface area of the HFO.

The total amount of HFO used in the model was calculated assuming that non-sulphide iron was 10% of the total iron content of the T2F tailings. A tailing sample with less non-sulphide iron content has a lower capacity for arsenic adsorption and needs more binding sites to reach the same level of attenuation than was presented in this report. Better characterization of field-scale tailings may result in a more precise HFO input to the model for a better estimation of arsenic attenuation.

The fraction of binding sites per mole of HFO appears to be a critical variable in establishing arsenic attenuation above a certain level. This may vary from a low fraction of total HFO, for example 10% mole/mole, to almost 100% likely as a function of the maturity or degree of

crystallinity of the oxide phase. Fresh precipitate is known to exhibit higher densities of binding sites than more aged or crystalline material.

The specific surface area available for adsorption also affects arsenic attenuation; although to a much lesser extent than the fraction of binding sites. A standard value of 600 m²/g HFO was used in this modelling approach (Parkhurst and Appelo, 1999). Increasing the surface area by two-fold did not significantly change the arsenic attenuation.

It was assumed in the arsenic sorption model that the quantity of HFO was fixed throughout time and that no HFO addition occurs. The lab results showed that iron oxyhydroxides precipitated during the test, as expected and HFO production will increase the capacity for arsenic sorption in the tailings.

4.3 Pyrite Oxidation Modelling

Sulphide oxidation modelling has shown that a 3-m layer of flotation tailings will prevent downward oxygen migration into the acidic, high sulphide layer. Eventually, the pyrite in the cover will become depleted. The depletion time is expected to be on the order of 30 to 100 years. After depletion, the flotation tailings will act as an ongoing passive barrier to oxygen by the natural moisture retention in the flotation tailings. The maximum flux of oxygen will on the order of 10 mol-O₂ m⁻² a⁻¹ for a cover with 70% saturation. If all of the oxygen is converted to sulphuric acid as a result of pyrite oxidation in the leach tailings, then about 0.5 kg of dolomite (with the stoichiometry of 2 mole H⁺ consumes 1 mole of CaCO₃ equivalent) will be consumed each year over a 1-m² area. If the average NP is 120 kg t⁻¹ (180 kg m⁻³), then depletion of the dolomite over a 1-m depth below the leach tailings will require about 400 years. There is excess NP below the leach tailings to consume all of the potential acid produced from oxidation of all of the pyrite within the leach tailings, and therefore the risk of acid breakthrough is considered to be negligible.

5.0 CONCLUSIONS

The results of the column tests do not provide definitive conclusions with respect to the long term behaviour of a tailings encapsulation system. However, these results clearly show that neutralization of acidic porewater is practical and effective. In addition, there is substantial benefit to water quality in such a system and natural attenuation will almost certainly play a key role in mitigating the quality of acidic drainage from the high sulphur-low NP tailings. A field trial is now in progress and ongoing monitoring is planned over the next decade in order to confirm the benefits of this tailings management strategy.

The conclusions from the column test program are summarized as follows:

- the column study results have clearly shown that the neutral flotation tailings result in neutralization of the initially acidic porewater on a temporal and spatial scale that would be appropriate for application in the field;
- the reactions between the initially acidic and metal rich porewater and the neutral tailings result in substantial attenuation to near complete removal of several constituents of potential concern including arsenic, cadmium, cobalt, copper, iron, nickel and zinc,
- the residence time for porewater in the bottom neutral tailings layer did not appear to affect the water quality benefits for the timescale of the test,
- the thickness of the bottom layer did, however appear to have an effect on effluent quality with better quality associated with the 30 cm than with the 20 cm layers,
- arsenic is a key constituent of potential concern that is likely controlled by sorption onto ferric hydroxide solids,
- sorption modelling results showed that arsenic in tailings drainage in the field could be effectively attenuated to concentrations that are protective of the receiving environment,
- the sorption modelling showed that the thickness of the bottom neutral tailings layer affected attenuation of arsenic such that more attenuation occurred with a greater thickness, representing a greater travel distance.
- pyrite oxidation modelling results suggested that a 3 m thick layer of neutral tailings over the acidic leach tailings in the field could effectively prevent ongoing acid generation in the encapsulated high sulphide tailings layer for many decades to centuries,
- the cover layer will continue to act as a diffusion barrier to oxygen even after sulphide is depleted and the small quantities of acid formed by the slow oxidation of the sulphides in the leach tailings layer will continue to be neutralized into the indefinite future,

-
- although unexpected, the effluent results from the uncovered column exhibited lower pH conditions after about 2.5 pore volumes had been collected and the results could not be explained by any differences other than the absence of a cover layer,
 - the lysimeter results in the acidic leach tailings layer showed that arsenic concentrations remained in the mg/L range after more than 3 pore volumes of water had passed through the layer, indicating that arsenic will not simply be flushed from the leach tailings as would be expected for non-reactive constituents;
 - because arsenic is an important constituent of potential concern and sorption onto HFO or ferric hydroxide solids plays a key role for arsenic removal, a more detailed assessment of arsenic sorption and attenuation for field conditions is recommended and,
 - periodic monitoring of pore waters in and below the leach tailings in the field will provide a basis for verifying the conclusions of this laboratory and modelling study.

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TABLES

Table 3.1 Sulfide and Carbonate Mineralogy (Weight %) of the Leach Tailings and Flotation Tailings, T1

Mineral	Ideal Formula	Leach Tailings	Flotation Tailings
Calcite	CaCO ₃	1.5	0.2
Dolomite	Ca, Mg(CO ₃) ₂	16.1	18.9
Siderite	FeCO ₃	1.3	1.9
Pyrite	FeS ₂	13.58	0.86
Pyrrhotite	Fe ₇ S ₈	0.02	0.04
Arsenopyrite	FeAsS	0.09	0.01
Chalcopyrite	CuFeS ₂	0.04	0.01
Galena	PbS	0.01	<0.01
Sphalerite	ZnS	0.1	0.05

Source: Knight Piésold, 2003b

Table 3.2 ABA Test Results (Arithmetic Means) for Tailings from T1 and T2 Tailings Stacks

Parameter	Units	T1 - Stack				T2 - Stack	
		² Leach at Surface (Oxidized) ³	Leach at Depth (Non-Oxidized)	Flotation ⁴ (Oxidized)	Flotation (Non-Oxidized)	Surface (Oxidized)	At Depth (Non-Oxidized)
Samples	n	10	5	5	12	18	45
Paste pH	ppm	2.77	7.66	7.70	8.60	9.11	8.87
NP	kg CaCO ₃ /tonne	-30	76	125	109	139	119
AP	kg CaCO ₃ /tonne	473	456	9.82	8.56	0.83	4.98
NNP	kg CaCO ₃ /tonne	-503	-380	116	100	138	114
NP/AP	ratio	-0.18	0.45	22	48	281	146
S	%	20.88	17.36	1.31	0.68	0.12	0.32
S=	%	15.14	14.59	0.31	0.27	0.03	0.18
SO4	%	17.25	8.25	2.99	1.23	0.32	0.49
C(t)	%	0.31	1.11	1.79	1.60	2.00	1.65
CO ₃	kg CaCO ₃ /tonne	6.67	49	108	102	135	112

1. Data Source: Knight Piésold, 2003

2. Leach tailings refer to high sulphur concentrate

3. Oxidized tailings refers to material with brown iron staining

4. Flotation tailings in the T1 Stack were located below the leach tailings

Table 3.3 Concentrations of Selected Constituents in the Flotation and Leach Tailings Solids from T1 and T2

Solid Content	Units	T1-Leach	T1-Float	T2-Float
Arsenic (As)	ppm	429	38	98
Cadmium (Cd)	ppm	3.00	1.00	nv
Calcium (Ca)	%	4.0	3.3	19500
Cobalt (Co)	ppm	412	14	13
Copper (Cu)	ppm	155	26	26
Iron (Fe)	%	22.2	4.7	40800
Lead (Pb)	ppm	nv	nv	14
Magnesium (Mg)	%	1.5	2.0	20443
Nickel (Ni)	ppm	125	32	32
Selenium (Se)	ppm	2	<1	nv
Zinc (Zn)	ppm	931	339	70

Data Source: Knight Piésold, 2003

Table 3.4: Summary of Leachate Quality from Shake Flask Tests

Parameter	Unit	Sample		
		T1-Leach	T1-Float	T2-Float
pH	---	4.09	7.360	7.54
Conductivity	mS/cm	6.29	1.690	0.68
Acidity (as CaCO ₃)	mg/L	3548	9.7	13
As	mg/L	2.31	0.003	0.02
Cd	mg/L	0.077	0.0001	0.0001
Ca	mg/L	470	306	80
Co	mg/L	11.02	0.003	0.001
Cu	mg/L	5.49	0.002	0.001
Fe	mg/L	1740	0.09	0.08
Mg	mg/L	290	79	40
Ni	mg/L	41.4	0.015	0.03
Se	mg/L	0.13	0.003	0.002
SO ₄	mg/L	7286	1273	228
Zn	mg/L	59.20	0.005	0.01

Table 3.5: Cumulative Pore Volume Fractions Collected from the Bottom Layer of Tailings in Each Column¹

Time (day)	0	6	14	24	41	58	80	103	134	167	259	283	321	401
Column 1	0	0.41	0.67	0.89	1.26	1.69	2.07	2.42	2.79	3.15	-	-	-	-
Column 2	0	0.21	0.44	0.86	1.25	1.67	2.01	2.35	2.68	2.93	-	-	-	-
Column 3	0	0.10	0.32	0.44	0.62	0.87	1.06	1.22	1.40	1.46	1.56	1.74	1.82	1.85
Column 4	0	0.21	0.44	0.65	0.87	1.12	1.33	1.55	1.80	1.99	2.16	2.29	2.32	2.34

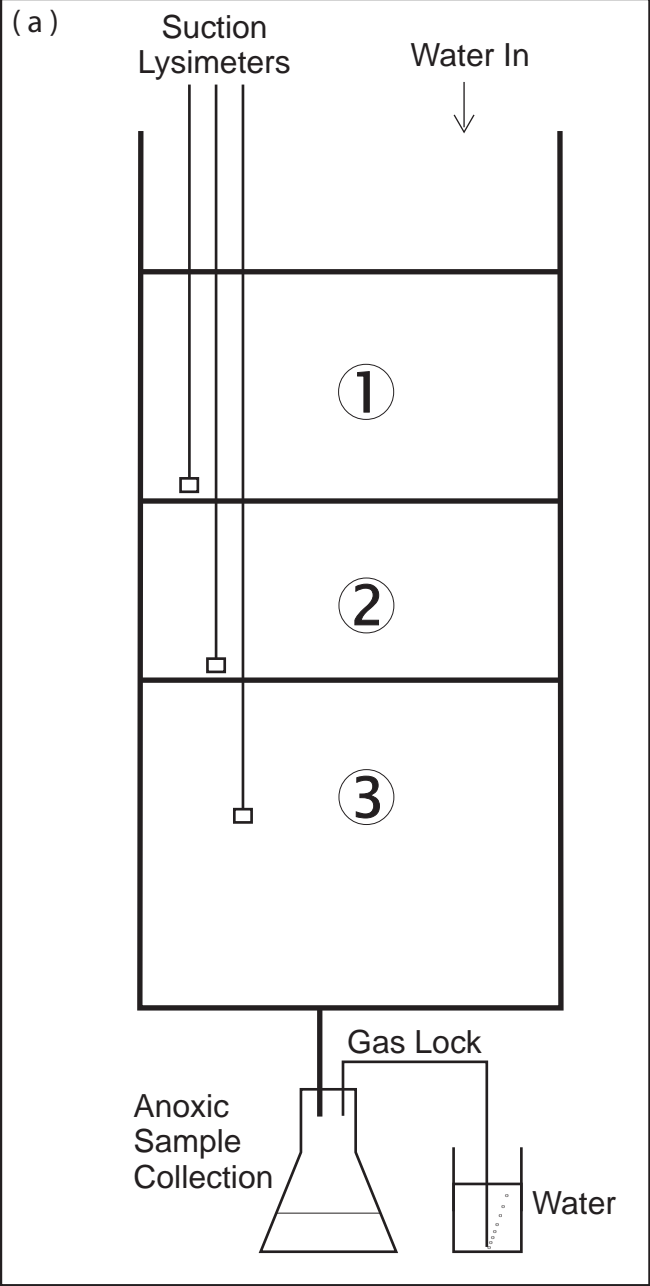
1 - Pore volume = 1.66 L for the 20 cm layer (columns 1 and 2), and 2.49 L for the 30 cm layer (columns 3 and 4)

Table 4.1: Summary of Mass Balance on Column 3 for Selected Constituents

Parameter	Total Mass Out of Bottom Layer (mg)	Initial Mass in Middle Layer (mg)	Difference in Mass	Percentage Difference
			(mg)	(%)
Arsenic	0.06	2.12	2.06	97
Calcium	1241	547	-694	-127
Cadmium	0.001	0.333	0.331	100
Cobalt	0.84	20.26	19.42	96
Copper	0.002	25.633	25.631	100
Iron	2.82	2872	2869	100
Magnesium	7774	575	-7199	-1252
Nickel	13.37	78.23	64.86	83
Selenium	0.03	0.05	0.02	41
Zinc	0.14	84.14	84.00	100

Note: Negative values indicate mass released from solids in the bottom layer

FIGURES




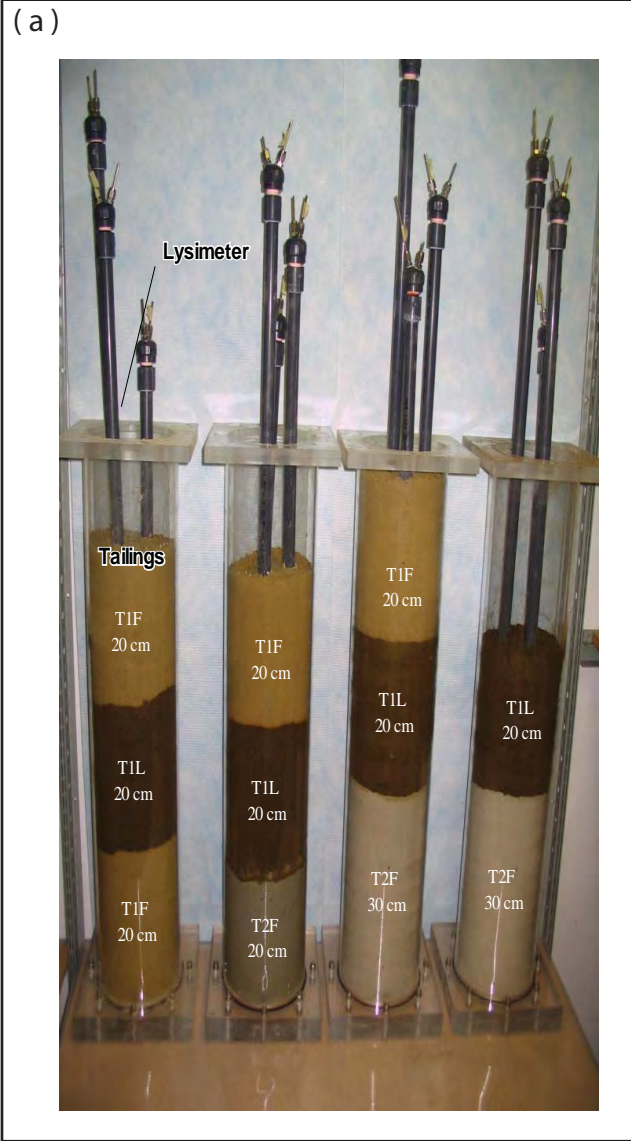
Tailings Layers

- ① - Neutral tailings (T1F)
 - ② - Acidic tailings (T1L)
 - ③ - Neutral tailings
- Options a) oxidized (T1F)
 b) non-oxidized (T2F)


Column Dimensions:
 0.75m long x 0.15 m diam.

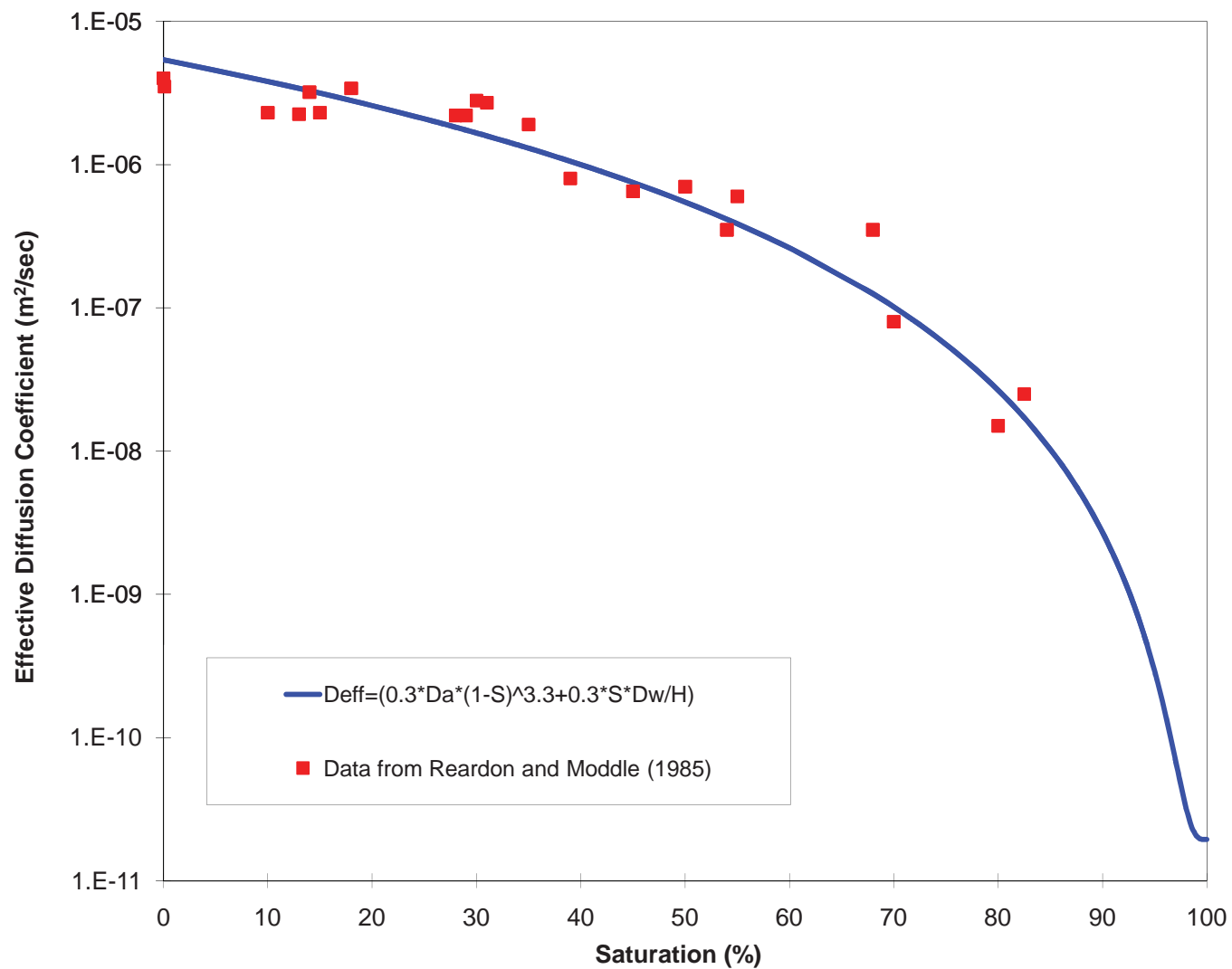
(a) Schematic (b) Column, tailings layers, and lysimeters.

MEND Tailings Encapsulation		
Schematic of Column Design with Layered Tailings		
	October 2010	Figure 2.1



(a) Before tests (b) After tests

MEND Tailings Encapsulation		
Four Columns Loaded Showing Tailings and Lysimeters Installed		
	October 2010	Figure 2.2



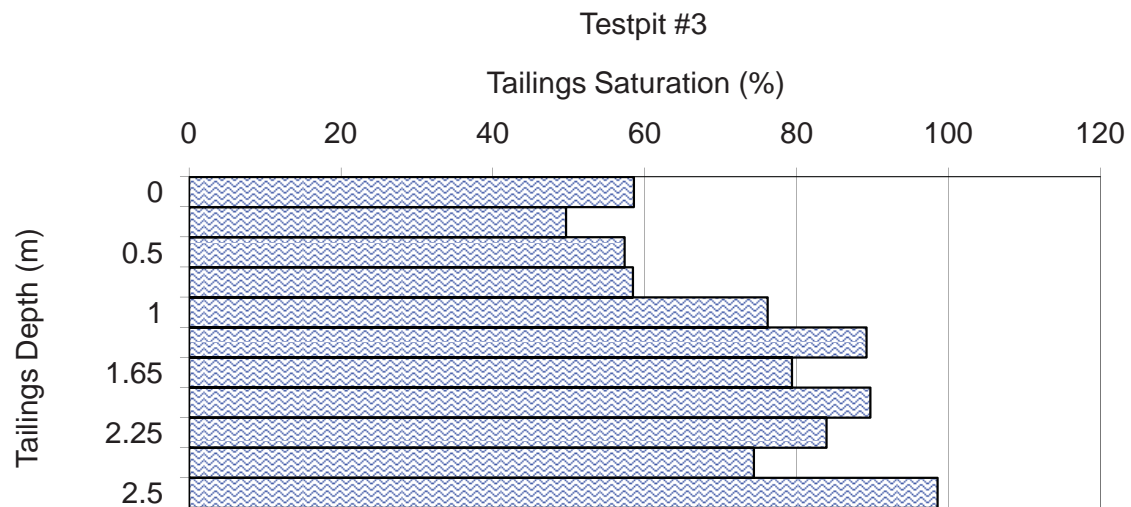
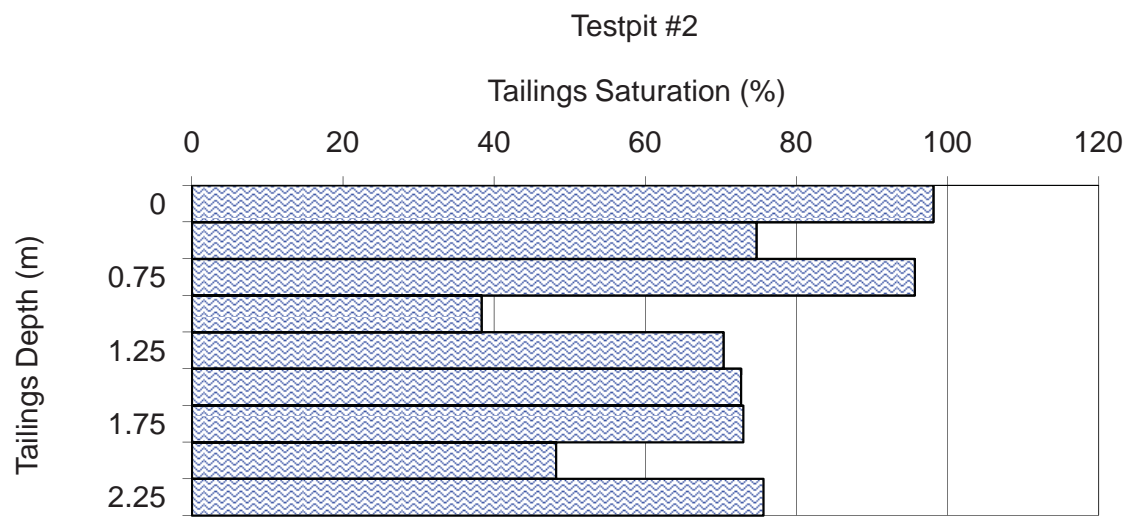
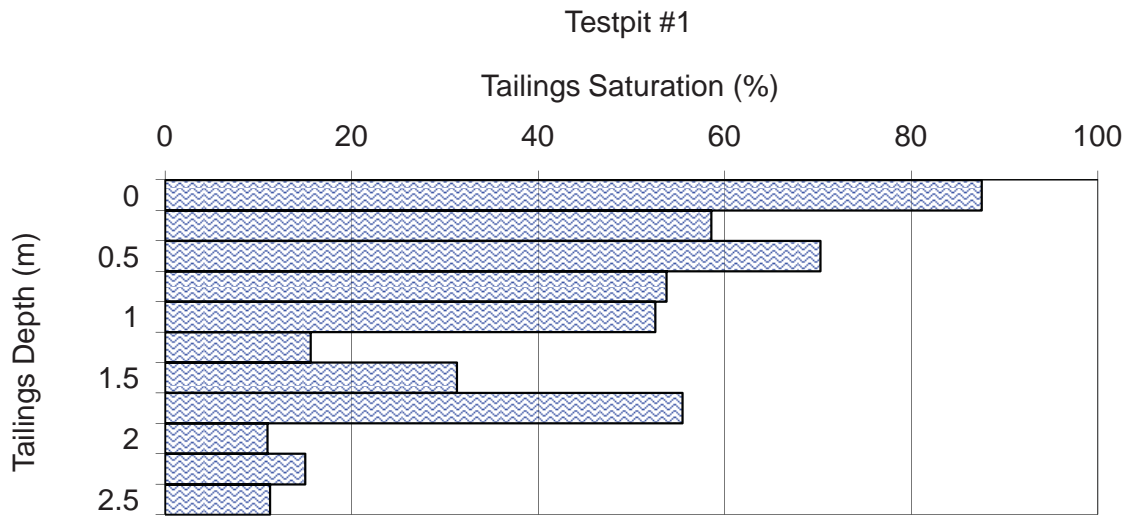
MEND Tailings Encapsulation


Plot of Effective Diffusion Coefficient for Oxygen in Tailings as a Function of Degree of Saturation (from Elberling *et al.*, 1994a)



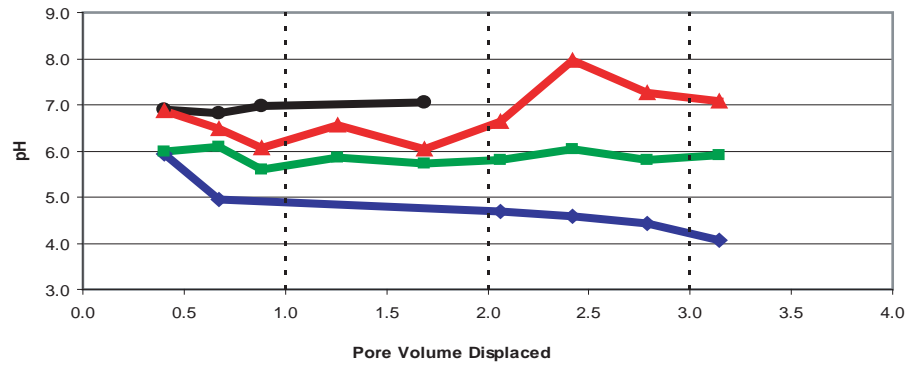
October 2010

Figure 2.3

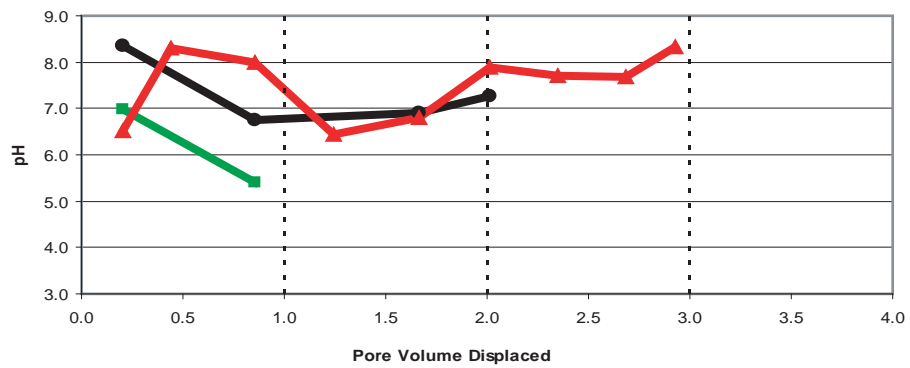


MEND Tailings Encapsulation		
Saturation Profiles from Three Test Pits on the T1 Tailings Sampled October 2004		
 EcoMetrix INCORPORATED	October 2010	Figure 2.4

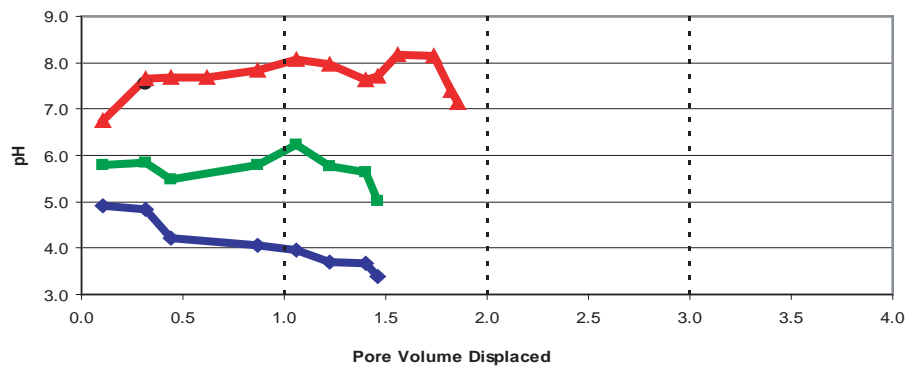
(a) Column 1



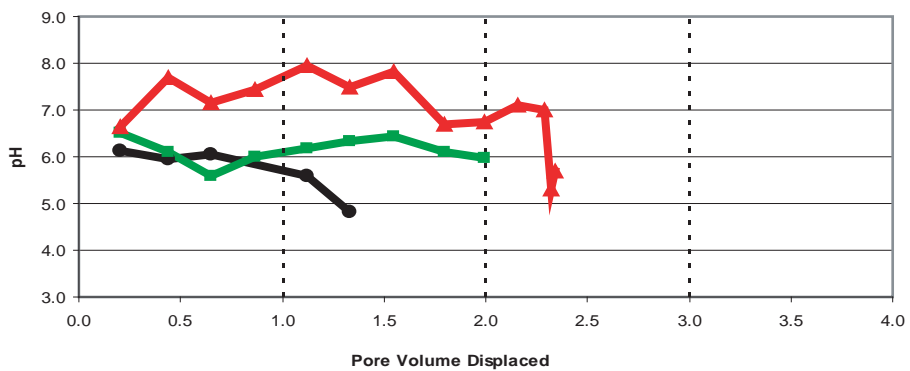
(b) Column 2



(c) Column 3



(d) Column 4



- Top
- ◆ Middle
- Bottom
- ▲ Drain

MEND Tailings Encapsulation

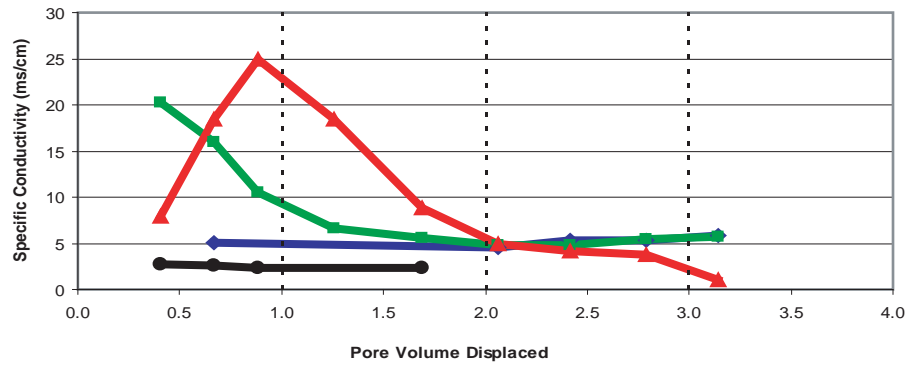
Comparison of the pH in Lysimeter and Drain Samples



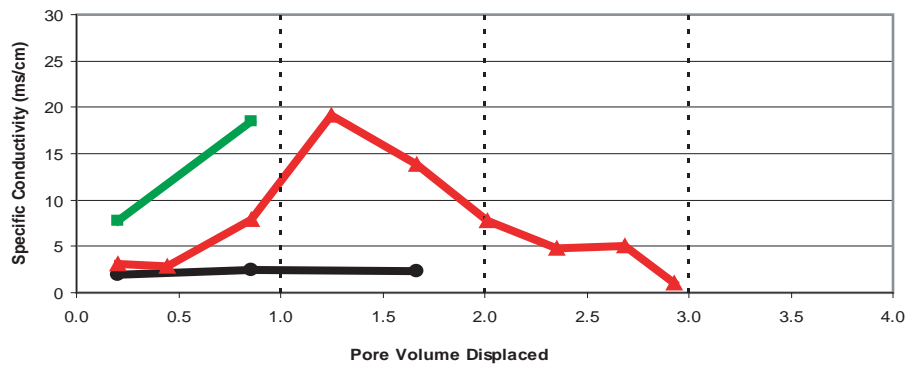
October 2010

Figure 3.1

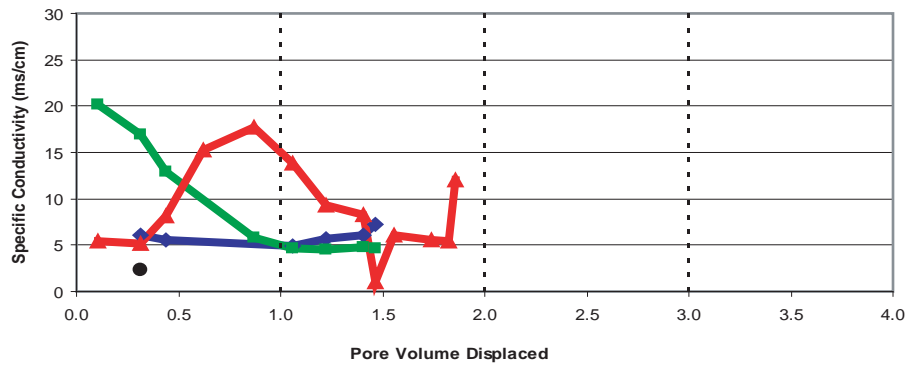
(a) Column 1



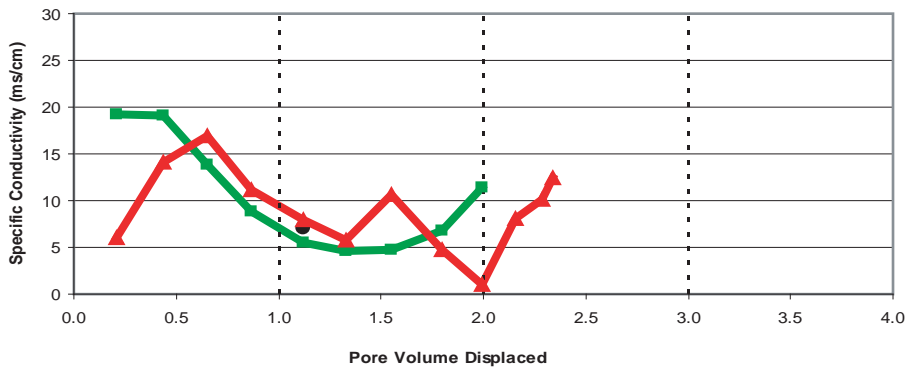
(b) Column 2



(c) Column 3



(d) Column 4



- Top
- ◆ Middle
- Bottom
- ▲ Drain

MEND Tailings Encapsulation

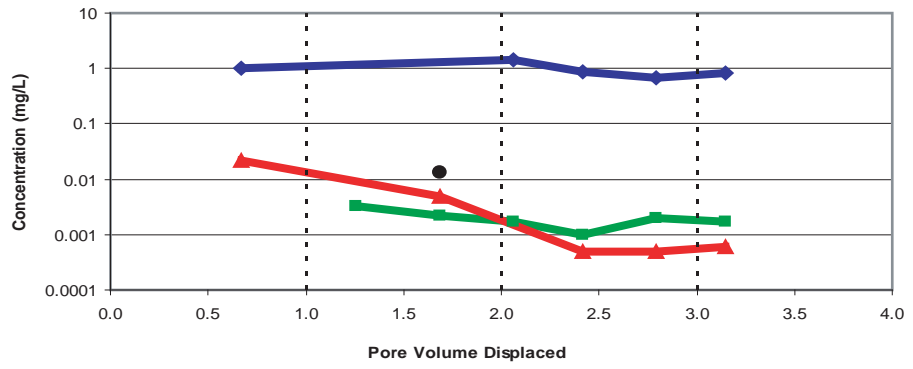
Comparison of the Specific Conductivity in Lysimeter and Drain Samples



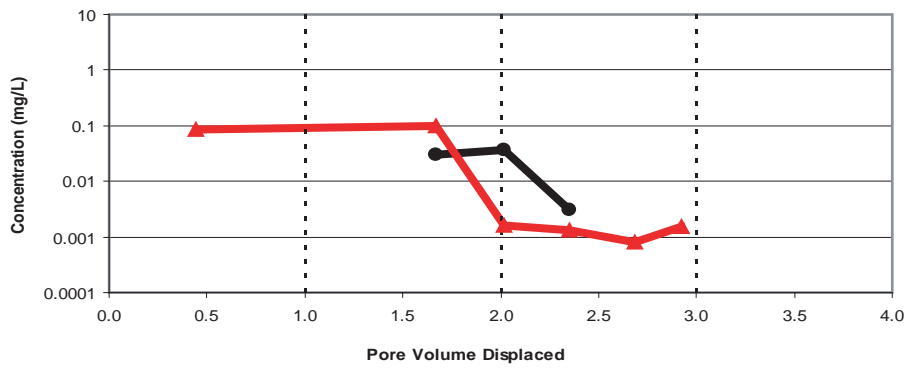
October 2010

Figure 3.2

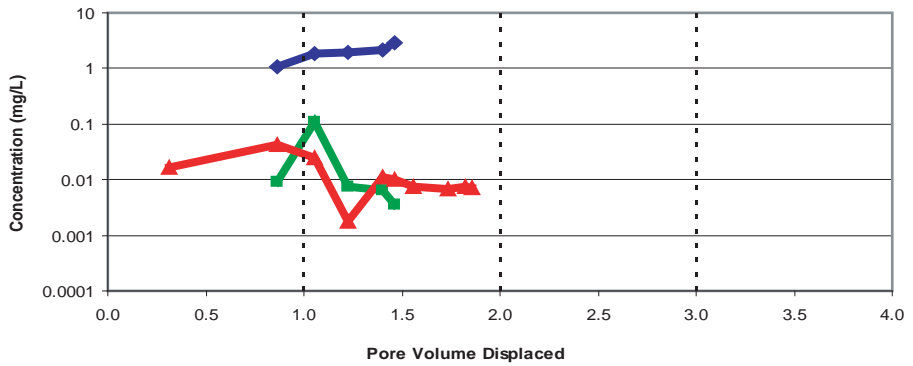
(a) Column 1



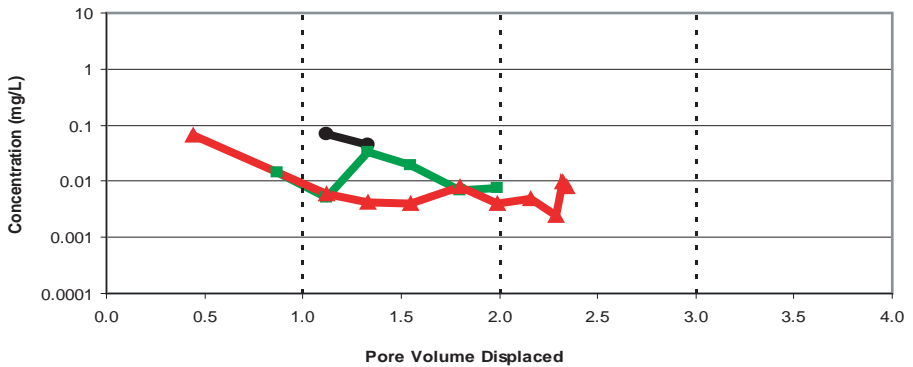
(b) Column 2



(c) Column 3



(d) Column 4



- Top
- ◆ Middle
- Bottom
- ▲ Drain

MEND Tailings Encapsulation

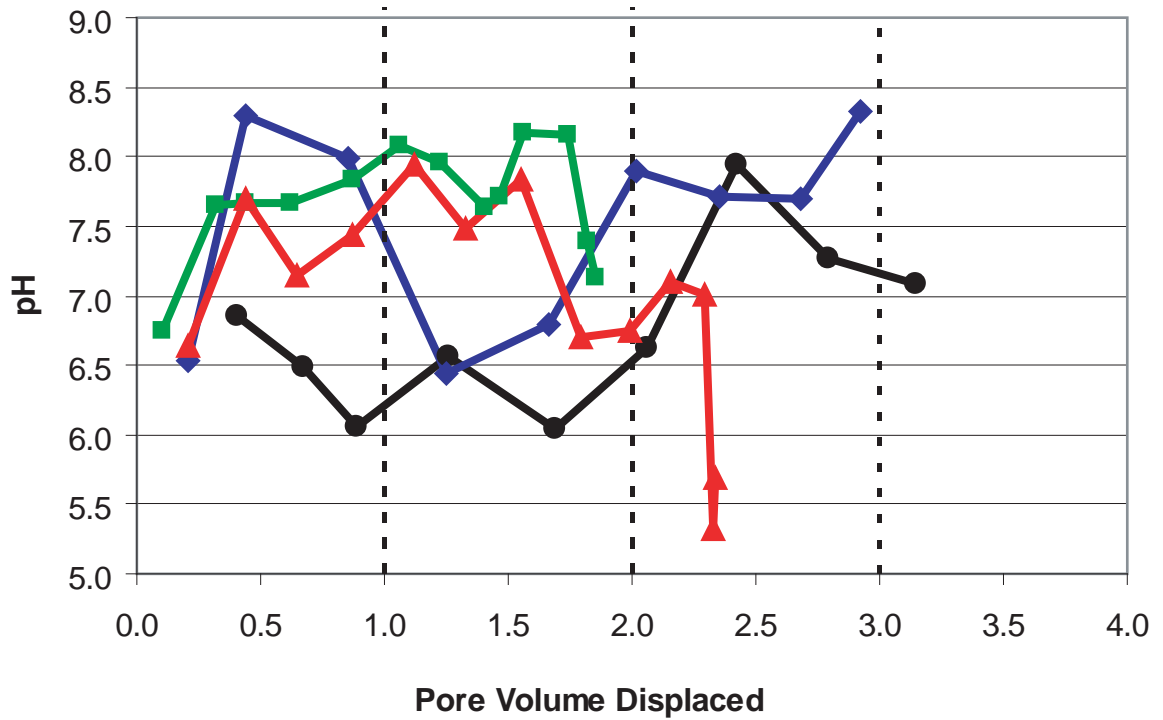
Arsenic Concentrations in Lysimeter and Drain Samples



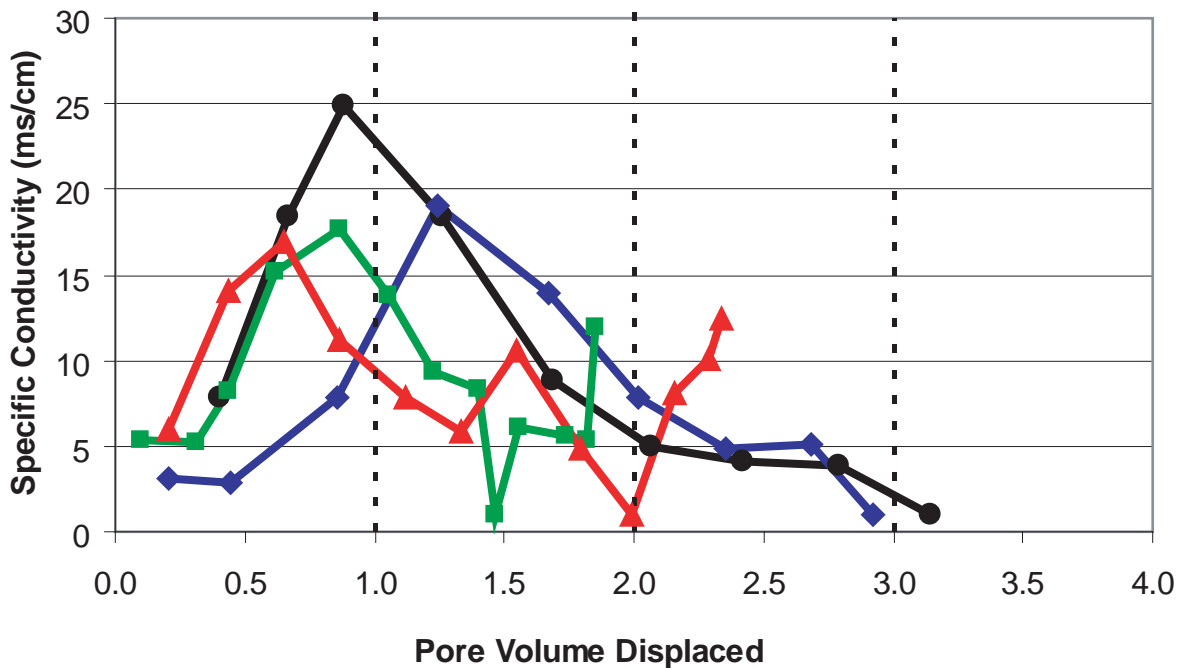
October 2010

Figure 3.3

(a) pH



(b) Specific Conductivity



- Column 1
- ◆ Column 2
- Column 3
- ▲ Column 4

MEND Tailings Encapsulation

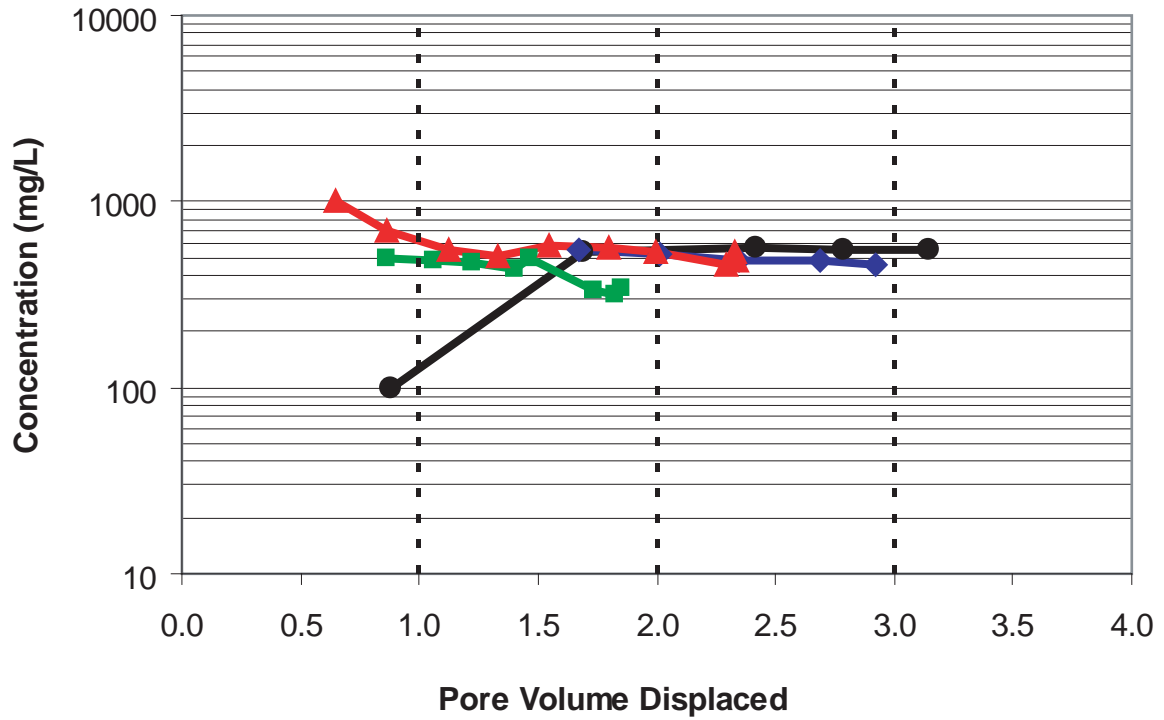
Comparison of the pH and Specific Conductivity Trends in Column Drainage Samples



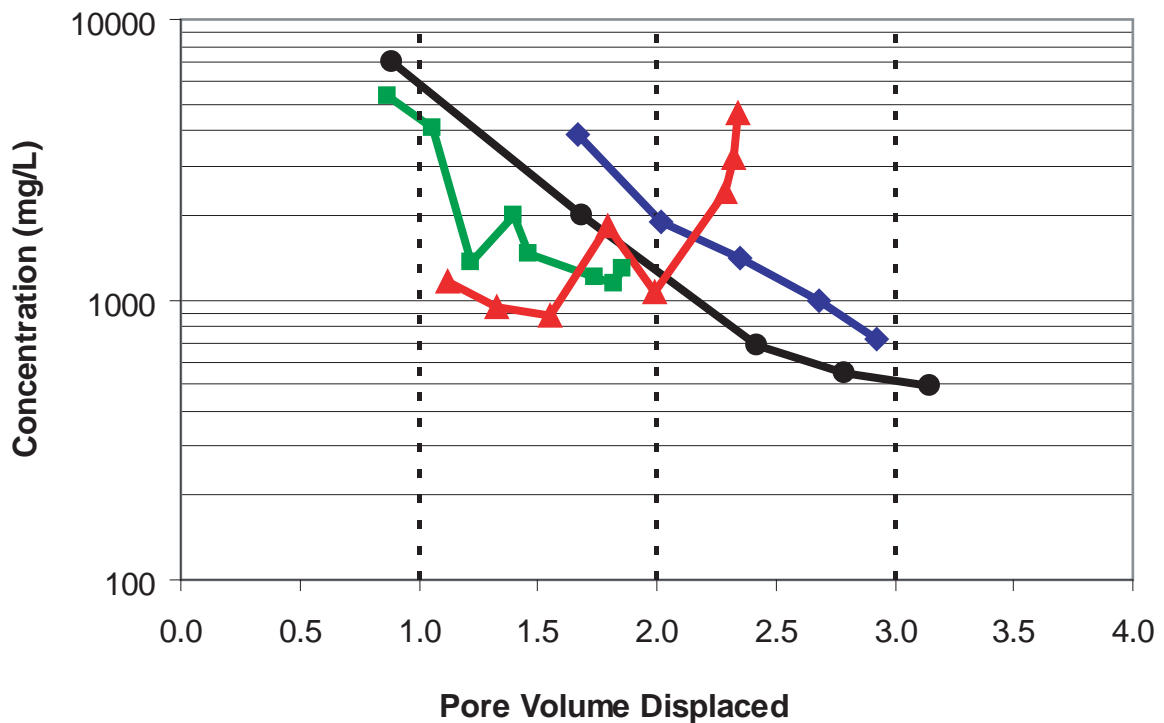
October 2010

Figure 3.4

(a) Calcium



(b) Magnesium



- Column 1
- ◆ Column 2
- Column 3
- ▲ Column 4

MEND Tailings Encapsulation

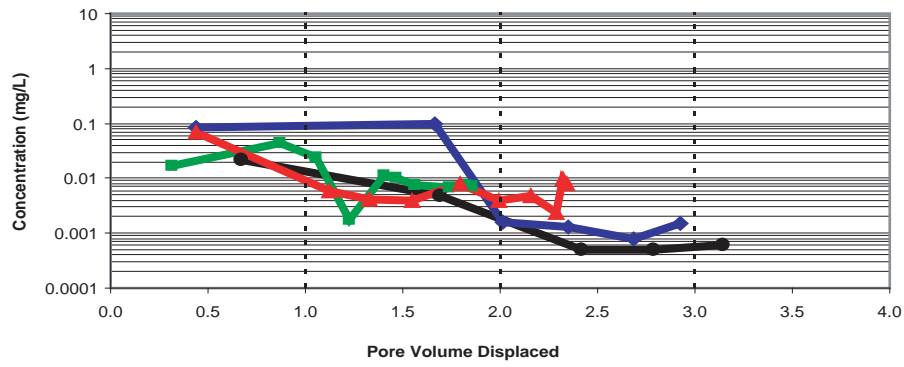
Concentration of Calcium and Magnesium
in Column Drainage Samples



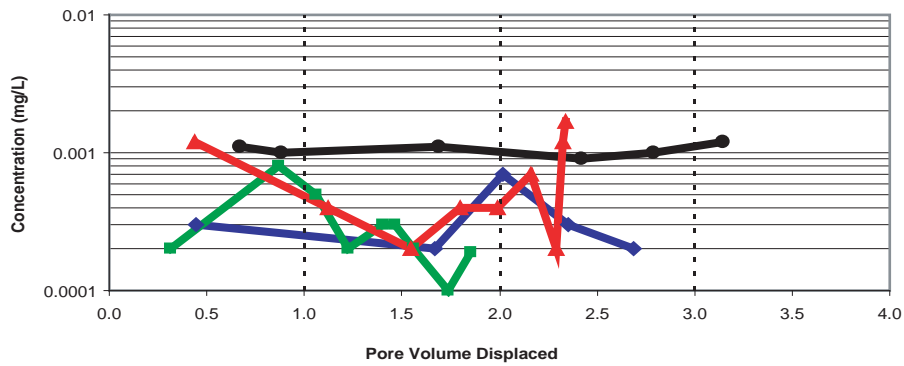
October 2010

Figure 3.5

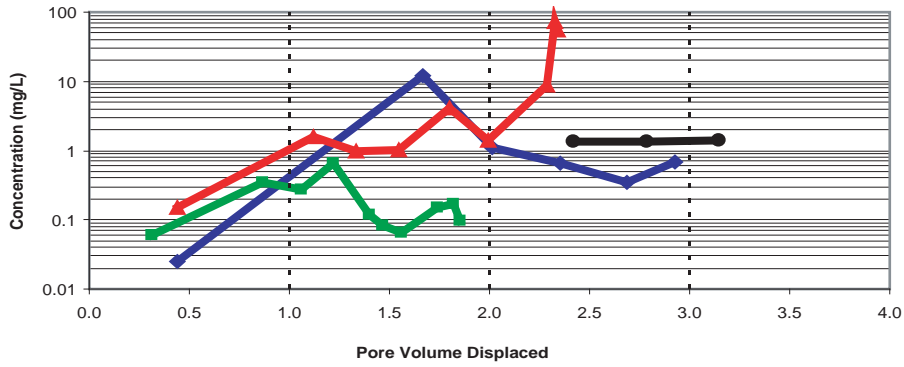
(a) Arsenic



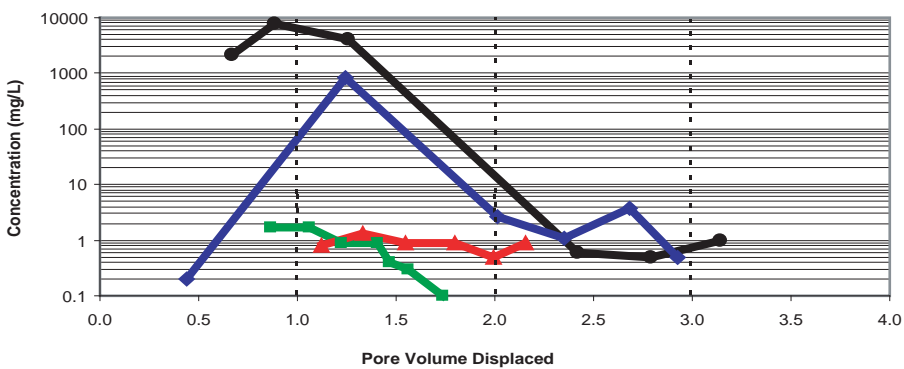
(b) Cadmium



(c) Cobalt



(d) Iron



- Column 1
- ◆ Column 2
- Column 3
- ▲ Column 4

MEND Tailings Encapsulation

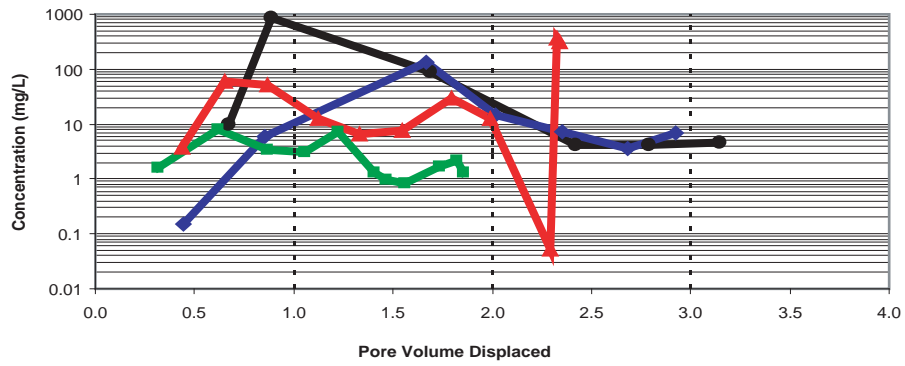
Concentrations of Select Constituents
in Column Drainage Samples



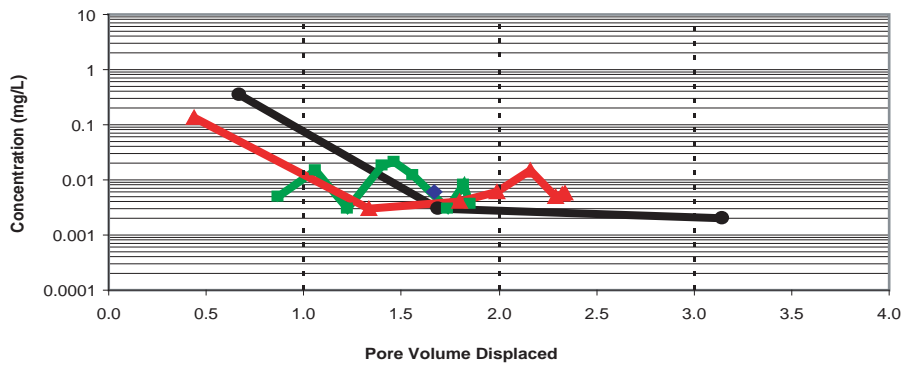
October 2010

Figure 3.6

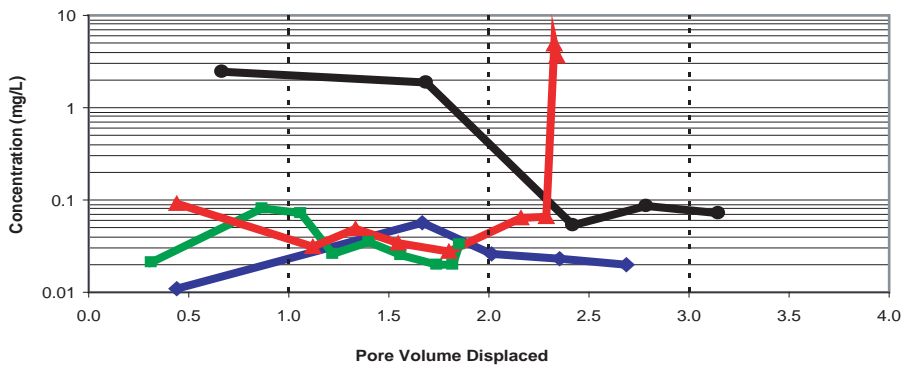
(a) Nickel



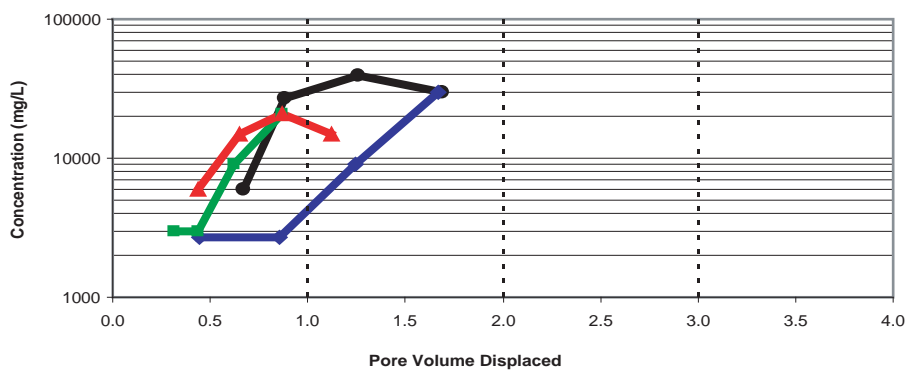
(b) Selenium



(c) Zinc



(d) Sulphate



- Column 1
- ◆ Column 2
- Column 3
- ▲ Column 4

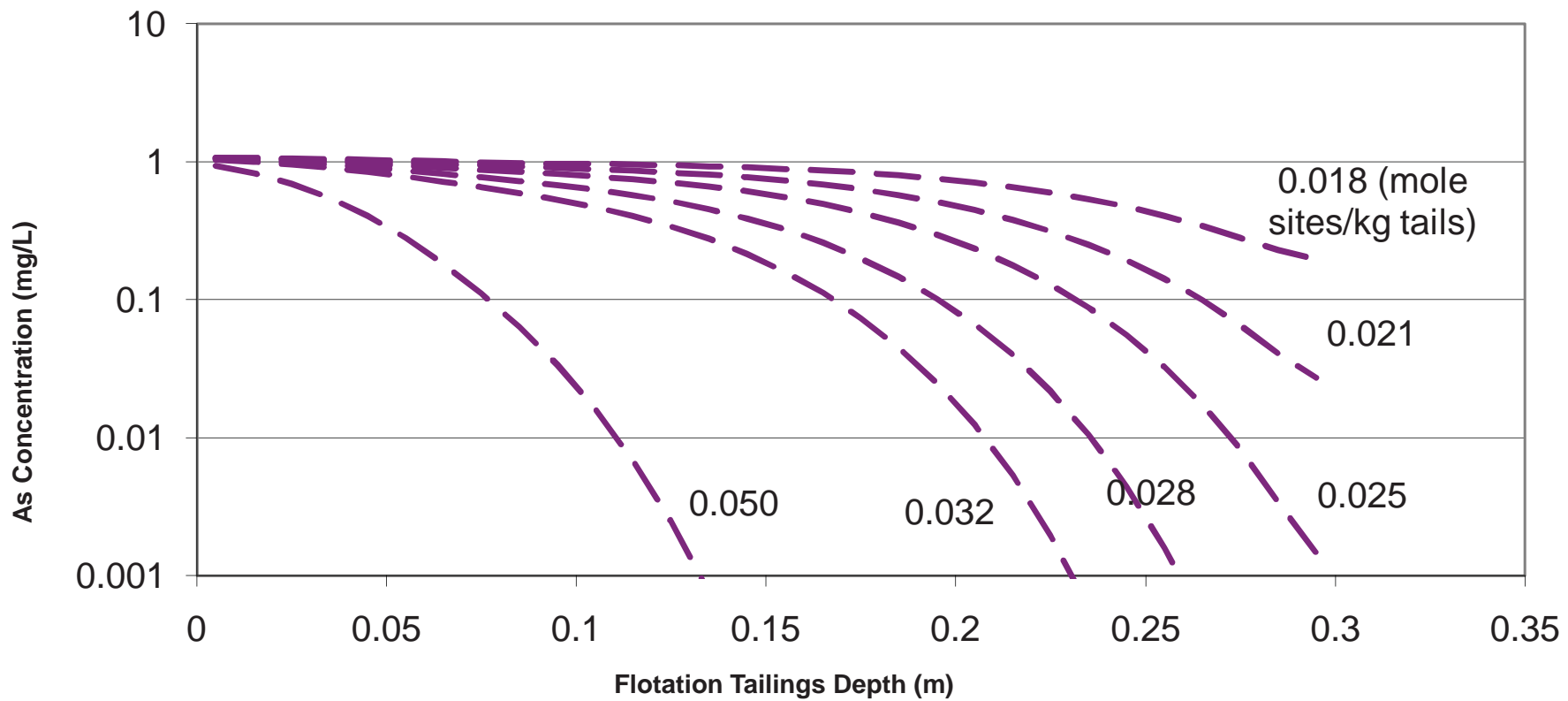
MEND Tailings Encapsulation


Concentrations of Select Constituents
in Column Drainage Samples

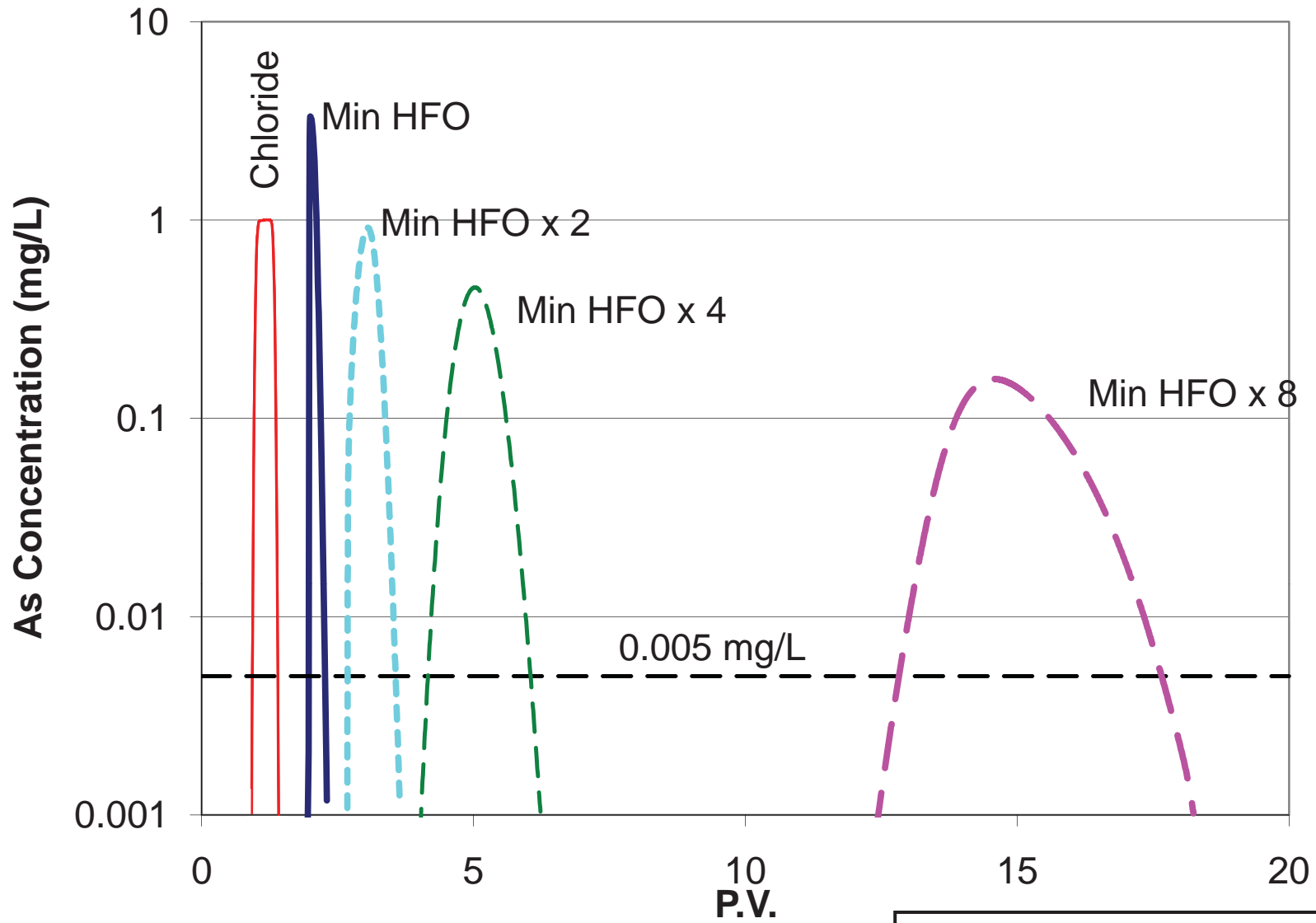



October 2010

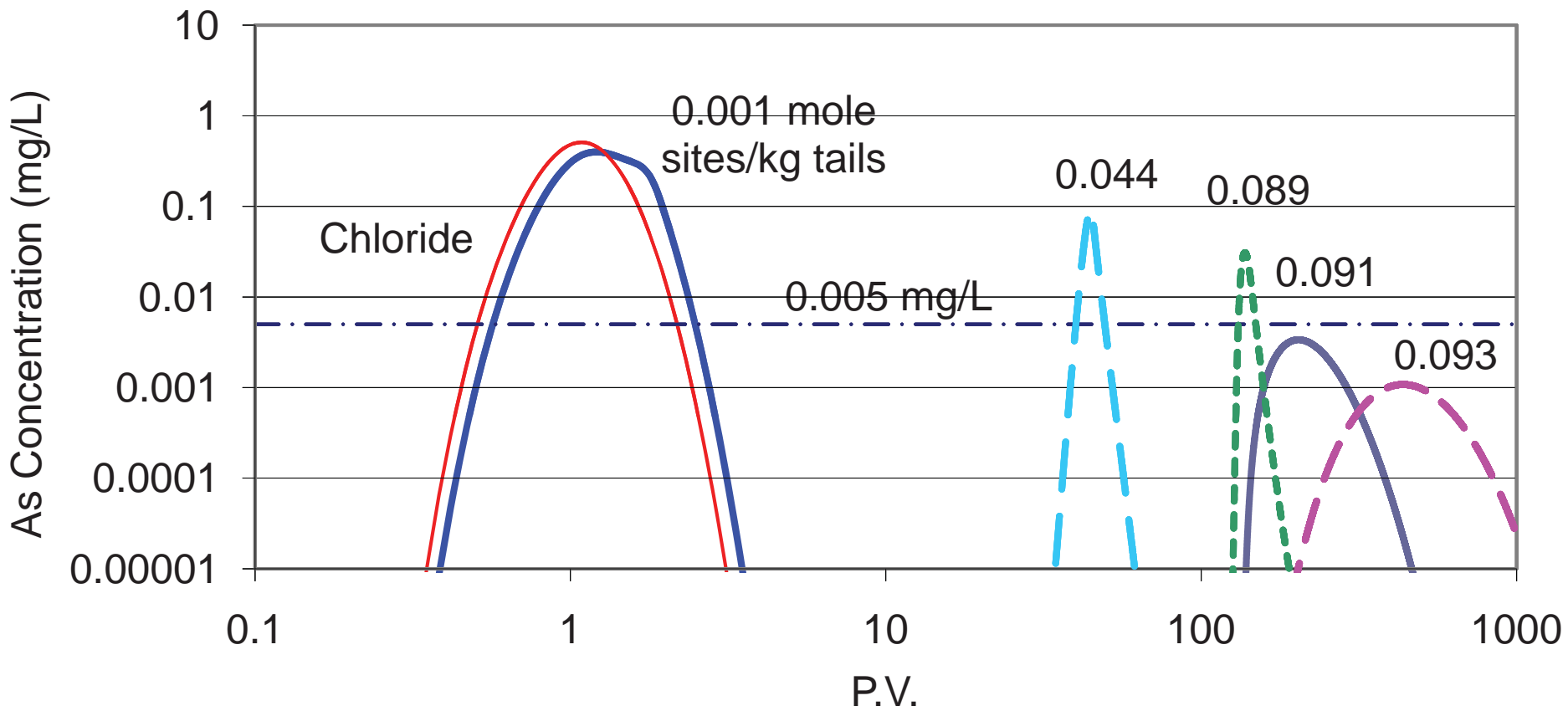
Figure 3.7




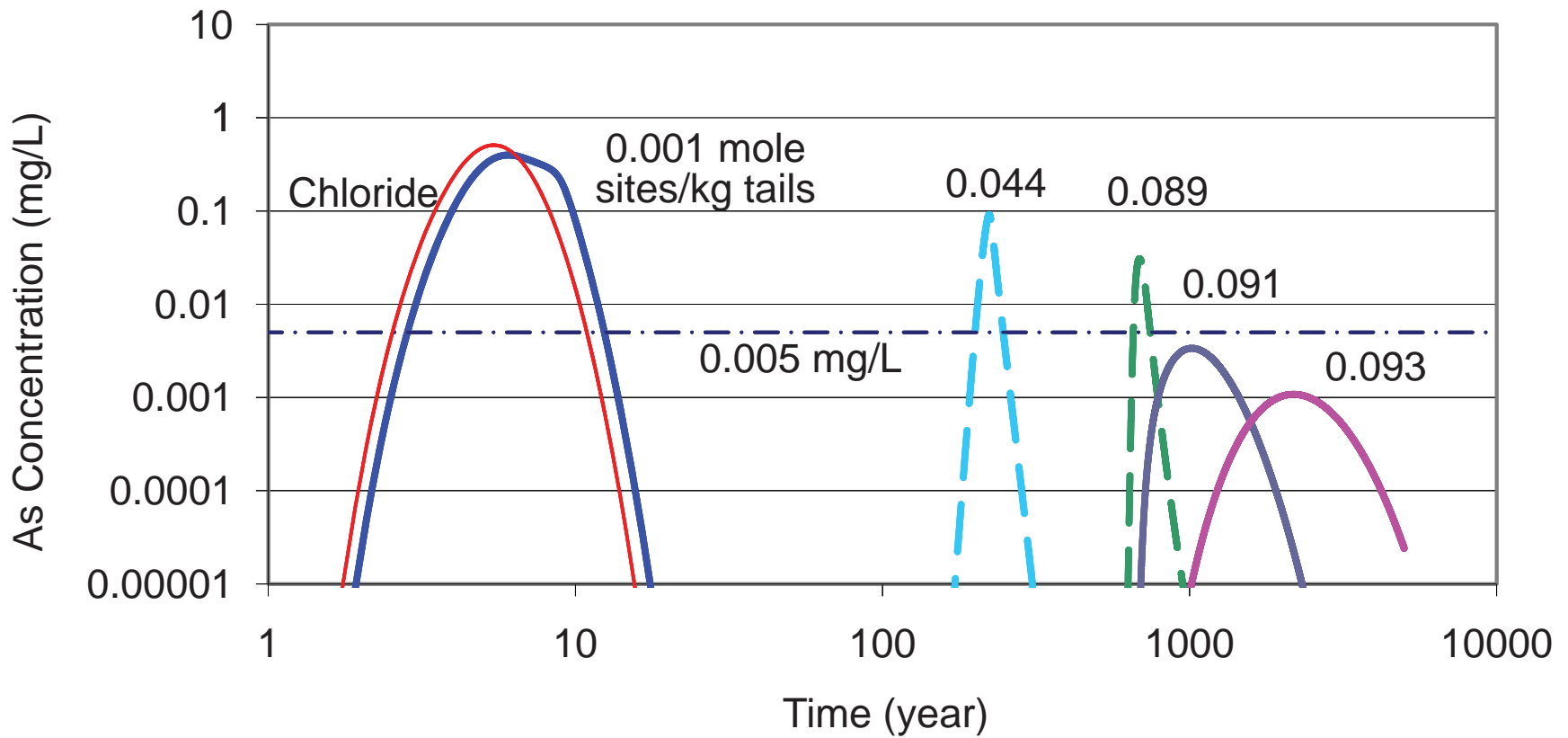
MEND Tailings Encapsulation		
Predicted Arsenic Concentration Profiles in the Bottom Layer of Column 3		
	October 2010	Figure 3.8



MEND Tailings Encapsulation		
Predicted Arsenic Concentrations as a Function of Effluent Pore Volume		
	October 2010	Figure 3.9



MEND Tailings Encapsulation		
Predicted Arsenic Concentration as a Function of Pore Volume at the Base of T2 in the Field		
	November 2010	Figure 3.10



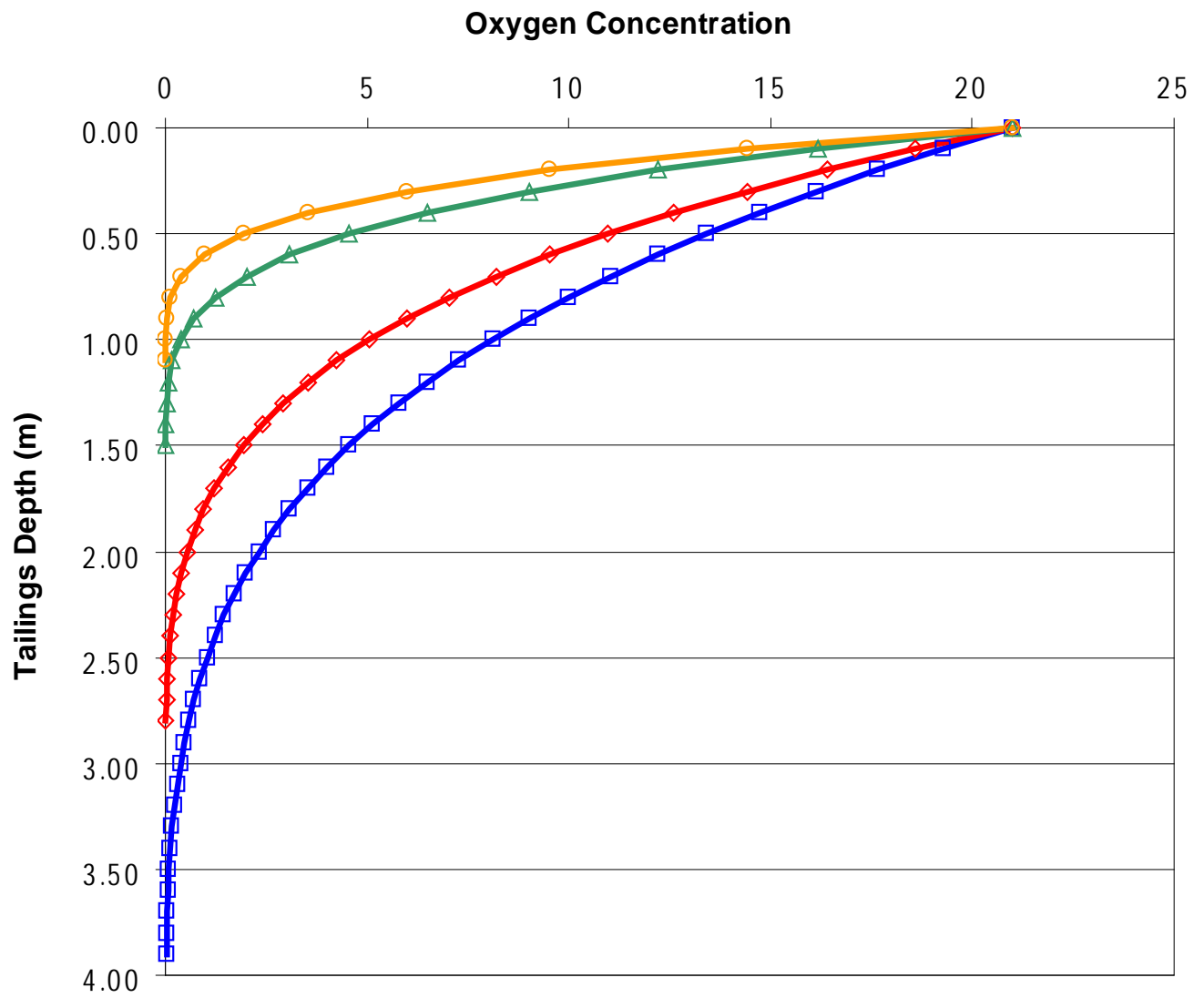
MEND Tailings Encapsulation

Predicted Arsenic Concentration versus Time at the Base of T2 in the Field




October 2010

Figure 3.11



- Sat = 50%; %S2- = 0.5%
- ▲ Sat = 70%; %S2- = 0.5%
- ◆ Sat = 50%; %S2- = 1.0%
- Sat = 70%; %S2- = 1.0%

MEND Tailings Encapsulation		
Calculated Oxygen Concentrations in Flotation Tailings with Depth from Surface		
	October 2010	Figure 3.12



APPENDIX A

Analyses of ABA and Elements in Solids

Final Report
Activation Laboratories

Solid Content	Units	T1-LEACH	T1-FLOAT	T2-FLOAT
		UT-3	UT-3	UT-3
Aluminum (Al)	%	1.17	2.97	3.92
Antimony (Sb)	ppm	34.8	<0.1	0.5
Arsenic (As)	ppm	6120	146	103
Barium (Ba)	ppm	113	427	580
Beryllium (Be)	ppm	0.4	0.8	1.2
Bismuth (Bi)	ppm	5.8	0.3	0.3
Bromine (Br)	ppm	<0.5	<0.5	<0.5
Cadmium (Cd)	ppm	3.7	0.3	<0.1
Calcium (Ca)	%	2.99	3.44	3.42
Cerium (Ce)	ppm	33	48	50
Cesium (Cs)	ppm	0.36	0.88	1.32
Chromium (Cr)	ppm	157	233	411
Cobalt (Co)	ppm	412	14	13
Copper (Cu)	ppm	1700	25.3	15.7
Dysprosium (Dy)	ppm	1.6	1.5	1.5
Erbium (Er)	ppm	1	0.9	1.1
Europium (Eu)	ppm	<0.2	0.9	1.3
Gadolinium (Gd)	ppm	2.3	2.7	2.5
Gallium (Ga)	ppm	5.8	17	21.5
Germanium (Ge)	ppm	0.3	<0.1	0.1
Gold (Au)	ppm	1.97	0.208	0.17
Hafnium (Hf)	ppm	1	<1	2
Holmium (Ho)	ppm	0.3	0.3	0.3
Indium (In)	ppm	0.3	<0.1	<0.1
Iridium (Ir)	ppb	<5	<5	<5
Iron (Fe)	%	21.8	3.58	4.69
Lanthanum (La)	ppm	12.5	17.5	15.8
Lead (Pb)	ppm	139	8.3	6.8
Lithium (Li)	ppm	2.5	7.6	21.2
Lutetium (Lu)	ppm	<0.05	0.32	0.39
Magnesium (Mg)	%	2.07	2.33	3.52
Manganese (Mn)	ppm	198	863	999
Mercury (Hg)	ppm	<1	<1	<1
Molybdenum (Mo)	ppm	25	2	3
Neodymium (Nd)	ppm	<5	34	12
Nickel (Ni)	ppm	1290	84.2	125
Niobium (Nb)	ppm	1.8	3.4	3.2
Phosphorus (P)	%	0.03	0.051	0.039
Potassium (K)	%	0.52	1.71	2.06
Praseodymium (Pr)	ppm	4.1	4.7	4.4
Rhenium (Re)	ppm	0.013	0.002	0.001
Rubidium (Rb)	ppm	15.6	39.6	52.3
Samarium (Sm)	ppm	3.3	3.5	3.8
Scandium (Sc)	ppm	8.3	16.7	25.7
Selenium (Se)	ppm	22	1.3	1.3
Silver (Ag)	ppm	4.2	0.2	0.18
Sodium (Na)	%	0.48	1.85	1.64
Strontium (Sr)	ppm	48.8	128	131
Sulphur (S)	%	> 20.0	0.26	0.15
Tantalum (Ta)	ppm	<0.1	0.2	0.1
Tellurium (Te)	ppm	11.2	0.8	0.6
Terbium (Tb)	ppm	<0.5	<0.5	<0.5
Thallium (Tl)	ppm	0.47	0.44	0.55
Thorium (Th)	ppm	6.7	3.5	4
Thulium (Tm)	ppm	0.1	0.1	0.1
Tin (Sn)	ppm	2	<1	<1
Titanium (Ti)	%	0.19	0.32	0.35
Tungsten (W)	ppm	11	13	12
Uranium (U)	ppm	2.8	0.9	1.1
Vanadium (V)	ppm	64	140	218
Ytterbium (Yb)	ppm	<0.2	1.8	2.1
Yttrium (Y)	ppm	6.9	6.2	6.3
Zinc (Zn)	ppm	881	50.3	60.3
Zirconium (Zr)	ppm	71	85	79
ABA Testing				
Paste pH	---	2.65	7.08	8.29
CO ₂	%	0.35	5.95	6.21
Total Sulphur	%	27.91	0.30	0.24
Sulphate Sulphur	%	2.56	0.30	0.24
Sulphide Sulphur	%	25.36	< 0.01	< 0.01
Neutralization Potential	kg CaCO ₃ /t	-14.48	76.08	103.07
Acid Generating Potentia	kg CaCO ₃ /t	792.36	0.00	0.00
Net Neutralization Potenti	kg CaCO ₃ /t	-806.84	76.08	103.07
Ratio (NP:AP)	---	-0.02	----	----



APPENDIX B
Analyses of Shake Flask Leachate

Shake Flask Results																
	T1 Float (1)	T1 Float (2)	T1 Float (3)	T1 Float (4)	T1 Float (5)	T1 Leach (1)	T1 Leach (2)	T1 Leach (3)	T1 Leach (4)	T1 Leach (5)	T2 Float (1)	T2 Float (2)	T2 Float (3)	T2 Float (4)	T2 Float (5)	
Units																
Paste pH	---	7.48	7.74	7.56	7.85	7.84	3.94	4.16	4.00	4.00	3.82	7.37	7.52	7.41	7.43	7.52
Paste Conductivity	mS	0.65	0.77	0.74	0.66	0.72	6.46	8.73	7.73	8.11	6.98	0.66	0.63	0.68	0.63	0.66
Shake Flask Lab Results																
pH	---	7.04	7.38	7.33	7.51	7.56	4.74	4.21	5.06	3.07	3.35	7.53	7.62	7.48	7.54	7.52
Conductivity	mS	1.72	1.56	1.88	1.63	1.69	6.30	6.10	5.90	7.62	5.54	0.67	0.65	0.74	0.66	0.70
Acidity as CaCO3	mg/L	10.4	11.2	10.4	9.6	6.8	2510	4780	3200	3750	3500	16.8	10.4	8.8	12.4	17.2
Dissolved Silver (Ag)	mg/L	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.005	0.100	<0.05	<0.05	<0.005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Dissolved Aluminum (Al)	mg/L	0.006	0.014	0.008	0.017	0.058	12.0	20.0	0.500	2.10	0.270	0.018	0.021	0.020	0.025	0.023
Dissolved Arsenic (As)	mg/L	0.003	0.002	0.004	0.002	0.004	5.80	1.70	2.00	1.20	0.830	0.024	0.028	0.014	0.014	0.024
Dissolved Barium (Ba)	mg/L	0.015	0.028	0.014	0.014	0.015	<0.05	<0.5	<0.5	<0.5	<0.05	0.029	0.027	0.036	0.037	0.032
Dissolved Boron (B)	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.1	<1	<1	<1	<0.1	0.051	0.049	0.056	0.034	0.056
Dissolved Beryllium (Be)	mg/L	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.005	<0.05	<0.05	<0.05	<0.005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Dissolved Bismuth (Bi)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Dissolved Calcium (Ca)	mg/L	300	270	350	290	320	450	440	430	520	510	77.0	73.0	88.0	80.0	83.0
Dissolved Cadmium (Cd)	mg/L	0.0001	<0.0001	0.0002	<0.0001	<0.0001	0.190	0.079	0.029	0.054	0.033	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Dissolved Cobalt (Co)	mg/L	0.0029	0.0019	0.0042	0.0017	0.0030	11.0	13.0	9.40	12.0	9.70	0.010	0.008	0.012	0.0015	0.0011
Dissolved Chromium (Cr)	mg/L	<0.005	0.007	<0.005	<0.005	<0.005	<0.05	<0.5	<0.5	<0.5	<0.05	<0.005	<0.005	<0.005	<0.005	<0.005
Dissolved Copper (Cu)	mg/L	0.002	0.002	<0.001	0.002	0.003	6.60	20.0	<0.1	0.540	0.200	0.001	0.001	0.001	<0.001	0.002
Dissolved Iron (Fe)	mg/L	0.079	<0.05	<0.05	<0.05	0.240	1300	2300	1300	2000	1800	<0.05	0.081	<0.05	0.065	0.140
Dissolved Potassium (K)	mg/L	5.30	5.00	5.10	5.10	5.40	<2	<20	<20	<20	<2	9.70	8.90	11.0	8.40	10.0
Dissolved Lithium (Li)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005	<0.05	<0.5	<0.5	<0.5	<0.05	<0.005	<0.005	<0.005	<0.005	<0.005
Dissolved Magnesium (Mg)	mg/L	79	71	82	79	82	190	250	350	320	340	39	33	47	39	42
Dissolved Manganese (Mn)	mg/L	0.061	0.027	0.140	0.018	0.042	13	13	20	19	20	0.11	0.077	0.190	0.190	0.130
Dissolved Molybdenum (Mo)	mg/L	0.008	0.008	0.007	0.008	0.008	<0.01	<0.1	<0.1	<0.1	<0.01	0.073	0.079	0.041	0.020	0.056
Dissolved Sodium (Na)	mg/L	6.7	6.2	6.7	6.8	7.3	2.4	<10	<10	<10	<10	3.3	5.4	6.9	6.2	6.5
Dissolved Nickel (Ni)	mg/L	0.017	0.012	0.022	0.009	0.015	38	46	34	50	39	0.027	0.021	0.044	0.041	0.034
Dissolved Lead (Pb)	mg/L	0.0012	0.0009	0.0011	0.0008	0.0013	0.018	<0.05	<0.05	<0.05	<0.005	0.0017	0.0011	0.0006	0.0008	0.0009
Dissolved Phosphorus (P)	mg/L	<0.05	<0.05	0.130	0.110	<0.05	<0.5	<5	<5	<5	<0.5	<0.05	<0.05	0.110	0.100	0.120
Dissolved Antimony (Sb)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	0.005	0.005	0.005	0.005	0.005
Dissolved Selenium (Se)	mg/L	<0.002	<0.002	0.005	<0.002	<0.002	<0.02	<0.2	<0.2	<0.2	<0.02	<0.002	<0.002	<0.002	<0.002	<0.002
Dissolved Silicon (Si)	mg/L	2.7	2.2	2.8	2.2	2.5	11	15	5.1	13	8.4	3.6	3.5	3.8	3.6	3.9
Dissolved Tin (Sn)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Sulphate	mg/L	1273	1115	1457	1205	1287	6378	9540	6611	6985	6918	225	201	260	201	253
Dissolved Strontium (Sr)	mg/L	0.420	0.380	0.450	0.400	0.430	0.910	1.20	1.10	1.20	1.20	0.320	0.280	0.370	0.260	0.330
Dissolved Tellurium (Te)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Dissolved Thorium (Th)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Dissolved Titanium (Ti)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005	<0.05	<0.5	<0.5	<0.5	<0.05	<0.005	<0.005	<0.005	<0.005	<0.005
Dissolved Thallium (Tl)	mg/L	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.0005	<0.005	<0.005	<0.005	<0.0005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Dissolved Uranium (U)	mg/L	0.0020	0.0015	0.0019	0.0015	0.0018	0.016	0.042	<0.01	<0.01	<0.001	0.0015	0.0014	0.0016	0.0020	0.0016
Dissolved Vanadium (V)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Dissolved Tungsten (W)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Dissolved Zinc (Zn)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005	54	66	42	77	57	<0.005	<0.005	<0.005	0.037	0.019
Dissolved Zirconium (Zr)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.1	<0.1	<0.1	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001



APPENDIX C

Analyses of Column Drainage Samples

Elemental Analysis of the Columns Drainage

			As ug/L	Ca ug/L	Cd ug/L	Co ug/L	Fe ug/L	Mg ug/L	Ni ug/L	Se ug/L	Zn ug/L	Na ug/L	Cu ug/L	Li ug/L	Be ug/L	Al ug/L	Si ug/L	K ug/L	Sc ug/L	Ti ug/L	V ug/L	Cr ug/L	
		Day from Start of test	Pore Volume Displaced																				
Col 1- Drainage		6																					
		14	0.46																				
		24	0.76	21.6	> 200000	1.1	> 2000	2196000	> 200000	10000	358	2430	116000	< 2	180	< 1	< 20	11000	76800	< 10	7	< 1	< 5
		41	1.00	< 30	98100	1	> 2000	7780000	7100000	876000	< 2	> 2500	45300	3	638	< 1	< 20	9000	69700	< 10	7	< 30	< 30
		58	1.42	< 1				4040000			< 5			< 1									
		103	1.91	4.9	529000	1.1	> 2000	> 100000	2010000	88300	3	1870	55300	< 2	310	< 1	20	9000	23400	< 10	2	< 1	< 5
		134	2.74	0.5	562000	0.9	1340	600	683000	4270	< 2	54	28600	< 2	180	< 1	< 20	8000	12300	< 10	2	2	< 5
		167	3.15	0.5	557000	1	1330	500	548000	4180	< 2	85	21700	< 2	170	< 1	< 20	7000	10700	< 10	2	< 1	< 5
		167	3.56	0.6	556000	1.2	1380	1000	495000	4690	73	17600	< 2	160	< 1	< 20	7000	7500	< 10	2	< 1	< 5	
Col 2- Drainage		6	0.18	< 1			< 0.5	< 50		< 2	< 3		< 1										
		14	0.38	86.4	> 200000	0.3	25.1	200	> 200000	150	< 2	11	74400	< 2	< 10	< 1	< 20	10000	67100	< 10	2	< 1	< 5
		24	0.74				< 0.5	40000		6000.00		< 3		< 1									
		41	1.07	< 1				820000				< 3		< 1									
		58	1.44	100	544000	0.2	12200	> 100000	3910000	133000	6	56	66000	< 2	210	< 1	< 20	23000	88800	< 10	7	< 1	< 5
		80	1.74	1.6	528000	0.7	1110	2700	1890000	14800	< 2	26	57400	< 2	150	< 1	< 20	17000	47900	< 10	3	< 1	< 5
		103	2.03	1.3	481000	0.3	671	1100	1410000	7420	< 2	23	57300	< 2	130	< 1	40	17000	37400	< 10	4	< 1	< 5
		167	2.52	0.8	480000	0.2	351	3700	992000	3670	< 2	20	45100	< 2	110	< 1	< 20	14000	26300	< 10	4	< 1	< 5
Col 3- Drainage		6	0.10	< 1			< 0.5	< 50		< 2	< 3		< 1										
		14	0.31	16.7	> 200000	0.2	60.8	< 100	> 200000	1630	< 2	21	115000	< 2	10	< 1	< 20	17000	88700	< 10	5	< 1	< 5
		24	0.43											< 1									
		41	0.61	< 1						8000		< 3		< 1									
		58	0.85	42.8	501000	0.8	344	1700	5310000	3460	5	81	96400	3	20	< 1	30	16000	175000	< 10	9	3	< 5
		80	1.04	24.3	488000	0.5	279	1700	4130000	3040	15	71	84700	3	20	< 1	< 20	15000	150000	< 10	6	3	< 5
		103	1.20	1.8	465000	0.2	669	900	1360000	7430	3	26	53100	< 2	160	< 1	< 20	16000	35300	< 10	4	< 1	< 5
		134	1.38	11.2	430000	0.3	117	900	1980000	1320	18	35	58500	< 2	20	< 1	< 20	10000	78400	< 10	3	< 1	< 5
		167	1.44	10.2	493000	0.3	81.6	400	1450000	976	21	< 5	54000	2	20	< 1	< 20	9000	62200	< 10	3	< 1	< 5
		259	1.53	7.6	> 200000	0.2	64.6	300	> 200000	824	12	25	52900	< 2	10	< 1	< 20	7000	50400	< 10	< 1	< 1	< 5
		283	1.71	6.9	330000	0.1	151	100	1200000	1720	3	20	47800	< 2	20	< 1	< 20	8000	46900	< 10	3	< 1	< 5
		321	1.79	7.6	316000	< 0.1	167	< 100	1150000	2150	8	20	48600	< 2	30	< 1	< 20	11000	52700	< 10	4	< 1	< 5
	401	1.83	7.21	344000	0.19	98.8	< 100	1300000	1330	3.6	33.3	44000	< 2	35	< 1	49	10800	45400	< 10	1.5	< 1	< 5	
Col 4- Drainage		6	0.24				< 0.5	< 50			< 3												
		14	0.51	67.4	> 200000	1.2	149	< 100	> 200000	3830	135	92	156000	< 2	10	< 1	< 20	19000	147000	< 10	8	3	< 5
		24	0.75					< 50		61000		< 3		< 1									
		41	1.00	< 1	700000			< 50		51000		< 3		< 1									
		58	1.29	6	552000	0.4	1570	800	1160000	12500	< 2	31	19500	< 2	60	< 1	< 20	13000	52700	< 10	4	< 1	< 5
		80	1.54	4.2	502000	< 0.1	978	1300	934000	6670	3	49	20800	< 2	60	< 1	< 20	12000	42100	< 10	4	< 1	< 5
		103	1.79	4	573000	0.2	1030	900	870000	7540	< 2	34	19400	< 2	60	< 1	< 20	12000	34400	< 10	4	< 1	< 5
		134	2.07	7.9	568000	0.4	4040	900	1830000	29700	4	28	23000	< 2	40	< 1	< 20	15000	81400	< 10	5	< 1	< 5
		167	2.30	4	537000	0.4	1420	500	1060000	12700	6	< 5	25900	< 2	70	< 1	< 20	14000	36900	< 10	3	< 1	< 5
		259	2.49	4.8		0.7	> 2000	900	> 200000	> 10000	15	63	31700	4	90	< 1	< 20	14000	38800	< 10	3	< 1	< 5
		283	2.64	2.4	456000	0.2	8620		2410000	53100	5	65	32600	< 2	130	< 1	40	6000	44000	< 10	3	< 1	< 5
		321	2.68	9.61	538000	1.19	72700		3200000	362000	5.5	4870	29800	< 2	675	< 1	< 20	10300	46100	< 10	2.5	< 1	5.8
	401	2.70	7.94	482000	1.68	55900		4630000	320000	5.9	3620	38400	6.9	971	< 1	< 20	14500	51900	< 10	4.7	1.1	< 5	

Elemental Analysis of the Columns Drainage

			Mn	Ga	Ge	Br	Rb	Sr	Y	Zr	Nb	Mo	Ru	Pd	Ag	In	Sn	Sb	Te	I	Cs	Ba	La
			ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Col 1- Drainage	Day from Start of test	Pore Volume Displaced																					
		6	0.46																				
	14	0.76	> 100000	5.1	4.6	< 30	37.5	> 2000	0.28	0.3	< 0.05	18	13.2	< 0.1	< 2	< 0.01	< 1	0.2	< 1	< 10	0.17	71	0.33
	24	1.00	> 100000	17.6	11.9	< 30	45.5	1570	2.77	1.6	1.14	42	< 0.1	< 0.1	< 2	< 0.01	< 1	0.7	< 1	< 10	0.38	55	1.76
	41	1.42																					
	58	1.91	39500	0.5	1	< 30	24.3	> 2000	0.41	0.1	< 0.05	5	3.2	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	50	0.31	32	0.46
	103	2.74	7520	0.2	0.2	< 30	15.6	> 2000	0.27	< 0.1	< 0.05	< 1	0.1	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	30	0.23	24	0.89
	134	3.15	7560	0.2	0.2	< 30	11.8	> 2000	< 0.03	< 0.1	< 0.05	3	0.1	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	20	0.15	19	< 0.01
	167	3.56	6780	0.1	0.1	< 30	10.3	2970	< 0.03	< 0.1	< 0.05	< 1	0.2	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	340	0.13	19	< 0.01
Col 2- Drainage	6	0.18	< 1																				
	14	0.38	467	0.3	0.5	< 30	41.2	> 2000	< 0.03	< 0.1	< 0.05	115	< 0.1	< 0.1	< 2	< 0.01	< 1	0.7	< 1	< 10	0.12	22	0.01
	24	0.74																					
	41	1.07																					
	58	1.44	7140	0.2	2.6	< 30	82.1	> 2000	0.04	0.2	< 0.05	16	1.3	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	60	0.59	33	0.04
	80	1.74	3050	< 0.1	0.6	< 30	51.9	> 2000	< 0.03	< 0.1	< 0.05	32	0.2	< 0.1	< 2	< 0.01	< 1	0.1	< 1	50	0.54	23	< 0.01
	103	2.03	2180	< 0.1	0.3	< 30	41.5	> 2000	< 0.03	< 0.1	< 0.05	46	< 0.1	< 0.1	< 2	< 0.01	< 1	0.2	< 1	20	0.44	18	< 0.01
	134	2.31	2190	< 0.1	0.3	< 30	29.6	> 2000	< 0.03	< 0.1	< 0.05	35	< 0.1	< 0.1	< 2	< 0.01	< 1	0.2	< 1	20	0.28	15	< 0.01
167	2.52	2230	< 0.1	0.2	< 30	26.4	1860	< 0.03	< 0.1	< 0.05	36	< 0.1	< 0.1	< 2	< 0.01	< 1	0.2	< 1	320	0.23	11	< 0.01	
Col 3- Drainage	6	0.10																					
	14	0.31	3350	0.2	0.7	< 30	48.5	1910	0.03	2.5	< 0.05	81	< 0.1	< 0.1	< 2	< 0.01	< 1	4.5	< 1	< 10	0.11	13	0.03
	24	0.43																					
	41	0.61																					
	58	0.85	3570	0.2	1.1	< 30	115	> 2000	2.02	12.8	< 0.05	203	< 0.1	< 0.1	< 2	< 0.01	< 1	5.4	< 1	130	0.52	28	2.18
	80	1.04	5090	0.2	0.7	< 30	94.9	> 2000	0.58	2.9	< 0.05	112	< 0.1	< 0.1	< 2	< 0.01	< 1	4	< 1	40	0.5	27	0.51
	103	1.20	2150	< 0.1	0.3	< 30	43	> 2000	< 0.03	< 0.1	< 0.05	47	< 0.1	< 0.1	< 2	< 0.01	< 1	0.2	< 1	50	0.42	17	< 0.01
	134	1.38	4910	0.2	0.4	< 30	55.7	> 2000	< 0.03	0.5	< 0.05	49	< 0.1	< 0.1	< 2	< 0.01	< 1	1.7	< 1	40	0.22	17	0.01
	167	1.44	4890	0.1	0.3	< 30	50.6	2060	0.23	0.2	< 0.05	39	< 0.1	< 0.1	< 2	< 0.01	< 1	1.1	< 1	280	0.24	21	0.25
	259	1.53	4320	0.2	0.2	< 30	42.7	1160	< 0.03	< 0.1	< 0.05	41	< 0.1	< 0.1	< 2	< 0.01	< 1	0.9	< 1	< 10	0.22	5	< 0.01
	283	1.71	7140	0.2	0.3	< 30	42	1360	< 0.03	0.2	< 0.05	24	< 0.1	< 0.1	< 2	< 0.01	< 1	0.8	< 1	< 10	0.19	4	< 0.01
	321	1.79	7970	0.2	0.3	< 30	51.1	1260	< 0.03	0.3	< 0.05	22	< 0.1	< 0.1	< 2	< 0.01	< 1	1.1	< 1	< 10	0.29	7	< 0.01
401	1.83	3810	< 0.1	0.18	< 30	43.4	1200	< 0.03	0.2	< 0.05	34.2	< 0.1	< 0.1	< 2	< 0.01	< 1	0.85	< 1	< 10	0.261	8.2	0.011	
Col 4- Drainage	6	0.24																					
	14	0.51	6240	< 0.1	1.4	< 30	80.9	> 2000	3.44	43.1	< 0.05	307	< 0.1	< 0.1	< 2	< 0.01	< 1	8.5	< 1	10	0.22	43	3.88
	24	0.75																					
	41	1.00																					
	58	1.29	9260	0.3	0.4	< 30	51.2	> 2000	0.27	0.2	< 0.05	18	0.2	< 0.1	< 2	< 0.01	< 1	0.9	< 1	50	0.29	31	0.25
	80	1.54	8770	0.2	0.3	< 30	41.6	1920	0.05	0.2	< 0.05	15	< 0.1	< 0.1	< 2	< 0.01	< 1	0.7	< 1	30	0.26	22	0.04
	103	1.79	9860	0.2	0.3	< 30	32.7	> 2000	0.13	0.2	< 0.05	11	0.1	< 0.1	< 2	< 0.01	< 1	0.8	< 1	20	0.16	19	0.06
	134	2.07	10800	0.3	0.7	< 30	72.7	> 2000	0.21	0.6	< 0.05	27	0.4	< 0.1	< 2	< 0.01	< 1	1.3	< 1	90	0.4	27	0.18
	167	2.30	14200	0.3	0.4	< 30	37.7	2630	0.34	0.6	< 0.05	8	0.2	< 0.1	< 2	< 0.01	< 1	0.6	< 1	260	0.2	18	0.38
	259	2.49	23000	1	0.8	< 30	42.8	> 2000	0.62	1.6	< 0.05	11	0.3	< 0.1	< 2	< 0.01	< 1	0.6	< 1	< 10	0.29	18	0.47
	283	2.64	44900	0.8	1.4	70	52.6	> 2000	0.04	< 0.1	< 0.05	10	1.8	< 0.1	< 2	< 0.01	< 1	0.1	< 1	20	0.31	16	0.02
	321	2.68	58300	1.3	4.2	< 30	73.7	> 2000	2.25	< 0.1	< 0.05	10.9	3.31	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	< 10	0.596	30.2	3.3
	401	2.70	> 100000	2.58	2.76	< 30	78.1	> 2000	1.62	< 0.1	< 0.05	11.5	2.95	< 0.1	< 2	< 0.01	< 1	< 0.1	< 1	< 10	0.677	38.3	3.27

Elemental Analysis of the Columns Drainage

			Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Pt	Au	Hg
			ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Col 1- Drainage	Day from Start of test	Pore Volume Displaced																					
	Col 1- Drainage	6	0.46																				
14		0.76	0.69	0.1	0.37	0.08	0.02	0.08	0.01	0.06	< 0.01	0.02	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.2	0.74	< 0.02	< 3	0.13	< 2
24		1.00	3.1	0.18	0.65	0.14	0.03	0.18	0.02	0.18	0.03	0.07	< 0.01	0.12	0.01	0.69	< 0.01	< 0.2	0.54	< 0.02	< 3	< 0.02	< 2
41		1.42																					
58		1.91	1.35	0.08	0.33	0.13	0.02	0.08	0.01	0.04	0.01	0.03	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.2	0.41	< 0.02	< 3	< 0.02	< 2
103		2.74	3.82	0.37	1.43	0.31	0.07	0.27	0.03	0.1	0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.5	< 0.02	< 3	< 0.02	< 2
134		3.15	0.27	< 0.01	< 0.01	0.02	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.36	< 0.02	< 3	< 0.02	< 2
167		3.56	0.05	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.2	0.22	< 0.02	< 3	< 0.02
Col 2- Drainage	6	0.18																					
	14	0.38	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.03	< 0.02	< 3	< 0.02	< 2
	24	0.74																					
	41	1.07																					
	58	1.44	0.39	< 0.01	0.02	0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.2	0.69	< 0.02	< 3	< 0.02	< 2
	80	1.74	0.46	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.96	< 0.02	< 3	< 0.02	< 2
	103	2.03	0.14	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.71	< 0.02	< 3	< 0.02	< 2
	134	2.31	0.1	< 0.01	0.02	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.2	0.31	< 0.02	< 3	< 0.02	< 2
167	2.52	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.25	< 0.02	< 3	< 0.02	< 2	
Col 3- Drainage	6	0.10																					
	14	0.31	0.04	< 0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.03	< 0.01	< 0.2	0.28	< 0.02	< 3	< 0.02	< 2
	24	0.43																					
	41	0.61																					
	58	0.85	4.5	0.53	2.37	0.47	0.1	0.43	0.05	0.27	0.05	0.15	0.02	0.13	0.02	0.16	< 0.01	0.4	0.75	< 0.02	< 3	< 0.02	< 2
	80	1.04	1.29	0.14	0.59	0.12	0.03	0.12	0.02	0.07	0.01	0.04	< 0.01	0.05	< 0.01	0.04	< 0.01	0.3	0.92	< 0.02	< 3	< 0.02	< 2
	103	1.20	0.56	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.69	< 0.02	< 3	< 0.02	< 2
	134	1.38	0.35	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.55	< 0.02	< 3	< 0.02	< 2
	167	1.44	0.42	0.05	0.22	0.02	< 0.01	0.03	< 0.01	0.03	< 0.01	0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.48	< 0.02	< 3	< 0.02	< 2
	259	1.53	< 0.01	< 0.01	0.05	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.44	< 0.02	< 3	< 0.02	< 2
	283	1.71	0.02	< 0.01	0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.34	< 0.02	< 3	< 0.02	< 2
	321	1.79	< 0.01	< 0.01	0.02	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.42	< 0.02	< 3	< 0.02	< 2
401	1.83	0.013	< 0.01	< 0.01	0.016	< 0.01	0.011	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.012	< 0.01	< 0.01	< 0.01	< 0.2	0.496	< 0.02	< 3	< 0.02	< 2	
Col 4- Drainage	6	0.24																					
	14	0.51	5.09	0.71	3.06	0.6	0.14	0.61	0.08	0.4	0.08	0.24	0.03	0.22	0.03	0.6	< 0.01	0.3	0.47	< 0.02	< 3	0.06	< 2
	24	0.75																					
	41	1.00																					
	58	1.29	0.63	0.05	0.24	0.05	0.01	0.04	< 0.01	0.03	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.26	< 0.02	< 3	< 0.02	< 2
	80	1.54	1.22	< 0.01	0.02	0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.25	< 0.02	< 3	< 0.02	< 2
	103	1.79	0.7	< 0.01	0.02	0.01	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.17	< 0.02	< 3	< 0.02	< 2
	134	2.07	0.79	0.04	0.15	0.04	0.01	0.04	< 0.01	0.03	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.28	< 0.02	< 3	< 0.02	< 2
	167	2.30	0.73	0.08	0.3	0.03	< 0.01	0.06	< 0.01	0.03	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.13	< 0.02	< 3	< 0.02	< 2
	259	2.49	0.99	0.11	0.44	0.07	0.02	0.11	< 0.01	0.07	< 0.01	0.05	< 0.01	0.04	< 0.01	< 0.01	< 0.01	< 0.2	0.14	< 0.02	< 3	< 0.02	< 2
	283	2.64	0.04	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.11	< 0.02	< 3	< 0.02	< 2
	321	2.68	6.88	0.297	0.894	0.125	0.033	0.257	0.025	0.079	0.024	0.053	< 0.01	0.031	< 0.01	< 0.01	< 0.01	< 0.2	0.145	< 0.02	< 3	< 0.02	< 2
401	2.70	2.9	0.177	0.651	0.107	0.028	0.138	0.02	0.06	0.018	0.039	< 0.01	0.023	< 0.01	< 0.01	< 0.01	< 0.2	0.172	< 0.02	< 3	< 0.02	< 2	

Elemental Analysis of the Columns Drainage

		TI ug/L	Pb ug/L	Bi ug/L	Th ug/L	U ug/L	S mg/L	Acidity mg CaCO3/L
	Day from Start of test	Pore Volume Displaced						
Col 1- Drainage	6	0.46						
	14	0.76						
	24	0.12	0.4	< 3	0.02	0.48	2000	4560
	41	0.55	1.2	< 3	0.07	5.55	9000	14000
	58						13000	9000
	103	0.02	< 0.1	< 3	0.02	0.53	10000	
	134	0.05	< 0.1	< 3	0.05	2.15		
	167	0.05	0.2	< 3	< 0.01	2.98		
	167	0.04	< 0.1	< 3	< 0.01	2.95		< 10
Col 2- Drainage	6	0.18						
	14	0.38						
	24	0.74						
	41	1.07						
	58	< 0.01	< 0.1	< 3	0.02	0.57	10000	2040
	80	0.02	< 0.1	< 3	< 0.01	16.2		
	103	0.01	0.2	< 3	< 0.01	16.5		
	134	< 0.01	0.1	< 3	< 0.01	12.5		
	167	< 0.01	< 0.1	< 3	< 0.01	12.4		< 10
Col 3- Drainage	6	0.10						
	14	0.31						
	24	0.43						
	41	0.61						
	58	0.15	0.2	< 3	< 0.01	13.9	1000	
	80						1000	
	103						3000	
	134	0.16	0.3	< 3	0.04	94.6	7000	
	167	0.2	0.2	< 3	0.01	51.9		
	259	< 0.01	0.1	< 3	0.01	16.3		
	283	0.14	0.6	< 3	0.01	18		
	401	0.14	< 0.1	< 3	< 0.01	15.2		< 10
Col 4- Drainage	6	0.24						
	14	0.51						
	24	0.75						
	41	1.00						
	58	0.07	0.2	< 3	< 0.01	10	5000	
	80	0.05	< 0.1	< 3	< 0.01	8.53		
	103	0.09	0.2	< 3	< 0.01	8.38		
	134	0.06	< 0.1	< 3	< 0.01	14.3		
	167	0.1	< 0.1	< 3	< 0.01	9.87		
	259	0.14	< 0.1	< 3	< 0.01	12.1		< 10
	283	0.01	0.3	< 3	0.43	0.09		
	401	0.101	< 0.1	< 3	< 0.01	0.678		



APPENDIX D
Analyses of Column Lysimeter Samples

Elemental Analysis of the Lysimeters Collected Water

			As ug/L	Ca ug/L	Cd ug/L	Co ug/L	Fe ug/L	Mg ug/L	Ni ug/L	Se ug/L	Zn ug/L	Na ug/L	Cu ug/L	Li ug/L	Be ug/L	Al ug/L	Si ug/L	K ug/L
	Day from Start of Test	Pore Volume Displaced																
Col 1-Top	64	1.91	13.3	618000	1	23.7	2400	173000	172	8	179	6790	11	40	< 1	30	35000	10500
Col 1-Middle	7	0.46				31800	700000	900000	89000		57000							
	21	0.76	1000		100	10000	1120000		40000		36000							
	84	2.34	1420	576000	206	9130	1270000	392000	33600	58	47700	12100	> 2000	110	2	7270	60000	4800
	111	2.74	873	568000	138	8060	1420000	477000	28200	47	34500	10400	324	100	1	4730	48000	2700
	141	3.15	676	491000	160	7450	1130000	500000	24800	37	28600	10700	1300	90	3	14300	55000	4200
	174	3.56	824	480000	176	6970	1350000	574000	24100	16	26500	10000	> 2000	90	4	> 20000	57000	2400
Col 1-Bottom	50	1.42	3.2	533000	0.7	20700	848000	1070000	64100	6	12400	43500	11	280	< 1	50	29000	11900
	64	1.91	2.2	590000	0.5	14300	1300000	733000	49900		8420	25000	2	240	< 1	< 20	25000	8600
	84	2.34	1.7	597000	0.4	8060	784000	471000	30200	2	4960	16900	3	250	< 1	< 20	23000	7000
	111	2.74	1	577000	3		811000	444000	29300		15300	14100	< 2	200	< 1	< 20	16000	10000
	141	3.15	2	534000	0.8	8500	1290000	462000	36800	3	7450	13800	9	190	< 1	< 20	19000	4700
	174	3.56	1.7	505000	0.6	8780	1620000	475000	39100	3	9720	13000	6	170	< 1	20	19000	3100
Col 2-Top	64	1.44	30.1	696000	< 0.1	102	1900	92300	296	< 2	41	4410	4	20	< 1	< 20	24000	7200
	84	1.74	36.1	671000	< 0.1	36.4	700	90500	95	< 2	17	4780	< 2	20	< 1	< 20	21000	6400
	111	2.03	3	353000	< 0.1	2.25	500	84400	9	7	16	6950	< 2	< 10	< 1	< 20	< 2000	5700
Col 3-Middle	7	0.10			200	21000	1980000	900000	68000		47000							
	21	0.31				7100	2010000		32000		23000							
	35	0.43				6300	1610000		29000		21000							
	64	0.85	1080	560000	99.9	8910	1050000	305000	38500	69	42300	11300	1000	100	3	11600	58000	6900
	84	1.04	1870	541000	218	10900	1440000	331000	44300	58	56100	11300	> 2000	110	6	> 20000	72000	4900
	111	1.20	1990	556000	277	12100	1830000	384000	46600	46	62400	12500	> 2000	140	8	> 20000	76000	6600
	141	1.38	2200	465000	321	11500	1620000	355000	43600	28	59000	12400	> 2000	110	7	> 20000	82000	4700
	174	1.44	2870	457000	453	17800	2010000	437000	67100	29	86200	15100	> 2000	160	12	> 20000	103000	2200
Col 3-Bottom	64	0.85	9.2	553000	0.3	7450	505000	915000	53600	< 2	1010	41100	< 2	210	< 1	< 20	24000	20500
	84	1.04	109	578000	0.2	2030	183000	694000	17400	< 2	584	32400	< 2	180	< 1	< 20	27000	17000
	111	1.20	7.6	556000	0.4	2630	189000	637000	19400	< 2	1190	28600	5	170	< 1	40	17000	14800
	141	1.38	6.6	506000	0.3	4400	570000	604000	30000	4	1720	26900	20	140	< 1	40	18000	13700
		174	1.44	3.6	499000	< 0.1	4310	482000	598000	28100	3	1610	26800	8	130	< 1	20	17000
Col 4-Top	7	0.24				202000	5850000	2900000	721000		212000	< 500						
	21	0.51				118000	4370000	1800000	437000		73000	< 500						
	35	0.75				52900	2340000	1000000	204000		9000	< 500						
	64	1.29	7	616000	0.3	32200	2490000	754000	158000	5	13400	14800	2	200	< 1	< 20	31000	11400
	84	1.54	13.8	543000	2.7	79500	6850000	1150000	354000	6	261000	20900	3	460	< 1	60	46000	13300
Col 4-Bottom	50	1.00	14.4	522000	0.4	36000	641000	1780000	177000	< 2	633	22900	35	210	< 1	30	26000	62500
	64	1.29	5.1	551000	< 0.1	6810	62000	1070000	49800	< 2	177	17100	< 2	170	< 1	< 20	22000	40500
	84	1.54	32.6	591000	< 0.1	1920	5000	792000	13700	< 2	67	16100	< 2	130	< 1	< 20	22000	31800
	111	1.79	19.6	610000	< 0.1	1800	1800	814000	15000	< 2	107	17200	< 2	110	< 1	40	21000	26400
	141	2.07	7	547000	< 0.1	10200	507000	1180000	88500	4	500	26000	6	180	< 1	< 20	22000	33900
		174	2.30	7.6	510000	< 0.1	42700	3290000	1650000	325000	5	22200	29200	2	280	< 1	< 20	23000

Elemental Analysis of the Lysimeters Collected Water

			Sc ug/L	Ti ug/L	V ug/L	Cr ug/L	Mn ug/L	Ga ug/L	Ge ug/L	Br ug/L	Rb ug/L	Sr ug/L	Y ug/L	Zr ug/L	Nb ug/L	Mo ug/L	Ru ug/L	Pd ug/L	
	Day from Start of Test	Pore Volume Displaced																	
Col 1-Top	64	1.91	< 10	5	105	< 5	80	< 0.1	0.5	< 30	6.41	1150	0.18	< 0.1	< 0.05	30	< 0.1	< 0.1	
Col 1-Middle	7	0.46	22000																
	21	0.76	11000																
	84	2.34	10	6	< 1	< 5	14100	0.5	1.4	< 30	7.12	> 2000	34.8	0.2	< 0.05	< 1	1	< 0.1	
	111	2.74	10	5	< 1	< 5	15800	0.4	1.2	< 30	5.25	> 2000	25.3	0.2	< 0.05	< 1	0.8	< 0.1	
	141	3.15	10	9	3	9	17700	0.5	0.9	60	5.67	2080	42	0.2	< 0.05	< 1	0.7	< 0.1	
	174	3.56	20	9	1	< 5	19300	0.8	1.1	110	5.46	2080	69.7	< 0.1	< 0.05	< 1	0.8	< 0.1	
Col 1-Bottom	50	1.42	< 10	5	< 1	< 5	19200	0.4	1	< 30	19.6	> 2000	0.84	0.2	< 0.05	5	2	< 0.1	
	64	1.91	< 10	3	< 1	< 5	16100	0.4	1	< 30	16	> 2000	0.36	0.1	< 0.05	3	1.4	0.1	
	84	2.34	< 10	3	< 1	< 5	11400	0.3	0.7	< 30	12.5	> 2000	0.35	< 0.1	< 0.05	3	0.8	< 0.1	
	111	2.74	< 10	3	< 1	< 5	11300	0.3	0.8	< 30	9.24	> 2000	0.22	0.1	< 0.05	2	0.7	0.1	
	141	3.15	< 10	4	1	< 5	14300	0.3	0.8	310	8.36	2400	0.38	< 0.1	< 0.05	2	0.8	< 0.1	
	174	3.56	< 10	7	< 1	< 5	15100	0.3	0.9	160	7.61	2100	0.39	< 0.1	< 0.05	2	0.9	< 0.1	
Col 2-Top	64	1.44	< 10	4	7	< 5	2600	< 0.1	0.1	< 30	5.47	1060	0.08	< 0.1	< 0.05	16	< 0.1	< 0.1	
	84	1.74	< 10	4	27	< 5	2310	0.1	0.1	< 30	5.35	911	0.11	< 0.1	< 0.05	7	< 0.1	< 0.1	
	111	2.03	< 10	< 1	< 1	< 5	15	< 0.1	0.1	< 30	2.49	479	< 0.03	< 0.1	< 0.05	14	< 0.1	< 0.1	
Col 3-Middle	7	0.10	18000																
	21	0.31	12000																
	35	0.43	13000																
	64	0.85	20	10	< 1	< 5	10300	0.4	1.5	< 30	7.18	1830	23.7	< 0.1	< 0.05	< 1	0.9	0.4	
	84	1.04	30	9	< 1	< 5	11100	0.6	1.6	< 30	6.11	1880	49.8	< 0.1	< 0.05	< 1	1	0.1	
	111	1.20	30	9	4	< 5	12000	1.1	1.7	< 30	5.4	1910	81.7	< 0.1	< 0.05	< 1	1.3	0.2	
	141	1.38	40	12	9	6	10800	1.2	1.7	< 30	4.48	1830	94.4	< 0.1	< 0.05	< 1	1.2	< 0.1	
	174	1.44	90	12	46	80	13700	2.6	2.2	< 30	4.79	2050	157	0.1	< 0.05	< 1	1.9	< 0.1	
Col 3-Bottom	64	0.85	< 10	5	< 1	< 5	8160	0.2	0.8	< 30	30.8	> 2000	0.31	< 0.1	< 0.05	4	0.9	< 0.1	
	84	1.04	< 10	5	< 1	< 5	3690	< 0.1	0.4	< 30	28.2	> 2000	0.09	< 0.1	< 0.05	4	0.3	< 0.1	
	111	1.20	< 10	3	< 1	< 5	5380	< 0.1	0.3	< 30	25.1	> 2000	0.27	< 0.1	< 0.05	1	0.3	< 0.1	
	141	1.38	< 10	3	< 1	< 5	8190	0.1	0.5	110	23	3050	0.64	< 0.1	< 0.05	2	0.4	< 0.1	
		174	1.44	< 10	4	< 1	< 5	7210	0.2	0.5	150	21.4	2860	1.01	< 0.1	< 0.05	2	0.4	< 0.1
Col 4-Top	7	0.24	135000																
	21	0.51	78000																
	35	0.75	46000																
	64	1.29	< 10		< 1	< 5	21600	0.6	2	< 30	22	> 2000	0.76	< 0.1	< 0.05	9	3.2	< 0.1	
	84	1.54	< 10	8	< 1	< 5	53500	1.6	5.1	< 30	28.8	> 2000	28.4	0.1	< 0.05	19	7.4	1.1	
Col 4-Bottom	50	1.00	< 10	5	< 1	< 5	15400	0.4	2	< 30	59.6	> 2000	0.59	0.1	< 0.05	14	3.6	< 0.1	
	64	1.29	< 10	6	< 1	< 5	3190	< 0.1	0.7	< 30	43.9	> 2000	0.11	< 0.1	< 0.05	3	0.8	< 0.1	
	84	1.54	< 10	5	< 1	< 5	3670	0.1	0.5	< 30	37.9	> 2000	0.06	< 0.1	< 0.05	8	0.2	0.3	
	111	1.79	< 10	5	< 1	< 5	5940	0.2	0.4	< 30	31.4	> 2000	0.08	< 0.1	< 0.05	8	0.2	< 0.1	
	141	2.07	< 10	4	< 1	< 5	16500	0.2	0.9	< 30	39.4	3790	0.12	< 0.1	< 0.05	6	1	< 0.1	
		174	2.30	< 10	4	< 1	< 5	43800	0.9	3.2	< 30	47.2	5290	1.19	< 0.1	< 0.05	19	4.4	< 0.1

Elemental Analysis of the Lysimeters Collected Water

			Ag ug/L	In ug/L	Sn ug/L	Sb ug/L	Te ug/L	I ug/L	Cs ug/L	Ba ug/L	La ug/L	Ce ug/L	Pr ug/L	Nd ug/L	Sm ug/L	Eu ug/L	Gd ug/L	Tb ug/L	
	Day from Start of Test	Pore Volume Displaced																	
Col 1-Top	64	1.91	< 2	< 0.01	< 1	1.7	< 1	20	0.16	40	0.09	0.45	0.02	0.08	0.03	< 0.01	0.02	< 0.01	
Col 1-Middle	7	0.46																	
	21	0.76																	
	84	2.34	< 2	< 0.01	< 1	0.5	< 1	30	0.32	41	27.5	38.7	4.31	16.9	4.19	1.39	5.43	0.81	
	111	2.74	< 2	< 0.01	< 1	< 0.1	< 1	30	0.22	28	19.1	25.9	2.77	11.1	2.63	0.83	3.6	0.54	
	141	3.15	< 2	< 0.01	< 1	< 0.1	< 1	520	0.22	36	29.7	40.5	4.63	18.3	4.33	1.41	6.52	0.96	
	174	3.56	< 2	< 0.01	< 1	< 0.1	< 1	590	0.23	32	46.4	69	7.84	31.3	7.58	2.72	11.6	1.71	
Col 1-Bottom	50	1.42	< 2	< 0.01	< 1	1.6	< 1	30	0.83	64	0.8	2.09	0.13	0.54	0.11	0.02	0.16	0.02	
	64	1.91	< 2	< 0.01	< 1	0.1	< 1	30	0.81	37	0.28	1.45	0.03	0.08	0.03	< 0.01	0.03	< 0.01	
	84	2.34	< 2	< 0.01	< 1	1.4	< 1	30	0.77	32	0.38	1.36	0.03	0.16	0.03	0.01	0.04	< 0.01	
	111	2.74	< 2	< 0.01	< 1	0.4	< 1	40	0.52	28	0.24	0.89	0.03	0.12	0.04	0.01	0.05	< 0.01	
	141	3.15	< 2	< 0.01	< 1	< 0.1	< 1	640	0.44	26	0.42	0.39	0.03	0.07	< 0.01	< 0.01	0.01	< 0.01	
	174	3.56	< 2	< 0.01	< 1	< 0.1	< 1	750	0.38	24	0.41	0.43	0.03	0.04	< 0.01	< 0.01	0.02	< 0.01	
Col 2-Top	64	1.44	< 2	< 0.01	< 1	0.5	< 1	20	0.14	15	0.04	0.16	< 0.01	0.02	0.02	< 0.01	< 0.01	< 0.01	
	84	1.74	< 2	< 0.01	< 1	0.1	< 1	20	0.15	15	0.06	0.25	< 0.01	0.03	0.02	< 0.01	< 0.01	< 0.01	
	111	2.03	< 2	< 0.01	< 1	0.3	< 1	10	0.02	15	< 0.01	0.13	< 0.01	0.02	0.01	< 0.01	< 0.01	< 0.01	
Col 3-Middle	7	0.10																	
	21	0.31																	
	35	0.43																	
	64	0.85	< 2	< 0.01	< 1	0.2	< 1	150	0.41	66	19.6	30.2	3.62	13.9	3.27	1.01	4.07	0.63	
	84	1.04	< 2	0.02	< 1	0.4	< 1	120	0.37	39	38.2	61.2	6.79	27.3	6.64	2.3	8.5	1.31	
	111	1.20	< 2	0.04	< 1	0.3	< 1	80	0.27	37	58.2	103	11.6	48.4	12.4	4.19	15.7	2.44	
	141	1.38	< 2	0.06	< 1	0.1	< 1	450	0.23	30	70.1	126	15.5	64.6	> 10.0	5.53	21.3	3.16	
	174	1.44	< 2	0.69	< 1	< 0.1	< 1	530	0.29	29	117	229	28.8	123	> 10.0	10.7	39	5.88	
Col 3-Bottom	64	0.85	< 2	< 0.01	< 1	0.2	< 1	60	0.5	63	0.31	1.03	0.02	0.08	0.03	< 0.01	0.03	< 0.01	
	84	1.04	< 2	< 0.01	< 1	1	< 1	70	0.47	26	0.08	0.68	< 0.01	0.04	< 0.01	< 0.01	0.01	< 0.01	
	111	1.20	< 2	< 0.01	< 1	< 0.1	< 1	80	0.39	18	0.21	1.04	0.02	0.07	0.02	< 0.01	0.02	< 0.01	
	141	1.38	< 2	< 0.01	< 1	< 0.1	< 1	1110	0.34	18	0.51	0.42	0.03	0.08	< 0.01	< 0.01	0.05	< 0.01	
		174	1.44	< 2	< 0.01	< 1	< 0.1	< 1	1840	0.33	17	0.97	0.88	0.08	0.31	0.04	< 0.01	0.07	0.02
Col 4-Top	7	0.24																	
	21	0.51																	
	35	0.75																	
	64	1.29	< 2	< 0.01	< 1	0.2	< 1	30	0.86	47	0.98	1.92	0.07	0.24	0.05	< 0.01	0.08	< 0.01	
	84	1.54	< 2	< 0.01	< 1	< 0.1	< 1	30	1.45	65	26.7	10.3	0.56	1.9	0.23	0.06	0.49	0.06	
Col 4-Bottom	50	1.00	< 2	< 0.01	< 1	0.8	< 1	80	0.75	28	0.48	1.45	0.05	0.21	0.03	< 0.01	0.08	< 0.01	
	64	1.29	< 2	< 0.01	< 1	< 0.1	< 1	60	0.51	50	0.06	0.73	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	
	84	1.54	< 2	< 0.01	< 1	0.8	< 1	120	0.44	26	0.04	0.41	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	
	111	1.79	< 2	< 0.01	< 1	0.4	< 1	40	0.39	20	0.04	0.23	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	
	141	2.07	< 2	< 0.01	< 1	< 0.1	< 1	430	0.36	22	0.08	0.06	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	
	174	2.30	< 2	< 0.01	< 1	< 0.1	< 1	400	0.47	33	0.74	0.44	0.02	0.06	< 0.01	< 0.01	0.02	< 0.01	

Elemental Analysis of the Lysimeters Collected Water

			Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Pt	Au	Hg	Tl	Pb	
			ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
	Day from Start of Test	Pore Volume Displaced																	
Col 1-Top	64	1.91	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	1.3	0.02	< 0.02	< 3	< 0.02	< 2	0.03	0.2	
Col 1-Middle	7	0.46																	
	21	0.76																	
	84	2.34	4.06	0.76	2.12	0.25	1.72	0.28	0.05	< 0.01	< 0.2	0.03	< 0.02	< 3	< 0.02	< 2	0.03	0.8	
	111	2.74	2.9	0.53	1.54	0.17	1.17	0.19	0.05	< 0.01	< 0.2	0.02	< 0.02	< 3	< 0.02	< 2	0.02	0.3	
	141	3.15	4.85	0.95	2.63	0.32	2.19	0.36	0.09	0.01	< 0.2	0.02	< 0.02	< 3	< 0.02	< 2	0.03	1.1	
	174	3.56	8.95	1.66	4.67	0.57	3.87	0.59	0.11	0.02	< 0.2	0.03	< 0.02	< 3	< 0.02	< 2	0.03	0.5	
Col 1-Bottom	50	1.42	0.08	0.01	0.04	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.2	0.25	< 0.02	< 3	< 0.02	< 2	0.07	0.9	
	64	1.91	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.2	0.08	< 0.02	< 3	< 0.02	< 2	0.06	0.2	
	84	2.34	0.02	< 0.01	0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.05	< 0.02	< 3	< 0.02	< 2	0.08	0.2	
	111	2.74	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.2	0.03	< 0.02	< 3	< 0.02	< 2	0.03	0.6	
	141	3.15	0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.04	< 0.02	< 3	< 0.02	< 2	0.02	0.2	
	174	3.56	< 0.01	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.2	0.03	< 0.02	< 3	< 0.02	< 2	0.02	< 0.1	
Col 2-Top	64	1.44	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.2	< 0.01	< 0.02	< 3	< 0.02	< 2	0.02	0.3	
	84	1.74	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	0.3	< 0.01	< 0.02	< 3	< 0.02	< 2	0.01	< 0.1	
	111	2.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.2	0.07	< 0.02	< 3	0.14	< 2	0.01	< 0.1	
Col 3-Middle	7	0.10																	
	21	0.31																	
	35	0.43																	
	64	0.85	3.29	0.63	1.75	0.23	1.61	0.27	0.04	< 0.01	< 0.2	0.05	< 0.02	< 3	< 0.02	< 2	0.1	0.7	
	84	1.04	6.62	1.22	3.44	0.42	3.19	0.44	0.07	< 0.01	< 0.2	0.05	< 0.02	< 3	< 0.02	< 2	0.13	1.8	
	111	1.20	12	2.18	6.11	0.75	5.38	0.81	0.18	0.02	< 0.2	0.04	< 0.02	< 3	< 0.02	< 2	0.08	7.9	
	141	1.38	15.8	2.89	7.92	1	7.28	1.11	0.22	0.03	< 0.2	0.02	< 0.02	< 3	< 0.02	< 2	0.08	5.3	
	174	1.44	29.7	5.25	14.5	1.84	13.4	2.07	0.44	0.05	< 0.2	0.04	< 0.02	< 3	< 0.02	< 2	0.09	9.9	
Col 3-Bottom	64	0.85	0.02	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.14	< 0.02	< 3	< 0.02	< 2	0.03	0.2	
	84	1.04	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.14	< 0.02	< 3	< 0.02	< 2	0.04	< 0.1	
	111	1.20	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.08	< 0.02	< 3	< 0.02	< 2	0.02	0.3	
	141	1.38	0.04	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.07	< 0.02	< 3	< 0.02	< 2	< 0.01	< 0.1	
		174	1.44	0.06	0.02	0.04	< 0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.2	0.06	< 0.02	< 3	< 0.02	< 2	< 0.01	< 0.1
Col 4-Top	7	0.24																	
	21	0.51																	
	35	0.75																	
	64	1.29	0.04	< 0.01	0.03	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.08	< 0.02	< 3	< 0.02	< 2	0.05	0.1	
	84	1.54	0.33	0.08	0.23	0.02	0.15	0.03	< 0.01	< 0.01	< 0.2	0.06	< 0.02	< 3	< 0.02	< 2	0.06	< 0.1	
Col 4-Bottom	50	1.00	0.05	< 0.01	0.03	< 0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.2	0.15	< 0.02	< 3	< 0.02	< 2	0.08	0.6	
	64	1.29	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.08	< 0.02	< 3	< 0.02	< 2	0.03	< 0.1	
	84	1.54	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.11	< 0.02	< 3	< 0.02	< 2	0.04	< 0.1	
	111	1.79	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.08	< 0.02	< 3	< 0.02	< 2	0.02	< 0.1	
	141	2.07	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.11	< 0.02	< 3	< 0.02	< 2	0.03	< 0.1	
	174	2.30	0.02	< 0.01	0.02	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.2	0.09	< 0.02	< 3	< 0.02	< 2	0.04	< 0.1	

Elemental Analysis of the Lysimeters Collected Water

			Bi ug/L	Th ug/L	U ug/L	S mg/L	Acidity mg CaCO3/L
	Day from Start of Test	Pore Volume Displaced					
Col 1-Top	64	1.91	< 3	< 0.01	31.9	1000	
Col 1-Middle	7	0.46				2000	
	21	0.76				2000	2150
	84	2.34	< 3	0.05	12.9		
	111	2.74	< 3	0.02	7.97		
	141	3.15	< 3	0.12	13.9		
	174	3.56	< 3	0.1	17.9		
Col 1-Bottom	50	1.42	< 3	0.02	3.74		
	64	1.91	< 3	0.02	2.36		
	84	2.34	< 3	0.02	1.75		
	111	2.74	< 3	< 0.01	4.92		
	141	3.15	< 3	0.1	1.56		
	174	3.56	< 3	0.09	1.61		
Col 2-Top	64	1.44	< 3	< 0.01	18.6		
	84	1.74	< 3	< 0.01	8.11		
	111	2.03	< 3	< 0.01	0.9		
Col 3-Middle	7	0.10				3000	
	21	0.31				2000	3750
	35	0.43				2000	3480
	64	0.85	< 3	0.1	14.7		
	84	1.04	< 3	0.13	19.5		
	111	1.20	< 3	0.31	33.7		
	141	1.38	< 3	0.31	34		
	174	1.44	< 3	3.45	78.4		
Col 3-Bottom	64	0.85	< 3	0.03	17.9		
	84	1.04	< 3	0.02	37.3		
	111	1.20	< 3	< 0.01	6.48		
	141	1.38	< 3	0.09	5.71		
	174	1.44	< 3	0.08	6.98		
Col 4-Top	7	0.24				10000	446
	21	0.51				5000	8560
	35	0.75				3000	
	64	1.29	< 3	0.06	13.7		
	84	1.54	< 3	0.13	19.6		
Col 4-Bottom	50	1.00	< 3	0.04	8.6		
	64	1.29	< 3	0.01	5.98		
	84	1.54	< 3	< 0.01	10.2		
	111	1.79	< 3	0.01	17.5		
	141	2.07	< 3	0.05	12		
	174	2.30	< 3	0.05	9.33		