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GEOCHEMISTRY AND WATER QUALITY

VOLUME III OF:

SEEPAGE AND WATER QUALITY FOR RECLAIMED TAILINGS CONTAINMENT AREA – LUPIN OPERATION

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SEEPAGE AND WATER QUALITY FOR RECLAIMED TAILINGS CONTAINMENT AREA – LUPIN OPERATION

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EXECUTIVE SUMMARY

A review of the geochemistry of, and water quality associated with, the Lupin tailings was performed to assess the future water quality performance of the proposed closure plan. Two conditions were considered: tailings closure with ongoing permafrost conditions and potential permafrost thaws at some future date.

The geochemistry and water quality data from the tailings site were reviewed and evaluated for the present and future conditions. The data indicate that the tailings will generate acid and elevated concentrations of some metals in tailings porewater if exposed to the atmosphere for prolonged periods. Some areas of the tailings had developed acidic conditions in the near surface in the early 1990s.

The tailings cells were constructed with frozen core dams to aid containment, retain water and facilitate construction of esker cover layers for progressive reclamation and closure. The covers are permeable and promote precipitation infiltration to maintain saturated conditions in the underlying tailings, and also to maintain a watertable above the tailings for existing permafrost conditions. Seepage from the tailings reports currently to two ponds within the tailings basin. It is expected to do so into the future with or without permafrost conditions. The current discharge from the basin is controlled seasonally by siphons and, in the future, will be allowed to flow naturally through an outlet at Dam 2.

The quality of porewater in the esker cover layer above the tailings in Cell 1 reflects the historic oxidation and metal leaching that occurred before cover construction. The pH of the porewater is mildly acidic, with pH values generally between 4 and 5. Elevated sulphate and metal concentrations are also observed in the porewater. The porewaters in the covers above the tailings migrate laterally through the esker layers during the unfrozen periods and seep into the internal ponds. The overall water quality in the ponds and in the discharge has generally improved over the last 20 years and appears to be continually improving with time.

Oxidation and acid generation reactions within the tailings have effectively ceased as the watertable developed above the tailings after the placement of the esker cover. The soluble oxidation products in the near surface tailings are expected to continue to leach into the porewater at the base of the esker covers, and to be slowly flushed annually by fresh infiltration. This water will either decant or seep into the ponds over the next several years to decades. The water quality in the ponds is expected to improve with time, because oxidation products will be removed by the ongoing flushing. There will be no significant production of new oxidation products for the continuing permafrost condition.

Below the watertable, the only potential source of oxygen for oxidation of tailings is dissolved oxygen that enters the top of the tailings in the active zone during seasonally unfrozen periods. Oxidation of pyrite by dissolved oxygen can result in sulphate concentrations in the tailings porewater of about 16 mg/L. The metal concentrations

corresponding to this sulphate concentration were estimated from scaling factors between sulphate and metals concentrations observed in a tailings oxidation column test, as well as in the wells or pipes in Cell 1. The scaling factors from the field were considered to reflect flushing of porewater and were conservatively high compared to those from the column test that reflect active oxidation and release of metals under acidic conditions. The calculated metal concentrations in porewater for tailings below the watertable were low, as expected, for the column test scaling factor adjustments. The calculated metal concentrations in porewater were higher than expected for the field scaling factors, and are therefore considered to be very conservative estimates.

The assessment of water quality for a post-permafrost (thawed tailings and dams) in the Lupin tailings involved (a) seepage analysis to determine the area of unsaturated tailings that could develop, and (b) diffusion modelling to estimate pyrite oxidation rates in the unsaturated tailings. The seepage analysis considered a range of physical conditions as reported by Holubec (2006a). The chemical assessment also considered a range of conditions for several variables affecting oxidation rates and water quality, including sulphide content, scaling factors for metal release, saturation of tailings near dams and areas of unsaturated tailings (from the seepage analysis). The high sulphide content was assumed to be representative and the saturation was assumed to range between 90 and 100% in the tailings where the watertable declines from the tailings surface in a parabolic manner to the base of the tailings at the base of the dams. High water content or saturation levels are expected in the tailings, because they are very fine-grained and will retain water, and also because the coarse esker cover enhances infiltration and prevents evaporation from the tailings.

Concentrations of elements in discharge water were conservatively calculated for simple dilution of porewater into the tailings basin discharge. The calculations showed that the quality of discharge related to constituents of potential concern (COPC) will generally meet surface water quality objectives for estimates using the column test scaling factors.

- Copper exceeded criteria by a factor of about 3 for the largest seepage flow and the lowest saturation of tailings.
- Arsenic exhibited a marginal exceedance for the same extreme conditions. The calculated concentrations of several COPCs exceeded CCME guidelines when the field scaling factor was used to estimate metal concentrations when saturation values were less than 98%.
- Only arsenic concentrations exceeded the guidelines in discharge for the minimum seepage flow.

The calculated exceedances were considered to be highly unlikely as a result of the conservatisms assumed in the calculations, primarily the simple dilution of pore water concentrations into the drainage that will in reality be significantly attenuated by chemical reactions such as sorption during migration through the unsaturated tailings.

The conclusion of this review is that the current closure plan provides adequate protection to water quality for ongoing permafrost conditions and for post-thaw conditions in the event that permafrost disappears in the area in the future.

The discharge water quality is expected to improve by the ongoing, slow flushing of soluble oxidation products from historic oxidation of tailings prior to cover placement on the tailings cells. The loadings of soluble oxidation products are expected to decrease over time for ongoing permafrost conditions.

If the permafrost thaws in the future, small areas of tailings near the dams will have low watertable levels and may partially desaturate. The oxidation and loadings are not anticipated to represent a significant source of impairment to quality in the basin drainage with or without permafrost conditions at the site.

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1.0 INTRODUCTION

The Lupin tailings have been impounded in four cells contained by a combination of natural topographic highs and number of perimeter dams. The tailings containment area (TCA) consists of four tailings cells and several ponds. Active tailings storage was terminated in February 2005. Presently, runoff from the tailings cells and natural ground within the TCA flows through several ponds to Pond 2 from where it is periodically discharged into Seep Creek. Flow from the TCA eventually reaches the West Arm of Contwoyto Lake, about 6.5 km downstream of the TCA. A detailed description of the TCA is given by Holubec (2005) and of the water management after closure by Holubec (2006b)

Cover construction on the tailings began in 1985 and presently about 75% of the tailings are covered with about 1 m of sandy gravel (esker). The remaining tailings were expected to be covered in 2006 but, because of premature closing of the winter supply road to fuel deliveries, the cover completion has been delayed until 2007.

In the late 1980s, the tailings were recognized as potentially acid-generating with about 3% sulphur (AP of about 90 kg-$CaCO_3$/t) and a low NP (about 10 kg-$CaCO_3$/t). The current Cell No. 5 tailings had exhibited acidic drainage (pH of about 3.5) after exposure and weathering. The closure plan for the tailings therefore included mitigation measures to prevent ongoing long-term acid generation from exposed tailings.

The closure plan for the Lupin tailings included construction of permeable esker covers that would allow infiltration of water, minimize evaporation during summer months, and act as a storage medium to maintain the watertable or phreatic surface above the tailings surface. The cover also raised the base of the active zone of the permafrost close to the tailings surface. It is well known that sulphide tailings are geochemically stable below the watertable. Any thickness of a water layer above the tailings will act as a barrier to oxygen diffusion, and therefore will limit oxidation rates to very low or negligible values. Because the watertable will remain in the esker cover above the tailings, oxidation rates will be limited to the rate diffusion through water, an extremely slow process, or to the rate of dissolved oxygen transferred into the tailings if infiltration occurs.

Climate warming is raising the air temperatures across the Canadian permafrost regions and it may thaw the permafrost before 100 years at the Lupin site (Holubec, 2005). In that case, the frozen dams and their foundations will thaw and allow seepage from the tailings cells. If this occurs, there may be a potential for declines in water levels within the tailings adjacent to the dams and a consequent exposure to the atmosphere if diffusion rates increase.

1.1 Objectives and Scope of Work

This geochemical review was initiated to verify that the closure plan is based on sound geochemical principles, and that water quality in the downstream environment will be protected from ongoing acid drainage for existing permafrost conditions. There is also some concern for the potential loss of permafrost conditions, as a result of global warming. In that case, the tailings and the containment dams and their foundations will thaw. This will allow seepage through the dams and drop the groundwater surface below the tailings surface for some distance from the dams (Holubec, 2006a). If this occurs, there may be a potential for declines in water levels within the tailings cells with a consequent exposure to the atmosphere if diffusion rates increase.

This review of current permafrost conditions was completed by assessing the available data on water levels and quality in the porewater associated with the esker cover above the tailings (Cell 1), as well as water quality in the internal ponds and the discharge water. The data were used to demonstrate the effect of the tailings covers, and to verify the trend of improving water quality with time as the historically produced acidic waters are slowly flushed from the tailings-cover interface. The seepage analyses (Holubec, 2006a) provided flow of seepage and locations of the watertable in the tailings cells if the permafrost thaws. Water levels predicted from the seepage analysis formed a basis to evaluate oxidation rates from diffusion calculations to provide loadings to surface water. A sensitivity analysis was completed to assess the potential range in water quality associated with surface water downstream of the tailings if thawing occurs.

This report presents the review of the current permafrost conditions expected after closure in Section 2.0. This section briefly discusses the key concepts of the closure plan that affect long-term geochemistry at the Lupin tailings. The current geochemical conditions are reviewed and the future estimated water quality in the downstream environment is presented. Section 3.0 of this report discusses future conditions if the existing permafrost thaws. It presents the groundwater and seepage modelling results and the results of diffusion calculations to estimate seepage and downstream quality over the long term. Section 4.0 presents the conclusions of this review.

This report should be read in conjunction with the two companion volumes that describe the seepage analysis and geotechnical issues associated with the tailings and reported by Holubec (2006a and 2006b).

1.2 Characteristics of the Lupin Tailings

Field observations have shown that the Lupin tailings become acidic when exposed on surface. Klohn-Leonoff (1993) presented data on the tailings in Area 3 (now Cell 5) (Figure 1.1). The exposed tailings in 1993 were reported to contain an average of 3.2% sulphur, with an average Neutralization Potential (NP) and Acid Generation Potential (AP) of approximately 9 and 99 kg CaCO3/t, respectively. The negative net neutralization potential (NNP) was confirmed by the low paste pH values of approximately 3 to 3.5 on weathered samples from Cell 5. The tailings were reported to contain greater than 10,000 mg/kg arsenic, 53 mg/kg copper, 64 mg/kg zinc and approximately 200 mg/kg lead.

Data on fresh tailings from Area 3 (Cell 5) was also presented in Klohn-Leonoff (1993), and indicated similar characteristics with 3.1% sulphur and an NNP of -70 kg CaCO3/t. No metals analyses were reported for the fresh tailings and it was assumed to be similar to the oxidized tailings.

As part of the Acid Rock Drainage Study (Klohn-Leonoff, 1992a), five tailings samples from each of Area 1 (now Cell 3), Cell 2 and Area 3 (Cell 5) were tested for ABA. The Area 1 tailings had paste pH values between 8.1 and 8.6, with 3.2 to 4% sulphur and a NNP between -79 and -100 kg $CaCO_3$/t. The Cell 2 tailings were reported to contain between 2.6 and 3.8% sulphur with NNP values between -45 and -100 kg $CaCO_3$/t. The Cell 2 tailings were typically neutral, with paste pH values with the exception of one sample which was acidic with a paste pH of 3.8. All five of the tailings samples from Area 3 (Cell 5) were acidic with paste pH vales between 3 and 3.4, 2.5 to 3.5% sulphur and NNP values between -80 and -110 kg $CaCO_3$/t.

Klohn-Crippen (1995) collected tailings samples from over 80 locations at various depths up to 1.2 m from the northern portion of Cell 1 (Figure 1.1), near Dam 3. Approximately 42 samples were analyzed for ABA and/or metals content. The tailings were reported to contain in between 2.7 and 4.5% sulphur, with an average NP and AP of approximately 47 and 100 kg $CaCO_3$/t, respectively. Paste pH values for the tailings were primarily neutral, with no change with depth. Concentrations of arsenic ranged from 7,500 to >10,000 mg/kg, with nickel and zinc concentrations ranging from 19 to 41 mg/kg and 26 to 66 mg/kg, respectively. The cadmium content of the tailings was below detection, while copper and lead ranged from 30 to 74 mg/kg and 94 to 346 mg/kg, respectively. There was no trend in concentrations with depth noted.

Static ABA testing was also completed on one sample of the esker cover material by Klohn-Leonoff (1992a). The sample was reported to contain and average sulphur content of 0.02% (near the method detection limit) with an NP of 8.3 kg $CaCO_3$/t. The esker material was also subjected to SWEP leach testing (Klohn-Leonoff, 1992b). Concentrations of metals in the leachate were typically low, with arsenic, cadmium and lead below detection (0.02 mg/kg, 0.002 mg/kg and 0.02 mg/kg, respectively). The average nickel, zinc and copper concentrations were 0.07 mg/kg, 0.06 mg/kg and 0.02mg/kg, respectively.

1.3 Constituents of Potential Concern (COPC)

The constituents of potential concern (COPC) evaluated included arsenic, cadmium, copper, nickel and zinc. Several other constituents (including those in a 22 element ICP-MS scan, cyanide, major ions, and other analytes) were examined initially, but were not part of the investigation since concentrations in the tailings porewater were typically low or below detection, or for which no applicable discharge or regulatory limits exist. Table 1.1 provides a summary of the 2005 porewater chemistry in the tailings, along with the discharge criteria for the Lupin site and Canadian Council of Ministers of the Environmental (CCME) Environmental Quality Guidelines for the protection of aquatic life for freshwater (CCME, 2005).

2.0 EXPECTED CASE FOR ONGOING PERMAFROST CONDITIONS

This section presents geochemical conditions in and downstream of the tailings cells, and rationale for the expected ongoing protection of the downstream environment. The processes that have led to the existing, and that will control the future, water quality in the active saturated zone of the tailings are discussed.

2.1 Key Closure Plan Components

The existing tailings impoundment consists of four large cells (Cells 1, 2, 3 and 5. Cell 4 was not filled). Each cell is separated from one of the two internal ponds by an esker dam with a frozen core. The outflow from the tailings basin occurs as seasonal discharge over a small dam (at a natural outlet of the watershed), through two 18-inch diameter syphons.

The permeable esker cover layers represent a layer in which the watertable or phreatic surface resides above the tailings surface. This water layer acts as a barrier to oxygen diffusion into the tailings. The layer also acts as an infiltration layer and an evaporation barrier that prevents loss of water during the summer. Annual infiltration but low evaporation would normally result in water infiltrating into the tailings if the tailings were not frozen. Under frozen or permafrost conditions, this excess water migrates laterally through the esker cover to emerge in cell depressions and decants (Cell 1) and/or seeps through the upper annual unfrozen layer of the dams into the adjacent ponds. If permafrost thaws in the future, the infiltration will maintain a high watertable in the underlying unfrozen tailings due to their low permeability. Water entering the esker cover will either infiltrate the tailings and flow downwards into the more permeable bedrock, and then flow laterally through the underlying bedrock toward the ponds, or flow through the esker cover along the saturated tailings surface until it reaches a point where the bedrock can absorb all available surface water. In this case, the groundwater surface will drop below and into the tailings. This will leave a small section of the tailings unsaturated near the dams. This is demonstrated in the seepage analysis (Holubec, 2006a). The high watertable that will be maintained throughout most of the tailings will protect the tailings from significant oxidation. The small areas adjacent to the dams that have a lower watertable, as shown in the seepage study, will maintain high moisture contents because of the fine-grained nature of these gold tailings. Some oxidation may occur in the upper zone of the tailings near the dams but it will be limited by high retained moisture. In addition, most of the water affected by oxidation will migrate vertically through the tailings to the bedrock before seeping into the surface ponds. The migration path through the tailings also provides a zone for chemical attenuation that can mitigate the water quality if it is affected by the limited oxidation that can occur in the tailings with a lower watertable adjacent to the dams. These issues will be described in further detail below.

2.2 Current Geochemical Conditions

2.2.1 Tailings Cover Porewater Chemistry

To obtain a better understanding of the porewater chemistry within the esker cover, nine standpipes (shallow monitoring wells) were installed in Cell 1 in August 2002 (Figure 2.1). The WC1-1 pipe was removed in 2004. The pipe was installed in an area where 0.5 m of waste rock had been placed over top of the tailings, and this rock was covered with about 1 m of esker. As a result, the bottom of the pipe butts against the top of the waste rock cover. Therefore, the pipe did not provide sufficient water for sampling. Subsequently, this pipe was replaced with Pipe WC1-7 and was placed deeper into the cover/tailings at that time.

Figure 2.2 presents a summary of the porewater chemistry within the cover over time since 2002. The pH values range from 3.3 to 4 in pipe WC1-2 to 5.3 to 6 in WC1-6. A general decreasing trend of impacted water quality was observed for all pipes with a decrease in pH between 0.5 and 1.0 between 2002 and 2005. The data suggest that there may have been some increase in pH between 2004 and 2005 in some pipes.

In general, the chemistry is quite variable with concentrations of arsenic ranging from <0.001 to 12 mg/L, nickel concentrations from <0.001 to 4 mg/L and copper from <0.001 to 0.4 mg/L in the cover porewater. A large increase in nickel and copper concentrations is noted for the final sample collected in WC1-7. A similar increase was also observed for copper in WC1-5.

The observed pH values and water quality in the porewater above the tailings interface is the result of historic oxidation prior to cover construction. The exposed tailings would have oxidized and some areas would have generated acid and released metals to the porewater near the surface where oxidation in tailings is known to occur. Generally, the oxidation zone in moist tailings is restricted to the upper-most zone of the tailings. The oxidation zone is more limited to shallow depths as the moisture content of the tailings increases. The porewater in the shallow tailings would have had low pH and elevated levels of metals and other oxidation products prior to cover placement. Once the cover was in place, water accumulated on top of the tailings surface to form a water-saturated zone at the bottom of the esker cover. This water does not flow down through the frozen tailings but mixes with the porewater in the shallow tailings in the thermally active layer before migrating laterally through the cover to eventually seep into the adjacent ponds. The historic acidic porewater would have mixed slowly with the water in the cover layer producing lower pH and elevated metals in the saturated esker zone. Over the next few years, the ongoing clean infiltration water will flush out and dilute the acidic waters affected by the top of the oxidized tailings. Because the covered tailings are below the watertable, the oxidation reactions have been shut down and the ongoing flushing by infiltrating water will eventually result in cleaner water in the esker layer.

2.2.2 Surface Water Chemistry

Water samples have been routinely collected from numerous locations from Pond 1, Pond 2 as well as the discharge as shown in Figure 2.3. In general, samples collected from the same water body (i.e. Pond 1 or Pond 2) exhibited consistent chemistry. Therefore, only the chemistry from sample points Station 104 representing Pond 1, and Station 102 representing Pond 2, along with the discharge water chemistry are discussed below. These sampling locations are shown in Figure 2.3. Data for samples collected from Station 104 and the discharge were available since 1985 while samples have been collected since 1991 for STN 102. Samples were generally collected on a yearly basis between 1985 and 1991, and on a monthly basis from 1991 until 1997, after which only seasonal (spring, summer and fall) sampling was completed.

Between 1985 and 1990, the tailings were primarily deposited in Cells 1 and 2. However, after the construction of Dam K in 1990, the tailings disposal moved to Cell 3 (formerly called Area 1). Most of the water deposited in Cell 3 with the tailings remained within the Cell, and as such Pond 1 only received approximately 1/6th of the tailings water formerly decanted into Pond 1 from Cells 1 and 2 prior to 1990 (Klohn-Leonoff, 1992b). This is significant since the tailings water was a major source of alkalinity to Pond 1. To account for the loss of alkalinity, lime was spread over the ice in Pond 2 during the winter months of 1992 (Klohn-Leonoff, 1992b). Approximately 25-30 tonnes of lime have been added on a yearly basis in April. However, in 2005, only 4 tonnes of lime were added, and the pH dropped as a result as can be seen in Figure 2.4. The influences of the water management practices can be seen in the surface water chemistry, as shown in Figure 2.4.

The pH of Pond 1 generally ranged between 7 and 8.5, while the pH of the Pond 2 water was variable, generally ranging from 4 to 7 (Figure 2.4). For both sample locations, a decreasing trend in pH was observed from 1991 to early 1992, followed by relatively constant pH values since 1992. The pH of the discharge has generally remained constant since 1985, ranging from pH values of 6 to 8.

Concentration trends with time in the ponds are presented in Figure 2.4. The time trends suggest that improvements in the water quality have occurred over the last several years since the placement of the cover on Cell 1 in 1995. In Pond 1, concentrations of arsenic exhibit an initial decrease in concentration from 2 mg/L in 1985 to 1 mg/L in 1988 before increasing to 3.5 mg/L in 1991. Concentrations decrease to 0.1 mg/L in 2001 in Pond 1. Similarly, arsenic concentrations in Pond 2 decreased from 0.25 mg/L in 1991 to relatively steady concentrations of 0.03 mg/L since 1992. Arsenic concentrations in the discharge water show an initial decrease from about 0.6 mg/L in 1985 to approximately 0.1 mg/L in 1991, and have remained below 0.1 mg/L since 1991.

Nickel concentrations in Pond 1 showed an increase in concentration from 0.05 mg/L in 1985 to a peak concentration of 0.25 mg/L in 1987 before decreasing again to approximately 0.06 mg/L in 1989. The nickel concentration in 1990 increased to 0.16 mg/L but decreased to below 0.05 mg/L in 1991. Between 1991 and 1996, nickel concentrations in Pond 1 show an increase from below 0.05 mg/L to about 0.15 mg/L. Concentrations generally ranged from 0.05 to 0.15 mg/L during the same period in Pond 2. Although the average nickel concentrations in Pond 2 increased after 1996, both Ponds 1 and 2 exhibit general decreases since 1996. Nickel concentrations in the discharge water generally ranged from 0.05 to 0.1 mg/L between 1985 and 1996, and similar to Pond 2, showed an initial increase in concentration with a decreasing trend since 1996.

Copper concentrations in Pond 1 showed similar trends as nickel, with an increase in concentration between 1985 and 1987 from 0.5 mg/L to 2.8 mg/L, a decrease to 0.35 mg/L over the next 2 years before increasing to 0.9 mg/L in 1990 and decreasing again to below 0.15 mg/L in 1991. Concentrations in Pond 1 exhibited an increase between 1991 and 1996 with a decrease in concentration since 1996. Copper concentrations range from 0.02 and 0.07 mg/L since 1996. Copper concentrations in Pond 2 show an initial increase to 0.25 mg/L from 1991 to 1992. Since 1992, concentrations are generally steady, ranging from 0.001 and 0.05 mg/L. The discharge water exhibited copper concentrations ranging between 0.1 and 0.3 mg/L between 1985 and 1991, with the peak concentration seen in 1987, and ranged between 0.001 and 0.03 mg/L between 1991 and 2005.

In general, the quality of the water in the ponds has exhibited improvement over time and appears to exhibit continual improvement. Nonetheless, the concentrations of COPCs in the ponds will likely exhibit influences from the slow flushing of soluble oxidation products in the porewater of the esker covers near the tailings interface for several years with diminishing concentrations over time.

2.2.3 Porewater Contribution to Surface Water

To evaluate the contribution of the tailings cover porewater to pond chemistry over time, the ratios of concentrations in the ponds to those in the porewater within the cover on Cell 1 was examined. The average concentrations of selected constituents were calculated in the pond, and porewater between 1997 and 2005 and for 2005 only. Ratios of concentrations in the ponds to those in the cover porewater were also calculated over the same time periods (Table 2.1). A higher number for the ratio relates to a higher contribution of the cover porewater to surface water. The results show that water quality in surface water is generally similar to or better in 2005 than the average water quality over the 1997 to 2005 time period. Similar trends are seen for the discharge water relative to the cover porewater chemistry.

The ratios of porewater to surface water with values greater than 1 reflect the effects of attenuation and dilution, and also indicate that the seepage flow of the porewater from the cover is only a small fraction of the flow in the tailings basin. The change in the ratios from the average over the last decade compared to 2005 values indicates that the progressive covering of the tailings has led to improved surface water quality in a relatively short period of time and that future improvement can be anticipated.

2.3 Anticipated Future Conditions with Permafrost

The quality of water in Ponds 1 and 2 in the Lupin TCA in the future, for ongoing permafrost conditions, will be influenced by two main processes.

The most important process over the intermediate timeframe of the next few years to decades will be the slow flushing of poor quality water that developed in the shallow exposed tailings prior to cover construction. This water will be displaced by fresh infiltration of rain and snowmelt annually. This ongoing flushing will result in a continual decline in loadings to Ponds 1 and 2 over time.

The second process that can affect water quality in the ponds is the residual, slow oxidation and leaching of the tailings immediately below the esker cover layer. Because the tailings will be below a shallow water cover with the watertable in the esker layer, the dominant means of oxygen entry at the tailings surface will be by infiltration of water containing dissolved oxygen (DO). The oxidation by DO will consume all available oxygen in the infiltrating water and the oxidation rate will be limited by the rate of infiltration.

Pyrite oxidation is assumed to be responsible for the majority of the sulphide oxidation and oxygen consumption. The oxidation reaction can be written as:

$$FeS_2 + 15/4\ O_2 \rightarrow 2SO^{2-}{}_4 + Fe(OH)_3 + 4H^+$$

This reaction allows the calculation of sulphate concentrations in infiltration if we assume that all DO converts to sulphate as it enters the surface of the tailings.

A reasonable estimate for the DO concentration in infiltrating water is 10 mg/L. If all of the DO is consumed by pyrite oxidation, then the concentration of sulphate will be 16 mg/L accounting for the appropriate stoichiometry and molar weights of oxygen and sulphate. This means that infiltration alone without any oxygen diffusion (that will be insignificant for saturated conditions, as shown later in this document) will only produce a sulphate concentration of 16 mg/L in the tailings porewater.

The concentrations of other oxidation products, specifically metals, can be estimated by scaling observed metal concentrations to observed sulphate concentrations for effluent from tailings oxidation. Column tests to assess oxidation in Lupin tailings were completed in the early 1990s (Klohn-Leonoff, 1993). The tests were conducted for more than 20 weeks, and the effluent was monitored for pH, sulphate and a suite of metals. The concentrations in the column effluent are shown in Table 2.2. Data are also available for the porewater in the esker cover above the tailings in Cell 1 for July and August 2005. These concentrations are also shown in Table 2.2. The ratios of individual metals to sulphate concentrations for individual samples and an average scaling factor for each metal were then calculated.

The ratios of metal to sulphate concentrations in the column effluent are good indicators of metal release rates in actively oxidizing tailings. The column was unsaturated, and the high sulphate levels and low pH values indicate that oxidation was occurring during the test. These conditions are also favourable for metal release and mobility with little potential for chemical attenuation (with the exception of lead that can form $PbSO_4$ under acidic conditions). Therefore, the scaling factors for metals from sulphate concentrations derived from the column test results should be good indicators of metal release rates and concentrations if the sulphate production rates or concentrations are known.

The concentration ratios of metals to sulphate in the esker porewater, collected in pipes from Cell 1 in 2005, represent a condition of flushing after oxidation has effectively ceased. The water chemistry, including low pH, elevated sulphate and metal concentrations, indicate that significant oxidation of tailings had occurred in the past. However, after construction of the cover and natural inundation of the tailings below the shallow watertable, rapid oxidation would have effectively stopped and flushing of the soluble oxidation products by infiltration would have started. In 2005, flushing would have been occurring for several years. The flushing process is suggested by the lower sulphate concentrations, with an average of just more than 800 mg/L (Table 2.2) compared to an average value of more than 2,000 mg/L for sulphate in the column test.

Table 2.2 shows that the scaling factors for the field data are consistently larger than those for the column test. This indicates that the field scaling factors would predict higher metal concentrations for a specific sulphate concentration than the column test scaling factors. The larger factors for the field data are likely an artifact of flushing of accumulated oxidation products in the historically oxidized tailings, and are likely overly conservative for estimating metal release rates and concentrations in tailings that will be subjected to low oxidation rates below the esker cover layer. Nonetheless, the field scaling factors were carried forward to provide conservative upper-bound estimates of metal concentrations for future conditions in the tailings.

The scaling factors were used to calculate the anticipated concentrations of metals based on the predicted sulphate values for infiltration of water containing 10 mg/L of DO. The predicted concentrations are shown in Table 2.3 for both the column test and field scaling factors.

These calculations show that the long-term steady-state concentrations of sulphate and metals, as a result of residual oxidation of Lupin tailings below the watertable, will be low in the tailings porewater. The concentrations estimated with the column test scaling factors are lower than applicable surface water criteria, and would be suitable for discharge directly to the environment without concern for additional dilution or other attenuating mechanisms. The estimated metal concentrations using the field scaling factors are higher than those using the column test data, but the majority remain below applicable surface water guidelines. Predicted arsenic concentrations in porewater, for the field scaling factor, were about ten times higher than the CCME guideline of 0.005 mg/L, and zinc marginally exceeded the CCME guideline of 0.03 mg/L in these predictions. Experience suggests that the predicted metal concentrations in flooded, previously unoxidized sulphide tailings would be lower than those predicted in Table 2.3 using the field scaling factors, and would likely be more similar to those predicted with the column test scaling factors.

3.0 FUTURE CONDITIONS IF THE PERMAFROST THAWS

Groundwater levels and seepage volumes expected in the thawed tailings were presented by Holubec (2006a, Volume I). The most important factor that was estimated is the area of unsaturated tailings that may be subject to limited dewatering or desaturation near the dams. The saturated tailings further from the dams will remain below the watertable and will produce water quality that is typical of flooded tailings as discussed in Section 2 of this report. The unsaturated tailings, in contrast, will be influenced by the diffusion of oxygen into the partially air-filled pores in the tailings, and the rates of oxidation of these tailings are potentially greater than those of the saturated tailings. A diffusion model was applied to estimate the pyrite oxidation rates for an expected range of saturation conditions in the tailings near the dams.

3.1 Diffusion Control on Pyrite Oxidation

Diffusion of oxygen through gas-filled pore spaces is an important process in the oxidation of sulphide tailings. The effective diffusion coefficient for oxygen is controlled by the degree of water saturation of the pore voids in the tailings if the surface of the tailings is exposed to the atmosphere. Although the tailings will be covered by an esker layer, the material is coarse-grained, and will be well-drained near the dams so the esker can be neglected in the diffusion calculations. It is assumed, conservatively, that the unsaturated tailings have free access to atmospheric oxygen.

The esker cover layer, adjacent to the dams where the groundwater surface will drop below the tailings surface, will not act as a moisture-retaining layer to impede oxygen diffusion. However, it will enhance infiltration and also provide an evaporation barrier. This will maintain high moisture in the fine-grained tailings in the unsaturated zone near the dams, even though the watertable will be below the tailings surface near the dams, as shown by Holubec (2006a, Volume I). Tailings, especially fine silts, are known to have very high water retention characteristics. The water retention is sometimes referred to as the air entry value (AEV) and can be expressed in pressure (e.g., kPa) or as the equivalent head or height of water suction needed to begin to initially drain water from the tailings pore spaces. Values of several metres of equivalent suction are common for AEVs in tailings especially for the finer-grained materials such as the Lupin tailings. The AEV is also the depth at which the watertable can decline before desaturation of the tailings surface begins. The AEV of the Kidd tailings in Timmins, ON, was found to be about 8 m, and this means that the watertable could decline to a depth of 8 m below surface before desaturation of the tailings surface can occur from suction (or gravity). Desaturation of exposed tailings is common as a result of evaporation from exposed surfaces, but evaporative desaturation will not occur below the esker cover layer.

Modelling of pyrite oxidation was completed to assess the oxidation rate in the tailings. It was assumed that the degree of saturation would be in the range of 90 to 100% in the fine-grained Lupin tailings and that the sulphur content would be in the range of 2.7 to 4.5% S. These assumptions provided bounds for the expected oxidation rates near the dams. The degree of saturation and the sulphur contents were utilized in a pyrite oxidation model that calculates the oxidation rate for steady-state conditions.

The objective of the pyrite oxidation modelling was to determine the probable rate of oxidation or flux of oxygen in the tailings immediately below the cover layer and to estimate the concentrations of oxidation products, including the key metals.

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/m^3)
t = time(s)
D_e = effective diffusion coefficient for oxygen in moist tailings (m^2/s)
x = depth (m)
K = pyrite oxidation rate constant (1/s)
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:

$C = C_o$ at $X = 0$
$C = 0$ at $X = \infty$

The gas-filled porosity is equal to 1-θw, where θw 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 2.2×10^{-9} mol-O_2/m^2/s for standard conditions presented in Nicholson (1994) and Elberling *et al.* (1994).

The most important parameter in this model is the moisture content or degree of saturation (θ_w/n) that controls the effective diffusion coefficient for oxygen in the tailings. The diffusion coefficient is calculated from an empirical relationship with the 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 3.1. 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 Lupin tailings have a very high silt content. The 27% of sand-sized particles floating within the silt give the tailings very low permeability that prevents the tailings from becoming readily dewatered (Holubec, 2006a). In addition, the esker cover will enhance infiltration of water and prevent evaporation from the tailings. 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 90 to 100%. The other unknown that may control the uptake of oxygen is the sulphide content. The sulphide content of the tailings is in the range of 2.7 to 4.5% 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 and the overall oxidation rate, in any case, are not very sensitive to reaction order.

The flux of oxygen can be calculated for the modelled conditions. The steady-state flux of oxygen at the surface of the tailings can be approximated by:

$$Fo_2 = C_o (K D_e \theta_g)^{1/2}$$

The oxygen flux can be converted to a sulphate flux using the stoichiometry of the pyrite oxidation reaction shown in Section 2 of this report. The sulphate flux can then be used to calculate a concentration in the porewater for based on the average annual infiltration with the equation:

$$C_{SO4} = F_{SO4}/I$$

where C_{SO4} is the sulphate concentration (mg/L) in porewater, F_{SO4} is the sulphate flux (mg/m^2/a) and I is the infiltration rate (L/m^2/a). This calculation conservatively assumes that all sulphate is produced at the tailings surface and is not diluted by deeper water in the tailings.

3.2 Loadings from the Unsaturated Tailings

The oxidation rates (oxygen flux) for the tailings were calculated for four saturation values between 90 and 100% and two sulphide contents (2.7 and 4.5% S). The oxygen flux values were converted to sulphate concentrations. The differences between the oxidation rates and sulphate concentrations for the range of sulphide contents are on the order of between 15 and 20%, and therefore only the upper value of 4.5% S was considered further in this evaluation. A summary of the calculated oxygen flux values from the diffusion model is presented in Table 3.1. The oxygen flux was adjusted to account for frozen conditions for a period of the year during which diffusion would not occur because the tailings will be frozen and will not consume oxygen. It was conservatively assumed that the oxidation or unfrozen period will be six months per year. The sulphate concentrations in porewater resulting from oxygen diffusion only were calculated and are shown in Table 3.1. In addition to diffusion, the oxidation will include reaction of the dissolved oxygen (DO) that enters the tailings with infiltration as discussed in Section 2. In most cases of sulphide oxidation, the oxidation by DO is trivial and only results in an incremental sulphate concentration of 16 mg/L. However, in low oxidation systems that are near saturation, with mitigation measures, the oxidation by DO can exceed that by diffusion, so that it was added to the diffusion component of oxidation for a total sulphate concentration in porewater resulting from diffusion plus infiltration as shown in Table 3.1.

The concentrations of metals in porewater were then calculated from the predicted sulphate concentrations in the unsaturated tailings. The concentrations of constituents in the discharge from the tailings basin were then estimated by considering the loadings from the unsaturated tailings porewater in the overall flow from the TCA.

3.3 Water Quality in Tailings Basin Discharge

The areas of unsaturated tailings near the dams and annual seepage volumes were presented by Holubec (2006a, Volume I) for several cases in the seepage analysis. These areas contribute porewater as seepage to flow in the basin. The overall flow from the tailings for a post-thaw condition was estimated to be about 1.18×10^6 m^3/a. A conservative estimate of the quality of the discharge water was developed by considering only the dilution of porewater from the unsaturated tailings into the overall flow from the TCA without any consideration of chemical attenuation. The areas of unsaturated tailings vary between cases, and depend on the hydraulic parameters assumed for the tailings and underlying bedrock, as discussed by Holubec (2006a, Volume I). A summary of the seepage volumes from the unsaturated areas of the tailings for the six cases presented by Holubec (2006a, Volume I) is given in Table 3.2. The seepage flows range from about 12,000 to 90,000 m^3/a. Dilution factors were calculated for each of these cases assuming that the seepage flows mix into the total flow from the basin (Table 3.2). The dilution factors range from a high of about 0.08 for the highest seepage flow to about 0.01 for the lowest seepage flow. These dilution factors were considered to calculate maximum and minimum concentrations to evaluate the predicted water quality ranges expected in the discharge from the TCA for long-term post-thaw conditions.

The predicted water quality of the TCA discharge is presented in two tables. Table 3.3 presents the range of concentrations expected from the minimum and maximum unsaturated tailings areas when the field scaling factor was used to estimate metal concentrations. These results are considered to be very conservative and unlikely to occur. Table 3.4 presents a summary of water quality when the column test scaling factor was applied to estimate metal concentrations in the tailings porewater.

All calculated concentrations, with the exception of those for arsenic, cadmium and copper for the lowest saturation values fall below the respective CCME guidelines when the column test scaling factors were used to estimate metal concentrations in the tailings porewater.

Arsenic exceeded the guideline only marginally while cadmium was about a factor of 10 in excess of the CCME value of 0.000017 mg/L (or 0.017 μg/L).

For the lowest saturation in the tailings and the maximum seepage flows, copper exceeded the upper limit of the CCME guideline by a factor of 3.

These values suggest that expected overall water quality in the TCA drainage will be acceptable in the long term for post-thaw conditions.

The calculated concentrations for arsenic, copper, nickel and zinc exceed surface water quality guidelines in the discharge for some conditions when the field scaling factors are applied (Table 3.3). Only arsenic exceeds the limit for the minimum seepage volume expected. Copper exceeds the limit by a maximum factor of about 6, nickel by a maximum factor of 8 and zinc by a maximum factor of about 2 for the largest seepage volume and lowest saturation conditions.

These concentration estimates are considered to be highly conservative for the following reasons.

First, as discussed in Section 2, the field scaling factors for metal concentrations appear to be high, and may be influenced by flushing and dissolution of historic oxidation products rather than by active oxidation of the tailings.

Second, these concentrations are based on a simple dilution of tailings porewater into the basin discharge. In reality, the porewater that is affected by oxidation in the unsaturated tailings will infiltrate vertically downward through the tailings to the watertable before migrating laterally to the dam to emerge as seepage. This is quite different from current conditions in which the soluble oxidation products are produced at the top of the tailings and migrate laterally through the sandy esker (across the frozen tailings) to emerge as seepage from the dam. The migration of porewater through the tailings in the post-thaw period will enhance attenuation of many constituents including arsenic, copper and nickel. The main process of chemical attenuation is expected to be in the form of sorption. Sorption onto ferric hydroxide surfaces is known to be an important control on arsenic and many metals. The sorption of metals on ferric hydroxides is known to be enhanced at neutral to alkaline pH. If oxidation rates are low, as expected, in the unsaturated tailings, the migration through the non-oxidized tailings below the surface will maintain neutral pH of the porewater. The slow vertical migration through the unsaturated tailings of about 0.6 m/a will also provide adequate time for chemical sorption and neutralization reactions to occur.

The chemical attenuation of metals along the flowpath through the tailings will be significant, and will act to decrease concentrations well below those predicted by dilution alone. Therefore, although conservative estimates of discharge concentrations suggest that some exceedances are possible, the degree of conservatism included in the calculations suggest that the exceedances are highly unlikely.

In addition, it is predicted that permafrost thawing will likely be accompanied by increased precipitation at the site. The seepage analysis assumed that the increase could be as high as 50% over normal values. This means that additional dilution can reduce concentrations by almost 35% over those shown in Tables 3.3 and 3.4. This adds further conservatism to the concentration estimates.

4.0 CONCLUSIONS

This review led to the following conclusions:

- Lupin tailings are potentially acid-generating if exposed to the atmosphere for prolonged periods.

- Quality of porewater in the esker cover immediately above the tailings has been influenced by historic soluble oxidation products that were generated in the near surface tailings prior to cover construction.

- Development of a shallow watertable in the esker cover layers above the tailings prevents significant oxidation of the tailings for ongoing permafrost conditions.

- Quality of water in the internal ponds and in discharge from the basin will continue to be influenced by the slow flushing of soluble oxidation products from the active zone of the tailings below the esker covers.

- Effects of the flushing of soluble oxidation products on discharge quality will diminish over the next several years to a few decades.

- With a watertable condition over the tailings, the generation of acid and leaching of metals have been effectively stopped for ongoing permafrost conditions.

- If permafrost thaws in the future, the unsaturated tailings adjacent to the dams will continue to retain high degrees of water saturation. The fine-grained nature of the tailings, enhanced infiltration and prevention of evaporation associated with the esker cover will likely keep the saturation of the tailings high.

- Majority of the tailings areas beyond the small unsaturated areas adjacent to the dams will remain fully saturated and thereby exhibit similar very low to negligible oxidation rates that occur under current saturated conditions.

- Predicted concentrations in discharge from the basin were estimated to be very near or below guideline values for protection of the aquatic environment based on realistic scaling factors for estimating metal concentrations in tailings porewater from known sulphate values and for simple dilution calculations.

- Using more conservative scaling factors for metal concentrations:

    - resulted in predicted concentrations of arsenic that exceeded the guideline for the minimum seepage volume into the basin when saturation values in the tailings were less than 98%; and

  - resulted in predicted concentrations of arsenic, copper, nickel and zinc that exceeded the guidelines for the maximum seepage volumes and when the saturation values in the tailings were less than 98%.

- Estimated exceedances for these constituents is considered to be highly unlikely as a result of the conservative assumption of dilution only with no chemical attenuation – a process that will be important as affected porewater migrates vertically through the unsaturated tailings.

- Overall, the current closure plan is considered to be protective of downstream water quality for the current permafrost conditions and for post-thaw conditions should permafrost disappear as a result of global warming.

5.0 REFERENCES

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Table 1.1: Summary of 2005 Tailings Cover Chemistry and Applicable Regulatory Limits

Parameter		Average Concentration in Cell 1 Cover Pipes (2005)	Discharge Criteria[1]		CCME Guidelines[2]	Comments
			Maximum Average Concentration	Maximum Concentration of any Grab Sample		
pH	---	4.6	6.5 - 9.5	6.5 - 9.5	6.5-9.0	
Alkalinity	mg $CaCO_3$/L	15	---	---	---	
Conductivity	mS	1145	---	---	---	Indicator Parameter
Hardness	mg $CaCO_3$/L	606	---	---	---	
Antimony	mg/L	0.0004	---	---	---	
Arsenic	mg/L	0.9	0.05	1.00	0.005	COPC
Cadmium	mg/L	0.003	---	---	0.000017 [3,4]	COPC
Cobalt	mg/L	1	---	---	---	
Copper	mg/L	0.2	0.15	0.30	0.002-0.004 [3]	COPC
Cyanide	mg/L	0.02	0.80	1.60	0.005	
Lead	mg/L	0.02	0.10	0.20	0.001-0.007 [3]	COPC
Mercury	mg/L	<0.0001	---	---	0.00001	
Molybdenum	mg/L	<0.001	---	---	0.073	
Nickel	mg/L	1.6	0.20	0.40	0.025-0.15 [3]	COPC
Sulphate	mg/L	660	---	---	---	Indicator Parameter
Uranium	mg/L	0.004	---	---	---	
Zinc	mg/L	0.5	0.40	0.80	0.03	COPC

Notes:

1 - Discharge Limits for Current Water Board License

2 - Guidelines for the Protection of Aquatic Life - Fresh Water

3 - Hardness Based Limits - Upper Limits for >180 mg $CaCO_3$/L

4 - Interim Guideline

Table 2.1: Ratios of Metal Concentrations in the Ponds Relative to Concentrations Observed in the Cover Porewater and Discharge

Average from 1997 to 2005

	Cyanide	Arsenic	Cadmium	Copper	Nickel	Zinc
Cover WQ	1	1	1	1	1	1
Cell pond	0.25	0.09	0.18	0.16	0.09	0.27
Pond 1	20.7	1.00	0.11	0.68	0.05	0.25
Pond 2	1.90	0.06	0.12	0.12	0.06	0.57
Discharge	1.71	0.04	1.49	0.05	0.06	1.69

2005 Values

	Cyanide	Arsenic	Cadmium	Copper	Nickel	Zinc
Cover WQ	1	1	1	1	1	1
Cell pond	0.25	0.06	0.18	0.16	0.09	0.26
Pond 1	17.0	0.05	0.04	0.25	0.05	0.40
Pond 2	1.99	0.01	0.05	0.07	0.06	0.51
Dischage	2.39	0.01	0.04	0.09	0.06	0.51

Table 2.2: Determination of Scaling Factors from Sulphate Data

Column 1 Data from Klohn-Leonoff (1993)								
	pH	**Sulphate (mg/L)**	**Arsenic (mg/L)**	**Cadmium (mg/L)**	**Copper (mg/L)**	**Zinc (mg/L)**	**Lead (mg/L)**	**Nickel (mg/L)**
Individual Data	3.08	11375	2.300	0.020	0.100	1.700	0.400	0.100
	3.36	4509	0.800	0.010	0.200	1.000	0.100	0.100
	3.22	2389	0.200	0.010	1.700	1.600	0.100	0.100
	3.20	2029	0.100	0.010	1.400	0.800	0.100	0.100
	3.85	2786	0.040	0.002	0.060	0.260	0.040	0.010
	3.87	1855	0.090	0.002	0.060	0.220	0.020	0.005
	0.52	1722	0.190	0.003	0.130	0.240	0.050	0.024
	3.47	1714	0.210	0.002	0.140	0.290	0.020	0.005
	3.45	1714	0.020	0.002	0.100	0.190	0.020	0.005
	3.47	1670	0.020	0.003	0.130	0.190	0.020	0.005
	3.39	1720	0.140	0.002	0.190	0.100	0.020	0.005
	3.25	1770	0.100	0.002	0.260	0.110	0.020	0.005
Average	3.18	2938	0.351	0.006	0.373	0.558	0.076	0.039
Scaling Factor Based on Sulphate		**1**	**8.08E-05**	**1.92E-06**	**1.72E-04**	**1.92E-04**	**2.17E-05**	**1.31E-05**
2005 Chemistry from Tailings Pipes								
	pH	**Sulphate (mg/L)**	**Arsenic (mg/L)**	**Cadmium (mg/L)**	**Copper (mg/L)**	**Zinc (mg/L)**	**Lead (mg/L)**	**Nickel (mg/L)**
Individual Data	**July 2005**							
	4.74	846	1.290	0.004	0.150	0.950	0.040	2.480
	5.98	989	0.877	0.003	0.221	0.645	0.034	2.090
	3.36	702	2.120	0.003	0.300	0.783	0.054	1.550
	4.17	1470	0.173	0.005	0.116	0.694	0.006	3.580
	5.28	270	4.360	0.001	0.118	0.156	0.108	0.093
	4.55	145	1.340	0.002	0.120	0.264	0.034	0.566
	4.44	375	1.320	0.002	0.083	0.402	0.029	1.170
Individual Data	**August 2005**							
	4.88	931	1.070	0.005	0.186	1.110	0.025	2.930
	6.96	1010	1.110	0.002	0.146	0.607	0.033	1.810
	3.34	681	3.390	0.003	0.263	0.884	0.054	1.780
	4.85	654	0.046	0.003	0.192	0.511	0.006	1.670
	4.13	1760	0.047	0.007	0.372	0.777	0.003	3.920
Average	4.72	819	1.429	0.003	0.189	0.649	0.036	1.970
Scaling Factor Based on Sulphate		**1**	**3.48E-03**	**4.82E-06**	**3.02E-04**	**9.29E-04**	**8.56E-05**	**2.45E-03**

Table 2.3: Predicted Metal Concentrations in Tailings Porewater Based on Infiltration of Dissolved Oxygen Only

Parameter	Predicted Porewater Concentration	
	Using Scaling Factor from Tailings Oxidation Column Test Data (Klohn-Leonoff, 1993)	Using Scaling Factor from 2005 Tailings Pipe Chemistry
Sulphate (mg/L)	16 [1]	16 [1]
Arsenic (mg/L)	0.0013	0.0557
Cadmium (mg/L)	0.00003	0.00008
Copper (mg/L)	0.0027	0.0048
Zinc (mg/L)	0.0031	0.0149
Lead (mg/L)	0.0003	0.0014
Nickel (mg/L)	0.0002	0.0392

Notes:

1 - Dissolved Oxygen = 10 mg/L yields a sulphate concentration of 16 mg/L based on pyrite oxidation

Table 3.1: Predicted Oxygen Flux into the Tailings and Sulphate Concentrations in the Tailings Porewater for a Sulphide Content of 4.5% (S)

Tailings Saturation	Oxygen Flux ($mg/m^2/a$)	Sulphate Concentration in Porewater (mg/L)	
		Diffusion Only	Diffusion and Infiltration
100	804	3	19
98	14,676	49	65
94	101,755	340	356
90	300,712	1006	1022

Table 3.2: Calculated Dilution Factors Based on Modelled Seepage Estimates

Model Case [1]	**Estimated Seepage Volume** [1] **(m^3)**	**Dilution Factor** [2]
Case 1	89,700	0.076
Case 2	17,940	0.015
Case 3	76,245	0.065
Case 4	77,740	0.066
Case 5	11,960	0.010
Case 6	71,760	0.061

Notes:
1 - Refer to Volume 1 (Holubec, 2006)
2 - Based on Total Annual Flow of $1.175x10^6$ m^3/a

Table 3.3: Predicted Concentration Ranges for Constituents in Discharge for Different Degrees of Tailings Saturation and the Range of Anticipated Seepage Volume
(Field Scaling Factors Applied to Estimate Metal Concentrations)

Water Saturation (%)	Sulphate (mg/L)		Arsenic[1] (mg/L)		Cadmium[1] (mg/L)		Copper[1] (mg/L)		Lead[1] (mg/L)		Nickel[1] (mg/L)		Zinc[1] (mg/L)	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
100	0.2	1.4	0.0007	0.005	0.000001	0.00001	0.00006	0.0004	0.00002	0.0001	0.0005	0.003	0.0002	0.001
98	0.7	5	0.002	0.017	0.000003	0.00002	0.0002	0.002	0.00006	0.0004	0.002	0.012	0.0006	0.005
94	4	27	0.013	0.095	0.00002	0.0001	0.001	0.008	0.0003	0.002	0.009	0.067	0.003	0.025
90	10	78	0.036	0.272	0.00005	0.0004	0.003	0.024	0.0009	0.007	0.025	0.191	0.010	0.072

Notes:
1 - Metal Concentrations Estimated with Scale Factor from 2005 Monitoring Data from Cell 1 Pipes (see Table 2.2)
2 - Min and Max based on predicted seepage volumes from unsaturated tailings

Table 3.4: Predicted Concentration Ranges for Constituents in Discharge for Different Degrees of Tailings Saturation and the Range of Anticipated Seepage Volumes (Column Test Scaling Factors Applied to Estimate Metal Concentrations)

Water Saturation (%)	Sulphate (mg/L)		Arsenic[1] (mg/L)		Cadmium[1] (mg/L)		Copper[1] (mg/L)		Lead[1] (mg/L)		Nickel[1] (mg/L)		Zinc[1] (mg/L)	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
100	0.2	1.4	0.00002	0.0001	0.0000004	0.000003	0.00003	0.0002	0.000004	0.00003	0.000002	0.00002	0.000036	0.0003
98	0.7	5.0	0.00005	0.0004	0.000001	0.00001	0.0001	0.0009	0.00001	0.0001	0.000009	0.00006	0.0001	0.0010
94	3.6	27.2	0.0003	0.002	0.00001	0.00005	0.0006	0.005	0.00008	0.0006	0.00005	0.0004	0.0007	0.005
90	10.4	78.0	0.0008	0.006	0.00002	0.00015	0.002	0.013	0.0002	0.002	0.0001	0.001	0.0020	0.015

Notes:

1 - Metal Concentrations Estimated with Scale Factor from the Tailings Column Test Results (see Table 2.2)

2 - Min and Max based on predicted seepage volumes from unsaturated tailings

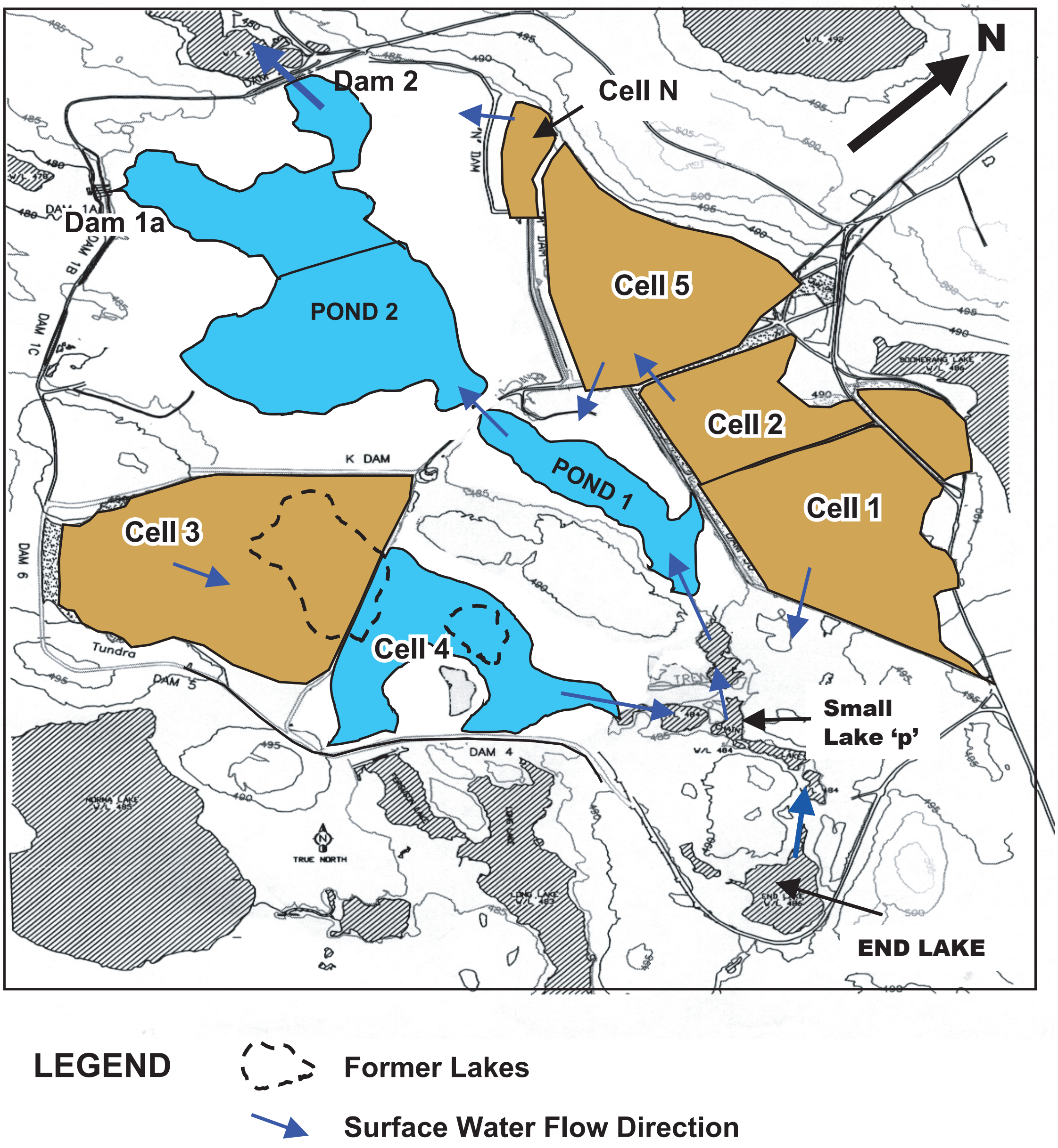
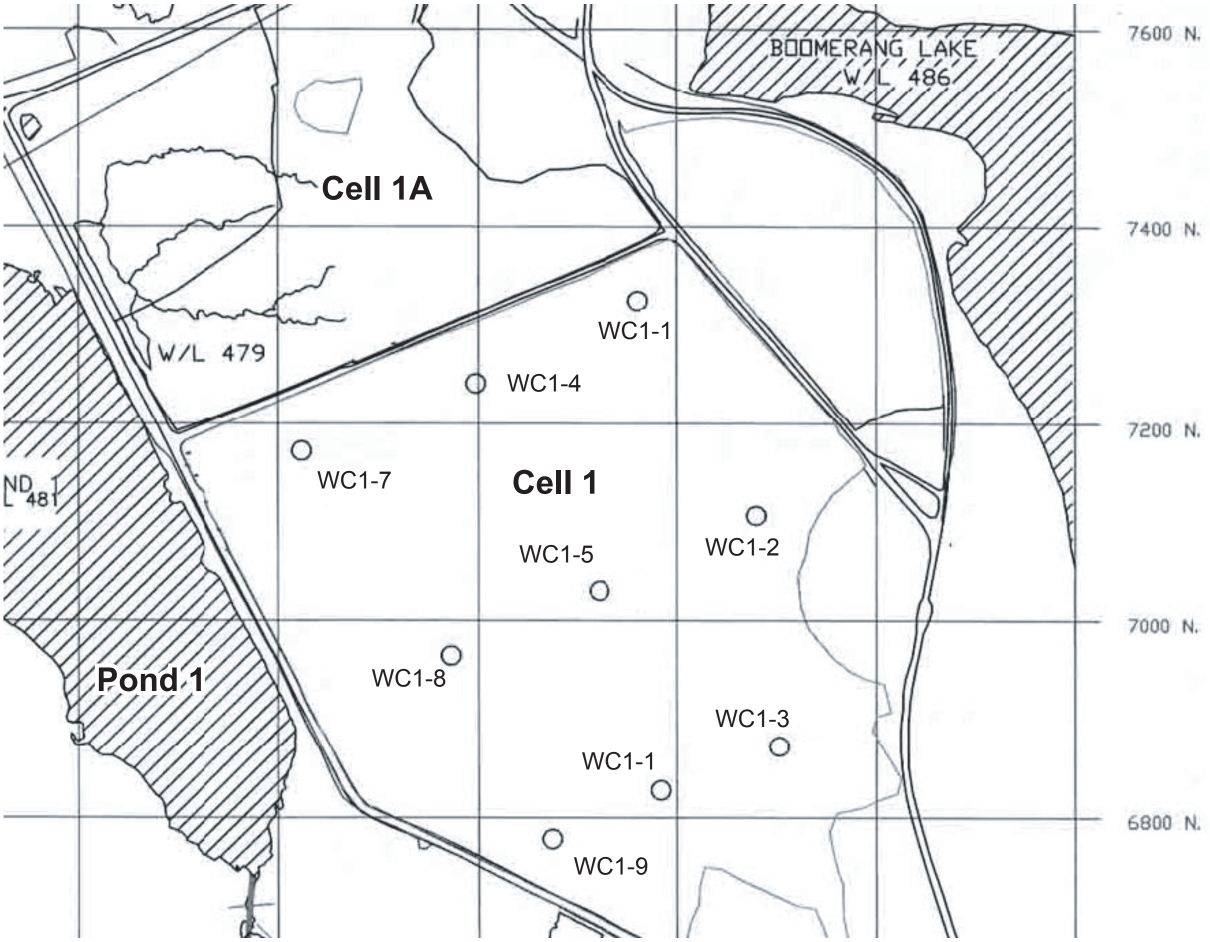


Figure Source: After Holubec (2006b)

Kinross - Lupin Mine

Location of Tailings Cells and TCA Surface Water Flows After Closure

EcoMetrix INCORPORATED	March 2006	**Figure 1.1**



Base Figure Source: Holubec (2005) Closure Plan for Tailings Containment Area

Kinross - Lupin Mine

Location of Pipes Installed in Cell 1 Cover in 2003

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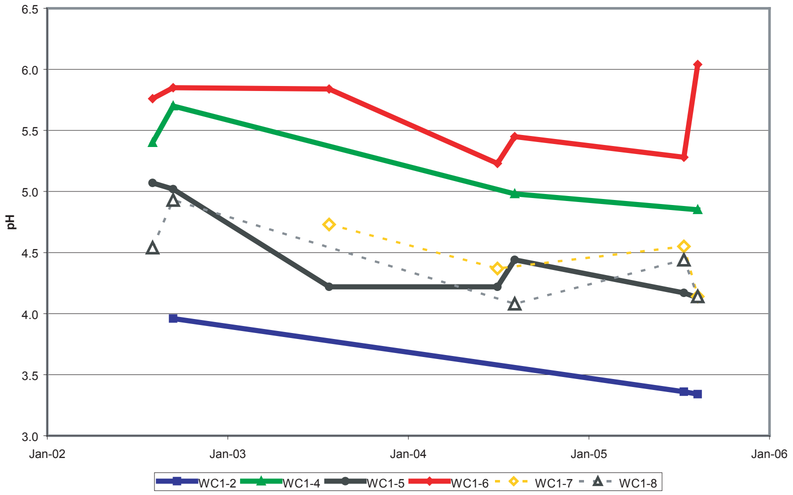
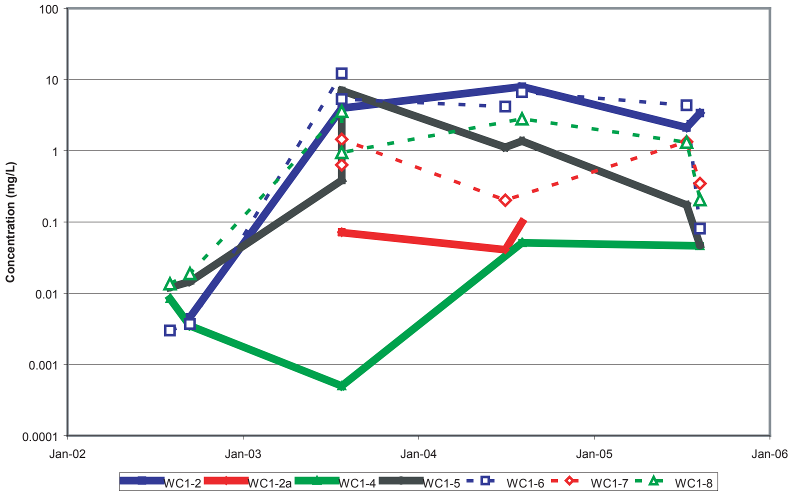
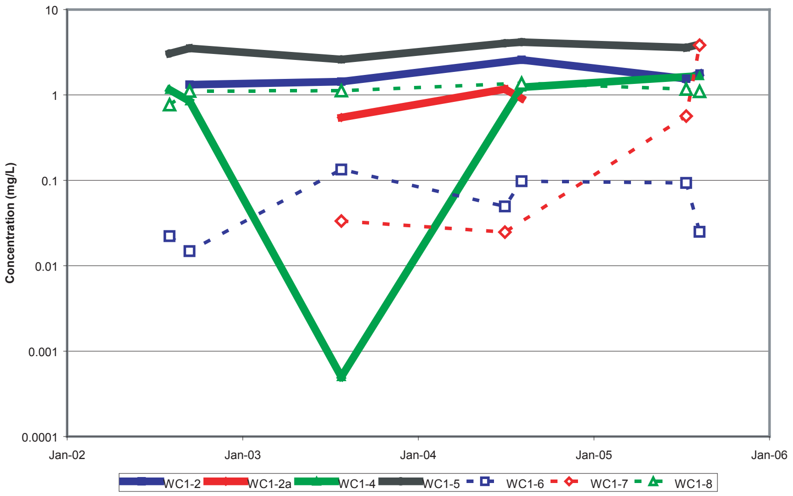
Figure 2.1



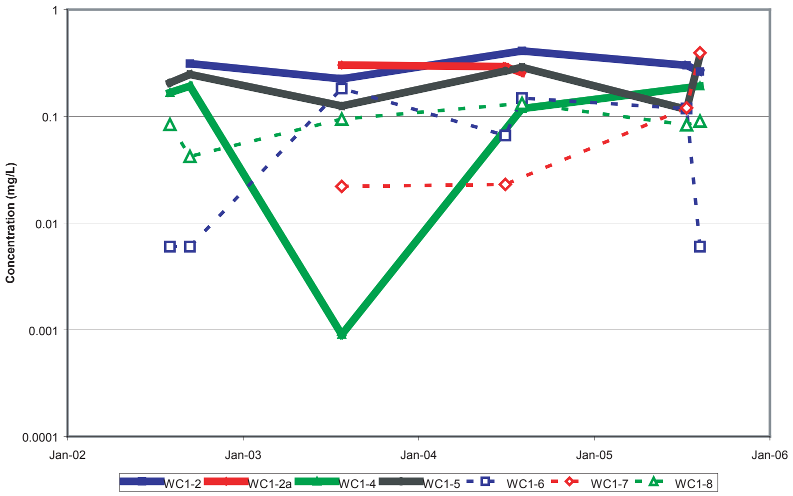
Cell 1 Water Quality - pH



Cell 1 Water Quality - Arsenic



Cell 1 Water Quality - Nickel



Cell 1 Water Quality - Copper

Kinross - Lupin Mine

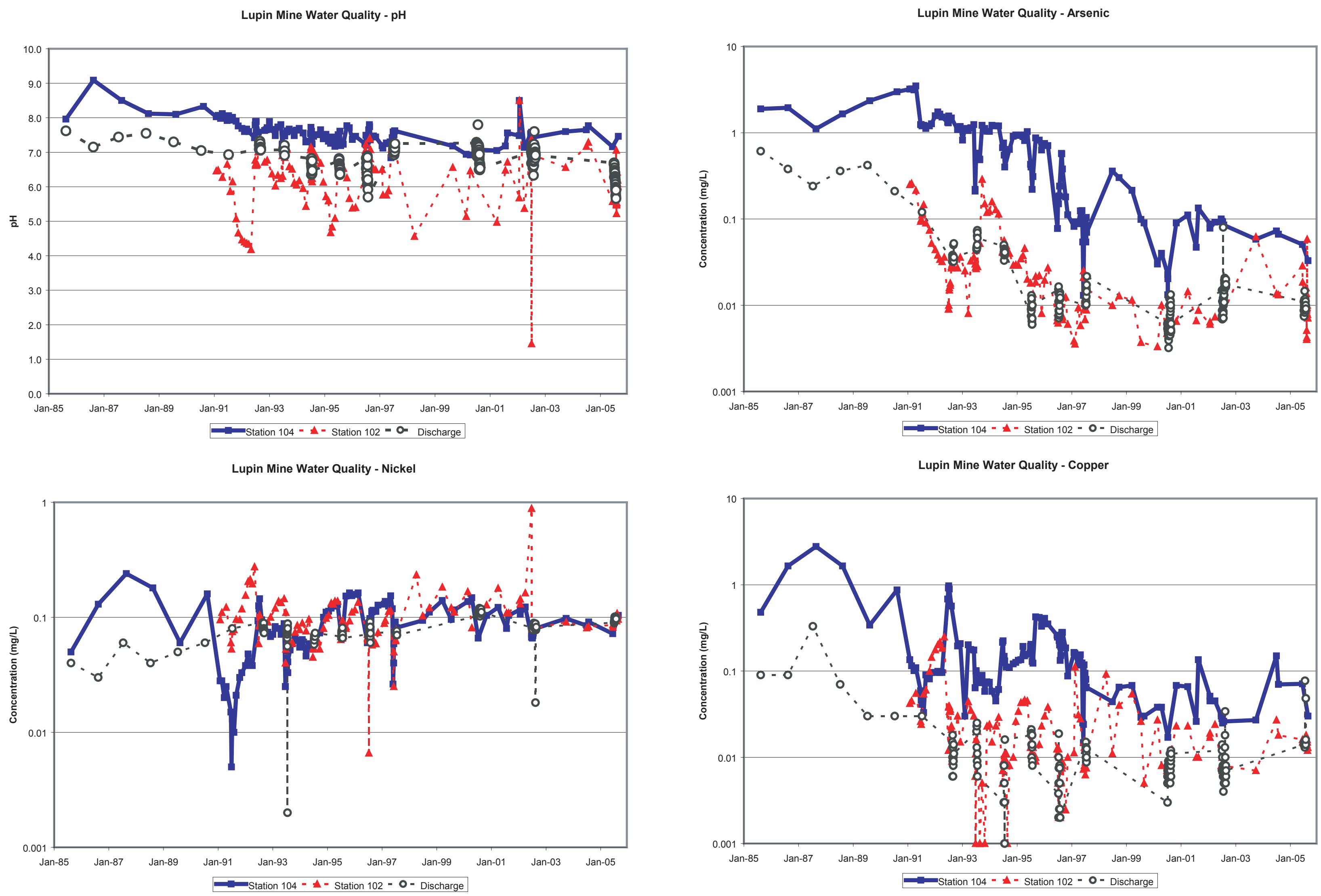
Summary of Cover Porewater Chemistry
in Cell 1

EcoMetrix INCORPORATED	March 2006	**Figure 2.2**

Kinross - Lupin Mine

Surface Water Quality Sampling Locations

EcoMetrix INCORPORATED	March 2006	**Figure 2.3**



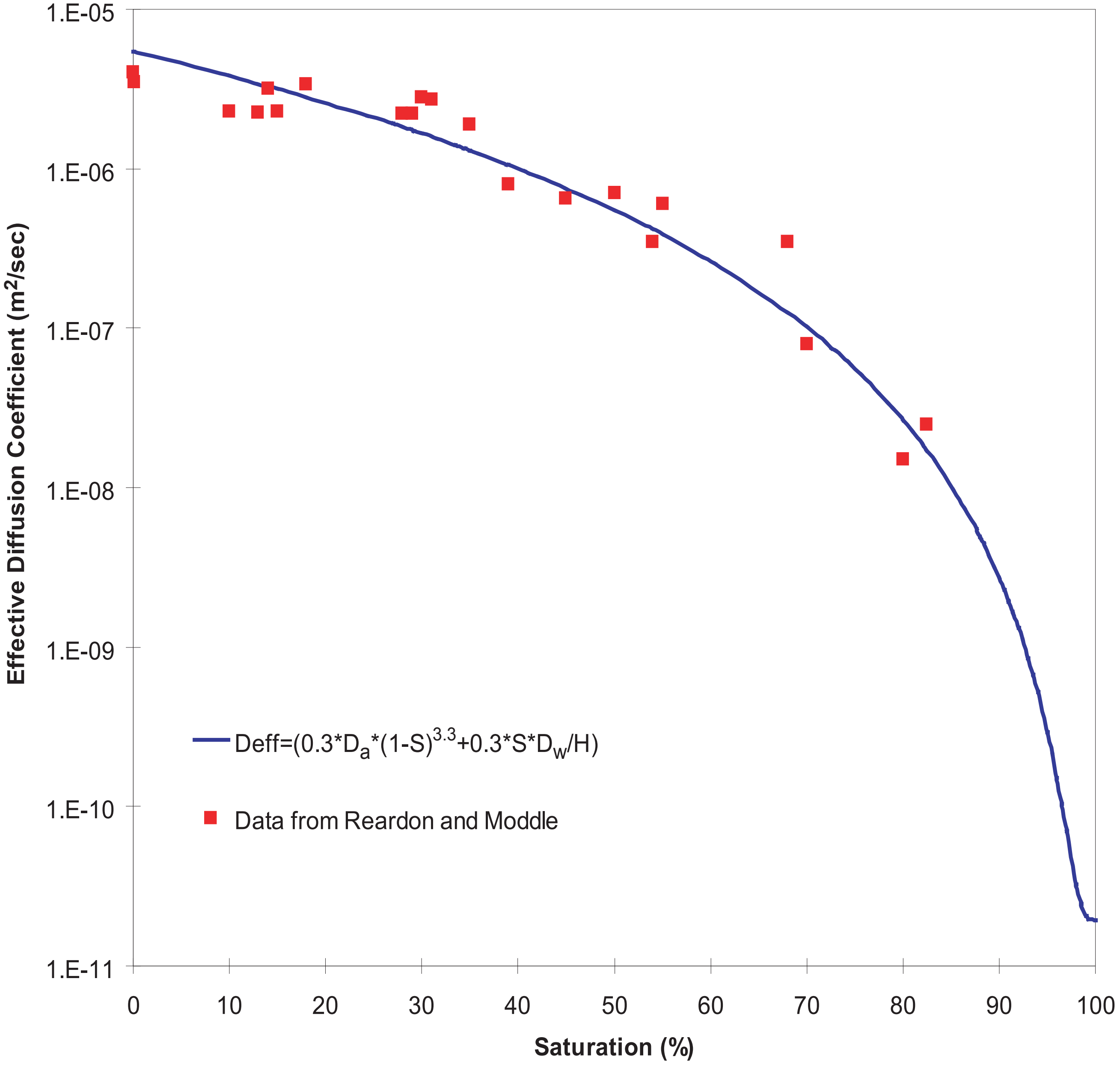
Kinross - Lupin Mine

Summary of Surface Water Quality at the Lupin Mine

EcoMetrix INCORPORATED

March 2006

Figure 2.4



Kinross - Lupin Mine

Effective Diffusion Coefficient for Oxygen in Tailings as a Function of Degree of Saturation (from Elberling et al., 1993)

EcoMetrix INCORPORATED	March 2006	**Figure 3.1**